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- FINAL REPORT -

REVIEW OF TAMPA BAY INFORMATION FOR INTERIM NUTRIENT BUDGETS AND HISTORICAL LOADINGS OF BAY SEGMENTS

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1.0 INTRODUCTION

Tampa Bay was added to the National Estuary Program (NEP) on April 20, 1990. The NEP was established by the Water Quality Act of 1987, which authorizes the U.S. EPA Administrator to convene Management Conferences to develop Comprehensive Conservation and Management Plans (CCMPs). The mandated NEP approach is a stepwise process to 1) convene a Management Conference, 2) characterize the estuary, and 3) develop and implement the CCMP. After the Tampa Bay NEP Management Conference Agreement was approved in March of 1991, the NEP staff initiated several projects aimed at characterizing the estuary. As part of the contract to review and synthesize historical Tampa Bay water quality data, the Tampa Bay NEP staff authorized KEA Environmental, a department of King Engineering Associates, Inc. (KEA), to also review existing information relevant to Tampa Bay regarding nutrient budgets and historical loadings of bay segments.

The report herein includes a review of literature for information pertinent to refining the interim Southwest Florida Water Management District/SWIM Tampa Bay nutrient budget in three categories. Categories addressed include nitrogen fixation, atmospheric loading, and ocean/bay exchanges. The SWIM Tampa Bay Bibliography and other more recent Tampa Bay literature sources were reviewed for information pertinent to Tampa Bay. Proposed Work Plans for possible future work not covered under this agreement were developed for each of the three categories based on the literature reviews. Work Plans were only intended to provide a general outline, not a Scope of Work, of research required to address each respective category.

In addition to the interim nutrient budget reviews, we have reviewed and summarized the relevant existing information to address nutrient loadings to bay segments. As part of this task an assessment was made as to whether or not further work is recommended to evaluate historical nutrient loadings and possible associations with selected water quality parameters for defined subdivisions of Tampa Bay. A Work Plan outline was also included in this section.

KEA assembled a team of local specialists to provide appropriate expertise in each category addressed. Drs. Gabriel Vargo and Kent Fanning were assigned to review nitrogen fixation and atmospheric deposition, respectively. Drs. Robert Weisberg and Boris Galperin completed the ocean and bay segment exchanges review. All of the above individuals, although serving as private subconsultants to KEA, are also faculty members at the University of South Florida, Department of Marine Science. The last category addressing historical nutrient loadings to bay segments was written by Mr. Andrew Squires of KEA Environmental.

2.0 INTERIM NUTRIENT BUDGET DATA REVIEW AND ASSESSMENT

2.1 NITROGEN FIXATION - (GABRIEL A. VARGO)

2.1.1 Introduction

Nitrogen fixation by diazotrophic bacteria and blue-green algae has been demonstrated to occur in a variety of estuarine environments. These include:

1. The water column
    a. photosynthetic cyanobacteria
    b. symbiotic cyanobacteria
    c. heterotrophic bacteria (Azotobacter)

2. Mud and sand flats (oxic and anoxic sediments)
    a. cyanobacterial mats
    b. other diazotrophic heterotrophic bacteria

3. The seagrass biosphere
    a. epiphytic bacteria and cyanobacteria
    b. root tissue associated bacteria
    c. the sediment rhizosphere

4. Salt marsh biosphere
    a. cyanobacterial mats
    b. heterotrophic bacteria in the sediment rhizosphere

5. Mangrove biosphere
    a. bacteria in the sediment rhizosphere
    b. root associated bacteria
    c. detritus associated bacteria

6. Benthic macroalgae
    a. epiphytic diazotrophic bacteria

Capone (1983) reviewed most of the early literature on nitrogen fixation in sediments. He included a summary of controlling factors, methodological limitations and fixation rates for most all of the habitats listed above. Howarth et al. (1988) also extensively reviewed the literature on nitrogen fixation in estuaries. The tabular data in their review for a variety of estuarine habitats relevant to Tampa Bay was taken from the same sources as the data referenced by Capone (1983).

Nitrogen fixation occurs in both oxic and anoxic environments in estuaries. Hence, given the diversity of environments found in estuaries, there is a great diversity of organisms which contribute to this process. These organisms include heterocystous and non-heterocystous cyanobacteria in the water column and sediments, aerobic bacteria such as Azotobacter associated with sediments and detritus, and strict anaerobic bacteria such as the clostridia and sulfate reducers.

The interest in nitrogen fixation as a potential source of nitrogen for primary production in the marine environment is largely the result of the implication that nitrogen is the limiting nutrient for primary production in marine waters (Ryther and Dunston, 1971). Estuaries, which are relatively shallow and have extensive benthic communities, have extensive coupling between sediment and shoreline processes and the pelagic ecosystem. Thus, nitrogen fixation has received considerable attention as a potential source of nitrogen for estuarine primary production.

2.1.2 Biochemical and Methodological Limitations

Several aspects of the process of nitrogen fixation and its measurement are relevant to this summary. All nitrogen fixing organisms possess the enzyme nitrogenase. The structure and biochemical regulation of this enzyme is essentially similar in all N-fixing organisms. It has a high energy requirement for ATP and reducing equivalents and a high degree of sensitivity to oxygen. Nitrogenase activity in the water column and sediment environments can be limited by high concentrations of ammonia, which represses enzyme activity, and a lack of sufficient organic substrates. Additionally, high nitrate levels may lead to competition with nitrogenase for reducing power by the assimilatory nitrate reductase pathway and/or through the pathways responsible for denitrification and dissimilatory nitrate reduction.

Two methods are commonly used to determine nitrogen fixation: the isotope ^{15}N, and the acetylene reduction method. In the isotopic method, nitrogen is added as N_2, the sample incubated and the ^{15}N composition of the particulate material determined. This is a highly sensitive method, although costly because of the equipment required for isotope determination, but it is the only method available for the direct determination of nitrogen fixation. In the acetylene reduction method, acetylene is added to the sample which is reduced by nitrogenase to ethylene. Ethylene concentration is then determined by gas chromatography. This method is also highly sensitive but its use has several limitations. Acetylene may inhibit a variety of sediment microorganisms such as denitrifying, methanogenic, methane-oxidizing, sulfate reducing and even nitrogen fixing bacteria (Capone, 1983). Acetylene may also be metabolized aerobically and anaerobically by organisms other than nitrogen fixers. Problems common to both methods are adequate dispersion/diffusion of the gas, especially in sediment cores and sediment environments and sample size since populations of nitrogen fixers may have a highly patchy distribution. Finally, the relationship between acetylene reduction rates and actual nitrogen fixation must be determined adequately. The theoretical ratio of 3 moles of acetylene reduced per mole of nitrogen fixed is commonly used as a conversion factor. However, intercalibration studies indicate that this ratio may vary from 1.9 to 15.4 (Capone, 1983, Potts, 1984). Capone (1983) has recommended that direct calibration of the acetylene method be made for each system being studied.

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2.1.3 Nitrogen Fixation in Tampa Bay

The only literature found to date which describes direct measurements of nitrogen fixation in Tampa Bay habitats is the PhD dissertation of D.A. Zuberer (1976). Two additional papers were published which incorporate most of the results of this dissertation work; Zuberer and Silver, 1975 and 1978. Zuberer and Silver (1978) also refer to a M.S. thesis by Babiarz (1976) for N-fixation by seagrasses.

N-fixation associated with all three species of mangroves found in the Tampa Bay area was studied using the acetylene reduction method at sites located at Fish Creek in Old Tampa Bay, Whiskey Stump Key near the mouth of Hillsborough Bay, and Cockroach Bay. Measurements were made of rhizosphere and non-rhizosphere sediment cores, washed excised roots, isolated root systems of intact plants, algal, mangrove and seagrass leaf litter, and the water column within the mangrove environment. All rates are reported as the quantity of acetylene reduced, normalized to wet or dry weight per unit time, with one or two exceptions. The exceptions are summaries of the quantity of nitrogen fixed per unit area and are used in the summary table listed below. Therefore the range of acetylene reduction rates for each habitat or experiment were not converted to N-fixation values.

Zuberer (1976) reports that fixation rates in sediments were relatively low but that amendments of the sediments by various carbon sources (hexose sugars and TCA derivatives) enhanced acetylene reduction dramatically. He suggested, therefore, that the diazotrophic microflora was carbon limited. High rates of acetylene reduction were associated with excised root systems of mangroves, particularly the white mangrove, Laguncularia. Relatively high rates of acetylene reduction were also associated with fresh and decaying mangrove leaf litter, litter composed of the green alga, Ulva, and seagrass litter. Water column acetylene reduction rates were negligible with the exception of a few experiments combining prolonged incubation and glucose amendments.

It was somewhat difficult to decide what overall nitrogen fixation value to use for the mangrove systems studied by Zuberer (1976). He gives converted acetylene reduction values of 5-10 kg N/ha/yr for model in situ enclosures containing sediments and red mangrove seedlings; 2-5 kg N/ha/yr for cores without a central insert to facilitate diffusion but with glucose amendments, and rates of 4.5 to 32.3 kg N/ha/yr for sediment cores with a central insert and glucose amendments. Potts (1984) uses a value of 4.2 mgN/m^2/yr (15.3 kg N/ha/yr) for Tampa Bay mangrove N-fixation rates and references Zuberer (1976), while Capone (1983) uses a value of 7.8 mg N/m^2/day (28.5 kg N/ha/yr) for mangrove subtidal rhizosphere sediments and references Zuberer and Silver (1978). The value of 7.8 mg N/m^2/day was used to represent N-fixation in mangrove environments since it is intermediate among the reported rates and since other values in the accompanying calculation were taken from the summary table presented by Capone (1983).

