DETERIORATION OF THE FLORIDA BAY ECOSYSTEM: AN EVALUATION OF THE SCIENTIFIC EVIDENCE

Report to the Interagency Working Group on Florida Bay

by

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Florida Bay Scientific Review Panel

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Executive Summary

This report to the federal-state Interagency Working Group on Florida Bay was prepared by a panel of scientists invited by the Assistant Secretary of the Department of the Interior to provide an objective analysis of the deterioration in the Florida Bay ecosystem to help guide management and research priorities.

Florida Bay has undergone changes during the past decade which have been unprecedented within the period of recorded observation and reflect a degradation of the ecosystem, in terms of its productivity of living resources, biodiversity and stability. Seagrasses have died over large areas and blooms of microscopic algae have occurred with increasing frequency and intensity, turning the once clear waters a turbid green. Populations of water birds, forage fish, and juveniles of game fish species seem to have been significantly reduced, catches of pink shrimp have declined, and many sponges have died, potentially threatening a significant decline in the catch of spiny lobsters. Because the freshwater flow through the Everglades into Florida Bay has been greatly reduced by consumptive use and drainage out of the watershed, much concern has been directed to this as the root cause of the deterioration of the Bay ecosystem.

The Panel examined the evidence (published and presented in oral testimony) to support 11 hypotheses stated or implied in the explanations of the degradation of the Florida Bay ecosystem offered by various scientists and concluded the following:

1. Significant reductions in the amount of fresh water entering Florida Bay through the Everglades have occurred and the timing of delivery has been altered, affecting the salinity in areas of northeastern Florida Bay. However, based on the evidence available, hypersaline conditions (salt concentration higher than that of seawater) in the remainder of Florida Bay do not seem to have intensified as a result of these reductions in freshwater inflow.

2. Qualitative observations suggest that the lack of major storms in the region over the last 30 years may have resulted in significant accumulation of calcareous muds and entrained nutrients.

3. Flushing of the waters has probably decreased by some unknown amount as a result of land filling along the Keys and mudbank shoaling. Except for the northeastern Bay, reductions of freshwater flows probably had no significant impact on the flushing rate of Florida Bay.

4. High salinity in central and western Florida Bay could have contributed to seagrass mortality by adding additional physiological stress to the dense beds of turtle grass, but salinity in the affected areas was not observed to exceed that in similar dry periods in the past.

5. There is no evidence to suggest that disease was the cause of seagrass mass mortality except possibly as a secondary contributing factor to other stressors.

6. A reported increase in seagrass density prior to the die-offs could have made the plants more susceptible to metabolic stress from high temperatures, high salinity and low oxygen levels.

7. Light limitation by algal growth was not the likely cause of the early mass mortality of seagrasses, but, as phytoplankton blooms intensified and spread, may have contributed to the further mortality and reduced growth of seagrasses.

8. There is a lack of scientific consensus that increases in Bay salinity are responsible for the observed mangrove die-off.

9. The most likely source of nutrients stimulating blooms of blue-green algae in central and eastern Florida Bay is release from sediments (phosphorus and nitrogen) following mass mortality of seagrasses. Of particular concern is phosphorus enrichment, because the supply rate of this nutrient may control microalgal growth in this area. Long water retention time and high concentrations of dissolved and particulate organic matter may also contribute to conditions which favor such blooms. Algal blooms to the west, however, seem to have predated the seagrass die-off and may be stimulated by long-term increases in land-based inputs of nutrients (especially nitrogen).

10. Changes in salinity seem to have had major effects on the distribution and productivity of organisms of the coastal transition zone along northern Florida Bay, but there is little evidence that these effects extend into the open Bay.

11. The combined effects of seagrass die-off, phytoplankton blooms, and changes in low salinity transition habitats on the living resources of the Bay have been substantial and should continue until these conditions are reversed.

The Panel believes that the dichotomy erected between reduction of freshwater inflows and nutrient enrichment by human activities as the causes of ecosystem deterioration is oversimplified and interferes with full understanding and effective solution of the problems. Elements of both "theories" may be in operation as may other factors such as occlusion of water flow by construction of the Flagler railway and climatic variations. Furthermore, both the level and coordination of research and monitoring have been insufficient for comprehensive decision making for this nationally and regionally important natural resource.

Although the preponderance of evidence indicates that the ecosystem of northeastern Florida Bay would benefit by restoring the amount and timing of freshwater flow through Taylor Slough and the Eastern Panhandle/C-111 basin, the benefits to the entire Bay (i.e., in allowing seagrasses to recover and eliminating plankton blooms) are uncertain. It is unlikely that this action would eliminate western Bay algal blooms, for example. Nonetheless, there are many compelling reasons to believe that such a strategy would improve wetland conditions in the Everglades and restore the ecological functioning of the coastal transition zone. Incremental restorations of flows can be treated as experiments (reversible if necessary) which, with careful monitoring of effects, could guide future management of the Bay.

The ecosystems from the Kissimmee River, through the Everglades and the Bay and onto the barrier reefs off the Keys are, in fact, connected and constitute an interdependent landscape-seascape, but have been viewed and managed as if they were in isolation from one another. What is now needed is a broader ecosystem perspective which integrates the watershed, the Bay, and the Keys and reef. The consequences of flood control, agriculture and Everglades wetlands management on delivery of fresh water and nutrients to the Bay and the interrelationships between the portion of Florida Bay within Everglades National Park and the adjacent Florida Keys National Marine Sanctuary illustrate the need for this broader ecosystem perspective in science and management.

Critical information needs and suggested approaches in research, monitoring and modeling are identified for water flow and characteristics; nutrients, plant growth and blooms; seagrasses and mangroves; and living resources. Many of these needs and approaches are similar to those included in a recent research program plan by National Park Service and in recommendations from a National Oceanic and Atmospheric Administration workshop. These agency plans have been uncoordinated and are not organized around tests of critical hypotheses to the degree the Panel feels is necessary. The next step in developing a more comprehensive, objective, focused and coordinated science strategy, which could gain governmental and public support, should be an integration and honing of the Panel's recommendations and those of the NPS plan and NOAA workshop report. The resulting science strategy should be appropriately balanced among research, monitoring and modeling; should provide for sustained support; and should involve the coordinated contributions of state and federal agencies and regional universities.

Reasons for Concern

Florida Bay is the large (2200 km^2), shallow (average depth less than 1 m) coastal lagoon lying between the southern tip of the mainland of Florida and the Florida Keys (Figure 1). It is of great national significance for several reasons. Florida Bay, the nearby terrestrial and wetland environments of southern Florida, and the Florida Keys and associated coral reefs together constitute the only tropical environments in the continental United States. Essentially the entire Bay is under direct management responsibility of the Federal Government, either the National Park Service, as part of the Everglades National Park, or the National Oceanic and Atmospheric Administration, as part of the Florida Keys National Marine Sanctuary. This ecosystem also harbors various threatened or endangered plants, fishes, birds, mammals and reptiles.

Florida Bay is a dynamic ecosystem and has undergone great natural variation over the past thousands of years due to long-term changes in climate and sea level[**1**]and during this century as a result of climatic cycles and storms[**2**]. Substantial disturbance, both from hurricanes and variations in freshwater inflow, is, in fact a natural part of the ecology of Florida Bay. However, the changes that have been observed in Florida Bay from at least the late 1980s have been unprecedented within the period of recorded observation and reflect a degradation of the ecosystem, in terms of its productivity of living resources, biodiversity and stability.

Beginning about 1987, seagrasses, large vascular plants rooted in bottom sediments which carpet the bottom of most of the Bay, began to die[**3**]. This die-off continues and has now affected an area as large as 100,000 acres (40,000 hectares or about 18% of the total area of the Bay)[**4**]. Blooms of microscopic algae suspended in the water have occurred with increasing frequency and intensity, extent and duration, turning the once clear waters a turbid green[**5**]. Populations of water birds, forage fish, and juveniles of game fish species seem to have been significantly reduced in the eastern portions of the Bay where fresh water flowing from the Everglades is normally mixed with saline Bay water[**6**]. Catches off the Tortugas of pink shrimp, which spend their early life in Florida Bay and other shallow water regions, have declined dramatically[**6**]. Many large sponges attached to the Bay bottom died, potentially threatening a significant decline in the catch of spiny lobsters, the juveniles of which use the sponges as critical habitat[**7**].

