EPA

United States
Environmental Protection
Agency

Water Quality Protection
Program – Florida Keys
National Marine Sanctuary

EPA 904-R-99-005
September 1999

WATER QUALITY CONCERNS IN THE FLORIDA KEYS: SOURCES, EFFECTS, AND SOLUTIONS

WATER QUALITY CONCERNS IN THE FLORIDA KEYS: SOURCES, EFFECTS, AND SOLUTIONS

PREPARED BY

WILLIAM L. KRUCZYNSKI
PROGRAM SCIENTIST
FLORIDA KEYS NATIONAL MARINE SANCTUARY
WATER QUALITY PROTECTION PROGRAM

SEPTEMBER 1999

TABLE OF CONTENTS

WATER QUALITY PROTECTION PROGRAM

FOR MORE INFORMATION

FLORIDA KEYS NATIONAL MARINE SANCTUARY
WATER QUALITY PROTECTION PROGRAM

STEERING COMMITTEE

John H. Hankinson, Jr., Regional Administrator
U.S. Environmental Protection Agency
Region 4

Kirby B. Greene, III, Deputy Secretary
Florida Department of Environmental Protection

Jeff Benoit, Director
Ocean and Coastal Resosurces Management
National Oceanic and Atmospheric Administration

Richard G. Ring, Superintendent
Everglades National Park

Colonel Joe R. Miller, District Engineer
U.S. Army Corps of Engineers
Jacksonville District

Tom Grahl
U.S. Fish and Wildlife Service

Steven M. Seibert, Secretary
Florida Department of Communities Affairs

Bart Bibler, Bureau Chief
Water and Onsite Sewage Program
Florida Department of Health

Mile Collins, Chairman
Governing Board
South Florida Water Management District

James C. Reynolds, Deputy Executive Director
Florida Keys Aqueduct Authority

Commissioner Nora Williams
Board of County Commissioners
Monroe County

William H. Botten
City of Key Colony Beach

Commissioner Jimmy Weekly
City of Key West

Charley Causey
Florida Keys Environmental Fund

Fran Decker, Chairman
Citizens Advisory Council
Florida Keys National Marine Sanctuary

Karl Lessard
Monroe County Commercial Fishermen

TECHNICAL ADVISORY COMMITTEE

Dr. John C. Ogden, Director
Florida Institute of Oceanography

Dr. Eugene A. Shinn
U.S. Geological Survey
Center for Coastal Geology

Dr. Jay Zieman
University of Virginia
Department of Environmental Sciences

Dr. Alina Szmant
University of Miami
Rosenstiel School of Marine and Atmospheric Science

George Garrett
Director of Marine Resources
Monroe County

Dr. Erich Mueller
Mote Marine Laboratory
Pigeon Key Marine Research Center
Dr. Ronald Jones, Director
Southeast Environmental Research Program
Florida International University

Dr. Kalthleen Sullivan
University of Miami
Department of Biology

Dr. Brian Lapointe
Harbor Branch Oceanographic Institute

Curtis Kruer
Consulting Biologist
Summerland Key, FL

Chris Schrader
Tavernier, FL

Dr. Roland Ferry
U.S. Environmental Protection Agency
Coastal Programs Section

Dr. Robert Brock
Everglades National Park

Dr. Kevin Sherman
Florida Department of Health

Joyce Newman
Big Pine Key, FL

Dr. Steven L. Miller
NOAA
National Undersea Research Center

Walt Jaap
Florida Marine Research Institute

John Hunt
Florida Marine Research Institute

Gus Rios
Florida Department of Environmental Protection
Susan Loder
Florida Keys Aqueduct Authority

Steve Traxler
U.S. Army Corps of Engineers

Richard Allemen
South Florida Water Management District

MANAGEMENT COMMITTEE

Fred McManus, Florida Keys Coordinator
U.S. Environmental Protection Agency

Dr. William L. Kruczynski
Florida Keys Program Scientist
U.S. Environmental Protection Agency

Billy Causey, Superintendent
Florida Keys National Marine Sanctuary
National Oceanic and Atmospheric Administration

G.P. Schmahl
Florida Keys National Marine Sanctuary
Florida Department of Environmental Protection

Ken Haddad, Director
Florida Marine Research Institute
Florida Department of Environmental Protection

George Garrett
Director of Marine Resources
Monroe County

FOR MORE INFORMATION ON THE WATER QUALITY PROTECTION PROGRAM, CONTACT:

William L. Kruczynski
Florida Keys Program Scientist
P.O. Box 500368
Marathon, FL 33050
(305) 743-0537

Fred McManus
Florida Keys Coordinator
U.S. Environmental Protection Agency- 4
61 Forsyth Street, S.W.
Atlanta, GA 30303-8960
(404) 562-9385

FOR MORE INFORMATION ON THE FLORIDA KEYS NATIONAL MARINE SANCTUARY, CONTACT:

Billy Causey, Superintendent
Florida Keys National Marine Sanctuary
National Oceanographic and Atmospheric Administration
P.O. Box 500368
Marathon, FL 33050
(305) 743-0537

EXECUTIVE SUMMARY

The Florida Keys are a chain of tropical islands composed of several interdependent community types, including tropical hardwood forests, fringing mangrove wetlands, seagrass meadows, hard and soft bottoms, and coral reefs. The tropical setting and ecological diversity have made the Florida Keys a popular place to live and vacation.

The natural communities that make up the Florida Keys ecosystem exist in a dynamic equilibrium, which means that changes that result in a direct impact to one community type can have profound effects on adjacent communities. The continued existence of the Keys marine ecosystem is dependent upon maintenance of clear waters with relatively low nutrients.

Historically, development in the Keys relied on the use of cesspits and septic tanks which provide little treatment of domestic wastewater in porous lime rock substrates. In addition, stormwater runs untreated into nearshore surface waters. Lack of nutrient removal from domestic wastewater and stormwater has resulted in the addition of nutrient-rich waste waters into confined waters and adjacent nearshore areas. The cumulative effects of these discharges have led to water quality degradation of these inshore areas.

The following statements on water quality issues in the Florida Keys are supported by the literature and knowledge of scientists:

1. There is a rapid exchange of groundwater and surface waters in the Keys that is driven by tidal pumping.

2. Cesspits are not appropriate for disposal of wastewater because they are illegal, provide very little treatment, and are a health hazard. Cesspit effluent can rapidly migrate to surface waters.

3. Properly functioning septic tank systems remove very little nutrients (4% N, 15% P) from wastewater and, depending upon their location, effluent from septic tank drainfields can rapidly migrate to surface waters.

4. Sewage discharged from cesspits and septic tanks are a source of nutrients and human pathogens to ground and surface waters.

5. Contaminants in stormwater runoff contribute substantially to the degradation of nearshore water quality.

6. Water quality problems due to on-site sewage disposal practices and stormwater runoff have been documented in residential canals. Water quality parameters that are

degraded include nutrient enrichment, fecal coliform contamination, and biochemical oxygen demand.

7. Long, dead-end canal systems, deep canals of any length, and poorly flushed basins accumulate weed wrack and other particulate matter.

8. The water column of many canals over six feet deep is stratified and bottom waters are usually in violation of Florida's Class III Surface Water Quality Standard for dissolved oxygen. Because they usually violate Class III Surface Water Quality Standards, canals were excluded from Outstanding Florida Waters designation.

9. Artificial aeration of canals does not eliminate the sources of excessive nutrients in canal waters but may result in better mixing which may facilitate nitrogen cycling.

10. Improving flushing of degraded canal systems may improve the water quality within the canal, but will also result in adding additional nutrients to the adjacent waters.

11. Canal systems and basins with poor water quality are a potential source of nutrients and other contaminants to other nearshore waters.

12. Seagrass beds located near the mouths of some degraded canal systems exhibit signs of eutrophication, such as increased epiphyte load and growth of benthic algae.

13. Vessel generated turbidity (re-suspended sediments) is a growing concern in many areas with high boat traffic including canals and open waters.

14. Aerobic treatment units and package plants provide secondary treatment, removing 80% - 90% of the total suspended solids (TSS) and organic wastes that are responsible for biochemical oxygen demand. In poor soil conditions with high groundwater tables, where drainfields are rendered inefficient, secondary treatment systems are better than septic tanks at removing organically bound nutrients associated with the TSS. These systems, however, are not designed to remove dissolved nutrients.

15. Disposal of wastewater from package treatment plants or on-site disposal systems into Class V injection wells results in nutrient enrichment of the groundwater. However, it is not known whether discharges into Class V wells results in substantial nutrient loading to surface waters. This question is currently under investigation.

16. In areas where groundwater is saline, injected wastewater is buoyant and rapidly rises to the surface.

17. Recent tracer studies have demonstrated rapid migration of Class V effluent to surface waters (hours to days). These studies demonstrated that tracers were greatly

diluted before reaching surface waters and that some phosphorus was stripped from groundwater by the substrate. The long term ability of phosphorus stripping by the substrate is currently under investigation.

18. Sewage discharges from vessels degrade the water quality of marinas and other confined water anchorages.

19. Florida Bay discharge, oceanic and Gulf of Mexico upwelling and currents, rainwater and other natural sources add nutrients to surface waters of the Keys.

20. Net water movement through the tidal passes between the Keys is toward the Atlantic Ocean. Once entering Hawk Channel, water direction and speed is controlled by prevailing winds and ocean currents.

21. Coral habitats are exhibiting declines in health; coral diseases are more common and benthic algae have increased in abundance and spatial coverage.

22. There are no definitive studies on the geographic extent of the impact of anthropogenic nutrients. Scientists agree that canal and other nearshore waters are affected by human-derived nutrients from sewage. Improved sewage treatment practices are needed to improve canal and other nearshore waters. Impacts further from shore that may be due to anthropogenic nutrients may be reduced or eliminated by cleaning up nearshore waters.

23. Planning and implementation of improvements to wastewater treatment are underway. A cesspit identification and on-site disposal certification program has been initiated. A Marathon Area Feasibility Plan has been completed and a Monroe County Wastewater Master Plan has been initiated. Funding is being sought for planning, design, and construction of wastewater and stormwater infrastructure.

24. A long term monitoring program has been implemented to provide information on the status and trends of water quality, coral, and seagrass communities.

25. The costs of water quality improvements are a small fraction of the long term asset value that natural resources, such as reefs, hard bottoms, and seagrasses, provide to the economy of the Florida Keys.

If sources of nutrient enrichment continue unabated, it is likely that the ecological balance of nearshore communities of the Keys will be changed. Changes in the structure and function of nearshore communities could result in stresses to other components of the Keys ecosystem. Since the economy of the Keys is directly linked to a healthy ecosystem, it is imperative that sources of excessive nutrients to this ecosystem be eliminated. In recognition of the warning signals of degraded water quality, the U.S. Environmental Protection Agency and the State of

Florida, in conjunction with the National Oceanic and Atmospheric Administration, have, at the direction of Congress, prepared a Water Quality Protection Program (WQPP) for the Florida Keys National Marine Sanctuary. Full implementation of the WQPP will help reverse the trend of environmental degradation and restore and maintain the Florida Keys marine ecosystem.

INTRODUCTION

The Florida Keys are a chain of tropical islands surrounded by clear ocean waters teeming with sea life. The uniqueness and diversity of natural communities combine to make the Florida Keys ecosystem one of the "crown jewels" of our Nation's natural treasure chest.

The Keys ecosystem is composed of several interdependent community types, including tropical hardwood forests, fringing mangrove wetlands, seagrass meadows, hard and soft bottoms, and coral reefs. This ecological diversity has made the Keys a popular place to live and an important vacation destination.

The current population of the Keys is approximately 78,000 permanent, year-round residents (1990 census). The population increases by about 25,000 during peak tourist season (winter months). Approximately 70 percent of Keys residents regularly participate in water-based activities, such as fishing (48%), snorkeling (45%), beach activities (38%), and observing wildlife and nature (36%) (Leeworthy and Wiley, 1997). Maintenance of the integrity and ecological health of marine and terrestrial environments is critical to the economy of the Keys. Approximately 3 million visitor trips annually are made to the Keys totaling over 16 million person days. Visitors generate over $1.3 billion in direct output and tourism supports over 21,800 jobs in the Keys (English et al., 1996). Tourists come to the Keys for a variety of reasons: snorkeling (28%), scuba diving (8%), fishing (21%), wildlife observation (28%), beach activities (34%), and sightseeing (55%) (Leeworthy and Wiley, 1997).

Shallow water environments surrounding the Keys constitute extensive nursery areas and fishing grounds for a variety of commercially and recreationally important marine species. Monroe County ranks first in Florida in total volume of seafood landed (10% of State landings). In 1990, 19.7 million pounds of fin fish, shellfish, and other aquatic organisms were landed in Monroe County with a dockside value of $48.4 million (Adams, 1992). The spiny lobster is the most valuable harvest (>$20 million annually). Monroe County accounts for 91% of the total spiny lobster harvest and 44% of total harvest of pink shrimp and stone crab (Adams, 1992).

The natural communities that make up the Florida Keys ecosystem exist in a dynamic equilibrium. Changes to the physical-chemical conditions that result in a direct impact to one community type can have profound effects on adjacent community types. For example, coastal fringing wetlands filter upland runoff, stabilize sediments, and absorb some nutrients. Thus, wetlands help maintain clear, relatively nutrient poor waters that facilitate luxuriant growth of seagrasses in adjacent waters. Upsetting this balance by removing wetland vegetation, can result in a localized increase in nutrients and turbidity in nearshore waters that may reduce seagrass coverage. Coastal wetlands and seagrasses are important habitats for juvenile fishes, and a reduction in spatial coverage of these habitats can result in decreased fish populations that can further upset ecosystem functions. Loss of wetlands and seagrasses can increase water turbidity due to re-suspension of sediments previously bound by their root systems that can have additional negative impacts on adjacent communities. Thus, subtle, single changes can have profound, cascading effects throughout the entire ecosystem.

Human activities have negatively impacted the ecological balance of the Florida Keys ecosystem (Voss, 1988). Cumulative, large-scale physical impacts, such as construction of barriers to tidal flushing, dredging and filling of seagrass beds and wetlands, and nutrient addition to waters surrounding the Keys have profoundly influenced the physical appearance of the Keys, as well as the balance of ecosystem functions. The impacts of many human activities are obvious, such as the approximately 30,000 acres of seagrasses which have been propeller scarred by boaters in the Keys (Sargent et al., 1995). Other impacts, such as water quality degradation, may not be immediately obvious to the casual observer. However, nutrient loading is a widespread factor that alters structure and function of aquatic ecosystems in coastal watersheds (Valiela et al., 1992).

The survival of the existing Florida Keys marine ecosystem is dependent upon clear, low-nutrient waters. This paper is a summary of available information of nearshore water quality (canals, basins, and waters immediately adjacent to the Keys). The data demonstrate that the cumulative effects of continued discharges of nutrient-rich wastewater and stormwater into confined and some other adjacent nearshore waters has degraded the water quality of those waters (Barada and Partington, 1972; U.S. Environmental Protection Agency, 1975; Florida Department of Environmental Regulation, 1985, 1987, 1990; Lapointe et al., 1990; Lapointe and Clark, 1992). There is evidence that the degraded water quality has adversely impacted other nearshore communities (Lapointe and Clark, 1992; Lapointe et al., 1994; Lapointe and Matzie, 1996). If sources of nutrient enrichmentcontinue unabated, it is likely that the ecological balance of nearshore communities of the Keys will be changed. Changes in nearshore community structure and function could result in stresses to other components of the Keys ecosystem. Since the tourist-based economy of the Keys is directly linked to a healthy Keys ecosystem, it is prudent to work diligently toward eliminating sources of excessive nutrients to this ecosystem.

Restoration of degraded portions of the Keys aquatic ecosystem may be possible, but it will require the combined effort of the entire community of the Florida Keys, with help from federal and State governments. Collectively, we are the stewards of this unique national treasure and restoring and maintaining this ecosystem is a national goal. In recognition of the warning signals of degraded water quality, the U.S. Environmental Protection Agency (EPA) and the State of Florida, in conjunction with the National Oceanic and Atmospheric Administration, have, at the direction of Congress, prepared a Water Quality Protection Program (WQPP) for the Florida Keys National Marine Sanctuary. It is hoped that full implementation of the WQPP will reverse the trend of environmental degradation and restore and maintain the Florida Keys marine ecosystem.

HISTORY AND PHYSICAL SETTING

The Florida Keys are a chain of limestone islands that extend from the southern tip of the Florida mainland southwest to the Dry Tortugas, a distance of approximately 220 miles. The Keys are island remnants of ancient coral reefs (Upper Keys) and sand bars (Lower Keys) that flourished during a period of higher sea levels about 125,000 years ago (Pleistocene) (Hoffmeister and Multer, 1968; Shinn, 1988; Lidz and Shinn, 1991). During the last ice age, that started about 100,000 years ago, sea level dropped and exposed the ancient coral reefs and sand bars that form the present Keys. At that time of lower sea level, the Florida land mass was much larger than it is today and Florida Bay was forested. Sea level began to rise as polar ice caps started melting about 15,000 years ago; that resulted in re-flooding of some of the exposed land and led to our present-day geography. The existing outer coral reef tract that parallels the Florida Keys on the Atlantic Ocean side began forming between 6,000 and 10,000 years ago. Reef growth rate ranges from 0.61 to 4.85 meters (2 to 16 ft) per 1000 years (Shinn et al., 1977).

A continued rise of sea level resulted in flooding what we now call Florida Bay about 4,000 years ago. At that time, coral communities thrived along the entire seaward edge of the Keys. As
sea level rose further, it resulted in the establishment of tidal passes between the Keys. This was a significant event since it resulted in the export of terrestrial material, sediments, and organic matter from Florida Bay to the Atlantic through the tidal passes. The export of that material resulted in conditions that no longer favored lush coral reef development in the regions of the major tidal passes (Middle Keys) (Ginsburg and Shinn, 1964; Shinn et al., 1989; Lidz and Shinn, 1991; Shinn et al., 1994a; Ogden et al., 1994).

Florida Bay is a shallow embayment composed of basins separated by mud banks and mangrove islands. Water quality in Florida Bay is highly variable. Discharges of either hot or cold water, with very high or low salinity, from Florida Bay through the tidal passes further limited development of the outer coral reefs. To the north and west of the Middle Keys, where the reef tract is more sheltered by the keys from waters discharged from Florida Bay, vigorous coral reef growth continued (Lidz and Shinn, 1991; Shinn et al., 1989). Thus, prior to human impacts in south Florida, water exchange between Florida Bay and the Atlantic Ocean significantly impeded coral growth in the areas of major tidal passes as well as offshore.

Today, the Florida Keys outer reefs are a disjunct series of bank reefs that are located at the northern zoogeographic boundary of tropical waters. Because it is at the northern limit of coral reef development, the Keys reef tract regularly experiences natural stresses, such as winter temperatures below those normally associated with vigorous coral reef development. Also, the reef experiences higher summer temperature extremes than many other reefs in the Caribbean basin (Vaughn, 1918).

The Keys themselves consist of limestone rock formations. In the upper Keys, these rock formations are composed of Key Largo Limestone, which is the skeletal remains of the ancient Pleistocene reef. The lower Keys, Big Pine Key and west, were formed by deposition and consolidation of sand bars (Miami Oolite) over the underlying Key Largo limestone. Over time, vegetation began growing on the exposed surfaces of the limestone and thin veneers of soils formed in some areas from weathering of limestone and accumulation of organic matter from plants.

The Keys were vegetated from seeds, propagules, and uprooted or detached plant material carried from the Florida mainland and from Caribbean islands. This has resulted in a curious mix of tropical and subtropical vegetation in this unique geographic setting. Prior to the arrival of Europeans, the Keys consisted of diverse West Indian tropical hardwood forests on high ground, pine rocklands and freshwater wetlands on the interiors of larger islands (e.g., Big Pine Key), and vast expanses of mangrove wetlands that surrounded the islands and extended into tidal waters.

The waters surrounding the Keys were clear and supported an abundance and diversity of plant and animal life. Shallow areas were vegetated by acres of lush seagrasses in areas where sediments accumulated. Hard and soft corals thrived where limestone was exposed under the water. Large populations of queen conchs, sea turtles, and many species of sea life were supported by the productivity of this diverse, shallow-water ecosystem. The shallow water and coral reef communities evolved in a low nutrient subtropical sea environment and the continued existence of this ecosystem is dependent upon maintenance of relatively low sediment and nutrient conditions.

CHANGING TIMES

Although known to exist, the Florida Keys were largely uninhabited during the sixteenth, seventeenth, and eighteenth centuries, even though waters just offshore provided a major shipping route to and from Europe. During that time, the islands were occupied by Keys Indians, some settlers, and pirates who preyed on sea traffic. Scarcity of fresh water and the lack of a vast expanse of fertile soil prevented the populous settlement of the Keys. Undoubtedly, mosquitos and disease also played a major role in the lack of development in the Keys.

After Florida was ceded by Spain to the United States in 1821, Key West became an important military post, and island trade began to grow. Trading, fishing, cigar making, recovering goods from shipwrecks, and a limited agriculture base provided livelihoods for Keys residents (Viele, 1996). The Overseas Railway and Overseas Highway, completed in 1912 and 1938, respectively, connected the Keys to the mainland through a series of filled causeways and bridges. This transportation system, together with a water pipeline from the mainland built to supply the military in Key West during World War II, set the stage for post-war development of the Keys (Halley et al., 1997). The attractive climate, inexpensive land, beauty of the coral reefs, clear waters with abundant fishes, diversity of wildlife, and mosquito control all combined to make the Keys a very popular place to live and vacation.

Much of the physical alteration of the Keys to support the growing human population occurred during the 1950's through the 1970's. During that period, many acres of tropical hardwood hammocks were cleared to provide land for housing and commercial development. The attractiveness of waterfront development prompted the creation of "fastland" through dredging and filling of mangrove forests and seagrass beds to construct networks of finger-fill residential canals. More than 200 canals and access channels were dredged during that period (FDER, 1987). Turbidity from the dredging and filling operations smothered adjacent areas of hard bottom and seagrass habitats. Many canals were dug 10- to 20-feet deep to maximize the production of fill material excavated from the canal, and most canal systems were designed as long, dead-end networks with little or no tidal flushing at their upper ends. In general, water quality of newly dug canals was the same as areas of adjacent nearshore waters due to lack of input of nutrients from runoff and development.

WATER QUALITY

The concept of what constitutes "good" water quality is complex. The definition of acceptable water quality is based upon several interrelated parameters, including how the water will be used (e.g., drinking, swimming, fishing), concentrations of materials in the water above natural background levels that could have a deleterious effect on plants or animals (pollution), and the presence of compounds not usually found in the water (contamination). Parameters typically measured during routine water quality studies are salinity, dissolved oxygen, turbidity, biochemical oxygen demand (BOD_5), chlorophyll, fecal coliform, and nutrient concentrations, predominantly nitrogen and phosphorus (Table 1). Contaminants include heavy metals, pesticides, herbicides, and other chemicals.

Water quality standards are acceptable limits for materials found in water and are defined in regulations. State of Florida water quality criteria are contained in Chapter 62-302 Florida Administrative Code. Rule 62-302.530 includes standards for Class III marine waters. Water quality standards for drinking water include acceptable levels, i.e. numeric limits, of odor, taste, color, pollutants, and contaminants. These standards are aimed at reducing or eliminating compounds that are displeasing or potentially hazardous to people who drink the water.

Defining environmental water quality standards is more complex than drinking water standards and must be evaluated in an ecological and aesthetic context. Water quality standards are based on conditions that may result in a change in the quantity or health of the organisms that live in the water. However, because even pristine natural ecosystems undergo changes in response to natural variations and all ecosystems gradually change over time, it can be difficult to determine the exact point that changes in water quality parameters begin to cause degradation of the ecosystem.

