Ecological Impacts on Biscayne Bay and Biscayne National Park from Proposed South Miami-Dade County Development, and Derivation of Numeric Nutrient Criteria for South Florida Estuaries and Coastal Waters

Final Report

A report prepared by the Southeast Environmental Research Center of Florida International University for the National Park Service, South Florida Natural Resources Center and the South Florida/Caribbean Cooperative Ecosystem Studies Unit

by

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EXECUTIVE SUMMARY

Water quality of South Florida's estuaries and coasts is the result of a long-term and poorly understood interplay of local, regional and global forcing, drivers, pressures and responses. South Florida's coastal and estuarine waters have experienced the impact of anthropogenic interventions since the early 1900's, including major disruptions of its hydrology and also sustained urban and agricultural development. Nevertheless, Biscayne Bay remains very productive and its biodiversity is noteworthy. Its waters nurture 800 species including 150 species of shrimp, crabs, sponges and lobsters, 512 tropical and temperate fish species, and prolific benthic communities dominated by seagrass meadows. Furthermore, its shorelines and intertidal areas are major stopover of migrating shorebirds where manatees, dolphins, alligator and crocodiles, also thrive. To protect these valuable resources, the U. S. Congress designated 69,605 hectares (172,000 acres) of central and southern Biscayne Bay, at the southeastern tip of the Florida Peninsula, as Biscayne National Park (BNP) in 1982. As such, BNP became the largest marine park in the U.S. national park system. The Park is bounded by protected areas on the south and east by the Florida Keys National Marine Sanctuary and on the north by the extension of the Biscayne Bay Aquatic Preserve, but its western boundary is with the Miami City metropolitan area, where sprawl growth and resource demands pose serious threats to the park integrity and to its natural resources.

The main objectives of this project are: first, to develop an understanding of nutrient inflows into Biscayne Bay, their effects on the bay's water, and to evaluate the ecological impacts on Biscayne National Park's resources associated with Miami's future population growth and land use changes; and second, the derivation of protective numeric nutrient criteria (NNC) for South Florida estuarine and coastal waters. Several institutions have implemented water quality (WQ) monitoring for over two decades in South Florida. We have selected Florida International University's database as a reference dataset given its spatial-temporal coverage at fixed 353 stations, completeness of measured variables (over 725,000 WQ measurements) and its sustained field and analytical protocols along the period of record. Other available databases would be used for comparison and verification purposes.

Although Biscayne Bay waters are in general oligotrophic, water composition is not uniform across the bay, and responds to magnitude and type of intervention. North Bay, the most affected by urban development, is the highest in total phosphorous, and chlorpphyll-a (CHLa) concentration, and relatively high silica (SiO2), inorganic nitrogen and turbidity, while oceanic waters on the reef-track display the lowest nutrient concentrations. North-central bay, impacted by urban and industrial development, shows values which are intermediate for all variables, while South-central bay, impacted by agricultural activities and urban development in its watershed, has the lowest CHLa, SiO2 and turbidity, and highest inorganic nitrogen concentrations. Finally, South Biscayne Bay, surrounded by wetlands and practically devoid of urban development in its watershed, has the lowest salinity and highest total nitrogen (TN), total organic nitrogen (TON) and total organic carbon (TOC).

We calculated descriptive statistics and performed long-term trend exploration of the time-series, to gain insight into patterns of behavior along the period of record (POR) for all relevant biogeochemical parameters. This exploration was performed with Akritas-Theil Sen and Z-score cumulative sum charts (Z-CUSUM) methodologies. The spatial-temporal variability within estuaries and coastal waters in individual South Florida basins called for a holistic approach to basin segmentation to account for variability not only dictated by a given nutrient concentration level, but by the combination of stressors conditions (nutrients, water clarity, climate, weather, extreme events, geomorphology, circulation and exchange, management, etc.). Basin segmentation was accomplished with an objective classification of station combining Principal Component Analysis (PCA) and Hierarchical Clustering methods in tandem. Besides statistics, spatial extension and pattern, geomorphology, water circulation and benthic ecosystem distribution played a major role on the final delineation of 40 segments extending from Biscayne Bay in the east to Dry Tortugas in the southwest and to Pine Island Sound in the northwest. This segmentation, or a modification of it, has been adopted by both, EPA and FDEP as fundamental framework for the derivation of numeric nutrient criteria for South Florida estuaries and coastal waters.

Substantial changes and climate-driven regime shifts have been documented for water quality in South Florida. The most relevant changes we identified in Biscayne Bay were those occurring in the early-to-mid nineties from lower to higher precipitation rates, leading in turn to a generalized region-wide decline in water nutrients and chlorophyll *a* (CHL-a) concentrations (Briceño and Boyer 2010). Based upon a detailed literature review and a recent assessment of natural resource conditions in Biscayne Bay and BNP natural resources (Harlem et al. 2009), we evaluated threats and stressors on water resources of BNP attempting to improve understanding of its resources, in order to inform management of the identified threats directly related to human impacts.

Given the oligotrophic nature of its waters, South Florida's ecosystems respond very rapidly to small nutrient enrichment, especially to increases of phosphorous, the limiting nutrient. Biscayne Bay watershed displays diverse agricultural, urban and wetland cover, leading to differences in freshwater characteristics as well as in bay water composition. Median NOx concentrations are higher in agricultural runoff than in urban or wetland runoff; median concentrations of ammonia, TP, and SRP tend to be higher in urban runoff than in wetland or agricultural runoff; and median TON concentrations are higher in wetland and urban runoff than in agricultural runoff.

Legacy and current-use pesticides, herbicides and their metabolites have been consistently detected, often at low concentrations, in canals and near-shore locations. Metals display little spatial difference except for lower values near Fisher Island and relatively high concentrations in sediments near the mouth of the Miami River. Also, some heavy metals are highest near marinas, where antifouling compounds were also high. Polychlorinated biphenyls (PCBs) are present in the highest concentrations and 5 times higher in male dolphins with sighting histories in the northern, metropolitan area of Biscayne Bay than to the south. Polynuclear aromatic hydrocarbons (PAHs) are commonly present in sediment samples, at relatively low concentrations with higher values occurring in marinas.

Climate change threats to Biscayne National Park resources are linked to changes in rainfall and evaporation patterns affecting the amount of available freshwater and potentially causing prolonged droughts and/or flooding; saltwater intrusion into the coastal aquifers and public water supply wells; reduction of coastal stormwater release capacity due to sea level rise; and changes in tropical storm and hurricane activity with increased surge levels. One aspect of great concern is the release of sediment and its associated nutrients and pollutants to the marine system as coastlines erode due to sea level rise and storm activity.

The Florida Department of Environmental Protection (FDEP) and the US Environmental Protection Agency (EPA) are in the process of developing numerical nutrient criteria for estuaries and coastal marine waters for Florida. Given the scarcity of information on the estuarine effects of nutrient enrichment on South Florida ecosystem components and the well documented relationship between nutrients and CHL-a, we approached the derivation of nutrient (Total Nitrogen and Phosphorus) concentration thresholds for each segment by identifying those concentrations above which significant increases in CHL-a occur. For this purpose we calculated and plotted CHL-a z-scored cumulative sum charts (Z-CUSUM) along nutrient gradients, mimicking cumulative results of nutrient dose-experiments. This allowed us to identify the successive phytoplankton biomass (CHL-a) reactions to nutrient enrichment, to select the main threshold and to assess the potential health status of phytoplankton communities in the water column.

The calculated thresholds fix the upper limit for mean nutrient concentration above which a mean NNC would not be considered protective of the actual segment's baseline conditions with respect to phytoplankton biomass. Hence, we propose the development of protective nutrient criteria that include only two limits, Long-Term Limit (LT-L) and Upper Limit (UP-L). The LT-L is the expected mean nutrient concentration in a water body at which no adverse effects would be expected or the effects would be insignificant for the type of designated use. The LT-L is equal to the nutrient threshold. The UP-L is a nutrient upper bound concentration of the LT-L that accounts for natural variability in nutrient drivers. The UP-L is the 80th percentile of a normal distribution with mean equal to the threshold and standard deviation equal to the nutrient's standard deviation for the segment under consideration. We suggest the UP-L should not be breached more than once in a three year period. The selection of the 80th confidence interval and one- in-three years criteria limits Type I error rates to about 10 percent.

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Acknowledgements
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INTRODUCTION

The history of Biscayne National Park begins with the authorization of the Biscayne National Monument by the Act of October 18, 1968 (82 Stat. 1188; 16 U.S.C. 450qq). Later, in June 28, 1980, of all Biscayne National Monument lands, waters, and interests therein were finally incorporated within and made a part of Biscayne National Park (BNP). Finally, the U. S. Congress designated 69,606 hectares of central and southern Biscayne Bay (BB) as Biscayne National Park (BNP) in 1982. As such, BNP became the largest marine park in the national park system. BNP is bounded by protected areas, on the south and east by the Florida Keys National Marine Sanctuary and on the north by the extension of the Biscayne Bay Aquatic Preserve, but its western boundary is with the city of Miami. Being adjacent to a major and fast-growing metropolis like Miami presents serious threats to the park integrity and to its resources, hence, besides monitoring and surveillance of those resources it is necessary to evaluate the potential impacts from land-use changes, such as those caused by industrial and urban development.

There are two main objectives in this project. One is to develop an understanding of nutrient inflows into BB, their effects on the bay's water quality, and to evaluate the ecological impacts on BNP's resources associated with future population growth and land use changes as detailed on the Miami-Dade County Watershed Study and Plan (MDWSP), which is covered in Sections 1 through 5. The other objective is the derivation of numeric nutrient criteria for estuaries and coastal waters in South Florida, which is discussed in Section 6.

The report provides a summary assessment of condition of the water resources of BNP aimed to identify and to evaluate threats and stressors that act on BNP natural resources posing risks to its biological integrity. The report is based exclusively on synthesis and exhaustive analysis of pre-existing data and covers resource groups located on terrestrial, freshwater and coastal-bay-marine areas within and adjacent to BNP. A regional scope is adopted, given the profound transformations experienced in the Bay watershed and the forecast changes derived from the MDWSP and also from the Comprehensive Everglades Restoration Plan (CERP).

The National Park Service Inventory and Monitoring Program (NPSIMP) use physical, chemical and biological elements and processes of park ecosystems to define "Vital Signs" that represent the overall health and condition of any given park. The South Florida/Caribbean network of the NPSIMP identified vital signs of concern to the managers of national parks in the region, nested within a hierarchical conceptual structure. NPSIMP Level 1 groups the vital signs into 5 classes – geology and soils, water, biological integrity, human use and landscape patterns and processes. Each one of these categories includes vital signs that are relevant to the conditions of the biotic resources of BNP. Given the fundamental relevance of water and its quality to ecosystem structure and functioning, water is the center of attention in the present study. Geology, soils, human use and landscape patterns and processes are considered under the scope of their impacts on water availability and quality. Within this general conceptual framework, we will describe the water resources of BNP.

To accomplish the objective above, broadly defined tasks shown in Table 1 were proposed. This Final Report has been structured into six sections, as follows:

SECTION 1: Data Collection and Quality Assessment-Control

Describes the data sources, the verification of their quality and steps taken to assure their potential and limitations, and presents the compiled numeric information in a Master Database in Microsoft Access format.

SECTION 2: Park Description

This section includes a summary description of BNP resources, highlighting relevant pre-modification system dynamics as well as those changes natural and/or anthropogenic, leading to WQ modifications.

SECTION 3: Statistical Analysis

Describes the methods applied for statistical characterization of water quality (WQ) in BNP and surrounding water bodies, as well as methods and results of trend analysis and biogeochemical segmentation of BB waters.

SECTION 4: Box Modeling

In this section the conceptual structure of the box-model developed in the study, as well as its results are presented. Given that box-modeling was performed in close cooperation with FIU and under sub-contract by Cetacean Logic Foundation Inc. (CLF), only a modified version of their Executive Summary is given in the body of this report, and the full CLF report is presented as Appendix 1.

SECTION 5: Summary of threats to Biscayne National Park Resources

This chapter summarizes and sets a hierarchy for the most relevant threats posed to BB water resources. It is intended to improve understanding of BNP resources in order to help guide BNP management to properly address the identified threats.

SECTION 6: Derivation of Numeric Nutrient Criteria

In this section we discuss the methods and results for the derivation of protective numeric nutrient criteria for TN, TP and CHLa, approached within the framework of stressor-response relationships.

Table 1 Summarized Purposes, Tasks and Goals of the study

PURPOSE	TASKS	GOALS
Synthesize existing WQ data	1- Literature Review 2- Collect data from SFWMD, DERM, FIU, CORPS, DBHYDRO and others 3- QA/QC data 4- Statistical Summary	* Provide general overview of WQ conditions in BNP and BB
Evaluate XPSWWM	5- Familiarization with project concept, components, characteristics 6- Evaluation of Model input/output to estimate Total Maximum Daily loads 7- Preapration of report on findings and conclusions	* To evaluate the use of the hydrologic/hydraulic model XPSWMM and the watershed loading model by an engineering consultant to estimate loads to BB for Miami/Dade County government
Recommended WQ Targets for BNP/BB	8- Review historicalWQ data for BNP to prepare a list of selected constituents ecological indicators and targets 9- Identify areas of most concern within BB with focus on BNP 10- Organize Expert's Workshop to evaluate indicators and targets	* Provide a general overview of WQ in BNP and a comprehensive list of ecological indicators and recommend preliminary numeric targets for selected surface WQ constituents * Identify areas within BNP that have been heavily, moderately and minimally impacted
BB Box Model development and calibration	11- Develop, calibrate and validate mass-budget calculations, and develop approach for estimating nutrient concentration in response to loadings	* Develop salinity-residence time modeling tool for BB waters
Evaluate WQ and ecological conditions in BB under proposed Watershed Study alternatives	12- Generate and run a series of scenarios in a box-model for BB including output from preferred WPSWMM scenario 13- Analyze results from proposed alternatives	* Estimate salinity and nutrient concentration in BB in response to loading scenarios * Provide classification of areas within BNP from box-modeling results that would become heavily, moderately, and minimally impacted * Provide comments on preferred alternative and its impact on BB ecosystems
Derive Numeric Nutrient Criteria for South Florida Estuaries and Coastal waters	14- Collect WQ data for South Florida estuaries and coastal waters 15- Perform necessary QA/QC 16- Develop a classification South Florida water types 17- Derive protective Numeric Nutrient Criteria for TP and TN	* Estimate TN and TP numeric nutrient criteria for 40 South Florida sub-basins * Estimate TN and TP numeric nutrient criteria for 40 sub-basins
Summarize Findings	18- Prepare Final Report	* Present recommendations to Watershed Advisory Committee

SECTION 1:
DATA COLLECTION AND QUALITY ASSESSMENT/QUALITY CONTROL

DATA SOURCES

The report presented herewith is an assessment of the conditions of water resources in BB, including BNP, and its relationship to biotic resources. The study is based on the evaluation of existing information on the bay natural resources, especially long-term data generated by networks of monitoring stations established in and around BB and its watershed. Additionally, data from individual research projects from various institutions dealing with diverse natural resources have been incorporated in our database (Appendix 2 and 3).

The most important sources of WQ data for South Florida (SoFlo) are the following:

i. NOAA/UM/RSMAS: Under the NOAA/AOML/South Florida Program surveys are conducted to study the hydrography and water quality of South Florida. These cruise surveys collect data for temperature, salinity, percent light transmission at l=660nm, chlorophyll a fluorescence, and CDOM fluorescence. In addition to the underway measurements, there are discrete sampling observations taken at stations which are used to calibrate the underway instrumentation and calibrate supplementary data. The result is a quickly produced, high spatial resolution “snapshot” of the temperature, salinity and water quality parameters for SoFlo ecosystem. No detection limit data is provided. (http://www.aoml.noaa.gov/sfp/data.shtml).

ii. DERM. The Biscayne Bay Surface Water Quality Monitoring Program is an ongoing routine surface water quality sampling program for BB and its watershed canals. The program began in 1979 and includes monthly surface water sampling for relevant WQ parameters to our research. DERM monitoring dataset included chlorophyll a (CHLa), color, turbidity, total Kjeldahl nitrogen (TKN) and orthophosphate (TPO4) sampled bimonthly; and coliforms (total and fecal), total ammonia (TNH3), nitrite+nitrate (NOx), and total phosphorus (TP), which were sampled monthly. Additionally, field measurements included, dissolved oxygen (DO), salinity, temperature, specific conductance, pH, photosynthetically active radiation (PAR), turbidity and apparent water color. Analysis for cadmium, copper, lead and zinc as well as total suspended solids were performed quarterly at over 105 stations throughout Miami-Dade County. Updated data was kindly supplied by Mr. Steve Blair. (http://www.gcrc.uga.edu/wqmeta/app/organizations.asp)

iii. USGS. Hydrological and water quality data has been recorded by many diverse research programs in the Everglades, Florida Bay and BB as a part of the U.S. Geological Survey South Florida Program, including satellite data for Florida Bay. http://sofia.usgs.gov/exchange/index.php

iv. EPA. WQ data from a variety of research and monitoring programs is available throughout the STORET Data Warehouse, which is a repository for water quality, biological, and physical data. (http://www.epa.gov/storet/).

v. FIU: a) SERC. Water quality data has been collected since 1989 and has been monitored under the South Florida Water Management District and EPA funded Water Quality Monitoring Network since 1991 for stations in Florida Bay, and 1993 in BB. Measured parameters include dissolved and total nutrients (N, P, C, SiO_2), CHLa, salinity, pH, temperature, DO, alkaline phosphatase activity, and Kd. (http://serc.fiu.edu/wqmnetwork/); b) FCE-LTER. The FCE LTER Program was established in May of 2000 in SoFlo to study how hydrology, climate, and human activities affect ecosystem and population dynamics in the ecotone and, more broadly, in the Florida Coastal Everglades. WQ data is available along transects from freshwater sites in the Everglades to West Florida Bay. The FCE-LTER website is also an outlet for the NPS data. (http://fcelter.fiu.edu/data/).

vi. NPS. Biscayne National Park, Miami-Dade County and United States Army Corps of Engineers are involved in monitoring hydrodynamics and salinity in Biscayne National Park, especially in the western portion of central and southern BB. The network consists of 36 sampling locations (14 instrumented at surface and sea floor, 22 with bottom units only) and records high frequency data (every 15 min.), including temperature, salinity, and depth. Sarah Bellmund from Biscayne N**a**tional Park kindly supplied the dataset

vii. NADP. The National Atmospheric Deposition Program (NADP) is a cooperative effort between federal, state, tribal and local governmental agencies, educational institutions, private companies, and non-governmental agencies to monitor precipitation chemistry. It provides data on the amounts, trends, and geographic distributions of acids, nutrients, and base cations in precipitation. Data for station FL-11, located at Everglades National Park, was downloaded from NADP website (http://nadp.sws.uiuc.edu/NADP/)

viii. DBHYDRO is the South Florida Water Management District's corporate environmental database which stores historical and up-to-date environmental data (hydrologic, meteorologic, hydrogeologic and water quality data) for the District’s 16-county region. (http://www.sfwmd.gov/portal/page/portal/xweb%20environmental%20monitoring/dbhydro%20application)

We have selected FIU’s database as our WQ reference dataset for bay waters given its spatial-temporal coverage at 39 fixed stations (Fig 1.1), completeness of measured variables (over 96,000 WQ measurements) and its sustained field and analytical protocols along the selected period of record (1991-2008). Other available databases, especially DERM’s database (Fig 1.2) would be used for inland (freshwater) and marine water quality assessment and for comparison and verification purposes in bay waters. NOAA’s database (Appendix 3) would be used with the same purpose for bay waters.

FIU unfiltered surface water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), TP and CHLa. Additionally, filtered surface water samples were analyzed for soluble reactive phosphorus (SRP), NOx, nitrite (NO_2^-), Alkaline Phosphatase Activity (APA), ammonium (NH_4^+) and silica (SiO_2). Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as NO_X^- - NO_2^- and dissolved inorganic nitrogen (DIN) was calculated as NO_X^- + NH_4^+. Details of sampling methodology and laboratory analysis have been described elsewhere (Boyer and Fourqurean 1999; Boyer and Briceño, 2007).

Preservation procedure for DERM samples was by acidification of unfiltered water samples, so adsorbed species and labile compounds, if present, would be incorporated into solution. FIU samples were not acidified and either unfiltered for total nutrients or filtered for dissolved nutrients; hence, direct comparison of some analytical results between DERM and FIU is not recommended. A detailed inter-laboratory comparison analysis was completed by Hunt and Todt (2006) using stations from FIU and DERM programs. Samples were either co-located (four stations) or within a few hundred meters of each other, and most reported measurements were from surface samples. Only salinity and dissolved oxygen were reported for depths in excess of 1 meter. Salinity, DO, NOx and CHLa values reported from both programs were similar and acceptable correlation were observed for salinity, DO and NOx between samples collected within a 24-hour window. Total phosphorous values were slightly different between programs perhaps due to differences in sampling schedule.

Major differences between DERM ammonia and FIU ammonium values were impossible to reconcile stoichiometrically, perhaps due to differences in sample preservation and analytical methods, let alone time and spatial differences in sampling events. Acidification of unfiltered water samples by DERM would incorporate nitrogen species, either contained in labile compounds or loosely bound on suspended particles, to the liquid phase. This combination of methodological differences would render higher total ammonia values for DERM than corresponding FIU ammonium data. In summary, FIU's dissolved ammonium measurements (Boyer and Briceño 2006) are not comparable to DERM's total ammonia measurements (Zhang et al. 1997). Each parameter seems to express a totally different chemical character of BB waters.

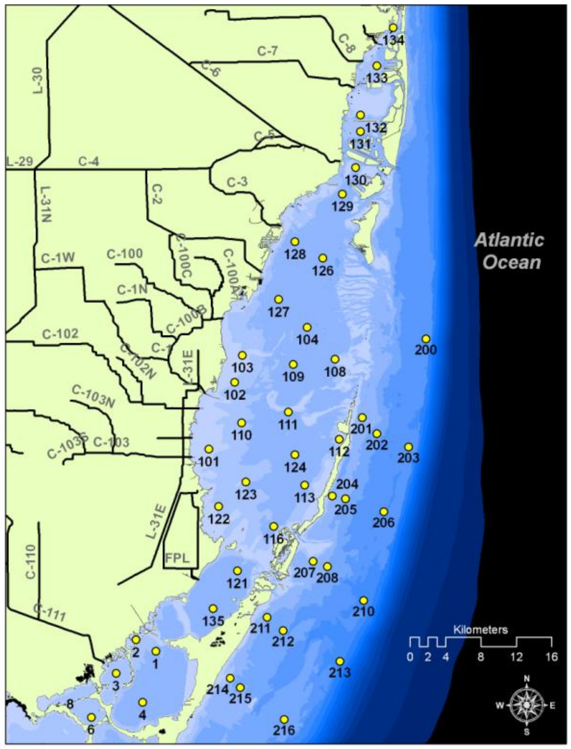

Figure 1.1: Location of FIU sampling sites in Biscayne Bay.