Several scientists and other observers have argued that most of these changes are related, one causing another, and have as a root cause changes in the freshwater flow--both its quantity and timing--through the Everglades into Florida Bay[**3,6,9**]. Other scientists have suggested that the changes may be manifestations of natural cycles, including the frequency of hurricanes[**9, 10**]; may be related to filling in and development of the Florida Keys[**10**]; or are caused by greater infusion of plant nutrients, particularly forms of nitrogen and phosphorous, from the watershed[**11, 12**]. Understanding the causes and relationships of these various changes in the ecosystem is, of course, key to determining how to protect the Bay from further deterioration and how to restore its characteristics and productivity. In specific, would restoration of freshwater flows through the Everglades reverse the deterioration of the Bay?

Nature of This Evaluation

This evaluation was conducted at the request of Mr. George T. Frampton, Assistant Secretary for Fish and Wildlife and Parks of the U.S. Department of the Interior, who appointed the authors of this report as the Florida Bay Scientific Review Panel. The goal of the Panel was "to provide an unbiased and credible analysis of the deterioration in the Florida Bay ecosystem to help guide management and research priorities...by reviewing the body of scientific, historical and anecdotal literature on Florida Bay and receiving oral testimony about the causes of the current decline." Specifically, the Panel was asked to review the evidence on the degradation of the Bay ecosystem, including, but not limited to: the decline in seagrass communities; increases in algal blooms; die-off of sponges; increases in nutrient levels; and the decline of aquatic organisms, including the pink shrimp. Further, the Panel was asked to review the relationship between these events and the freshwater inputs to the Bay and review the draft research plan developed by the Everglades National Park and the Interagency Working Group on Florida Bay. Mr. Frampton charged the Panel with producing a report of our findings and recommendations to the Interagency Working Group on Florida Bay; this is that report.

The time available to the panel for this evaluation was very short. We received an assortment of background publications on Florida Bay in early August, 1993; participated in an overflight and small boat tour of the Bay and adjacent wetlands; received one day of testimony from scientists, managers and members of the public on August 17; and prepared this report over the following four weeks. Consequently, the depth of our evaluation has been commensurably limited. We could not analyze or reanalyze data. We could not read and critique all of the scientific literature. Our evaluation is shaped by our collective scientific judgment and experience as well as the literature and presentations we have been able to assimilate. As a result of our time constraints, predictably it will emerge that we did not take into account certain data or did not seem to understand someone's explanation. For this we apologize.

We have approached the scientific and anecdotal evidence made available to us skeptically, for this is an attitude demanded by the scientific method. Furthermore, much of the scientific information and interpretations concerning recent phenomena were available only in unpublished manuscripts or from oral presentations and have not undergone rigorous peer review. We have tried to dissect the sometimes complicated scientific explanations into their component assumptions, inferences and beliefs and to state them as 11 simple hypotheses against which we could critically weigh the evidence. But mindful of the risk of paralysis which can result from extreme scientific uncertainty, we have attempted to draw conclusions to guide environmental managers which are both based on evidence and reasoning and averse to risking further deterioration. Finally, because much of the intended audience of the report is comprised of non-scientists, we have attempted, to the extent practicable, to state and evaluate phenomena, evidence and research in a non-technical fashion, but with extensive technical references provided as endnotes following the report narrative.

Evaluation of Scientific Hypotheses

For each of 11 hypotheses stated or implied in the explanations of the ecosystem deterioration offered, we below briefly evaluate the existing information, including quantitative data, qualitative observations often passed on anecdotally, and interpretations inferred by scientists who have studied Florida Bay. Although interpretations based on the analysis of quantitative data are generally more readily accepted, long-term, qualitative observations by Park managers, fishermen and fishing guides often provide very convincing evidence.

Freshwater Inflow, Water Circulation and Salinity

1. **Reduced freshwater flows through the Everglades have elevated the salinity of Florida Bay and reduced the extent of low-salinity, estuarine conditions.**

   Freshwater is delivered to Florida Bay through Taylor and Shark River Sloughs and coastal drainage outside of these sloughs. Consumptive uses of water and the diversion of flows by the network of water supply and flood control canals across the Atlantic Coastal Ridge and out of Taylor Slough and into Barnes Sound via the C-111 canal have resulted in a significant reduction of the pre-development flows of fresh water into Florida Bay. For example, models have been used to estimate that less than one-fifth of the "natural" surface water flow through Taylor Slough and into Florida Bay is now discharged under "managed" conditions (31,500 ac-ft/yr versus 162,500 ac-ft/yr or 4 million versus 20 million m^3) [**13**]. At least for the Taylor Slough system, actual surface flow measurements seem to track the model predictions under present-day conditions, but few data are available on groundwater flows--an important component of freshwater delivery in this region of porous limestone subsoil. In addition to reductions in the total freshwater flow though the Taylor Slough system into eastern Florida Bay, there have been changes in the timing of this delivery.

   The extent to which changes in freshwater delivery from the Shark River Slough have affected Florida Bay is much less well known. The flow of the Shark River has been significantly reduced from "natural" conditions due to water consumption and diversion upstream, but flows during 1991 and 1992 were nearly three times the annual average for the 1980s[**12**]. This fresh water (an order of magnitude greater in volume than the natural flow through Taylor Slough) enters the coastal zone to the north of Cape Sable, is mixed with saline waters and is transported into Florida Bay via tidal action through Whitewater Bay or, more significantly, through the coastal flow of somewhat brackish water around Cape Sable and into Florida Bay. This net current has been estimated at 2.5 to 3.0 cm/sec through an approximately 1 km wide channel, 1.5 to 2 m deep[**14**]. Thus, the net flow of water from the inner Gulf shelf through this one channel alone would be approximately 48 m^3/sec or about 1.2 million acre-ft/yr (about 40 times the present flow of fresh water through Taylor Slough into the northeastern Bay). Evidence for long-term changes in the freshening effect of

Shark River discharges is indirect and includes lessening of the inclusion of humic substances into coral skeletons in southern Florida Bay since the early 1930s[**15**].

Salinity records, anecdotal evidence from fishing guides and Park personnel, and predictive models linking groundwater levels in northern Taylor Slough to salinity in Little Madeira and Joe Bays [**16**] provide convincing evidence that salinity in the "upper estuary" of northeastern Florida Bay has increased as a result of reductions in freshwater inflow. While under "natural" conditions, these regions would be expected to experience salinity usually less than 20 $^{o}/_{oo}$, salinity has usually been above 20 $^{o}/_{oo}$ since at least the mid 1960s and has commonly been significantly hypersaline (40-50 $^{o}/_{oo}$ compared to the salinity of the open sea of about 35 $^{o}/_{oo}$).

The relationship between salinity levels in the open central Bay, which typically show the most hypersaline conditions, and reductions in freshwater discharge is much less obvious. Discontinuous salinity measurements made in the more open eastern, central and western Florida Bay from 1955 through 1990 show no obvious changes in salinity. Hypersaline conditions have characterized the central and western Bay at least since the mid 1950s [**17**]. Yet unpublished analyses of the oxygen isotopes in a coral skeleton in southwestern Florida Bay have been interpreted as showing no evidence of changes in salinity over longer time scales[**10**], but additional measurements and scrutiny of the assumptions on which this interpretation is based are required. Interannual variations in freshwater flow do, on the other hand, indicate that large increases in freshwater inflow during extended periods of heavy rainfall (e.g. during 1983) can eliminate hypersaline conditions in the eastern and central Bay [**17**], but hypersaline conditions still developed during dry years before most of the flow through Taylor Slough was diverted down the C-111 canal.

In summary, **significant reductions in the amount of fresh water entering Florida Bay through the Everglades have occurred and the timing of delivery has been altered**. Moreover, there is convincing evidence that **this has affected salinity levels and variations in Joe and Little Madeira Bays and the nearby areas of northeastern Florida Bay.** However, **there is presently a lack of unambiguous evidence that the development of hypersaline conditions in the remainder of Florida Bay has intensified as a result of these reductions in freshwater inflow**.

2. The relative lack of storms over the past three decades have caused a buildup of sediments, nutrients and organic material in the Bay.

There have been relatively few hurricanes and other storms impacting Florida Bay since 1965. Such storms may be a major factor in that they resuspend and transport sediments and organic detritus out of the shallow Bay. Absent such erosional events, the prodigious production of calcareous sediments by organisms and the efficient trapping of these sediments by seagrasses and mangroves may effectively choke up the Bay reducing water circulation and thereby affecting salinity distribution, water temperature, nutrient supply, and movement of marine organisms and their larvae.