The waters surrounding the Keys have been declared as "Outstanding Florida Waters" (OFW) by the State of Florida (FDER, 1985). By regulation, input of materials that could be considered pollutants to open surface waters cannot exceed the concentration of those materials that naturally occur in water. However, ambient background conditions can change seasonally or at different phases of a tidal cycle. From a scientific standpoint, the declaration of OFW status for the waters of the Florida Keys does not solve the problem of defining acceptable limits of pollution. The range of water quality parameters measured throughout the Keys during a survey to support designation of the Florida Keys as OFW is given in Table 2 (FDER, 1985). Because of the OFW designation, direct surface water discharges of pollutants have been eliminated, or are being phased out.

In order to establish pollutant standards, the effects of the pollutants on biological communities must be determined. Pollutant (or contaminant) levels become unacceptable when they result in detrimental changes to an organism or the biological community. This concept is easy to understand when the pollutant or contaminant results in loss or replacement of a community or a species; no one can argue against the fact that concentrations which cause death are unacceptable to the community or species that died! Measurements must be sufficiently sensitive to detect the subtle, non-lethal changes that can slowly result in shifts in species dominance and community structure. These changes are signs that pollutants have reached concentrations that are resulting in unacceptable changes to the natural ecosystem. This threshold is called a non numeric or "narrative" water quality standard.

In the Keys there are two main problems associated with wastewater pollution: fecal contamination (health risk) and nutrient enrichment (eutrophication). One important water quality standard concerns the presence of fecal coliform bacteria in the water. Birds and mammals excrete fecal coliform bacteria in fecal matter. The presence of fecal coliform bacteria in the water column is used as a measure of possible wastewater contamination of the water. Although fecal coliform bacteria are not a major health risk, they are easy to measure and can indicate the presence of other enteric (intestinal), disease-producing microbes. Presence of fecal coliform bacteria above the State standard of 800 colonies/100 ml of water (monthly average) is indicative of contamination by untreated sewage and is a public health concern. This bacteriological standard was developed for fresh water. Fecal coliform bacteria normally die when exposed to marine waters. However, fecal coliforms sometimes are present in tropical environments in the absence of any source of fecal contamination (Hansen, 1988). Therefore, it is questionable whether the existing standard is meaningful for marine systems (Dutka et al., 1974; Goodfellow et al., 1977; Loh et al., 1979). Normally, when fecal coliform bacteria are present in marine systems, it is an indicator of very recent fecal contamination. Low concentrations of fecal coliform bacteria should not necessarily be equated to low abundance of bacterial or viral pathogens in marine waters.

Coprostanol is a chemical that is produced during the digestion process and is a product of cholesterol decomposition. It is a better indicator of discharge of untreated sewage because unlike fecal coliform bacteria which are relatively short-lived in the marine environment, coprostanol accumulates in sediments and provides a long-term record of sewage pollution. However, measurement of coprostanol is impractical for routine monitoring because it requires sophisticated, expensive analysis and, at the present time, there is no regulatory standard for coprostanol.

EUTROPHICATION

Nutrients, such as carbon, nitrogen and phosphorus, are essential for the normal healthy functioning of all living cells. They are used in biosynthesis in all living matter. These nutrients and others, such as potassium and magnesium, which are present in very small amounts, are recycled in the ecosystem. When organisms excrete waste products or die, the nutrients present in the waste or carcass are made available through the decomposition process. The growth of plants is generally limited by the lack of one or more of these nutrients. New plant growth is dependent upon this recycling of bound nutrients. In this manner, an ecosystem maintains a "balance."

Ecosystems can utilize a certain amount of "new" nutrients. New nutrients may come from other adjacent (upstream) natural systems or may be introduced by human activities. Domestic wastewater is one major source of new nutrients to the aquatic environment. If nutrients are released into the environment in excessive amounts (eutrophication), they become pollutants because they disrupt the natural nutrient balance and result in unacceptable changes of community structure. Dramatic changes in community structure can result in a catastrophic collapse of an ecosystem.

Eutrophication often progresses through a sequence of stages. A typical progression involves: (a) enhanced primary productivity, (b) changes in plant species composition, (c) very dense phytoplankton blooms, often toxic, (d) anoxic conditions, (e) adverse effects on fish and invertebrates, and (f) changes in structure of benthic communities (GESAMP, 1990).

There are many documented examples of the collapse of an ecosystem due to nutrient enrichment. For the sake of simplicity, consider a simple pond ecosystem that is rarely visited by people. The pond ecosystem is in balance because the aquatic vegetation (grassbeds) that grow on the bottom of the pond supports a population of shrimp, which in turn supports a population of fish. As shrimp and fish grow and defecate, and eventually die, they return nutrients to the water which are taken up by the grasses and support grassbed growth. If you (or a raccoon) defecate or urinate into the pond, the nutrients that are added may result in increased grass growth which may cover more area of the pond bottom. Increased grassbeds will result in increased numbers of shrimp and bigger and more abundant fish. Thus, the pond ecosystem can assimilate some additional new nutrients without a significant negative change in structure or function.

However, if the area surrounding the pond becomes a popular campground, and all the campers dump their wastewater directly into the pond, the structure of the pond ecosystem will change drastically. Microscopic algae which were always present in the pond, but were held in check by low amounts of available nutrients,

will grow, divide and result in an algal bloom that will change the water color from clear to green. The green water (high chlorophyll) will absorb most of the sunlight that strikes the pond and will result in the death of the aquatic grasses living on the bottom of the pond. Death of the benthic grasses will result in death of the shrimp that are dependent upon them. The fish that eat shrimp will also starve since they are not physically able to eat algae. Death of the benthic grasses, shrimp, and fish will result in the release of more nutrients into the water which will further fuel the algal bloom. The small number of fish in the pond that can eat algae can now explode in population size because of a seemingly unlimited amount of algae. Ultimately, the blooms of algae and fish will cause the collapse of the ecosystem when they respire at night, utilize all the dissolved oxygen, and die. This hypothetical,
catastrophic collapse of a pond ecosystem is exactly the scenario that resulted in the ecological collapse of Lake Erie, portions of Tampa Bay, and many other bodies of water that received unacceptably high levels of nutrients. Addition of high levels of nutrients result in major changes in ecosystem structure and function and can lead to the eventual collapse of the ecosystem.

Generally, it is the total amount of nutrients, including micro-nutrients, entering a water body that can result in overloading of the system, not necessarily their concentration. It matters little whether nutrient addition comes from a single or a few concentrated sources of nutrients discharging into a water body or from many sources discharging lower concentrations of nutrients. The effect of the total loading to the receiving water body will be the same. When the system can no longer absorb increased levels of new nutrients without significantly changing ecosystem structure and function, the threshold of nutrient assimilative capacity of the system is reached.

A principal objective of wastewater treatment processes is to remove nutrients and other pollutants and dispose of them in a manner that does not cause unacceptable changes to the environment. Indeed, re-use of wastewater in suitable areas may be used to cause desirable changes to the productivity of a cultivated field or forest (e.g., land application of wastewater).

Tropical marine hard bottom and seagrass communities have evolved and thrive in relatively low nutrient (oligotrophic) conditions. Species in these communities efficiently take up nutrients and out-compete other less adapted species in low nutrient environments. They can not successfully compete with organisms that have evolved to take advantage of elevated nutrient loads. Therefore, nutrients added to oligotrophic systems are very quickly taken up by opportunistic species. Because of rapid uptake, nutrient concentrations in the water can be quite low and may not be detectable using traditional water quality sampling methods. Changes in the structure of the biological community (species abundance and composition) are important signs of nutrient enrichment in oligotrophic systems.

Nutrients are found in the foods, drinks, fertilizers, drinking water, and the like that are imported into the Keys every day. If these new nutrients get into the surface waters, they become available for use by the marine ecosystem. Small additions of nutrients may cause inconsequential changes, but if continued or increased over time, they can cause drastic shifts in the numbers and kinds of plants and animals. The change to ecosystems due to excess nutrients is called eutrophication, which means "too much food".

SOURCES OF WATER QUALITY CONCERNS

STORMWATER RUNOFF

Pollutants can be conveyed into surface waters when stormwater accumulates on land surfaces and runs off. Stormwater is considered a major source of pollutants to surface waters nationally. Runoff typically contains substances like organic debris, silt, nitrogen, phosphorus, metals, and oils. The amount or load of pollutants is largely a function of rainfall quantity, imperviousness (i.e. the degree to which rainwater cannot soak into soil), and land use. In residential areas, for example, nutrients are a major part of the load. Pollutants from roadways include oils and metals. Soil characteristics can also play a major role in the types and quantities of pollutants that are retained on land.

In Florida, the Water Management Districts and local governments now impose a minimum level of stormwater treatment for all new developments. The criteria are intended to protect surface waters according to their use classification. Much of the development in the Florida Keys occurred prior to the existence of these criteria. Similar to other parts of the State at the time, stormwater was considered a nuisance since it resulted in flooding. Therefore, if stormwater systems were employed at all, they were typically designed to efficiently convey water off land surfaces as quickly as possible. These old systems are considered to be the most liable to cause water pollution and, therefore, policies now in place seek to retrofit them whenever possible. In most areas of the Keys, there was no stormwater management. Uncontrolled runoff can cause pollution of surface waters.

In the Keys, stormwater runoff from roadways, bridges, driveways and yards, roof tops, and shopping center parking lots contribute stormwater loading to surface waters. The amount of pollutant load caused by stormwater runoff can be estimated mathematically from the factors given above. Estimates of total loadings of nitrogen and phosphorus from wastewater and stormwater were summarized in the Phase II Report of the WQPP (EPA, 1993) Assumptions used to generate those figures were recently reevaluated and the numbers have bee revised (Table 4). These recent estimates attribute about 20% of the nearshore nitrogen load and about 45% of the phosphorus to stormwatr (Table 4). These estimates, however, can vary widely depending on the magnitude of each factor. No estimate should be considered absolute, but viewed only in relationship to its potential impact.

WASTEWATER

As is true for all animal life, humans derive nutrients and energy from the food we eat. We are not totally efficient in removing nutrients from our food, so human waste contains nutrients, such as carbon, nitrogen, and phosphorus. Typical residential wastewater flow is approximately 45 gallons per person per day. Of that, approximately 35% (16 gallons) is from the toilet (black water) and 65% (29 gallons) is from sinks, bathtubs, and appliances (gray water) (Harkins, 1996). Nutrient concentrations of pollutants in black water and gray water are summarized in Table 3. Wastewater can enter canals and other nearshore waters from cesspits (4,000 estimated), septic tanks (approximately 20,000), injection wells (750), ocean outfalls (1), and live-aboard vessels.

Based upon current best estimates (Table 4), approximately 80% of nitrogen loadings comes from wastewater. Onsite disposal systems (septic tanks and aerobic treatment systems) and cesspits account for 40.3% of nitrogen loadings. Approximately 55% of phosphorus loadings are from wastewater. Onsite disposal systems and cesspits account for 33.2% of total phosphorus loadings.

Disposal of wastewater from live-aboard vessels is a significant localized problem because of the low level of treatment, the tendency for live-aboard vessels to congregate in certain marinas or anchorages, and potential adverse health effects of discharging untreated wastewater. Many live-aboard vessels are permanently anchored and mobile pumpout facilities are required to service those vessels. There are no mobile pumpout facilities in the Keys. Overall, live-aboard vessels account for approximately 2.7% of total nitrogen and 2.9% of total phosphorus loading to the region's surface waters.

OTHER SOURCES

Nutrients come from a variety of other sources. Loadings to the waters of the Keys from most other sources, such as Florida Bay, Gulf of Mexico, oceanic upwelling, and atmospheric deposition have not been quantified. Nutrient inputs from those sources external to the Keys may be greater than anthropogenic loadings from wastewater or stormwater emanating from the Keys. However, that does not diminish the importance of focusing on anthropogenic nutrient loadings and their effects on water quality and biological resources. Since maintenance of healthy, natural communities of the Keys is dependent on low nutrient environments, localized sources of nutrients can have immediate negative impacts that can result in cascading effects throughout the ecosystem. Nutrient loadings from atmospheric sources are diffuse and evenly distributed over the Florida Keys. Wastewater nutrient loadings emanate from the land-water boundary and may cause concentration increases in canals and confined nearshore waters well above those caused from atmospheric or other sources. Similarly, upwelling of deep ocean waters can provide nutrients, particularly to the outer reef tract and areas seaward of the Keys. Although the concentration of nutrients in upwelled oceanic waters is low, the total loading to the reef system can be significant because of the high volume of water. External advective nutrient inputs are more diffuse than land-based, human-induced sources. Very little data are available on the physical processes driving advective and atmospheric loadings and their effects on water quality of the Florida Keys. This is a topic that requires further research.

Florida Bay has represented a source of nutrient-rich and turbid waters to the Florida Keys for approximately the last 4,000 years. The discharge of Florida Bay waters through the major tidal passes between the Keys has arrested development of the outer reefs near those locations. In 1987, a significant decline of seagrasses began in Florida Bay. Although the cause of that die-off is still debated, it was probably related to manipulation of historic delivery of freshwater to the Everglades. Several very dry years immediately preceded the initiation of the die-off and salinities in some parts of Florida Bay were approximately twice seawater strength (70 parts per thousand). The dead seagrasses decomposed and their stored nutrients became available for phytoplankton algae. Also, sediments which the seagrasses bound with roots and rhizomes became water-borne with wind events and resulted in highly turbid water. Since corals thrive in clear, low nutrient waters, the discharge of turbid, nutrient-rich Florida Bay water is probably having a detrimental effect on coral reef communities seaward of the tidal passes. Cook et al. (1997) demonstrated that effect by measuring growth of coral transplants in the discharge from Florida Bay. Corals exposed to Florida Bay water grew slower and were less dense than corals transplanted to a reference site (Tennessee Reef). Corals within the influence of Florida Bay water also had a significantly higher concentration of symbiotic algae in their tissues, presumably in response to the more turbid conditions. Brand (1997) and others have tracked Florida Bay water out to the reef tract using chlorophyll concentrations or satellite imagery reflectance as a fingerprint of the water mass.

Several studies have analyzed sediments, primary producers, and/or consumers for trace metals and pesticides (Glynn et al., 1989; Manker, 1975; Skinner and Jaap, 1986; Strom et al., 1992). In general, the results are consistent with a relatively clean environment with some localized anthropogenic effects. For example, Strom et al. (1992) found relatively high cadmium at stations near the Seven Mile Bridge and Newfound Harbor Key. Highest metal concentrations were found in consumers (sponges) which is indicative of bioaccumulation.

Marinas have the potential for polluting water or sediments from boat scraping and painting operations, fueling, and engine repair. Data are not available to quantify loadings of pollutants from marina operations.

Pesticides are a potential threat to marine life. Chemicals used in mosquito control are known to be toxic to aquatic crustaceans, such as lobsters, shrimp, and crabs. Pesticide levels in samples from the Keys have been historically low (Strom et al., 1992). Although the amounts of pesticides currently used by the Mosquito Control Program are known, no information is available on the amount of pesticides that reach marine waters. Also, nothing is known about the environmental concentrations or effects of residual pesticides in marine waters. That is an area of research that will be examined in 1998.

Other "natural" sources of pollutants include animal wastes, runoff from natural environments, and weed wrack. Although bird droppings can be a significant source of nutrients locally, for example around breeding or roosting islands, they represent a redistribution and recycling of nutrients currently in the system and are generally not considered pollutants.

Weed wrack consists of detached blades of benthic seagrasses and algae that become wind-driven into large floating mats. These mats can become trapped along shorelines and in canal systems along the windward side of the Keys. Decomposition of the weed wrack removes oxygen from the water, releases nutrients, and forms toxic hydrogen sulfide gas. With wind shifts, weeds trapped along shorelines move offshore. However, weed wracks trapped in canal systems result in the build up of organic debris. Decomposition of organic matter quickly strips all oxygen from stagnant canal waters. Mobile life forms (e.g., fish) may be able to leave the canal before succumbing to low oxygen concentrations. Other relatively non-mobile life forms that require oxygen (e.g., corals, benthic worms and mollusks) can not survive.

Many nearshore waters are very shallow with bottoms consisting of fine sediments. Fine sediments can be re-suspended in the water column by disturbances, such as boat traffic. High use areas are experiencing chronic turbidity generated by the growing number of recreational and commercial vessels that transit those waters. Turbid waters could detrimentally affect seagrass (shading) and adjacent hard bottom communities (smothering). Research and monitoring are needed to quantify the effects of chronic turbidity on biological communities.

CANALS AND OTHER CONFINED WATERS

There is much variability in the design and physical characteristics of canal systems in the Keys. Differences in length, depth, slope, geometry, and underlying geology of canal systems, as well as the population density, affect the impacts of nutrient loading, flushing rates, and the water quality in the canals. The following summary of information on water quality findings in canals is based on studies for particular canal systems. However, many generalities about canal systems can be gleaned from this information.

Much of the pre-1970 information on canal systems in Florida was summarized by Barada and Partington (1972) who reviewed the literature and performed a survey of environmental officials. Based on water quality data and the personal experience of the individuals surveyed, Barada and Partington concluded that excavating artificial canals causes serious environmental degradation within the canals themselves and in waters adjacent to canals. Deep, narrow, box-cut canals with dead-end configurations gradually accumulate oxygen-demanding and toxic sediments and organic wastes, causing low dissolved oxygen, objectionable odors (hydrogen sulfide gas), floating sludge, fish kills, and anaerobic and putrid conditions. Eutrophication of canals with poor circulation is accelerated by a heavy pollution load which is related to population density and shoreline length. Sources of pollution into the canals investigated include stormwater runoff, septic tanks, sewage effluent, and live-aboard houseboats.

Citing Smith, Milo, and Associates (1970), Barada and Partington concluded that none of the soils in Monroe County are suitable for septic tanks. The high water table and extremely porous soils "nullifies the filtering capacity and virtually raw sewage is leached into the waterways." The report also recommended against the discharge of effluent from package plants into canals. Package plants with secondary treatment remove most of the organic material and bacteria, but do not effectively remove dissolved contaminants, such as phosphates, nitrates, and other chemicals that contribute significantly to the degradation of water quality.

Chesher (1973) performed an environmental study of canals and quarries in the lower Keys and concluded that the flow-through canal system at Summerland Key Cove had excellent water quality. Construction of that canal system was begun in 1957 and completed in 1971. At the time of Chesher's study, 69 houses were constructed on the 614-lot subdivision. The total population of the subdivision was 207, which included winter-only residents. All houses utilized septic tanks. Chesher generally found low levels of nutrients in the canals, relatively high oxygen, and no evidence of stratification. Mean nitrate concentration was about 0.03 mg/l (parts per million) and mean phosphate was 0.06 mg/l. Fecal coliform bacteria ranged from 0 to 37 colonies/100 ml. The canal system configuration and orientation prevented any algae or seagrass from accumulating in the canal. Chesher also observed a diverse and numerous biotic community living in the canal system, including seagrasses, fish, lobsters, and many other species.

Chesher's results are atypical of other canal studies for a number of reasons. The Summerland Key Cove canal system was only 11% developed at the time of sampling. Also, nutrients were measured with a HACH kit which is not as sensitive as standard analytical methods. There is no indication that oxygen measurements were made in early morning when daily minimums are expected.

It would be interesting to revisit the Summerland Key Cove canal system today. Chesher's findings of lush marine life is typical of newly dug canals. Barada and Partington (1972) reported that it is a common fallacy that finger canals provide a haven in which fish thrive. That condition may occur in the very early stages after canal excavation. A typical pattern is that in the first few months of spring, bottom animals and fish are abundant in newly-dug canals. However, with the advent of summer and hot weather, dissolved oxygen in deeper waters of the canals drops to zero, or nearly so. There is heavy mortality of benthic organisms and fish are absent. When cooler weather returns, benthic animals and fish may recolonize. But, as dead and decaying organic materials gradually build up in the canal bottom, the number and diversity of marine creatures declines and eventually there is virtually no desirable biological production in the canal. Taylor and Saloman (1968) found very little benthic life and half as many species of fish in a ten year old, box cut canal near St. Petersburg as in surrounding areas. They concluded that the accumulation of organic material and low dissolved oxygen in canals has a permanent adverse affect on fish and other marine life.

In 1972, during the peak of finger fill canal construction in the Keys, the Florida Department of Pollution Control (FDPC) issued a dredge and fill moratorium halting all canal construction in the Keys until completion of a study to assess the effects of canal development on the marine habitats, plants, and animals. One important reason for that study was the apparent drop in average underwater visibility at the outer reefs from approximately 175 feet in 1968 to approximately 35 feet in 1973. They found that major turbidity problems persisted up to two years after the completion of a canal dredging project due to slow settling of very fine particles. Also, the repopulation by seagrasses in areas dredged for access channels was very slow; dredged grassbeds showed no signs of new growth after ten years.

Ten canal systems were studied in the FDPC (1973) study. Depressed dissolved oxygen levels were frequently encountered in all canals. The average bottom concentration was less than 4.0 mg/l (the State standard) and often less than 1.0 mg/l. Surface and mid water levels of dissolved oxygen of less than 4.0 mg/l were frequent. Long term conditions of low oxygen concentrations resulted in the growth of anaerobic bacteria which produce hydrogen sulfide which is toxic to most other organisms. Most canal systems studied had reduced number of animal species and densities compared to reference sites. At the conclusion of the study, the moratorium on dredge and fill operations was lifted provided strong enforcement measures were taken for violators of turbidity and other water quality parameters. In addition, water exchange and circulation of future canal systems would be critically examined. The FDER study and its recommendations effectively stopped construction of additional finger fill canal systems in the Keys.

The U.S. Environmental Protection Agency (EPA) (1975) conducted a study of finger fill canals in Florida and North Carolina and came to the same conclusions as the FDPC (1973) study. EPA concluded that poorly designed canals result in poor flushing, which coupled with a seasonal inflow of freshwater, produced extensive salinity stratification in the canals. The bottom layer of high salinity water resulted in stagnation, putrification, and extensive nutrient enrichment of the water column. Canals greater than four- to five-feet deep regularly experienced violations of State water quality standards for dissolved oxygen (<4 mg/l).

The EPA (1975) compared the water quality of two canals on Big Pine Key at Doctor's Arm Subdivision. At that time, one of the canals was recently constructed and undeveloped and the other was sparsely developed with septic tank systems in Miami Oolite substrate. Even though the canal was sparsely developed, they found reduced oxygen concentrations, increased biochemical oxygen demand, and increased fecal coliform bacteria compared to the undeveloped canal. The water quality in both the developed and undeveloped canals was poorer (higher nutrients and lower dissolved oxygen) than ambient conditions in a well-flushed adjacent area, Bogie Channel.

Other canal systems tested during the EPA study were in Punta Gorda, Florida and several locations in North Carolina. Those systems had greater nutrient levels in developed canals than the Big Pine site, probably because the canals systems at those locations were more densely developed. Total nitrogen and organic carbon were the most salient chemical constituents characterizing water quality differences between developed and undeveloped canal systems. In nearly every case, concentrations of those two nutrients were significantly greater in the developed waterways.

At all canals studied by EPA (1975), a dye tracer was flushed down toilets to measure the time septic tank leachate reached adjacent waters. At Punta Gorda, the dye appeared in the canal within 25 hours at two sites. In North Carolina, the dye appeared after 60 hours in one test and 4 hours in a second test. Septic tanks at those locations were approximately 50 feet from the adjacent canals. Dye introduced into two septic systems on Big Pine Key did not appear in the canal within 150 hours, the duration of the study. The reason was thought to be due to a period of sustained high tides. Septic systems were installed in porous Miami Oolite which has a high percolation rate (2 minutes per inch). However, during the time of the dye tracer study, the water surface in the canal was kept high due to natural tidal amplitude (spring tides) and wind driven waters. During the time frame of the study at Doctor's Arm Subdivision, the observed high tides were higher than normal and the low tides were not low enough to effect a hydraulic gradient that would flush the leachate from the seepage field and disperse it to the canal. Subsequent to the EPA (1975) study, other studies in the Keys have demonstrated the rapid transmissivity of Keys substrates to wastewater and the influence of tides on the movement. Those studies are discussed below.