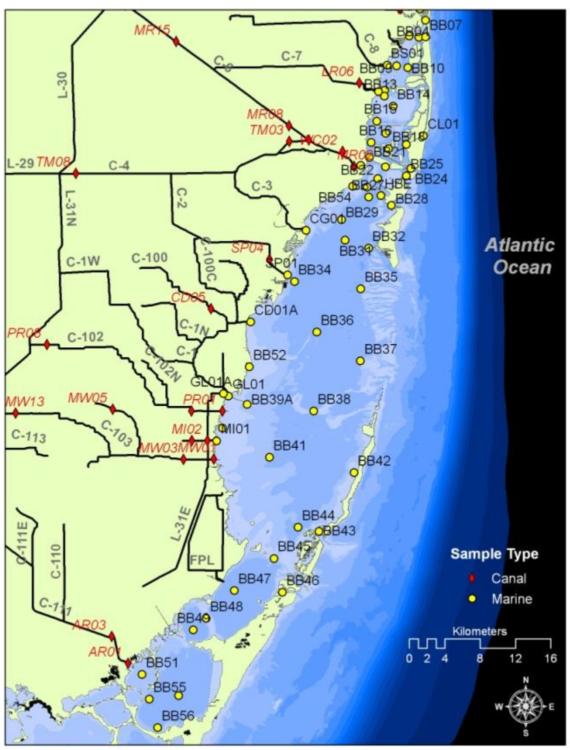

Figure 1.2: DERM sampling sites in Biscayne Bay and its watershed

National Park Service data includes daily and monthly averages based on 15 min samplings of temperature, conductivity, salinity and depth, from 47 sampling sites (Fig 1.3). Monitoring began in 2004 and it is still active.

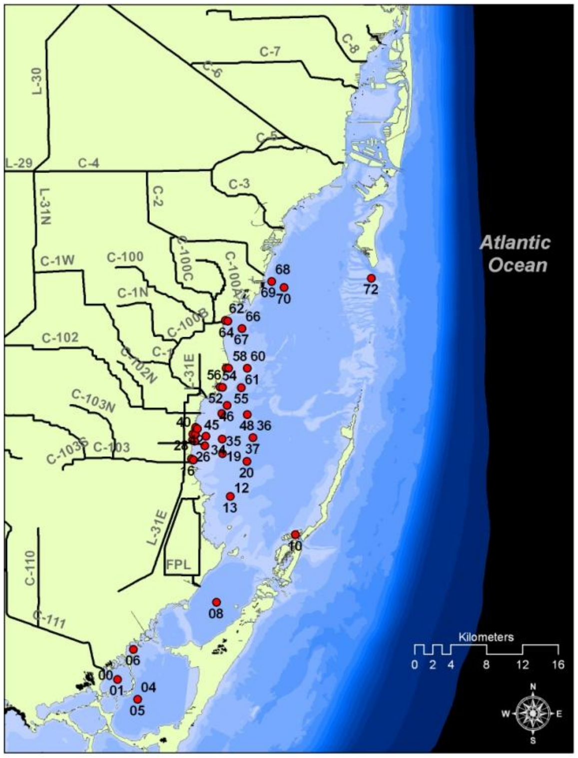

Figure 1.3: Location of BNP sampling stations in Biscayne Bay.

The USGS data set contains groundwater, rain and well data. NOAA data sets include rain and salinity measured along about-monthly cruises of BB. NADP data set contain chemical Ca, Mg, K, Ca, NH4, NO3, Cl, SO4, pH, conductivity and precipitation.

Besides nutrients and physical chemical properties of surface waters in the bay and its immediate watershed, we collected data for metals, pesticides, herbicides, and organic and inorganic pollutants in waters and sediments to identify areas most impacted by these contaminants. Among the studies, usually short-term and lasting less than 4 years and/or covering restricted areas, we could mention those of Brand (1986), Cantillo and Lauenstein (2004), Corcoran (1984, 1984b), McKinley (1995) and Carnahan (2005, 2008).

QUALITY ASSESSMENT / QUALITY CONTROL

Water quality data was subjected to detailed QA/QC procedures. The initial steps are summarized in Figure 1.4. In general it involved corrections for negative values, flagging values below detection limit (BDL), detection of data gaps and potential outliers, and correction of miscellaneous typographical errors and formatting. Detection limits (DL) posed a special complication because of their variability along the period of record (POR) and/or lack of reporting levels. When DLs were available, values below detection limit (BDL) were flagged for further statistical analysis with applicable methods (Helsel 2005). Special care was taken on suspected statistical outliers, because ecological data may contain extremely high (i.e. CHLa data) or extremely low (i.e. salinity) values which are in fact valid system responses, so their deletion or substitution would impair a correct analysis. Outlier identification in data sets was part of the data screening process done routinely before further statistical analysis. The simplest case was the identification of univariate outliers in symmetric distributions where extreme data values to the right or left are the obvious outlier candidates. Generally in our case, most potential outliers to the left are bundled together in the non-detects and are incorporated as such in the statistical treatment. In skewed distribution, as in most ecological data sets, the suspect outliers are likely to be the extremes of the longer tail (extreme high).

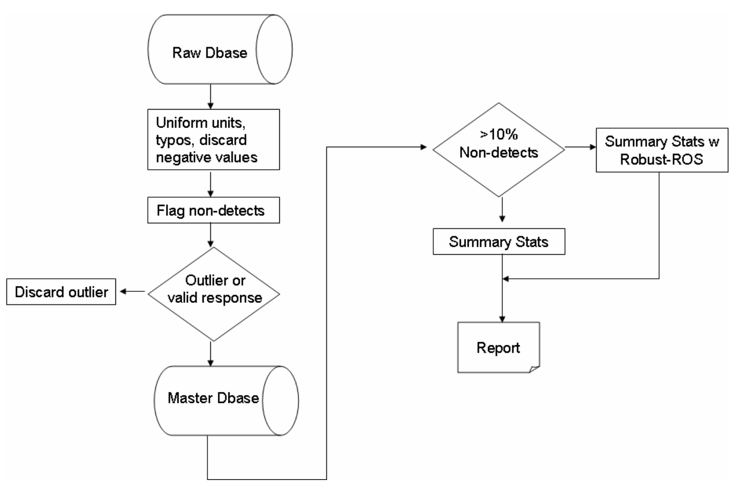

Figure 1.4: Summary of QA/QC procedures and summary statistics calculation for WQ data

Criteria for assessing if a value is an outlier are complicated (Burke 2009; Montgomery 2001) because ecological data do not necessarily follow a specific type of statistical distribution. We applied the golden rule of “no value should be removed from a data set on statistical grounds alone”. First, we used box-plots as non-parametric tool to display data without making any assumptions of the underlying statistical distribution to isolated potential outliers. The box and- whisker plot is a powerful statistic as it shows the median, range, the data distribution as well as serving as a graphical, nonparametric ANOVA. The center horizontal line of the box is the median of the data, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch in the box is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are considered significantly different.

Each suspected outlier was analyzed individually to assess its validity when the overall time-series was displayed together with its corresponding z-scored running-sum (Zcusum) plots. If the value belonged to a dataset where extreme values are expected, like in CHLa or salinity, we verified if the occurrence(s) responded to seasonality or to extreme events of canal flows or storm events. If so, the value was not considered an outlier favoring knowledge-based criteria over purely statistical considerations. If the value was a unique (way above/below any other value) and isolated occurrence, not appearing periodically and/or was not accompanied by high values before and/or after its occurrence, it was flagged as outlier and was discarded before calculation of summary statistics. This approach, although time-consuming and perhaps tedious, renders the best results. Major complications arise when analyzing metal and pollutant concentrations. These data are usually the result of eventual sampling responding to specific needs, hence, data is scattered in space and time, values show extreme spread, and a direct connection with other data sets is rarely possible. Finally, after QA/QC procedures were completed, data were consolidated in a Master Database as described in Appendix 3.

SECTION 2:
PARK DESCRIPTION

Most of Biscayne National Park is within BB, a shallow subtropical estuary located along the southeast coast of the Florida Peninsula (Fig 2.1). This coastal lagoon extends 56 km from north to south and up to 13 km wide, for a total marine ecosystem of about 701 square km, and a watershed spanning 2,434 square kilometer, most of it draining urban and agricultural lands. The bay is bordered on the east by barrier islands separating it from the Atlantic Ocean, and is rimmed on the west by the City of Miami. Most of BB is shallower than three meters (Wang et al. 2003; Harlem et al. 2009) and deeper waters are only found in the North Central portion of the bay and in eastern Card Sound.

Biscayne Bay has been traditionally divided for purposes of discussion and analysis intro three general areas differing in geographical and hydrodynamic characteristics: north (from Dumfoundling Bay south to the Rickenbacker Causeway), central (extending from the Rickenbacker Causeway south to Black Point), and south BB (from Black Point south to Barnes Sound) (Wang and van de Kreeke, 1994; Corcoran et al., 1984; SFWMD 1995; Bellmund et al. 2009). Our modeling work focus on Central and South BB and the inland watershed to the west, including urban, industrial and agricultural areas as integral part of the analysis. The southern limit of North-central BB is marked by the shallow waters on the Featherbed Banks. This portion of the bay is significantly affected by urban development in the communities of Coral Gables and Coconut Grove and canal inputs on the west and Virginia Key and Key Biscayne on the east, and experiences the most active ocean exchange of the overall bay through the “Safety Valve” (Fig 2.1). On the west margin of South-central BB urban development is less dense and a fringe of wetlands rims the shoreline. While direct ocean exchange is limited in South-Central BB, large volumes of freshwater are contributed from canals, especially from Black, Princeton, Military and Mowry canals

(Fig 2.1). Finally, Card Sound, Barnes Sound and Manatee Bay make South BB. These water bodies are somewhat separated from the rest of the bay by extensive shallow banks and have restricted oceanic exchange. Their watersheds are mostly located within Everglades wetlands with little urban development.

Figure 2.1: Biscayne National Park and adjacent areas.

Manatee and Barnes Sound are more like Florida Bay in terms of ecosystem structure and biogeochemistry (Boyer and Briceño, 2006; Rudnick et al. 2006), but their hydrological connection is with Card Sound. Besides run-off from the wetlands, surface freshwater contribution to South BB is mostly from the C-111 canal.

GEOLOGY AND SOILS

The outcropping rock units underlying BB and its watershed are carbonates of the Plio-Pleistocene Fort Thompson and Caloosahatchee formations and the Quaternary Miami Limestone and the Key Largo Formation (Parkinson, 1989; Wanless et. al 1994). The Pleistocene Epoch (1.8 million years to 10,000 years ago) was a period of intense shifts in sea level caused by cyclic changes in the earth ice cover. Those sea level fluctuations resulted in the accumulation of the Fort Thompson, the Key Largo and the Miami formations. The Fort Thompson Fm. is made of marine and fresh water shell, sand and lime mud facies typical of shallow coastal environments. The Key Largo Fm. is dominated by coralline and reef facies and forms the rock structure of the Florida Keys including most of the islands within the Park. The Miami Formation, contemporaneous with the Key Largo, forms the low ridge along the Park's west side and the bottom floor of much of BB. Its oolitic sand, carbonate sand and burrowed mud facies are interpreted as marine inner-shelf deposits influenced by high tidal fluctuations. The karst surface developed on this marine unit has the greatest effect on the park's resources as the principal geomorphological control.

The Holocene Epoch, which began 10,000 years ago, includes the recent modifications done by man. The dominant Holocene sediment in the Park is carbonate sand comprised of a gamut of biologically derived components as Halimeda plates, mollusk fragments, cohesive pelloids, coral fragments, and invertebrate tests (Wanless et al. 1976, 1994). Muddy carbonate sediment is the common matrix component and is derived from the breakdown of biological carbonate material. Quartz sand is the third most common sediment and is derived from terrestrial sources usually transported to the region by longshore drift and submarine currents.

Figure 2.2 shows the sediment types in BB (Wanless 1976). Holocene sediments and soils provide the habitat for most plant species and many important animal species in the Park. Much of the bottom of BB is bare rock, especially to the south. Thicker intervals of mud-size sediments develop banks in the Safety Valve area and south of the Rickenbacker Causeway (Fig 2.1). Sand deposits occur at Featherbed Bank and No Name Bank. Seaward of the keys carbonate sedimentation occurs in patch reef complexes, seagrass meadows and the barrier reef. Finally, thick peat deposits developed in mangrove forest rim the western shoreline (Harlem et al. 2009).

Geomorphologically, BB is a shallow depression in bedrock resulting from severe differential weathering and erosional events of the Neogene carbonate rock pile and from sedimentation processes, both fostered by Pleistocene changes in sea level, under significant tectonic stability (Parkinson, 1989; Wanless et. al 1994). During low sea level conditions intense chemical weathering, mass movement and river transport and sedimentation prevailed. The shoreline and coastal and terrestrial ecosystems migrated seaward expanding the land mass. During those periods, BB was a north-south trending valley subjected to stream erosion and sedimentation along its main axis. As sea level increased, the river valleys were drowned and sediments were remobilized by waves and tides.

Under sea level rising conditions flooding of BB began approximately 3,200 years ago (Wanless et. al 1994). This fundamental geomorphologic setting is responsible for subsequent development and distribution of habitats and the current ecosystem framework. Relevant to the present study are those rock formations supporting the landforms and those lying underground which contain the shallow and highly dynamic aquifers (Harlem et al. 2009).

Palaeocological studies of sediment cores in BB (Wingard et al 2004) indicate that the bay has been a dynamic environment over the last 500 years, with natural salinity changes and marked benthic habitat variability. Some changes may be connected to anthropogenic intervention (canal construction, declined freshwater supply, etc) while others seem to respond to regional or global changes (sea level rise). Salinity has increased while seagrass has declined. Estuarine species assemblages were replaced by open-marine species around 1900 AD, and increases in foraminifera abundance (*Archaias* and *Articulina) began* around 1947; a decline in *Thalassia* appears to have occurred in the 20th century at Featherbed Bank and after 1950 at No Name Bank

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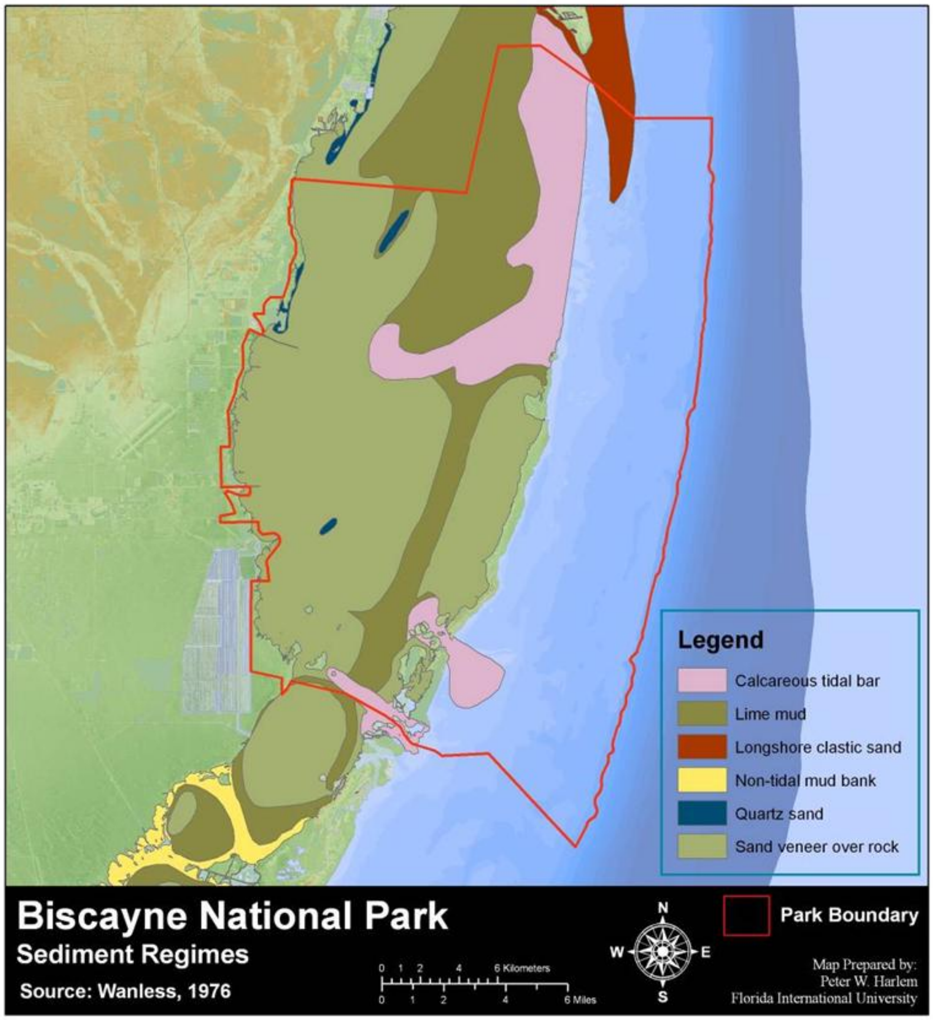

Figure 2.2: Sediment type map for Biscayne Bay bottom (from Harlem et al. 2009)

Little is known about the distribution of soil types within BNP and there seems to be three soil types inside the park. First, silty marl (carbonate mud) is the dominant soil type along the west side of the park landward of the mangrove fringes (Gaiser, et al., 2006b, Ross, et al. 2003). The second major soil type in the Park is peat derived from mangrove detritus. This is the common soil along the fringe of the coastline, along former freshwater streams and seeps, and on most of the islands. The third major soil type in Biscayne National Park are histosols developed under hardwood hammock vegetation on the barrier islands. These organic soils develop in well-drained upland settings that combine relatively high above ground production with some level of recalcitrance to decomposition (Coultas, 1977; Ross et al. 2003; Harlem et al. 2009).

WATER RESOURCES

Natural habitats in BB have been severely affected by rapid urbanization and coastal development linked with the growth of the Greater Miami area, and by disruption of its natural drainage system. Southern BB has been additionally impacted by agricultural activities. Overall, most of the surface water flow into BB is now controlled by a system of canals, levees and structures contributing to the bay's transition from an estuary to a marine lagoon over the last 100 years (Harlem, 1979; 2009). Biscayne Bay estuarine waters have experienced the impact of anthropogenic interventions since the early 1900's, including major disruptions of its hydrology (RECOVER 2009) and sustained urban and agricultural development. Hence, despite their oligotrophic nature, BB aquatic ecosystems bear the heritage and signals of such a long and sustained influence.

Prior to construction of the South Dade Conveyance System coastal wetlands and nearshore areas in BB maintained estuarine condition most of the year (Smith 1896; Meeder et al. 1999, Meeder et al. 2001) and supported a diverse assemblage of estuarine biota, including oyster reefs and American crocodile (Kushlan and Mazzotti 1989; SFWMD 1995; SFNRC 2006). The southern bays and sounds have experienced significant reductions in historical freshwater flows, leading to hyper saline conditions during extended periods of low rainfall (Wingard et al. 2003, 2004). Nevertheless, BB remains very productive and its biodiversity is still noteworthy.

These outstanding features have driven the establishment of protected areas besides BNP and encompassing central and southern BB, among them, the Florida Keys National Marine Sanctuary, Biscayne Bay Aquatic Preserve, John Pennekamp Coral Reef State Park, Bill Baggs State Park and Biscayne Bay-Card Sound Spiny Lobster Sanctuary (Fig 2.3). Furthermore, within the Comprehensive Everglades Restoration plan there are subcomponents to re-establish estuarine habitat through the Biscayne Bay Coastal Wetlands (CERP 2010), whose main goals are to re-hydrate coastal wetlands currently drained by canals and redistribute freshwater flow to the Bay.

This restoration endeavor might affect salinities in the bay, especially in nearshore habitats of BNP (Serafy et al. 2001).

Figure 2.3: Protected areas in the vicinity of the Biscayne National Park. EEL= Miami-Dade Environmentally Endangered Lands; FKNMS = Florida Keys National Marine Sanctuary (from Harlem et al, 2009).

Rainwater

Given the extension of the Bay's watershed and the diversity of water sources entering the Bay the characterization of its climate requires a regional approach, because components and balances among the freshwater budgets and the marine inputs play a critical role on WQ and ecosystem responses. Long-term climate data has been downloaded from the South Florida Water Management District (DBHYDRO) website (http://www.sfwmd.gov) for the following weather stations: Florida Coastal Everglades Long Term Ecological Research Station (LTER; 25º51'00"; 81º22'59");

Tamiami Trail Station (25º45’37”; 80º49’29”); Miami International Airport Station (25º49’01”; 80º16’59”); and Joe Bay Station (25º13’28”; 80º32’28”). The location of these stations could provide insight on the loads and flows derived from three major sources of rain and different settings. Additional to geographical variability, the LTER and Tamiami stations would provide information on rainwater locally derived from inland evaporation and recycling (i.e. Everglades), while the Miami station would have a stronger signal from the Miami urban area, and Joe Bay Station rain data would bear information on marine contributions to rain water.

Rainfall in South Miami-Dade ranges from 102 to 165 cm yr^{-1}. The wet season extends from June to November with a bimodal pattern peaking in summer (June) and fall (September-October). The dry season spans between December and May (Fig 2.4). Although there is not enough data to substantiate spatial rain patterns given the lack of stations on the Bay itself or the keys to the east, it is generally accepted that more rain occurs over the coastal ridge on the mainland than over the barrier islands (Schmidt and Davis, 1978).

Little information can be derived from the time-series of Figure 2.4, except for an important decline of rainfall at Joe Bay station since 1994. The bimodal pattern observed at most rainfall stations is absent at Joe Bay (Fig 2.4) where data dispersion is significant. The dry season usually runs between November and April. Higher precipitation and larger contrast between dry and wet season occurs inland, towards the Everglades as compared to Joe Bay in the south.

Zcusum charts of long-term precipitation data (Fig 2.5) clearly show the occurrence of common cycles of diverse spans (for details on construction and interpretation of Zcusum charts see Appendix 4). Fourier analysis of precipitation time-series suggests cycles of about 47-50 years; 14 years cycle and its harmonics at 7 and 3½ years; and 1 year (seasonality). A long cycle (~50-year) occurred from 1940s to 1990s and was characterized by higher precipitation rates until early 1970s when a significant shift to below average rates began and lasted until the early 1990s. Precipitation changes in early 1990s parallel changes in surface water chemistry, rainwater chemistry, flows and ecosystem response in South Florida estuaries and coastal waters (Briceño et al. 2010).

