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LONG-TERM TRENDS OF NITROGEN LOADING, WATER QUALITY AND BIOLOGICAL INDICATORS IN HILLSBOROUGH BAY, FLORIDA

J. O. R. Johansson

INTRODUCTION

At the time of the first BASIS meeting in 1982, water quality conditions in Hillsborough Bay were very degraded and the bay had been in this state for many decades. Few improvements had been seen by 1982, despite that three years earlier one major point source of nutrients to the bay—the City of Tampa's wastewater plant at Hookers Point—had converted its process from primary to state of the art advanced wastewater treatment. The cost of this conversion was close to $100 million.

Within a year after the Hookers Point conversion in 1979, total coliform counts in Hillsborough Bay were reduced dramatically. However, it was a surprise and of concern to some of those working with the bay that no apparent improvement of other important water quality parameters and biological indicators, such as dissolved oxygen and chlorophyll, had occurred several years after the conversion. Further, no reduction of the dominant late summer to early winter blue-green phytoplankton community had been noted. It was not until 1984 that chlorophyll concentrations were reduced substantially, coincidental with a large decrease in planktonic blue-green algae. Dissolved oxygen in bottom waters of central Hillsborough Bay during the summer also improved at this time. Another concurrent sign of the recovery of Hillsborough Bay and areas close to Hillsborough Bay was the limited return of seagrasses to the shallow tidal and subtidal bars at the perimeter of the bay (Avery, this volume; Johansson and Lewis, in press; Lewis et al., this volume).

It is now evident that substantial improvements of several water quality parameters and biological indicators have occurred in Hillsborough Bay and other subsections of Tampa Bay since the mid-1980s. Although it is impossible to definitely demonstrate the cause of the recovery, a general understanding of the Tampa Bay ecosystem, coupled with comparative information from other estuaries, strongly suggests that the documented improvements have resulted from a large reduction of nitrogen loading from external sources. Nitrogen loading has not only been reduced from domestic wastewater sources, but also from industrial sources—specifically from the large and economically important central Florida fertilizer industry.

This report addresses general background information on Hillsborough Bay water quality, compares long-term nitrogen loading trends to water quality indicators, and recommends management options for improving bay conditions. First, the study area and its water quality history during the last several decades are described. The condition of Hillsborough Bay in the late 1960s was reported by the Federal Water Pollution Control Administration (FWPCA 1969). This was the first, and is to date, the most comprehensive eutrophication management study conducted in Tampa Bay; results and recommendations from the study are referenced extensively in this report. Second, long-term trends of nitrogen loading to Hillsborough Bay are discussed and compared to long-term trends of water quality and phytoplankton parameters. Specifically, nitrogen loading from external sources and ambient chlorophyll concentrations measured by the FWPCA are compared to the current Hillsborough Bay loadings and chlorophyll concentrations. In addition to the FWPCA (1969) report, sources of information used are from the City of Tampa Bay Study Group (COT), the Hillsborough County Environmental Protection Commission (HCEPC), the U.S. Geological Survey (USGS), the Fish and Wildlife Service (FWS), the Tampa Port Authority (TPA), the Southwest Florida Water Management District (SWFWMD), the Tampa Bay Regional Planning Council (TBRPC), and the Florida Department of Environmental Regulation (FDER). Finally, the report addresses water quality management needs, specifically the need to develop tools to help protect and enhance the natural resources found in Tampa Bay. A simple eutrophication model which

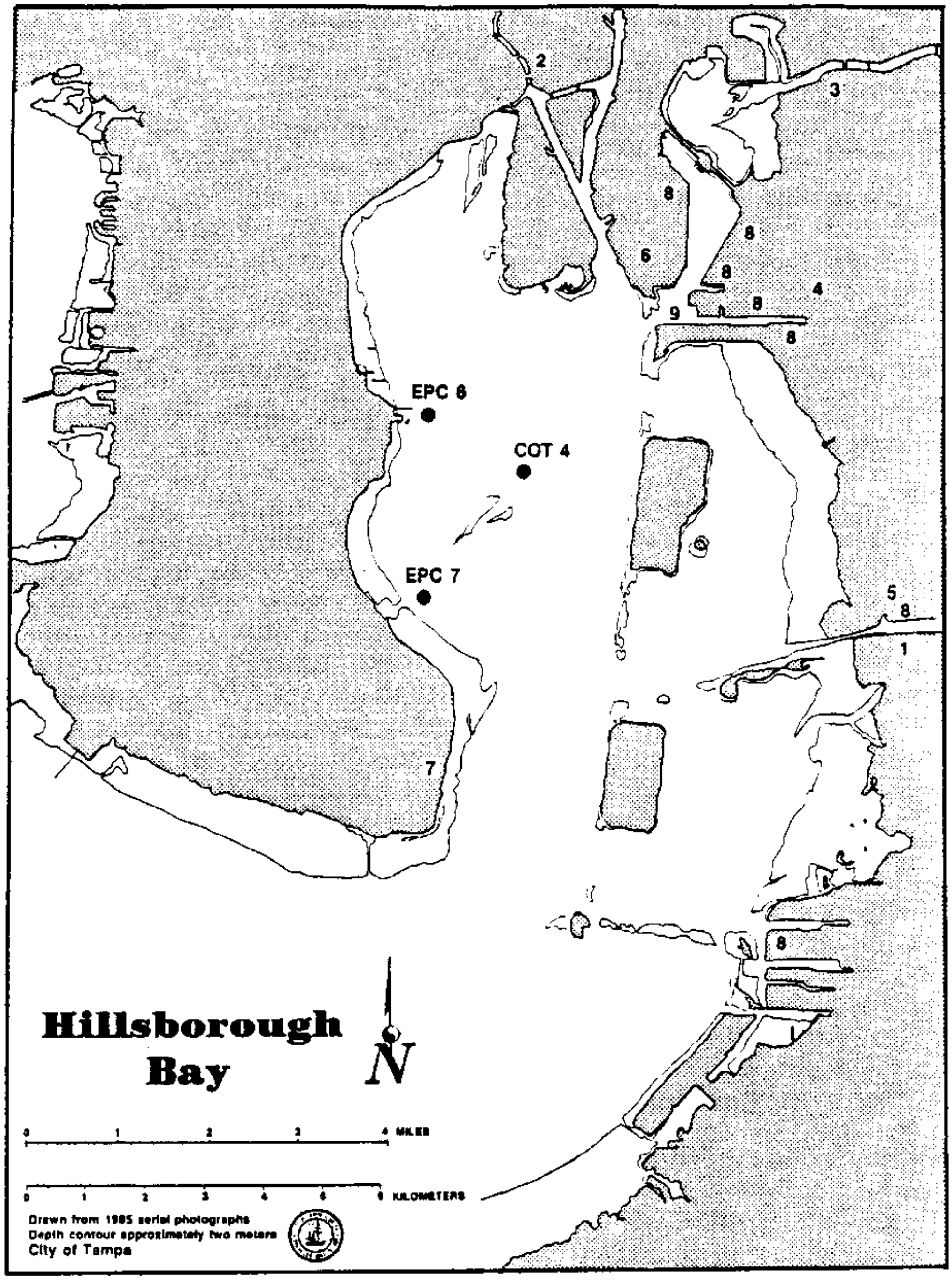

Figure 1. Hillsborough Bay, Florida.

1. Alafia River
2. Hillsborough River and downtown Tampa
3. Palm River/Tampa Bypass Canal
4. Nitram, Inc. and Delaney Creek
5. Cargill Fertilizer, Inc.
6. Hookers Point Wastewater Plant
7. MacDill AFB Wastewater Plant
8. Fertilizer shiploading terminals
9. Sutton Channel in East Bay

may link external nitrogen loading to valuable resources such as seagrasses and other benthic communities is discussed.

THE STUDY AREA

Tampa Bay is a shallow subtropical estuary located on the Gulf of Mexico coast of central Florida. It is one of the largest estuaries in the southeastern United States with an open water surface area of 1030 km^2 and with a watershed area of 5700 km^2. Population growth of the Tampa Bay region is one of the fastest in the United States. Approximately 1.7 million people now live within 80 km of the bay (TBRPC 1989). Hillsborough Bay is the eastern uppermost section of the Tampa Bay system with an open water area of 105 km2 (Figure 1). Although this is only 10% of the Tampa Bay surface area, three of Tampa Bay's five major rivers empty into Hillsborough Bay and the bay receives approximately 60% of the total surface freshwater flow to Tampa Bay (Goodwin 1987). Generally, Hillsborough Bay is the head of the Tampa Bay estuarine system, the area where freshwater and seawater mix, and it should not be surprising by this fact alone, that Hillsborough Bay historically had the "poorest" water quality of the Tampa Bay subsections. However, human impacts in the drainage basin have certainly been the major cause of eutrophication and degraded water quality.