In 1985, the Florida Department of Environmental Regulation (FDER) studied the water quality of the waters surrounding the Florida Keys in preparation for the proposed designation of the waters of the Florida Keys as Outstanding Florida Waters. That study concluded that the majority of the Florida Keys met the criteria for designation as Outstanding Florida Waters, but that certain areas, including canals and the vicinity of the Key West outfall should not be included. Many of the canal systems tested exhibited low values in dissolved oxygen, high nutrient values, and violations of the fecal coliform standard. Ranges of some water quality parameters from canals and other ambient stations are given in Table 2.

Canals and other confined water bodies that demonstrated signs of eutrophication during the OFW study were listed as "hot spots" in the Phase II Report of the Water Quality Protection Program (EPA, 1993; Table 6-4). That hot spot list was revised (Table 5) at an interagency workshop sponsored by the South Florida Water Management District (April 16, 1996). The revised list includes a relative priority ranking of the top 19 canal systems and other waters that demonstrate poor water quality based upon the literature and the collective experience of participants of the workshop. It also includes a brief description of potential solutions to the water quality problems for each prioritized hot spot. Three recommendations were made for all high priority, poorly designed canal systems: install best available technology (BAT) sewage treatment, collect and treat stormwater runoff, and improve canal circulation. Installation of pumpout facilities was added to the list of recommended solutions for hot spots that included live-aboard vessels. Improved circulation to canal systems is an essential component of restoration because water quality of even undeveloped canals generally deteriorates due to cumulative, long term loading of fine organic matter (high BOD), salinity stratification, and long residence time (EPA, 1975). However, construction of flushing channels or installation of culverts to improve circulation may not be practicable at all locations due to physical constraints and quantity and quality of natural resources that would be impacted during or after construction.

The FDER (1987) measured thirty-two water quality parameters at twelve nearshore sites in Marathon for one year (1984). Primary sampling sites were in canals and marina basins at Faro Blanco Marina, City Fish Market, Winn Dixie Shopping Center, Key Colony Beach Sewage Treatment Plant, and the 89th to 91st Street canal system. High levels of nutrients (0.14 mg/l ammonia) and fecal coliform bacteria (3400 colonies/100 ml) were found at Faro Blanco Marina during the tourist season (November to May) due to discharge of raw sewage from live-aboard vessels. Total Kjeldahl nitrogen, total phosphorus, and biochemical oxygen demand were significantly higher in the marina than in adjacent waters.

The 90th Street canal station was selected to monitor leachate from septic tanks and cesspits. FDER consistently found violations of dissolved oxygen (<4 mg/l) at the head of the dead-end canal. With a single exception, mean monthly fecal coliform bacteria were higher at the end of the canal (3 to 37 colonies/100 ml) than mean concentrations at the canal mouth (1 to 6 colonies/100 ml). Fecal coliform concentrations were highest during Thanksgiving, Christmas, and New Year's holiday periods. The maximum reading was 1220 colonies/100ml. Orthophosphate (0.04 mg/l) and mean chlorophyll concentrations (29 ug/l) were also significantly higher in the canal than at the reference site, indicating eutrophication and algal blooms. FDER also found high levels of mercury, lead, zinc, copper, and hydrocarbons in the canal sediments, presumably from boats. Iron levels were significantly higher in the canal which is indicative of stormwater runoff (EPA, 1975).

FDER (1987) measured coprostanol, a degradation product of cholesterol, which is excreted in human waste. The presence of coprostanol in marine sediments provides a historic record of sewage contamination. Coprostanol levels at Faro Blanco Marina were 2 to 50 times higher in marina sediments than in reference sediments. Coprostanol levels (mean = 256; maximum = 1645 ng/g) were highest in sediments directly below boat slips, indicating that the primary source of fecal contamination was from discharge of untreated sewage from vessels. Reference stations averaged 34 ng/g coprostanol.

Concentration of coprostanol at the outfall of the Key Colony Beach sewage treatment plant (secondary treatment) was 294 ng/g. Of the three locations in which coprostanol was measured in that study, the area surrounding the Key Colony Beach outfall was the least impacted by sewage. That is not surprising because secondary treatment plants remove between 85% and 95% of total suspended solids (TSS) in raw sewage, and coprostanol is normally associated with TSS.

Coprostanol was found in sediments from the 89th, 90th, and 91st Street canals and exhibited spatial and temporal variability. Sediments from the 90th Street canal contained the highest coprostanol concentrations found in the study (2206 ng/g). All three canals sampled contained high levels of coprostanol and were heavily impacted by sewage-derived materials. Mean coprostanol concentration ranged from a maximum at the head of the 91st Street canal (1363 ng/g) to a minimum at the middle of the 90th Street canal (160 ng/g). In general, coprostanol levels decreased from the end of each canal toward the canal mouth, probably reflecting a flushing gradient within each canal. Substantial amounts of sewage-associated, fine-grained material appeared to be transported out of the canals by tidal exchange and deposited in the nearshore access channel, where coprostanol was measured at 681 ng/g. Coprostanol was undetectable (<10 ng/g) in four out of five sampling events at a station located approximately one mile offshore; at one sampling event, coprostanol was detected at that reference site in very low concentration (28 ng/g).

FDER (1987) measured water quality in a canal system that received stormwater drainage from the Marathon Winn Dixie shopping center. An occluded effluent pipe and inefficient drainage of the parking lot reduced the amount of stormwater discharged to the canal and the impact of stormwater runoff at that location could not be definitively evaluated due to the low discharge volume. Regardless, FDER reported significant gradients in the canal that could be the result of septic tank seepage and stormwater. Dissolved oxygen levels were significantly depressed at the head of the canal. Mean monthly levels ranged from 3.06 mg/l to

4.93 mg/l, whereas those at the mouth of the canal fell below 5.0 mg/l only once during the study. On 76% of the days sampled, the dissolved oxygen at the head of the canal was below the State minimum criterion.

At the Winn Dixie site, monthly concentrations of total nitrogen and ammonia nitrogen were statistically indistinguishable between canal waters and ambient waters. However, phosphorus concentrations at the stormwater discharge site (maximum = 0.04 mg/l) were significantly higher than those measured at the mouth of the canal (0.01 mg/l) and offshore (0.01 mg/l). Orthophosphate levels peaked during July and autumn (rainy season) at the canal head and averaged two to three times above those measured at the canal mouth.

FDER (1990) conducted an intensive, one-year study to assess the water quality in Boot Key Harbor. Boot Key Harbor has approximately 400 live-aboard vessels during winter months. Stations were located in canals, the Harbor basin, and a reference site. Annual mean dissolved oxygen concentrations were lowest in canals and basin (4.2 mg/l) compared to the reference stations (6.1 mg/l). Low dissolved oxygen levels in the canals and basin were due to poor flushing characteristics that resulted in the canals serving as sinks for organic matter. Regular violations of the State standard for dissolved oxygen were observed in the canals.

Fecal coliform bacteria concentrations were highest at canal stations and were practically absent at reference stations. Highest fecal coliform levels were observed at stations with onsite disposal systems after a heavy rainfall. Fecal coliform levels in Boot Key Harbor basin stations were highest during winter months at stations in close proximity to live-aboard vessels. Violations of the State standard for fecal coliform bacteria were common.

Florida Bay Watch is a volunteer program to collect water quality data in Florida Bay and the Florida Keys. Bay Watch volunteers take water quality data that augment ongoing studies by agencies and institutions. Between July 1995 and June 1996, Bay Watch volunteers sampled 38 fixed nearshore stations, of which 16 were in residential canals, 1 in a boat basin, and 21 at natural shorelines (Florida Bay Watch, 1996). Immediately apparent is the variability of the data, both at any station and between stations. This may be due in part to varying climatological differences between sampling intervals. However, some basic generalities appear from this data set. Twenty one of the stations had enough data to determine seasonal trends. Of those, 5 of the canal sites had higher nitrogen during the wet season; others showed no seasonal variation. There were no significant trends spatially or seasonally of total phosphorus with station location. Highest chlorophyll levels occurred in bay side canal sites.

In 1997, Bay Watch volunteers sampled 36 fixed nearshore stations for water quality. Nutrient data varied among stations because of the many differences between sampling sites, such as flushing rates, density and number of residences, proximity to injection wells or other discharges, and stormwater controls. However, these data are very useful in comparing and ranking nearshore waters. For example, the canal system on Duck Key is very well flushed due to its flow-through design and proximity to open waters of the Atlantic Ocean. Also, density of residences is comparatively low on Duck Key. In contrast, The Eden Pines (Big Pine Key) and Ramrod Key canal systems are long, with many dead-end fingers and relatively dense development. Differences in water quality parameters from Duck Key and the Eden Pines and Ramrod Key canals are striking (Table 6). For example, in 1997 mean total nitrogen was approximately twice as high in Eden Pines (40.5 uM) and Ramrod (35.8 uM) compared to Duck Key (19.8 uM). Mean total phosphorus and mean total chlorophyll-a showed similar trends. A natural, unobstructed shoreline at Grassy Key (bay side)is included in Table 6 for comparison. These data document the degraded water quality in poorly flushed, long dead-end canal systems (Baywatch, 1997).

OTHER NEARSHORE WATERS

Because the Florida Keys ecosystem is an "open" system and receives water from many sources, defining the causes of changes in the community structure becomes more difficult farther from the shore. Several studies have been performed to investigate the extent of impacts from land-based nutrient loading to nearshore habitats.

Lapointe and Clark (1992) measured water quality parameters at 30 stations during summer and winter to characterize seasonal extremes of measured variables. Sampling at each site was performed along an onshore-offshore transect. They found a gradient in nutrients from inshore to offshore. Man-made canal systems had significantly elevated concentrations of soluble reactive phosphorus (0.3 uM) compared to seagrass meadows (0.1 uM), patch reefs(0.05 uM), and offshore reef banks (0.05 uM). Ammonia was highest in canal systems and seagrass meadows (>1 uM) compared to patch and bank reef stations (<0.3 uM). Chlorophyll and turbidity were highest in canal systems and seagrass meadows and reached peak levels during summer months. Chlorophyll was >1 ug/l at canal and <0.3 ug/l at bank reef stations They concluded that widespread use of septic tanks increases the nutrient contamination of groundwaters that discharge into shallow nearshore waters, resulting in coastal eutrophication.

Seagrasses and other community components integrate the effects of nutrients in the water column over time. Growth of benthic algae, increased chlorophyll (phytoplankton) in the water column, as well as increased nutrient concentrations have been used to gauge the onset of eutrophication in tropical marine ecosystems (Bell, 1992). Lapointe et al. (1994) assessed how nutrient enrichment affects algal growth on seagrass blades (epiphytes), and the productivity and structure of the shallow water turtlegrass (Thalassia testudinum) community in the Keys. A stratified-random sampling technique was utilized along three onshore-offshore transects perpendicular to shore in the Middle and Lower Keys. Inshore stations (hypereutrophic) were selected in areas receiving direct impacts of wastewater nutrient discharges, and included a canal mouth with septic tanks and cesspits (Doctor's Arm Subdivision, Big Pine Key), live-aboard vessels (Houseboat Row, Key West), and a package sewage treatment plant (Fiesta Key Campground). Eutrophic and mesotrophic stations were located within approximately 1 km from land. Oligotrophic stations were located along the back reef at Alligator Reef, Looe Key, and Sand Key.

Total nitrogen and total phosphorus decreased linearly from inshore stations to offshore stations. Offshore stations had the highest shoot densities, areal biomass, and areal production rates, and lowest epiphyte levels. Nearshore seagrass meadows had greater diversity of primary producers, including macroalgae, attached seagrass epiphytes, high phytoplankton concentration (green water), and jellyfish (Cassiopeia spp.) Lapointe et al. (1994) concluded that nutrient-enhanced productivity of macroalgae and attached epiphytes leads not only to decreased productivity of turtlegrass, but also may reduce dissolved oxygen levels that results in significant habitat damage prior to actual die-off. Eutrophic seagrass meadows in the Florida Keys were found to have pre-dawn hypoxia (<2.0 mg/l dissolved oxygen) or anoxia (<0.1 mg/l) during warm, rainy periods. McClanahan (1992) reported low predawn oxygen concentrations were negatively correlated with species richness and diversity of mollusks in Florida Bay compared to waters with higher oxygen found offshore Key Largo. Lapointe et al. (1994) found that at concentrations of approximately 25 uM nitrogen and 0.45 uM phosphorus, turtlegrass is replaced by shoalgrass (Halodule wrightii), an opportunistic seagrass. They concluded that nutrient enrichment from land-based sewage inputs can have significant effects on seagrass productivity for considerable distances from shore.

OUTER CORAL REEFS

Szmant and Forrester (1996) measured distribution patterns of nutrients to determine whether anthropogenic nutrients from land-based sources may be reaching the outer reef tract. Samples were collected along seven transects oriented perpendicular to the shoreline and located from Biscayne National Park to Looe Key. Samples were taken along transects at stations located in tidal passes and canal mouths to approximately 0.5 km seaward of the outermost reef. Water column and sediment concentrations of nitrogen and phosphorus were measured.

In the Upper Keys, water column nitrogen (1 um NO_3) and chlorophyll (1 ug/l chl a) were elevated near marinas and canals, but returned to oligotrophic concentrations within 0.5 km of shore. Phosphorus concentrations were higher at offshore stations (>0.2 uM PO_4) and were attributed to upwelling of deep water along the shelf edge at the time of sampling. Sediment interstitial nitrogen concentrations decreased from inshore to offshore stations which is indicative of an onshore source of nitrogen. There was some indication of a reverse trend for phosphorus that may be indicative of upwelling of deep oceanic waters as a source.

In the Middle Keys, both water column nutrients and chlorophyll concentrations were higher than observed in the Upper Keys, and there was less of an inshore-offshore gradient than noted in the Upper Keys. Sediment nutrients were also higher, and there were no differences in nutrient concentrations at nearshore and offshore areas. These observations may be explained by the mixing of Florida Bay waters with the waters adjacent to the Keys.

These data support the conclusion that outer reef areas in the Upper Keys are not accumulating elevated loads of land-derived nutrients via surface water flow, but do document moderately elevated nutrient and chlorophyll levels in many developed nearshore areas. The authors concluded that most of the anthropogenic and natural nutrients entering the coastal waters from shore appear to be taken up by nearshore algal and seagrass communities before they reach patch reef areas (about 0.5 to 1 km from shore). Further work is needed to determine whether nutrient-enriched groundwaters reach the reefs, however these would be expected to cause an enrichment of reef sediments, which was not observed.

Lapointe and Matzie (1996) used high frequency sampling to track effects of periodic rainfall events on a transect that included stations in a canal on Big Pine Key (Port Pine Heights), a seagrass meadow (Pine Channel), a patch reef (Newfound Harbor), and an offshore reef (Looe Key). Lowest dissolved oxygen (<0.1 mg/l), maximum concentration of NH_4^+, total dissolved phosphorus, and chlorophyll, and minimum salinities were measured in the canal during a rain event. Concentrations of total dissolved phosphorus also increased at the seagrass, patch reef, and offshore reef stations after the initial rainfall event. Concentrations of NH_4^+ and chlorophyll increased at offshore stations approximately 1 to 3 weeks following the rain event. The authors suggested that rainfall events can rapidly flush nutrients into canals and adjacent nearshore waters. These nutrients may have the potential of impacting water quality for considerable distances from land; however, more research is required to substantiate these findings and define the area of impact. Lapointe and Matzie (1996) concluded that the effects of increased concentrations of nutrients in nearshore waters justifies that special precautions be taken in the treatment and discharge of wastewaters and stormwater runoff.

Lapointe and Matzie (1997) measured water quality parameters along a transect from the eastern shoreline of Big Pine Key to Looe Key from January to October 1996. The inshore station was located off Avenue J Canal and was down gradient of approximately 1,000 septic tanks and cesspits. A patch reef station was located off Munson Island, and an offshore station was located along the back reef at Looe Key. Monthly samples were taken, along with high frequency sampling prior to, during, and following selected rainfall and wind events. Lapointe and Matzie also measured nitrogen isotope ratios in macroalgae and seagrass blades to determine the source of the nitrogen; there is a higher ratio of $^{15}N/^{14}N$ in wastewater.

Highest levels of dissolved inorganic nitrogen, soluble reactive phosphorus, and chlorophyll occurred during periods of high winds, low tides, and rain events. The highest nitrogen and phosphorus concentrations were measured at the inshore station at low tide when tidal ranges were highest. Low tides allow rapid drainage of nutrient enriched groundwater to adjacent surface waters.

Ratios of nitrogen isotopes were highest in a benthic algae at the nearshore station (5.0 o/oo), intermediate at the patch reef station (3.5 o/oo), and lowest at Looe Key (3.0 o/oo). These data may indicate increasing wastewater nitrogen contributions to algae with increasing proximity to shore. However, because there are many sources of nitrogen, only one isotopic indicator was used in that study, and there may be more denitrification inshore than offshore, additional research is required to quantitatively define the sources of nitrogen.

Lapointe and Matzie (1997) observed that a large area of seagrasses located near the mouth of the Avenue J Canal was covered by a heavy growth of attached and benthic algae and that approximately 2.5 acres of seagrasses had been replaced by benthic algae at that location. They also documented blooms of benthic algae and epiphytes on seagrass blades at Looe Key.

It is very difficult to quantify all sources of nutrients and their effects at offshore areas. For example, there is no quantitative information available on the impacts of increased numbers of charter boats or other vessels that flush their heads and holding tanks at offshore areas. Reduction of predators and grazers is another confounding factor affecting the community composition of the outer reef. Preparation of a detailed nutrient budget for nearshore and offshore areas in the Florida Keys is a topic that requires further research.

GROUNDWATER

Information on the geology and hydrogeology of the Florida Keys is summarized by Halley et al. (1997). Several studies have been performed that demonstrate the transmissivity of the substrates of the Florida Keys and the rapid exchange of wastewater from onsite systems or injection wells to surface waters.

Lapointe et al. (1990) measured significant nutrient enrichment of groundwaters contiguous to onsite disposal systems at several sites. Mean dissolved inorganic nitrogen (987 uM) was 400 times higher and mean soluble reactive phosphorus (9.77 uM) was 70 times higher in groundwater adjacent to a septic tank seepage field compared to a reference site. Concentrations of nitrogen and phosphorus decreased in the groundwater away from the septic tank toward the adjacent canal, presumably due to dilution by groundwater. They also theorized that some of the soluble reactive phosphorus was absorbed by the substrate. Concentrations of nutrients in the canals (dissolved inorganic nitrogen 4.91 uM; soluble reactive phosphate 0.43 uM) were elevated compared to control sites. Concentrations of nutrients in the canals were highest in the summer because of seasonally maximum tidal ranges and increased flushing during the summer wet season. Lapointe et al. (1990) used a groundwater flowmeter to demonstrate that lateral rates of shallow groundwater flow increased by approximately three times during ebbing tides as compared to flooding tides. This observation was supported by Lapointe and Matzie (1997) who found the maximum concentration of dissolved inorganic nitrogen off the Avenue J Canal (Big Pine Key) when tidal ranges were the highest during the study period.

Shinn et al. (1994b) placed and sampled 24 wells beneath the Keys, nearshore areas, and outer reefs to determine if sewage effluent from Class V wells is reaching offshore reef areas via underground flow. Class V wells (drilled 90 feet and cased to 60 feet) are currently permitted by the Florida Department of Environmental Protection (FDEP) for disposal of wastewater. Sample wells were located in transects off Ocean Reef Club, Key Largo, and Saddlebunch Keys and were sampled quarterly for one year. Investigators found well water to be consistently hypersaline with a marked increase in ammonia in offshore groundwater. Other forms of nitrogen and phosphorus present in offshore groundwater were only slightly elevated above levels found in surface marine waters. Highest levels of nitrate, nitrite, and phosphorus were found in shallow onshore groundwaters.

Nearshore wells were observed to discharge water during falling tides and draw water into the wells during rising tides. This "tidal pumping" results in considerable water movement in and out of the upper few meters of limestone and is a likely mechanism for mixing and transferring nutrient-rich groundwater into overlying surface waters.

Gene Shinn (personal communication) described Key Largo limestone as having a consistency of Swiss cheese, and several other studies have confirmed the rapid connection of groundwaters with surface waters in the Key Largo limestone matrix.. Paul et al. (1995a) placed a man-made tracer virus in a septic tank and into a 13.7 m (45 ft) deep injection well in Key Largo and found the virus in the surface waters of an adjacent canal and the Atlantic Ocean in 11 and 23 hours respectively. Rates of migration ranged from 0.57 to 24.2 m/hr (1.87 to 79.3 ft/hr). They concluded that current onsite disposal practices in the Florida Keys can lead to rapid nutrient enrichment and fecal contamination of subsurface and surface marine water in the Keys. Viral tracers were detected on falling tides confirming the findings of tidal pumping by Shinn et al. (1994b), Lapointe et al. (1990), and Lapointe and Matzie (1997).

Paul et al. (1997) repeated the viral tracer experiment with 12.2 m (40 ft) deep injection wells on Key Largo and a permitted 27.4 m (90 ft) deep Class V injection well on Long Key. At both sites, viral tracers appeared in the groundwater within 8 hours after injection, and in marine surface waters 10 hours in Key Largo and 53 hours in Long Key.

Chanton et al. (1998) are using natural tracers to locate areas of groundwater discharge to surface waters surrounding the Florida Keys. They are also using artificial tracers to quantify rates of flow of materials injected into groundwater to surface waters.

Chanton et al. have completed two extensive surveys and have mapped areas of concentrations of natural tracers near the Keys. Groundwater seepage areas have been found on both the Florida Bay and Atlantic Ocean sides of the Keys. Two injection studies have been completed, one on Key Largo and one on Long Key. In both tests, the tracer was injected into groundwaters and was observed, greatly diluted (approximately one million times), within hours to days in nearby surface waters. At the Long Key site it was found in a canal located across U.S. 1 from the injection site. Wastewater injected into the groundwater at Long Key rapidly migrated toward the surface due to the fact that freshwater "floats" on the highly saline groundwater.

Kump (1998) has sampled groundwater in wells drilled to various depths surrounding a wastewater injection well on Long Key. He confirms the presence of a shallow, low salinity lens floating on top of groundwaters. Distribution of nutrients away from the site of injection is variable, but phosphate, nitrate, and ammonia concentration appears to be highest nearest the injection well at a depth of 5 meters. However, the elevated concentrations of these nutrients were observed in sampling wells located in different directions from the point of injection. The absence of phosphate in high pH waters in shallow wells leads to the postulation that phosphate may be removed by adsorption onto the limestone substrate.

In October 1996, Kump injected phosphate at the same time that Chanton et al. injected a non-reactive tracer (sulfur hexafloride- SF_6) into a Class V injection well (60/90 feet) at Long Key. Within four hours there were elevated tracers at the sampling well located between the injection well and the Atlantic Ocean. The peak of both tracers occurred after about 3 hours. After the peak, the ratio of the tracers fell because the concentration of PO_4 fell more rapidly than that of SF_6. Using data from one of the sampling wells, it was calculated that the tracer SF_6 appears to be moving vertically at about 7 m/day. The pattern of early SF_6 peaks in some wells that are associated with phosphate peaks, and later SF_6 increases with no increase in phosphate concentration at other wells, cannot be ascribed simply to dilution of phosphate by groundwater. The predicted phosphate concentrations based on the assumption of no preferential uptake and the observed tracer concentrations would be well above detection at many of the wells. These observations support the hypothesis that phosphate is being stripped from the groundwater. The rate and long term capacity of substrates in stripping phosphate are topics that require additional research.

FECAL COLIFORM BACTERIA AND DISEASE ORGANISMS

In addition to nutrient enrichment of subsurface and surface waters, onsite disposal systems and injection wells are known to be a source of microbial contamination of groundwater (Keswick, 1984). Because the groundwaters and surface waters are very closely linked in the Keys, it is not surprising that fecal coliform bacteria are common in canals and boat basins. As discussed above, fecal coliform violations were common in some studies (FDER, 1987, 1990). To date, there has not been a systematic public health survey of canals and other confined waters of the Keys to determine their risk to human health. That is a topic that is currently undergoing study.