The following estimates of N-fixation in Tampa Bay (Table 2-1) are based solely on values for equivalent habitats summarized by Capone (1983). The only rate actually measured in Tampa Bay is for mangrove N-fixation, as noted above. The areal extent of each habitat was derived from Table 13 in Lewis and Estevez (1988). I substituted their reported areal extent for production of benthic microalgae for the potential areal extent of N-fixation in estuarine sediments. The range of values reported for N-fixation in each of the listed habitats is extremely wide. For example, Potts (1984) gives a range of 0.6 to 304 mg $N/m^2/day$ for salt marshes while the range given by Capone (1983) is similar; 1.5-270 mg $N/m^2/day$; the range for seagrass beds is .03-137 (Potts) and 5.5 to 137 (Capone). Rates for subtidal non-rhizosphere sediments show less variability with ranges of 0.2 to 1.7 mg $N/m^2/day$. Since there is a range of 1 to 2 orders of magnitude in the published rates of N-fixation in estuarine habitats, the annual potential inputs I have calculated can also vary by the same orders of magnitude.

Table 2-1. ESTIMATED NITROGEN FIXATION RATES FOR TAMPA BAY

HABITAT	*AREA km^2	N-FIXATION mg $N/m^2/day$	N-FIXATION kg x $10^3/yr$
Mangrove forest	64.5	7.8	184
Sediments (flats)	200.0	1 - 1.7	73 - 124
Tidal marsh	10.5	43 - 142	165 - 544
Seagrasses and epiphytes	57.5	21 - 38	440 - 798
Macroalgal epiphytes	100.0	?	?
Water column	967.2	?	?

* From Lewis and Estevez (1988)

Using the low and high values for N-fixation in the above table yields a total potential nitrogen input range of 8.62 X 10^5 kg N per year to 1.65 X 10^6 kg N/yr without values for the water column. The most recent version of the Interim Nutrient Budget for Tampa Bay prepared by TAI Environmental Sciences, Inc. estimated two values for nitrogen loading in Tampa Bay; a low value of 4.45 X 10^6 kg/yr and a high value of 8.48 X 10^6 kg/yr. Adding the low N-fixation rates to the low N-loadings and the high N-fixation rates to the high N-loadings yields new totals of 5.31 X 10^6 and 10.13 X 10^6 kg/yr, respectively. The estimated N-fixation rates account for

16% of the new total N-loadings for Tampa Bay. Nitrogen fixation could be considered a significant source of nitrogen for Tampa Bay.

TAI also estimated denitrification rates for Tampa Bay. Their estimates are based solely on published values for other regions and an assessment of the fine sediment distribution in Tampa Bay. Low and high values were calculated: 1.26 X 10^6 and 2.81 X 10^6 kg/yr, respectively. Depending upon the credence given to the estimated denitrification rate, this process would effectively release all of the potential fixed nitrogen in Tampa Bay yielding no net input.

However, several other factors must also be considered. Zuberer (1976) and Zuberer and Silver (1978) speculated that N-fixation in the roots and in the fibrous root sediment layer would supply essentially all of the nitrogen requirements for growth of the red mangrove, Avicennia. In seagrasses, nitrogen fixation occurs in both the phyllosphere and rhizosphere. Transfers between leaves and epiphytes have been demonstrated (Harlin, 1971; McRoy and Goering, 1974). As noted by Zieman (1987), Capone and Taylor (1980) found that nitrogen fixed in the phyllosphere primarily contributed to the epiphytic biomass while rhizosphere fixation contributed to the macrophyte production. Capone and Taylor (1980) also suggested that nitrogen fixed in the rhizosphere contributed 20% to 50% of the macrophytes nitrogen requirements. Nitrogen fixing bacteria, Klebsiella sp. have also been found intercellularly in the root and rhizome of Halodule wrightii (Schmidt and Hayasaka, 1985).

Information on water column nitrogen fixation is lacking for Tampa Bay. Water column organisms which might contribute to N-fixation would include: Cyanobacteria such as Trichodesmium and some picoplankton, symbiotic cyanobacteria and diazotrophic bacteria found in large vacuolate diatoms such as Rhizosolenia spp., and Hemiaulus spp., and bacteria such as Azotobacter. In the case of symbiotic cyanobacteria (e.g., Richelea intracellularis), fixed nitrogen is utilized by the diatom (often Rhizosolenia spp.; Martinez et al., 1983) to supplement its nitrogen requirements. Populations of Rhizosolenia spp. and Hemiaulus spp. are common in Tampa Bay. However, lack of information on the distribution and population abundance of water column N-fixers precluded an assessment of their potential contribution to N-fixation in Tampa Bay.

Diazotrophic epiphytic bacteria and cyanobacteria have been found on numerous species of red and green algae. High rates of N-fixation have been measured for Codium, Enteromorpha, Laurencia and Jania (see Capone, 1983). Reported rates for these species were not used in the above table since information on the abundance, biomass, and areal and temporal distribution of macroalgal species in Tampa Bay is not available.

It is highly probable, therefore, that nitrogen fixed in some of the normal estuarine habitats is directly utilized by the surrounding vegetation. This increases the difficulty of how to account for nitrogen fixation in an input-output type of nitrogen budget since, as noted above, denitrification can obviate any input by N-fixation. This, of course, is not a true picture of the contribution of N-fixation in an estuary. One solution would be to construct individual component nitrogen budgets which would then provide values for utilization and output for use in an input-output budget.

Howath et al. (1988) suggested that nitrogen fixation was generally unimportant in more estuaries. Their conclusion was admittedly based on very limited data and on data acquired mainly from temperate estuaries. The only two estuaries with sufficient information for a confident estimate of the role of N-fixation were the Baltic Sea and the Peel-Harvey estuary. Approximately 15% to 17% of the annual nitrogen requirements were met by N-fixation. Both are temperate estuaries with high N-fixing blue-green algal populations. The estimates for the fraction of the N-budget met by fixation in these locations is approximately the same as our back-of-the envelope calculation for Tampa Bay (without epiphytes and water column contributions). There is a major lack of information on N-fixation in tropical and sub-tropical estuaries, with the exception of some tropical lagoon systems which have high N-fixation rates (Howarth et al., 1988). Many sub-tropical estuaries have surrounding mangrove forests,significant sea grass populations and extensive shallow water with mud and encrusting algal flats. The potential for a major role of N-fixation in the nitrogen budget for such areas is substantial. In addition, we also noted in our review that many species may utilize fixed nitrogen directly (see above) for growth and reproduction and that water column phytoplankton may also use fixed nitrogen directly. Therefore, we do not support the assessment made by Howarth et al. (1988) that N-fixation is generally unimportant in estuaries particularly with regard to such subtropical estuaries as Tampa Bay.

At this time, however, the magnitude of nitrogen fixation in Tampa Bay is unknown. If our calculation of potential nitrogen fixation is reasonable then it is an important process in the nitrogen dynamics of Tampa Bay. Further quantification is required and should include direct measurements of denitrification and ammonia volatilization.

2.1.4 Work Plan

Goals and Objectives

To provide a quantitative assessment of the contribution from nitrogen fixed by diazotrophic procaryotic organisms found in a variety of habitats in the Tampa Bay estuary to total nitrogen inputs to the estuary. Specific objectives include:

1. To determine nitrogen fixation rates for the water column, seagrass rhizosphere and phyllosphere, mangrove rhizosphere and detritus zone, and other benthic habitats (sediment communities) of Tampa Bay.

2. To determine denitrification rates for each of the habitats noted in objective 1 and compare denitrification with N-fixation.

Recommended Program

1. General Study Design

The study should be designed to include a minimum of 6 sampling dates for each habitat described in objective 1, over a one year time span, and must include at least two sampling dates during the summer/fall wet season. Sufficient areal coverage should be included to provide an assessment of spatial variability. Either the ^{15}N or acetylene reduction method may be used to determine nitrogen fixation, but if the acetylene method is used, calibration procedures to confirm the relationship between moles acetylene reduced and nitrogen fixed must be provided. All N-fixation rates must be expressed as N-fixed/unit area/time. Denitrification measurements should be made using the most recent methodology available. Sufficient areal coverage of submerged benthic, shallow water mud and sand flats, mangrove/salt marsh, and seagrass environments should be made to provide a direct comparison with N-fixation rates.

Ancillary measurements required for interpretation of results should include, but not be limited to, standard physical and chemical water column parameters, sediment pH, Eh, and carbon and nitrogen content, and pore water ammonia and nitrate concentration.

2. Habitat Specific Measurements

Water column N-fixation measurements should be done in at least one location in each bay segment. Whole water samples may be used with sufficient incubation times to allow for lag periods. Measurements in Lower Tampa Bay should include a surface and near bottom sample. A quantitative assessment of the abundance of symbiotic nitrogen fixing cyanobacteria should also be made. Measurements during the summer/fall Schizothrix bloom must be included.