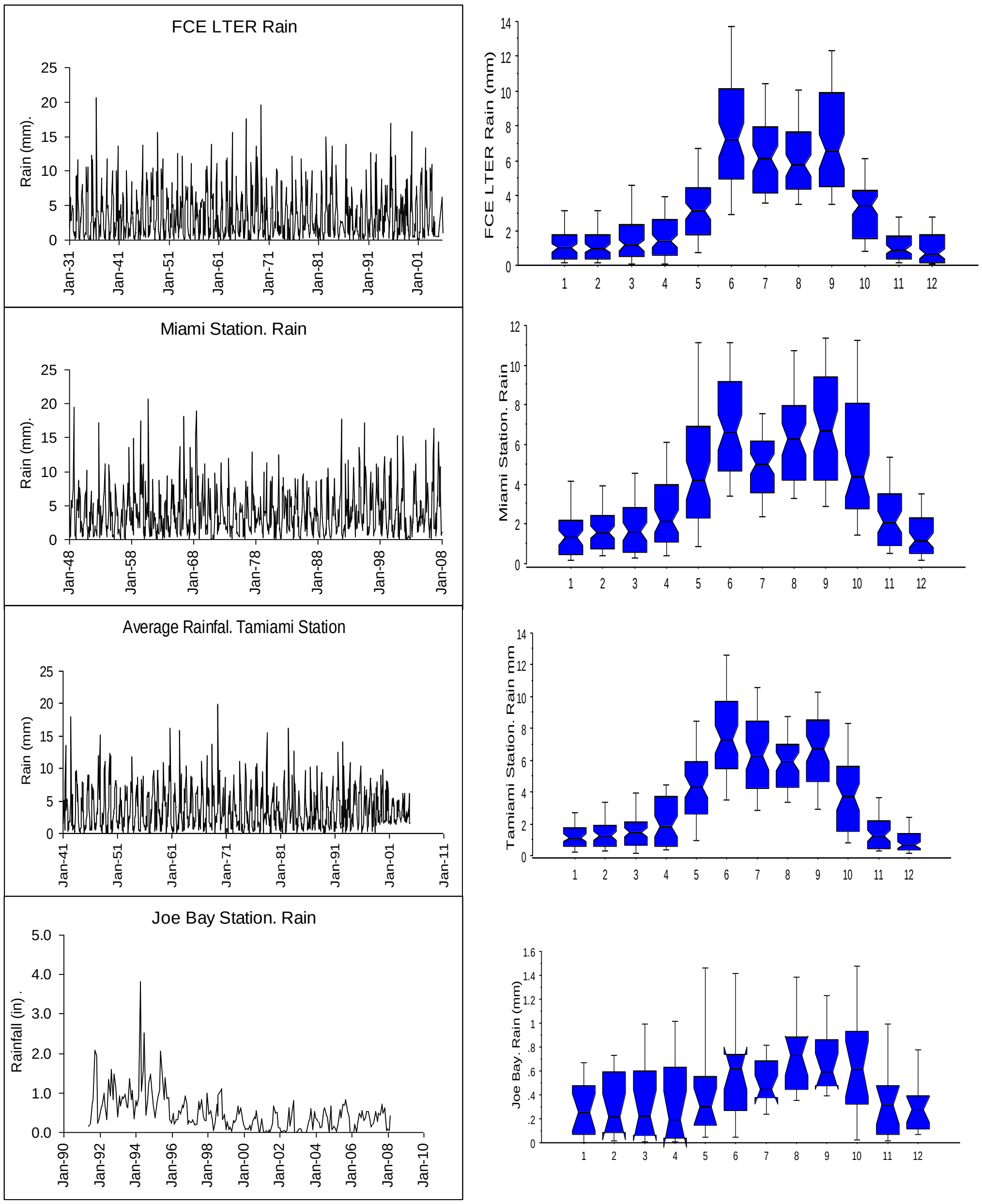

Figure 2.4: Precipitation time-series and seasonality of precipitation for Florida Everglades, Miami Airport, Tamiami and Joe Bay weather stations

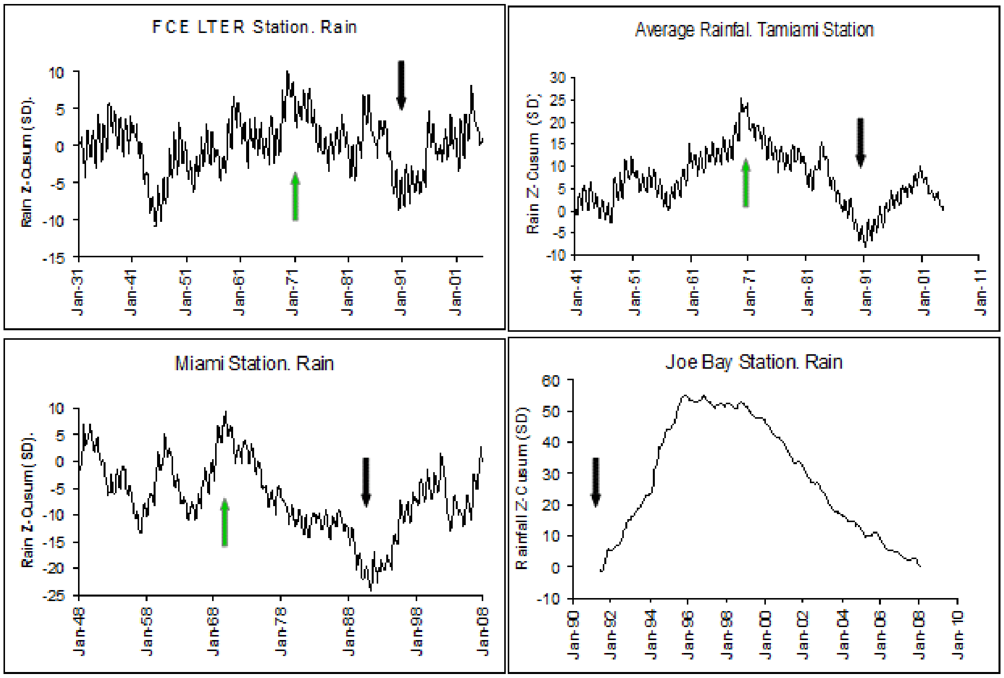

Figure 2.5: Zcusum charts for precipitation on Lower Everglades watershed. Significant inflections from higher to lower precipitation rates (green arrows) and viceversa (black arrows) occurred in 1971 and 1991 respectively

Rainwater chemistry data is scarce for South Florida and the only National Atmospheric Deposition Program (NADP) monitoring station with available data is the one located in Everglades National Park (site FL11; Lat: 25.39, Lon:-80.68; Table 2.1). Concentrations and fluxes of NO3 and NH4 increased in atmospheric deposition until 2007 (Fig 2.6). On the other hand, Ca, Mg, K, Na and Cl have declined and the pH experienced a sharp decline from 5.42 to 5.07 pH units during 1994. Sodium and chloride display similar pattern and their molar relationships are very close to that of sea water indicating their origin as cyclic salts. The decline in these salts is important because it suggests changes from ocean to land source of rainwater.

As shown in Table 2.1, average concentration of inorganic nitrogen species in rain water (NH_4=0.159 mg/l and NO_3=0.811 mg/l), are significantly higher than those found in South Florida estuarine and coastal waters (mean NO_3=0.016 mg/l; mean NH_4=0.028 mg/l) . That chemistry has the potential to cause impact especially in waterbodies like BB where rainfall contributes 40% of the freshwater budget with concentrations one order of magnitude above those of Bay waters. Additionally, the pH drop of about half a pH unit in 1994 has important environmental implications especially for potential impacts on soil biogeochemistry and nutrient release/fixation processes (Burns et al. 1998, 2006; Hejzlar et al. 2003; De Wit 2007; Briceño and Boyer 2009).

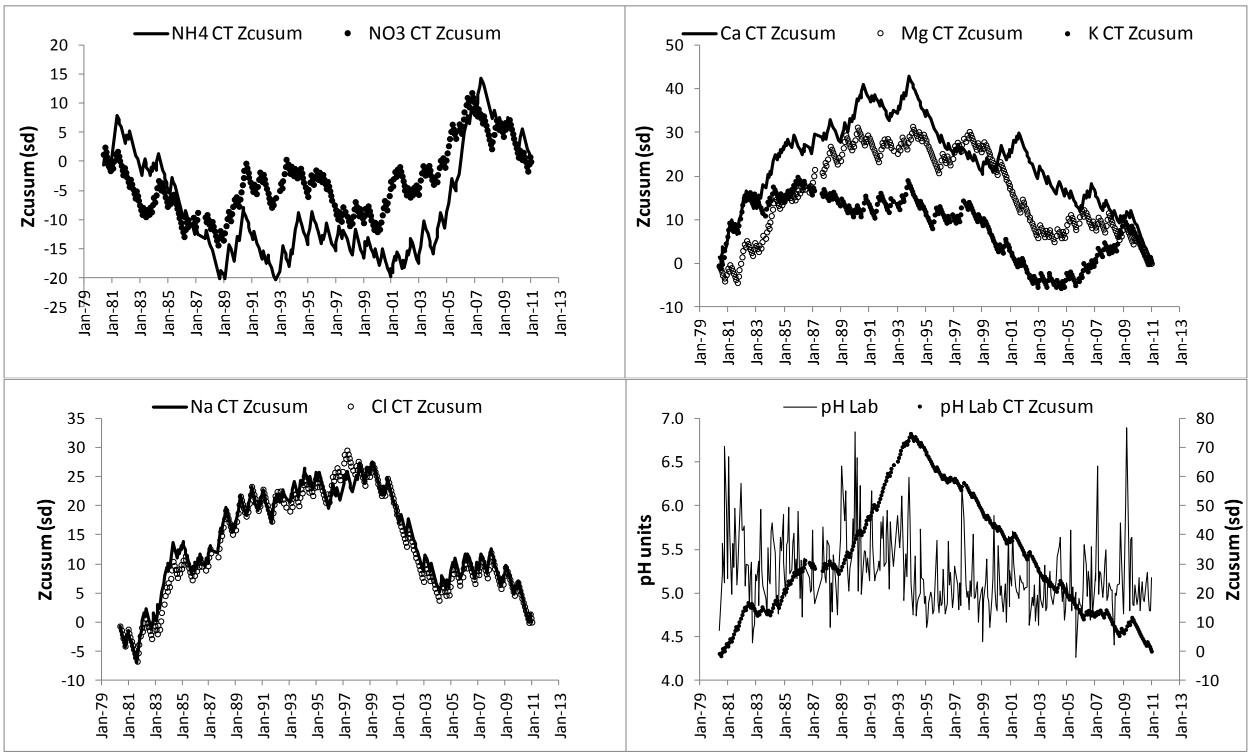

Figure 2.6: Zcusum charts picture detailed and complex patterns, where NH4 and NO3 have similar increasing trends (cup-shaped cusums), while Ca, Mg, K, Na and Cl declined (skewed dome-shaped cusum), and the pH shifted from above to below average tendency in 1995.

Table 2.1. Descriptive statistics of rainwater chemical composition at station NADP FL11, Everglades National Park for the period Jun/1980 to Jan/2011 (units are mg/l except for pH)

	Ca	Mg	K	Na	NH4	NO3	Cl	SO4	pH Lab
Average	0.251	0.143	0.098	1.078	0.159	0.811	1.868	1.178	5.182
Median	0.147	0.080	0.045	0.610	0.082	0.592	1.050	0.880	5.080
St.Dev.	0.493	0.218	0.203	1.489	0.221	0.866	2.581	1.110	0.522
Minimum	0.009	0.006	0.003	0.048	0.004	0.009	0.090	0.069	3.950
Maximum	9.795	2.656	3.570	15.910	2.200	11.970	26.890	15.420	7.360

Bay waters

Our flow calculations with available data for rain, canal discharge, groundwater and overland flows from DERM, NOAA, SFWMD, USGS and DBHYDRO datasets, render a total average of monthly freshwater flow to Biscayne Bay south of Rickenbacker Causeway of 150 million cubic meters per month. Canal discharge to the bay is the largest contributor to freshwater budget with 66 million cubic meters per month (MMm^3/m) or 44% of the total flow, while rain, groundwater and overland flow supply 61 (40%), 15 (10%) and 8 (6%) MMm^3 per month respectively. Average monthly loss due to evapotranspiration is 79 MMm^3, or 53% of the total input (Fig 2.7).

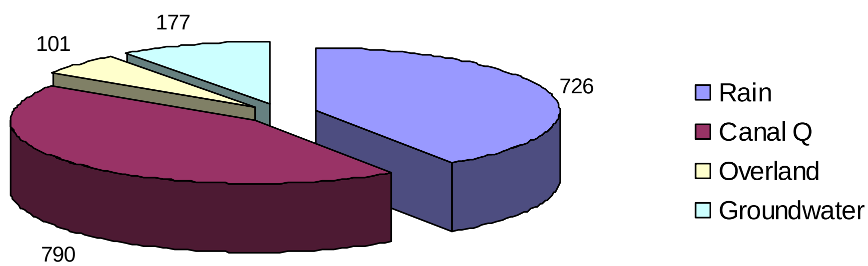

Figure 2.7: Average flow contributions (million m^3/month) to Biscayne Bay south of Rickenbacker Causeway.

Main canals draining into Central and South Biscayne Bay from just south of Rickenbacker Causeway to Manatee Bay, include Coral Gables Waterway (C-3), Snapper Creek (C-2), Cutler Drain (C-100),), Black Creek (C-1), Princeton Canal (C-102), Military Canal, Mowry Canal (C-103), Card Sound (S20) and the Aerojet Canal (C-111). Additionally, some water from the Miami River, draining into the southern North Biscayne Bay flows south under Rickenbacker Causeway and into North-Central BB. Finally, there are some plugged canals and mosquito ditches which despite not emptying directly into Biscayne Bay, affect groundwater contribution to the bay by modifying the local groundwater level (i.e. North Canal and Florida City Canal south of Mowry Canal). Previous exchange dynamics studies (Wang et al. 2003; Nuttle et al. 2000) rendered average water residence times in the order of 1 month for the bay, ranging from practically zero close to inlets and the Safety Valve to 3-4 months in the southern extreme at Manatee Bay and Barnes Sound.

Although Biscayne Bay waters are in general oligotrophic, water composition is not uniform across the bay (Fig. 2.8). North Bay, the most affected by urban development, is the highest in DIN, TP, CHLa, SiO2 and Turbidity, while oceanic waters on the reef-track display the lowest nutrient concentrations. Central Bay, impacted by urban and industrial development, shows values which are intermediate for all variables. Finally, South Biscayne Bay, with moderate urban development, extensive agricultural development and surrounded by wetlands, has the lowest TP, CHLa, SiO2 and the highest salinity range, TN and TOC concentrations.

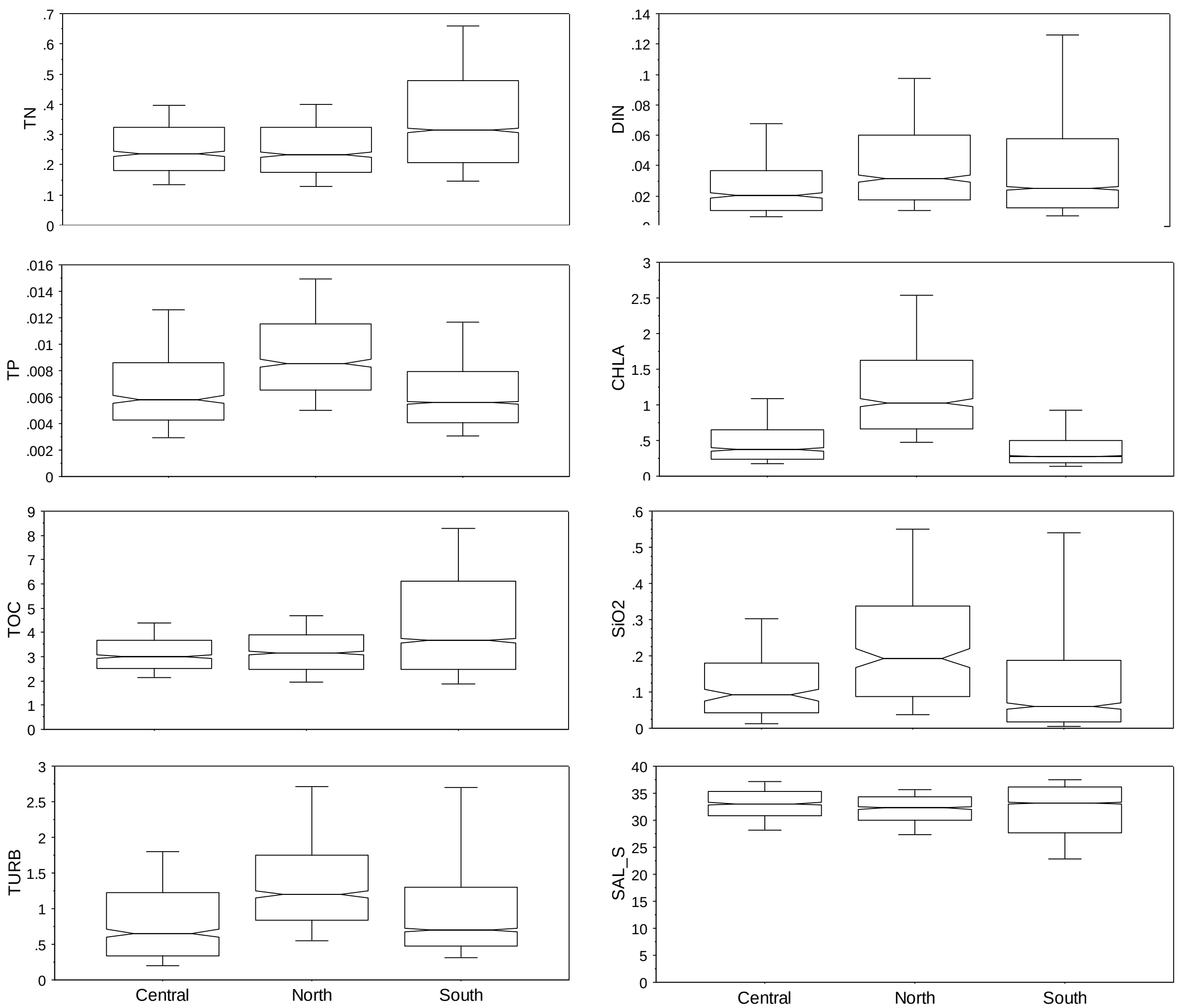

Figure 2.8: Box-plots of WQ biogeochemical variables in different sectors of Biscayne Bay.

Paleoecological studies indicate that Biscayne Bay has become increasingly marine over the last 100 years (Ishman et al. 1998; Stone et al. 2000; Wingard et al. 2003, 2004), with smaller inter-decadal and decadal salinity fluctuations after 1915. Among the significant changes in the bay during the last century are declines in submerged vegetation (SAV) in central BB, and reduced molluscan faunal abundance and diversity bay-wide (Berkeley and Campos 1984, Serafy et al. 1997, Ault et al. 1999a, b) and changes in the benthic foraminifera communities as reported in core and sediment samples from South Florida (Ishman 1996, 1997, 1998).

Besides impacting SAV, salinity conditions affect some animal species in Biscayne Bay whose life cycles are closely linked to salinity conditions ranging from 12 to 28 ppt such as: the American crocodile (*Crocodylus acutus*), oyster (*Crassostria virginica*), spotted seatrout (*Cynoscion nebulosus*), silver perch (*Bairdiella chrysoura*), mojarras (*Eucinostomus*) and red drum/"redfish" (*Sciaenops ocellatus*) (Bellmund et al 2004).

BISCAYNE BAY COASTAL WETLANDS

Over a century of water management has caused estuarine habitats in the bay to shrink, while at the same time expanded areas of low biological productivity within Biscayne Bay's watershed. This is particularly evident in areas that have been cut off from freshwater sources by canals or roads. The dwarf mangrove forest, known as the "white zone" along the coast of south Biscayne Bay is a good example of this inland impact (Fig 2.9). This zone is expanding and its landward boundary has moved inland by an average of one and a half kilometers (0.9 miles) since 1940 (CERP 2010). The low productivity of the white zone is primarily a result of absence of freshwater input from upstream sources. Perhaps one of the most important projects in the Comprehensive Everglades Restoration Plan (CERP) is to restore wetlands within Biscayne Bay (Fig 2.9). The project will divert runoff that currently discharges through regional canals and redistribute the freshwater through a spreader canal system into the coastal wetlands adjoining Biscayne Bay to provide a more natural and historic overland flow. The slower, more natural delivery of fresh water over a broad area is expected to reduce hypersaline conditions and re-establish appropriate estuarine salinities that are important to provide nursery habitat for fish and shellfish in tidal wetlands and nearshore bay habitats. This project is expected to create conditions that would be conducive to the re-establishment of oysters and other components typical of a healthy estuarine ecosystem.

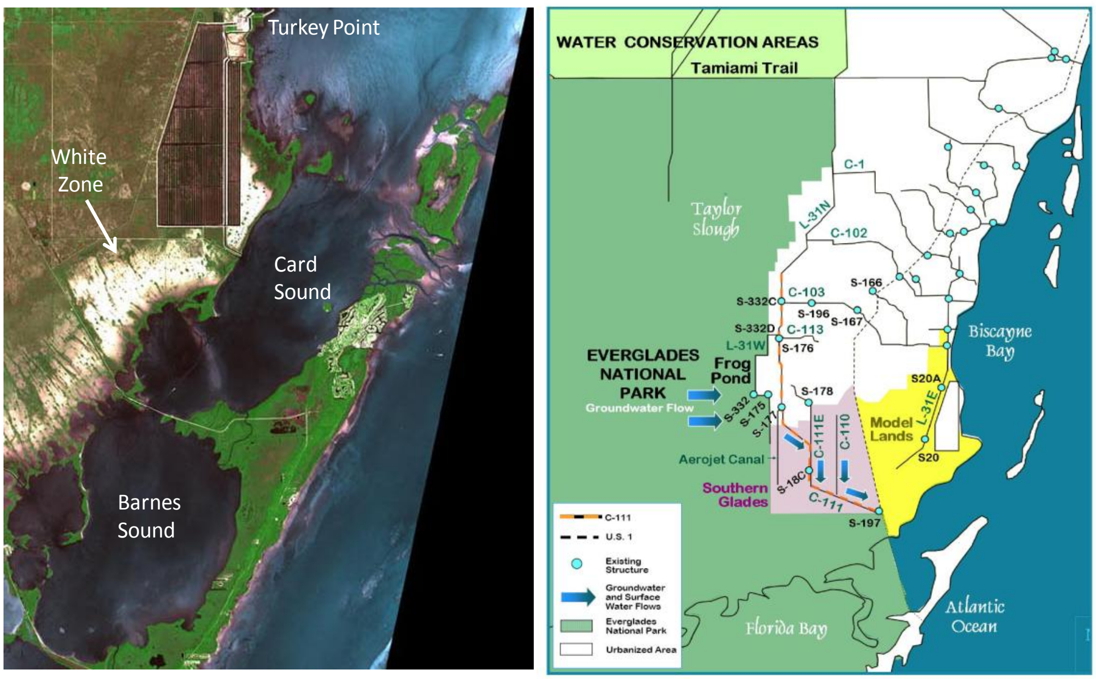

Figure 2.9: Satellite image showing the low-productivity dwarf mangrove forest, or “white zone” along the western coast of Card and Barnes sounds, and the location of the Biscayne Bay Coastal Wetlands Project (modified from CERP 2010)

SECTION 3:
STATISTICAL ANALYSIS

SUMMARY STATISTICS

Each WQ parameter at each sampling station was subjected to preliminary calculation of its statistics. Those dataset with more than 10% non-detects, were subjected to additional non-parametric calculations of robust regression on order statistics (Robust-ROS) and analysis of their probability plot. These calculations were only required for SRP and DIN for the overall BB dataset for initial characterization and clustering (Appendix 5), and for SRP, NOx, NO3, DIN and SRP for some individual sub-basins. Robust-ROS procedure uses probabilities and applies survival analysis methods on log transformed and flipped data, without assuming normal distribution of the data. This procedure computes summary statistics avoiding transformation bias from logs to original data units (Helsel and Cohn 1988). A detailed discussion of the calculations is presented elsewhere (Helsel 2005). Detection limits for FIU data were not constant along the POR (Appendix 7), posing additional complications to the calculation of statistics for characterization and cluster analysis. Finally, summary statistics for all variables at each station are presented in (Appendix 5).