Paul et al. (1993) sampled the occurrence of viruses and bacteria in the vicinity of Key Largo. Water column viral counts were highest in Blackwater Sound, decreased to the shelf break, and lower salinity waters had higher numbers of viruses. Viral counts in sediments averaged nearly 100 times those found in the water column and did not correlate with salinity. They concluded that viruses are abundant in the Key Largo environment, particularly on the Florida Bay side, and that processes governing their distribution in the water column are independent of those governing their distribution in sediments.

Shinn et al. (1994b) found fecal coliform and fecal Streptococci bacteria in several of their wells. At the Saddlebunch transect, they found that the inshore well and the wells farthest from the shore (>2 nm) tested positive for fecal coliform bacteria during several rounds of testing. The investigators speculated that the source of the bacteria in the well on shore may be from septic tank drainfields at a recreation vehicle park on Saddlebunch Key. The source of the bacteria in the offshore wells is unknown because the locations of the wells are remote from areas of large human populations. The authors speculated that contamination of the more offshore wells could be the result of rapid flow through the underlying Key Largo limestone from a remote site, such as Marathon, where there is a large community built on Key Largo limestone. The investigators theorized that if the bacteria are not some unknown, anoxic, non-fecal, non-human form indigenous to hypersaline groundwater, then their presence suggests a land source and considerable offshore groundwater movement.

In Key Largo, Shinn et al. (1994b) found fecal coliform and Streptococci bacteria consistently in the shallow well and once in a deep well on the island. The shallow well was within 50 ft of a septic tank drainfield. At Ocean Reef Club, the shallow onshore well also had fecal bacteria during all four sampling rounds. Fecal bacteria were also found in offshore wells, including a well located approximately 5 nm offshore.

Supporting evidence of nearshore contamination by fecal bacteria is provided by Paul et al. (1995b). They found two or all three fecal indicators for which they tested (fecal coliform, Clostridium perfringens, and Enterococci) in onshore shallow (1.8 to 3.7 m; 6 to 12 ft deep) monitoring wells at Key Largo. Deep wells (10.7 to 12.2-m; 35 to 40 ft deep) at the same sites contained few or no fecal bacteria. Fecal indicators were found in two of five nearshore wells that were 1.8 and 2.9 miles from shore. Wells further offshore showed little signs of contaminations. All indicators were also found in surface waters in a canal in Key Largo and in offshore surface waters in March, but not in August. These results suggest that fecal contamination has occurred in the shallow onshore aquifer, parts of the nearshore aquifer, and certain surface waters. Paul et al. (1995) concluded that current sewage waste disposal practices may have contributed to the observed contamination.

Finally, Griffen et al. (1997) have found fecal coliform, E. coli, and Clostridium at most stations sampled in Boot Key Harbor on June 8-13, 1997.

EFFECTS ON BIOLOGICAL COMMUNITIES

Nutrient-rich, land-based sources of pollution from runoff and wastewater disposal practices in the Keys rapidly gets into surface waters. Data on nutrient enrichment in canals is compelling. Several investigators observed that canals were depauperate in marine life (Taylor and Saloman, 1968; Barada and Partington, 1972; EPA, 1975) and fish kills in residential canals are common (Taylor and Saloman, 1968; Barada and Partington, 1972). Seagrasses, which are common in shallow waters around the Keys, are generally absent or reduced in density in stagnant canals because of canal depths and/or periodically high phytoplankton blooms, turbidity, and hydrogen sulfide gas (EPA, 1975). Lapointe et al. (1994) observed a shift in community structure in an enriched canal and that the seagrass meadows adjacent to the mouth of the canal was eutrophic, as demonstrated by lush macroalgae growth, high epiphyte load on seagrass blades, and high phytoplankton (chlorophyll) concentration. A large area of seagrasses was stressed and approximately 2.5 acres of seagrasses were replaced by benthic algae at the mouth of the Avenue J Canal (Lapointe and Matzie, 1997). Waters in Boot Key Harbor and adjacent canals had high nutrient and chlorophyll concentrations (FDER, 1987, 1990).

It would be beneficial, but costly, to have long term water quality data from all canal systems and harbors in the Keys. However, there is no reason to believe that other dead end canals systems, enclosed marinas, and harbors are radically different from the ones that have been studied.

There are natural gradients in community structure related to depth, current flow, sediment types, and other environmental conditions. The marine life in many confined water bodies and some nearshore areas are dissimilar, structurally and functionally, to natural communities found in less disturbed, more oligotrophic waters. The causes of these differences are differences in physical conditions (e.g., circulation, temperature) and nutrient enrichment (eutrophication). Based on available information, it is reasonable to conclude that poorly flushed canals, other confined water bodies, and nearshore areas in the Keys have reached and exceeded their assimilative capacity for nutrient addition. If nutrient loading continues, impacted areas will become increasingly dysfunctional and the impacts will extend further from shore.

Previous sections have summarized scientific information that demonstrated the effects of human-derived pollutants on marine waters. Perhaps even more compelling than the scientific data is the general acknowledgment by long-time residents and visitors that water quality has declined in the Florida Keys. Although long term climatic cycles can not be completely excluded, there is abundant, albeit anecdotal, evidence that deteriorating environmental conditions in the Keys are correlated with increased population and human activities. DeMaria (1996) interviewed 75 individuals who have spent many years on the waters surrounding the Florida Keys. These individuals were asked to identify changes in fisheries, seagrass, communities, the coral reef, algae blooms, and water quality. Each person interviewed was asked to comment on the most significant changes that they observed. The results included the following conclusions:

> Water quality has declined, particularly in canals, nearshore areas, Florida Bay, and the coral reefs.
>
> Algal blooms are larger, more frequent, and more persistent.
>
> Seagrass beds have fluctuated in extent and species composition throughout the area and have drastically declined in Florida Bay.
>
> Corals and coral reefs show signs of declining health; disease is more common and benthic algae have increased in abundance and spatial coverage.
>
> Populations of sponges, giant anemones, long-spine sea urchins, and queen conchs have declined in nearshore waters. Jellyfish have increased in abundance.
>
> Tropical fish, specifically butterfly fish, angel fish, and groupers have declined.

With very few exceptions, DeMaria (1996) reported that long term Keys residents observed changes for the worse.

More research is required before definitive statements can be made on the long term health of the Florida Keys reef tract and the extent and effects of anthropogenic nutrients. Szmant and Forrester (1996) reported that reefs off Key Largo and Long Key are not receiving a nutrient subsidy via surface waters from land-based sources at the present time, although the potential exists due to observed higher nutrient concentrations near shore. It is their opinion that land-based nutrients are absorbed by algae and seagrasses within 0.5 km of shore.

Lapointe and Clark (1992), Lapointe and Matzie (1996), and Lapointe and Matzie (1997) concluded that nutrient enrichment at offshore reefs is possible following heavy rains and/or high wind events. It is their opinion that sampling during storms is required to document rapid, episodic transport of nutrients. However, if land based nutrient subsidy to the reef is common, Szmant and Forrester (1996) theorized that reef sediments should have elevated nutrient concentrations. Their findings demonstrated that nutrient concentrations in sediments decreased rapidly from the shore.

Upwelling of deep, relatively nutrient-rich oceanic water may be a source of nutrients to the outer reefs. Szmant and Forrester (1996) concluded that upwelling was probably responsible for elevated phosphorus observed in offshore waters in the Upper Keys. Upwelling events have also been reported at Looe Key during spring and summer and may be a source of nitrogen to at least the fore reef (Lapointe and Smith, 1987). However, coral reefs generally do not develop in areas influenced by persistent upwelling due to the cold temperatures and high nutrient content (Dubinsky and Stambler, 1987). The frequency, duration, geographic extent, and nutrient loading of upwelling events is an area that requires further study.

Worldwide, there has been a marked acceleration of the deterioration of coral reefs. Wilkinson (1993, 1996) estimated that 30% of all coral reefs have reached the "no-return" critical stage, another 30% are seriously threatened, and less than 40% are stable. The main factors in the demise of coral reefs are human pressures, such as over fishing, physical damage, nutrient enrichment, and sediment loading. Since there does not seem to be any measurable global-scale increase in oceanic productivity, which would have been evident in the case of significant overall eutrophication, Dubinsky and Stambler (1996) concluded that human impacts on coral reefs are on a local and regional scale, rather than a global scale (excluding impacts of global warming and increases in ultraviolet light exposure).

Long term, quantitative studies of coral reef community structure in south Florida have documented high coral loss rates. Porter and Meier (1992) monitored six coral reef locations between Miami and Key West in 1984 and 1991. They found that all six areas lost coral species and that these losses constituted between 13% and 29% of their species richness. Coral cover decreased at five of the six sites and net losses ranged between 7.3% and 43.9%. Porter and Meier (1992) concluded that loss rates of this magnitude cannot be sustained for protracted periods if the coral community is to persist in a configuration resembling historical coral reef community structure in the Florida Keys. Porter et al.(1994) suggested that regional patterns of decline are suggestive of large scale flow of water masses, e.g. influence of Florida Bay of Gulf of Mexico waters.

A variety of diseases have caused coral decline and mortality (Antonius, 1981a, b; Peters, 1984; Santavy and Peters, 1997). These diseases have been reported worldwide from pristine as well as heavily polluted areas. Recent systematic monitoring in the Keys has revealed that the incidence of coral diseases may be increasing. Disease decimated the long-spine urchin populations throughout the Caribbean during 1983-1984. Determining the etiology and distribution patterns of these diseases are topics for future research and monitoring.

Mass mortalities of sea fans have been reported throughout the Caribbean for many years. The causative agent of sea fan mass mortalities has been determined to be a fungal pathogen (Aspergillus) that is typically a soil inhabitant. It is thought that the primary infection by the fungus is probably associated with sediment particles from land-based sources (runoff) (Smith et al., 1996).

Bell (1992) critically reviewed case studies of eutrophication of coral reefs and noted that eutrophication typically causes phase shifts from slow-growing corals to faster growing macroalgae and phytoplankton. Macroalgal blooms have been correlated with nutrient enrichment of reefs in Jamaica (Lapointe, 1997; Lapointe et al., 1997), the southeast coast of Florida (Lapointe and Hanisak, 1997), Belize (Lapointe, et al., 1993), and the inner Great Barrier Reef Lagoon, Australia (Bell and Elmtri, 1996). Others have pointed out that over fishing and reduction of algal grazers must be taken into account (Zieman and Szmant, personal communication).

The impacts of nutrient enrichment to coral reefs are not always clear cut or devastating to the coral community. Nutrient enrichment studies performed at One Tree Island, Southern Great Barrier Reef demonstrated that daily additions of both nitrogen and phosphorus to a single patch reef for eight months enhanced community primary production by approximately 25% and inhibited calcification of the system by approximately 50% (Kinsey, 1988). An extensive nutrient enrichment experiment (ENCORE: Enrichment of Nutrients on a Coral Reef Experiment) (Larkum and Steven, 1994) was performed on the Australian Great Barrier Reef to quantify the response of the community to nutrient additions. Larkum and Koop (1996) found that fertilization had no effect on growth or primary production of epilithic algae; these results are contrary to the widely held opinion that enhanced levels of nutrients cause rapid growth of algae and problems for associated biota.

EXAMPLES OF AREAS WITH SIMILAR PROBLEMS

This section is not meant to be a comprehensive analysis of coastal eutrophication, but rather to highlight several other areas that have experienced nutrient enrichment that are reminiscent of observations in the Florida Keys. It is hoped that we can learn from the actions taken in other locations to correct nutrient enrichment problems. In several instances, providing additional treatment of wastewater resulted in rapid improvement of degraded biological communities.

Coastal eutrophication is a national and worldwide problem (Valiela et al., 1992). It is most evident in enclosed and semi-enclosed seas and estuaries and the main sources of nutrient enrichment are agriculture and urban run-off and domestic wastewater (Nixon, 1990; 1995). It is estimated that the input of nutrients to the coastal waters and oceans from human sources (via rivers) is currently equal to or greater than natural input (Windom, 1992). Some prominent examples of collapses of coastal ecosystems from anthropogenic nutrient loading include the loss of seagrasses and benthic fauna in the Chesapeake Bay (Officer et al., 1984), noxious algal blooms in the Adriatic Sea (Justic, 1987), anoxia problems in the Baltic Sea (Larsson et al. 1985) and off the Mississippi River delta (Gulf of Mexico) (Rabalais et al., 1996; Turner and Rabalais, 1994), and regular toxic algal blooms in the North Sea (Underdal et al., 1989).

AUSTRALIA

Australian coastal waters in the vicinity of the Great Barrier Reef are naturally nutrient poor. All coastal water bodies with long residence times (poor flushing) in the populated part of the Australian coast have experienced some measurable
effects of enhanced eutrophication. Phytoplankton blooms and seagrass losses are the most prominent evidences of nutrient loading (Brodie, 1994). As is true in the Florida Keys, the farther offshore, the more difficult it becomes to link community changes with land-based sources of nutrients. However Bell (1991, 1992) and Brodie (1995) have proposed that the Great Barrier Reef is showing evidence of eutrophication, as evidenced by an increase between historic and current levels of phytoplankton.

The Australian government is sponsoring a nationally coordinated approach to monitoring and managing sources of nutrient enrichment (National Water Quality Management Strategy). The goals and objectives of the Australian Strategy are very similar to those in the Water Quality Protection Program for the Florida Keys. In Sydney, inadequate sewage treatment has resulted in significant degradation of nearshore waters. Improvements to the sewage treatment system is being partially financed through a household levy of $80/year (Brodie, 1994).

ST. LUCIE COUNTY

Over the past 50 years, seagrass coverage in the Indian River Lagoon declined overall about 6%. However large losses (60%) occurred in the Melbourne to Grant area (Woodward-Clyde Consultants, Inc. (1994). The Indian River National Estuary Program concluded that seagrass losses were predominantly due to nutrient enrichment from domestic wastewater and stormwater discharges (EPA, 1996).

In 1993, St. Lucie County completed a S.W.I.M. Program (Surface Water Improvement and Management Act) project to identify areas where existing onsite sewage disposal systems were a threat to the water quality of the Indian River Lagoon. Ten high priority areas were identified based upon their pollutant loads.

Principal recommendations of the S.W.I.M. study included (Moses and Anderson, 1993):

1. Port St. Lucie should be considered a threat to the water quality of the Indian River Lagoon by way of the C-24 Canal and North Fork of the St. Lucie River. Expansion and improvement of sewage treatment facilities in this area should be pursued aggressively.

2. The entire County must be regarded as a single environmental area with respect to water and wastewater policies regarding effects of septic tanks and reducing potential for water degradation.

3. Establish a full time county position responsible for identifying and procuring funding sources for program implementation.

In 1990, the State of Florida Legislature passed the Indian River Lagoon Act which required all domestic wastewater treatment facilities to cease discharges into the Lagoon by 1996. It is estimated that implementation of the Act resulted in a 60% reduction of nutrients entering the northern half of Indian River Lagoon. In the past year, seagrass beds at six fixed transects in the Vero Beach area have extended in length an average of approximately 260 feet past previous seagrass bed limits. In the Melbourne area, seagrass beds at seven transects have extended an average of 195 feet (Vernstein and Morris, Indian River National Estuary Program, personal communication).

TAMPA BAY

Between 1950 and 1982, seagrass coverage in Tampa Bay declined from approximately 40,000 acres to 21,600 acres. Associated with the seagrass loss were declines in commercial and recreationally important fishes. Three factors were believed responsible for the decline: dredging and filling of seagrass beds for residential, commercial, and port development; shading by algae, both phytoplankton and macroalgae, which bloomed in response to excessive nutrient inputs from sewage treatment plants and industrial discharges; and turbidity induced by dredging the main shipping canal. In 1987, the Florida Legislature passed the Grizzle-Figg Bill which required that all discharges into Tampa Bay meet strict nutrient guidelines (advanced wastewater treatment). Also, in 1984, the Legislature established a Bay study group which, in 1985, resulted in the formation of the Agency on Bay Management. The Agency on Bay Management has become a vigilant guardian of Tampa Bay. From 1982 to 1992, seagrass coverage increased by about 4000 acres (18.5%). Most "new" grass has been shoalgrass (Halodule wrightii), an early colonizer which may eventually be replaced in many areas by turtlegrass. Increase in seagrass coverage has been attributed to the substantial reduction in nitrogen loadings to the Bay. Reduction in nitrogen has allowed more light to penetrate deeper into the water column, thus allowing seagrass to reestablish itself.

OPTIONS FOR CORRECTING WASTEWATER PROBLEMS

ONSITE DISPOSAL SYSTEMS

During the early development of the Keys, human wastes were disposed directly on the ground, into shallow holes, or in the water. Since there was a very small population of humans, the ecosystem absorbed these additional nutrients with little or no change to ecosystem structure or function. During the "period of rapid growth" in the Keys, cesspits were constructed under or immediately adjacent to residences and commercial establishments. Cesspits average approximately 4- to 5-feet deep and may be supported with timbers or stacked cement blocks. Cesspits are directly connected to groundwater, adjacent canals, or other surface waters through the porous limerock substrate. Because of the limited amount of land in the Keys, developments are generally crowded, and many early developments featured 50-foot by 50-foot lot sizes. That circumstance not only maximized the development of many areas, but also provided a concentrated source of nutrient enrichment of groundwater and surface waters. Cesspits provide no treatment of wastewater nutrients. They also do not provide any confinement or treatment of human fecal pathogens. The Florida Department of Health estimates that there are currently approximately 4,000 cesspits in the Florida Keys (Jack Teague, personal communication).

In the mid 1960's, there was a gradual shift to the use of septic systems for onsite waste disposal. This shift was prompted by the newly formed State Board of Health which recognized that use of cesspits was a public health concern. Septic systems consist of a concrete or fiberglass tank designed to hold waste material anaerobically. Some nutrients are removed through the production of biomass which settles in the tank. The accumulated organic sludge must be pumped periodically and disposed. Pumped sludge is currently disposed by transporting it to Dade County, where it is added to the wastewater entering sewage treatment plants. Liquid wastewater effluent exits from the outlet of the septic tank and is distributed to the surface substrate (drainfield). Ideally, the drainfield is composed of soils with cation exchange sites that trap and hold chemical nutrients. Unfortunately in the Florida Keys, the substrate is predominantly porous limestone and has few bonding sites for nutrients other than phosphorus, and the long-term capability of limestone to trap phosphorus is not known. Thus, in the Keys, wastewater from septic systems can rapidly seep into the groundwater with little nitrogen removal. Removal of nutrients by septic systems can vary greatly because of design, installation methods, and operation, but on the average septic systems remove approximately 4% of nitrogen and 15% of phosphorus (Table 7). Location of septic tanks near surface waters, as in closely spaced canal developments, represents a significant source of nutrient-rich wastewater to surface waters. Rain events and low tides can result in the rapid movement of septic tank effluent into surface waters. There are approximately 25,000 parcels in the Keys with onsite disposal systems. Of those, 18,000 are permitted septic tank systems. There are approximately 7,900 lots with no record of sewage disposal method (Jack Teague, personal communication).

Since 1992, the State Department of Health has required that septic tank drainfields be underlined by 12 inches of clean sand. This requirement has little impact on nutrient removal in the effluent, but may trap some pathogens by filtration through the sand bed.

Since the elevations of the Keys are very close to sea level, the groundwater is very close to the surface. The ground level of most dredge and fill subdivisions is only three to four feet above sea level. On most keys, the groundwater is as salty as seawater. The groundwater responds to tidal action that connects it with Florida Bay and the Atlantic Ocean. The net movement of groundwater is toward the Atlantic Ocean (Shinn et al., 1994b).

Septic tanks are installed underground and during installation they can float in areas where groundwater is high. Many of the early installed septic tanks had holes punched in their bottoms to sink them in the groundwater before they were covered over with fill material. Because of that practice, many septic systems function as cesspits, where wastewater is in direct contact with groundwater without settlement or treatment.

Chapter 381.0065(4)(k) of Florida Statutes currently mandates that the Florida Department of Health (FDOH) permit only onsite systems capable of meeting Advanced Waste Treatment (AWT) standards. AWT is defined in Section 403.086 of the Florida Statutes as 5 mg/l $CBOD_5$, 5 mg/l total suspended solids (turbidity), 3 mg/l nitrogen, and 1 mg/l phosphorus. In order to remove nutrients to those levels, additional processes must be incorporated into the treatment process. In the nitrification/denitrification process, ammonia is first converted to nitrate (aerobically) and then nitrate is converted to nitrogen gas (anaerobically) and released to the atmosphere. Phosphorus can be removed either biologically or chemically. In either case, excess phosphorus is removed from the effluent stream through settling and subsequent disposal of the solids.

Ayres and Associates, Inc., under contract to FDOH, is field testing five onsite systems at a test facility on Big Pine Key. This research has been recently funded through 1998. Pending the results of that research, the Florida Department of Health (FDOH) has been permitting onsite systems which meet current best available technology (BAT). FDOH has determined that aerobic onsite treatment systems which discharge to either a bore hole or a drainfield currently meet BAT. There is a wide variety of designs of onsite aerobic treatment systems, but in general they are a small scale version of a conventional secondary treatment plant. Some nutrients are removed through the growth of bacterial biomass and subsequent disposal of biosolids. Operation and maintenance is critical to the efficient performance of aerobic systems. Aerobic systems are much more efficient than septic tanks in removal of carbon (77%), but are only slightly better than septic systems in removing nitrogen (Table 7).

There are currently no AWT treatment facilities in the Florida Keys. By State statute, advanced wastewater treatment facilities are required in two locations in Florida, Tampa Bay and Indian River Lagoon. The statutes were enacted to address eutrophication of those waters due to excess nutrient loading and to reverse the pending collapse of the ecosystems.

PACKAGE PLANTS

During the early development of the Keys, multifamily dwellings, motels, and resorts utilized cesspits and septic tank systems. Florida Administrative Code (F.A.C.) Rule 62-620.100 currently requires a valid permit from the FDEP for construction and operation of domestic wastewater facilities with flows exceeding 10,000 gpd and for commercial establishments with wastewater flows greater than 5,000 gpd.

At the present time there are 250 FDEP-permitted wastewater treatment plants (WWTP) in operation in Monroe County. There are approximately 14 additional FDEP wastewater permits that have been issued for new WWTP that have not yet been constructed. Most of these WWTP consist of on-site facilities with permitted flows under 100,000 gpd and are commonly known as "package plants". However, it is important to note that discharges from package plants represents about 33% of the total wastewater flow from FDEP package plants. The remainder of the flow (67%) comes from discharges from a few large facilities with permitted capacities exceeding 100,000 gpd (0.1 mgd).

All FDEP-permitted WWTP systems are required to meet, at a minimum, secondary treatment and disinfection in accordance with Chapter 62-600 F.A.C. That regulation requires supervision and monitoring of these facilities by a Florida licensed operator and submission of discharge monitoring reports, containing all required test results, for each month of operation. These facilities are also inspected by FDEP personnel to ensure compliance with permit requirements.

Secondary treatment provides up to 90% removal of the total suspended solids and organic (carbon) wastes producing oxygen demand (CBOD) in the wastewater. This process also removes organic nitrogen and phosphorus associated with the suspended solids, but does little to remove nutrients dissolved in the wastewater, such as nitrates and phosphates. Chlorination is employed for disinfection of the effluent in order to protect public and environmental health. The wastewater sludge from the settled solids is periodically removed and transported to the mainland for disposal at FDEP-permitted treatment facilities. Alternatively, disinfected wastewater sludge can also be delivered to approved land application sites for disposal, as long as the wastewater sludge meets the treatment criteria specified in Chapter 62-640, F.A.C., and the Code of Federal Regulations Part 503.

Because of strict regulatory standards required for surface water discharges, the primary method of effluent disposal employed by the package plants is discharge to the groundwater by means of Class V wells. Currently there are 750 FDEP-permitted Class V wells in the Florida Keys. These disposal wells are required to be drilled to a depth of 90 feet and lined with cement (cased) to 60 feet. As of June 1997, Chapter 62-528, F.A.C. requires that all Class V wells designated to inject domestic wastewater in Monroe County are required, as part of their operation permit application, to provide reasonable assurance that operation of the well will not cause or contribute to a violation of surface water standards as defined in Chapter 62-302, F.A.C.