The City of Tampa, which borders Hillsborough Bay to the north and the west, discharges stormwater to Hillsborough River and to the bay directly. Tampa also operates the largest domestic wastewater treatment plant in the area and currently discharges approximately 60 MGD of highly treated wastewater into the upper portion of the bay. Agricultural lands, extensive phosphate mines and many large fertilizer processing plants are located within the drainage area of the Alafia River to the east. In addition, several fertilizer facilities, such as processing plants, storage facilities and shiploading terminals are located near the eastern shores of the bay. The bay serves as a major shipping port of fertilizer products. In 1988 some 20 million short tons of fertilizer material were shipped from Hillsborough Bay (TPA, unpublished), which comprises approximately 80% of the United States production of phosphatic fertilizer and 50% of the production of nitrogen-containing fertilizer (Bureau of the Census 1988).

PAST WATER QUALITY CONDITIONS

Almost 40 years ago, Tampa Bay was described as grossly polluted due to discharges of poorly treated domestic wastewater and industrial waste from phosphate mines, citrus canneries and other industrial sources (Galtsoff 1954). However, water quality problems specific to Hillsborough Bay may have been present as early as 1928 when occasional noxious odors along the western shore of Hillsborough Bay were noted (FWPCA 1969). The odor was associated with abundant growth of macroalgae and poor water quality caused by discharges of untreated domestic and industrial waste. Odors continued sporadically until the City of Tampa completed the Hookers Point primary wastewater treatment plant in 1951. With the start-up of the primary plant the odors apparently subsided temporarily. However, odors from large amounts of macroalgae decomposing on beaches and next to seawalls became severe during the early 1960s; as a result, citizens living close to Hillsborough Bay complained to the authorities about the noxious odors. Also during this period, the water in the bay was not suitable for body contact due to high bacteria content. Signs were posted at several popular beaches to warn swimmers of the contaminated water.

The Federal Water Pollution Control Administration Study

In 1965, the City of Tampa and the Florida State Board of Health requested technical assistance from the FWPCA to help identify the causes of the poor water quality and the noxious odors in Hillsborough Bay and to recommend solutions to the problems. FWPCA conducted an extensive study of Hillsborough Bay water quality problems in 1967 and 1968 (FWPCA 1969). The FWPCA study confirmed the earlier observations of highly deteriorated conditions in Hillsborough Bay. Indicators of the poor water quality included high turbidity, high fecal coliform counts, anoxic bottom waters and large amounts of drift macroalgae in the shallows.

The study identified point source discharges with high nutrient and organic content as the underlying cause of the odor and degenerated water quality in Hillsborough Bay. Specific sources identified were the Alafia River and the fertilizer industry in its basin, the City of Tampa's wastewater plant at Hookers Point, the U.S. Phosphoric Products Company (now Cargill Fertilizer, Inc.) and the Nitram Chemical Company (now Nitram, Inc.). After an extensive monitoring program of these sources, it was estimated that the Alafia River and the chemical companies supplied 63% of the total nitrogen and 94% of the total phosphorus entering the bay. The Hookers Point facility discharged 32% of the total nitrogen and less than 5% of total phosphorus. However, this facility was the major contributor of organic material to the bay, supplying more than 85% of all carbonaceous material from point sources. Further, the study established that nitrogen was the growth-limiting nutrient in Hillsborough Bay and that any reduction in available nitrogen could be expected to produce a corresponding reduction in plant growth. Table 1 lists total nitrogen loadings from all sources identified and measured by FWPCA (1969) and one additional source, losses from shiploading terminals, which are discussed below.

Table 1. Total nitrogen loadings from major external sources to Hillsborough Bay during two time periods, 1967-68 and 1987-90.

SOURCES	TN (METRIC TONS/YR) 1967-68	1987-90	PERCENT CHANGE
Alafia River + fertilizer industry	1170	430	-63
Hillsborough River	160	280	75
MacDill AFB Wastewater Plant	20	0	-100
Nitram, Inc. + Delaney Creek	870	60	-93
Palm River/Tampa Bypass Canal	50	390	680
Hookers Point Wastewater Plant	1210	240	-80
Cargill Fertilizer, Inc.	350	20	-94
Fertilizer shiploading terminals	140	770	450
TOTAL	3970	2190	-45

The study recommended several short-term measures to improve conditions in Hillsborough Bay. In addition, an extensive long-term water quality management plan was outlined to restore and protect the bay. This plan recommended a 90% reduction of nitrogen loading to the bay from the sources studied to reduce phytoplankton and macroalgae growth. Further, to improve the dissolved oxygen conditions in the bay, it was recommended that the Hookers Point facility remove 90% or more of the carbonaceous material discharged. The study concluded that the degraded conditions in Hillsborough Bay developed over many years and, likewise, efforts to restore the bay would take time. However, it was also suggested that the implementation of the management plan, combined with the natural self-purification process of the estuary, may eventually restore Hillsborough Bay to a healthy aquatic environment.

City of Tampa Wastewater Discharges

The FWPCA (1969) management plan recommended that the City of Tampa upgrade its Hookers Point wastewater treatment plant from primary to secondary treatment, to greatly reduce the discharges of nitrogen and organic material to Hillsborough Bay. The City of Tampa initiated plans to construct an upgraded facility in 1970. The decision to upgrade was based on the recommendations of the FWPCA report and by public outcry in response to the poor conditions in Hillsborough Bay (Tampa Tribune 1969). However, in 1972, before plans for the secondary upgrade had been completed, the Florida legislature passed a law which required all domestic wastewater dischargers to tidal waters of west central Florida to provide advanced wastewater treatment (AWT). AWT was defined as 5 mg/l BOD_5, 5 mg/l total suspended solids, 3 mg/l total nitrogen and 1 mg/l total phosphorus. Directed by this law, the City of Tampa upgraded the Hookers Point facility from primary to AWT with a 60 MGD capacity. Nitrogen removal has been maintained at AWT levels since 1979. The AWT phosphorus requirement has been waived by the state because of evidence indicating that nitrogen is the limiting nutrient for algal growth in Hillsborough Bay and other sections of Tampa Bay (FWPCA 1969, COT 1983, FDER 1983).

Loadings of total nitrogen and carbonaceous material to Hillsborough Bay from the Hookers Point facility were reduced substantially when the plant converted from primary to advanced treatment. Current nitrogen loadings have been reduced by 80% compared to the loadings measured by the FWPCA study (Table 1), despite the fact that the discharge flow from the plant has nearly doubled since 1967-68.

Fertilizer Industry and Alafia River Impacts

The second major source of nutrients identified by the FWPCA (1969) management plan was the Alafia River and the fertilizer industry. The report specifically referenced three sources—Nitram, Cargill, and the Alafia River and the fertilizer companies located in its upper basin.

During the late 1800s, rich phosphate deposits were discovered east of Hillsborough Bay and in 1908 the first large vessels were used for transport of phosphate rock from the Tampa Bay area (Tiffany and Wilkinson 1989). Prior to the 1960s, fertilizer production and export consisted mostly of phosphate rock. Later, the production and export of processed fertilizer containing nitrogen became increasingly important. In 1990, approximately 10 million short tons of ammonium-phosphate product were exported from the Port of Tampa in Hillsborough Bay (TPA, unpublished). This large nitrogen processing industry in Tampa Bay is unique among estuaries.

The FWPCA (1969) study estimated that 63% of the point and nonpoint nitrogen sources entering the bay was derived from the combined contribution of Nitram, Cargill, and the Alafia River and the fertilizer companies located in its upper basin. Current nitrogen loading from the two large nitrogen processing industries, Nitram and Cargill, has been reduced by more than 90% since 1967-68 (Table 1), apparently through improved regulation of the industry and better production practices (Estevez and Upchurch 1985). Similarly, nitrogen loadings from the Alafia River have also been reduced, but to a smaller extent. However, it is unclear what fraction of the Alafia River loadings are contributed by the fertilizer industry. Other sources, such as runoff from agricultural lands and urban areas, must also be important nitrogen sources to the river. The Alafia River, which supplied slightly less nitrogen to Hillsborough Bay than the Hookers Point facility in 1967-68, is now the largest of the nitrogen sources originally identified and measured by FWPCA (1969).

In addition, the Hillsborough River and the Palm River/Tampa Bypass Canal (TBC) system show loading increases between 1967-68 and 1987-90 (Table 1), which may be a result of increased development in the basins. However, a major portion of the increase shown for the TBC system was caused by an unusually large discharge in

September 1988 following a large rain event. Excluding this event would result in an average nitrogen loading from this system of approximately 160 metric tons/year.