N-fixation in sediments from submerged locations and from mud and sand flats, mangrove environments and salt marsh environments should include surface samples and cores. The relative merits of in situ incubations compared to subsampling with laboratory incubation or "model" systems as used by Zuberer (1976) requires further investigation. The apparatus used for core sample incubations should be designed to ensure maximum diffusion of substrate throughout the sample. Organic amendments of sediment samples are not required, however, the selection of locations for sediment sampling should pay particular attention to regions of elevated organic content.

N-fixation in seagrass communities should partition measurements of the phyllosphere and rhizosphere. Separate measurements of fixation by epiphytes would also be useful. Representative fixation rates from each of the species of seagrasses present in Tampa Bay should be made since there are differences in sediment characteristics, epiphyte coverage, and detrital abundance in each species habitat. Ongoing and future studies will provide areal coverage for each species for calculated estimates of N-fixation in these habitats. A comparison of highly productive versus low productivity and/or replanted sites should be made since Capone et al. (1979) demonstrated a direct relationship between nitrogen fixation rates and production rates in a *Thalassia testudinum* community in Bimini.

2.1.5 References

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2.2 ATMOSPHERIC DEPOSITION - (KENT FANNING)

2.2.1 Background Information

Atmospheric deposition of nitrogen-bearing compounds that can impact the biota of Tampa Bay is of two basic types: wetfall and dryfall. Wetfall similarly may be considered in two categories: rainout and washout. Rainout occurs when particles serve as condensation nuclei within clouds, and washout occurs when falling raindrops scavenge gases, aerosols, and other particles beneath clouds. Atmospheric nitrogen deposition as dryfall occurs when particles settle onto surfaces, gases adsorb onto surfaces, (Hinga et al. 1991). The ultimate loading due to dryfall is highly dependent on the type of surface -- grass, forest, wetland, urban area, etc. (ESE 1986).

The principal forms of nitrogen in atmospheric deposition are oxidized nitrogen such as HNO_3 and NO_2 molecules, NO_3- ions, etc, (which are sometimes labelled as NO_x) and reduced nitrogen in the form of ammonium ions (NH_4+) or particles or aerosols containing ammonium ions (ESE 1986).

Measurements of nitrogen depositing in wetfall is reasonably straightforward. Typically, monitoring stations are set up to collect rain on a regular basis -- daily, weekly, monthly, etc, and NH_4+ and NO_3- are measured in the samples. With proper attention to the representativeness of the sample site, the sampling frequency, and the rainfall distributions, wetfall loading for a region can be estimated reasonably well.

Measurement of dryfall nitrogen loading is much more complicated, primarily because the fraction of the solids or gases that "stick" is heavily dependent of the nature of the surface. Automated dryfall buckets can be installed at representative sites, but the inner surface of a metal or plastic bucket does not simulate a natural surface such as cropland, or even a manmade surface such as asphalt. In fact, buckets can underestimate dryfall by factors of as much as 5.0 (ESE 1986). The most common technique to predict dryfall is to measure the concentrations of atmospheric nitrogen present as particles, aerosols, or gas and then multiply those concentrations by a factor called the "deposition velocity" which is appropriate for the surface under consideration. Deposition velocities are determined by studies and models of the uptake of atmospheric nitrogen by particular types of surfaces.

The importance of atmospheric deposition of nitrogen to estuaries is a subject of considerable debate at the moment. This debate began in some seriousness when Fisher et al. (1988) asserted that much of the nitrogen entering the Chesapeake Bay in rivers first fell onto the Chesapeake watershed from the atmosphere. A more recent estimate claims that at least 74% of the riverine nitrogen loading into the Chesapeake is of atmospheric origin and constitutes ~32% of the total nitrogen loading to the Chesapeake (Hinga et al. 1991). Almost all of this loading is anthropogenic. These studies (and a few others) suggest that to consider only the atmospheric loading falling directly onto the surface of an estuary may overlook a major fraction of the atmospheric impact on the estuary or even the major source of all nitrogen entering the estuary.

Critical management decisions could be affected. Closer to Tampa Bay, Hinga et al. concluded that 100% of the nitrogen entering Ocklockonee Bay in north Florida was atmospheric wetfall + dryfall and 50% of that loading was anthropogenic.

2.2.2 Atmospheric Deposition on Tampa Bay

No effort appears to have been made to evaluate the fraction of the atmospheric loading to the Tampa Bay watershed that reaches the Bay's waters. Also, studies and estimates that might be used to predict the direct loading of atmospheric nitrogen onto Bay waters are in rather wide disagreement. The most thorough study of atmospheric nitrogen deposition in Florida appears to have been the Florida Acid Deposition Study (FADS) conducted by Environmental Science and Engineering (ESE 1986) in which 7 carefully selected sites were monitored for wetfall and dryfall between 1982 and 1984. Great care was taken to evaluate the variability and procedural artifacts to be expected from automated samplers. The site closest to the Tampa Bay area was #8, located in southeastern Pasco County, and, in addition, they also reported (with caution) a value for the average wetfall nitrogen loading within the city of Tampa in 1980.

The FADS study reached the following conclusions. Site #8 had the largest volume-weighted mean concentration of NH_4+ and NO_3- of any of the 7 Florida sites (Table 2.3-1). Concentrations at sites south of Tampa were considerably lower. Wet deposition of NH_4+ at site #8 was considerably higher than elsewhere in Florida; however wet deposition of NO_3- was only slightly higher than elsewhere in peninsular Florida and was slightly lower than wet deposition at site #2 in the Panhandle (Table 2.3-4). The particulate NO_2 concentrations at site #8 were much higher than elsewhere in Florida, but the particulate HNO_3 concentrations were not different from other sites (Table 2.3-7). Particulate NO_2 + HNO_3 concentrations were higher north of Tampa than south of Tampa. Average areal wet loadings (in eq/ha/yr) at site #8 were 150 for NO_x (= HNO_3 + NO_3- + NO_2) and 119 for NH_4+.

The FADS values for dry NO_x deposition were especially uncertain because deposition velocities for the types of surfaces considered were evaluated much further north in the U.S. Those values ranged from 0.8 cm/sec for NO_x in a deciduous forest during the day to 2.9 cm/sec for HNO_3 in a pasture. ESE assumed 1.5 cm/sec for HNO_3 and 0.3 cm/sec for NO_2. Estimated dry NO_x deposition at site #8 was 286 eq/ha/yr, which was considerably higher than the measured dry deposition at site #8: 39 eq/ha/yr (Table 2.3-9). Dry NH_4+ deposition at site #8 was only measured and was 82 eq/ha/yr (Table 2.3-9).

The trends in atmospheric nitrogen deposition in Florida that show a decrease from north to south are in concert with nationwide trends (ESE 1986). For example, concentrations of NO_3- in rainfall in the Mid-west and Northeastern U.S. are twice those in Florida. Interestingly, the total wet deposition of NO_3- in those areas is only 1.5-to-2 times that in Florida because of the higher annual rainfall in Florida.

The FADS study showed some evidence that atmospheric nitrogen deposition had increased in Florida since 1955.

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There have been at least four other studies that dealt with the input of atmospheric nitrogen to Tampa Bay. CH^2M Hill (1991) prepared a study of Lake Maggiore in St. Petersburg which estimated an atmospheric loading to the lake from wetfall data in northern Pinellas County in early 1987 and then used "correction" factors to estimate the wet + dry nitrogen loading and the total nitrogen loading (=inorganic + organic). No other study investigated made an attempt to quantify "organic" loadings. Hartigan and Hanson-Walton (1984) estimated wetfall nitrogen loadings based on average annual rainfall information and average nitrogen concentrations in rain water reported from the Tampa NURP study (see Table IV-18 in Hartigan and Hanson-Walton). The third study is in the draft version of the Interim Nutrient Loading Budgets for the Tampa Bay System (TAI Env. 1991) in which average "coastal" and "urban" loadings for Florida were used to estimate total atmospheric nitrogen deposition on the surface of Tampa Bay. Finally, a fourth study measured nitrogen wetfall and dryfall loadings at or near the Verna Wellfield which is located about 20 miles east of Sarasota, Florida. The Verna Wellfield site has been studied as part of the National Acid Deposition Program (NADP) conducted by Colorado State University (Jay Gibson, Colorado State Univ., personal communication). Jay Gibson, of Colorado State University, provided the Verna annual nitrogen loading values from his unpublished data that are shown in Table 2-2.

The range of estimates of atmospheric nitrogen loadings to the surface of Tampa Bay is given in Table 2-2: 546-1466 $mgNm^{-2}y^{-1}$. This range may be compared with that given for 4 U.S. and 1 Swedish estuary by Hinga et al. (1991): 610-14,000 $mgNm^{-2}y^{-1}$. The lowest value in this range is from the Swedish estuary, and the highest is from Ocklockonee Bay in north Florida. The Chesapeake Bay had 2,700 $mgNm^{-2}y^{-1}$. It should also be noted that the Hinga et al. range includes atmospheric deposition to watersheds that survives to enter the estuaries in runoff, while the range for Tampa Bay ignores atmospheric inputs via the watershed. Therefore, it is probable that the total impact of atmospheric nitrogen deposition on Tampa Bay is as high as for any U.S. estuary. The estimated total atmospheric nitrogen loading to Tampa Bay by direct deposition is obtained by multiplying the range from Table 1 by the area of the Bay (900×10^6 m^2) and is 491,000-1,320,000 $kgNy^{-1}$. This compares favorably with the estimated range of nitrogen inputs to the Bay in major tributaries: 935,000-2,620,000 $kgNy^{-1}$ (TAI Env. 1991).