At least nine WWTP in Monroe County utilize wastewater reuse systems, such as subsurface or spray irrigation, as either their primary or secondary effluent disposal method. The use of drainfields and percolation ponds for groundwater effluent disposal is also allowed in accordance with Chapter 62-610, F.A.C., but the use of those systems is limited in Monroe County because they require large surface areas and because of the lack of soil and high ground water table in the Keys.

CENTRAL SEWAGE SYSTEMS

Central sewage systems involve the collection of wastewater from multiple sources by means of a sewer system and pumping the wastewater to a sewage treatment facility for treatment and disposal. Construction of sewage collection systems for wastewater is difficult and expensive in the Keys because of the rock substrate. Central treatment of wastewater in a large volume sewage treatment plant is very efficient because of the economy of scale and the presence of full-time operators. There are two municipal central sewage collection and treatment systems currently operating in the Keys: Key Colony Beach and Key West. In addition, there are several privately owned utilities in Monroe County with central collection systems, including Key West Resort Utilities (Stock Island), Key Haven Utilities, Key West Naval Air Station, and Key Largo Utility (Ocean Reef Club). All these facilities, with the exception of the City of Key West, use Class V wells and/or wastewater reuse systems for effluent disposal.

The City of Key Colony Beach operates a wastewater treatment plant with a current capacity of 0.22 mgd. This facility is over 28 years old and provides secondary treatment of wastewater. Wastewater is collected through a gravity sewer line system which includes 15 lift stations. The 20 to 30 year old collection pipes are subject to infiltration of saline groundwaters, particularly during extreme high tides. Prior to 1994, effluent was discharged directly to the Atlantic Ocean. In late 1994, the discharge was rerouted to six Class V injection wells. The wastewater treatment plant services 1,233 residential units and 96 business units. The facility has not utilized reuse of treated wastewater for irrigation because the cost of additional treatment facilities required and the need for increased operator attendance are much greater than the cost of potable water presently being used to irrigate greens of the nine-hole, par 3 golf course. Also, the high amounts of saline groundwater infiltration into the collection system would make the effluent too saline at times for irrigation use. Plans are being developed to replace the existing facility with a facility that can achieve AWT standards. Efforts to correct the infiltration problem are ongoing.

The City of Key West collects and treats wastewater at a central treatment plant with a permitted capacity of 7.2 mgd of secondary treated wastewater. Discharge is through a submerged ocean outfall located about 1000 meters (328 ft) from the southern tip of Key West. The ocean outfall is the largest single source of nutrient pollution in the Keys. In 1997, the effluent included an average of 342 pounds of nitrogen and 62 pounds of phosphorus daily. However, because of the tremendous dilution at the location of the outfall, Ferry (undated) concluded impacts from the ocean outfall are mainly limited to localized eutrophication and some sewage contamination of the benthos in the immediate vicinity of the outfall. The probability of transport of any significant amounts of pollutants or contaminants from the outfall to offshore bank reefs appears to be low.

Key West is currently under an enforcement action by FDEP for violations related to collection system failure and excessive infiltration. During 1996, a Consent Judgement was prepared by FDEP requiring the City to take corrective action to reduce the infiltration problem. The City has proposed a five-year schedule and has initiated an aggressive sewer rehabilitation program. The level of treatment currently approaches advanced treatment standards; since 1995, the effluent has averaged 4.2 mg/l nitrogen and 1.1 mg/l phosphorus. Also, the City has decided to eliminate the ocean outfall and inject treated wastewater into a deep injection well drilled into the boulder zone (2500+ feet). The FDEP has issued and intent to issue a deep well permit.

Key Haven Utility is a private system serving the subdivision of Key Haven on Raccoon Key, located just east of Stock Island. The plant is currently permitted for 0.20 mgd that is provided by two connected facilities. One unit was constructed in approximately 1970 and is currently in poor condition. The second unit was built in 1994. Plant upgrades are underway to replace the original unit. Improvements should be completed in 1998. The wastewater collection system consists of a gravity sewer with five lift stations. The collection system has a history of infiltration problems. None of the treated wastewater is reused.

Key West Resort Utility provides service to approximately 90% of the Stock Island area south of U.S. Highway 1. This includes approximately 600 residences and several commercial establishments. Plant capacity is 0.499 mgd and the plant is in excellent condition. The collection system consists of a gravity sewer, force mains, and 13 lift stations. The primary disposal method is spray irrigation on the Key West Golf and Country Club golf course located on Stock Island north of U.S. 1. The effluent is treated to public access reuse standards as required in Part III, Chapter 62-610 F.A.C. Secondary disposal is to Class V injection wells during wet periods of the year. The plant does not currently serve the entire area of the utility district. Plans are currently underway for an expansion that will include the entire utility area. Also, the utility is interested in expanding its boundaries to include adjacent areas.

Key West Naval Air Station treatment plant has a capacity of 0.4 mgd and serves the Naval Air Station. The plant has a history of exceeding peak flow capacities and has significant infiltration problems. Improvements have been recently made to
the plant and to the 11 lift stations. In addition, Class V wells have been installed to better manage effluent disposal.

The Key Largo Utility serves Ocean Reef and Anglers Club developments located at the extreme north end of Key Largo. The plant consists of two connected units, one older than the other, and has a capacity of 0.55 mgd. Both units are in good condition. The collection system consists of gravity sewers, force mains, and 37 lift stations. The collection system has infiltration problems that are currently be improved by replacing older clay and cast iron pipes with PVC pipes. Effluent is treated to secondary standards and disposed into Class V injection wells. The facility does not currently provide for reuse because infiltration problems results in an effluent with high chloride concentration. The three 18 hole golf courses in the development currently irrigate using a 1.7 mgd reverse osmosis plant ($1.75 per 1,000 gallons). Complete rehabilitation of the collection system for reuse would be more costly than costs of water from the reverse osmosis plant.

WASTEWATER FACILITIES PLAN FOR THE MARATHON AREA AND PHASED IMPLEMENTATION FOR LITTLE VENICE (VACA CUT TO 94TH STREET)

In February 1996, Monroe County completed a Marathon Area Facilities Plan. That plan originated in recognition of the need to develop a long-range wastewater management plan for Monroe County. Marathon was chosen as the first area in Monroe County for this planning because of the large number of high density developments with small lot sizes, a large number of identified cesspits, and documented degraded water in canals. The purpose of the plan is to define the most cost-effective, environmentally sound, and implementable program for the management of existing and future wastewater pollutants that presently act, or will act, to deteriorate the water quality in the Marathon area. The Plan will be a part of a comprehensive Wastewater Master Plan for Monroe County. In general, three steps comprise implementation of a wastewater management system: planning, design, and construction. The Marathon Area Facilities Plan is the first step in the implementation of a wastewater management system for the Marathon area.

The Facilities plan includes:

- Evaluation of existing water quality;
- Identification of existing point source pollution sources;
- Documentation of existing background environmental conditions;
- Preparation of an inventory of existing wastewater plants;
- Estimation of future waste loads and flows;
- Development and evaluation of collection, treatment, and disposal alternatives;
- Identification of a potential site, or sites, for location of treatment facilities;
- Selection of the most cost-effective, environmentally sound, and implementable wastewater management alternative;
- Development of conceptual design and planning level cost estimates for the recommended plan;
- Assessment of the recommended plan's environmental impact; and
- Discussion of the institutional framework and financial requirements needed to implement the plan.

The Marathon Area Wastewater Facilities Plan concluded that a regional wastewater collection, treatment, and disposal system be implemented to serve the primary service area (Seven Mile Bridge to Coco Plum, excluding Key Colony Beach). The recommended technology for the wastewater collection system is a vacuum system, that would be comprised of vacuum collection mains, combination vacuum/conventional pumping stations, and force mains. Based on direction provided by the Monroe County Board of County Commissioners, the regional wastewater treatment plant will treat the wastewater to AWT standards to provide a high level of solids and nutrient removal. The recommended effluent management system is deep underground injection of highly treated effluent to the Boulder Zone (2,500 ft). The Plan recommends that reuse of effluent be explored. The estimated capital and annual operation and maintenance costs for collection, treatment, and disposal are given in Table 8.

In February 1996, the Monroe County Board of County Commissioners approved the recommendations in the Facilities Plan provided that the connection fee per household does not exceed $1,600 and monthly service fee does not exceed $35. Monroe County has applied for a loan from the State Revolving Fund for approximately $30 million for design and construction costs. In October 1997, Congress, with the assistance of the Governor's Office and EPA Region 4, appropriated $4.3 million of de-obligated Title II construction fund monies to be used in wastewater improvements in Monroe County. These funds will be used by amending the Marathon Area Wastewater Facilities Plan to include a first phase for Little Venice (Vaca Cut to 94th Street on the ocean side of U.S. 1). An offer and award of these monies is expected in October 1998 and design will begin in Fall 1999 after contracts have been approved. Construction should begin in 2001 and be completed by early 2002.

During the second session of the 105th Congress, Monroe County and others spent considerable time working with Congress to develop additional wastewater funding proposals for the Marathon Area Facilities Plan and for the projected needs for the remainder of Monroe County. Included in these discussions was the concept of developing a non-transportation toll on U.S. 1, located somewhere north of Key Largo. Efforts are on-going and will continue in the 106th Congress and beyond.

MONROE COUNTY WASTEWATER MASTER PLAN

Monroe County initiated the development of a county-wide Wastewater Master Plan in August 1997. The purpose of the Wastewater Master Plan is to identify environmentally acceptable and cost effective wastewater treatment and disposal alternatives for geographic service areas within the Florida Keys. Different wastewater management practices, from onsite systems to community and/or regional collection and treatment systems, will be evaluated for each geographic service area and the costs and environmental benefits compared. The cost of development of the Wastewater Master Plan is approximately $2.2 million. The plan will be completed in December 1999.

At the outset, Monroe County and the Water Quality Protection Program Steering Committee approved a Technical Advisory Committee (TAC) consisting of approximately 20 individuals with interest and/or special knowledge and expertise to oversee the development of technical documents produced in the project. The TAC will review work products and meet with the consultant approximately six times during the course of the project. When complete, the Wastewater Master Plan will be evaluated by the Water Quality Program Steering Committee and approved by the Board of County Commissioners (BOCC).

New legislation has been recently passed regarding the authority of the Florida Keys Aqueduct Authority to function as a wastewater utility. A Memorandum of Understanding has been finalized between Monroe County and the FKAA regarding the agencies' roles in wastewater. Based upon that Memorandum, it is anticipated that the FKAA will begin to assume a greater role in the further development and review of the Wastewater Master Plan. After the BOCC approves the Wastewater Master Plan, it will be provided to the FKAA for implementation. It is expected that FKAA will become the utility authority for only the most densely populated areas of the Keys.

CESSPIT IDENTIFICATION AND REPLACEMENT

In conformance with the Governor's Executive Order 96-108 and Polity 901.2 of the Monroe County Year 2010 Comprehensive Plan, Monroe County and the FDOH initiated a five-year operating permit procedure for onsite disposal systems. The ordinance requires homeowners to have their onsite disposal system inspected within 30 days of notification. Notification dates are based upon the age of the structure; older structures are notified first. Inspection results must be submitted to the FDOH. Disposal systems found to be in compliance with current requirements will receive a five-year operating permit. Disposal systems that are found to be in compliance with requirements in place when the structure was built, but do not meet current minimum standards, will receive a two-year temporary operating permit. Those systems must be replaced within two years. Structures found to have cesspools or a septic tank that does not meet the standards in place at time of construction must comply with current standards within 180 days of written notice.

Low interest loans are available to assist homeowners in funding replacement of inadequate onsite disposal systems. Homeowners in the Marathon Service Area have been exempted from compliance with this ordinance because central collection and treatment was determined to be the most cost effective and environmentally acceptable solution of wastewater disposal in that service area. In other geographic areas, homeowners with an approved system for which an operating permit has been obtained may continue to use the approved system so long as:

1. The system is properly maintained and remains in satisfactory operating condition;
2. The operating permit is properly renewed;
3. An approved sewage treatment plant has not been available for connection for longer than 365 days; and
4. No alterations are made to the residence, commercial structure, or site that would change the sewage or wastewater characteristics, increase sewage flow, or impede the performance of the onsite disposal system.

CANAL BEST MANAGEMENT PRACTICES

There are many simple activities that homeowners can undertake that will help improve water quality in canals adjacent to residences. Activities can be divided into two categories:

1. Reduce nutrient loading into canal water; and
2. Increase circulation and flushing (where applicable).

1. Reduce Nutrient Loading

Because canals generally exhibit poor circulation and flushing, they are very susceptible to eutrophication due to excess nutrients. The following activities are required to minimize nutrient loading into canals:

- Eliminate cesspits

- Install adequate drainfields for septic systems that results in binding of nutrients.
- Pump out septic tanks on a regular basis to prevent organic loading from tanks full of sludge.
- Do not apply fertilizers on lawns or other vegetation adjacent to canals.
- Do not dispose of organic wastes into canals, including grass clippings, animal droppings, fish carcasses, etc.
- Slope lots adjacent to canals so that surface drainage is directed away from canals.
- Eliminate fast growing exotic vegetation from canal banks (e.g., Australian pine, Brazilian pepper) and maintain native vegetation (e.g., buttonwood and mangroves) as a buffer.
- Use phosphate-free detergents.
- Do not discharge gray water onto soil or into canals.
- No live-aboard discharges into canals.

2. Canal Circulation

Deep, dead end canal systems exhibit poor water quality due to the geometry of the canal system. Several physical alterations can be attempted that may improve canal water quality. These include:

- Backfilling canals to a maximum of -6 ft MSL at the mouth of the canal and sloped to -4 ft MSL at its distal end.
- Aerating canal waters to assist vertical circulation.
- Dredging canals or otherwise treating canal bottoms to remove accumulation of organic, oxygen-demanding sediments.
- Install flushing channels/culverts in suitable areas if actions will not degrade receiving waters.

The orientation of some canals make them susceptible to accumulation of wind-driven, floating organic matter, predominantly seagrass leaves. Physically preventing transport of floating organic matter into canals will improve quality of canal waters. Floating booms, air curtains, and other devises are used as weed gates at mouths of canals.

There are several canal systems in the Keys that were constructed but never connected to adjacent waters. Those canal systems are plugged with fill material at their mouths. Recently, there has been increased interest in removing the plugs from those canal systems to connect them with adjacent surface waters. Removal of plugs requires federal, State, and County permits. Permit agencies recognize that existing open canal systems represent a source of degraded water quality to receiving waters and that water quality within open canals may violate State water quality standards. Therefore, there is a great reluctance to consider requests to open additional canal systems. Before such a request can be considered, there must be overwhelming evidence that the canal currently does not violate water quality standards and that opening of the canal system will not degrade receiving waters. Generally, currently plugged canals systems will not meet those requirements.

DISCHARGES FROM VESSELS

There is a large community in the Keys that live on boats. Many live-aboard vessels are permanently anchored in harbors and are not capable of movement. Transient vessels also anchor in harbors and other protected sites and are very numerous in winter months. The number of live-aboard vessels has increased dramatically in recent years. For example, the number of live-aboards in the Key West area increased from 235 in 1992 to 393 in 1995 (Monroe County Grand Jury Report). Approximately 400 anchored or moored vessels were observed in Boot Key Harbor (Marathon) in February 1995 (Kruczynski, personal communication). A Monroe County Grand Jury received testimony that up to 80% of live-aboard vessels do not use sewage dumping facilities.

The Clean Vessel Act (Florida Statute 327.53) prohibits the discharge of raw sewage from any vessel, houseboat, or floating structure into Florida waters. A houseboat is a vessel that is used primarily as a residence (21 days out of any 30 day period), and its use as a residence precludes its use as a means of transportation. Houseboats and floating structures must have permanently installed toilets attached to Type III Marine Sanitation Devises (MSD) or connect their toilets directly to shore-side plumbing. A Type III MSD is one that stores sewage onboard in a holding tank for pumpout. Houseboats may also have other approved MSDs on board; but, if they do, the valve or other mechanism selecting between devices shall be selected and locked to direct all sewage to the Type III device while in State waters. All vessels that have MSDs capable of flushing raw sewage directly overboard or of being pumped into a holding tank, shall set and secure the valve directing all waste to the holding tank, so that it cannot be operated to pump overboard while in State waters. All waste from a Type III MSD or from portable toilets shall be disposed in an approved sewage pumpout or waste reception facility.

While the Clean Vessel Act prohibits the dumping of raw sewage, treated wastewater from transient vessels may be discharged into State waters. Wastewater treatment (disinfection) by Type I and II MSDs does not remove nutrients from wastewater. Graywater does not have to be stored or treated from any vessel and may be discharged directly into water of the State.

There are few land-based pumpout facilities in the Keys and no mobile pumpout facilities. There is one land-based pumpout facility in Boot Key Harbor. Thus, many live-aboard vessels and most transient vessels discharge wastewater into surface waters. It is estimated that nutrients from vessel wastewater account for 2.8% of nitrogen and 3.0% of phosphorus loadings into nearshore waters of the Keys (Table 4). Although nutrient loadings from vessels may be relatively minor contributions to the total loading, loadings from vessels are a significant source to harbors and result in eutrophication of waters that typically exhibit poor circulation/flushing. Violations of fecal coliform standards are common in marinas and harbors (FDER 1987, 1990).

The EPA, State, Monroe County, and the City of Key West are pursuing the designation of marinas, harbors and anchorages as "no discharge zones" (NDZ). The NDZ designation will require all boats, live-aboards and transients, to use Type III holding tanks and have wastes pumped at approved facilities. Federal regulations require that adequate pumpout facilities be available before an area is designated as a NDZ. Plans are being developed for construction of land-based and mobile pump out facilities and for strict enforcement of the prohibition against disposal of wastewater into surface waters of the State.

STORMWATER TREATMENT

Stormwater runoff can be successfully treated with the use of one or more "Best Management Practices" (BMPs). Stormwater treatment BMPs in Florida typically are described in Florida Department of Environmental Regulation (undated) and usually consist of a retention or detention facility, such as a pond or large swale area. These facilities are designed to capture 80 to 95% of the runoff. Effectiveness of BMPs can vary, however. One national study of pond BMPs used in urban areas found that about half of the phosphorus was removed from the runoff and roughly one-third of the nitrogen (Center for Watershed Protection, 1997). Therefore, even under the best of circumstances, treatment of the runoff downstream raises several questions:

1. What are the water quality criteria or success criteria to be met?
2. What are the sources of pollutants?
3. How much land is available to install BMPs?
4. What types of BMPs will be most effective?

Waters surrounding the Florida Keys are Outstanding Florida Waters (OFW), one of the most protective in State law. Where a discharge to an OFW is permitted, the SFWMD requires that ambient water quality is not degraded. Specific water quality targets for some substances are listed in Appendix K of the OFW report to the Environmental Regulation Commission (FDER, 1985). Currently, all stormwater systems permitted in the Keys by the SFWMD must retain from 1 to 2.5 inches of runoff on site. Most storm events are less than this, so discharge volumes are zero most of the time. Where an outfall discharges into the OFW, an additional 1 to 1.25 inches (50%) must be retained on site. These design criteria are presumed to achieve OFW water quality criteria, although a detailed analysis for the Keys has not been conducted.

Source control is an important issue. If pollutants can be prevented from entering the runoff stream at the source, it can greatly reduce the expense of treating runoff downstream. This can often be accomplished by implementing better housekeeping practices on individual properties and can sometimes save property owners money. A homeowner, for example, may use less fertilizer and get identical results. A business owner may find that captured wastes can be recycled and turned into an asset. Government and educational programs like "Florida Yards and Neighbors" can assist property owners in identifying low cost ways to reduce pollutant loads.

The very limited land available in the Florida Keys profoundly affects the types of BMPs that can be utilized. The typical land-intensive BMPs used elsewhere in Florida are not feasible in the Keys. There are, however, BMPs utilized in urban areas of south Florida that can be implemented in the Keys. These BMPs take advantage of salt intruded groundwater and high percolation rates of the soils. In some cases, pumps may be required because of low elevations. No single BMP is typically adequate to treat a runoff stream. Well designed stormwater treatment systems include a series of BMPs that ensures that as much as possible of the pollutant load is removed.

These issues and the issue of where and how to best spend public funds to improve stormwater runoff in the Keys is best analyzed within the context of a master plan. A good stormwater master plan will include an objective evaluation and recommendations tied to specific outcomes. Some of these kinds of analyses have been conducted in specific locations, like Key Colony Beach. However, a regional plan is needed. To this end, Monroe County and the SFWMD have established a partnership. Monroe County is developing the scope of work for a master plan. Once the project is "scoped", professional services can be retained to complete the plan. One of the areas of investigation in the plan will be the issue of "hot spots" of water quality degradation. Hot spot areas will be evaluated to determine what portion of the pollutant load could be related to stormwater runoff. The plan will recommend measures that will be effective for remediation in those areas. The plan will include a state-of-the-art load analysis for the Keys. It will examine current design feasibility of various BMPs.

Implementing stormwater treatment measures in the Keys will be very expensive. The cost of stormwater improvements is estimated to be between $370 million and $680 million, depending on the percentage reduction in stormwater pollutant loadings to be achieved and areas selected for retrofitted treatment BMPs (EPA, 1993).

CARRYING CAPACITY

Ecosystems are able to assimilate and adjust to certain levels of stresses. When stresses reach threshold levels, a change to the ecosystem structure and function will occur. Some changes are acceptable or reversible once the stress is removed. Other changes are detrimental and permanent and can lead to the collapse of the existing ecosystem. Carrying capacity is an ecological concept that delineates acceptable limits of stresses to an ecosystem.

Carrying capacity analysis can define threshold limits of nutrients that will result in eutrophication of waters. As a result of a legal challenge of the Monroe County Comprehensive Plan, the State Hearing Officer in that case determined that the nearshore waters adjacent to the Florida Keys have exceeded the carrying capacity for assimilation of nutrients.

Determining the number of people a geographic area can support without irreversible or unacceptable damage to the ecosystem is a complex analysis. Carrying capacity has many components including socio-economic, aesthetic, public health and safety, as well as environmental. Quantifying these elements requires defensible data and consensus on assumptions of thresholds, limiting factors, and acceptable limits.

The U.S. Army Corps of Engineers has completed a "Draft Scope of Work" for a carrying capacity analysis of the Florida Keys. The Scope has been submitted to the Florida Department of Community Affairs and it is being reviewed by experts in carrying capacity analysis. The results of this important study will be used by planners in setting acceptable limits of growth and use of this important and unique ecosystem.

MONITORING

A long term, comprehensive monitoring program is required by the Florida Keys National Marine Sanctuary and Protection Act. Monitoring is critical in maintaining and improving the ecological condition of the Sanctuary since it will provide information on the status and trends of water quality and important biological parameters. Data generated by monitoring programs will provide managers information necessary to identify or confirm problem areas. In addition, monitoring is required to evaluate the effectiveness of corrective actions taken to reduce pollution sources. Water quality, coral reef and hard bottom, and seagrass monitoring programs were designed in 1993 (U.S. EPA, 1993) and finalized in 1995 (U.S. EPA, 1995).

WATER QUALITY

The Water Quality Monitoring Program uses a stratified random design based upon the EPA Environmental Monitoring and Assessment Program (EMAP) hexagonal grid (Overton et al., 1990). Strata were based upon variability of physical transport regimes, as described by Klein and Orlando (1994). Nearshore to offshore transects are randomly located within strata (Figure 1). Segment 1 includes the Tortugas and surrounding waters and is most influenced by the Tortugas gyre of the Loop Current (Lee et al., 1994). Segment 2 includes the Marquesas Keys and the Quicksands. Segment 4 is the shallow waters around the myriad of keys in the "Back Country". Segment 6 is the Sluiceway that is heavily influenced by transport from Florida Bay and Gulf shelf waters. Segments 5, 7, and 9 include inshore, Hawk Channel, and reef tract waters on the Atlantic side of the Keys.