Although nitrogen loading from the fertilizer industry sources identified and measured by FWPCA (1969) has been reduced, it should be recognized that the study did not account for nonpoint losses of nitrogen-containing fertilizer from storage facilities and shiploading terminals located near or next to Hillsborough Bay. This loss is mainly in the form of surface runoff and dust. There are no quantitative measurements of these losses. The potential loading to the bay has been estimated from the amount of ammonium-phosphate product shipped from the Port of Tampa (TPA, unpublished). Abu-Hilal (1985) lists estimates of fertilizer product losses, ranging from 0.05% to 1%, from transportation and shiploading at the Port of Aquaba in the Gulf of Jordan. The most conservative estimate, 0.05% loss, has been used in this report to calculate nitrogen losses from the Hillsborough Bay storage facilities and shiploading terminals.

Port of Tampa shipping statistics suggest that nitrogen lost from storage facilities and shiploading terminals was a minor component of nitrogen loading to Hillsborough Bay during the period of the FWPCA study (Table 1). However, based on the amounts currently shipped, the loss of material may now be one of the largest sources of external nitrogen to Hillsborough Bay. In addition, water column measurements of dissolved ammonia in the port area of Hillsborough Bay (Figure 2) often show high concentrations of nitrogen near these facilities in comparison to central Hillsborough Bay locations (COT, unpublished). The concentration peaks in the port area generally occur during, or immediately following, rain events. These field measurements suggest that losses from the loading facilities may be a relatively large nitrogen source to Hillsborough Bay. Furthermore, future loadings from these facilities may become increasingly important, because the amount of nitrogen containing fertilizer shipped from the Port of Tampa is increasing rapidly (TPA, unpublished; Figure 3).

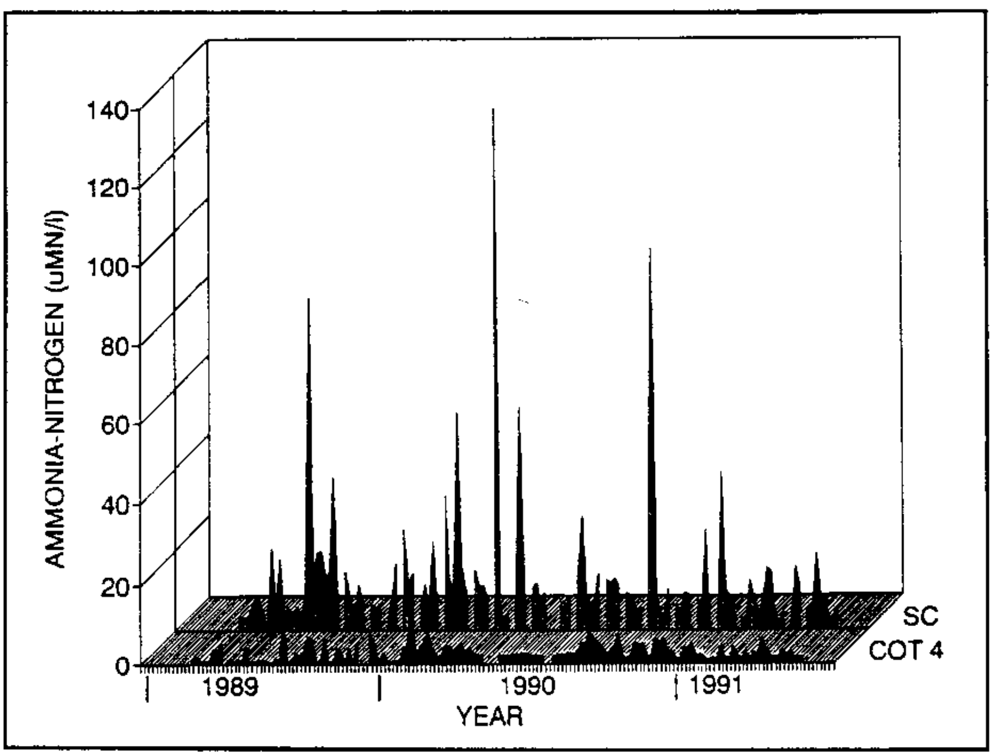

Figure 2. Surface ammonia-nitrogen concentrations in Sutton Channel (SC) and central Hillsborough Bay (COT 4), 1989-1991.

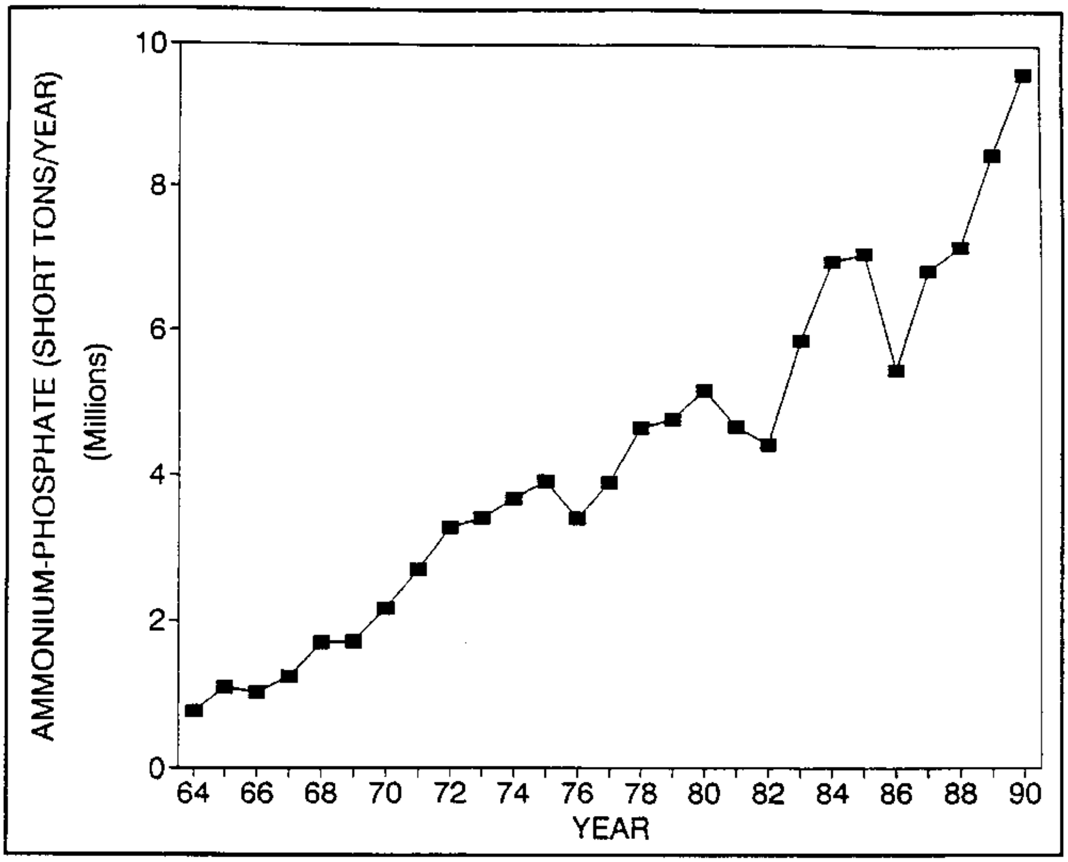

Figure 3. Outbound ammonium-phosphate fertilizer from the Port of Tampa, Hillsborough Bay, 1964-1990.

LONG-TERM TREND OF EXTERNAL NITROGEN LOADING

The comparison of total nitrogen loading measured by FWPCA (1969) for the period 1967-68 and current loadings for the period 1987-90 indicate that there has been a 64% reduction in loading from the sources identified in the FWPCA study. If the estimated losses from the shiploading terminals are included in this comparison, then the reduction is decreased to 45%. The comparison clearly establishes that there has been a substantial reduction of nitrogen loading from these external sources to Hillsborough Bay during the last two decades. However, the nitrogen loading record must be examined in greater detail to determine, as accurately as possible, when the large changes occurred. This detail is needed to establish a meaningful relationship between loading and bay conditions. Annual nitrogen loading rates have been calculated for the largest sources identified in the FWPCA report (the Alafia River, the fertilizer industry and Hookers Point) and the estimated loading from shiploading terminals (Figure 4). Of course, these are not the only external sources of nitrogen to Hillsborough Bay. Atmospheric loadings, most stormwater loadings, and loadings from groundwater, septic waste and several tributaries have not been included in the calculations. However, the included sources may be the most important ones and also the sources that have shown the greatest change over the period of study. Kelly and Harwell (1990) suggest that it may be more relevant to determine the response of a system from a relative change over time than from an absolute understanding of the system.