This is of particular concern in Florida Bay because it consists of a number of basins which are to varying degrees isolated by mud banks which form on top of underlying limestone deposits. Accretion of sediments on these very shallow and nearly continuous mud banks further isolate the basins.

There is much anecdotal evidence, mainly based on the difficulties of small boat access and observations of fishing guides [**18**], of shoaling of portions of the Bay, but few quantitative measurements of accretion. The frequency of hurricanes impacting the area has been clearly less over the last 30 years than earlier in the century[**2, 10**]. Even Hurricane Andrew which struck in 1992 had little disruptive effect on the sediments of the Bay because it was so compact and fast moving and crossed the Florida Peninsula well north of Florida Bay. The "storm of the century" which struck the Florida and the U.S. East Coast in March, 1993, reportedly had a greater impact on Florida Bay than Andrew[**17**].

Although quantitative evidence is lacking, **qualitative observations suggest that the reduced occurrence of major storms in the region over the last 30 years has resulted in significant accumulation of calcareous muds and entrained nutrients**. There is **no direct evidence that unusual amounts of undecomposed organic detritus also accumulated during this period**.

3. **Retention time for water flowing through the Bay has been increased (decreased flushing rate) by restrictions to flow through channels between the Keys, shoaling of the Bay, and reduced freshwater inflows.**

A decrease in the flushing rate of the Bay could have widespread consequences to this ecosystem. This could increase the Bay's salinity by allowing more evaporative concentration of Bay water, especially if this is coupled with decreased freshwater inputs. The greater stagnation could also result in greater temperature extremes as a result of heating on bright summer days or cooling during cold frontal passages during the winter. Increased retention time would also have consequences to the supply and recycling of plant nutrients and the movements of marine organisms such as the larvae of fish and shrimp in the Bay.

Water exchanges among the Gulf of Mexico, Florida Bay and Hawk Channel, which runs between the Keys and the barrier bank reef on the Atlantic side, are very poorly understood, but undoubtedly play a very important role in the salt balance, nutrient dynamics and ecology of Florida Bay[**19**]. Water circulation in Florida Bay is characterized by persistent flows around Cape Sable and into the Bay from the west. For most of the western half of the Bay, currents are presumed to move southerly, although there are few, if any, direct measurements to support this pattern. The presence of extensive mud banks should restrict this flow from influencing the eastern Bay. Currents on the Bay side of the Upper and Middle Keys are presumed to flow to the southwest. These flows toward and along the Keys set up a strong net flow from the Bay toward the Atlantic side through the channels between the Keys[**14**]. Thus, constrictions of the channels between the Keys could reduce this flow through the Bay. The chronology of oxygen isotope ratios in the coral skeleton in the southwestern Bay has been interpreted to represent a major change in retention time of water in the Bay as a result of construction of the Flagler railway around 1910[**10**]. At this time, there was extensive filling for construction of the railbed, closing some channels and narrowing others.

Circulation could also be inhibited by the aforementioned shoaling due to sediment accretion on the mudbanks, while it may have been facilitated to some degree by cuts through the banks for small boat passage. This could have a very great effect on the flushing rates for basins in the central and eastern Bay, but his effect has not been measured or estimated.

A third possibility is decreased flushing rate by decreased freshwater inflow. If one assumes that flow through Taylor Slough has been reduced by 130,000 ac-ft/yr or 16 million m^3[**13**] and that the average depth of the Bay is somewhat less than 1 m, the total diverted flow during a full year would, on the average, be sufficient to replace only about 10% of the volume of the Bay. Tidal and wind driven flows surely exchange far more of the Bay's volume, probably on the scale of days. Also, because the Bay is shallow and well mixed vertically, there should be no appreciable gravity flows of the type found in deeper, stratified estuaries through which the flushing effect of freshwater inputs is greatly magnified.

Some increase in water retention time in Florida Bay as a result of land filling along the Keys is likely. Mudbank shoaling may also have further decreased flushing of isolated basins in the Bay. But the extent to which flushing may have been decreased by channel constriction or shoaling is unknown. Except for the regions of the northeastern Bay directly affected by the Taylor Slough discharge, reductions of freshwater flows probably had little impact on the flushing rate of the Bay.

Seagrass Mortality

4. High salinity was and is the primary cause of seagrass mass mortality.

The first noted, extensive mortality of seagrasses occurred in Rankin Basin in central Florida Bay, the region of most hypersaline conditions[**3**]. Salinities averaging about 50$^{o}/_{oo}$ and as high as 70$^{o}/_{oo}$ (i.e. up to twice the concentration of salts as sea water) are characteristic of this area. Although the dominant seagrass species, *Thalassia testudinum*, commonly known as turtle grass, can tolerate some hypersaline conditions, it has been suggested that the extreme salinities in central Florida Bay, perhaps in combination with high temperature and other physiological stresses, caused the observed mortalities. Temperatures in excess of 32^{o}C have been shown to interfere with *Thalassia*'s ability to maintain ionic conditions within its cells[**20**]. Such osmoregulation is a critical physiological function for an organism confronted with hypersaline conditions.

It should be noted that mass mortality of seagrass reportedly continued after the end of the long-term drought in 1990 brought somewhat lower salinities[**21**]. Furthermore, salinity levels in central or western Florida Bay during the late 1980s and early 1990s were not observed to be higher than those observed during periods in the 1950s, 1960s and 1970s[**17**], despite the increasing diversion of freshwater from the Bay and the drought in effect during the 1980s. The reportedly higher standing crop of *Thalassia* which had developed by the late 1980s--perhaps as a result of the lack of storms--may have created a condition wherein the metabolic demands (photosynthesis>respiration) of the seagrass could not be sustained when confronted with the additional burden of high salinity and temperature[**9**]. This explanation evokes a complex interplay of factors, which while consistent with the observed patterns of mortality, has not been experimentally demonstrated.

High salinities in central and western Florida Bay could have contributed to seagrass mortality. However, less dense beds did not seem to have been affected by comparably hypersaline conditions. Furthermore, mortality in some dense beds was observed after hypersaline conditions abated in 1990. Furthermore, salinity in the affected areas was not observed to exceed that in similar dry periods.

5. **Disease organisms were and are the primary cause of mass mortality of seagrasses.**

A pathogenic slime mold, *Labyrinthula*, was presumably the cause of widespread epidemic which decimated eelgrass in the temperate waters of Europe and North America in the 1930s. *Labyrinthula* has been isolated from seagrasses in the affected area of Florida Bay, raising the possibility that this pathogen is the primary cause of *Thalassia* mortality. But *Labyrinthula* commonly occurs in healthy seagrasses and it did not cause plant death in laboratory experiments[**21**]. **There is no evidence to suggest pathogens as the cause of seagrass mass mortality in Florida Bay except as a secondary contributing factor to other stressors**.

6. **Conditions allowed for dense growth of *Thalassia* beds which created a situation in which the large biomass could not be physiologically sustained.**

Turtle grass (*Thalassia*) may have become more prevalent and occurred in denser beds in the 1980s than in the previous period, ostensibly as a result of higher and less variable salinity (at least in the northeastern Bay) and the lack of storms[**9**], although nutrient enrichment has also been proposed as a cause of the observed increase in biomass[**12**]. It has been widely observed that *Thalassia* will out compete other seagrasses, particularly shoal grass (*Halodule wrightii*), if the salinity conditions are not below its tolerance limits and disturbances are infrequent. However, a significant increase in *Thalassia* biomass would probably also require some alleviation of nutrient limitation[**22**]. If the *Thalassia* bed is the disturbed or dies off, *Halodule* colonizes and the successional sequence begins again. Both the *Halodule* to *Thalassia* succession and the *Halodule* recolonization have been observed in the Bay. But the biomass of *Thalassia* in areas which experienced mass mortality was well within the range of biomass for other beds in Florida, beds which sustain themselves for decades without die-offs.

It was argued that biomass, particularly of below-ground rhizomes, had grown to a point wherein the respiratory demands (R) of the plant tissue could not be met by photosynthetic production(P)[**9**]. However, below-ground biomass cannot develop unless there is a positive carbon balance from photosynthesis. Seagrasses have a number of adaptations to metabolic stresses, including food storage in rhizomes, defoliation without death of the plant when confronting a significant deficit of P compared to R, and fermentation of carbohydrate stores in the rhizomes when confronted by anoxic conditions. Explanation of the observed mass mortality would seem to require additional external stressors (temperature, salinity, etc.) as well as dense plant growth.