Approximately 150 stations have been sampled quarterly since March 1995. Data for 1997 are summarized in Figures 2 to 5. Several trends are apparent in the data. Silicate is an indicator of freshwater and was highest in the Sluiceway (6) and Back Country (Figure 2). Total phosphorus was highest in Back Country and Sluiceway and lowest in the and Upper Keys (9). Total inorganic nitrogen was highest in the Back Country and at stations adjacent to the Keys in the Upper(5) and Middle (7) Keys. Chlorophyll was highest in the Marquesas Quicksands (2), probably due to Gulf shelf water input, and lowest in the Tortugas and Upper Keys. Turbidity was highest and most variable in the shallow waters of the Back Country and Sluiceway and lowest in the Tortugas.

Concentrations of total inorganic nitrogen, total phosphorus, silicate, and turbidity were highest inshore and declined toward the reef tract (Figures 3 and 4). Lower and Middle Keys had much higher nearshore concentrations than Upper Keys. Total inorganic nitrogen, total phosphorus, silicate, chlorophyll, and turbidity were highest in individual transects situated along passes between the Keys, indicating the prevalence of Sluiceway and shelf influence (Figure 5). Waters in Biscayne Bay passes had lower concentrations of nutrients compared to waters in passes between the Keys.

CORAL REEF AND HARD BOTTOM

There is very little existing robust information on long-term changes in coral reef ecosystems. The Coral Reef and Hard Bottom Monitoring Program is designed to evaluate the status and trends of 40 permanently located reef and hard bottom sites. Stations have been observed annually using video techniques since 1996. A summary of the data on number of taxa by habitat type for 1996 and 1997 are shown in Figure 6. Although it is much too early to detect long term trends and variability, mean species numbers declined for patch reef and offshore deep reef stations. In addition, coral diseases appear to have significantly increased, whether reported in terms of number of monitoring stations affected, number of coral species affected, or number of different diseases recorded.

SEAGRASSES

A comprehensive seagrass monitoring program in the Sanctuary has been in place since 1996. Distribution, productivity, and morphometrics of seagrasses are monitored quarterly throughout the Sanctuary. Sampling is performed at three levels. At Level I sites, shoot morphometrics and productivity of turtlegrass are measured quarterly. Level II sites are sampled annually to obtain shoot morphometrics. Level III sites are sampled annually to assess percent cover. Locations of sites sampled in 1996 and 1997 are shown in Figure 7. There are approximately 30 Level I stations, 87 Level II stations, and 187 Level III stations. Level I sites were selected to conform with water quality monitoring sites. Level II and III sites are randomly located within segments using the EMAP grid system. The mix of site types is designed to monitor trends through intense quarterly sampling of a few permanent locations (Level I) and to annually characterize the broader seagrass population through less intensive, one-time sampling at more locations (Level II and III).

Turtlegrass and manatee grass are the most stable and widely distributed of the seagrasses within the Sanctuary(Figures 8). The overall average standing crop biomass 21.9 g/m^2 for turtlegrass and 8.2 g/m^2 for manatee grass (above ground, dry weight). Seasonal variations of standing crop and productivity are evident, with increases in third and fourth quarters of sampling (Figure 9). Short shoot density of turtlegrass ranged from 66 to 1025/m^2 for all sites. Above sediment standing crop ranged between 5 and 93 g/m^2. Leaf mass exhibited high variation (21 to 415 mg/short shoot). Short shoot production ranged between 0.18 and 8.31 mg/short shoot/day. Higher values were observed in Florida Bay than on the Atlantic side. Areal productivity ranged between 0.07 and 3.37 g/m^2.

The seagrass monitoring has not observed the marked effects of nutrient enrichment described by Lapointe et al. (1994). The reason, at least in part, is probably due to differences in sampling methodologies employed. Lapointe et al. (1994) selected hypereutrophic areas associated with a known source of pollutants and sampled transects from those sources. They found gradients in nutrients and biological changes along the transects that they attributed to source pollutants. The long term seagrass monitoring program is on a much broader scale and utilizes a random sampling pattern. If the observations of Lapointe et al. (1994) are more widespread than their selected sampling sites, the seagrass monitoring program should detect similar variations when enough samples are taken. To date this has not been the case.

THE ECONOMICS OF CLEAN WATER AND NATURAL RESOURCES

Natural resources have market values and non-market values. Market values are the prices of commodities on the open market (e.g., an acre of land). Non-market values are less immediately tangible and include the values of being part of a balanced, self-sustaining ecosystem (e.g., habitat value). Effects of habitat loss and other non-market values may take years to become apparent, but these values have long lasting socio-economic effects. A sustainable market economy depends on maintenance of non-market values over long time periods. For example, the tourist-based economy of the Florida Keys depends upon clean water and abundant natural resources. If non-market values of these resources decline, the market value will eventually decline.

Leeworthy and Bowker (1997) recently quantified the non-market value of natural resources in the Florida Keys. The study estimated that values tourists receive from the natural resources that are over and above the costs for them to come to the Keys to use them. The study determined that the overall non-market user value for visitors to the Florida Keys is $654 per visitor per trip, or $1.2 billion annually. The study estimated that 76% of all activity days by visitors are spent in some sort of natural resource-related activity. Thus, the amount of non-market value attributed to natural resources is $910 million annually (76% of $1.2 billion). When market values ($1.3 billion) are added to non-market user values ($1.2 billion), the total annual value of the Florida Keys to tourism is $2.5 billion.

In a sustainable economy, market values do not come at the expense of declines in non-market values. Non-market user values calculated on a sustainable basis are called asset values, which are a long-term market value. The total non-market value of the Florida Keys to tourism was calculated to be $24.1 billion and the natural resource total market value was calculated to be $18.3 billion.

Non-market user values can be used in benefit-cost analysis of projects that impact natural resources. For example, the cost to improve wastewater and stormwater treatment in the Keys to improve water quality of surface waters may range from $500 million to $1 billion million depending on options selected (U.S. EPA, 1996). Although that is a large cost, it is small compared to the estimated $2.5 billion in annual market and non-market values of tourism to the Keys. Even if just the annual natural resource non-market value of $910 million per year is used as a comparison, the investment to improve water quality still makes sound economic sense.

Cost of water quality improvements (assume $1 billion) are only 5.5% of the long term asset value of the natural resource ($18.3 billion). Clearly, the costs of water quality protection and improvement measures are a relatively small proportion of the non-market economic user value of the resources they are designed to protect.

Table 1. Parameters measured in routine water quality monitoring and examples of methods of analysis.

Water Quality Parameter	Examples of Methods of Analysis
Physico-chemical parameters	
Temperaure	thermistor or mercury thermometer
Conductivity/salinity	elecrometric
Dissolved oxygen	Winkler titration or polarographic sensor
pH	electrometric
Light attenuation	PAR attenuation
Turbidity	Secchi disk or nephelometry/beam attenuation
Depth	measured line or presssure transducer
Nutrients	
Dissolved ammonia	indophenol
Dissolved nitrate and nitrite	diazo after Cd reduction
Dissolved nitrite	diazo
Total nitrogen	high temperature combustion nitrous oxide chemoluminenscence
Soluble reactive phosphorus	molybdate
Total phosphorus	high temperature digestion molybdate
Non-purgeable organic carbon	high temperature combustion/IR detection
Biological parameters	
Chlorophyll a	fluorometric
Alkaline phosphatase activity	fluorometric
Fecal coliform bacteria	incubation and plate count
Biochemical oxygen demand	incubation and oxygen analysis

Table 2. Ranges of water quality parameters measured during a survey to support designation of waters surrounding the Florida Keys as Outstanding Florida Waters (From: FDER, 1985).

Water Quality Parameter	Ambient Stations (mg/l, except pH)	Canals (mg/l, except pH)
Dissolved oxygen	6.0-9.4	0.0-9.6
pH	7.0-8.4	7.3-8.3
Total phosphorus	0.001-0.054	0.005-0.083
Total Kjeldahl nitrogen	0.128-0.693	0.196-1.15
Ammonia nitrogen	0.051-0.160	0.057-0.239
Organic nitrogen	0.019-0.580	0.066-0.850
Nitrate plus nitrite	0.000-0.027	0.002-0.054

Table 3. Nutrient loadings from residential wastewater. Typical residential wastewater flow is 45 gallons/capita/day (from: Harkins, 1996).

Total Nutrient Loading (gm/person/day) by Fixture

NUTRIENT	TOILETS	SINKS, SHOWERS	TOTAL WITHOUT GARBAGE DISPOSL	TOTAL WITH GARBAGE DISPOSAL
carbon	18	30	48	59
nitrogen	6.5	1.5	8.0	9.0
phosphorus	1.2	2.8	4	4.0

Nutrient Concentration of Wastewater (mg/l)

NUTRIENT	WITHOUT GARBAGE DISPOSAL	WITH GARBAGE DISPOSAL
carbon	280	350
nitrogen	47	53
phosphorus	24	24

Table 4. Estimated Nutrient Loading (pounds per day) in the Florida Keys by Source (from: U.S. EPA, 1993, Table 3-1, as revised by Robert Freeman, Fred McManus, and Bill Thiess).

SOURCE	NITROGEN pounds/day	NITROGEN percent	PHOSPHORUS pounds/day	PHOSPHORUS percent
Wastewater				
OSDS	932	30.9	226	23.0
cesspits	283	9.4	100	10.2
package plants	758	25.2	152	15.5
central treatment plants	320	10.6	36	3.7
live-aboards	84	2.8	30	3.0
SUBTOTAL	2377	78.9	544	55.4
Stormwater				
developed areas	401	13.3	364	37.0
undeveloped areas	234	7.8	75	7.6
SUBTOTAL	635	21.1	439	44.6
TOTAL	3012	100	983	100

Table 5. Florida Keys Water Quality "Hot spots": Areas with Known or Suspected severely degraded Water Quality (From: U.S. EPA, 1993, Table 6-4, as revised on March 19, 1996 by an Interagency Panel.

ID #	Site		Location
1	Ocean Reef Marina		Key Largo
2	Phase I and Dispatch Creek		Key Largo
	~~Worlds Beyond~~	DELETED-PURCHASED BY STATE	~~Key Largo~~
3	C-111 Canal		Mainland
4	Sexton Cove and Lake Surprise Subdivisions		Key Largo
5	Cross Key Waterways Subdivision		Key Largo
6	Port Largo		Key Largo
7	Key Largo Fishery Marina		Key Largo
8	Marian Park and Rock Harbor Estates		Key Largo
9	Pirate Cove Subdivision		Key Largo
10	Winken, Blynken, and Nod		Key Largo
11	Blue Water Trailer Park		Key Largo
12	Hammer Point		Key Largo
13	Campbell's Marina		Key Largo
14	Tropical Atlantic Shores Subdivision		Plantation Key
15	Plantation Key Colony[a]		Plantation Key
16	Indian Waterways		Plantation Key
17	Plantation Yacht Harbor		Plantation Key
18	Treasure Harbor		Plantation Key
19	Venetian Shores		Plantation Key
20	Holiday Isle Resort		Windley Key
21	Islamorada Fish House	NEW	Upper Matecumbe Key
22	Lorelei Restaurant	NEW	Upper Matecumbe Key
23	Stratton's Subdivision	NEW	Upper Matecumbe Key
24	Port Antigua		Lower Matecumbe Key
25	White Marlin Beach		Lower Matecumbe Key
26	Lower Matecumbe Beach		Lower Matecumbe Key
27	Caloosa Cove Marina[a]		Lower Matecumbe Key
28	Kampgrounds of America Marina		Fiesta Key
29	Long Key Estates and City of Layton[a]		Long Key
30	Outdoor Resorts of America		Long Key
31	Conch Key		Conch Key
32	Coco Plum Beach area[a]		Fat Deer Key
33	Bonefish Towers Marina[a]		Fat Deer Key
	~~Key Colony Beach Sewage Outfall~~	INJECTION WELL	~~Fat Deer Key~~
34	Coco Plum Causeway	NEW	Fat Deer Key
35	Key Colony Subdivision[a]		Vaca Key (Marathon)
36	Sea-Air Estates		Vaca Key
37	90th Street Canal		Vaca Key
38	Winner Docks		Vaca Key
39	National Fish Market		Vaca Key
40	Faro Blanco Marina		Vaca Key
41	Boot Key Marina		Vaca Key
42	Boot Key Harbor drainage area		Vaca Key
43	Marathon Seafood		Vaca Key
44	Little Venice	NEW	Vaca Key

Table 5. continued

ID #	Site		Location
45	Knight Key Campground		Knight Key
46	Sunshine Key Marina		Ohio Key
47	Bahia Shores		No Name Key
48	Doctors Arm		Big Pine Key
49	Tropical Bay		Big Pine Key
50	Whispering Pines Subdivision		Big Pine Key
51	Sands Subdivision area		Big Pine Key
52	Eden Pines Colony		Big Pine Key
53	Pine Channel Estates		Big Pine Key
54	Cahill Pines and Palms		Big Pine Key
55	Port Pine Heights		Big Pine Key
56	Sea Camp[a]		Big Pine Key
57	Coral Shores Estates		Little Torch Key
58	Jolly Roger Estates		Little Torch Key
59	Breezeswept Beach Estates[a]		Ramrod Key
60	Summerland Key Fisheries		Summerland Key
61	Summerland Key Cove		Summerland Key
62	Cudjoe Ocean Shore		Cudjoe Key
63	Venture Out Trailer Park		Cudjoe Key
64	Cutthroat Harbor Estates[a]		Cudjoe Key
65	Cudjoe Gardens Subdivision[a]		Cudjoe Key
66	Orchid Park Subdivision		Lower Sugarloaf Key
67	Sugar Loaf Shore Subdivision		Lower Sugarloaf Key
68	Sugar Loaf Lodge Marina[a]		Lower Sugarloaf Key
69	Bay Point Subdivision		Saddlebunch Keys
70	Porpoise Point[a]		Big Coppitt Key
71	Seaside Resort		Big Coppitt Key
72	Gulfrest Park[a]		Big Coppitt Key
73	Boca Chica Ocean Shores		Geiger Key
74	Tamarac Park		Geiger Key
75	Boca Chica Naval Air Station		Boca Chica Key
	~~Key Haven Subdivision~~	DELETED	~~Raccoon Key~~
76	Boyd's Trailer Park		Stock Island
77	Alex's Junkyard		Stock Island
78	Ming Seafood		Cow Key
79	Oceanside Marina		Cow Key
80	Safe Harbor		Cow Key
81	Key West Landfill		Key West
82	House Boat Row		Key West
83	Garrison Bight Marina		Key West
84	Navy/Coast Guard Marina and Trumbo Point Fuel Storage Facility		Key West
85	Truman Annex Marina		Key West
86	Key West Sewage Treatment Plant Outfall		Key West
87	Key West Bight	NEW	Key West
88	Key West Stormwater Discharge	NEW	Key West

---

[a] Potential water quality degradation. No data available.

Table 5. continued

Florida Keys - Priority Water Quality "Hot Spots"

Hot Spot Name	Location	Priority	Cause of WQ Problem	Potential Solutions
Sexton Cove/Lake Surprise Subdivisions	Key Largo	H	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, install surface water system, improve canal circulation
Cross Key Waterways Subdivision	Key Largo	H	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, install surface water system, improve canal circulation
Winken, Blynken and Nod	Key Largo	H	High density, poorly designed canals, use of septic tanks or cesspits, marina, live-aboards, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install or improve marina surface water system to provide treatment, install pump-out , install surface water system
Conch Key	Conch Key	H	Poorly designed canals, use of septic tanks or cesspits, marina, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install or improve marina surface water system to provide treatment, install pump-out , install surface water system
Boot Key Harbor area, incl. Winner Docks, Boot Key Marina	Vaca Key - Marathon	H	Poorly designed canals, use of septic tanks or cesspits, marinas, live-aboards, seafood processing plants, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation,install or improve surface water system to provide treatment, install pump-out, wastewater treatment facilities for plants

Results of Florida Keys Water Quality "Hot Spot" Workshop, 3-19-96
Listed from north to south by relative priority level - high, medium, low

Table 5. continued

Florida Keys - Priority Water Quality "Hot Spots"

Hot Spot Name	Location	Priority	Cause of WQ Problem	Potential Solutions
Little Venice Subdivision	Vaca Key - Marathon	H	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Knight Key Campground	Knight Key	H	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Doctors Arm	Big Pine Key	H	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Eden Pines Subdivision	Big Pine Key	H	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Bay Point Subdivision	Saddlebunch Key	H	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Boca Chica Naval Air Station	Boca Chica Key	H	Discharge of wastewater Treatment plant effluent to surface waters	Install injection well
Key West Sewage Treatment Plant Outfall	Key West	H	Discharge of wastewater treatment plant effluent to surface waters	Install injection well
Key West Stormwater Discharge Outfalls	Key West	H	Discharge of untreated stormwater runoff into nearshore waters	Retrofit surface water system to provide water quality treatment - retention/detention, filters, etc.

Results of Florida Keys Water Quality "Hot Spot" Workshop, 3-19-96
Listed from north to south by relative priority level - high, medium, low

Table 5. continued

Florida Keys - Priority Water Quality "Hot Spots"

Hot Spot Name	Location	Priority	Cause of WQ Problem	Potential Solutions
Hammer Point Subdivision	Key Largo	M	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Tropical Bay Subdivision	Big Pine Key	M	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Sands Subdivision area, incl. Whispering Pines	Big Pine Key	M	Poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Port Pine Heights Subdivision	Big Pine Key	M	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Cudjoe Gardens Subdivision	Cudjoe Key	L	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system
Gulfrest Park Subdivision	Big Coppitt Key	L	High density, poorly designed canals, use of septic tanks or cesspits, untreated runoff	Install Best Available Technology OSDS or WWTP, improve canal circulation, install surface water system

Results of Florida Keys Water Quality "Hot Spot" Workshop, 3-19-96
Listed from north to south by relative priority level - high, medium, low

Table 6. Water quality data from selected Bay Watch monitoring sites (Bay Watch, 1997).

	Total N (uM)	Total P (uM)	Chlorophyll-a (ug/l)
Grassy Key (open)	19.8	0.34	0.57
Duck Key Canal	19.8	0.21	0.28
Eden Pines Canal	40.5	1.04	2.78
Ramrod Key Canal	35.8	0.64	2.27

Table 7. Percent Nutrient Removal by Central Treatment and Onsite Treatment Systems (from Harkins, 1996).

Pollutant	Central Treatment Systems			Onsite Treatment Systems		
	Secondary	Adv. Sec.	AWT	Septic	Aerobic	Composting Toilet
Carbon	85	97	97	44	77	65
Nitrogen	12	13	93	4	17	82
Phosphorus-no ban	10	13	93	15	9	40
Phosphorus-with ban	20	26	86	30	18	81

Pollutants Remaining after Treatment (grams/person/day)

Pollutant	Central Treatment Systems			Onsite Treatment Systems		
	Secondary	Adv. Sec.	AWT	Septic	Aerobic	Composting Toilet
Carbon	7.2	1.4	1.4	26.9	11.0	16.8
Nitrogen	7.0	7.0	0.6	7.7	6.6	1.4
Phosphorus-no ban	3.6	3.5	0.3	3.4	3.6	2.4
Phosphorus-with ban	1.6	1.5	0.3	1.4	1.6	0.4

Table 8. Estimated Costs for Marathon Central Collection and Treatment. All costs are 1995 dollars (from Draft Wastewater Facilities Plan for the Marathon Area of the Florida Keys, February 1996).

ITEM	**AMOUNT (MILLIONS)**
A. Construction Costs	
1. Collection/Transmission System	$29.1
2. Wastewater Treatment Plant	$ 5.0
3. Effluent Disposal System	$ 2.3
4. Solids Management System	$ 1.7
5. Land Acquisition	$ 3.5
Subtotal	**$41.6**
B. Other Project Costs	
1. Contingency (25%)	$10.4
2. Engineering, Legal, Administrative (15%)	$ 6.2
3. Financing (assume 33.3% financed @ 12%)	$ 2.3
Subtotal	**$18.9**
TOTAL CAPITAL COSTS	**$60.5**
C. Annual Operation and Maintenance	$ 1.4
D. Annual Renewal and Replacement	$ 0.1
E. Administrative Costs	$ 0.4

Figure 1. Location of segments (strata) in the Florida Keys National Marine Sanctuary and location of water quality monitoring stations.

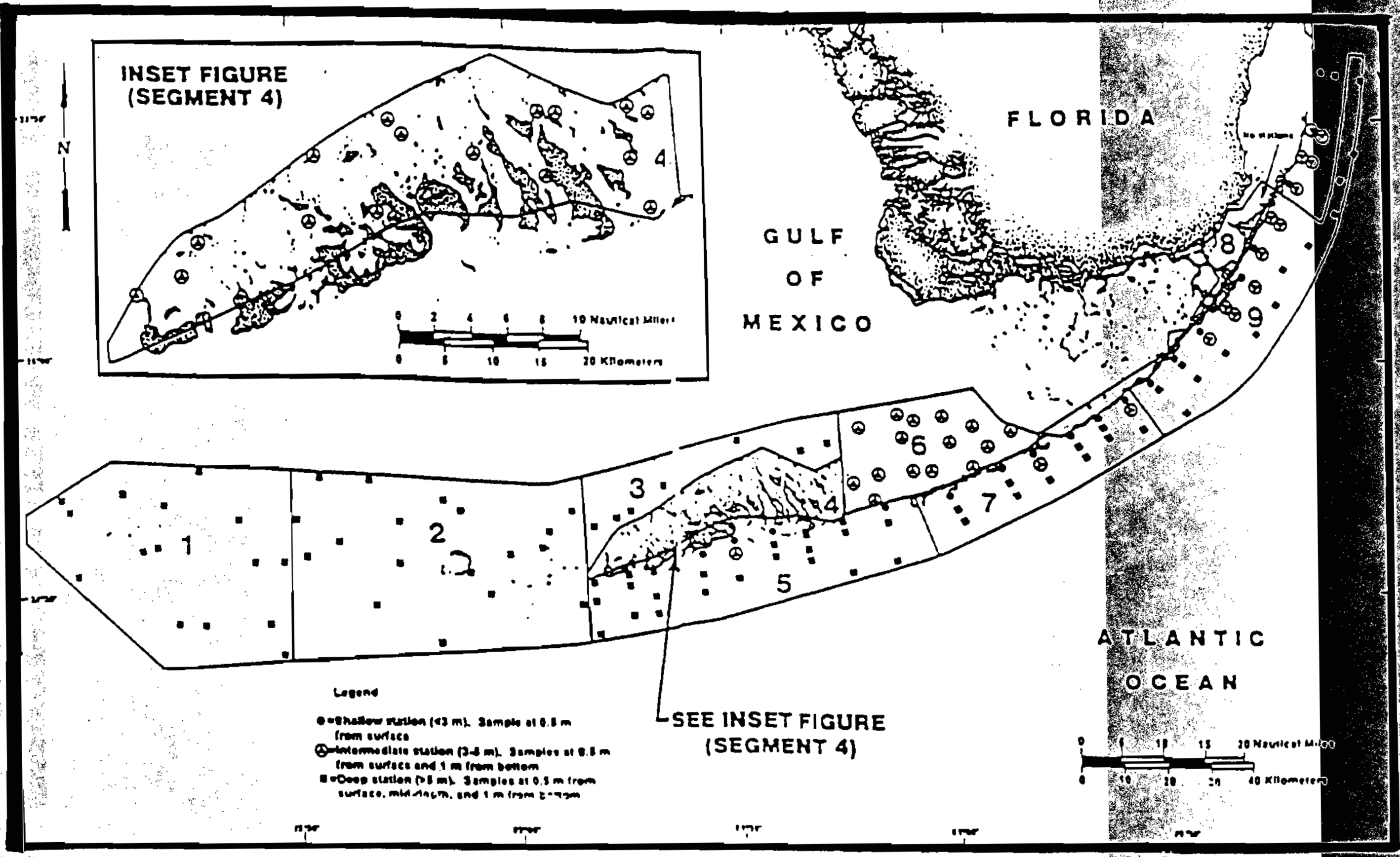


Figure 2. Water Quality Values for 1997 by Strata. Center horizontal line in the box is the median, the top and bottom of the box arethe 25th and 75th quartiles, and the ends of the whiskers are the 5th and 95th percentiles. The notch is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are significantly different.