Table 2-2. Estimates of Areal Atmospheric Nitrogen Loading to Tampa Bay ($mgNm^{-2}y^{-1}$).

Sampling Site	NO_x Wet Meas.	NO_x Dry Meas.	NO_x Dry Estim.	NH_4 Wet Meas.	NH_4 Dry Meas.	NH_4 Dry Estim.	Organic Nitrogen Estimate	Total
FADS Site 8 (1982-4)	210	54.6	--	166.6	114.8	--	--	546
	210	--	400.4[1]	166.6	114.8	--	--	892
FADS Tampa (1980)	386.5[2]	--	750[1]	166.6[3]	114.8	--	--	1418
L. Maggiore (CH^2M Hill)	359[4]	--	--	359[4]	--	--	--	718
	359[4]	--	154[5]	359[4]	--	154[5]	--	1026
	359[4]	--	154[5]	359[4]	--	154[5]	440[6]	1466
Fla. Aver. (TAI Env.)	--	--	--	--	--	--	--	580[7]
	--	--	--	--	--	--	--	760[8]
Verna (1984-90)	190[9]		190[10]	85[9]		85[10]		550

[1]assumes Dry = 66% of Wet + Dry

[2]assumes 52.5 in y^{-1} rainfall on Tampa Bay

[3]measured at FADS site 8

[4]measured at Cross Bayou, northern Pinellas County by the Pinellas County Air Quality Division from January 6, 1987 to March 7 1987

[5]assumes Wet = 70% of Wet + Dry

[6]assumes that inorganic Wet + Dry = 70% of Total Nitrogen Loading

[7]coastal loading

[8]urban loading

[9]Jay Gibson, Colorado State Univ. (pers. comm.)

[10]assumes dryfall = wetfall (Jay Gibson, Colorado State Univ., pers. comm.)

2.2.3 Work Plan

Goals and Objectives

The preceding narrative indicates the growing awareness that atmospheric wetfall and dry fall may supply not only significant nitrogen loadings to the surfaces of estuaries but also a major fraction of the nitrogen loadings entering estuaries form the surrounding watershed. Reductions in the nitrogen loading from non-atmospheric sources such as sewage, agriculture/fertilizer, or industry may be of minimal value if, as preliminary evidence suggests, the atmosphere plays an equally important role in Tampa Bay. The following program is designed to evaluate that role.

Recommended Program

1. Nitrogen Measurements in Wetfall

   A. Five automated stations modeled after ESE (1986)

      1) one (1) in Pinellas County
      2) four (4) in the watersheds of the major tributaries to the Bay

         a. Hillsborough river
         b. Alafia river
         c. Little Manatee river
         d. Manatee river

      3) sample rain events for 6-12 months (dry + wet seasons)
      4) measure ammonia and nitrate loadings
      5) possibly measure dissolved organic nitrogen loadings

   B. Evaluate area rainfall records and correct loadings departures during the sampling period from "typical" rainfall patterns.

2. Estimate nitrogen loading in dryfall

   A. Measure concentrations of particulate forms of nitrogen at the five wetfall stations (ESE, 1986) on a weekly basis

   B. Use literature values for deposition velocities to estimate dry fall loadings

3. Estimate total atmospheric nitrogen to major tributaries and non-point source runoff into Tampa Bay.

   A. Add dryfall and wetfall loadings at each station

B. Use watershed analysis (TAI Env., 1991) to estimate loading to entire watershed.

C. Predict survival percentages for the sub-portions of this total nitrogen loading

1) based on the percentages of surface types in the Tampa Bay watershed
2) yields the fraction of the total loading consumed within the water shed
3) use the approach outlined by Hinga et al. (1991).

4. Correct the total atmospheric loading in run-off by the extent of denitrification in the tributaries

A. Both sediment-water interface and water column

B. Procedural references in Hinga et al. (1991).

2.2.4 References

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2.3 OCEAN AND BAY SEGMENT EXCHANGES

2.3.1 Introduction

Attempts at estimating nutrient budgets for Tampa Bay (e.g., see TAI Env. 1991) have generally resulted in an imbalance, on the order of 50%, prior to adjusting parameters, or invoking other sources/sinks for removing the imbalance. One potentially major source or sink for nutrients within the bay is the exchange of waters between the bay and the coastal ocean (The Gulf of Mexico). For example, previous studies (Dragovich and Sykes, 1967) have shown that the adjacent Gulf of Mexico waters may be richer in nitrogen than are the bay waters. Similarly, for different bay segments such as Old Tampa Bay, Hillsborough Bay, middle Tampa Bay and lower Tampa Bay, exchanges of nutrients between segments may be a major term in the overall nutrient budget for a given segment. There are several factors which may affect the exchange between Tampa Bay as a whole and the Gulf of Mexico, or between segments comprising the bay. These include tidal current exchanges, river throughflow, buoyancy-driven convection (generally referred to as estuarine circulation in the refereed professional journals) and wind-driven circulation. These various processes occur over different time scales and, furthermore, they may be seasonally varying. One way of assessing their potential importance *a priori* is to examine their potential for influencing the residence time of the estuary. This discussion on ocean and bay segment exchanges will therefore proceed as follows. Section 2.3.2 will develop estimates of residence time based upon some very crude assumptions regarding the four factors previously mentioned. These are *a priori* estimates based upon physical concepts and not upon actual measurements, which are presently either non-existent or have not been analyzed. The important finding is that the range of residence times extends over one to two orders of magnitude, suggesting that waters within the bay can be exchanged very quickly, or much more slowly, depending upon what the dominant factors really are. Section 2.3.3 presents a brief review of what previous studies have suggested regarding these factors and their impact upon ocean and bay segment exchanges. The results are summarized in Section 2.3.4 along with some recommendations for how the estimates of ocean and bay segment exchanges can be improved upon. The principal result of this review is that while ocean and bay segment exchange is a very important issue requiring resolution (a 50% imbalance in the nutrient budget), we know relatively little about such exchanges, given the existing data and models for Tampa Bay.

2.3.2 Factors Affecting Residence Time

The concept of residence time follows from the conservation of mass for a given quantity in solution. Assuming that this quantity is well mixed throughout the bay, then, by balancing inputs against outputs, where the output is proportional to the concentration, an estimate of the residence time, for an average particle of solute within the bay, may be derived. Four estimates based upon four different physical processes will be considered; by: 1) river throughflow, 2) tidal exchange, 3) buoyancy-driven convection exchange and 4) wind-driven circulation exchange.

The simplest estimate, and the one leading to the longest residence time, is the one pertaining to the inflow of river water, which we refer to above as the river throughflow estimate. Consider a uniform input of fresh water to the estuary at a volume flow rate of R. If the estuary is well mixed, and the uniform salinity of the estuary is to remain a constant, then, in order to conserve the mass of fresh water within the estuary, the residence time, by river throughflow alone, equals the volume of the estuary divided by the volume flow rate of the river, or $t_1 = V/R$.

If the estuary is not uniformly mixed, and a buoyancy driven mode of estuarine circulation exists, then a second measure of residence time, t_2, may be estimated. This is similarly derived from conservation of mass arguments, where now two quantities must be conserved; the mass of water and the mass of salt. For the simplest model of two layered estuarine circulation, with a layer of relatively fresh water, which flows seaward on average near the surface, compensated by a layer of relatively salty water, which flows landward on average near the bottom, the residence time follows from Knudsen's Hydrographic Theorem (introduced at the turn of the century and available in most introductory texts on Physical Oceanography):

$$T_i = [S_o/(S_i - S_o)]R,$$

$$T_o = [S_i/(S_i - S_o)]R,$$

where T_i, S_i and T_o, S_o are the volume flow rates and salinities in the lower and upper layers, respectively. The associate residence time is given by the volume of the estuary divided by the volume flow rate of the incoming lower layer water, or $t_2 = V/T_o = V/\{[S_i/(S_i - S_o)]R\}$. As such, t_2 is much shorter than t_1 because of the salinity terms.

Note that in the discussion of the Knudsen Hydrographic Theorem the concept of an average was introduced. From observations it is known that water generally flows into the estuary at all depths during the flood stage of the tide and that it flows out of the estuary at all depths during the ebb stage of the tide. The average is, thus, defined as the average over many tidal cycles, i.e., the sub-tidal residual circulation that remains after the tidal currents are averaged out. This residual circulation, in the absence of further complicating factors such as winds, topography and the associated non-linear coupling that occurs between processes at different time and space scales, is what is generally referred to as "estuarine circulation". Typical of the sub-tidal residual circulation are the following features:

a. It is small compared to the tides; usually 10-20% of the tidal current amplitude, depending upon the estuary.

b. Unlike the tidal circulation which is fast and only weakly coupled to the density field, the residual circulation is slow and intimately related to the density field (i.e., it is baroclinic).

c. The residual circulation may actually determine the long-term transport processes within Tampa Bay, as in other estuaries, and it may therefore be a primary agent in shaping the spatial and temporal distributions of water quality characteristics.

d. Extracting the residual circulation from a tidal record required careful scientific planning (of the location and length of the measurements) and analysis, since the residuals are generally small relative to the tidal currents and they are easily aliased or biased.