FACTOR ANALYSIS AND CLUSTERING

Caccia and Boyer (2005) performed an objective classification analysis on FIU's water quality data set from 25 sites collected monthly during 1994–2003. Water quality parameters used for classification included: TN, TON, DIN, NH4, NO3, NO2, TP, SRP, TN:TP ratio, TOC, DO, CHLa, turbidity, salinity and temperature. This spatial analysis extended from North Biscayne Bay and to Card Sound but excluded Barnes and Manatee Bay. They applied Principal Components, retained the scores and input mean and standard deviations of scores to K-means cluster analysis. They defined five zones having similar water quality characteristics (Fig 3.1), where a robust DIN gradient was determinant in the spatial clustering from alongshore to offshore in the main Bay. This gradient results from the dominating influence of freshwater input from canals which drain the South Dade agricultural area, Black Point Landfill, and sewage treatment plant. Their South Bay zone (i.e. Card Sound) was high in dissolved organic constituents and low in inorganic nutrients, reflecting the little urban development and the extended mangrove wetlands of its watershed. Lowest nutrient concentrations occurred in the Main Bay, the area most influenced by water exchange with the Atlantic Ocean. Caccia and Boyer (2005) concluded that water quality in Biscayne Bay is highly dependent on the land use in the watershed and on the exchange with oceanic waters.

Hunt & Todt (2006) subdivided Biscayne Bay waters into five geographic domains based on direct clustering analysis of a set of stations (SAS PROC CLUSTER, Ward method-Euclidean distance) combining temperature and salinity data from FIU and DERM programs. Their geographic domains were only based on12 quarterly data of surface samples (<0.5m). Their cluster analysis explained 81 percent of variability in the data and the distribution pattern is in general similar to that of Caccia and Boyer (2005). In both approaches, the characteristics of North Biscayne Bay extend just south of Rickenbacker Causeway (dark blue dots in Fig 3.1) suggesting an active connection and exchange. In both classifications an east-west gradient is evident in Central Biscayne Bay, driven by salinity and nutrient differences, in turn caused by mixing of oceanic and freshwaters. Card Sound appears as a distinct class in both subdivisions, defining an additional north-sound gradient.

Factor Analysis

FIU monitoring program began in Manatee and Barnes Sound in 1991 as part of their Florida Bay program and in Biscayne Bay (including Card Sound) in 1993. Ten of the initial sites in Biscayne Bay were discontinued and ten new sites were incorporated after an assessment by the SFWMD and FIU in 1996. Several of the new sites were located out in North Biscayne Bay. Additionally, reassessment of the monitoring program in September 2007 dropped 6 additional sites. Finally, the period between

June-1996 to September-2007 contains the largest number of stations simultaneously sampled. Hence, we selected that period and those 21 stations distributed throughout the bay for our segmentation. To differentiate data from this time interval from the overall POR, we have called it Selected Period of Record (SPOR).

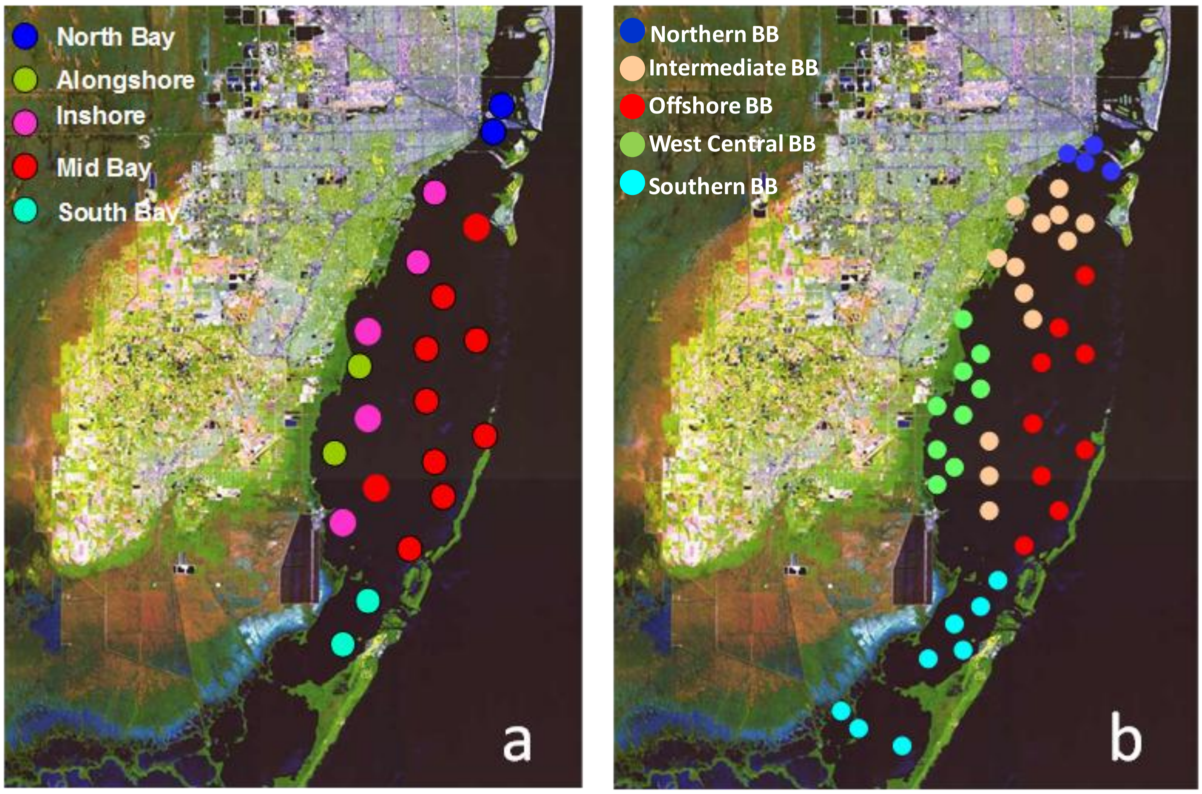

Figure 3.1: a) Caccia and Boyer (2005) subdivision of Biscayne Bay waters into 5 zones, North Bay, Alongshore, Inshore, Mid Bay and South Bay; and b) Classification of Biscayne Bay waters by Hunt and Todt (2006) into five geographic domains, using salinity and temperature from DERM and FIU data sets combined.

The SPOR included fourteen biogeochemical parameters, TOC, TN, TON, TP, SRP, CHLA, NOx, NO_2^-, NO_3^-, NH_4^+, DO, salinity, turbidity, and temperature, for 4,941 samples and a total of 73,368 analytical determinations. After considering: 1) the high correlation between TN and TON, and NOx and NO_3^-; 2) the high proportion of non-detects for SRP; and 3) the constancy of temperature across the bay, we included only ten biogeochemical variables in the model: TOC, TN, TP, CHLA, NOx, $NO2^-$, NH_4^+, salinity, turbidity, and DO. The number of determinations was now 39,078.

For the segmentation we used similar factor analysis and clustering techniques as those described by Briceño and Boyer (2009) for Florida Bay. Briefly, raw data was transformed into z-scores and used as input for factor analysis with VARIMAX rotation of axes (Minitab 16® statistical software) to obtain five Principal Components (PC). We did not apply the Kaiser criterion or the scree test rigorously (Kaiser 1960) for the selection of PCs, but the magnitude of our retained eigenvalues was above 0.9 and the contribution to the accounted variance of the five selected PCs was above 10%. These PCs are linked to specific water quality parameters controlling their structure (Appendix 8). PC1 is mostly a positive function of inorganic N species, NO_2^-, NO_x and NH_4^+ and is negatively correlated with salinity. PC2 is linked to TN and TOC perhaps representing inland contributions, and it is also negatively correlated to salinity. PC3 is strongly dependent on TP and CHLa, perhaps representing a driver:response pair. PC4 depends upon CHLa and turbidity, perhaps representing a system response. Finally, PC5 is a function of DO. In total, these five PC account for 79.2% of the total variance.

There is a striking similarity between our PCs and those PCs derived by Caccia and Boyer (2005) for the whole Biscayne Bay for a shorter period of record. This similarity in results suggests a highly robust and long-lasting relationship among WQ variables in Biscayne Bay.

Hierarchical Clustering

The scores from the five PCs were retained and their descriptive statistics calculated for each sampling station. After trying different combinations of statistics, grouping was performed with a combination of two parametric statistics (mean and standard deviation) and two non-parametric statistics (median and MAD) of the scores for each sampling site as input for hierarchical clustering routines. Our hierarchical clustering metrics were Euclidean distances and linkage was Ward minimum variance (Minitab 16® statistical software). In summary, our final model included ten biogeochemical parameters **(**TOC, TN, TON, TP, SRP, CHLA, NOx, $NO2^-$, NH_4^+, salinity, turbidity, and DO), four statistics (mean, standard deviation, median and median absolute deviation) for the five retained Principal Component scores.

Final results of hierarchical clustering are shown in the dendrogram (cluster tree) of Fig 3.2 for eight water-classes. Using the cluster tree output from MINITAB-16® we analyzed the progression of subdivisions by sliding a threshold level along the statistical distance axis and plotted the resulting clusters as coded maps to visualize such progression. An example of this process is provided in Figure 3.3, depicting the progression of BB clustering as statistical difference declines. The 3-cluster arrangement separates waters from the southernmost bays (Barnes and Manatee; blue), the most exposed stations to oceanic influence in central bay (light blue), and those with strongest influence from land sources (brown). Progressive disaggregation to 5, 7 and 8 clusters reveals the persistence of the E-to-W gradient resulting from water exchange and the development of a N-to-S pattern. This superimposed trends seem to reflect both, circulation and differential impact from land sources, in turn linked to changes in urban development (larger in North Bay) to agricultural areas (larger in South Central) to mostly un-habited wetlands at the southern extreme. The 7-cluster results for Central Bay and Card South are exactly the same as those of Caccia and Boyer (2005).

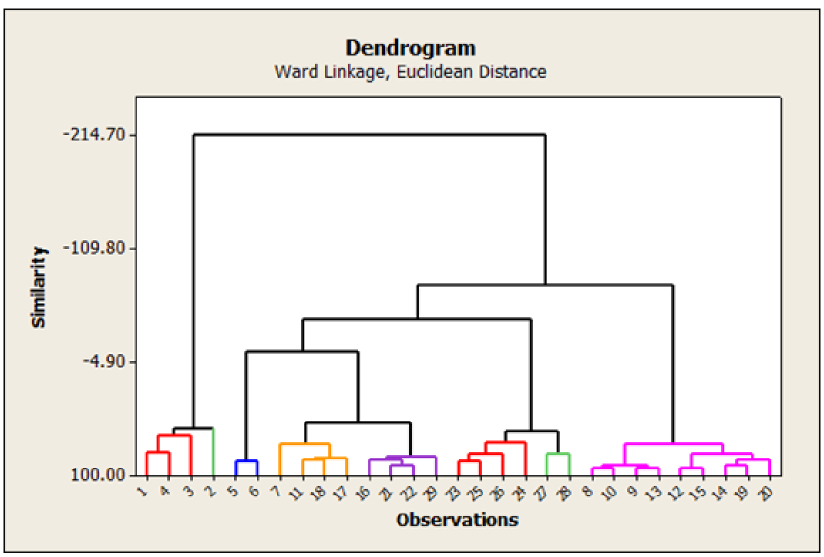

Figure 3.2. Cluster tree showing water classes for Biscayne Bay (NOTE: Observations along the x-axis are not station numbers)

The purely biogeochemical-statistical classification of Biscayne Bay waters into 8 water classes was partially modified by incorporating additional water circulation and geomorphological criteria, as well as location and distribution of canal outlets. This modification was required for structuring the box-model calculations, which only included stations in Central and South Biscayne Bay (from Rickenbacker Causeway to Manatee and Barnes Sound). Modifications for the box-model were as follows: (1) Station 103 (from cluster 4) was incorporated to the South Central Inshore segment (to cluster 3); and (2) Station 129 (from cluster 7), just south of Rickenbacker Causeway was clustered together with Station 126 (from cluster 5) to make a new cluster, North-Central Inshore (NCI)

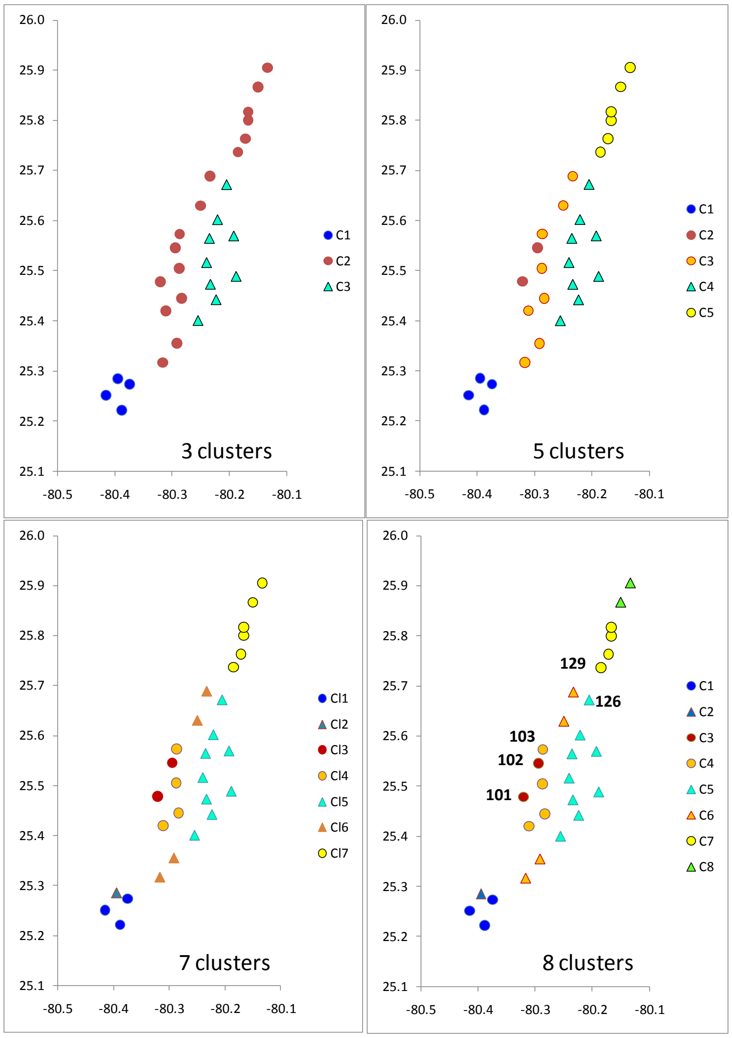

Figure 3.3. Cluster evolution of Biscayne Bay. The 3-cluster arrangement shows the fundamental subdivision of bay waters. Progressive clustering tracks the development of two gradients in water quality, E-to-W and N-to-S

The resulting segmentation after taking these changes into consideration is shown in Fig. 3.4, where the clusters are:

- Manatee-Barnes Sound (MBS): includes stations 1, 2, 3 and 4. For detailed calculation in the box-model, Manatee and Barnes sound samples were separated as individual clusters.
- Card Sound (CS): includes stations 121 and 135
- South Central Inshore (SCI): includes stations 101, 102 and 103
- South Central Mid-Bay (SCM): Includes stations 110, 112 and 123
- South Central Outer-Bay (SCO): includes stations 104, 108, 109, 111, 112, 113, 116 and 124
- North Central Inshore (NCI): includes stations 127 and 128
- North Central Outer-Bay (NCO): includes stations 126 and 129
- Southern North Bay (SNB): includes stations 130, 131 and 132
- Northern North Bay (NNB): includes stations 133 and 134

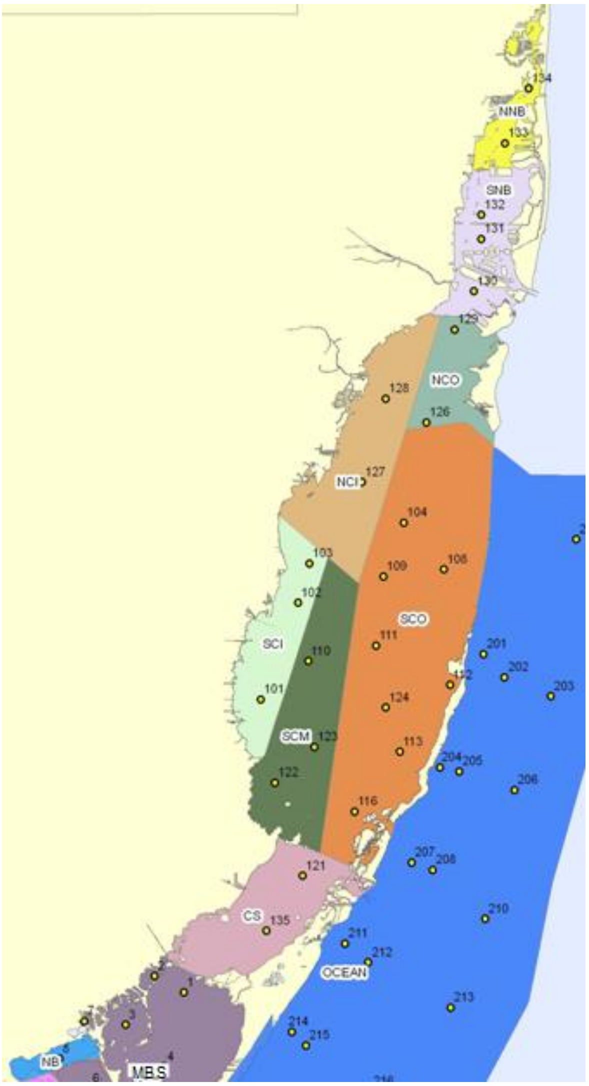

Figure 3.4: Final biogeochemical segmentation of Biscayne Bay waters. NCI=North-Central Inshore; NCO=North Central Outer bay; SCI=South Central Inshore; SCM=South Central Mid bay; SCO=South Central Outer bay; CS= Card Sound MBS=Manatee-Barnes Sound.

The subdivision of Biscayne Bay into biogeochemical water classes seems to follow geomorphological characteristics and patterns defined by physical properties of the water masses, such as: water depth (Fig 3.5.a; Harlem et al 2009); flood current velocity (Fig 3.5b; Wang et al 2003); bay bottom type (Fig 3.5c; FWRI 1992); benthic communities (Fig 3.5d; Roessler et al. 1973; Thorhaug 1976); salinity (Fig 3.5e; Gaiser et al. 2006); and sedimentary regimes (Fig 3.5f; Wanless, 1984)

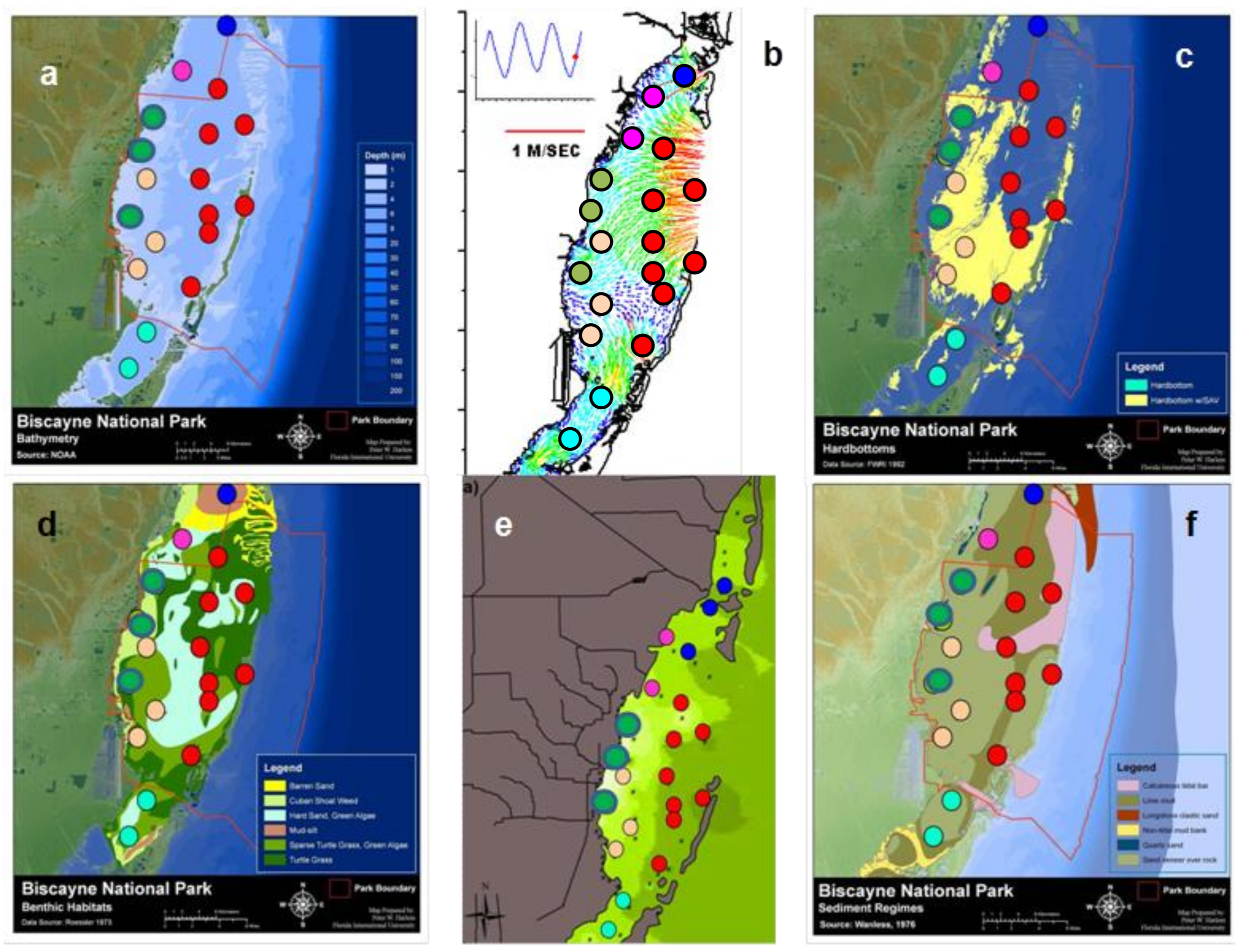

Figure 3.5: Correspondence of previous spatial classifications of Biscayne Bay with the segmentation obtained in this study (colored dots). (a) Bathymetry (Harlem et al 2009); (b) Flood Current velocity (Wang et al 2003); (c) Bay bottom type (FWRI 1992); (d) Benthic communities (Roessler et al. 1973; Thorhaug 1976); (e) Salinity (Gaiser et al. 2006); (f) Sedimentary regimes (Wanless, 1984)

CLUSTERS CHARACTERISTICS

The following statistics were calculated from the SPOR dataset, spanning from June 1996 to Sept 2007

Freshwater Flow

Net freshwater contributions to each segment in Central and South Biscayne Bay were calculated for the box-model as the sum of Canal flow + Precipitation + Groundwater flow + Overland flow – Evaporation for the period Sep 1993-June 2007. Seasonal freshwater flows (Fig 3.6) display a marked seasonality with very low to negative contributions from November to May, a sudden and highly variable flow in June, and peak values in September. Median flows into SCI, although very low in January-May, are always positive. There are four month with negative net flows in NCI, five in MBS and CS, and seven in the more offshore segments (NCO, SCM and SCO). In general, canal discharge to Biscayne Bay south of Rickenbacker Causeway is the largest contributor to the freshwater budget with 66 million cubic meters per month (Mm^3/m) or 44% of the total flow, while rain, groundwater and overland flow supply 61 (40%), 15 (10%) and 8 (6%) Mm^3 per month, respectively. Average monthly loss due to evapotranspiration is 79 MMm3, or 53% of the total input (Fig 2.7). Hence, nutrient loads are basically a function of canal flows and precipitation but residence time and evapotranspiration would modulate the final effects of these loads. Individual nutrient loads brought about by these different contributions and the exchange with oceanic waters determines the final concentration of nutrients within each bay segment (Appendix 1).