A reported increase in seagrass density prior to the die-off could have made the plants more susceptible to metabolic stress from high temperature, high salinity and low oxygen.

7. **Lack of sufficient light because of the growth of epiphytic and planktonic algae is the principal cause of mass mortality of seagrasses.**

Studies in other parts of the world have demonstrated that nutrient enrichment from human activities frequently results in the loss of seagrasses. The nutrients stimulate the growth of both microscopic plants in overlying waters and algae attached to the blades of the seagrass and, in the process, absorb light needed for photosynthesis by the seagrass. In the case of Florida Bay, however, the first observations of heavy mortality of seagrasses in 1987 preceded the observations of dense phytoplankton blooms in those areas[**3,21**]. Also, the heavy fouling of the seagrass by attached or drifting algae typical in overenriched conditions has not been observed except near the Keys inhabited by humans[**9**,**7**].

There is no evidence that light limitation by algal growth was the cause of the mass mortality of seagrasses observed in the open Bay during the late 1980s, but as phytoplankton blooms have been intensifying and spreading, they may be contributing to the further mortality and reduced growth of seagrasses.

Mangroves

8. Increases in salinity have resulted in mortality of mangroves.

The numerous washover isles in Florida Bay are vegetated with species of mangroves and frequently have barren areas in their centers (salt pannes) where evaporation from infrequently flooded soils increases soil salinity to a level not tolerated by the mangroves. Mortality of mangroves around these interior zones has been observed and it has been posited that higher salinities of ambient Bay water were resulting in increasing soil salinity and, thus death, of mangrove trees. Other long-time observers discount this explanation, suggesting that high salinity conditions have long been existent in these mangrove soils[**23**]. Some suggest that the infrequency of hurricanes over the past 30 years has not allowed thinning of the mangroves and has allowed sediment to accumulate on the islands decreasing soil drainage. **There is a lack of scientific consensus that increases in Bay salinity are responsible for the observed mangrove die-off.**

Nutrients and Algal Blooms

9. Nutrients released from sediments after the die-off of seagrasses were and are the principal cause of algal blooms rather than increased nutrient inputs from land.

Based on limited research and monitoring efforts, recent publications[**11**,**22**,**24**] and testimony [**15,12,21**] linking production and nutrient cycling dynamics to water quality and trophic state, Florida Bay appears to be experiencing increasing frequencies and intensities of phytoplankton blooms. Nonetheless, despite this growing scientific and public consensus surprisingly little quantitative historic information exists on the Bay's water quality.

Enhanced bloom activity is suspected of being linked to increased loads of plant nutrients, primarily forms of nitrogen (N) and phosphorus (P), a theme all too familiar in other coastal waters where light is not limiting to primary production. Scientists and managers are, however, remarkably uninformed of the sources, cycling and assimilatory dynamics of enhanced loading, because these aspects of Florida Bay simply have not been studied adequately. A basic issue of contention is the source of the increased nutrient loadings responsible for the more frequent and persistent blooms. Do the nutrients emanate from the massive seagrass die-off, both from the decay of the seagrass and from release of nutrients which have built up in now more erodable bottom sediments? Or is an infusion of nutrients from land-based sources, either from the Everglades watershed or from sewage on the Florida Keys the primary culprit?

The notable lack of information available to us regarding specific nutrient sources, nutrient fluxes to the Bay, and nutrient concentrations within the entire Bay made these questions impossible to answer at this point. However, based on the limited evidence available (water quality monitoring data collected over the past three years were not available to the Panel in a form which allowed interpretation of patterns and trends), both of these sources may be important. There may in fact be two contrasting (in terms of nutrient-production relationships), yet contemporaneous, bloom phenomena taking place with increasing frequency and intensity in Florida Bay. This is consistent with differences in the location, timing, and plankton composition of the blooms. The intense blooms of cyanobacteria (blue-green "algae") in the central and eastern Bay may be more closely related with events associated with the massive seagrass-die offs, including the release of "internal" sources of nutrients which resulted[**8,9**]. On the other hand, blooms such as those observed in the western and southern Bay which are dominated by diatoms (microalgae with silica shells) may have resulted from gradual (years to decades) increases in nutrient loading from a variety of external, anthropogenic sources. Such "chronic" blooms would manifest themselves over a large region and might contribute to an elevated background level of phytoplankton over much of Florida Bay. In either case, restricted intra- and interbasin circulation and increased water retention times (Hypothesis 3) may have affected the bloom potential by playing a critical synergistic role in promoting the establishment, proliferation and persistence of blooms throughout the Bay.

The central and eastern Bay blooms may be characterized as acute and more localized in nature than the western Bay blooms. This does not imply, however, that such blooms could not affect large tracts of the Bay. This "acute" type of bloom appears to be supported by sudden (days to weeks), relatively high nutrient loading events in some of Florida Bay's shallow sub-basins experiencing restricted water exchange with the rest of the Bay and coastal waters. The most notable example is the recent emergence of planktonic cyanobacterial (*Synechococcus* sp.) blooms, which has been closely linked in time and space to seagrass die-off events in the eastern and central Bay [**8,9,21**]. The release of large quantities of P from the sediments is probably particularly important because water in these parts of the Bay are already rich in N compared to P and it is assumed that plant productivity is therefore P-limited [**23**,**24**].

The following speculative scenario, based on knowledge of similar systems rather than direct observation, could be developed to describe processes linking the seagrass die-offs to blooms of cyanobacteria:

- The massive die-off of *Thalassia* in these regions leads to sudden, large releases of both nutrients and dissolved and particulate organic matter (DOM, POM) in isolated sub-basins, both via decay of biomass and destabilization of sediments.
- High DOM and POM concentrations, coupled with long retention, fuels enhanced sediment and water column nutrient (N and P) regeneration and efficient nutrient exchange between benthic and planktonic habitats. The attendant microbial activity reduces oxygen availability to the bottom sediments, further enhancing nutrient (PO_4^{3-}, NH_4^+) release into the water column.

- The synergistic effect of high water retention time and elevated DOC concentrations in combination with the released nutrients favors the establishment and proliferation of cyanobacteria [**25**].
- Environmental extremes including wide swings in oxygen concentration, sulfide release into the water column, light reduction caused by the bloom, high temperature and high salinity act to favor the highly tolerant *Synechococcus*.
- Blooms persist because the limited flushing in affected sub-basins allows effective nutrient regeneration to continue without a significant net loss of either biomass or products of its decay.

In a broad sense, these cyanobacterial blooms are strikingly reminiscent of classic examples of bloom phenomena in nutrient-enriched, shallow lakes exhibiting periodic (summer) long water retention times (> 100 days). Examples include Clear Lake, California, Lake Washington, Washington, Lake Erie during the 1950s and early 1960s, and Lake George, Uganda [**26**].

Anecdotal evidence from lobster and stone crab fishermen working to the west of Florida Bay suggests that the current western Bay diatom blooms may have been presaged by changing water color noted in that area in the late 1970s[**27**]. The first algal blooms were noted by fishermen in 1979, well before massive seagrass die-offs were first observed, and proliferating drifting macroalgae began advancing southwestward toward the Keys in 1983. In the instance of these increasingly-prevalent diatom blooms in the western Bay (near Cape Sable) as well as blooms near the Florida Keys, natural and anthropogenically enhanced nutrient loading from sources external to the Bay, originating from freshwater inputs along the Florida Gulf Coast (e.g. Shark River Slough and rivers to the north), from the West Florida Shelf, or from on-site sewage disposal systems could supply the needed nutrients. Blooms in these regions were reported to be dominated by diatoms (*Rhizosolenia* was mentioned). Remobilized nutrients released from sediments resuspended by wave action along the western margin of the Bay (the region of "chalky" blooms) could also contribute to these blooms.