Tidal currents, however, do, in and of themselves, result in an exchange of mass between the coastal ocean and the estuary, or between segments comprising the estuary.

Ketchum (1950) recognized the importance of tides in flushing estuaries and he presented a scheme for calculating flushing times. This scheme is highly dependent upon the length of the estuary relative to the tidal excursion. For Tampa Bay, a typical tidal excursion (using velocity measurements in lower Tampa Bay of amplitude 1.0 to 1.5 kts) is about 4 to 6 nm (less than the distance between the mouth of the bay and the Sunshine Skyway Bridge) compared to the length of Tampa Bay which is about 30 nm. However, not all of the inflowing tidal prism (the volume of water exchanged with each tidal cycle) gets mixed with waters already within the bay since most of this water simply flows back out with the ebb tide. By dividing the volume of the bay by the portion of the tidal prism that gets mixed within the bay a third measure of residence time is arrived at, i.e., $t_3=V/(n)(TP)$, where TP is the tidal prism and n is some fraction of the tidal prism that gets mixed within the bay. Ketchum (1951) decomposed an estuary into segments and carried out an analogous exercise between segments to arrive at a total flushing time. This work preceded the recognition of "estuarine circulation" and winds as other important modes of flushing. A review on the development of these estuarine circulation concepts may be found in Beardsley and Boicourt (1981).

Along with river throughflow, buoyancy-driven convection and tides, there are the ever pervasive wind-driven currents. As has been shown in most major estuaries the effects of winds, even the typical day to day fluctuations let alone major storms, can be larger than the buoyancy-driven mean currents by themselves. Thus, the time averaged residual circulation generally shows sub-tidal fluctuations, within the range of time scales associated with synoptic weather patterns (2-10 days), which may be as large or larger than the longer term means. A fourth measure of residence time is therefore the volume of the bay divided by the incoming volume transport of water associated with these wind-induced flows, or $t_4=V/(WT)$.

These four modes of flushing result in residence times that range from very long times to very short times as summarized in Table 2-3.

Table 2-3. A comparison of residence times from *a priori* estimates of river throughflow, buoyancy-driven convection, tidal prism mixing and wind-driven currents.

Mechanism	Formulation	Assumptions	Result (days)
River Throughflow	$t_1=V/R$	$V=3.27x10^9m^3$ $R=53.9\ m^3/sec$	702
Buoyancy-Driven	$t_2=V/T_o=V/\{[S_i/(S_i-S_o)]R\}$	$S_i=34psu$ $S_o=33psu$	20
Tidal Prism	$t_3=V/(n)(TP)$	$TP=0.6x10^9m^3/cycle$ $n=0.01-0.10$	28-280
Wind-Driven	$t_4=V/(WT)$	see note below	21

Tidal Prism Note: Our interpretation, with regard to n, from the Ross (1973) study is n=0.05.

Wind-Driven Note: WT was estimated to be $1.5x10^8m^3/sec$ using the recent current meter data from under the Sunshine Skyway Bridge, by multiplying the typical wind-induced current fluctuation by a fraction of the cross-sectional area.

The results shown in Table 2-3 albeit crude back-of-the-envelop estimates, based upon *a priori* information, show that the range of flushing times for the bay can be very broad depending upon which mechanisms are deemed to be important. These estimates are given merely to illustrate this point, and we stress that without adequate data we can made no scientific claim beyond their relative values. Clearly, the river throughflow mechanism alone is not a very useful measure of flushing time since all of the other mechanisms give much shorter times. Curiously, the other three mechanisms may be of the same magnitude, suggesting that all of these processes are important for flushing the bay. The wind-driven estimate is a conservative one since it is based upon a root mean square (rms) wind-driven current magnitude. Along with the result from an rms value of 6 cm/sec, we note that an observed event, having say 20 cm/sec wind-driven currents and lasting say 2 days, could effectively flush a large fraction of the bay volume within that time scale. Such events are not atypical, and these episodic flushing events may be important in maintaining the water quality of the bay.

2.3.3 Results From Previous Studies of Tampa Bay

One of the first accounts for residual circulation in Tampa Bay was that by Ross (1973). He wrote that "the bays, estuaries, and nearshore areas of the eastern Gulf of Mexico are very similar in hydrology and basic mechanism of flushing. They are shallow (less than 20 feet average depth), well mixed bodies of water, flushed by the combination of tidal action and a throughflow of fresh water." Ross (1973) has also suggested that there is an additional flushing mechanism in these estuaries, due to the residual gyres generated primarily by the bathymetry irregularities. His assertion that calculated particle trajectories indeed shows that particles are trapped inside such eddies is poorly supported by Figs. IID-22 and 23 in his report. Using his barotropic model, Ross (1973) calculated flushing time, defined as time necessary for "90% reduction in concentrations of a substance in Tampa Bay," as approximately 180 days. Also, "combining known input data, flow information and field data," Ross (1973) made an estimate of tidal flushing for 1968 and 1972. He found that "25.8% of the tidal quantity of water is permanently removed from Tampa Bay by mixing with Gulf of Mexico water. The mechanism of tidal flushing is such that as the tide leaves Tampa Bay it carries dissolved material in solution. Outside Tampa Bay the water mixes with Gulf water. The new tide coming into Tampa Bay returns much of the same dissolved substance - in fact, 74.2 percent of the substance returns." This estimate does not allow us to determine flushing time due to the bay-shelf exchange. It does not provide any account for the wind effect. Finally, and most substantially, this estimation does not take any account of density driven residual circulation which, as has been shown by preliminary analyses of the NOS data (Weisberg and Williams, 1991) and the application of a three-dimensional circulation model (Galperin et al., 1991) may be as much as 5 times stronger than that due to the tides and determines the entire character of the bay-shelf exchange. The disregarding of the baroclinic mode of circulation would make any approach unrealistic.

Another account for residual circulation and bay-shelf exchange was provided by Goodwin (1987) based upon some observations and vertically-integrated (barotropic) numerical model that excluded horizontal, salinity-induced pressure gradients. He calculated "residual water transport" as the local transport averaged over a tidal cycle, so he was actually dealing with the subtidal transport. He produced a set of vector maps, showing direction and magnitude of the subtidal transport at every node of the computational grid. He found that "each vector map shows a series of 20 or more circulatory features or gyres that range in diameter from about 1 to 6 mi. These features define tide-induced water circulation for a mixed tide in the absence of density stratification and wind effects."

Compared to the previously discussed work by Ross (1973) the study of Goodwin (1987) provides a more systematic and better documented account of residual circulation in Tampa Bay.

However, both works have the same critical flaw in that they disregard effects related to the horizontal density structure, the importance of which was emphasized earlier in this report. An interesting numerical experiment was described by Galperin *et al.* (1991) who first excluded baroclinic effects in their numerical model. The remaining barotropic residual currents were in very good agreement with the results by Goodwin *et al.* (1987). These currents form easily identifiable gyres that have the same location, size and the sense of rotation as those found by Goodwin. However, when baroclinicity is turned on, the residual circulation is grossly intensified and the barotropic gyres are totally overwhelmed and are not identifiable anymore. Instead, the residual circulation gains the well known, classical estuarine character whereas surface, lighter water flows out of the bay while heavier, saltier shelf water flows landward in the bottom layers. In summary, Goodwin's (1987) account for subtidal circulation, similarly to Ross' (1973) study, related to its weakest, barotropic component. This makes it virtually useless for any practical estimate of the residual bay-shelf exchange or a flushing time related to such an exchange. Goodwin (1987) realized that due to the mass conservation, total residual mass flux through any cross section should be equal to the corresponding river flow and indeed his Table 13 reflects this fact. However, the effects of baroclinicity, disregarded by Goodwin, result in a complicated residual flow through the mouth cross section, whereas large water masses enter and exit the bay at the same time at different locations. As follows from Knudsen relations, since subtidal top-to-bottom salinity difference in Tampa Bay is fairly small, of the order of about 1-3 ppt, these incoming and outgoing residual fluxes may be fairly large, far exceeding their residual equal to the river flow (if evaporation and precipitation are neglected).

Recently, subtidal bay-shelf exchange, among other things, was studied observationally (Foth & Van Dyke Preliminary Report for SWIM, 1991). This study was related to the extensive circulatory observational program carried out for Tampa Bay by the National Oceanographic Survey. Residual transport was found as an average over an approximately 24 hour period of 3 hour spaced samplings. Although this effort was the first of its kind for Tampa Bay and very useful as such, the design of the data collection program had some flaws. The most important of them was that the tidal cycle was unbalanced, which means that the tidally-averaged result was not entirely clear of tidal contribution. As was discussed earlier, subtidal residuals are only about 10% of the tidal signal, such that even small errors in tidal analysis may produce errors as large as the residuals. Another problem of the study was unknown sensitivity to the wind forcing and conditions at the shelf, each of which can dramatically affect estimated residuals. In other words, the results are biased by unbalanced tides, wind effect and shelf boundary conditions.