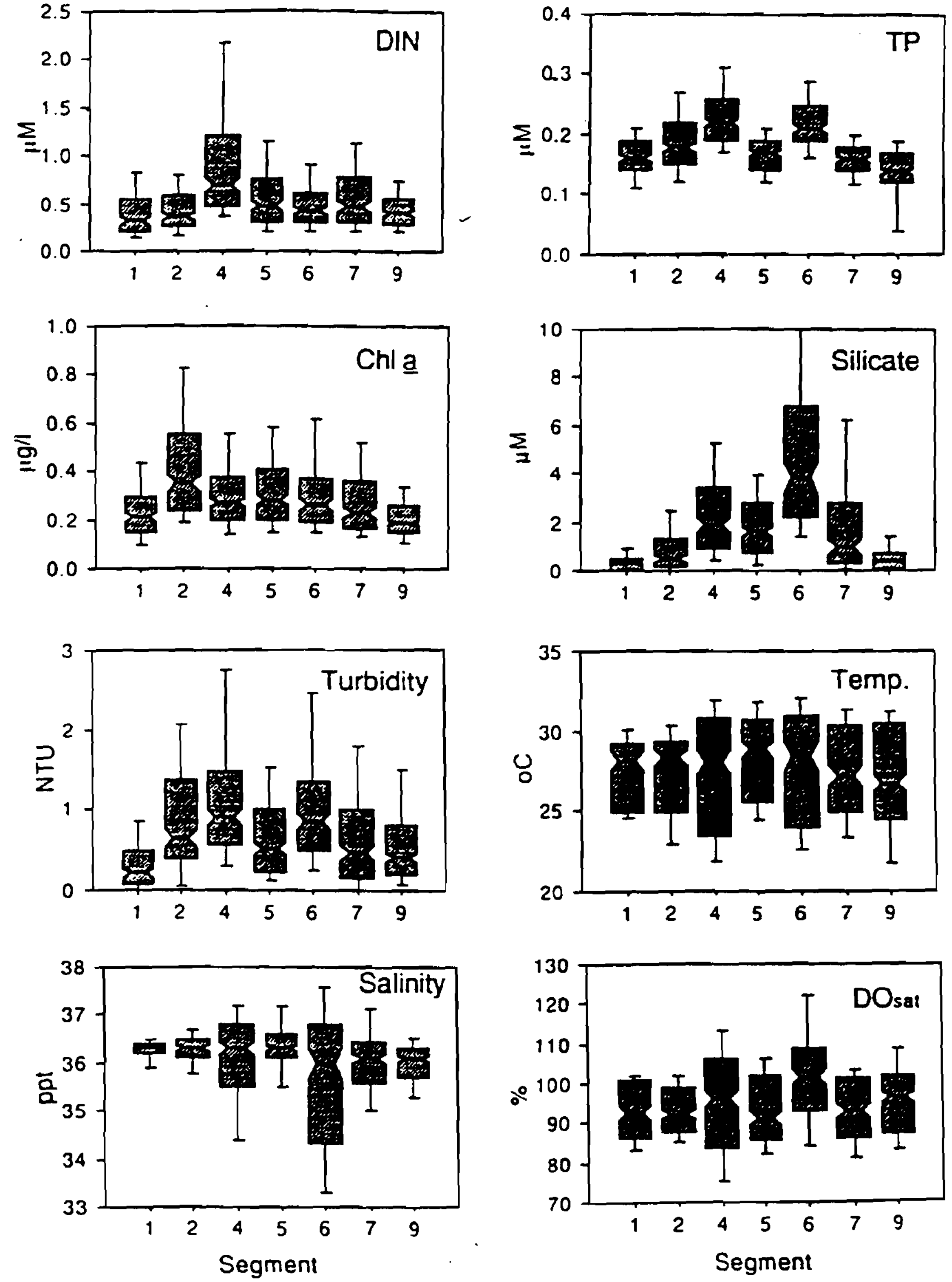


Figure 3. Water Quality Values for 1997 for Onshore-Offshore Transects in Upper (9), Middle (7), and Lower (5) Keys and other sites. See legend for Figure 2. When notches between boxes do not overlap, the medians are significantly different.

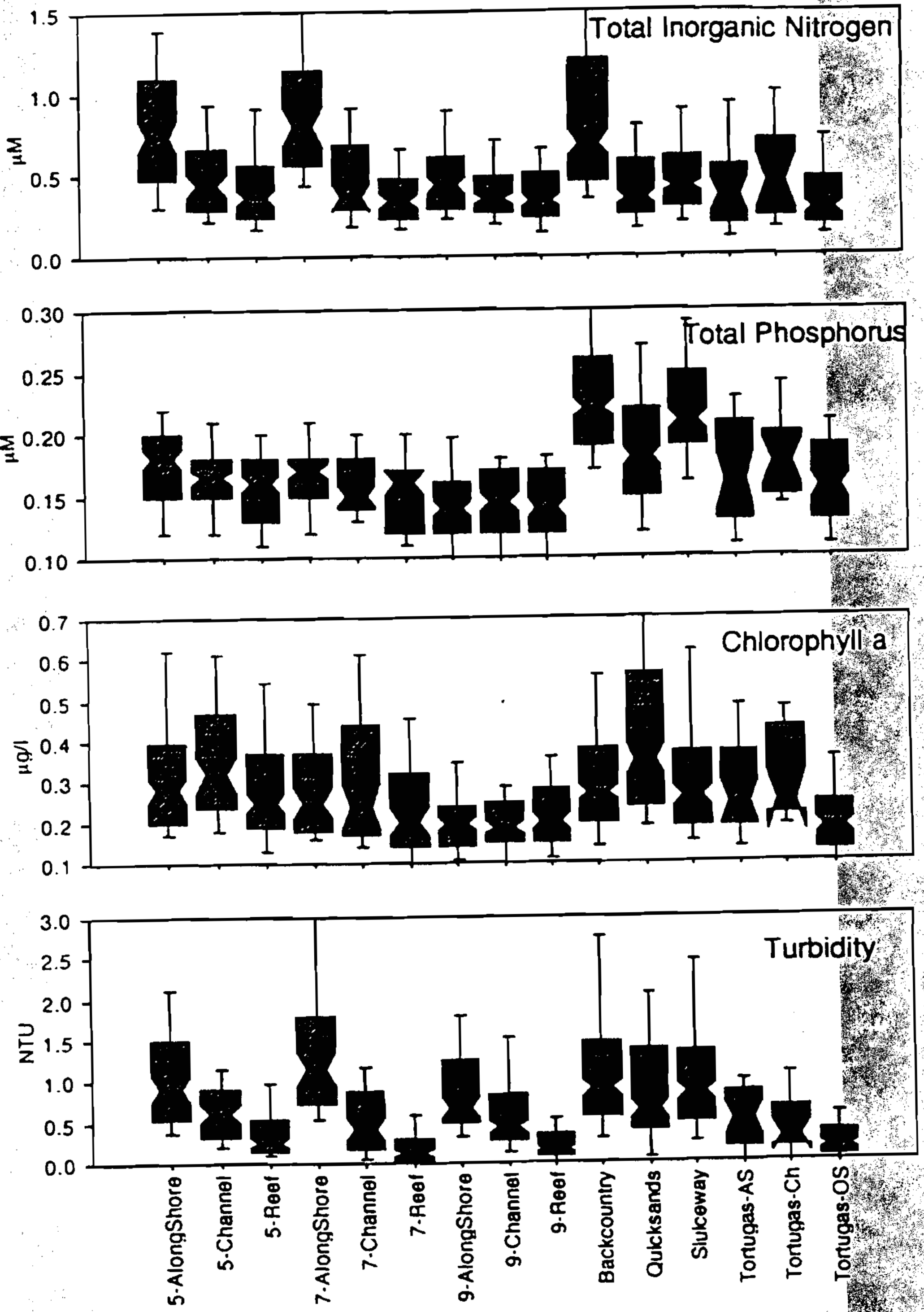


Figure 4. Water Quality Values for 1997 for Onshore-Offshore Transects in Upper (9), Middle (7), and Lower (5) Keys and other sites. See legend for Figure 2. When notches do not overlap, medians are significantly different.

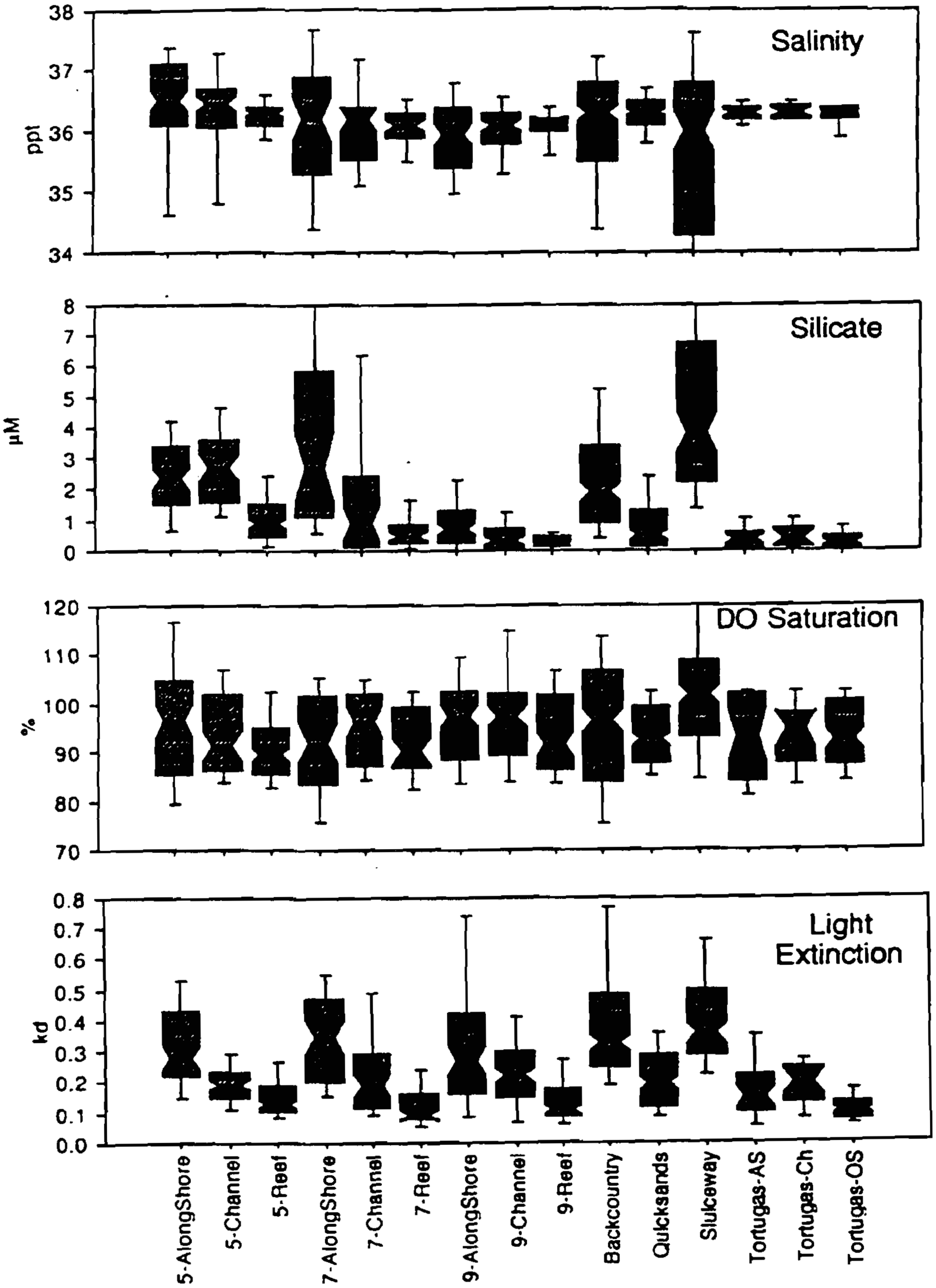


Figure 5. Water Quality Values for 1997 from Stations at Florida Keys Tidal Passes (Pass), Adjacent to Keys (Land), and Biscayne Bay (Bisc). See legend for Figure 2. When notches do not overlap, medians are significantly different.

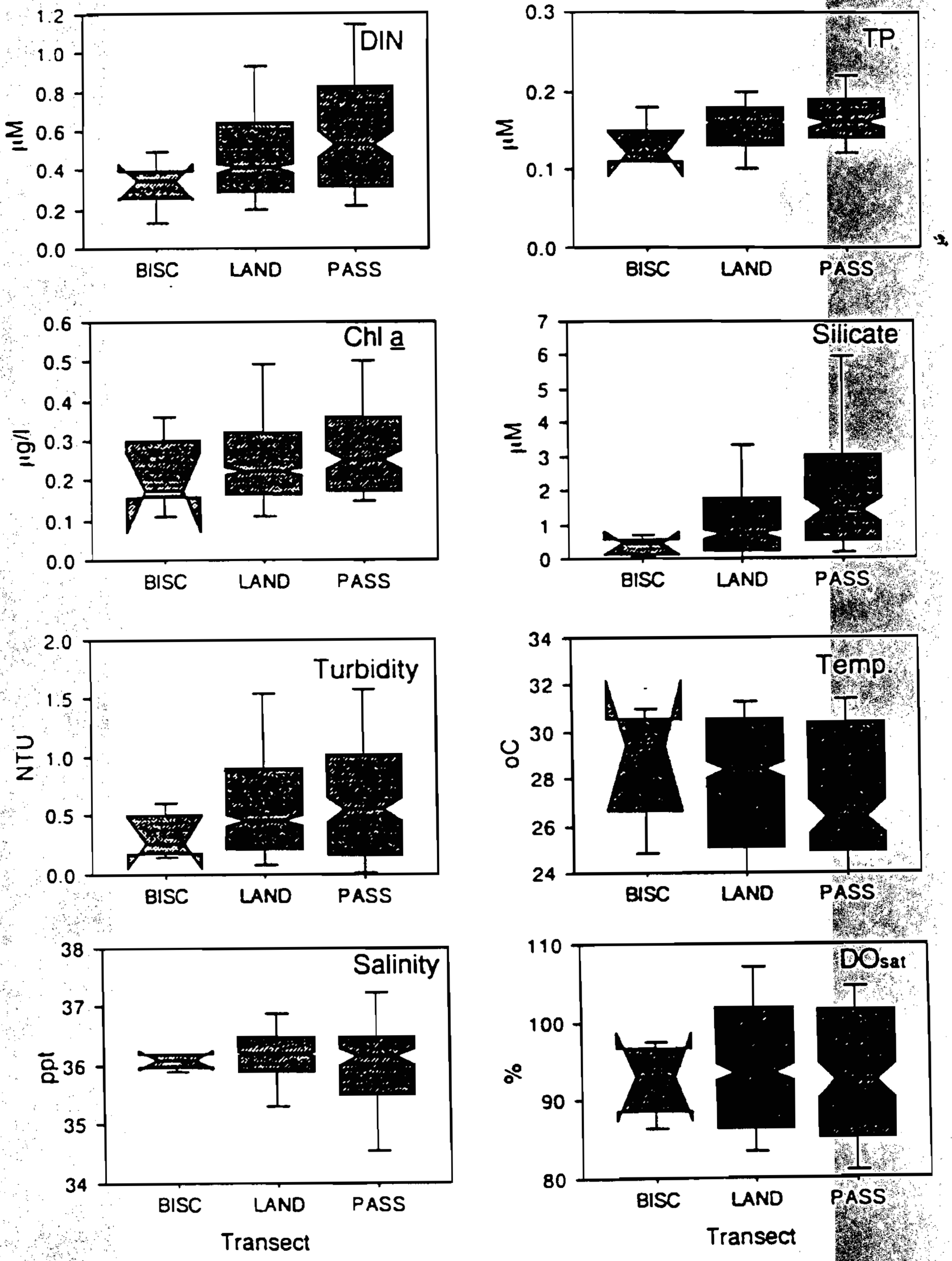


Figure 6. Number of Coral Taxa Observed by Habitat Type in 1996 and 1997.
HB = Hard Bottom Stations; OS = Offshore Reef Shallow Stations;
OD = Offshore Reef Deep Stations. Range, Mean, and +/- one standard error.

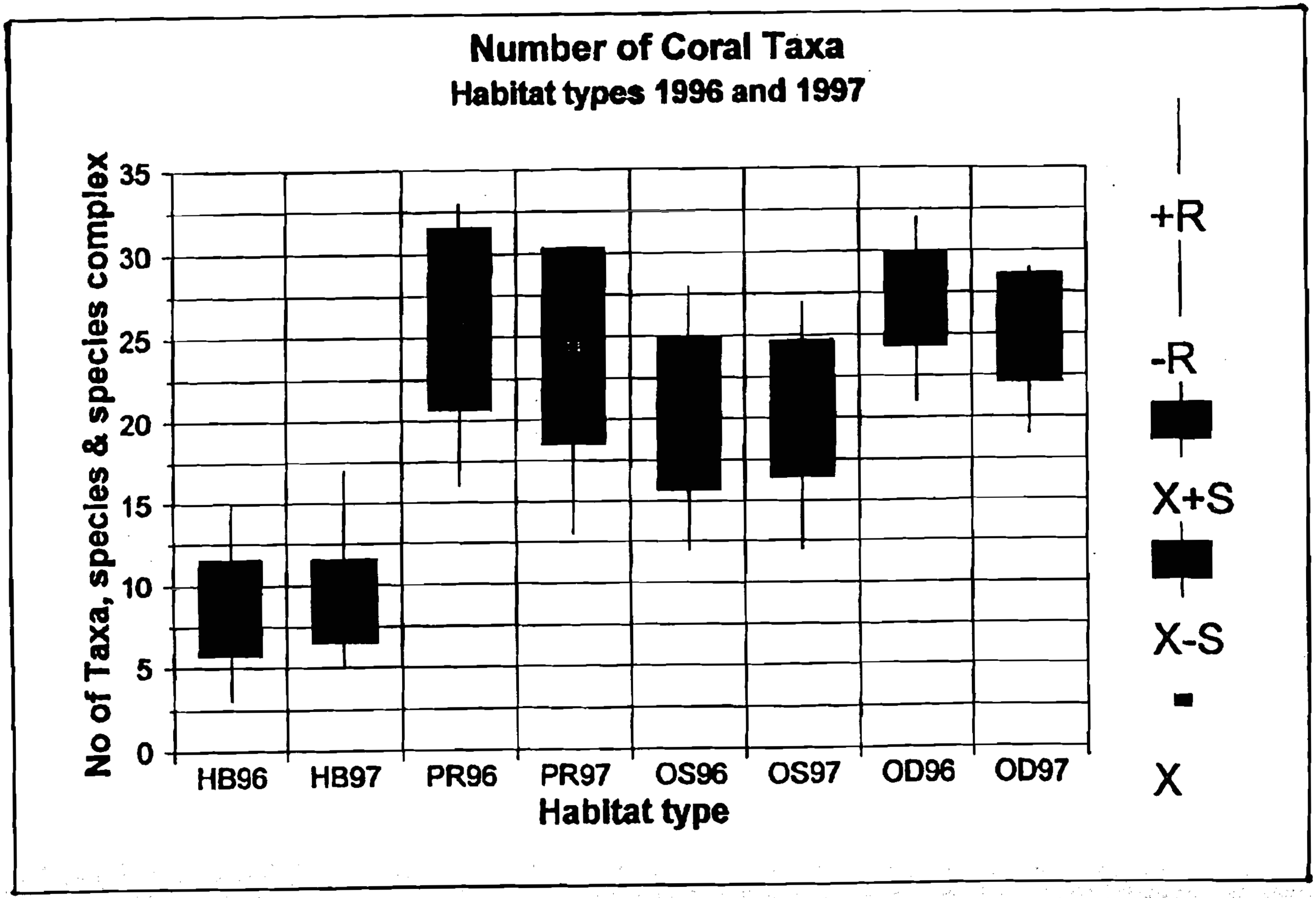


Figure 7. Location of seagrass sampling sites in 1996 and 1997. Large circles are Level I sites sampled quarterly. Other sites are randomly located within strata and sampled annually.

Figure 8. Spatial variability of standing crop biomass of Thalassia testudinum and Syringodium filiforme.