Information describing the sources used for loading calculations and the procedures used to deal with missing data are detailed in the Appendix. It should be emphasized that loadings for the fertilizer industry are very approximate for the period 1969-80. Figure 4 indicates that nitrogen loading remained relatively high and stable until 1979, when a substantial reduction began. Both the upgrade of Hookers Point and changes in fertilizer industry practices apparently caused the large nitrogen reduction. Loadings have remained relatively low since 1981.

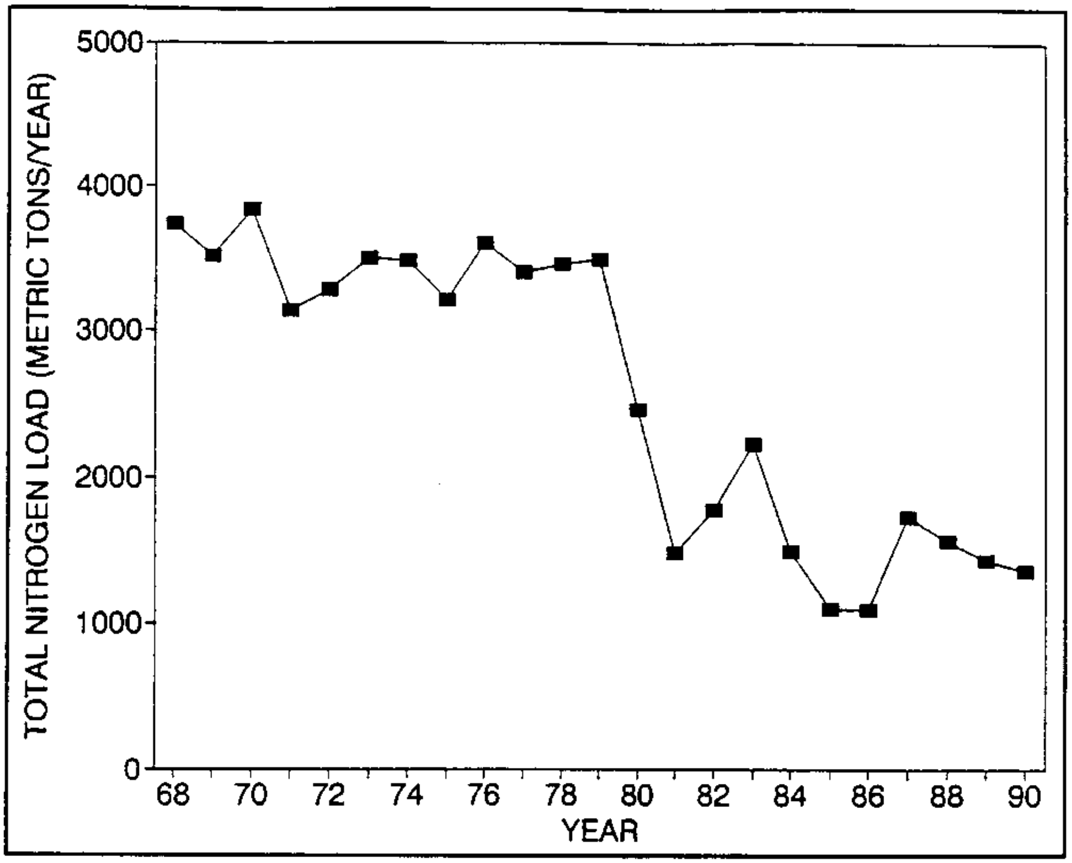

Figure 4. Total nitrogen loading to Hillsborough Bay from major external sources, 1968-1990.

Phytoplankton Biomass and Blue-Green Algae Abundance

With the recent reduction of nitrogen loading to Hillsborough Bay, reductions in phytoplankton biomass and changes in phytoplankton composition could be expected. Several reports discussing nitrogen loading to Tampa Bay have suggested that a direct relationship exists between nitrogen availability and growth of phytoplankton and macroalgae (FWPCA 1969; Spaulding et al. 1989; Johansson and Lewis, in press). Further, this relationship has been demonstrated, particularly for phytoplankton, in many estuaries world wide (Boynton et al. 1982). Chlorophyll *a* concentration is an estimate of phytoplankton biomass, but it is also an important indicator of estuarine eutrophication and has been linked to seagrass survival (Cambridge et al. 1986, Pearce 1991). The long-term Tampa Bay record shows a substantial chlorophyll reduction, particularly in Hillsborough Bay, since the mid-1980s (Figure 5). Sources of the long-term chlorophyll record are identified in the Appendix. Hillsborough Bay annual average concentrations have decreased from approximately 30 µg/l during the period prior to 1984 to the current level of less than 15 µg/l. The chlorophyll decrease is similar to the reductions in nitrogen loading discussed above. Although the large loading reduction occurred just prior to 1980, ambient chlorophyll concentrations did not decrease substantially before 1984. Three years may have been necessary for the bay's internal processes to equilibrate to the new level of nitrogen loading after several decades of excessive loadings from Hookers Point and the fertilizer industry. However, with smaller reductions of nitrogen loading anticipated from future management actions, the time lag may be shorter. Recent information has shown that several estuaries retain nitrogen poorly and may export most of the nitrogen they receive (Nixon 1987; Nowicki and Oviatt 1990; Boynton et al., in press).

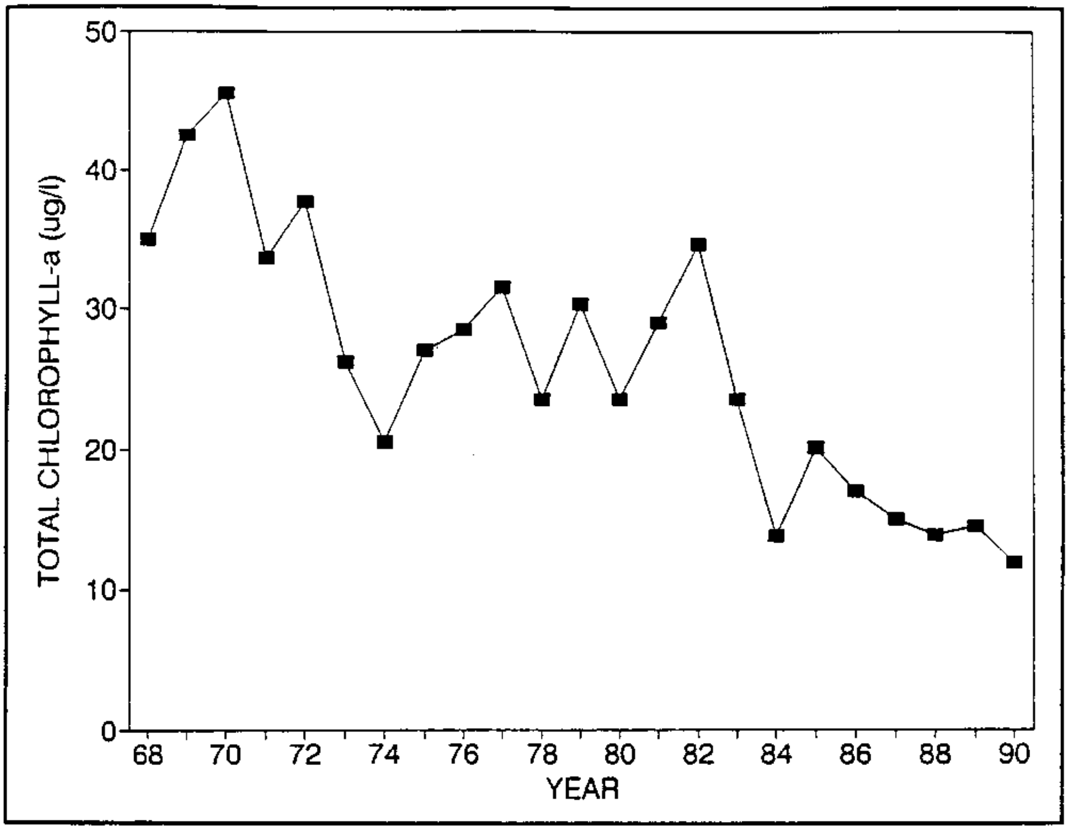

Figure 5. Total chlorophyll a concentrations in Hillsborough Bay, 1968-1990.