2.3.4 Summary and Recommendations

The principal result of this review is that ocean and bay segment exchanges are potentially very important for understanding the circulation of the bay, closing the nutrient budget and generally understanding the factors that control water quality for Tampa Bay. Previous studies have not adequately addressed these important issues. Addressing these issues will require a careful scientifically planned set of measurements and analyses, including the application of a fully three dimensional model; the only type of model capable of including the relevant physical processes controlling ocean and bay segment exchanges.

2.3.5 Work Plan

Goals and Objectives

The overall goal of this work plan is to determine the exchanges of material between the coastal ocean and Tampa Bay and between selected segments within Tampa Bay that occur by the physical processes of advection and diffusion. This is important from a control volume perspective (the bay as a whole, or segments of the bay) since it is the convergence of these advective and diffusive fluxes, together with the bio-geochemical sources and sinks, that governs the concentration of material within the control volume. For conservative properties such as salinity, the bio-geochemical sources and sinks are zero so only the advective and diffusive flux convergences are important. For non-conservative properties such as nutrients the bio-geochemical processes are also important; however, one can not make *a priori* statements regarding the relative importances of the various processes, and hence the gross imbalance that presents itself when attempting to close a nutrient budget for Tampa Bay. Specific objectives of this work plan include:

1. Determine the fluxes of material through selected cross-sectional areas of the bay, including:

   A. the mouth of Tampa Bay,
   B. the entrance to Hillsborough Bay,
   C. the entrance to Old Tampa Bay and
   D. a mid-bay cross-section.

2. Quantitatively partition these fluxes into the various modes of circulation that are responsible for them, including:

   A. tides,
   B. buoyancy-driven convection and
   C. wind-driven circulation.

3. Determine the mechanisms by which the conservative properties of water and salt are balanced over all relevant time scales, including:

   A. tidal,
   B. synoptic and
   C. seasonal.

Recommended Program

Based upon the conceptual understanding of estuarine circulation and its partition into the above reference modes of flow, a field program should be developed to determine, quantitatively, the partition of the flow field into these modes of tidally-driven, buoyancy-driven and wind driven circulations. Care must be taken to adequately sample these processes so that the results won't be aliased or biased. For example, the time series must be sampled frequently enough to avoid aliasing and they must be long enough to resolve the modes of flow without bias. Spatial aliasing and biasing also form important sampling criteria. The existing estuarine literature gives specific case studies on these issues. For example, Weisberg (1976) addressed the issue of record length in distinguishing between the mean circulation due to buoyancy-driven convection, and the large sub-tidal variations that were attributable to the wind-driven circulation.

The recently acquired NOS data set for Tampa Bay is the first comprehensive data set on the circulation of Tampa Bay. It will be very useful in assisting with experimental design and these data should be fully explored. However, the NOS program was not specifically designed to look at sub-tidal budgets, and it is already known from preliminary analyses (e.g., Weisberg and Williams, 1991) that these data do not define how the sub-tidal water budget is closed, at least at the mid-bay cross-section corresponding to the Sunshine Skyway Bridge. Closing the water budget will require measurements made both closer to the surface and away from the channel.

The geometrical complexity of the bay posses additional sampling problems. A programmatic strategy, aimed toward integrating the few well designed measurements that can be made into an overall picture of the bay, is the implementation of a numerical model that is complete enough to include the relevant physical processes as defined above. This is the strategy adopted by the NOS. Such a model exists, e.g., Galperin et. al. (1991), and it could be used to explore the questions raised above, when supported with a carefully planned field and data analysis program.

In summary, despite the large effort recently undertaken by the NOS, there exists continued uncertainty regarding the role of the circulation in the water budget, let alone the nutrient budget. The NOS data set contains a wealth of information that should be fully explored; however, additional measurements are necessary to resolve issues that the NOS data set will not clarify. A carefully designed field program (the NOS program was carefully designed, but with emphasis on the tidal flows that occur within the main shipping channels), taking into account temporal and spatial sampling requirements, should be implemented at specific cross-sections, as given above. This field work should be complimented by numerical analyses of actual field measurements and numerical model outputs should be aimed at resolving the issue of the importance of the advective and diffusive material fluxes (salt and nutrients, in particular) on the ocean and bay segment exchanges, with the goal of understanding the nutrient budget for Tampa Bay.

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3.0 HISTORICAL LOADINGS OF BAY SEGMENTS

3.1 TAMPA BAY LOADING STUDIES

Several studies have addressed nutrient loadings into Tampa Bay (Hartigan and Hanson-Walton 1984; Dooris and Dooris 1985; Palmer and McClelland 1988; Flannery 1989; Dames and Moore 1990; TAI-Env 1991) including relatively detailed studies on Hillsborough Bay loadings compared to selected water quality parameters and indicators (FWPCA 1969; Johansson and Lewis 1990; Johansson 1991). More attention has been given to Hillsborough Bay since it is generally regarded as the most impacted, in terms of pollutant loadings and poor water quality conditions, of the four major segments of Tampa Bay as defined by Lewis and Whitman (1985). In addition, Hillsborough Bay receives roughly two-thirds (Goodwin 1987) to three-fourths (Lewis and Estevez 1988) of the total freshwater input into Tampa Bay.

In order to provide external nutrient loading values to the bay, discharge information must be combined with nutrient concentration data. The availability of discharge and concentration data collected at the same time and place is only sporadically available for tributaries entering Tampa Bay, and is virtually unavailable on a short term (less than monthly) continuous basis. The lack of frequent concentration data for major tributaries is a major disadvantage since the occurrence of a few anomalous natural events could be the predominant contributor to overall loadings to a system. For example, Troup and Bricker (1975), observed that the Susquehanna River delivered 30% of the total annual suspended solid load in one week.

Most loading estimates of surface water flows to Tampa Bay have utilized discharge data obtained continuously or daily from several non-tidally influenced United States Geological Survey (USGS) gaging stations located in the Manatee, Little Manatee, Alafia, and Hillsborough River basins. The USGS also sample for water quality constituents at some of these gaging stations (see Dooris and Dooris (1985) for a review), however, typically these data are obtained every two months, and can only provide approximate concentrations to characterize a given time period.

It should be noted, as pointed out by Flannery (1989), that the USGS freshwater inflow gaging stations are typically located upstream of a large proportion of their respective drainage basin area and, as such, may lead to an underestimate of actual loadings to the bay. As a result, loading estimates for some tributaries have incorporated a correction factor to compensate for additional loading occurring downstream of the gaging stations. Correction factors are typically based on the relative area of the drainage basin downstream of the gaging station compared to the drainage basin upstream of the gaging station. A larger proportion of most drainage basins are urbanized near the tributary mouth relative to the head of the tributary. One would expect, therefore, that a greater amount of the nitrogen loaded to the bay per unit area is derived from the portion of the drainage basin downstream of the existing gaging stations.

The excellent long-term water quality data collected by the Environmental Protection Commission of Hillsborough County (EPC) has provided monthly data for several freshwater tributary locations, some of which are located near established USGS gaging stations. Although these water quality data are not the ideal choice for estimating loads, they may represent the best available concentration data, in combination with USGS water quality values where they are available, to integrate with discharge values, thereby enabling loadings to be determined.

Nutrient loading contributions from many of the most significant point source dischargers (for example, wastewater treatment plants and industries) can be obtained from a review of the permitting records kept by the FDER. Loading estimates for Tampa Bay have made ample use of these records (Palmer and McClelland 1988, Johansson 1991).

3.2 NUTRIENT LOADING STUDIES OF TAMPA BAY

The FWPCA (1969) produced an excellent report on Hillsborough Bay pollutant loadings and the observed water quality conditions from 1967 to 1968. Their work is summarized and used for comparison in recent publications by Johansson and Lewis (1990) and Johansson (1991). They accomplished a detailed evaluation and estimation of nutrient loadings from industrial and municipal sources as well as the major tributaries. Their characterization of loadings and documentation of ambient water quality conditions for a variety of parameters and biological indicators for the 1967-1968 time period provides the best available benchmark from which to compare post 1970 conditions in Hillsborough Bay.

Dooris and Dooris (1985) compiled flow data from some eight USGS discharge stations located within the Tampa Bay watershed. They primarily utilized USGS and EPC data to calculate annual loadings for nitrate-nitrogen, total organic nitrogen, fluoride, and total phosphorus. They concluded that much information on surface waters entering the bay existed, but that many streams do not have routine collection programs for discharge or water quality, and therefore, recommended an expanded data collection network be created.

Palmer and McClelland (1988), as part of FDER's Tampa Bay Water Quality Assessment (205(j) Water Quality Study), attempted to develop an assessment of historical and existing water quality in Tampa Bay and then devise a method that would use those data whereby water quality based effluent limitations could be determined for specific dischargers. They developed streamflow and loading inputs of nitrogen, phosphorus and BOD for a model covering eight tributary basins under both wet season and dry season conditions. Point source loadings from 1982 to 1983 were compiled primarily from NPDES Discharge Monitoring Reports on file at FDER. Palmer and McClelland referenced Hartigan and Hanson-Walton (1984) for much of their loading information details.