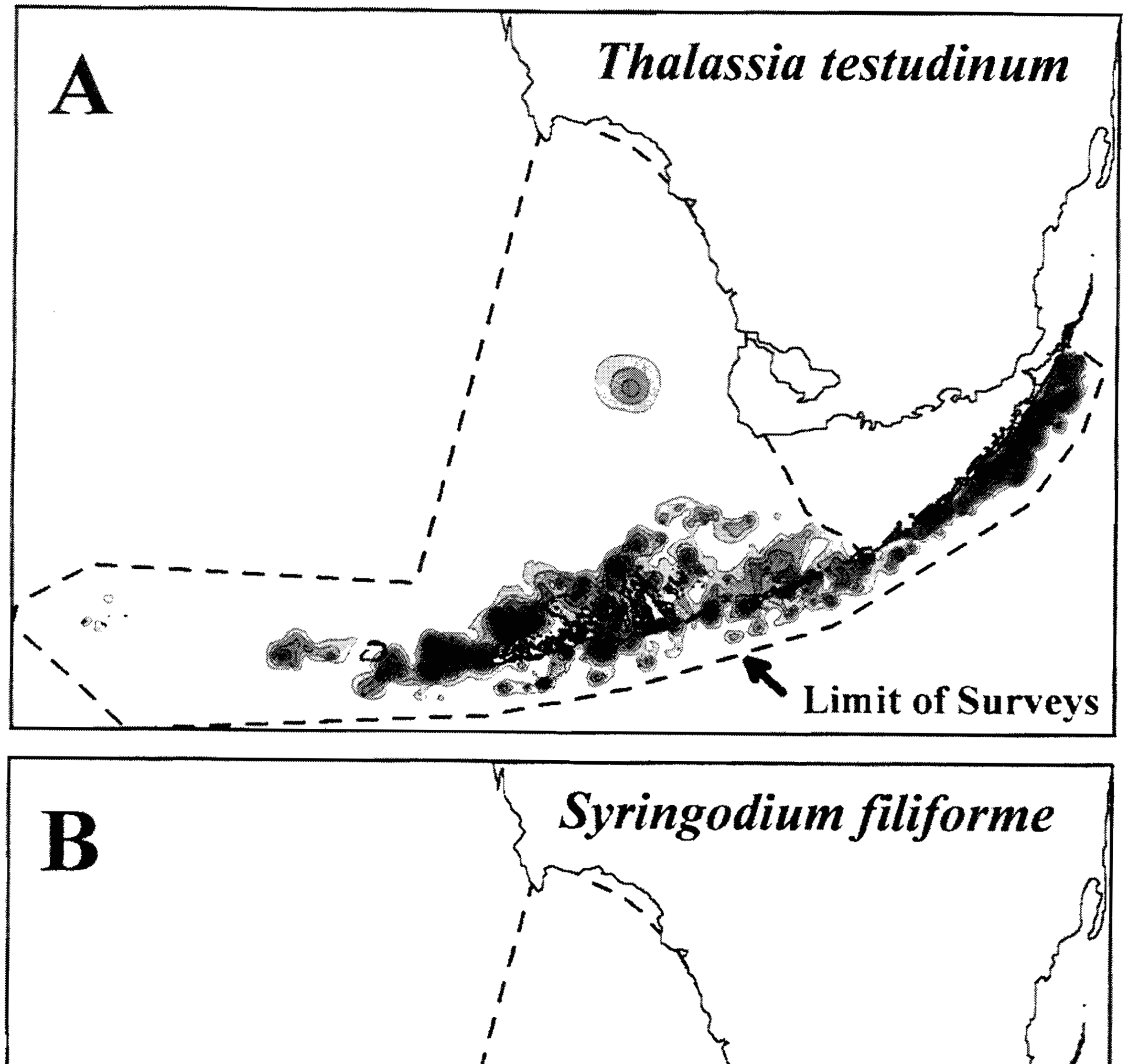
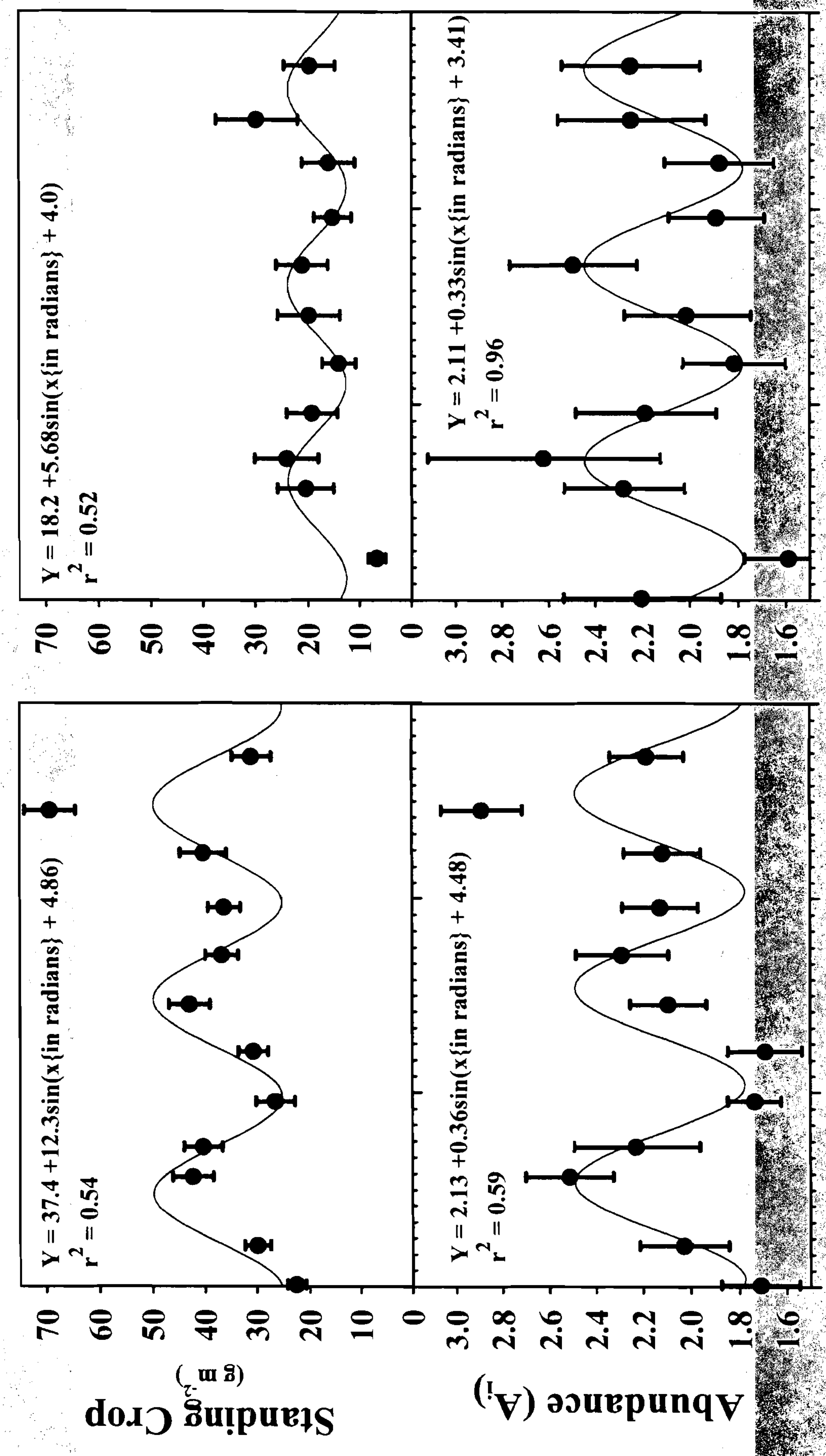


Figure 9. Seasonal variation in standing crop and abundance of Thalassia testudinum and Syringodium filiforme.



LITERATURE CITED

Adams, C. 1992. Economic activities associated with the commercial fishing industry in Monroe County, Florida. Univ. Florida Food and Resources Economics Dept., Inst. Food and Agr. Sci. Staff Paper SP92-27, 20 pp.

Antonius, A. 1981a. The "band" diseases in coral reefs. Proc. 4th Int. Coral Reef Symp. 2:7-14.

Antonius, A. 1981b. Coral reef pathology: a review. Proc. 4th Int. Coral Reef Symp. 2:3-6

Barada, W. and W.M. Partington, Jr. 1972. Report of investigation of the environmental effects of private waterfront canals. Environmental Information Center, Florida Conservation Foundation, Inc., 63 pp.

Bell, P.R.F. 1991. Status of eutrophication in the Great Barrier Reef lagoon. Marine Pollution Bulletin 23:89-93.

Bell, P.R.F. 1992. Eutrophication and coral reefs- some examples in the Great Barrier Reef lagoon. Water Research 26:553-568.

Bell, P.R.F and I. Elmetri. 1993. Validation of 1928-1929 phosphate and microplankton data for Low Isles as a baseline for eutrophication in the Great Barrier Reef lagoon. Report to the Great Barrier Reef Marine Park Authority, Townsville, 33 pp.

Brand, L. 1997. Semi-synoptic sampling of phytoplankton in the Florida Keys National Marine Sanctuary. Final Report Submitted to Water Quality Protection Program, 6 pp.

Brodie, J. 1994. The problems of nutrients and eutrophication in the Australian marine environment. The State of the Marine Environment Report for Australia Dept. Environ., Sports and Territories Special Report, Canberra, 29 pp.

Brodie, J. 1995. Nutrients and the Great Barrier Reef. The State of the Marine Environment Report for Australia Dept. Environ., Sports and Territories, Special Report, Canberra, 17 pp.

Center for Watershed Protection. 1997. Comparative pollutant removal capability of urban BMPs: A re-analysis. Technical Note 95 2(4):32 pp.

Chanton, J. 1998. Use of natural and artificial tracers to detect subsurface flow of contaminated groundwater in the Florida Keys National Marine Sanctuary. Final Report submitted to the Water Quality Protection Program, 52 pp..

Chesher, R.H. 1973. Environmental Analysis: Canals and Quarries, Lower Florida Keys.

Prepared for Charley Toppino and Sons, Inc., Rockland Key, FL. Marine Research Foundation, Inc., Key West, FL, 162 pp.

Cook, C. 1997. Reef corals and their symbiotic algae as indicators of nutrient exposure. Final Report submitted to the Water Quality Protection Program, 37 pp.

DeMaria, K. 1996. Changes in the Florida Keys Marine Ecosystem Based upon Interviews with Experienced Residents. The Nature Conservancy and the Center for Marine Conservation, 105 pp.

Dubinsky, Z., and N. Stambler. 1996. Marine pollution and coral reefs. Global Change Biology 2:511-526.

Dutka, B.J., A.S.Y. Chau, and J. Coburn. 1974. Relationship between bacterial indicators of water pollution and fecal sterols. Water. Res. 8:1047-1055.

English, D.B.K., W. Kriesel, V.R. Leeworthy, and P. Wiley. 1996. Economic contribution of recreating visitors to the Florida Keys/Key West. Linking the Economy and Environment of Florida Keys/Florida Bay. NOAA, The Nature Conservancy, Monroe County Tourist Development Council, 22 pp.

Ferry, R.E. Undated. Key West ocean outfall study: Synopsis of results and conclusions. Draft Report, U.S. EPA Region 4, 37 pp.

Florida Bay Watch Program. 1996. Annual Report on Water Quality Data Collected by the Florida Bay Watch Volunteer Program. July 1995-June 1996, 16 pp.

Florida Bay Watch Program. 1997. Annual Report on Water Quality Data Collected by the Florida Bay Watch Volunteer Program, July 1996-June 1997, 7 pp.

Florida Department of Environmental Regulation. Undated. Stormwater Management: A Guide for Floridians, 72 pp.

Florida Department of Environmental Regulation. 1985. Proposed designation of the waters of the Florida Keys as Outstanding Florida Waters. Report to the Florida Environmental Regulatory Commission. FDER, 57 pp.

Florida Department of Environmental Regulation. 1987. Florida Keys Monitoring Study: Water quality assessment of five selected pollutant sources in Marathon, Florida. FDER, Marathon Office, 187 pp.

Florida Department of Environmental Regulation. 1990. Boot Key Harbor Study. FDER, Marathon Office, 21 pp.

Florida Department of Pollution Control. 1973. Survey of water quality in waterways and canals of the Florida Keys with recommendations. Final Report, 19 pp.

GESMAP. 1990. The state of the marine environment. UNEP Regional Seas Reports and Studies. UNEP, Nairobi, 115 pp.

Ginsburg, R.N. and E.A. Shinn. 1964. Distribution of the reef-building community in Florida and the Bahamas (abstr.). Am. Assoc. Perrol. Geol. Bull. 48:527.

Ginsburg, R.N. and E.A. Shinn. 1994. Preferential distribution of reefs in the Florida reef tract: the past is the key to the present. Global Aspects of Coral Reefs, Health Hazards and History. Univ. Miami, H21-H26.

Glynn, P., A.M. Szmant, E.F. Corcoran, and S.V. Cofet-Shabica. 1989. Conditions of coral reef cnidarians from the northern Florida Reef tract: Pesticides, heavy metals, and histopathological examination. Unpublished Rept., National Park Service, Contract No. CX5280-5-1447, U.S. Dept. Interior.

Goodfellow, R.M., J. Cardoso, G. Eglinton, J.P. Dawson, and G.A. Best. 1977. A fecal sterol survey in the Clyde Estuary. Mar. Poll. Bull. 8:272-276.

Griffin, D.W., J.B. Rose, and J.H. Paul. 1997. Summary of water quality testing in Marathon, Florida, June 8-13, 1997. Unpublished.

Halley, R.B., H.L. Vacher, and E.A. Shinn. 1997. Geology and Hydrogeology of the Florida Keys. Geology and Hydrogeology of Carbonate Islands: Developments in Sedimentology, H.L. Vacher and T. Quinn (eds.), pp. 217-248.

Harkins, J. 1996. Nutrients in Wastewater and Nutrient Removal. Technical Suppoart Team, Water Management Division, U.S. EPA Region 4, 8 pp.

Hazen, T.C. 1988. Fecal coliforms as indicators in tropical waters: a review. Toxic. Assess. 3:461-477.

Hoffmeister, J.E. and H.G. Multer. 1968. Geology and origin of the Florida Keys. Geol. Soc. America Bull. 79:1487-1502.

Jaap, W.C. 1984. The ecology of the south Florida coral reefs: A community profile. U.S. Fish and Wildlife Service and Minerals Management Service. FWS OBS-82/08 and MMS 84-0038, 139 pp.

Keswick, B.H. 1984. Sources of groundwater pollution. G. Bitton and C.P. Gerba (eds.). Groundwater Pollution Microbiology. John Wiley and Sons, Inc., New York.

Kinsey, D.W. 1988. Coral reef system response to some natural and anthropogenic stresses. Galaxea 7:113-128.

Klein, C.J. and S.P. Orlando, Jr. 1994. A spatial framework for water quality management in the Florida Keys National marine Sanctuary. Bull. Mar. Sci. 54(3)1036-1044.

Kump, L. 1998. Wastewater nutrients in groundwaters of the Florida Keys: Contrasting behaviors of phosphorus and nitrogen. Final Report submitted to the Water Quality Protection Program, 56 pp.

Lapointe, B.E. 1997. Nutrient thresholds for bottom up control of macroalgal blooms on coral reefs in Jamaica and southwest Florida. Limnol. Oceanogr. 42:1119-1131.

Lapointe. B.E. and M.W. Clark. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. Estuaries 15:465-476.

Lapointe, B.E. and D. Hanisak. 1997. Algal blooms in coastal waters: Eutrophication on coral reefs of southeast Florida. Final Report, Florida Sea Grant Project R/C-E-34, 23 pp.

Lapointe, B.E. and W.R. Matzie. 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. Estuaries 19:422-435.

Lapointe, B.E. and W.R. Matzie. 1997. High frequency monitoring of wastewater nutrient discharges and their ecological effects in the Florida Keys National Marine Sanctuary. Final Report submitted to the Water Quality Protection Program, 25 pp.

Lapointe, B.E. and N.P. Smith. 1987. A preliminary investigation of upwelling as a source of nutrients to Looe Key National Marine Sanctuary. NOAA Technical Memorandum. NOS MEMD 9.

Lapointe, B.E., M.M. Littler, and D.S. Littler. 1993. Modification of benthic community structure by natural eutrophication: the Belize Barrier Reef. Proc. 7th Int. Coral Reef Symp. 1:323-334.

Lapointe, B.E., M.M. Littler, and D.S. Littler. 1997. Macroalgal overgrowth of fringing coral reefs at Discovery Bay, Jamaica: bottom-up versus top-down control. Proc. 8th Int. Coral Reef Symp. 1:927-932.

Lapointe, B.E., J.D. O'Connell, and G. Garrett. 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters, and nearshore surface waters of the Florida Keys. Biogeochemistry 10:2289-307.

Lapointe, B.E., D.A. Tomasko, and W.R. Matzie. 1994. Eutrophication and trophic state classification of seagrass communities in the Florida Keys. Bull. Mar. Sci. 54:696-717.

Larkum, A.W.D. and A.D.L. Steven. 1994. ENCORE: The effect of nutrient enrichment on coral reefs. 1. Experimental design and research programme. Mar. Poll. Bull. 29:112-120.

Larkum, A.W.D. and K. Koop. 1997. ENCORE: Algal productivity and possible paradigm shifts. Proc. 8th Int. Coral Reef Symp. 1:881-884.

Larson, U., R. Elmgren, and R. Wulff. 1985. Eutrophication and the Baltic Sea: Causes and consequences. Ambio 14:9-14.

Lee, T.N., M.E. Clarke, E. Williams, A.F. Szmant, and T. Berger. 1994. Evolution of the Tortugas gyre and its influence on recruitment in the Florida Keys. Bull. Mar. Sci. 54:a621-646.

Leeworthy, V.R. and J.M. Bowker. 1997. Nonmarket economic user values of the Florida Keys/Key West. Linking the Economy and Environment of Florida Keys/Florida Bay. NOAA, The Nature Conservancy, Monroe County Tourist Development Council, 41 pp.

Leeworthy, V.R. and P.C. Wiley. 1996. Visitor Profiles: Florida Keys/Key West. Linking the Economy and Environment of Florida keys/Florida Bay. NOAA, The Nature Conservancy, Monroe County Tourist Development Council, 159 pp.

Leeworthy, V.R. and P.C. Wiley. 1997. Visitor Profiles: Florida Keys/Key West. A socioeconomic analysis of the recreation activities of Monroe County Residents in the Florida Keys/Key West. Linking the Economy and Environment of Florida Keys/Flroda Bay. NOAA, The Nature Conservancy, Monroe County Tourist Development Council, 41 pp.

Lidz, B.H. and E.A. Shinn. 1991. Paleo shorelines, reefs and a rising sea: South Florida. J. Coastal Res. 7:203-229.

Loh, P.C., R.S. Fujoika, and S. Lau. 1979. Recovery, survival and dissemination of human enteric viruses in ocean waters receiving sewage in Hawaii. Water Air Soil Bull. 12:1997-2017.

Manker, J.P. 1975. Distribution and concentration of mercury, lead, cobalt, zinc, and chromium in suspended particles and bottom sediments, upper Florida Keys, Florida Bay, and Biscayne Bay. Ph.D. Dissertation, Rice University, Houston, Texas.

McClanahan, T.R. 1992. Epibenthic gastropods in the Middle Florida Keys: the role of habitat and environmental stress on assemblage composition. J. Exp. Mar. Biol. Ecol. 160: 169-190.

Moses, J.H. and J.E. Anderson. 1993. S.W.I.M. Program Septic Tank Study, St. Locie County, FL., 16 pp.

Nixon, S.W. 1990. Marine eutrophication: A growing international problem. Ambio 19:101.

Nixon, S.W. 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41:199-219.

Officer, C.B., R.B. Biggs, J.L. Taft, L.E. Cronin, M.H. Tyler, and W.R. Boynton. 1984. Chesapeake Bay anoxia: origin, development and significance. Science 223:22-27.

Ogden, J.C., J.W. Porter, N.P. Smith, A.M. Szmant, W.C. Jaap, and D. Forcucci. 1994. A long-term interdisciplinary study of the Florida Keys seascape. Bull. Mar. Sci. 53:1059-1071.

Overton, W.S., D. White, and D.L. Stevens, Jr. 1990. Design Report for EMAP: Environmental Monitoring and Assessment Program. Report for U.S. Environmental Protection Agency, Corvallis, OR EPA600/3-91/053.

Paul, J.P., J.B. Rose, S.Jiang, C.A. Kellogg, and L. Dickson. 1993. Distribution of viral abundance in the reef environment of Key Largo, Florida. Appl. Environ. Microbiol. 59:718-724.

Paul, J.P., J.B. Rose, J. Brown, E.A. Shinn, S. Miller and S.R. Farrah. 1995a. Viral tracer studies indicate contamination of marine waters by sewage disposal practices in Key Largo, Florida. Appl. Environ. Microbiol. 61:2230-2234.

Paul, J.P., J.B. Rose, S. Jiang, C. Kellogg, and E.A. Shinn. 1995b. Occurrence of fecal indicator bacteria in surface waters and the subsurface aquifer in Key Largo, Florida. Appl. Environ. Microbiol. 61:2235-2241.

Paul, J.P., J.B. Rose, S.C. Jiang, X. Zhou, P. Cochran, C. Kellogg, J. Kang, D. Griffin, S. Farrah, and J. Lukasik. 1997. Evidence for groundwater and surface marine water contamination by waste disposal wells in the Florida Keys. Water Research 31:1448-1454.

Peters, E.C. 1984. A survey of cellular reations to environmental stress and disease in Caribbean scleractinian corals. Hel. Meer. 37:113-137.

Porter, J.W. and O.W. Meir. 1992. Quantification of loss and change in Floridian reef coral populations. Am. Zool. 32:625-640.

Porter, J.W., O.W. Meier, J.I. Tougas, and S.K. Lewis. 1994. Modification of the south Florida hydroscape and its effect on coral reef survival in the Florida Keys. Bull. Ecol. Soc. Am. Abst. Suppl. 75:184.

Rabalais, N.N., R.E. Turner, D. Justic, Q. Dortch, W.J. Wiseman, Jr., and B. Sen Gupta. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386-407.

Santavy, D.L. and E.C. Peters. 1997. Microbial pests: Coral disease in the western Atlantic. Proc. 8th Int. Coral Reef Symp. 1:607-612.

Sargent, F.J., T.J. Leary, D.W. Crewz, and C.R. Kruer. 1995. Scarring of Florida's Seagrasses: Assessment and Management Options. Florida Department of Environmental Protection, Florida Marine Research Institute Technical Report TR-1, 37 pp.

Shinn, E.A. 1988. The geology of the Florida Keys. Oceanus 31:47-53.

Shinn, E.A., J.H. Hudson, R.B. Halley, and B.H. Lidz. 1977. Topographical control and accumulation rate of some Holocene coral reefs, South Florida and Dry Tortugas. Proc. 3rd Int. Coral Reef Symp. 2:1-7.

Shinn, E.A., B.H. Lidg, J.L. Kindinger, J.H. Hudson, and R.B. Halley. 1989. Reefs of Florida and the Dry Tortugas, A Guide to the Modern Carbonate Environments of the Florida Keys and the Dry Tortugas. Int. Geol. Cong., IDC Field Trip T176. Am. Geophyus. Union, Washington, DC, 54 pp.

Shinn, E.A., B.H. Lidz, and M.W. Harris. 1994a. Factors controlling distribution of Florida Keys reefs. Bull. Mar. Sci. 54:1084 (abstr.).

Shinn, E.A. R.S. Reese, and C.D. Reich. 1994b. Fate and pathways of injection well effluent in the Florida Keys. U.S. Geological Survey Open File Report 94-276, 116 pp.

Skinner, R. and W.C. Jaap. 1986. Trace metals and pesticides in sediments and organisms in John Pennekamp Coral Reef Stat Park and Key Largo National marine Sanctuary. Unpublished report to the Florida Department of Environmental Regulation, Office of Coastal Zone Management.

Smith, G. L.D. Ives, I.A. Nagelkerken, and K.B. Ritchie. 1996. Apergillosis associated with Caribbean sea fan mortalities. Nature 382:487.

Smith, M and Associates, and Hale and Kulligren, Inc. 1970. Environment and identity, a plan for development in the Florida Keys. Land use Plan prepared for Monroe County, Florida.

Strom, R.N., R.S. Braman, W.C. Jaap, P. Dolan, K.B. Donnelly, and D.F. Martin. 1992. Analysis of selected trace metals and pesticides offshore of the Florida Keys. Florida Scientist 55:1-13.

Szmant, A.M. and A. Forrester. 1996. Water column and sediment nitrogen and phosphorus distribution patterns in the Florida Keys. Coral Reefs 15:21-41.

Taylor, J.L. and C.H. Saloman. 1968. Some effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida. Fishery Bull. 67:212-241.

Turner, R.E. and N.N. Rabalais. 1994. Coastal eutrophication near the Mississippi River delta. Nature 368:619-621.

U.S. Environmental Protection Agency. 1975. Finger-fill canal studies: Florida and North Carolina. EPA 904/9-76-017, 232 pp.

U.S. Environmental Protection Agency. 1993. Water quality Protection Program for the Florida Keys National Marine Sanctuary. Phase II Report, Contract No. 68-c2-0134.

U.S. Environmental Protection Agency. 1995. Water Quality Protection Program for the Florida Keys National marine Sanctuary. Phase III Report, Implementation Plan for Water Quality Monitoring and Research Programs. Contract No. 68-C2-0134, 70 pp.

U.S. Environmental Protection Agency. 1996. Indian River Lagoon comprehensive Conservation and Management Plan. Indian River National Estuary Program.

Underal, B. O.M. Skulberg, E. Dahl, and T. Aune. 1989. Disasterous bloom of Chrysochromulina polylepis (Prymnesiophyceae) in Norwegian coastal waters 1988-mortality in marine biota. Ambio 18:265-270.

Valiela, I., K. Foreman, M. LaMontagne, D. Hersh, J. Costa, P. Peckol, B. DeMeo-Anderson, C. D'Avanzo, M. Babione, Chi-Ho Sham, and K. Lajtha. 1992. Couplings of watersheds and coastal waters: Sources and consequences of nutrient enrichment in Waquoit Bay, Massachusetts. Estuaries 15:443-457.

Vaughn, T.W. 1918. The temperature of the Florida coral reef tract. Papers from the Tortugas Laboratory of the Carnegie Institute of Washington 9:319-339.

Viele, J. 1996. The Florida Keys: A History of the Pioneers. Pineapple Press, Inc., Sarasota, FL, 80 pp.

Voss, G. 1988. Coral Reefs of Florida. Pineapple Press, Inc., Sarasota, FL., 80 pp.

Wilkinson, C.R. 1993. Coral reefs are facing widespread devastation: Can we prevent this through sustainable practices. Proc. 7th Int. Coral Reef Symp. 1:11-21.

Wilkinson, C.R. 1996. Global change and coral reefs: Impacts on reefs and human cultures. Global Change Biology 2:547-558.

Windom, H.L. 1992. Contamination of the marine environment from land-based sources. Marine Pollution Bull. 25:1-4.

Woodward-Clyde Consultants, Inc. 1994. Historical imagery and seagrass assessment of the Indian River Lagoon. Indian River National Estuary Program.