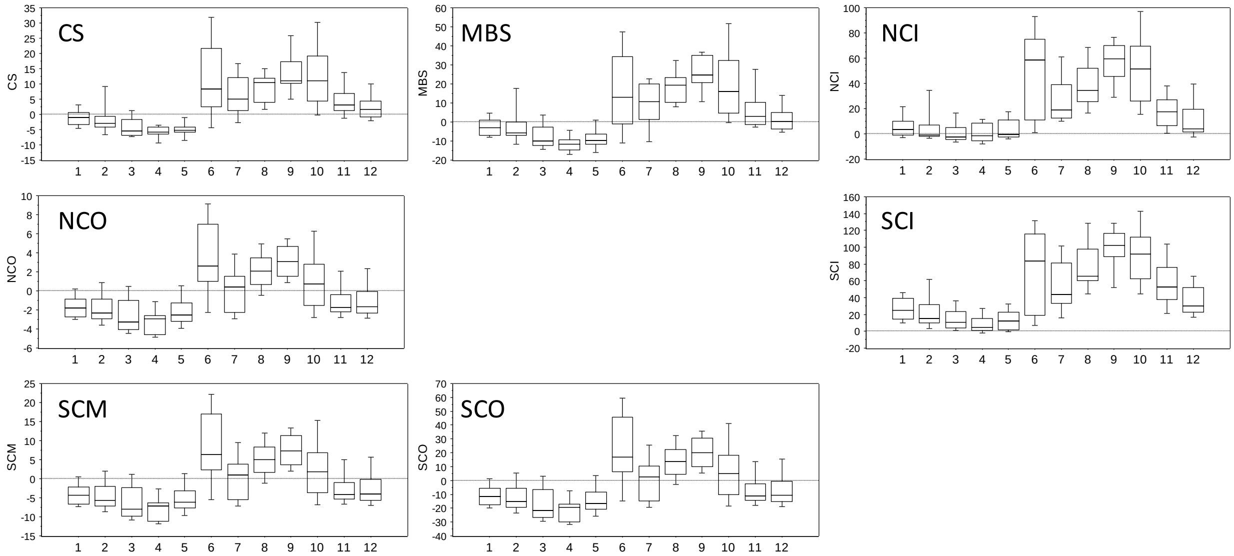

Figure 3.6: Estimated net freshwater contribution in Mm3/month to Biscayne Bay segments (Net= Canal + precipitation + groundwater + overland - evaporation). North Biscayne Bay was not included in the box-model effort.

Salinity

Salinity increases eastwards from shoreline (SCI) to offshore (SCO). The highest mean and median salinities occur in SCO (35.8 and 36.1 PSU), where most exchange with oceanic waters takes place, while maintaining its seasonality with little change along the year (Fig 3.7). Nevertheless, maximum salinity events do not occur in SCO but closer to shore, in SCI (44.1 PSU) perhaps responding to high evaporation of shallower water masses. Salinity has reached hypersalinity levels (>40 PSU) in all clusters during the POR, while median and mean values are similar at each cluster (Fig 3.7). The lowest minima occur also in MBS and SCI (3 and 6 and PSU respectively), where the standard deviations are the highest (6 PSU), coinciding with previous observations that sample sites along the shoreline exhibit the highest and the lowest salinity values and the greatest variation (Serafy et al. 1997; Bellmund et al. 2009). BNP data shows the occurrence of low salinity events in surface waters away from shore at the middle of the Bay in November 2004, April 2005, November 2006 and January 2007. These fresher water bodies surrounded by saltier masses have been reported as caused by groundwater springs (Bellmund et al. 2009) seeping through the bay floor. Events of salinity inversion appear in FIU dataset but differences are always less than 1 PSU, except in a couple of events

Highest salinity occurs across the bay in May and lowest salinity occurs in September to November (Fig 3.7). There is a significant drop in salinity between May and June, reaching up to 9 PSU (NNB and SCI) at the beginning of the wet season. Non-parametric Mann-Whitney tests indicate that salinities among the defined WQ clusters are significantly different ($p<0.05$) except for NCI and SCM, and NCO and CS with non-significant statistical differences at $p=0.12$ and $p=0.51$ respectively.

The salinity patterns derived from monthly data shown here are clearly an oversimplification when compared to high frequency data (15 min sampling rate) as those reported by the BNP for NCI, SCI and SCM (BNP 2008; Bellmund et al. 2009). In fact, salinity in the mangrove areas is substantially different from the salinity further east in Biscayne Bay, displaying frequent hypersalinity conditions and responding more to groundwater variability than to local canal flow. A consequence of salinity variability is that extension of estuarine conditions (salinity < 20 PSU) in the bay is rather variable. According to Bellmund et al. (2009) average estuarine area for the wet season (2004-2008 period) was 2,714 hectares, but in the dry season it contracted to only 454 hectares. FIU's data indicate that estuarine conditions have occurred since June 1996 in only 14% and 7% of the records for MBS and SCI, respectively. These figures clearly indicate how little Biscayne Bay resembles a true estuary.

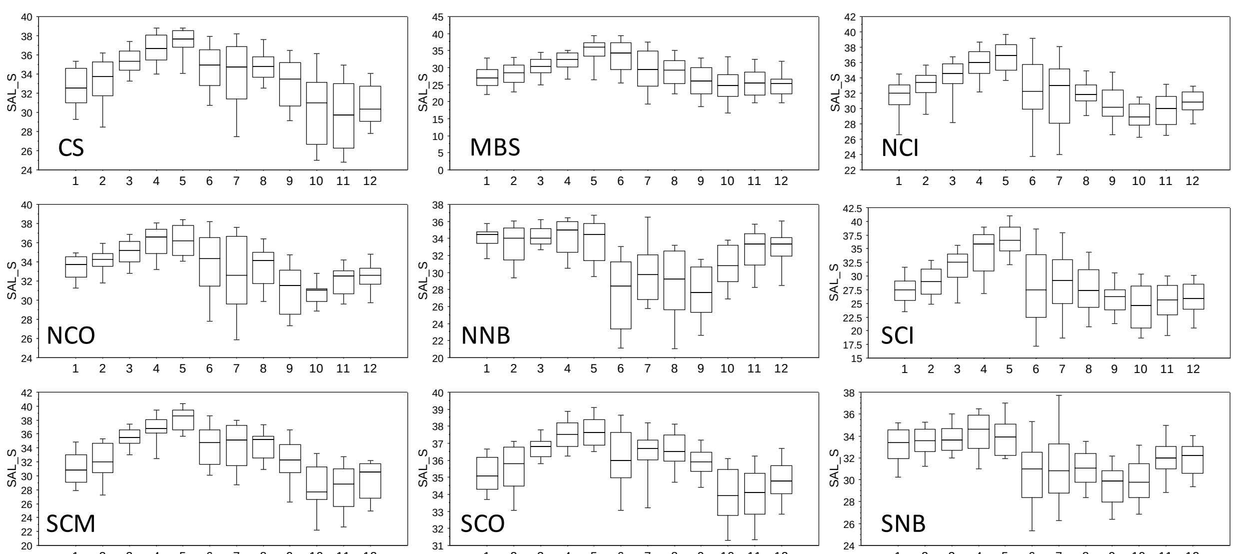

Figure 3.7: Seasonal variability of Salinity in Biscayne Bay

Temperature

Averaged mean and averaged median surface water temperatures in Biscayne Bay are remarkably stable around 25.8 and 26.1 ºC, respectively, with the highest maximum of 37.4 ºC and lowest minimum of 10.2 ºC at SCI (Fig 3.11). Seasonality is also very similar across the bay, with maxima in July-August and minima in January, when variability is higher. Results from Mann-Whitney tests indicate no significant temperature differences among WQ clusters. This general constancy in temperature is reflected in DO concentrations, whose solubility in water is strongly controlled by temperature.

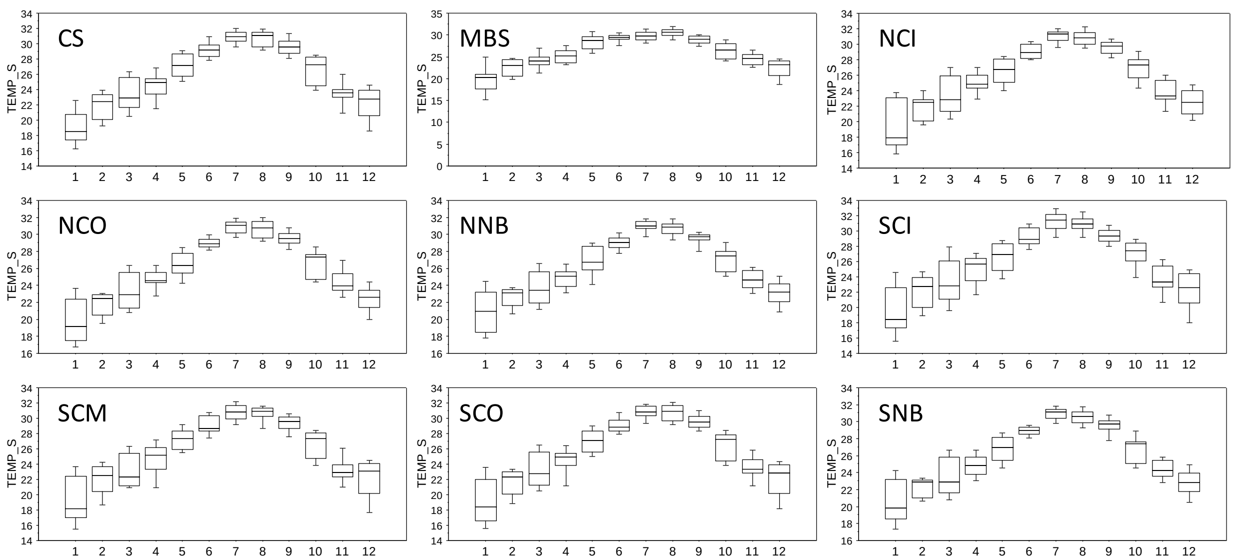

Figure 3.8: Seasonal variability of Temperature in Biscayne Bay

Turbidity

Average water turbidity is in general low in DERM and FIU monitoring programs, although slightly higher values are reported by DERM. Average turbidity values in bay waters are lower than those observed in canal waters, ranging from 0.5 (CS and SCI) to 1.9 NTU (MBS), while the maximum recorded value (42.7 NTU) and highest standard deviation (3.8 NTU) occurred in MBS, followed by SNB (22.4 and 1.4 NTU respectively). In general lower turbidity occurs from May to August (Fig 3.9) during the rainy season. CS and MBS display higher turbidity and dispersion from September to December. Seasonal variability of turbidity follows diverse patterns (Fig 3.9) although in NCI, NCO, SCO and CS higher values and higher variance occur during the dry season. MBS, NNB and SNB have an apparent bimodal pattern peaking in October-November and March. SCI and SCM display higher variance and values in September-October. Finally, there is a consistent high variability in October-December across the bay, and in general, turbidity does not seem to be related to canal input.

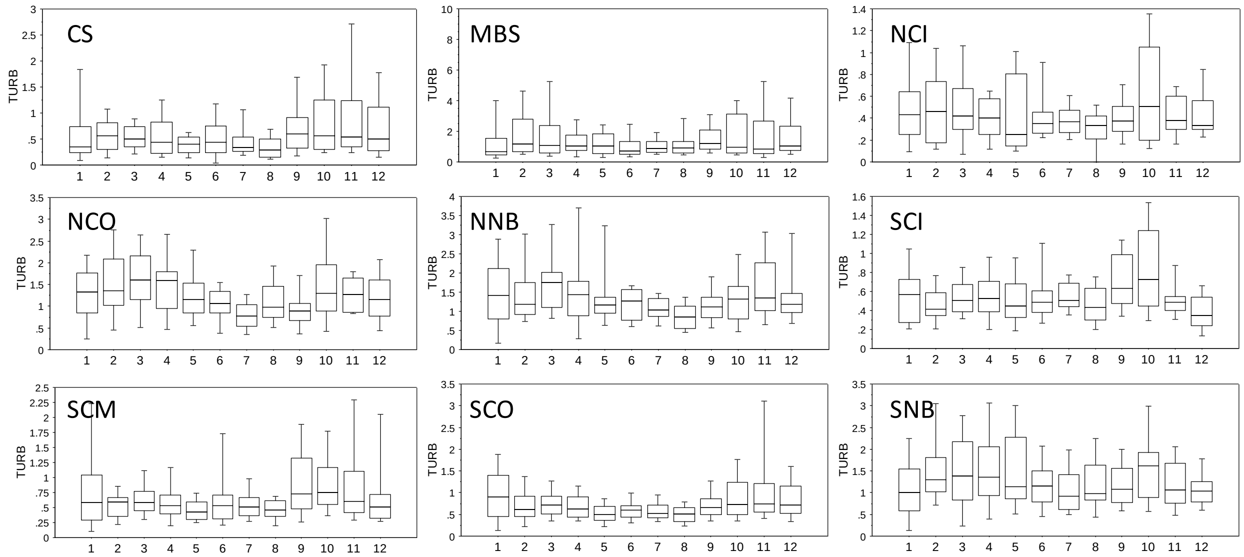

Figure 3.9: Seasonal variability of Turbidity in Biscayne Bay waters

Nitrite (NO2)

Average nitrite concentrations are very low in BB and close to analytical detection limits. Hence, it's difficult to assess a clear cut differentiation among segments. In very general terms the highest values occur in the southern portion of the bay (Fig 3.10), especially in SCI (max 0.006 mg/l) followed by CS (0.003 mg/l). Stations in the northern zones, most affected by runoff from the City of Miami, display low levels of NO2 (0.002 mg/l). Differences between north and south are also statistically significant (Mann-Whitney p<0.0001). Finally, the lowest values (0.001 mg/l) characterize SCO, supporting the idea of nitrite coming from land sources, especially from areas without public sewer systems.

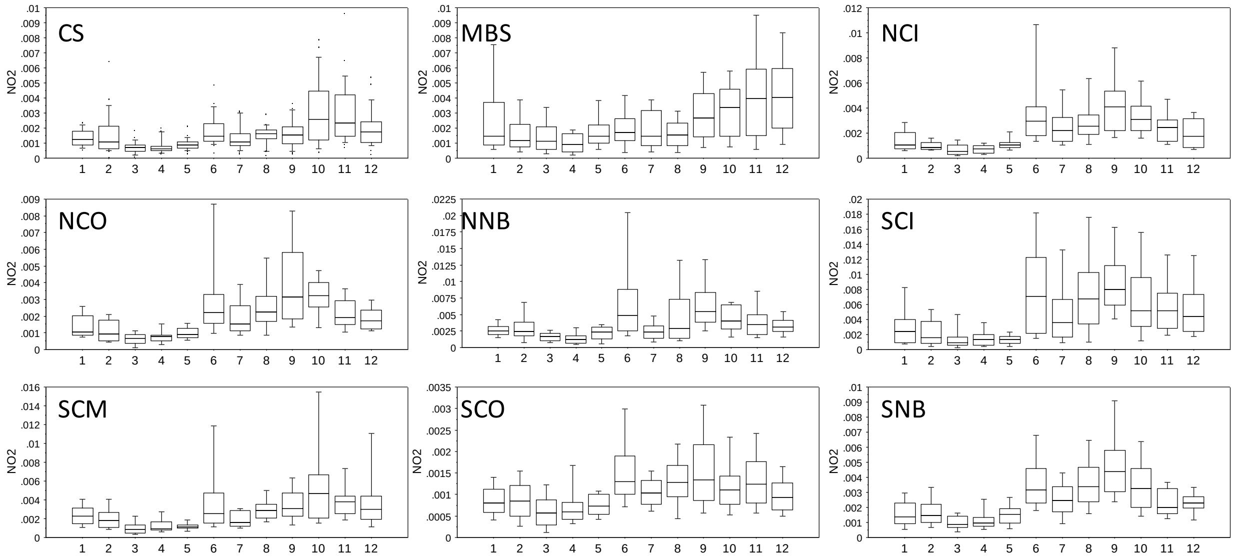

Figure 3.10: Seasonal variability of Nitrite (NO2) in Biscayne Bay waters

Despite the uncertainty derived from the generally low concentrations, a clear seasonal pattern characterizes NO2 in most WQ clusters (Fig 3.10). NCI, NCO and SCI have a common pattern where higher values and spread occur from June to December, especially SCI, and there is a sharp contrast between May small variance and the large spread of values in June, when the rainy season begins. Nitrite seasonalities are strikingly similar to those of freshwater flows (Fig 3.6).   SCM and SCO show the same seasonal patterns but more subdued. MBS displays higher concentrations from September to January and CS from October to December..

Nitrate (NO3)

Lower average nitrate concentrations (<0.020 mg/l) occur in CS, MBS, NCI, NCO, and SCO, while higher values (0.028 to 0.094 mg/l) occur in SCI and SCM. This pattern suggests a sharp west-east gradient for NO3 in South Central Biscayne Bay linked to inland sources of nitrate, especially in SCI, and mixing gradients with oceanic waters of the reef-track. This pattern underscores the importance of agricultural areas as main source on inorganic nitrogen to Biscayne Bay. Two fundamental seasonal patterns exist for NO3 in the studied area. Nitrate seasonal pattern is well defined (Fig 3.11) with very low values late in the dry season (Feb-May) and a sharp increase in June, first flush of rainy season, followed by gradual increase, which peaks in either September or October, and a gradual decrease during the late wet season (Jun-Nov). In MBS and CS, which don't have regular canal discharges, low values persists until September and the peak lags into October-November. Finally, NO3 and NOx (not shown) follow the same seasonal pattern, which closely follows water flow seasonality (Fig 3.6).

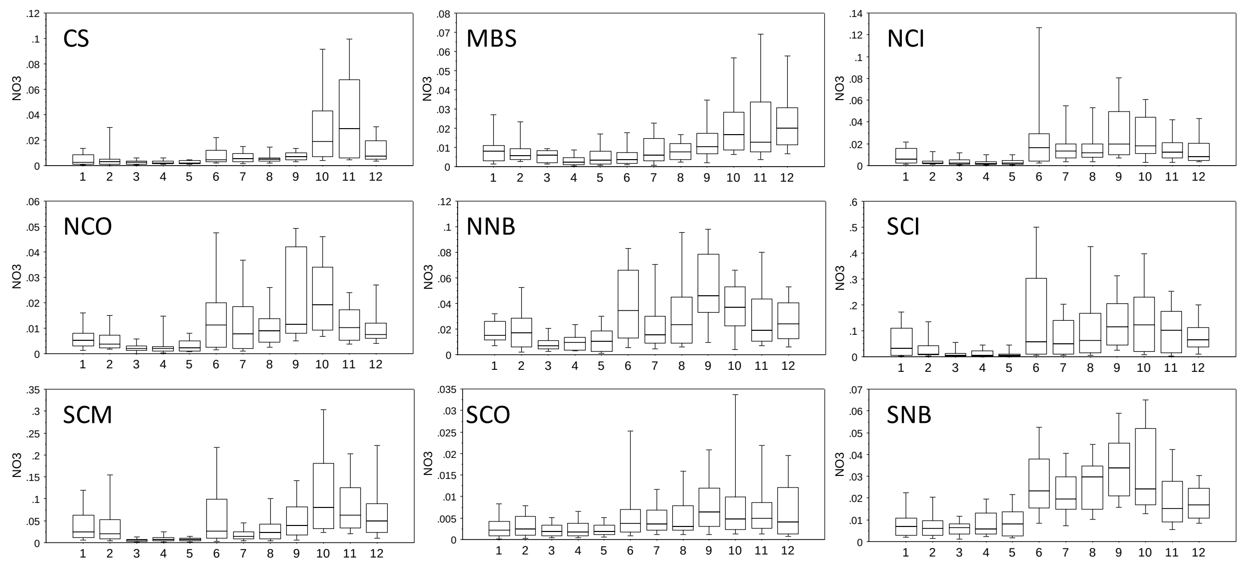

Figure 3.11: Seasonal variability of Nitrate in Biscayne Bay

Ammonium (NH4)

Ammonium follows the same spatial pattern as that of NO3 with higher values in SCI, NNB and SCM (with means of 0.029, 0.024 and 0.021 mg/l respectively) and the lowest in SCO (mean of 0.011 mg/l). Seasonality of NH4 indicates lower values during the late dry season and higher concentrations and variability during the wet season peaking in September or October (Fig 3.12). Also, there is a noticeable increase in June, which is the first rainy month after the dry season.

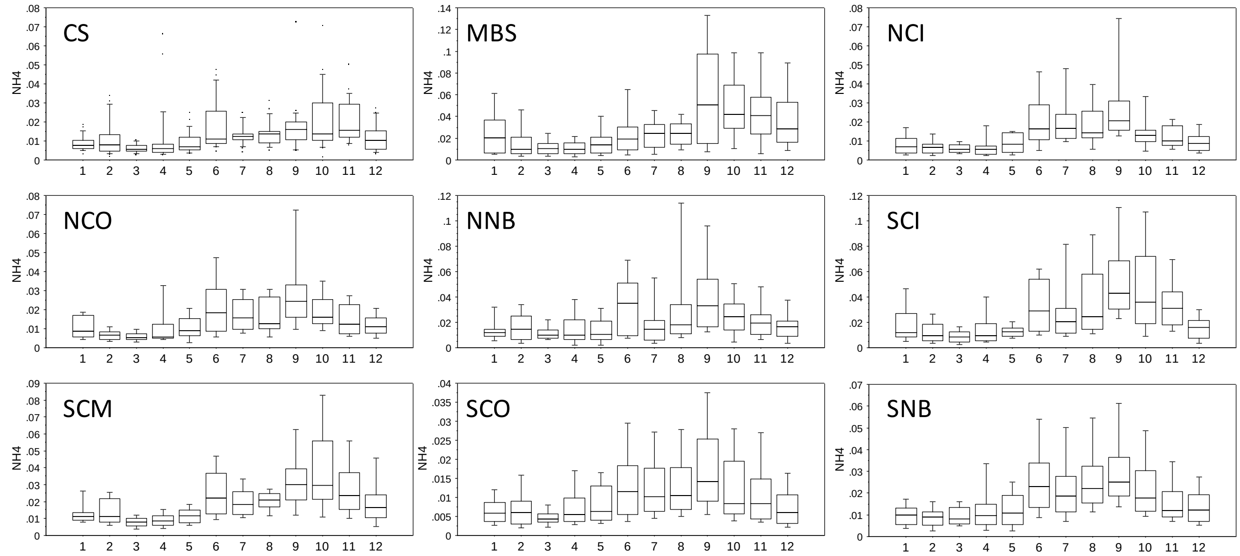

Figure 3.12: Seasonal variability of Ammonium (NH4) in Biscayne Bay

Total Nitrogen (TN) and Total Organic Nitrogen (TON)

Most of the TN (about 75%) is in organic form (TON). The TN spatial distribution varies across the bay, with the southern portion having higher values and the northern one lower values. The highest mean TN concentrations are observed at MBS (0.468 mg/l) and SCI (0.433 mg/l) and the lowest at SCO (0.216 mg/l). Although TN displays slightly higher values in the wet season, a clear seasonality (Fig 3.13) is not well defined. However, a persistent high occurs in August. The exceptions are CS and MBS, both of which display a seasonal pattern with higher values in the wet season. TON, on the other hand, has no defined seasonal pattern (Fig 3.14).The high TN values observed at MBS are difficult to explain considering that TN loads from the C-111 canal into Manatee Bay are less than 50 Ton/yr, nearly 1/10th from that of canals discharging into SCI. Hence, the significantly higher median TN and TON concentrations in MBS and SCI may be due to contributions from wetlands, either as overland flow or from groundwater.