Nutrient inputs stimulating blooms in the western Bay could result from increased nutrient loading in the Shark River Slough discharge or from discharges by rivers and coastal drainage to the north. Rivers to the north (e.g. Peace River) carry high loadings of phosphorus as they drain areas containing phosphatic rock formations and phosphate mining activities may further increase P loadings to the sea. Drainage from the Everglades, including from Shark River Slough, has characteristically low phosphorus concentrations, because P, but not N, tends to be taken up by wetland plants whose growth is highly P-limited. Thus, waters from the Everglades drainage has very high concentrations of total nitrogen and, particularly, of ammonium but very little phosphorus[**12**, **28**]. Although some denitrification (conversion of nitrate to gaseous nitrogen which returns to the atmosphere) takes place in Everglades wetland soils, most of the nitrogen taken up by plants and microbes appears to be converted to ammonium and exported[**29**].

Given such a scenario, western Florida Bay may be a mixing pot for shelf waters which have high concentrations of available P (in which the phytoplankton may be N-limited) and coastal waters into which the N-rich Everglades water is mixed. Although the volume of flow through Shark River Slough is now lower that "natural" levels, the concentration of nitrogen may be much higher as a result of the heavy use of fertilizer in agricultural areas to the north, waste disposal and atmospheric deposition. Furthermore, freshwater flow through the Shark River Slough greatly increased in 1991 and 1992 compared to the 1980s, potentially increasing N-loading to the coastal zone three-fold[**12**]. At the same time, potentially diminished flushing rates of the Bay may have intensified conditions which increase the recycling of nutrients and intensify bloom conditions(Figure 2).

It is widely assumed that both phytoplankton and seagrass production in Florida Bay is always P-limited based on the relative concentrations of N and P in Bay waters. There are typically 16 N atoms for every P atom in living phytoplankton. Thus it is assumed that if the molar concentration of available forms of N is more that 16 times that of available forms of P, phosphorous should be the nutrient limiting plant growth. Total N:P ratios for central and eastern Florida Bay waters were found to be in excess of 50 and were as high as 140 in the most hypersaline parts of the Bay, suggesting that phytoplankton growth in these portions of the Bay (e.g. the regions of the cyanobacteria blooms) is strongly P-limited[**24**]. However, in the western Bay this ratio was 20 or less, indicating that--especially when considering the fact that not all forms of N or P can be used by the algae and that the required nutritional ratios of N:P vary among algal types [**30**]--either N or P may be limiting to the western, diatom-dominated blooms. Also, silicon (Si) may limit the growth of diatoms, which require it for their siliceous shells, under N- and P-rich conditions. But, because even the simplest of experiments involving the addition of N, P or Si to Bay water (bioassays) have not been conducted, there exists a great deal of uncertainty as to which nutrients are in fact "limiting" and hence controlling bloom development and proliferation.

The western Bay blooms may be characteristic of a troublesome and growing trend of coastal eutrophication, the symptoms of which range from incipient stages of bloom development (barely perceptible increases in chlorophyll accompanied by losses in transparency) to more obvious massive, and problematic concentrations of nuisance taxa (e.g. dinoflagellate "red tides"). The frequency of such blooms seems to be increasing worldwide in response to increased human development of coastal areas[**31**].

In conclusion, **the most likely source of nutrients, especially phosphorus, stimulating cyanobacterial blooms in central and eastern Florida Bay is released from sediments following mass mortality of seagrasses. The presumably long water retention time and high concentrations of dissolved and particulate organic matter may also contribute to conditions that favor such blooms. Algal blooms to the west, however, seem to have predated the seagrass die-off and may**

have been stimulated by long-term increases in land-based inputs of nutrients (particularly nitrogen). However, knowledge of the causes and dynamics of these blooms is yet rudimentary and awaits experimental determination.

Effects on Living Resources

10. Changes in salinity have resulted in changes in the composition and productivity of the biota.

Particular attention has been paid to how long-term changes in salinity may have affected the biota of the freshwater-marine transition zone along the mainland shore in northern Florida Bay. As discussed under Hypothesis 1, this is the region which has clearly been experiencing higher salinity under the present water management scheme. Also the transition zone provides an important nursery habitat for sport fish, such as spotted sea trout, red drum and snook, and for the endangered American crocodile and is a critical foraging area for wading birds, ospreys and eagles.

The evidence that increased salinity has affected the distribution and productivity of this biota is indirect and less than complete, but nonetheless makes a credible case. Differences in the seasonal succession of submerged aquatic vegetation have been observed between areas subjected to freshets and those influenced by freshwater diversion; few juveniles of sport fish have been collected in mangrove edge habitats in the northeastern Bay; annual catches of spotted seatrout and red drum and recruitment of snook are correlated with rainfall during postlarval periods; crocodile nesting patterns have changed; nesting colonies of several wading birds have collapsed and been relocated to the north; and nesting pairs of ospreys have been reduced from 200 to 70 between the 1970s and 1990s[**6**]. Also, catches of pink shrimp on the Tortugas fishing grounds have been shown to be highly correlated with freshwater inflow as reflected by water level in the Shark River Slough[**32**]. Pink shrimp landings have dramatically declined since 1980, dropping below 5 million pounds per year during 1988-1991 from the average of 10 million pounds during 1963-1980[**7**]. However, it is thought that the primary nursery of juvenile pink shrimp is in the seagrass beds of the western Florida Bay rather than the coastal transition zone. Thus, the recent decline of shrimp catches may be more directly related to the loss of seagrass habitat (but see below).

In summary, **changes in salinity (increased incidence of hypersalinity and decreased extent of brackish conditions) seem to have had major effects on the distribution and biota of the coastal transition zone along northern Florida Bay, but there is little evidence that these effects extend into the open Bay**.

11. Loss of seagrass and the proliferation of algal blooms have adversely affected living resources, including pink shrimp, spiny lobsters, and sponges.

Several important living resources of the Florida Bay seem to be affected by the complex ecosystem deterioration observed over the past decade and perhaps even earlier. As mentioned above, pink shrimp catches have declined dramatically and because juvenile pink shrimp seem to especially utilize the seagrass habitats of western and central Florida Bay, the massive die-off of seagrass in these regions may seem a likely cause. But the decline in the shrimp catch seemed to precede the first observations of mass mortality of seagrass in 1987 by at least two years[**7**]. Areas which have experienced significant seagrass die-off also support lower densities and fewer species of fishes[**7**].

Large mortalities of a number of species of sponges along southern Florida Bay have been observed immediately following dense phytoplankton blooms in 1991 and 1992-1993[**8**]. Because several species of sponges were similarly affected and the mortalities were so coincident with cyanobacterial blooms, it is highly likely that the blooms were the cause of mortality, either through clogging of the filtering mechanisms of the sponges or through the toxic effects of the cyanobacteria. It was also observed that the sponge die-off resulted in reduction of refuge habitat used by juvenile spiny lobster and, therefore, fewer juvenile lobsters[**8**]. It is still too early to say whether this will translate into lower catches of spiny lobsters, but lobster fisherman have reported that they must avoid bloom areas to trap lobsters successfully in creels[**27**]. Algal blooms, even those not toxic, could also negatively affect living resources by decreasing clarity, and hence visibility, thus affecting the ability of predatory fish to recognize and capture prey. Also, the phytoplankton although far more concentrated in the blooms, may consist of forms of poor food quality for animals living in the plankton or on the bottom or may clog their feeding apparatus. Lastly, localized sags and large oscillations in dissolved oxygen resulting from increasing concentrations of bloom organisms may negatively affect physiological and environmental (habitat) requirements/tolerances of a vast variety of tropical fauna and flora. Such an explanation of "cascading" effects (seagrass mortality affecting blooms, in turn affecting sponges, which in turn affect lobsters) must be regarded as speculative until more information can be obtained.

In summary, **there is considerable evidence that the combined effects of seagrass die-off, phytoplankton blooms, and changes in low salinity transition habitats on the living resources of the Bay have been substantial and are likely to continue until these conditions are reversed**.

Multiple of Causes of Deterioration

The explanations of the causes of the deterioration of the Florida Bay ecosystem have been simply cast and polarized in the technical media as well as the popular press.

For example, a briefing report prepared for the Governor of Florida and his Cabinet[**36**] stated:

> "Two theories exist to explain the problems in Florida Bay. The first identifies the ecosystem collapse as the ultimate result of our long-term Everglades water management regime associated with some recent natural events. An alternative theory supported by a few scientists has been postulated that states that the die-off and blooms have occurred through addition of external, mostly anthropogenic nutrients."

This Panel believes that the dichotomy so erected is oversimplified, if not false, and interferes with full understanding and effective solution of the problems. Elements of both "theories" may be in operation and other factors and interactions may be overlooked.