The substantial decrease of chlorophyll in Hillsborough Bay correlates with a large reduction of a planktonic filamentous blue-green alga (*Schizothrix calcicola sensu* Drouet), which prior to 1984 dominated the phytoplankton population from late summer to early winter (Johansson et al. 1985; COT, unpublished; Figure 6). This alga has been present in much reduced concentrations since 1984. There is no information to support that this blue-green alga is able to fix atmospheric nitrogen. Nutrient bioassay experiments with natural phytoplankton communities dominated by *S. calcicola*, from both Hillsborough Bay and Old Tampa Bay, clearly demonstrated the community to be strongly nitrogen limited (COT 1983). Therefore, growth of this blue-green alga is apparently limited by available water column nitrogen, and it is not surprising that its biomass has been reduced as nitrogen loadings have decreased. Many blue-green algae are considered nuisance species and are often indicators of poor water quality (Pearl 1987). The reduction of blue-green algae biomass agrees with other indicators suggesting decreased eutrophication in Hillsborough Bay.

Further, the decrease in blue-green algae biomass during late summer to early winter may be a key factor of the recent recovery of Hillsborough Bay. For example, the blue-green reduction should have caused less organic matter (blue-green algae filaments) to settle to the bottom, and sediment oxygen demand should have been lowered (see below). Similarly, there should have been less water column respiration. These changes should have improved water column and bottom oxygen conditions

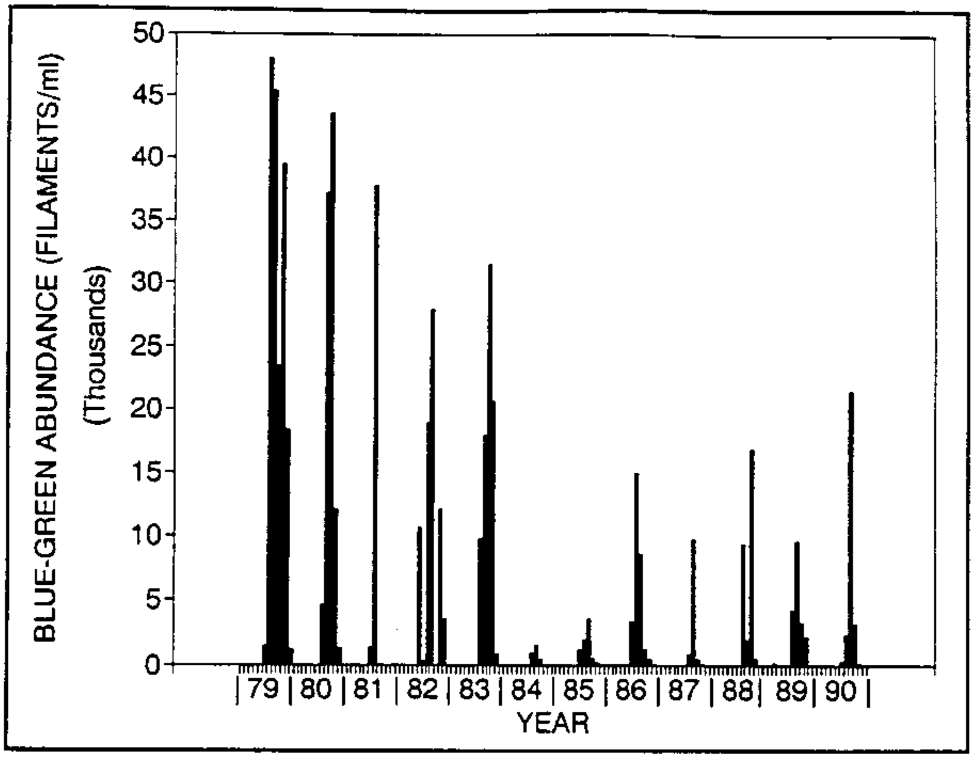

Figure 6. Monthly concentrations of a filamentous blue-green alga (Schizothrix calcicola sensu Drouet) in surface waters of central Hillsborough Bay (COT 4), 1979-1990.

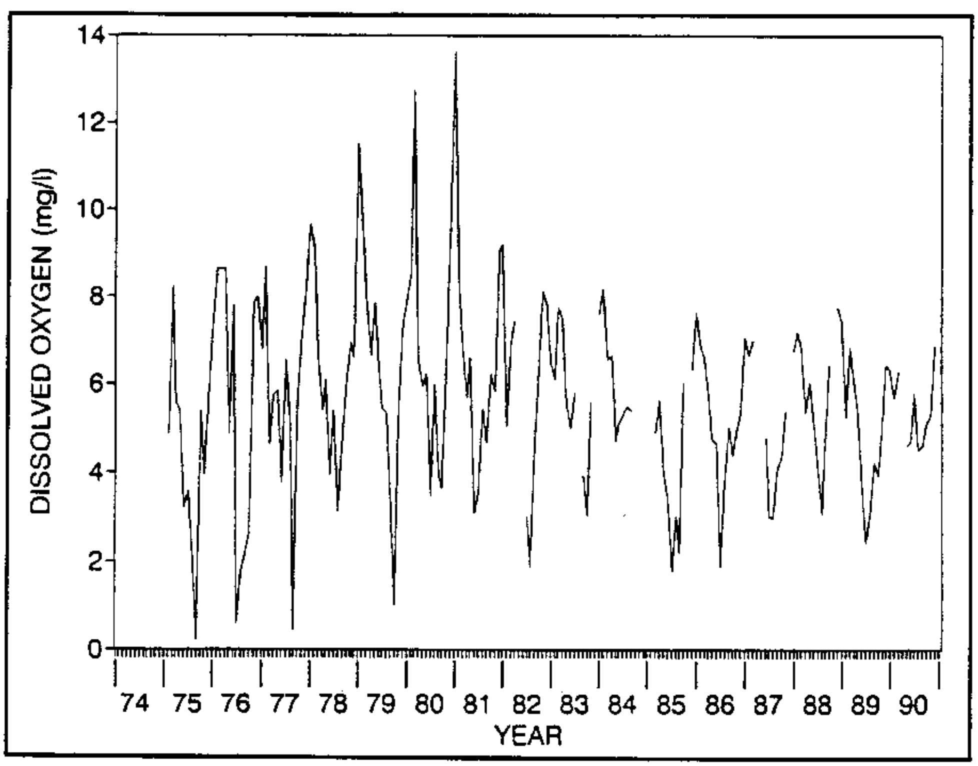

Figure 7. Monthly averages of near-bottom dissolved oxygen concentrations in Hillsborough Bay (EPC 6 and 7), 1974-1990.

during the critical summer period. Evidence that these changes have occurred concurrent with the reduction in blue-green algae abundance is apparent in the long-term near-bottom oxygen record for two stations located in the muddy section of Hillsborough Bay (HCEPC, unpublished; Figure 7). The annual amplitude of the near-bottom dissolved oxygen curve has narrowed considerably compared to the period of high blue-green algae abundance. In addition, hypoxia events have also become less frequent.

Phytoplankton biomass is an important factor limiting water column light penetration in phytoplankton-dominated estuaries such as Hillsborough Bay. Further, the dense concentrations of blue-green algae found in the bay prior to 1984 may have additionally suppressed light penetration. Kirk (1977) found that blue-green algae reduce light to a greater degree than other phytoplankton types. These findings may lend support to the improved Secchi depth readings in Hillsborough Bay after the blue-green algae biomass was reduced (Boler 1990; HCEPC, unpublished; Figure 8). Sufficient water column light penetration is essential for the survival of submerged seagrasses.