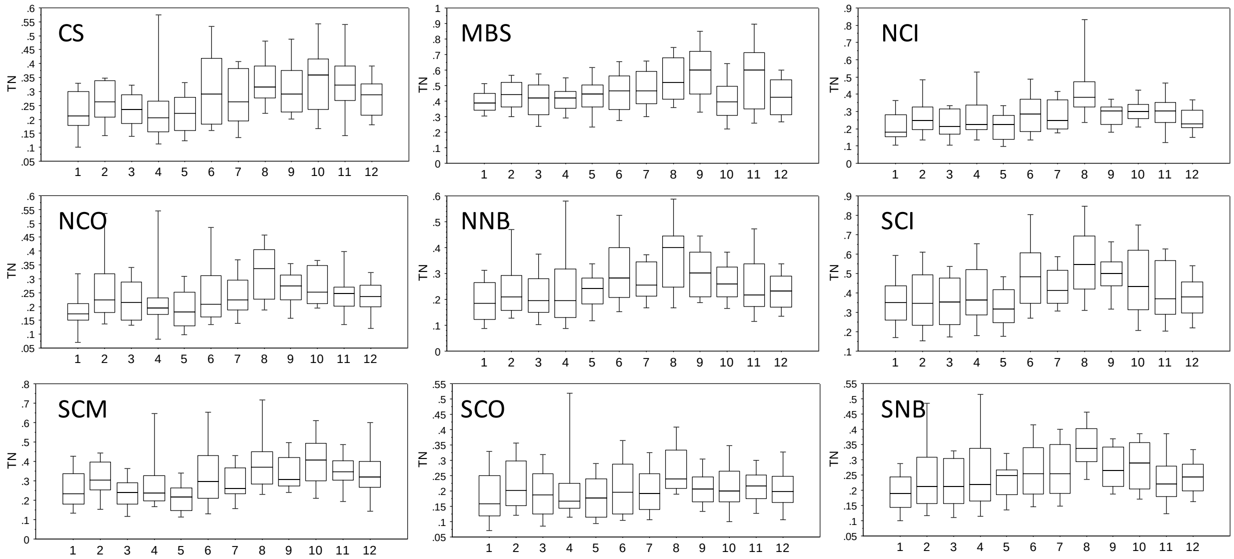

Figure 3.13: Seasonal variability of Total Nitrogen (TN) in Biscayne Bay waters

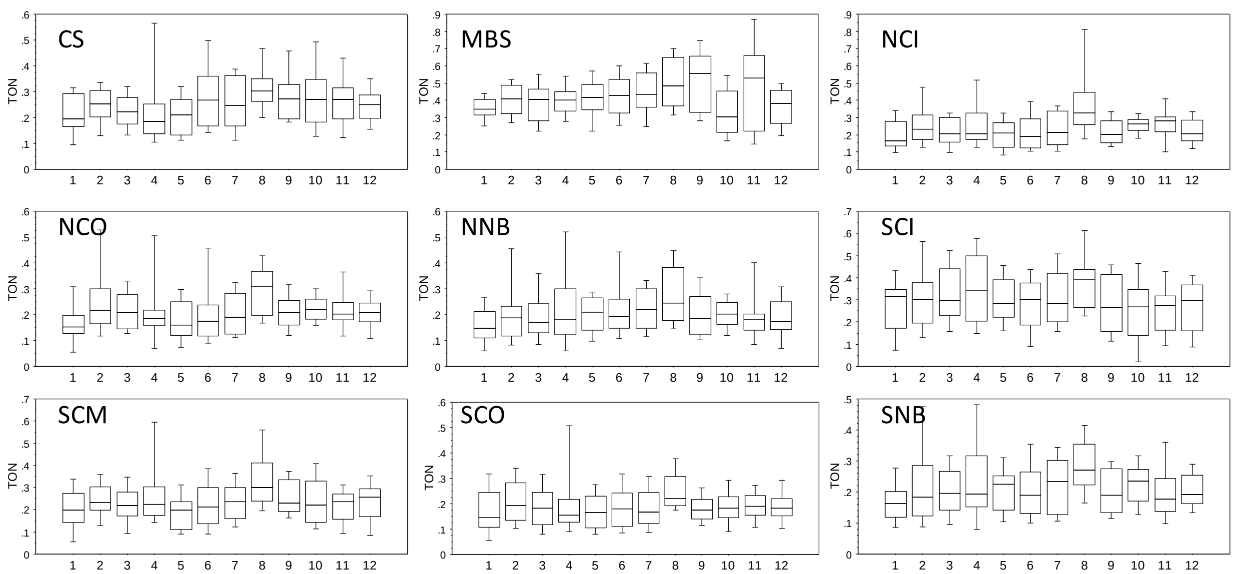

Figure 3.14: Seasonal variability of Total Organic Nitrogen (TON) in Biscayne Bay waters

Total Phosphorous (TP)

Compared to most estuaries worldwide, phosphorous concentrations in Biscayne Bay are extremely low. Mean TP concentrations are lowest (<=0.007 mg/l) for CS, NCI, NCO, SCM and SCO, while the highest means occur in North Biscayne Bay (NNB =0.011 mg/l and SNB =0.09 mg/l) reflecting urban impact. Total phosphorous does not show any seasonal pattern and values are rather flat along the year with just a faint increase of TP values from May to December is suggested from Fig 3.15. Extreme sporadic high values occur associated to anthropogenic and storm driven inputs, as occurred in MBS after the impact of hurricanes Katrina, Rita and Wilma in 2005 (i.e. 0.096 mg/l).

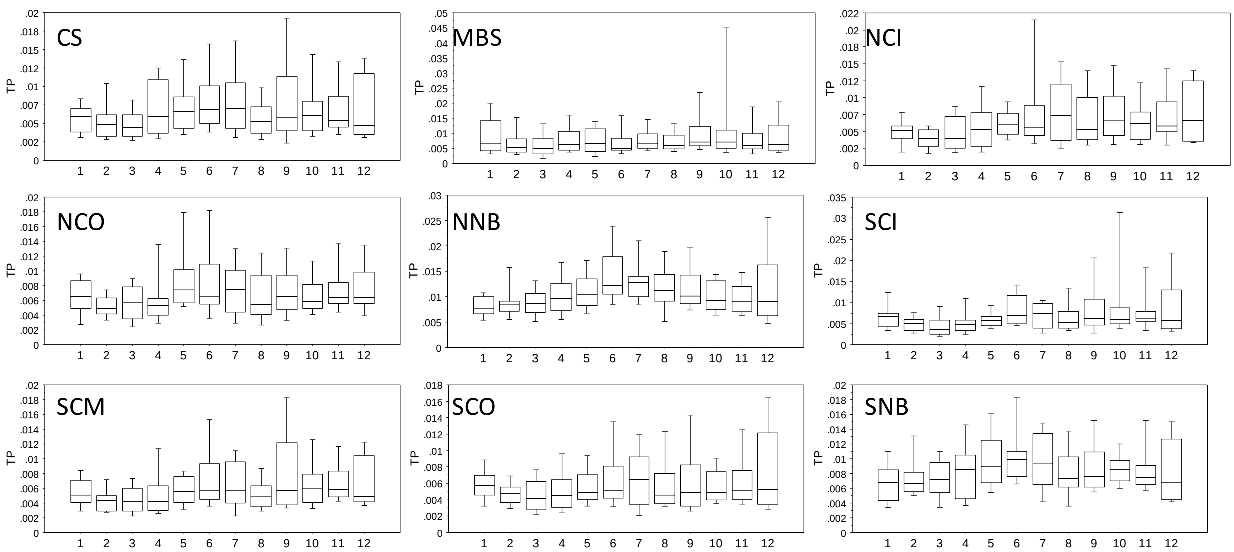

Figure 3.15: Seasonal variability of Total Phosphorous (TP) in Biscayne Bay waters

Previous researchers in the coastal Everglades have suggested an “upside-down” control on nutrient supply, with seawater providing the limiting nutrients, (Childers et al. 2006). This concept has been extrapolated to most south Florida’s estuaries, but our results indicate otherwise for Biscayne Bay. In fact, waters most influenced by oceanic input (SCO) have average and median TP concentrations lower than most Biscayne Bay waters (Fig 3.15). Perhaps in the past, when the watershed was still pristine, natural overland flow across the Everglades freshwater marshes allowed an effective fixation of the already low phosphorous in vegetation and soils, making land

TP contribution nil, but today, with the canal network practically conveying runoff waters from agricultural areas south of Lake Okeechobee and Homestead, as well as from the Great Miami area to Biscayne Bay more TP is supplied to the bay by canals than from ocean waters.

Chlorophyll a (CHLa)

Chlorophyll-a concentrations are very low as compare to most estuaries, with maximum concentration below 10 ug/l and mean values ranging from 1.72 (NNB) to .256 ug/l (SCO). Chlorophyll-a values display a conspicuous spatial pattern with larger average values and larger standard deviations occurring in the extreme north (NNB and SNB) and the southern extreme (MBS), while lower values appear in the south central portion of Biscayne Bay (SCI, SCM and SCO) (Fig 3.16). This pattern is similar to that of TP, underscoring a potential driver (TP)--response (CHLa) relationship. Disparities between mean and median values and the large standard deviations are indicative of high CHLa episodic events (blooms). CHLa seasonality is also crudely defined in Biscayne Bay waters. Generally higher values appear in September-December and -minimum in March-May. High mean CHLa in MBS was caused by blooms occurring after hurricanes Katrina, Rita and Wilma in 2005 (Rudnick et al. 2006, 2007; Briceño and Boyer 2010), which were sustained by nutrient input from a nearby road construction project.

The maximum individual measurement ever observed by FIU WQMN in Biscayne Bay was 8.6 ug/l CHLa in Manatee Bay on January 2006. Even after such events, the 90th percentile reached only 0.8 ug/l CHLa, indicating that South and Central Biscayne Bay waters are far from being considered impaired waters under the Florida impaired water rule, which states that an estuary is impaired if the annual mean CHLA concentration is greater than 11 ug/l.

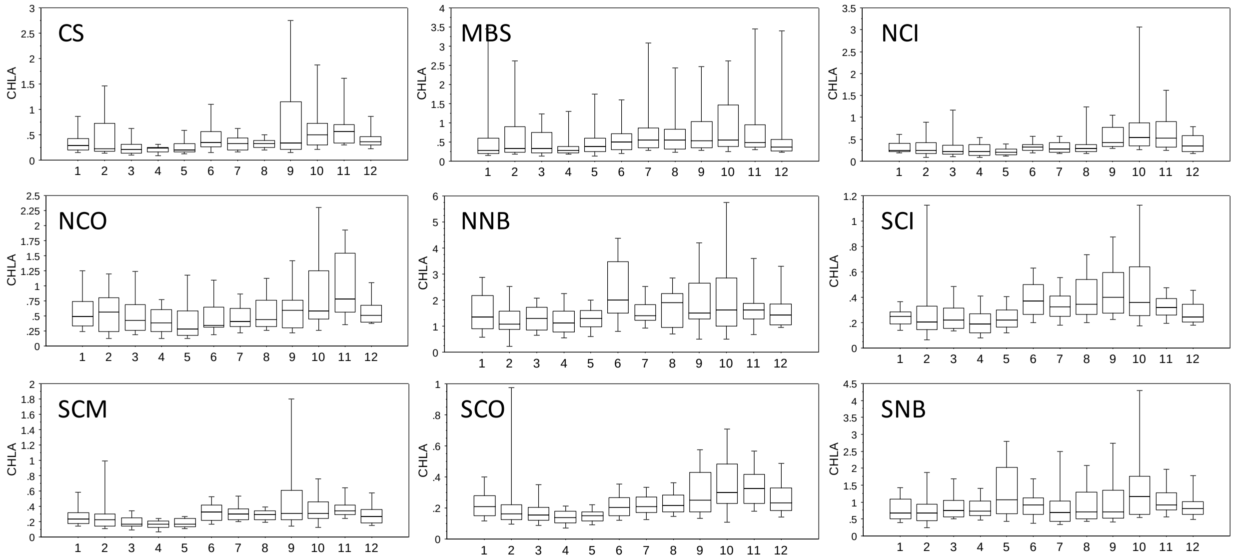

Figure 3.16: Seasonal variability and descriptive statistics of Chlorophyll a (CHLa) in Biscayne Bay

Total Organic Carbon (TOC)

Average TOC concentration is largest in MBS (7.18 mg/l) and lowest in SCO (2.45 mg/l). TOC seasonal pattern shows higher concentrations and larger variability in August-September and lower values in January-April (Fig 3.17). Hence, TOC concentrations are somehow related to climatic conditions with higher concentrations occurring during the rainy season (June-November).

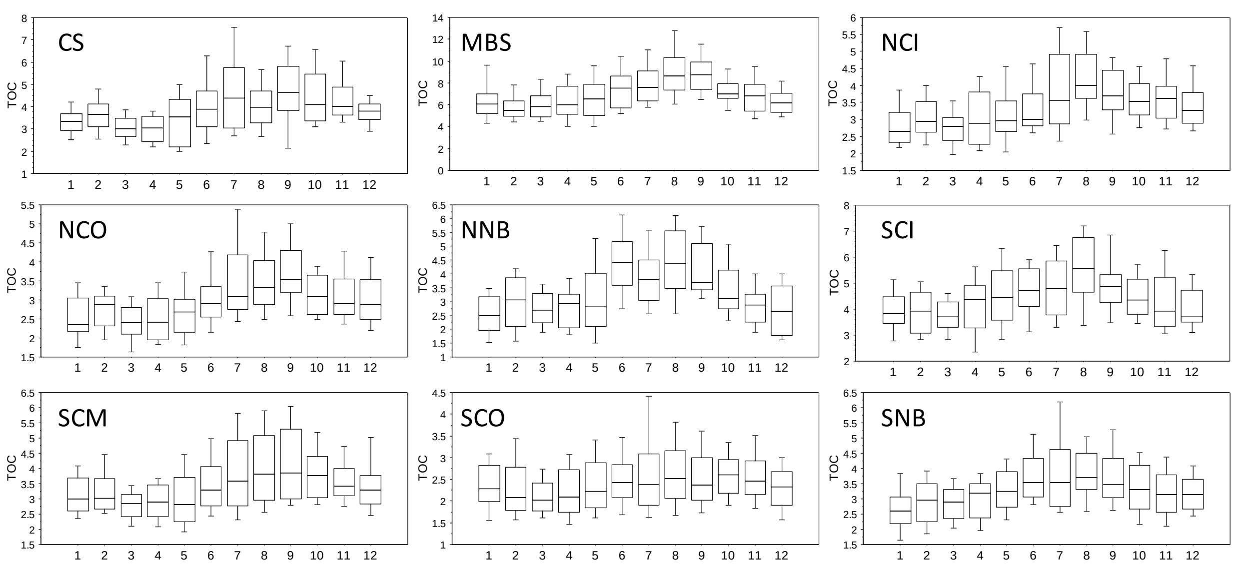

Figure 3.17: Seasonal variability of Total Organic Carbon (TOC) in Biscayne Bay

Dissolved Oxygen (DO)

Bay wide mean and median DO concentrations are 6.45 and 6.43 mg/l indicating oxygenated waters with only 0.8% and 1.6% of the total values being below the 4 mg per liter DO threshold for surface and bottom waters respectively (Fig 3.18). Maxima DO concentrations occur in January-February and minimum in August across the bay, in an opposite pattern as that of temperature (Fig 3.18) with one-month lag. State of Florida Rule 62-302.530, for Class III marine waters, specifies that DO “shall never be less than 4.0 mg l^{-1}”. Application of this rule is complicated because there are locations in South Florida where coastal waters have natural DO concentrations below 4 mg/l (Boyer and Briceño 2007). Exceedances of this norm are usually below 1% for surface waters except for MBS (1.65%) and SCI (1.72%). Bottom waters are slightly less oxygenated, with % exceedances ranging from 1.11% (CS) to 3.14% (MBS) (Table 3.1).

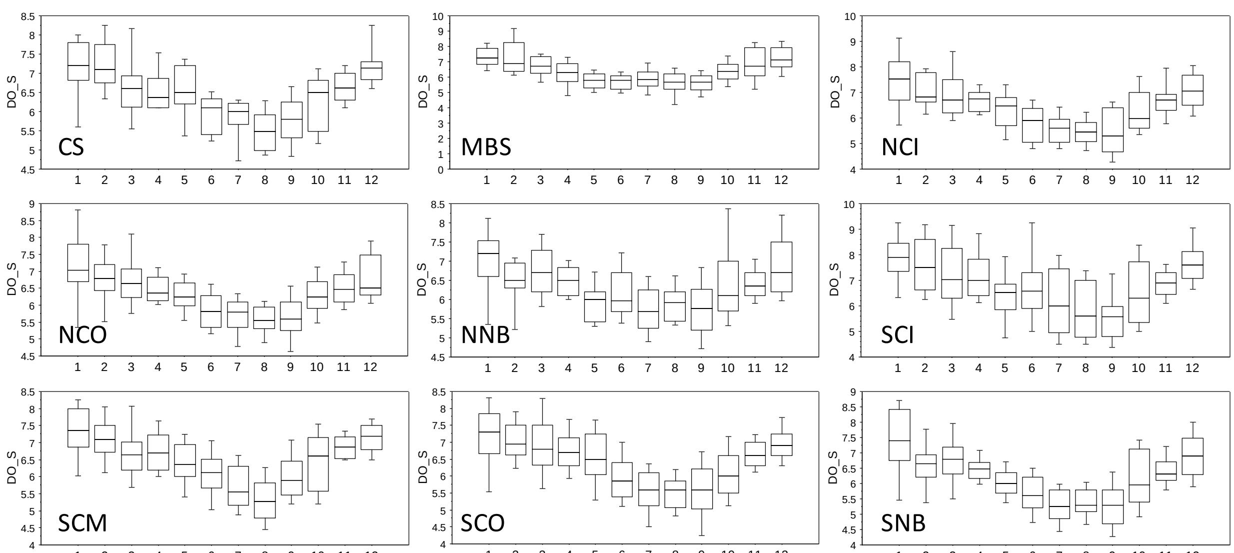

Figure 3.18: Seasonal variability of Dissolved Oxygen (DO) in Biscayne Bay

Table 3.1: Percent DO exceedances (below 4 mg/l DO) in surface and bottom waters

	CS	MBS	NCI	NCO	NNB	SCI	SCM	SCO	SNB
Surface	0.00%	1.65%	0.37%	0.74%	0.37%	1.72%	0.99%	0.09%	0.74%
Bottom	1.11%	3.14%	2.58%	1.48%	2.95%	2.46%	1.23%	1.57%	1.97%

Finally, we compared similarities (differences) in nutrient concentration among segments using Kruskal-Wallis test for three parameters of interest for numeric nutrient criteria development, TN, TP and CHLa. Results are shown in Table 3.2. Differences in Total Nitrogen distribution are not statistically significant for CS-NCI; NCO-SNB-NNB; NCI-SNB-NNB; and SNB-NNB. For TP, there are not statistically significant differences for MBS-NCO; SCI-CS-NCI; SCM-SCI; and CS-NCO-NCI. For CHLa, there are not statistically significant differences for MBS-NCO; and CS-NCI. In summary, for those segment pairs (triplets) with no significant differences the same criteria may apply.

Table 3.2: Results of Kruskal-Wallis test comparing TN, TP and CHLa distribution among segments of Biscayne Bay. Probabilities highlighted in bold (p>0.05) are those pairs whose differences are not statistically significant.

	p-value for Total Nitrogen								
	MBS	SCI	SCO	SCM	CS	NCO	NCI	SNB	NNB
MBS	1	*	*	*	*	*	*	*	*
SCI	0.000	1	*	*	*	*	*	*	*
SCO	0	0	1	*	*	*	*	*	*
SCM	0	0	0	1	*	*	*	*	*
CS	0	0	0	0.012	1	*	*	*	*
NCO	0	0	0.000	0	0.002	1	*	*	*
NCI	0	0	0	0.001	**0.458**	0.018	1	*	*
SNB	0	0	0	0	0.020	**0.285**	**0.127**	1	*
NNB	0	0	0	0	0.050	**0.246**	**0.221**	**0.846**	1

	p-values for Total Phosphorous								
	MBS	SCI	SCO	SCM	CS	NCO	NCI	SNB	NNB
MBS	1	*	*	*	*	*	*	*	*
SCI	0.000	1	*	*	*	*	*	*	*
SCO	0	0.000	1	*	*	*	*	*	*
SCM	0	0.009	0.340	1	*	*	*	*	*
CS	0.001	**0.795**	0.001	0.036	1	*	*	*	*
NCO	**0.269**	0.053	0	0.000	**0.044**	1	*	*	*
NCI	0.000	**0.295**	0.021	**0.193**	**0.470**	0.006	1	*	*
SNB	0	0	0	0	0	0	0	1	*
NNB	0	0	0	0	0	0	0	0	1

	p-values for Chlorophyll-a								
	MBS	SCI	SCO	SCM	CS	NCO	NCI	SNB	NNB
MBS	1	*	*	*	*	*	*	*	*
SCI	0	1	*	*	*	*	*	*	*
SCO	0	0	1	*	*	*	*	*	*
SCM	0	0.016	0	1	*	*	*	*	*
CS	0	0.016	0	0	1	*	*	*	*
NCO	**0.661**	0	0	0	0	1	*	*	*
NCI	0	0.075	0	0.000	**0.568**	0	1	*	*
SNB	0	0	0	0	0	0	0	1	*
NNB	0	0	0	0	0	0	0	0.000	1

TREND ANALYSIS

Biscayne Bay has been a dynamic environment over the last 500 years, experiencing marked salinity and benthic habitat variability. Some changes may be connected to anthropogenic intervention while others seem to respond to regional or global changes. Salinity has increased, seagrass has declined; open-marine species have replaced estuarine assemblages and the reduction of managed freshwater deliveries into BB has been coupled with increases in foraminifera abundance (*Archaias* and *Articulina)* since 1947 and declines in *Thalassia* after 1950 (Wingard et al 2004). Since the middle 1980's significant regional ecosystem shifts have been documented in South Florida coastal waters (Boesch et al. 1993; Fourqurean and Robblee 1999; Hunt and Nuttle 2007; Briceño and Boyer 2010). Some of the significant changes were: seagrass die-off beginning in 1987; large plankton blooms in the western and central portions of the Florida Bay (Robblee et al. 1991); increased phytoplankton abundance (Phlips and Badylak 1996); increased turbidity; significant declines in fisheries and shrimp harvest (Tabb and Roessler 1989; Tilmant 1989); sponge mass mortality in hard bottom areas of southern Florida Bay (Butler et al. 1995); extended coral bleaching in the Florida Keys reef tract after the 1980's; and sustained nutrient concentration decline in waters leaving the Everglades (Briceño and Boyer 2007, 2008).