Flannery (1988) calculated nutrient loadings representing 1984-1985 conditions for most of the tributaries previously examined by Dooris and Dooris (1985), where streamflow and water quality data were available. His results supported the tributary ranking by nutrient loads estimated by Dooris and Dooris (1985), however, notable differences in loading magnitudes for several tributaries were discussed. Flannery (1988) attributed differences in loading estimates to differing methodologies of stream flow determinations and the fact that different stations were used for water quality data. He concluded that the two studies should not be compared to identify trends over time due to the differing methodologies.

Dames and Moore (1990) estimated non-point source loadings (TN, TP, O-P, BOD, DO, Zn, Pb, Coliform) for 75 minor subbasins in the overall Tampa Bay watershed. Their estimates did not utilize existing Tampa Bay tributary flow and concentration information but instead were based on runoff and treatment coefficients that were researched and developed for categories of land uses, soil types and stormwater treatment configurations. The report emphasizes that loading results provide a relative comparison of sub-basins, and that **results should not be used as a prediction of actual loadings to the bay.**

TAI Environmental Sciences, Inc. recently completed a draft interim nutrient budget of Tampa Bay for the SWFWMD's SWIM program. They addressed a variety of potential external loading sources including atmospheric, tributary, point source, stormwater, tidal exchange and groundwater. Their estimates of annual nitrogen and phosphorus loadings to Tampa Bay were in the same range calculated by Flannery (1989) and Dorris and Dooris (1985).

3.2.1 Review of Johansson and Lewis (1990) and Johansson (1991)

Two recent papers have investigated annual loadings relative to ambient water quality conditions in Hillsborough Bay (Johansson and Lewis 1990, Johansson 1991).

INTRODUCTION: Mr. Roger Johansson, of the City of Tampa (COT), Bay Study Group, has assessed major nutrient loading sources to Hillsborough Bay relative to several water quality parameters and biological indicators of water quality.

OBJECTIVES: Demonstrate the magnitude between relative nitrogen loading sources to Hillsborough Bay and the relationship between the trend of decreasing nitrogen loads to Hillsborough Bay and measured improvements in water quality and biological water quality indicators.

<u>LOADING CALCULATION/ESTIMATION METHODS:</u>

BAY SEGMENT Hillsborough Bay

TRIBUTARY **SOURCES:** Alafia River, Delaney Creek, Hillsborough River, Tampa By-Pass, Bullfrog Creek
FLOWS: USGS continuous flow measurements, water years 1980-1988

CONCENTRATIONS: Hillsborough County Environmental Protection Commission (EPC) monthly mid-depth total nitrogen concentration data from 1979-1981 and 1984-1987; USGS nitrogen concentration measurements for Alafia River at Lithia Springs, water years 1980-1988

POINT SOURCE

SOURCE: City of Tampa Hooker's Point Wastewater Treatment Plant, Cargill Fertilizer, Inc.

FLOWS AND CONCENTRATIONS:

Hooker's Point - Continuous flow measurements from 1975-1990.
- Flow proportionate composite samples (contains 375 samplings per day).

Cargill - Point source loadings from 1981-1990. Loadings from 1969-1980 were estimated equal to 1968 loadings.

FERTILIZER INDUSTRY

ESTIMATED: Assuming 0.1-.05% loss of ammonium phosphate product shipped from Hillsborough Bay.

WETFALL

AMOUNT: Rainfall measured at Tampa International Airport by NOAA.
CONCENTRATION: Rain content from Hartigan and Hanson-Walton (1984).

SUMMARY REMARKS

Tributary flows were calculated from USGS gaging stations that are located some distance upstream from the mouth of each tributary. Concentrations for the Alafia River were derived from an EPC station located near the USGS station at Lithia Springs and from the USGS Lithia Springs station. For other tributaries only the nearest EPC station to the USGS station were used for concentration data.

The resulting loads, although only rough estimates, represent a laborious and detailed review of available flow and concentration data. Additional loadings were added to the Alafia River (+25% flow) and Hillsborough River Dam (+30% of Dam loads) estimates in an attempt to address and compensate for loads entering below the gaging stations.

As shown in Table 3-1 below, the annual total nitrogen loading from major tributaries and other major external sources calculated by Johansson (1991) compares favorably with other recent estimates of loadings to Hillsborough Bay.

Table 3-1 Annual Total Nitrogen Loading Estimates for Hillsborough Bay from External Sources (kg x 1000/year).

Study	Tributaries	Other Sources	Total
Flannery 1989.	1456	-	-
TAI Env. 1991.	699-2167	1103-2061	1802-4228
Johansson 1991.	1100-1380	1090-2590	2190-3970

WATER QUALITY INDICATORS:

Nitrogen loadings were compared to ambient nitrogen concentration, bottom dissolved oxygen values at two representative EPC stations, phytoplankton biomass (chlorophyll a), blue-green alga concentrations (Schizothrix calcicola sensu Drouet), Secchi disk depths, a rhizophytic macroalga, Caulerpa prolifera), and seagrass coverage.

A long-term relationship was discovered showing that for every 150 metric ton reduction in annual total nitrogen loading to Hillsborough Bay, a corresponding 1.0 ug/l decrease in mean ambient chlorophyll a concentration was observed (Johansson 1991).

3.3 CONCLUSIONS AND RECOMMENDATIONS

1. Annual loading estimates published to date for major tributaries of Tampa Bay have provided adequate estimates of nutrient loadings considering the available information at hand.

2. The information available to accurately assess nutrient loadings to all segments of Tampa Bay is not available. An expanded data collection effort to better quantify coincident flow and concentration information, and to collect information at a greater frequency is needed. Such an expanded effort should include flow and concentration data collection programs for the large number of ungaged tidal creeks that predominantly occur in the Pinellas drainage basin which drains into Old Tampa Bay. Presently the relative and cumulative loading impacts of these tidal creeks is unknown.

3. The EPC has developed an excellent water quality data set that provides the best available information to characterize long term ambient nutrient conditions (except Silica), chlorophyll a, and dissolved oxygen for the major segments of Tampa Bay. Possible modifications to the current EPC monitoring program will be presented as part of Task 2 of our review and synthesis of historical Tampa Bay water quality data.

4. We recommend an assessment be made of the results of the ongoing USGS studies of the Alafia River, Hillsborough River, Palm River, and East Bay where nutrient loads (fluxes) are being measured at the mouth of these water bodies. Assuming these studies are successfully completed, the loading results should be compared to loading estimates during the same time period that incorporate upstream gaging station flow data with EPC or USGS monthly concentration data. This evaluation should help determine the relative accuracy of previous loading estimates.

5. Annual loading and water quality assessments, recently made available by Johansson, have compared conditions in late 1960 to late 1980. These assessments have made relevant and representative use of existing information in order to make reasonable loading estimates in Hillsborough Bay relative to water quality conditions in Hillsborough Bay.

   Johansson's approach could possibly be taken one step further by presenting loadings on a monthly basis in addition to annually. The historical flow and concentration information must be carefully assessed to determine if it is representative of monthly loading conditions. Preliminary inspection has revealed that many tributary loading measurements are less frequent than monthly, and such a data record may preclude the determination of comprehensive monthly loading estimates. Following the completion of Task 2 of this project, the TBNEP program will have monthly EPC data in a readily assessable PC database format. This will enable a variety of monthly water quality parameters in Hillsborough Bay for all stations, or selected groupings of stations, to be plotted against total Hillsborough Bay monthly loading estimates or against selected loading sources.

6. Additional "hindcasting" of nutrient loadings compared to water quality parameters is not recommended for Old Tampa Bay, middle, or lower Tampa Bay. Historical data to adequately characterize nutrient loadings into Old Tampa Bay is not available. Loading estimates from the Little Manatee River are probably as good as the tributary loadings estimates calculated for Hillsborough Bay. However, the greater tidal flushing expected in middle Tampa Bay relative to Hillsborough Bay, and the unknown status of the water exchange occurring between middle Tampa Bay and Hillsborough Bay, Old Tampa Bay, and lower Tampa Bay segments, would tend to weaken the probability of detecting cause and effect relationships between loads and bay water quality. The large tidal

flushing component relative to nutrient loads occurring in lower Tampa Bay should preclude the detection of cause and effect relationships between loads and bay water quality.

3.4 WORK PLAN

Goals and Objectives

Assess the historical data that is available to enable loading calculations on a monthly basis from major tributaries entering Hillsborough Bay. If the data will enable reasonable estimations of loadings, then proceed with loading evaluation.

Recommended Program

1. Compile historical data from all available sources to enable nutrient loading calculations on a monthly basis into a computerized database.

    A. Point source dischargers

        1) Wastewater treatment plants
        2) Industrial facilities

    B. Tributary discharges

    C. Stormwater?

    D. Atmospheric?

    E. Tidal?

2. Plot a series of monthly trends comparing baywide loadings to baywide averaged water quality parameters.

    For example, three water quality parameters could be compared to total nitrogen loads on a monthly basis for ten years.

    Each plot could illustrate 12 months of data, for three water quality parameters, for ten consecutive years (30 plots).

3. Plot a series of monthly trends comparing tributary or area specific loadings to area specific water quality parameters (150 plots).

4. Correlation statistics could be calculated for trends which appear to be related.

3.5 References

Dames and Moore. 1990. Urban stormwater analysis and improvement study for the Tampa Bay watershed. Prepared for the Southwest Florida Management District. 178 p.