Florida Bay has been affected by humans in many ways. Flow from the Bay through the channels between the Keys has been partly occluded. The flow of fresh water entering the Bay through the Everglades has been greatly reduced and the seasonal timing of the flow has been altered. The concentration of nutrients and other contaminants has probably been increased in this flow and such materials have also been introduced through waste disposal practices on the Florida Keys. The exploitation of living resources also has almost certainly not been without its effects. In addition, there are natural phenomena such as climatic cycles, droughts, and storms (or lack thereof) which act on the Bay ecosystem. All of these may contribute to the degradation (seagrass and mangrove die-offs, algal blooms, and declines in living resources) observed within the past decade.

Management Implications

Restoring the Linkage Between the Bay and the Upland Hydrologic Cycle in South Florida

This is the restoration goal which has been proposed by the Everglades National Park[**33**]. The focus on attaining this goal would be "the restoration of natural flows and hydroperiods in the headwaters of Florida Bay, Taylor Slough and the Eastern Panhandle/C-111 Basin." Thus the primary, if not exclusive, focus of this Florida Bay restoration approach, would deal with freshwater inputs from the eastern side of the Everglades. The freshwater flows from the upper Everglades and the watershed to the north through the Shark River Slough system are not specifically addressed, nor or any other remedial actions, such as increasing the flushing rate of the Bay.

Long-term changes in salinity in the estuarine transition zone in northeastern Florida Bay have certainly occurred as a result of a reduction of natural flows. The restoration of natural flows and hydroperiods would undoubtedly lower salinity within the transition zone and affect the plant and animal life which inhabit this region of the Bay.

Recovery of affected fish and bird populations could reasonably be expected to occur. However, there is not yet compelling evidence to be even modestly certain that increasing the discharge through Taylor Slough will alleviate the hypersaline conditions in the central and western Bay during dry periods; prevent further seagrass mortality; promote recovery of the seagrass beds in the regions most affected by die-offs; or alleviate the cyanobacteria blooms in the central Bay. Moreover, there is little reason to believe that restoration of natural flows into northeastern Florida Bay would reduce or eliminate the plankton blooms in the western Bay, especially if nutrient levels in these fresh waters have increased in the last several decades.

Although the effects on the open Bay of restoration of the flow and hydroperiod through the Taylor Slough-Panhandle region of the Park cannot be predicted with great confidence, there are many compelling reasons to believe that such a strategy would improve wetland conditions in the Everglades and restore the ecological functioning of the coastal transition zone. Furthermore, there seems to us little likelihood of negative effects of increasing flow as long as freshets are not exaggerated by the new management scheme, because plant growth in eastern Bay appears to be strongly phosphorus limited and these discharges are relatively P-depleted.

Although the preponderance of evidence indicates that the ecosystem of the northeastern Bay would benefit by restoring the flow and hydroperiod, the benefits to the entire Bay are uncertain. Incremental restoration of flows can be treated as a potentially reversible experiment which, with careful monitoring of effects, can produce results that would be very effective in guiding future management.

The South Florida Landscape-Seascape

Florida Bay is affected by flow along the coast from the north, including the entrained discharge from Shark River Slough, and from the Southwest Florida shelf to the west. It further experiences some impact from development on the Florida Keys. At the same time, the Bay affects both the coastal margins of the Everglades and the Keys, Hawk Channel and the barrier reefs along the Atlantic side. **The ecosystems from the Kissimee River, through the Everglades and the Bay and onto the barrier reefs off the Keys are, in fact, connected and constitute an interdependent landscape-seascape. Yet, to the extent that these environments have been purposefully managed at all, they have been managed as if they were in isolation from one another. It is clear that what is now needed is a broader ecosystem management perspective which incorporates the watershed, the Bay and the Keys and reef.**

Two sets of present management challenges are particularly illustrative of the need for such a broader perspective. The first deals with the objective of restoring water levels and water quality in the more northerly portions of the Everglades and potential ramifications to Florida Bay. Agreements for increased water delivery and reductions in phosphorous loadings from agricultural areas to the north have recently been negotiated. This might mean increased discharges of nitrogen through the Shark River Slough as flows increase without any limitation on N loading from agricultural practices. Thus, under such a scenario algal bloom conditions in the potentially N-limited western Florida Bay may worsen (undesirable effect) as a result of greater freshwater delivery to the Everglades (desirable effect). If this happened, the consequences could even extend through the Keys out to the reef as plumes of algae are transported from the Bay through the channels offshore.

The second management challenge concerns the relationships between objectives of those two adjacent special reserves, the Everglades National Park and the Florida Keys National Marine Sanctuary. Florida Bay, most of which lies in the Park, has a significant influence on the Sanctuary, both along the Bay side of the Keys and as a result of offshore flowing Bay water. A restoration activity which may offer some benefits to the Bay ecosystem, such as "reopening" channels through the Keys may have deleterious effects on patch and barrier reefs within the Sanctuary if the transport of harmful algal blooms or water of high nutrient content and excessively high or low salinity offshore is increased.

Research, Monitoring and Modeling Needs

On the basis of its assessment of the causes of the deterioration of the Florida Bay ecosystem and the requirements for its restoration, the Panel identified the following information needed to determine causes and effectively guide restoration. We also offer some suggestions for research, monitoring and modeling to address those needs.

Water Flow and Characteristics

Knowledge of water flow, both within the watershed (hydrology) and with and within the Bay (coastal hydrodynamics) is essential both to understanding changes in the delivery of fresh water and the nutrients it contains to the Bay and to understanding the distribution and dynamics of salinity, nutrients, and organisms within in the Bay. It is the lynchpin on which the capability to predict future conditions and the effects of management actions on them will be based. Specific information needs include 1) the quantification of the effective flow of fresh water into estuarine transition zone, including both surface and groundwater flows; 2) the relationship of water stage and timing of release on effective flow both in the nearfield (below Tamiami Canal) and the farfield (above the Canal); 3) exchanges between the Bay and Gulf of Mexico to the west and the Bay and Hawk Channel; and 4) circulation within the Bay and exchange rates among its basins. Appropriate approaches toward developing this information include

- Devise ways to measure the actual freshwater flows (surface and groundwater) into the Bay, estimate the monthly inflows from both sources, and determine the points of entry for these flows.
- Extend present hydrologic modeling efforts to include the entire watertershed and provide realistic predictions of the location and rates of freshwater delivery to the Bay as a function of rainfall and water levels.

- Develop an accurate and up-to-date bathymetry of the Bay.
- Develop and verify a two-dimensional hydrodynamic/water quality model of the Bay into which boundary currents, tides, surface and groundwater flows, precipitation, evaporation, and winds are incorporated to create a tool capable of predicting circulation, residence time, salinity and water quality under different flow and climatic conditions.
- Apply sufficient *in situ* meters for continuous measurement of salinity, temperature, and currents at selected locations to characterize flow throughout the Bay and aid in verifying hydrodynamic/water quality models.
- Apply aircraft and satellite remote sensing for periodic synoptic measurements, particularly of salinity and blooms in the Bay, on the southwestern Florida coast and shelf, and in the Keys and adjacent reefs.
- Continue and, where necessary, expand water quality monitoring in Florida Bay, the coastal waters of southwestern Florida and the inflows into the Bay, including the Taylor and Shark River Sloughs and drainage canals. Current investigations should be reviewed to ensure they are providing the necessary scope of measurements, adequate spatial and temporal coverage, and effective quality assurance and control.

Ultimately, a predictive understanding of both the effects of freshwater delivery to the Bay and changes in the Bay's channels and shoals will require effective hydrologic models of the watershed coupled with hydrodynamic coastal circulation models.

Nutrients, Plant Growth and Blooms

We emphasize the potential differences in the causes, phytoplankton responsible and ecological manifestations of different bloom events in the Bay. Nonetheless, information and research needs addressing physical, chemical and biotic cause and effect relationships generally apply to the various bloom dynamics. The information needs and scientific approaches recommended are itemized below; the first four needs are absolutely essential to clarify the heretofore poorly studied nutrient-bloom dynamics in Florida Bay.