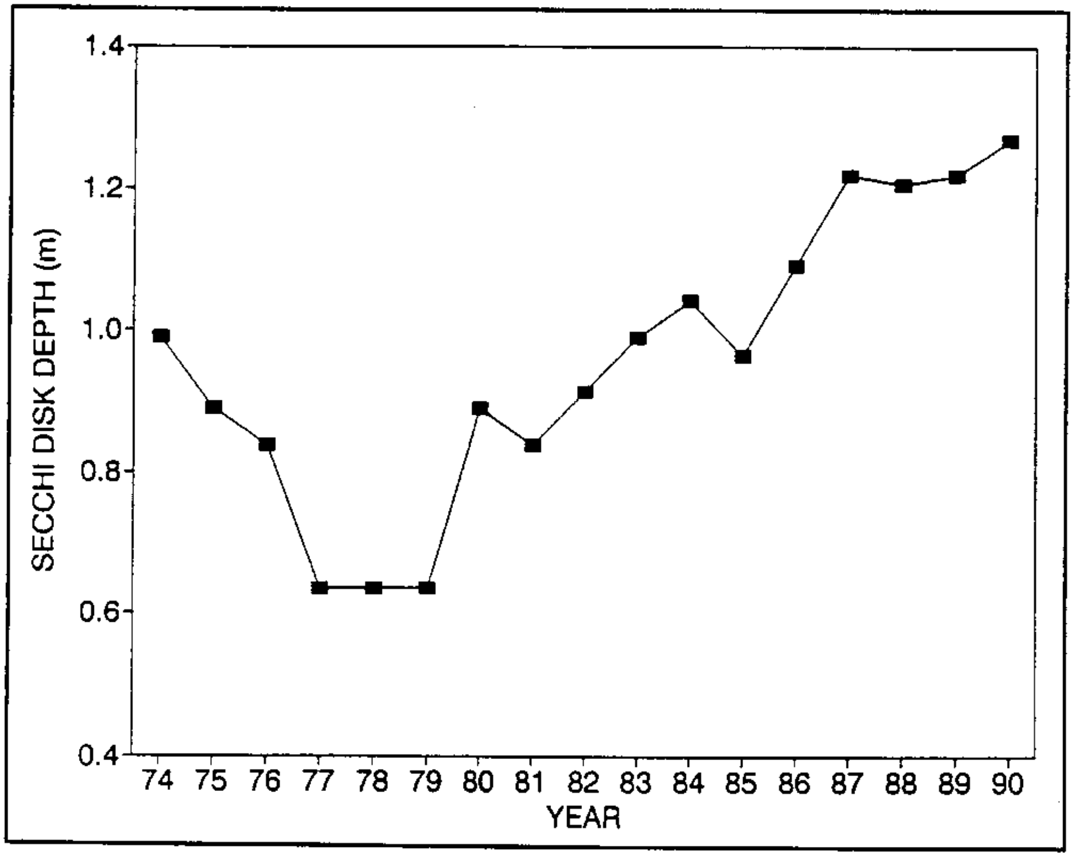

Figure 8. Secchi disk depth in Hillsborough Bay, 1974-1990.

Seagrass Recovery

Hillsborough Bay, and Tampa Bay as a whole, have had serious losses of seagrass. Historic records show that the areal coverage of Tampa Bay seagrasses has decreased dramatically during the last 100 years. In 1982, approximately 20% of the originally estimated seagrass coverage still remained (Lewis et al. 1985). Most seagrasses in Hillsborough Bay were lost between 1950 and 1980. However, modest seagrass recolonization was observed in Hillsborough Bay and other sections of Tampa Bay in 1984 and 1985 following the decrease in chlorophyll concentrations. Seagrass cover continues to increase in these areas. More detailed discussions of this issue are given by Avery (this volume), Johansson and Lewis (in press), and Lewis et al. (this volume).

Rainfall and Chlorophyll Concentration

Nutrient loading from runoff caused by rainfall has been suggested as an important driving force influencing Hillsborough Bay water quality (Lewis and Estevez 1988; Lewis et al., this volume). It is suggested that lower than average rainfall in the Tampa Bay area during the last three to five years may be responsible for the improvements in water quality and the recolonization of seagrasses in Hillsborough Bay and other areas of Tampa Bay. It is often difficult to separate ecosystem responses caused by natural variability from responses caused by management actions (National Research Council 1990). However, a general evaluation of the importance of rainfall on long-term water quality conditions in Hillsborough Bay is attempted here. Figure 9 shows the 1975-90 annual rainfall record at Tampa International Airport (TIA) (NOAA 1991), and at 27 locations in the Hillsborough and Alafia River basins that are monitored by SWFWMD (SWFWMD, unpublished). During the period 1975-90, annual rainfall at TIA has been consistently lower than the average rainfall over the basins. The result of this comparison suggests that many rainfall measuring sites must be used to estimate rainfall affecting Hillsborough Bay. Average rainfall during the recent period of low chlorophyll levels (1984-90) was approximately 6% lower than the long-term record (1975-90). It is unlikely that this small reduction in rainfall could have exclusively caused the substantial reduction in chlorophyll.

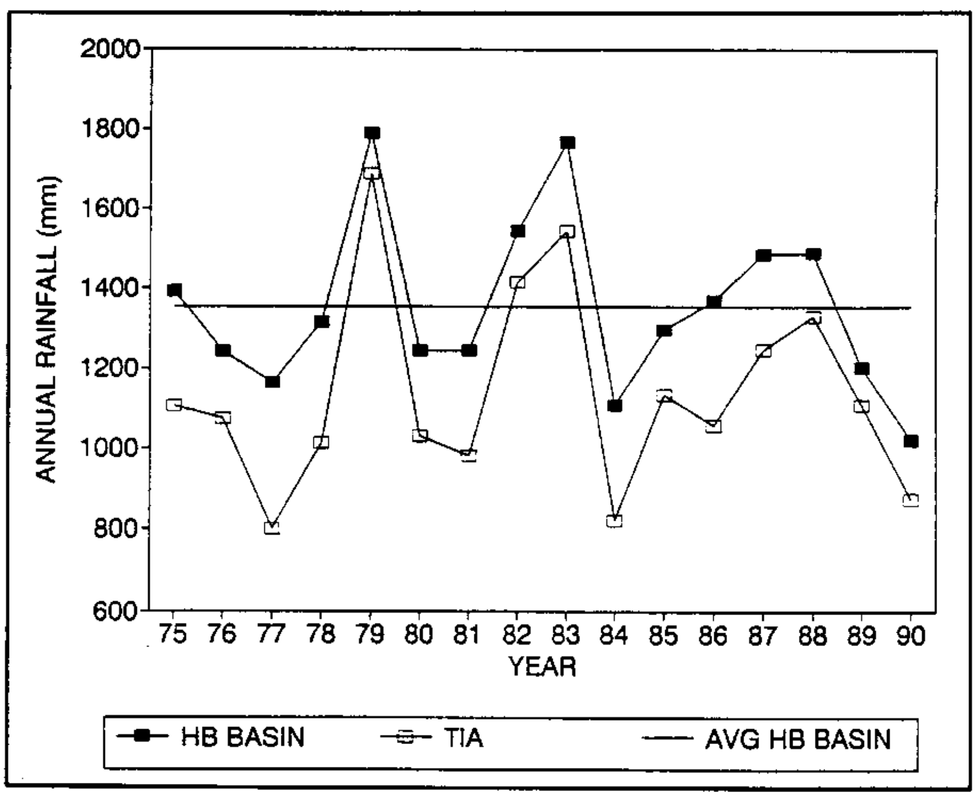

Figure 9. Annual rainfall at Tampa International Airport and at 27 rainfall measuring sites in the Hillsborough Bay basin, 1975-1990.

The relationship between rainfall over the Hillsborough Bay drainage area and ambient chlorophyll concentrations for the period 1975-90 is plotted in Figure 10. The lack of a relationship is encouraging because it implies that management actions taken during the last decade or two, aimed to decrease point-source nitrogen loading to the bay, have apparently been effective in reducing eutrophication.

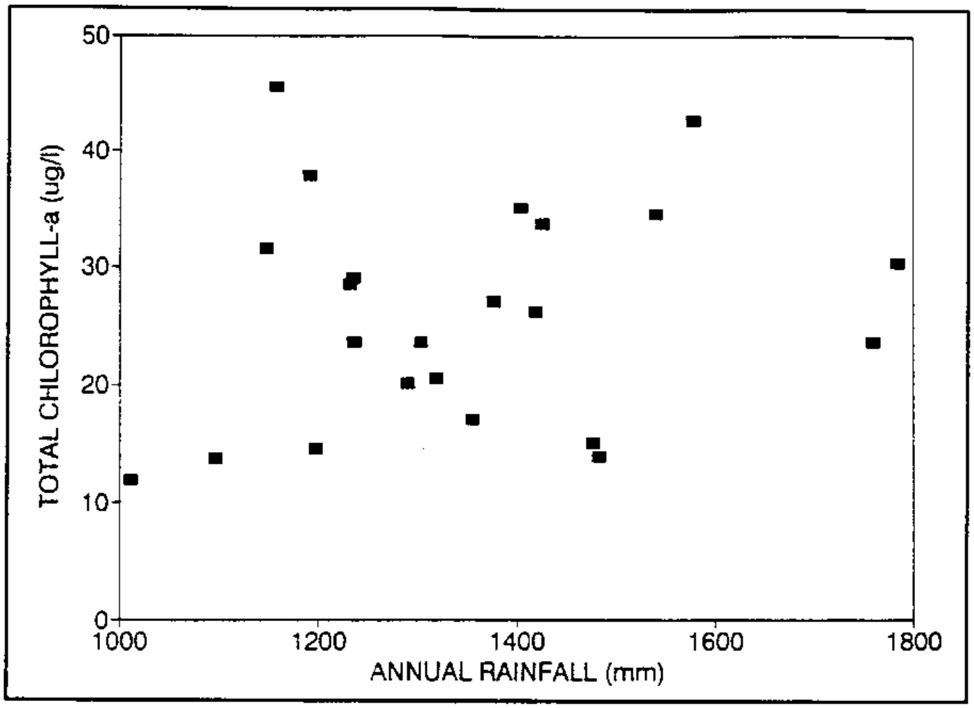

Figure 10. Relationship between annual rainfall over the Hillsborough Bay basin and Hillsborough Bay total chlorophyll a concentrations, 1968-1990.