Dooris, P.M. and G.M. Dooris. 1985. Surface flows to Tampa Bay: Quantity and quality aspects, pp. 88-106. In: S.F. Treat, J.L. Simon, R.R. Lewis, III, and R.L. Whitman, Jr. (eds.), Proceedings Tampa Bay Area Scientific Information Symposium.

Flannery, M.S. 1989. Tampa and Sarasota bays: Watersheds and tributaries, pp. 18-48. In: E. Estevez (ed.), Tampa and Sarasota Bays: Issues , resources, and management. NOAA Estuary-of-the-Month Series No. 11, NOAA, Washington, D.C.

FWPCA. 1969. Problems and management of water quality in Hillsborough Bay, Florida. Hillsborough Bay Technical Assistance Project, Technical Programs, Southeast Region, Federal Water Pollution Control Administration. 88 p.

Goodwin, C.R. 1987. Tidal-flow, circulation, and flushing changes caused by dredge and fill in Tampa Bay, Florida. U.S. Geol. Surv. Water-Supply Paper 2282. 88 p.

Hartigan, J.P. and S.A. Hanson-Walton. 1984. Tributary streamflows and pollutant loading delivered to Tampa Bay. Camp, Dresser & McKee, Inc. IX-22+ p.

Johansson, J.O.R. 1991. Long-term trends of nitrogen loading, water quality and biological indicators in Hillsborough Bay, Florida, pp. 157-176. In: S.F. Treat, P.A. Clark (eds.), Proceedings, Tampa Bay Area Scientific Information Symposium 2. 1991 February 27-March 1; Tampa, Fla. 528 p. Available from: TEXT, Tampa, Fla.

Johansson, J.O.R. and R.R. Lewis, III. 1990. Recent improvements of water quality and biological indicators in Hillsborough Bay, A highly impacted subdivision of Tampa Bay, Florida, U.S.A. Manuscript submitted to the International Conference of Marine Coastal Eutrophication, Bologna, Italy.

Lewis, R.R., III and E. Estevez. 1988. Ecology of Tampa Bay, Florida, an estuarine profile. Prepared for U.S. Department of Interior Fish and Wildlife Service, National Wetlands Research Center, Washington, D.C. 20240.

Lewis, R.R., III and R.L. Whitman, Jy. 1985. A new geographical description of the boundaries and subdivisions of Tampa Bay, pp. 10-18. In: S.F. Treat, J.L. Simon, R.R. Lewis, III, and R.L. Whitman, Jr. (eds.), Proceedings Tampa Bay Area Scientific Information Symposium.

Palmer, S.L. and S.I. McClelland. 1988. Tampa Bay water quality assessment (205(j) water quality study). Florida Department of Environmental Regulation, Water Quality Technical Series, Vol. 3, No. 17, Tallahassee, Florida.

TAI Env. 1991. Interim nutrient loading budgets for the Tampa Bay system. Prepared for Foth and Van Dyke and the Southwest Florida Water Management District by TAI Environmental Sciences Inc. Mobile, Alabama 36604. 74 p.

Troup, B.N. and O.P. Bricker. 1975. Processes affecting the transport of materials from continents to oceans, p. 133-151. In: T.M. Church (ed.), Marine Chemistry in the Coastal Environment. ACS Symposium Series 18, American Chemical Society, Washington, D.C. (NOT SEEN, cited in Wolfe, D.A., R. Monahan, P.E. Stacey, D.R.G. Farrow and A. Robertson. 1991. Environmental quality of Long Island Sound: Assessment and management issues. Estuaries 14: 224-236.)

4.0 RESPONSES TO COMMENTS ON DRAFT REPORT

HS

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Engineers | Planners | Scientists | Surveyors

March 5, 1992

Ms. Holly Greening
Tampa Bay National Estuary Program
111 7th Avenue South
St. Petersburg, Florida 33701

RE: Responses to Task 1 comments in letter dated January 13, 1992, from Holly Greening of the Tampa Bay National Estuary staff.

Dear Holly:

All Task 1 comments (see attached letter dated 1/13/92), are addressed in this letter. Some responses will be incorporated into the main text of the Draft Final Report, while other responses will only be found in this letter. A copy of this letter will be included in the Appendix of the Draft Final Report. Please refer to the January 13, 1992 letter for the actual comments; only comment numbers and the respective responses are given below.

Nitrogen Fixation

Comment 1. A review of Howarth et al. (1988) will be inserted as the seventh paragraph after Table 2-1 in the Draft Final Report.

Comment 2. "AREA" Table heading will be corrected. Lewis and Estevez (1988) reference will be added to the table. Other data sources for Table 2-1 are adequately referenced in the text.

Comment 3. Denitrification and its potential impact on N-fixation was discussed numerous times in the review. It is objective 2 in the work-plan and a statement of its necessity is also found under Recommended Program/General Study Design in the Work Plan.

Comment 4. Schizothrix, a non-heterocystis blue-green alga, has been mentioned as a potential nitrogen fixer. No evidence is available for N-fixation in this species in particular. A statement saying it should be included in a survey of nitrogen fixing cyanobacteria was included in the paragraph under Recommended Program/Habitat Specific Measurements.

Atmospheric Deposition

Comment 1. Information about the Verna Wellfield will be included in the second-to-last paragraph of the "Atmospheric Deposition on Tampa Bay" Section of the Draft Final Report.

Comment 2. ESE and TAI have already been spelled out in the reference section to the best of my information. None of the TAI documents in my possession indicate what "TAI" means other than "TAI."

Historical Loadings of Bay Segments

Comment 1. Cargill Fertilizer will be added to "Source" listings.

Comment 2. The frequency of tributary loading estimates in the data record will be discussed in #5 of the "Conclusions and Recommendations" Section of the Draft Final Report.

I trust you will find these responses acceptable. We are currently producing the Draft Final Report with the above mentioned additions and corrections, and we look forward to your comments following the submittal.

Sincerely,

Andrew P. Squires

Andrew P. Squires
Project Manager

cc: Doug Robison, KEA
File #5042-001.N637 (L3107)

January 13, 1992

Andy Squires
King Engineering Associates, Inc.
5400 Beaumont Center Boulevard, Suite 460
Tampa, Florida 33634

Dear Andy:

As we discussed last week, King Engineering's contract with the Tampa Bay National Estuary Program to perform a Synthesis of Historical Water Quality Data will be amended to include a no-cost time extension, with the following stipulation. The due date of the entire Draft Final Report has been extended from February 3 to March 16, 1992, with the stipulation that two bound and one unbound copies of the results of the long-term time series plots (with interpretation), at a minimum, be submitted to the TBNEP by Monday, February 3, 1992. All other contractual conditions remain unchanged. Please sign, date, and witness the enclosed Addendum to Contract form, and return to Karen Lind in our office.

Several minor comments were received from the TBNEP Review Committee (including the TBNEP staff review) for this project regarding your review and summary of the literature pertaining to the refinement of the interim SWFWMD-SWIM Tampa Bay nutrient budget. You and I have discussed several of these already; however, please address them in your Final Report.

Overall: Update BASIS II references from "in press" to the final citation.

Nitrogen Fixation

1). Several reviewers commented that the review by Howarth, et.al. 1988, should be included in the Nitrogen Fixation section. Howarth et.al. found that water column N-fixation was generally unimportant in estuaries, with the exception of those with high concentrations of N-fixing cyanobacteria.

2). Table 2-1. Should "AREA" column title be "RATES"? Also, for clarity, please include references for the values in the table (i.e., km is from Lewis & Estevez 1988 and the current "AREA" column is from Capone 1983).

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3). Please include a brief discussion of the value of including denitrification measurements as well as N-fixation in the Recommended Program general study design, and (if useful) how it might be incorporated into the general study design.

4) Is Schizothrix thought to be a nitrogen-fixer in Tampa Bay?

Atmospheric Deposition

1). There is a National Acid Deposition Program (NADP) collection site located at or near the Verna Wellfield. Please include information from this site- I believe that there should be some additional nutrient concentration information collected from this station. The NADP contact is Jay H. Gibson, Colorado State University, Ft. Collins. Phone number (303) 491-1978.

2). Please spell out ESE and TAI in the References.

Ocean and Bay Segment Exchanges

no comments

Historical Loadings of Bay Segments

1). pg. 41. In addition to City of Tampa Hooker's Point Wastewater Treatment Plan, SOURCE should also include Cargill Fertilizer.

2). pg. 43. Under number 5, second paragraph. Many tributary loading measurements are monthly or less frequently, which may preclude a more detailed loading estimate than annually.

Finally, as I mentioned the other day, we are requesting that you and/or your research team present a brief (15 minute) review of the results of your investigations (focusing on the time series trends) to the Modeling Strategy Workshop on February 12, and a more detailed report (30-45 minutes) to the entire TAC on March 5. Please let me know if I can answer any questions concerning the amendment, requested revision, or the presentations.

We look forward to seeing the results of this important project.

Sincerely,

Holly

Holly Greening, Project Manager

cc: Richard Eckenrod, TBNEP
Karen Lind, TBNEP
Manny Pumeriega, TBRPC
Dean Ullock, EPA Region IV