- Determine which nutrients currently control (limit) phytoplankton production and bloom formation. In terms of nutrient supply rates, what are the nutrient-production thresholds and assimilative capacities of Florida Bay? Efforts should include *in situ* nutrient addition bioassays, using multi-parameter (chlorophyll, photosynthetic production-using either ^{14}C uptake or O_2 evolution measurements) approaches. These assays should compliment ongoing stoichiometric evaluations of nutrient limitation.
- Characterize and quantify the supply and fluxes of nutrients. These determinations should include land-based (channelized discharge, surface runoff and groundwater) and atmospheric nutrient loadings; advection of nutrients from the West Florida shelf into Florida Bay; and within-Bay water exchange and residence time characteristics.
- Determine the relative importance of "external" (i.e. origin outside of the basin) vs. "internal" (regeneration, N_2 fixation, denitrification) nutrient (N and P) inputs and losses in Florida Bay. What proportions of primary and secondary production are

based on external ("new production") vs. regenerated sources? Simple box models should be constructed as a first step in understanding nutrient budgets.
- Identify, monitor and characterize (in terms of physical, chemical and biotic controls) phytoplankton and epiphyte communities in Florida Bay and immediate surroundings on appropriate spatial and temporal scales. Characterization by the primary producers by microscope, pigment analysis (fluorometry, spectrophotometry, HPLC-multispectral analysis), and immunoassays (whenever and wherever appropriate immunoprobes are available). Relate the primary producers to the dynamics of bloom formation and the physical conditions at the initiation and during blooms.
- Determine the specific nutritional requirements (i.e. autotrophy vs. heterotrophy) of nuisance bloom organisms. What is the functional role of organic matter enrichment in Florida Bay with respect to production and nutrient cycling dynamics?
- Determine routinely planktonic primary production in relation to nutrient inputs and regeneration rates and physical conditions.
- Determine the trophic (food web alterations, toxicity) and biogeochemical (nutrient cycling) structure of Florida Bay; specifically, how are blooms altering trophic and biogeochemical characteristics of Florida Bay and what are the ramifications for higher trophic level resources.

Seagrasses and Mangroves

The following are information needs and recommended research and monitoring approaches attendant to determining the causes of seagrass die-off and enhancing seagrass restoration:

- Determine experimentally the effects of prolonged high salinity and temperature on survival of *Thalassia* and mixed species seagrasses (2-way experiments). Emphasize survival estimates and not just photosynthesis and growth.
- Monitor light conditions and develop extinction coefficients appropriate to predicting light conditions at seagrass canopy. Fairly good light criteria for seagrass growth exist for extrapolation. This information is necessary to predict the recovery potential for seagrasses and the effects of plankton blooms on yet unaffected seagrasses.
- Monitor epiphyte abundance and composition as an "indicator" of eutrophication and to understand the potential competitive effects on seagrasses.
- Develop through remote sensing and other appropriate means a complete spatial depiction of the distribution, composition and relative density of seagrasses in the Bay and place this information in a geographic information system for future analyses of trends and environmental relationships.
- Assess the incidence of disease pathology (*Labyrinthula* and other pathogens) and determine its dependence on seagrass density and salinity regime.
- Determine the effects of salinity and temperature on seagrass re-establishment (particularly on *Halodule* germination and seedling growth).
- Determination of the extent of nitrogen versus phosphorus limitation on seagrass biomass accumulation to resolve questions remaining from inferences based solely on nutrient ratios or measured responses to both N and P additions.

- Determine the dependence of seagrass growth and survival on plant density and explore the causes of any density dependency (light limitation, detritus loading, oxygen availability, etc.).
- Estimate and where possible measure the nutrient release rates from seagrass detritus decomposition, sediments and sediment resuspension.
- Examine the seagrass-nutrient-epiphyte-grazer relationships, including top-down vs. bottom-up controls[**34**], in order to understand better nutrient enrichment and other environmental stresses in the context of the whole seagrass community.
- Determine the relationship between seagrass biomass accumulation, sediment deposition and shoaling, and resultant changes in water circulation in the Bay.

The recent history of mangrove mortality is not very well known, thus it is difficult to focus research to test hypotheses regarding the causes of mangrove die-off. As a first step, historical aerial imagery should be analyzed to document the patterns and rates of mangrove losses. On the basis of that information specific hypotheses may be tested observationally or experimentally.

Living Resources

A complex nexus of critical information must underpin effective environmental and resource management of living resources. There is a need to move beyond correlative relationships (e.g. the statistical relationship between freshwater flow and shrimp landings) to a more mechanistic understanding (e.g. physiological effects, growth, habitat availability, food, predation, etc.). Generally these information needs all require much better understanding of the role of habitat quality and quantity on population success and of food chains. The following are but a few of the more compelling needs:

- Determine the post-larval recruitment of pink shrimp and estuarine dependent game fish as it relates to environmental conditions and transport; the most important habitats for juvenile survival; and the relationship of habitat quality (food and refuge) to environmental conditions, including seagrass cover, salinity and freshwater inflow. This will require a three-pronged approach involving observations (field sampling), field and laboratory experiments, and spatially-explicit, population dynamic models.
- Resolve the assumed critical linkages between wading bird and osprey nesting and food availability and quality and relate this to environmental conditions, including salinity and vegetation.
- Quantitatively determine the effects of habitat modification resulting from the mortality of sponges and other refuge forming organisms on spiny lobsters. Do these losses make a difference to the adult populations and sustainable harvests?

Historical Analysis

In addition to monitoring carefully existing conditions and trends, great insight can frequently be gained through retrospective analyses. These may include more thorough analyses of existing data, such as salinity, water levels in the Everglades, and Bay water levels measured by tide gauges; assembling and analyzing aircraft and satellite imagery; structured surveys of lay observers; and more extensive analyses of "paleoindicators" (isotopes, chemical markers, microfossils) in sediments, shells and skeletons. In particular, we got the impression that not much effort has been spent assessing archived remote imagery (e.g., Landsat thematic mapper) and suspect that such imagery may hold many clues about what has happened in Florida Bay.

National Park Service and NOAA Research Plans

The National Park Service's South Florida Research Center has recently produced A Research Program for Restoration of Florida Bay[**33**] which commands our respect, if for no other reason, because this small group of dedicated scientists are among those with the most experience on the Bay. The NPS plan addresses many of the information needs we have identified above and has the advantage of tightly linking scientific research, monitoring, modeling and integration to management actions. However, the NPS plan seems to take as a fundamental premise that problems of the Bay are all linked in one way or another to changes in the delivery of freshwater from the northeast, and as a consequence has relatively little emphasis on nutrient inputs and chronic algal blooms, circulation within the Bay and between the Gulf and the Bay, and interactions with the Keys. The NPS plan describes the research, monitoring and modeling that should be conducted with rather broad brush strokes and seems to rely heavily on extensive surveys and monitoring. In our view, a comprehensive science strategy should be more organized around testing critical hypotheses as we have attempted to do above. This would naturally place greater emphasis on experimental approaches focused on specific questions and not just the "whole ecosystem" experiment (change freshwater flow and observe what happens) which the NPS plan emphasizes.

Also recently, NOAA held a workshop on the restoration of Florida Bay for the purpose of developing a science plan which includes retrospective analyses, monitoring, modeling and research[**7**]. It appears to us that there was little coordination between the NPS and NOAA efforts. For example, none of the three authors of the NPS plan participated in the NOAA workshop. The NOAA workshop report does, however, include a critique of the NPS plan.

As with the NPS plan, the NOAA workshop recommendations identify many of the information needs and research, monitoring and modeling approaches that we have listed above. NOAA's recommendations place greater emphasis on areas of NOAA capability and responsibility, including meteorology, hydrodynamics of the Bay, contaminant studies, commercial fisheries and endangered marine mammals and turtles and are less directly focused on freshwater inflows as the grand regulator of the Florida Bay ecosystem. But, like the NPS plan, the NOAA science plan places great emphasis on extensive survey, monitoring and modeling and does not focus on testing critical hypotheses to the degree to which the Panel feels would be most effective. Also the workshop recommendations read, with its frequent references to NOAA's mission and capabilities, more like a NOAA science initiative than a comprehensive plan to understand and manage Florida Bay.

As the next step in developing a more comprehensive, objective, focused and coordinated science strategy which could gain governmental and public support, we recommend that the Interagency Working Group on Florida Bay undertake a comparison, amalgamation and honing of our recommendations with those contained in the NPS plan and NOAA workshop report.