NITROGEN LOADING AND CHLOROPHYLL CONCENTRATION

The long-term trend of nitrogen loading to Hillsborough Bay from the largest sources identified by the FWPCA in 1969 (the Alafia River, the fertilizer industry, and Hookers Point) and the estimated loading from the shiploading terminals have been plotted against the long-term Hillsborough Bay chlorophyll record (Figure 11). The linear relationship shown is statistically significant ($P>0.01$), but the regression coefficient ($R^2=0.49$) is weak. It is interesting to note that if a three-year time lag (see above) is assumed between nitrogen loading and the response in chlorophyll, then a much stronger regression coefficient is found ($R^2=0.76$) (Figure 12). In either case, the relationship suggests that over the period analyzed, each 150 metric tons/year reduction in nitrogen loading from major external sources has corresponded to a 1 μg/l reduction of ambient chlorophyll. This relationship describes a simple eutrophication model. With additional work to refine the relationship, it could be used by Tampa Bay managers to evaluate eutrophication abatement strategies.

The model must be used with care for predictions of future Tampa Bay chlorophyll concentrations, pending a better understanding of the chlorophyll/nitrogen loading relationship. It can not be assumed that the long-term relationship will remain linear as future nitrogen loading reductions are implemented. Several natural estuarine eutrophication control processes may become increasingly important with additional nitrogen reductions. FWPCA (1969) referred to these controls as processes of self-purification and suggested that these, combined with management actions, may eventually restore Hillsborough Bay to a healthy aquatic environment. Consequently, predictions of future chlorophyll concentrations from

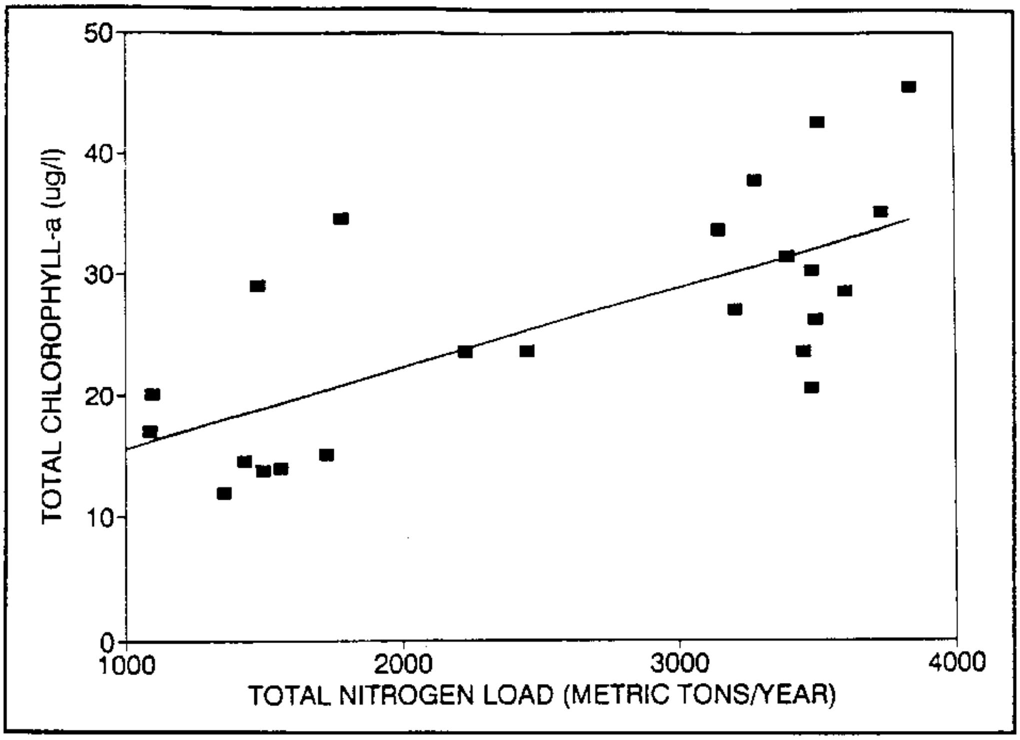

Figure 11. Relationship between total nitrogen loading to Hillsborough Bay from major external sources and Hillsborough Bay total chlorophyll a concentrations, 1968-1990.

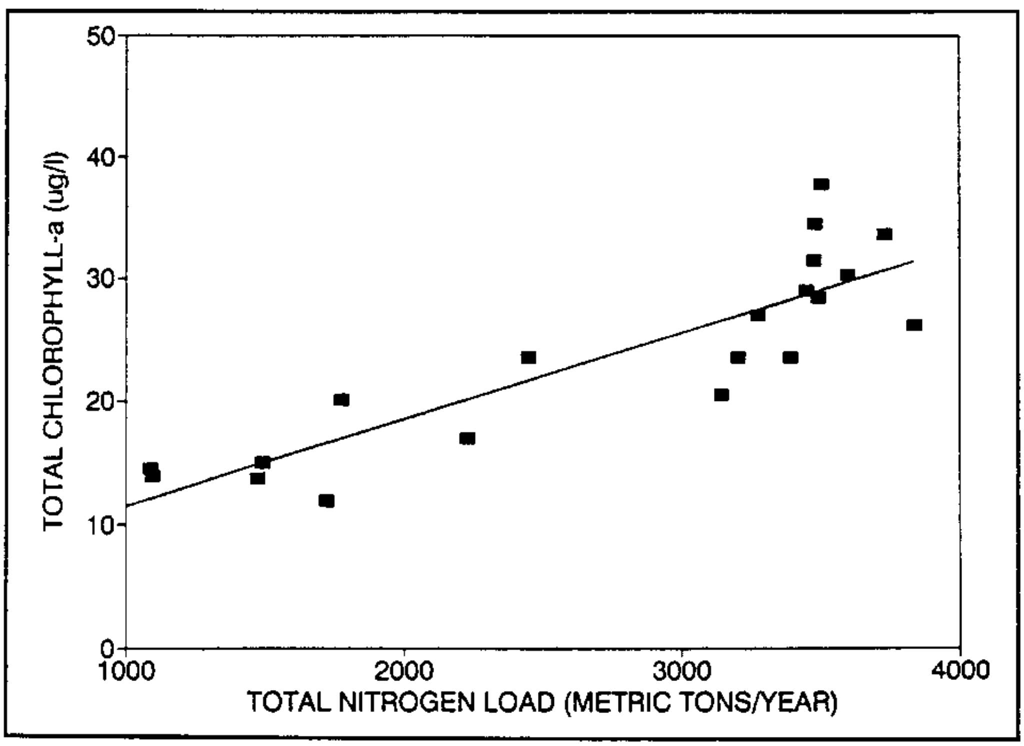

Figure 12. Relationship between total nitrogen loading to Hillsborough Bay from major external sources (1968-1987) and Hillsborough Bay total chlorophyll a concentrations (1971-1990). A three-year time lag has been applied to the chlorophyll concentrations in relation to the nitrogen loadings.

the long-term relationship without accounting for the natural eutrophication control processes may result in overestimated chlorophyll levels. Therefore, it is important to identify and evaluate the natural processes which could have large impacts on the development and the ultimate results of eutrophication management strategies. Three of these processes are addressed below. These may be some of the most important ones; however, there may be other important processes not addressed here.

First, hypoxia of bottom waters during the summer, specifically in Hillsborough Bay, which has the largest area of muddy bottom of the Tampa Bay system (Johansson and Squires 1987; USGS, unpublished), has been an annual phenomenon (Santos and Simon 1980a and 1980b). Although large areas in the deeper sections of the bay still experience hypoxia, it is now evident that both the area covered by and the duration of poor summer oxygen conditions have been reduced (see above and Figure 7). The improvement may be related to the substantial reduction of blue-green algae which occurred in 1984 (see above and Figure 6).