Recent changes in BB have been reported by Migliaccio et al. (2008) who studied biogeochemical trends from years 1996 to 2007, using DERM, NPS and FIU data. They reported increasing trend for chlorophyll-a likely responding to the increase in NH_4-N, SRP, and TPO_4-P, in turn responding to a dramatic population increase and land use change in the watershed from agricultural land to residential and urbanizing areas.

Our analysis of time-series components was performed with Akritas Theil/Sen regression (ATS) for secular trend (Appendix 9) and Zcusum charts for detailed scrutiny. A Cusum chart is a plot of the cumulative sum of deviations ($S_n = \Sigma[z_i - T]$ for i=1….n) from a target (T), in our case, the time-series grand mean, against n, the sample number (or date if regularly sampled) (Ewan, 1963). Cusum charts and Cusum analysis are standard procedure in the field of industrial process control (Duncan 1974; Grant and Leavenworth 1980; Montgomery 2001). For a detailed explanation on construction, properties and applications of Zcusum charts, the reader is referred to Appendix 4). Visual inspection of Zcusum charts gives a detailed history of the parameters variability along the time-line or another variable gradient providing more information than ATS, ordinary linear regression or Line of Organic Correlation.

Finally, we must always keep in mind that trend analysis is limited to the window of observation; trends change with continued data collection. In addition, water quality in South Florida may fluctuate according to disturbance events of longer periodicity, and trends may even reverse during a given period of record.

Total Nitrogen

As shown in Fig 3.19, TN declined across the Bay displaying two cycles common to all segments during the POC. From 1996 to 1999 values were in general above average (positive Zcusum slope), followed by a decline to below average values until 2002, except in SCO where the decline began in 1998. The second cycle extends from 2003 to 2007, with the break from above to below average approximately occurring at the end of 2004. In MBS the second cycle is less developed. Finally, seasonality is crudely developed, perhaps reflecting managed water deliveries non tuned to natural rain cycles and water inflow.

Total Phosphorous

Phosphorous displays a common pattern to all segments in Biscayne Bay, except MBS, consisting of (Fig 3.20):

- Below average TP values until the end of 1998, followed by above average TP to early-mid 2001
- Seasonal changes with below average values until early 2002 followed by above average TP to late 2002

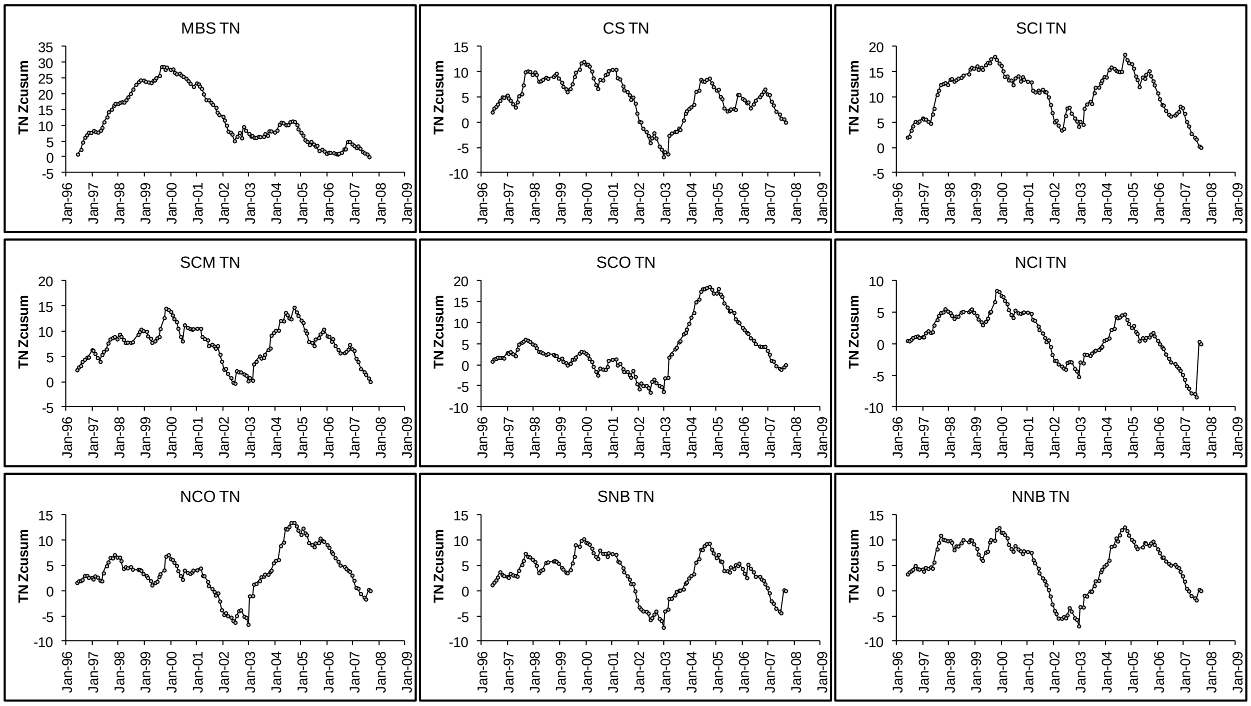

Figure 3.19: TN Zcusum charts for water quality segments in Biscayne Bay

- Below average TP until early 2005 followed by a long above average period, which started with a sudden increase in concentration in the summer 2005 (Wilma impact), followed by a less steep decline until mid-to-late 2006 when again a sudden increase in TP occurred.
- Finally, TP declines from early 2007 to the end of the POC.

The extreme impact of hurricanes Katrina, Rita and especially Wilma in 2005, distorted the TP pattern at MBS (Fig 3.20) which otherwise would follow a similar pattern as the rest of the Bay. In this context, TP across all Biscayne Bay was declining until 2005. As for TN, seasonality is not well defined for TP either.

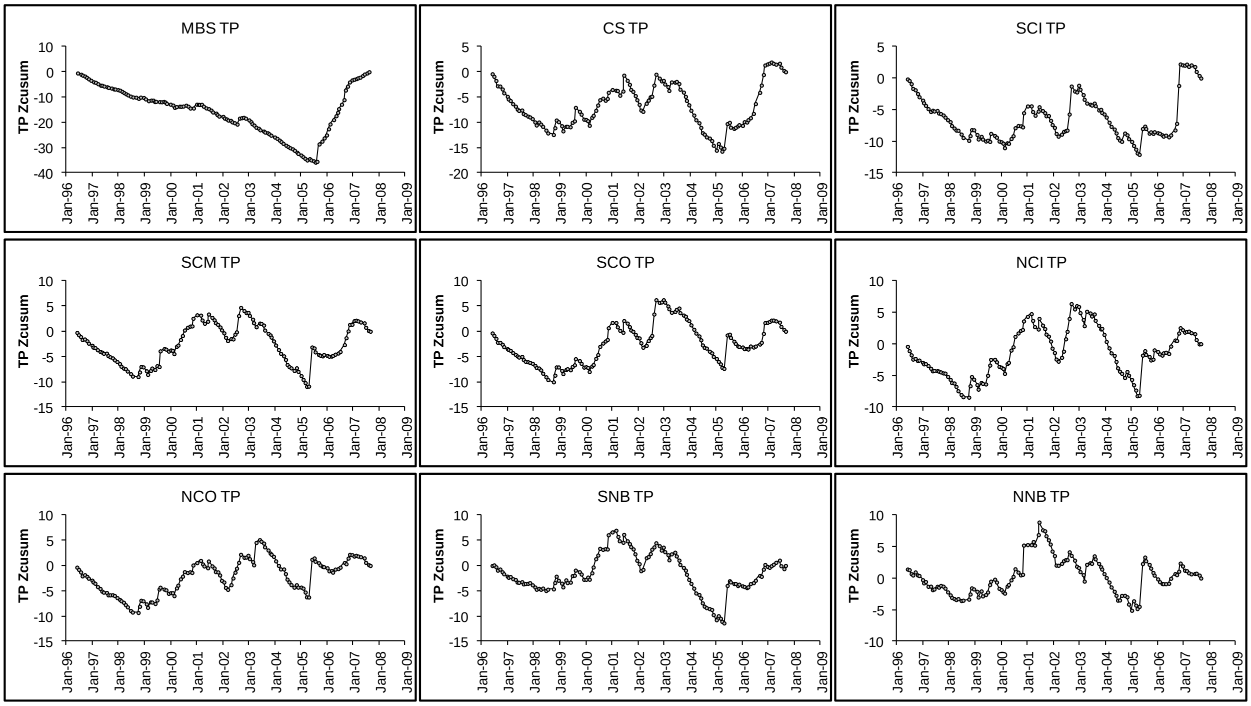

Figure 3.20: TP Zcusum charts for water quality segments in Biscayne Bay

Total Organic Carbon

Total Organic Carbon has declined continuously in Biscayne Bay in the POC as indicated by the dome-shaped Zcusum charts of Fig 3.21. Only MBS and CS and perhaps SCM show evidence of hurricane impacts in 2005-2006, highlighted by sudden increases in TOC concentration, lasting until the end of 2006. Except for SCO, where oceanic exchange is the largest, seasonality is well displayed across the Bay, as shown by the wavy pattern of cusum charts (Fig 3.21). The constant decline of TOC, since early 1990s, has been reported for all South Florida coastal and estuarine waters (Briceño and Boyer 2007, 2008 and 2010), and has been linked to a major system shift in North Atlantic SST which cascaded into regional wetter-warmer climatic conditions.

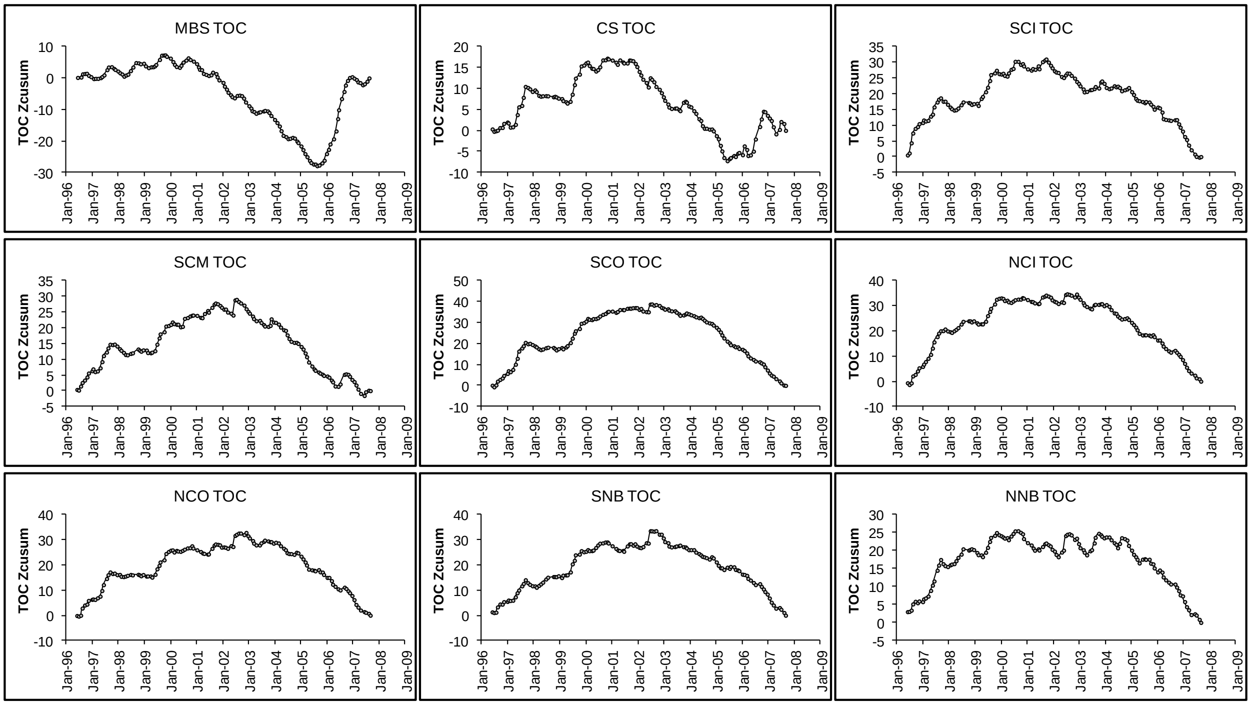

Figure 3.21: TOC Zcusum charts for water quality segments in Biscayne Bay

Chlorophyll a

Chlorophyll a followed a similar pattern in all segments, except at MBS and CS. As for TP, hurricanes Katrina, Rita and Wilma triggered unprecedented CHLa blooms in MBS and CS, which distorts the time-series pattern. As shown above, when post-hurricane data is discarded, all segments display a common pattern (Fig 3.22). This pattern is characterized by a below-average tendency until 1999 when Hurricane Irene impacted South Florida. Irene produced heavy rainfall across southeastern Florida, peaking at 17.45 inches at Boynton Beach and 10-15 inches in Miami Metropolitan area. Most heavy rain from Irene was concentrated over Biscayne Bay watershed (Fig 3.23), which coupled with large water releases from canals to avoid flooding of Miami, contributed to the development of a large algal bloom in the Bay. After ten months (early-mid 2000) CHLa concentrations had returned to mostly below average levels in SCI, SCM, SCO, SNB and NNB (similar Zcusum slope as before impact). After mid-2003 an above average trend set in lasting until 2007, when a new decline began. On the other hand, and underscoring the combined natural and anthropogenic impacts, the 2005 bloom persisted for four years in MBS.

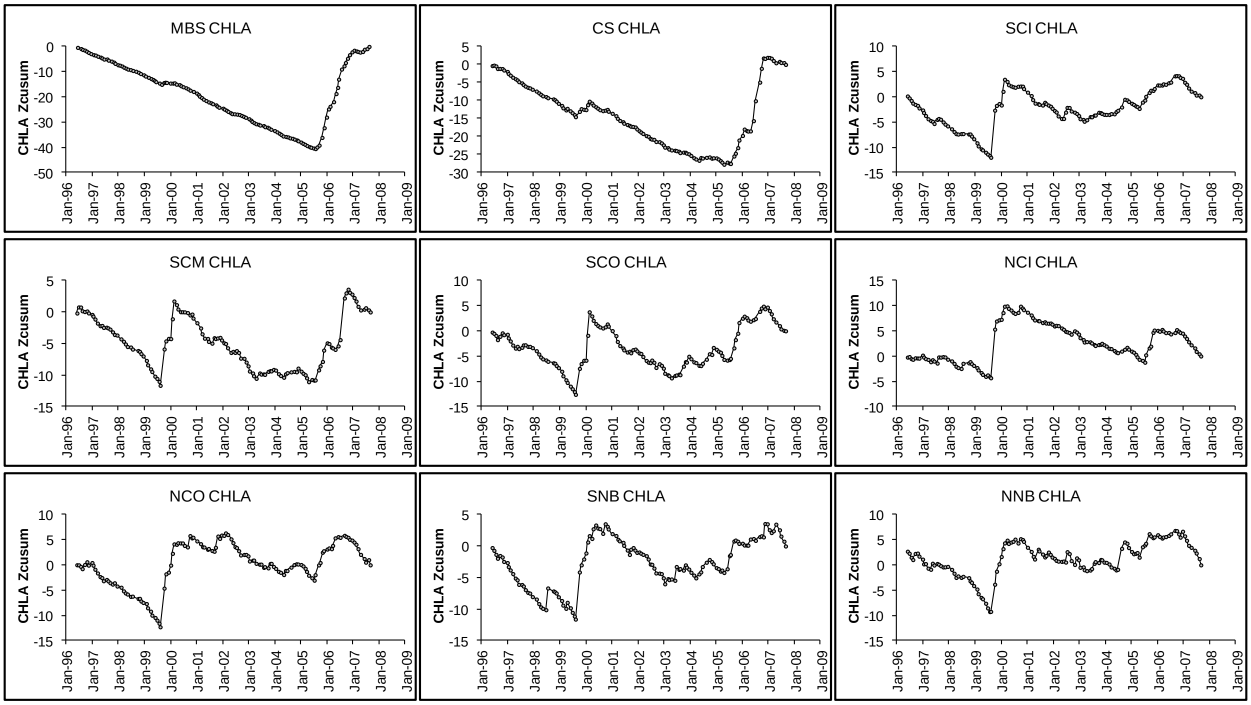

Figure 3.22: CHLa Zcusum charts for water quality segments in Biscayne Bay

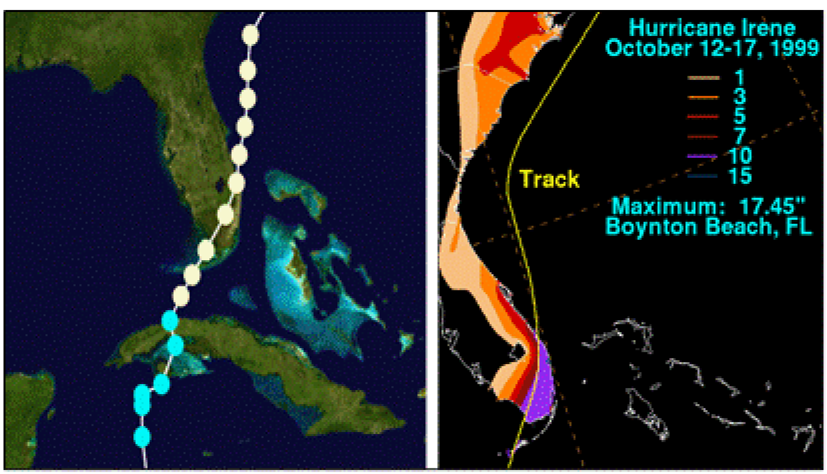

Figure 3.23: Hurricane Irene track over Southeast Florida and recorded precipitation. http://en.wikipedia.org/wiki/1999_Atlantic_hurricane_season

Dissolved Inorganic Nitrogen

Dissolved Inorganic Nitrogen (NOx+NH4) has declined in MBS and CS, and increased in SCI, SCM, NCI, NCO and NNB (Fig 3.24). Hurricane impacts seem to generate sudden DIN increases, as shown for MBS after the 2004-2005 hurricane seasons. A systematic break from above or average DIN concentrations to below average levels occurred at the end of year 1999. Stations displaying an overall increasing trend over the period of record (SCI, SCM, NCI, NCO and NNB) also show low values extending until 2002 at SCI, SCM, NCI, NCO and NNB.

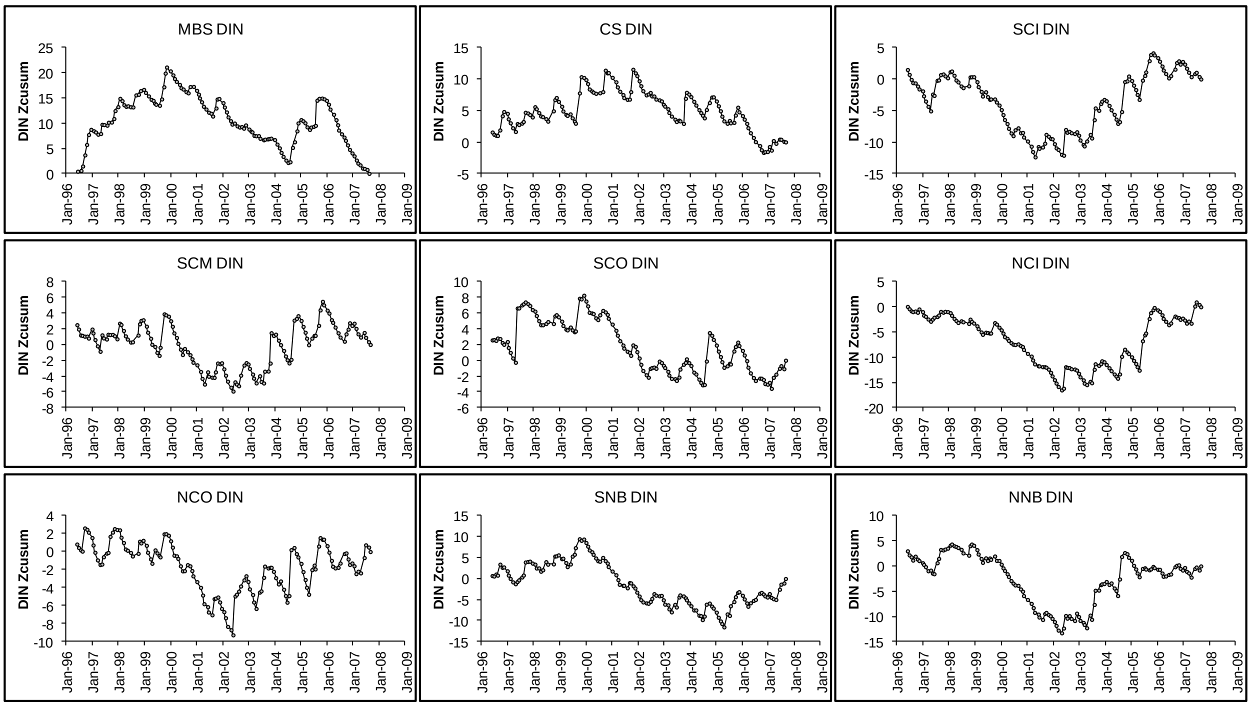

Figure 3.24: Dissolved Inorganic Nitrogen Zcusum charts for water quality segments in Biscayne Bay

Salinity

Salinity displays long-term increasing trends over the POC (Fig 3.25). In general, salinities well below average characterized all segments until the end of 1998. From 1999 to the end of 2003, salinity either increased to slightly below average values (MBS, CS, SCM, SCO) or developed a short cycle of increase-decline (NCI, NCO, SNB, SCI and especially NNB). This short (4-year) cycle prevails in those sub-basins most affected by canal inflow, and is directly linked to water volumes delivered by the SFWMD to the bay. Finally, salinity tended to be above average bay-wide since 2004

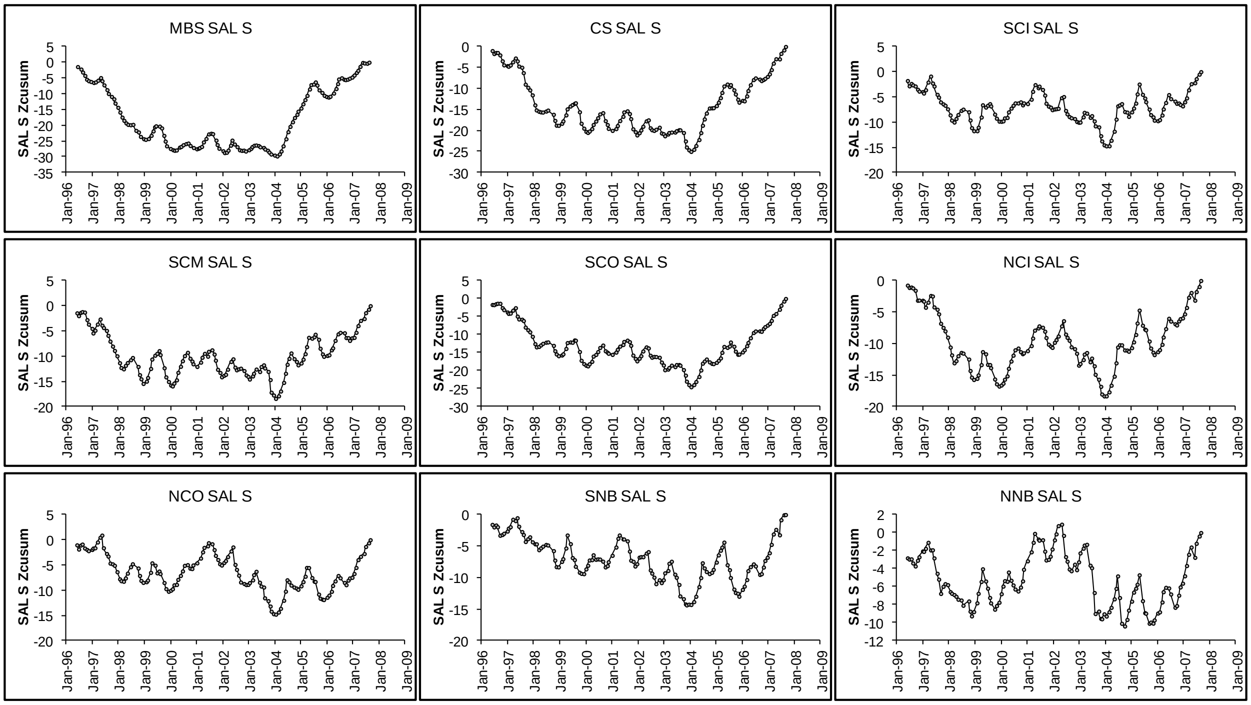

Figure 3.25: Salinity Zcusum charts for segments in Biscayne Bay

Dissolved Oxygen

Dissolved oxygen in Biscayne Bay waters (Fig 3.26) displays a rather persistent pattern characterized by slightly above average concentrations from 1996 to 2001-2002; followed by a decline to below average values until the end of 2004, when above average concentrations began to dominate and persisted until 2007. SCI and NCI partially departed from this general pattern by developing an above average DO tendency from 1996 to the end of year 2000.