Focused, Sustained and Coordinated Research, Monitoring and Modeling

The primary responsibility of our review panel was to evaluate existing information and recommend research needs that will provide the knowledge necessary to manage Florida Bay and the adjacent ecosystems that affect the Bay. However, we also feel a responsibility to communicate our conclusions and concerns that existing information is greatly inadequate for making such major policy and management decisions. Further we are struck that both the level and the coordination of research and monitoring have been insufficient for comprehensive decision making for this nationally and regionally important natural resource.

We realize that many agencies and institutions have responsibilities and interests in Florida Bay, as well as neighboring South Florida, the Gulf of Mexico, and the Florida Keys. Major managerial and scientific roles are played by numerous federal agencies and subagencies including the Department of the Interior (National Park Service, U.S.G.S., National Biological Survey, and Fish and Wildlife Service), the Environmental Protection Agency, the Department of Commerce (National Oceanic and Atmospheric Administration, including the National Marine Fisheries Service), the Department of Energy, the Department of Agriculture and the Department of Defense (Army Corps of Engineers). State and local agencies are also involved such as the South Florida Water Management District, the Florida Department of Environmental Protection (formerly, the Florida Departments of Natural Resources and Environmental Regulation), and Dade, Monroe, Broward and other counties.

Although many local universities and research organizations have developed a recent interest in promoting research in Florida Bay and surrounding environs, we think it remarkable that only a few institutions and researchers have had much historical involvement in "local" problems. This is, in part, certainly a consequence of inadequate investment in research. Nonetheless, it is a sad indictment of local management agency/university relations that perhaps the most widely recognized expert on Florida Bay is a University of Virginia researcher who struggled to piece together support for long-term research in the Bay.

We clearly recognize that the understanding and management of Florida Bay are extremely complex, involving not only the multiple jurisdictions and responsibilities alluded to above, but more importantly, very intricate relationships between unique and complex ecosystems. Given the difficult problems and the institutional relations involved, not to mention the contentious environmental history of the region, it is hardly surprising to us that research has been poorly coordinated or that information has been poorly communicated among interested parties. This predicament is all too commonplace in comparable environmental management situations. However, this situation must be rectified if the problems of the region are to be understood and managed properly.

Above, we have listed in some detail a series of hypotheses relating to the Florida Bay ecosystem. We have also listed some specific research objectives to address these hypotheses. However, it would be useful to provide some general guidance on research and monitoring management.

In our experience, a major challenge is the integration of research, monitoring and modeling. Emphasis on monitoring is often favored by practically minded managers who see the results as realistic and useful. But, unsupported by a vibrant research program and vigorous on-going scientific analysis, monitoring may constrain one to simply describing phenomena and not understanding them. Overemphasis on research, on the other hand, may lead to lots of interesting facts but without a phenomenological (monitoring) or conceptual (modeling) basis to extend their meaning. Putting all one's eggs in the basket of numerical simulation models risks oversimplification and overconfidence. Often simple box models of such processes as nutrient dynamics are more instructive than complex physical models. They can be refined as research advances and be used to direct research toward the most critical questions. **Balance and interplay among research, monitoring and modeling and interaction of these technical elements with management are the keys**.

Secondly, **we cannot overemphasize the need to provide sustained support for research, monitoring and modeling activities to provide managers proper information.** The piecemeal, catch-as-catch-can approach by which most environmental research seems to be conducted is not only slow and inefficient, but is bound to lead to understanding which is replete with uncertainty and lead to decisionmaking fraught with error.

Finally, in this era of reinventing government, interagency rivalries, duplications, and omissions in pursuit of environmental science are no longer excusable. Strides are being made at the national level to better coordinate coastal research among federal agencies under the Federal Coordinating Council for Science, Engineering and Technology. There are also many regional programs where some successes in coordination across state, federal and academic lines have been met and from which lessons for Florida Bay can be learned (e.g., the National Estuary Program estuaries and Chesapeake Bay Program). The National Park Service's Research Program[**34**] plan contains a reasonable proposal for coordination via the Interagency Working Group, a Policy Oversight Committee, a Technical Working Group, a Research Committee for peer review, and a Modeling and Integration Working Group. **Surely, the problems of the Florida Bay are so severe and the difficulties in understanding them so challenging**

that Interior, NOAA, EPA, the Corps, Florida DEP, the South Florida Water Management District and Florida universities can find a way to make complementary contributions and encourage synergy in the scientific enterprise.

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[17] Presentation to the Panel by Dr. Michael Robblee (Everglades National Park), August 17, 1993.

[18] Presentation to the Panel by Mr. Michael Collins (Florida Fishing Guides and member, Florida Keys National Marine Sanctuary Advisory Council), August 17, 1993.

[19] National Oceanic and Atmospheric Administration. 1993. Spatial Framework for Water-Quality Management in the Florida Keys National Marine Sanctuary. Physical Environments. Strategic Environmental Assessments Division, Office of Ocean Resources Conservation and Assessment, National Oceanic and Atmospheric Administration, Silver Springs, MD. The following summary of circulation in the area is based on this publication and references cited therein:

The circulation of the outer part of Florida's southwest shelf is influenced by the Loop Current which enters the Gulf of Mexico through the Yucatan Straits and loops in a clockwise direction to the south, paralleling the edge of the West Florida Shelf before turning eastward, southwest of the Dry Tortugas. Continuing as the Florida Current, it meanders through the Florida Straits confined by the 250 m and 500 m isobaths. The current pinches landward, south of the Marquesas Keys and is then deflected seaward by the Pourtales Terrace. Near the Middle Keys, the Florida Current turns northeasterly, proceeding as the Gulf Stream. Periodic changes in current locations result in the formation of circulation gyres affecting both transport and entrainment of waters along the outer shelf. Such cold cyclonic features may move at speeds ranging from 2 to 20 km per day along the landward boundary of the Loop Current. Off the Dry Tortugas, at the Straits of Florida, a gyre can grow to 100 by 200 km in size and can become quasi-stationary and elongated to the southwest. It may then move easterly along the northern boundary of the Florida Current, decreasing in size to about 50 by 100 km over the Pourtales Terrace, before decaying near the Middle Keys. A gyre has been observed to upwell and trap nutrients along the bank reefs near the Lower Keys. A mean westward countercurrent, located just seaward of the Lower Keys, has been observed as part of the gyre positioned over the Pourtales Terrace, potentially enhancing mean westerly transport within Hawk Channel. Near the Upper Keys, landward deflection of the Florida Current sets up small frontal eddies (10-30 km in diameter) just seaward of the reef tract. These disturbances occur, on average, once a week and provide cool, nutrient-enriched water to the reef tract due to upwelling at the eddy's core. In contrast to the sluggish Dry Tortugas Gyre, these features move quickly, requiring only 1-2 days to pass a fixed point. Hence, the area along the Atlantic side of the Upper Keys is relatively well-flushed and has limited capacity to retain nutrients.

Circulation and transport occurring landward of these regional boundary currents are dominated by wind. A mean westward current is setup in Hawk Channel, due to the prevailing southeasterly winds caused by the persistence of the Azores-Bermuda atmospheric high, and is most pronounced during the spring and summer. The current conveys waters from the Middle to Lower Keys and enhances exchanges between the Gulf and Atlantic through the large channels between the Middle Keys. Within the Lower Keys, surface waters are forced onshore due to the earth's rotation and shoreline orientation, causing an offshore movement of water at depth. Transport processes occurring on the southwest Florida shelf are complex and relatively unstudied, but are particularly important for exchanges throughout the Middle and Lower Keys. Prevailing trade winds dominate most of the region, forcing water in a westerly direction. Other processes, however, appear to control shelf-water movement along the western boundary of Florida Bay. The net transport appears to be north-to-south or Gulf-side to Atlantic-side. A weak along-shore current in the lee of south Florida peninsula potentially transports near-coastal waters of southwest Florida toward the Middle and Lower Keys. This effect appears to be further enhanced during the fall months when an atmospheric high develops over the southeastern U.S., producing southward winds that persist for 5 to 10 days. In the extreme, frontal passages occurring during the winter and spring can change flow direction over the entire shelf region, resulting in significant fluxes from the Gulf to the Atlantic Ocean.

Circulation within Florida Bay appears to be easterly along the south shore of Cape Sable turning southerly after short penetration in the Bay. For most of the western half of the Bay, currents are presumed to move southerly although there is little, if any, information from current measurements to support this pattern. The eastern half of the Bay, however, is effectively shielded from this flow by shallow mudflats. Currents on the Bay side of the Upper and Middle Keys are presumed to move southwesterly.

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