With the recent increase of oxic conditions in time and space it can be assumed that denitrification in the surface sediments has become increasingly important (Kemp et al. 1990; Koop et al. 1990). The loss of nitrogen by denitrification is an important natural eutrophication control process in estuaries, and may account for as much as half of the terrestrial input (Seitzinger 1988). Denitrification losses must therefore be included in Tampa Bay eutrophication strategies to accurately project results of management actions and to avoid costly overprotection. Field measurements and/or extensive comparisons with other estuaries should be conducted to estimate current and future denitrification rates.

Second, the potential of benthic filter feeding communities to reduce phytoplankton biomass and chlorophyll concentrations may increase from present levels as bottom oxygen conditions improve and areas of suitable habitat increase in Tampa Bay. Benthic macroinvertebrate filter feeding has been shown to act as a natural eutrophication control in many shallow estuaries (Officer et al. 1982, Hily 1991). Extremely clear water and low chlorophyll concentrations have been noted concurrent with dense concentrations of a solitary tunicate that has occasionally been present during the winter since 1987 in shallow areas of Hillsborough Bay (Pinson 1991). Also, survival of the benthic filter feeding amphipod *Ampelisca* appears to have improved recently with better bottom oxygen conditions (COT, unpublished). Santos and Simon (1980a and 1980b) attributed large scale die-offs of *Ampelisca* and other benthic animals to annual recurring hypoxia events of bottom waters in Hillsborough Bay during the late 1970s. A comprehensive benthic inventory study and a long-term monitoring program should be initiated. Further, the benthic habitats found in the large muddy areas in Hillsborough Bay should receive protection from damage caused by activities such as shrimp trawling and bait purse-seining. Protection of these habitats would also reduce sediment resuspension (USGS, unpublished).

Third, seagrasses may become important storage of nutrients, and as such, act as natural eutrophication control processes. It has been shown in Chesapeake Bay that seagrasses assimilate nitrogen primarily during spring and summer, and thus effectively reduce the amount of nitrogen available to the phytoplankton during the most active phytoplankton growing period (Kemp et al. 1984). Seagrass mortality and nitrogen release usually occurs during late fall and early winter when the nitrogen demand by the phytoplankton is relatively small. Kemp et al. (1983) estimated that the submerged vascular plant community that existed in Chesapeake Bay in 1960, before large vegetation losses occurred, could have acted as a seasonal sink for 7% of the nitrogen input from external sources. Therefore, the restoration of Tampa Bay seagrass meadows may not only increase physical habitat, particle trapping and food resources, but may also accelerate the recovery from eutrophication.

It is important to estimate and include the natural control processes in predictions of future chlorophyll concentrations. Consequently, before these processes are better understood, use of the nitrogen loading/chlorophyll model is limited to conservative estimates of future chlorophyll concentrations in Hillsborough Bay. With these shortcomings in mind, two examples are given below to illustrate the potential use of the model as a management tool.

First, the loss of nitrogen from the fertilizer loading terminals in Hillsborough Bay has been estimated at approximately 770 metric tons/yr (see above). If this estimate is accurate and the loss was eliminated, then the ambient chlorophyll concentrations in Hillsborough Bay should be reduced from the current 15 μg/l to a conservatively estimated concentration of near 10 μg/l. Actions are now underway to reduce this source and a study is planned to evaluate its current impact on water quality.

Second, if current external loadings to Hillsborough Bay from the sources discussed in Figure 4 were reduced by more than 1000 metric tons/year, a level of 5 μg/l or less of chlorophyll would be reached. This chlorophyll concentration has been suggested as the required level for Tampa Bay seagrass survival and propagation by TBRPC (1989). Improved handling of fertilizer at the shiploading terminals will probably account for a significant fraction of the needed reductions. However, the 1000 metric tons/yr reduction may be a difficult goal to reach in the near-term. The large external nitrogen sources to Hillsborough Bay that were identified several decades ago have already been reduced substantially. Several remaining potentially large sources, all inadequately evaluated, include losses from shiploading terminals, stormwater runoff from urban and agricultural lands, and loadings from the atmosphere, groundwater and septic waste. Assuming that the shiploading terminal losses will be corrected, then it may become difficult to implement additional large scale nitrogen reductions. However, it is encouraging that the projection above does not include the potential increase in future nitrogen losses from natural eutrophication control processes and may, as a result, be overly pessimistic.

These examples have illustrated the potential of the nitrogen loading/chlorophyll model to predict future Tampa Bay conditions and responses to management actions. Additional work to refine the relationship include improved loading estimates and increased knowledge of natural control processes. Further, the relationship needs to be linked to important natural resources, such as seagrasses and soft bottom communities, to help protect these and other valuable resources. A model based on the nitrogen loading/chlorophyll relationship is currently used in an Australian coastal embayment to manage and protect seagrasses (Pearce 1991). In Chesapeake Bay, a similar model is proposed to maintain adequate bottom oxygen conditions and protect benthic communities (Boynton et al., in press).

CONCLUSION

Several important water quality and biological indicators have recently improved in Hillsborough Bay in an apparent response to a substantial reduction in nitrogen loading to the bay from many important external sources. The reduction may have been as large as 50% and is related to actions aimed at reducing nutrient loadings to Tampa Bay, specifically from wastewater plants and the fertilizer industry. There is little evidence that the recent lower than average rainfall has been a significant factor of the improvement. Seagrasses have apparently responded to the improved water quality by colonizing shallow areas in Hillsborough Bay and other sections of Tampa Bay. The return of seagrass meadows is in an important sign of bay recovery.

In this report, a first attempt has been made to relate the long-term nitrogen loading to Hillsborough Bay from external sources to water quality conditions in the bay. A simple eutrophication model based on the nitrogen loading/chlorophyll relationship is presented. However, much work is still needed to refine the relationship. Specifically, the major external nitrogen sources and the natural eutrophication control processes should be better quantified. Atmospheric loadings, most stormwater loadings, and loadings from groundwater, septic waste and several tributaries have not been included in the current calculations due to lack of adequate information. However, the sources which have been addressed are some of the most important ones and also the ones which probably have shown the greatest change over the period of study. It is important that the eutrophication model is based on a long-term record spanning several decades to allow for separation of natural and manmade effects, and also to reduce the potential for costly overprotective actions. The model should be used in combination with a comprehensive monitoring program of loading sources, water quality, biological indicators and important natural control processes. Further, the nitrogen loading/chlorophyll model should be linked to valuable natural resources, such as seagrasses and soft bottom communities, to help protect these and other important resources in Tampa Bay.

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APPENDIX

The source of all nitrogen loadings for the period 1967-68 (Table 1) and the year 1968 (Figure 5), except shiploading losses, are from FWPCA (1969). Shiploading losses have been estimated as 0.05% of the amount of ammonium-phosphate product shipped from the Port of Tampa (TPA, unpublished).

Loadings from rivers and creeks for the period 1969-90 have been calculated from the sources listed below and at the locations described by Johansson and Lewis (in press). However, the Alafia River lacks concentration information for the period 1969-1973; therefore, concentrations for 1969-73 were calculated from 1969-73 flows and a regression relationship between flows and concentrations for the period 1973-79. Further, Delaney Creek lacks flow information for the period 1969-84 and concentration measurements for the period 1969-80. Therefore, 1980-84 loadings were calculated from a regression relationship between Delaney Creek and Bullfrog Creek flows for the period 1985-89. Delaney Creek loadings for the period 1969-79 were estimated to be equal to 1968 Nitram loadings.

River and creek flows are from USGS (1976, 1977, 1978, 1979, 1980a, 1980b, 1982, 1983, 1985, 1986a, 1986b, 1987, 1988, 1989, 1990), USGS (unpublished) and SWFWMD (unpublished). Concentrations are from Wilkins (1980, 1981, 1982), Cardinale and Boler (1984), Boler (1986, 1988, 1990) and HCEPC (unpublished). Additional Alafia River concentrations are from USGS flow references.

Cargill Fertilizer, Inc. supplied point-source loadings for the period 1981-90. Loadings for the period 1969-80 were estimated to be equal to 1968 loadings.

Hookers Point Wastewater Treatment Plant loadings for the period 1975-90 are from plant operation reports. Loadings for the period 1969-74 have been estimated from a linear relationship between 1968 and 1975 measurements.

McDill AFB Wastewater Treatment Plant has had no direct discharge to the bay during the last decade.

Chlorophyll concentrations are from FWPCA (1969), Saloman and Taylor (1972), Saloman (1973, 1974), Collins and Finucane (1974), Saloman and Collins (1974), Shaw and Wilkins (1975, 1976, 1977, 1978), Wilkins (1979, 1980, 1981, 1982), Cardinale and Boler (1984), Boler (1986, 1988, 1990), and HCEPC (unpublished).

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