Temperature

Water temperature is characterized by well developed seasonality and two patterns of variability along the POC (Fig 3.27). For MBS, SCI, NCI, SNB and NNB the central tendency of temperature remained equal or slightly above average until 2000, while for CS, SCM, SCO and NCO below average values prevailed. After 2000 temperatures were predominantly below average bay-wide until 2002-2003, when it shifted to about average levels.

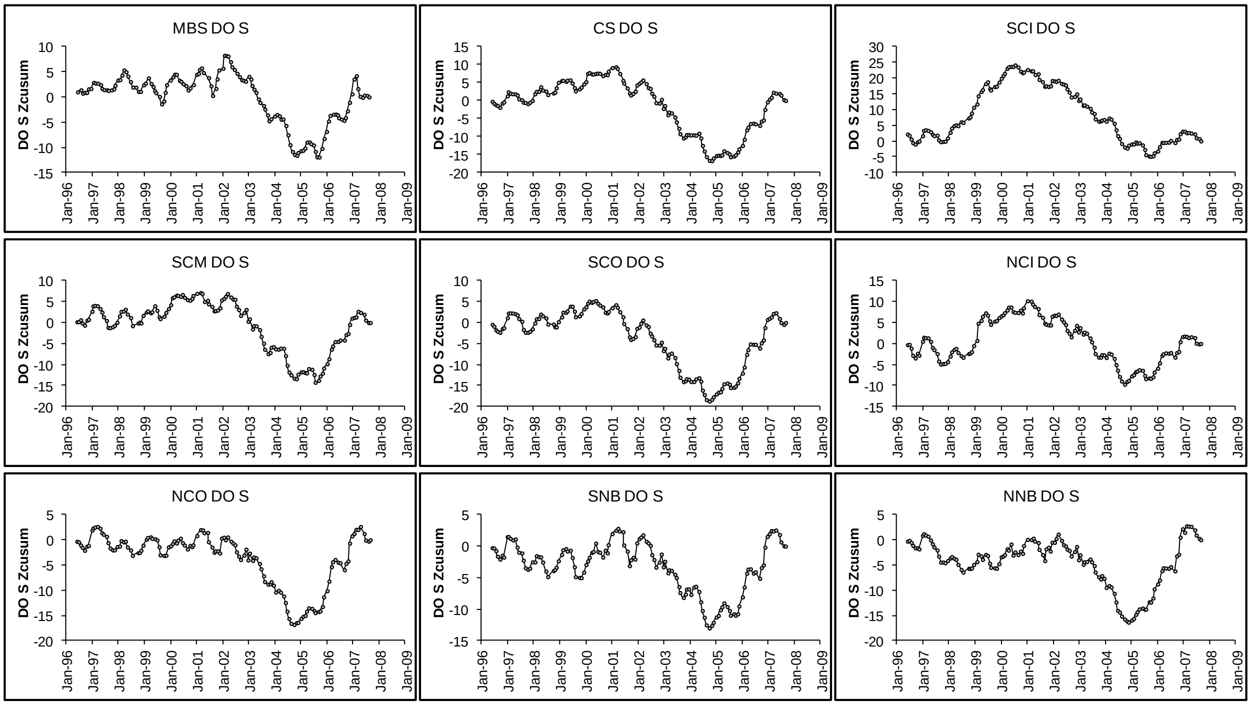

Figure 3.26: Dissolved Oxygen Zcusum charts for segments in Biscayne Bay

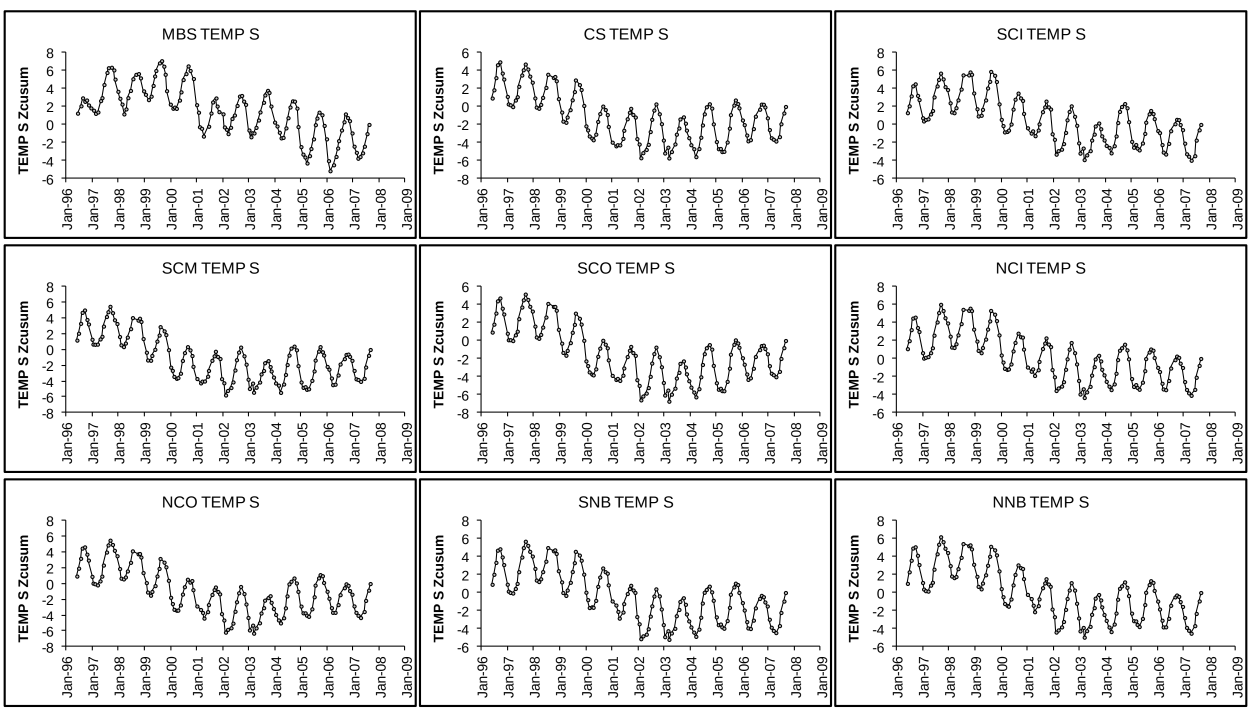

Figure 3.27: Temperature Zcusum charts for segments in Biscayne Bay

In summary, results from the ATS analysis (Appedix XXX) indicate that salinity increased in all sub-basins, perhaps responding to reduced freshwater deliveries and also to sea-level rise. Likewise, TP increased across the Bay but most changes were small and non-significant. On the other hand, TN declined across de bay, especially in MBS and SCI. DIN declined in MBS and increased in SCI with other stations unchanged. TOC consistently dwindled in all sub-basins especially in NNB, NCI and SCI. This decline of TOC in BB parallels similar TOC drop in the whole South Florida. Changes along the POC were not linear, but followed variable, sometimes complex paths with sharp discontinuities. Table 3.3 shows the most important breaks along the time series obtained from the cusum analysis charts of key biogeochemical parameters. Links to hurricane impact may be postulated for breaks in 1998 (Hurricanes Georges and Mitch), 1999 (topical storm Harvey and hurricane Irene) and late 2005 (hurricanes Katrina, Rita and Wilma). Breaks in early 2002 are the most common and seem to be related to water management by the SFWMD.

Table 3.3: Year of occurrence of major breaks along the POR for key biogeochemical parameters in Biscayne Bay

	Main breaks							
	TP	TN	Sal	TOC	CHLa	DIN	DO	Temp
Late 1997				X				
Late 1998	X		X		X			X
Late 1999		X		X	X	X		
Early 2001	X							
Early 2002	X	X	X	X	X	X	X	X
Early 2004			X					
Late 2004		X					X	
Late 2005	X			X	X	X	X	

SECTION 4:
BOX-MODEL SUMMARY

Cetacean Logic Foundation Inc, under FIU Subcontract No. 205500521-01 developed a box-model to estimate nutrient loads to Biscayne Bay from its watershed and implemented mass-balance calculations to estimate the long-term average nutrient concentrations in the Bay based on these loads. The study consisted of a series of steps to: (1) review an existing nutrient loading study, (2) estimate nutrient loads to the Bay for all water budget components, (3) expand an existing hydrology/salinity model to utilize the nutrient loads for mass balance calculations, and (4) use the nutrient box model with estimated loads for future land use scenarios and interpret the output.

The first step in this study was to review nutrient loads previously estimated in an engineering study performed for Miami-Dade County using land-use coefficients. The South Miami-Dade Watershed Study and Plan estimated existing and future nutrient loads to Biscayne Bay based on patterns of land use in south Miami-Dade County. However, only one component of the Biscayne Bay water and nutrient budget was characterized and the estimated loads were found to be inconsistent with more recent information on nutrient loads based from measured water flows and associated nutrient concentration data, such as work done by Caccia and Boyer (2007).

Because of this, nutrient loads for Total Phosphorous (TP), ammonium (NHx-N), nitrate-nitrite (NOx-N), and Dissolved Inorganic Nitrogen (DIN) were independently developed for all components of the water budget (step 2) based on various existing sources of information, including canals, overland flow (ungauged surface water), groundwater, and atmospheric contributions. With the exception of freshwater inflows and nutrient loads from canals, few direct data exist for estimating these nutrient loads. Indirect data and regression models were used to fill the data gaps. Nutrient loads across the boundaries of the model including the Atlantic Ocean were also estimated from existing data.

Schematic diagram showing the components of the water and salt mass balances for A) a single estuarine basin in connection with the coastal ocean and B) additional fluxes introduced by flow and exchange among sub-basins within an estuarine basin. Conditions in any estuarine basin or sub-basin are characterized by its volume (equal to the product of its area A and average water depth *d)* and average salinity *S*. In case A, salinity in the single basin is maintained through water exchange with the coastal ocean at salinity S_O. In case B, salinity in a sub-basin is maintained by water exchange with adjacent basins and the ocean

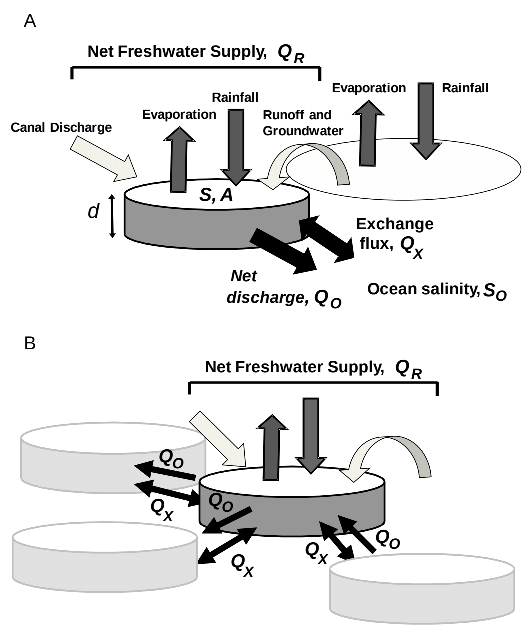

Figure 4.1: Components of box-model used for mass-balance calculations

Calculations of nutrient concentrations in Biscayne Bay based on the estimated loads extended an existing hydrology/salinity mass-balance model (step 3) that had been developed previously for the South Florida Water Management District. This model was used to investigate the linkage between freshwater inflows from the watershed and salinity patterns in the Bay. The model domain and the hydrology/salinity calculations were upgraded based on peer-review comments and the model was extended to incorporate mass-balance nutrient calculations. The model was then calibrated against measured salinity to estimate the water fluxes between each box and validated against an independent set of salinity observations.

Overall the hydrology/salinity model captured well the patterns of spatial and temporal variability in salinity in Biscayne Bay. Calibration and verification statistics show that the box model accounts for greater that 70 percent of the variability in measured salinity. Calculated values agree with measurements made within the same week with an error of between 2 to 3 psu. Errors are comparable between the calibration and verification time periods and are comparable to results achieved in the previous box model study.

Schematic diagram of the structure of the Biscayne Bay nutrient box model showing canal discharges, exchanges (quantified by parameters X1, X2, …), and net discharge between the boxes. Salinity boundary conditions for the Atlantic Ocean SB1 and northeast Florida Bay SB2 are indicated

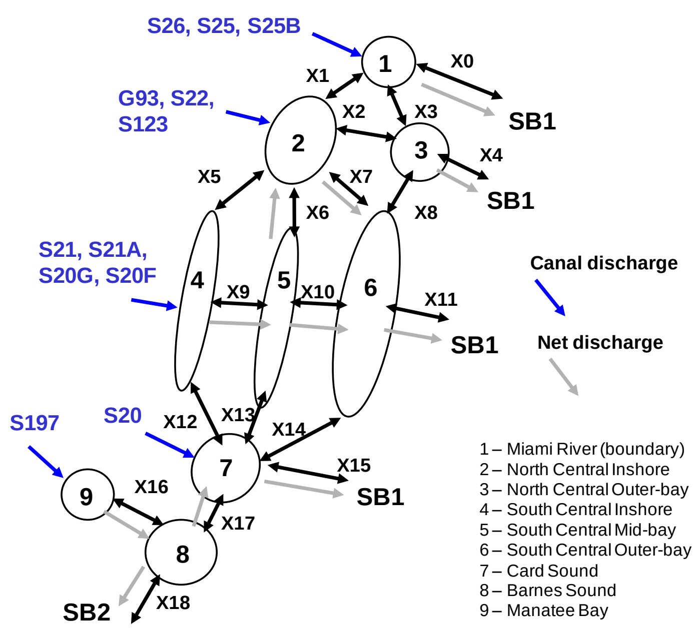

Fig 4.2: Spatial structure of the nutrient box-model.

When the model was used for nutrient mass balance calculations (step 4), the results showed varied success at characterizing the link between nutrient loads and concentrations in the Bay. Average values for TP concentrations assuming no loss or transformation of TP exceeded average measured values by between 17 and 44 percent. Of particular interest, the calculated values of TP concentration reflect the effect of very large loadings of TP caused by hurricanes Katrina, Rita and Wilma in 2005 and Ernesto in 2006. Average values for NOx-N concentrations without accounting for losses due to net denitrification greatly exceed average measured values. Calculated values are between about 1.5 and 4 times higher than measured values. The disparity between calculated and measured values indicates the degree to which uptake, removal, and wash-out of nitrogen species may exert a significant influence over NOx-N concentrations in the Bay. When an average net denitrification rate of 0.3 month^{-1} was applied Bay-wide in the DIN calculations, calculated values for DIN concentrations were equal to or substantially less than observed values in all but one of the sub-basins. In general this means that the net denitrification rate in most areas of the Bay is capable of being estimated by the default rate or a lower rate.

The exception to the general agreement between calculated and observed concentrations of DIN occurs in the South Central Inshore (SCI) sub-basin. Six hypotheses were developed to possibly explain the large discrepancy between calculated and measured NOx-N and DIN in the SCI sub-basin:

1. Estimated NOx-N and DIN loads are too high,
2. There is an error in the mass-balance calculations,
3. Uptake and removal of NOx-N and DIN occurs at a higher denitrification rate in the SCI sub-basin than in the rest of the Bay,
4. Biological uptake or other removal processes in addition to denitrification are at work in the SCI sub-basin and may be at work in the southernmost sub-basins,
5. Tidal circulation patterns remove some of the NOX-N and DIN to adjacent boxes,

6. Measured values of NOx-N and DIN concentration are not representative of average conditions through the whole SCI sub-basin.

Of these hypotheses, the first two hypotheses are less likely to be true, because the same model calculations and application of monitoring data are used for salinity and TP without apparent problems. It is unlikely that the third hypothesis is true because the denitrification rate needed to reduce the calculated DIN concentrations in SCI to the observed values is much higher than has been documented in the literature that was reviewed. The sixth hypothesis cannot be tested without a more frequent monitoring interval in the Bay; these data are not available.

Tidal circulation (hypothesis five) may be an important removal process in the Bay and acts at a higher temporal resolution than the temporal resolution of the box model. Examination of tidal circulation plots from a numeric model indicates that tidally-generated currents may exist that transport waters to both the south and to the north depending on the point in time in the tidal cycle. This may mean that the high nitrogen canal discharges may be flushed out of the parts of the Bay that are influenced by the tide on a sub-daily basis, thereby not affecting the long-term average DIN concentration that is measured in a monthly grab sample.

Biological uptake of NOx-N and DIN (hypothesis four) may also be an important factor in the SCI sub-basin. Recent research indicates that the ecosystem in the SCI sub-basin may be supporting a high rate of uptake and removal of nitrogen from the water column. A combination of hypotheses four (biological uptake) and five (tidal circulation) may also be a plausible explanation.

Lastly, the load estimates were used to simulate the effects of large-scale land use changes from agricultural to urban land uses in the SCI sub-basin. The NCI sub-basin is already at urban build-out, and the areas of the NCI and SCI contributing drainage basins are somewhat similar. At urban build-out, assuming that the SCI drainage basin will be contributing the same area-based TP loads as the current NCI TP loads, the build-out TP loads to the SCI sub-basin will be about 75% of the current SCI TP loads, about 300 kg/mo. However, the canal TP loads do not appear to be controlling the water column TP in the NCO, SCM, and SCO sub-basins; instead the Atlantic Ocean TP load may be the determining factor. In Card Sound and Barnes Sound the atmospheric TP load and limited oceanic influence will likely determine water column TP values. In Manatee Bay relatively large TP loads from S-197 discharges will affect TP (and nitrogen) concentrations.

For NOx-N and DIN, the urban build-out conditions of the NCI drainage basin can also be used to estimate future loads at urban build-out of south Miami-Dade County. If this is the case the future NOx-N and DIN loads to the SCI sub-basin will be about 2700 and 4500 kg/mo, respectively. This is about 3% of the current NOx-N SCI loads and about 5% of the current SCI DIN loads. There will likely be little or no apparent impacts on nutrient loads to NCI (already at build-out) or to Card Sound, Barnes Sound, and Manatee Bay from future land use changes in south Miami-Dade County unless S-197 discharges are reduced, which will reduce loads to Manatee Bay and Barnes Sound. Additionally, because there is little, if any, undisturbed private land in south Miami-Dade County that remains in a native or otherwise natural state and there are no plans to purchase developable lands and return them to a protected natural state, little benefit was seen in evaluating a natural landscape alternative in this metropolitan area. Other ongoing changes in the diverse mix of land uses present in the watershed as well as the political and regulatory activities also affect the ability to infer current and future nutrient loads simply from land use.

The mass-balance calculations provide an incomplete description of the processes contributing to the variation of nutrient concentrations in Biscay Bay, and one must keep in mind the particular capabilities and limitations of this modeling approach in interpreting the results. First, the mass-balance model represents the long-term balance between nutrient loads from external sources and nutrient removal by advection and exchange of surface water. Therefore, the nutrient concentrations calculated by the model are comparable only to long-term average concentrations in the water column and they are not predictive of short-term variations around the mean concentrations. Second, with the exception of a net rate of denitrification in the calculation of dissolved inorganic nitrogen (DIN) concentrations, internal fluxes due to the uptake of nutrients by biota, excretion by organisms, and exchange with benthic sediments are not included in the model calculations. These internal fluxes of nutrients may affect the variation of nutrients in the water column in response to short-term events, such as runoff from storm events, and seasonally. By excluding internal processes of nutrient uptake and transformation, it is assumed that they make a negligible contribution to balancing nutrient inputs from external sources over the long-term. Third, mass-balance calculations for nitrogen do not account for all nitrogen species known to be present in the water column. Calculations are applied only to NOx-N (NO2 plus NO3) and DIN (the sum of NOx-N and NHx-N) concentrations.

Even with these limitations, this study showed that the mass-balance nutrient calculations work well for an evaluation of estimated nutrient loads from the watershed by comparing the long-term average concentrations calculated based on these loads to the long-term average of concentrations measured in the Bay. The average concentrations calculated for total phosphorous and dissolved inorganic nitrogen in the Bay are generally within 25 percent of the average of measured concentrations for the recent period July 1997 through June 2007. This lends confidence that the nutrient loads developed in this study are reasonable estimates of the actual long-term average nutrient loads to Biscayne Bay under current conditions, and that the box model may be a useful tool for investigating the fate and transport of nutrients in the Bay.

In conclusion, the mass-balance approach to linking nutrient loads to Biscayne Bay with the resulting water column concentrations has proven to be useful as a check on the magnitude of the nutrient loads estimated from available data as well as to provide information on the fate and transport of nutrient loads. The mass-balance approach is simple to implement compared to the more costly alternative of developing a coupled hydrodynamic/water quality model, and the simpler approach lends itself to the analysis of uncertainty and alternatives by sensitivity analysis. However, the down-side of the simpler approach is that the mass-balance calculations are not able to predict the short-term response of nutrient concentrations in the Bay to changes in loads. As a result the model calculations may not account for the effect of higher frequency (relatively) processes that may drive nutrient fluxes to and from the water column within the Bay itself. To a large extent, these limitations are imposed by the data that are available to calibrate and verify water quality calculations no matter what model is used. Even so the model was capable of being used in a sensitivity analysis mode to provide a rough-order-of-magnitude estimate of future nutrient loads to Biscayne Bay and the resulting water quality in the Bay.

Feedback received at a workshop convened to review the results of this project recommended that further work be undertaken to understand better and refine the mass-balance calculations. Seasonal variation in nutrient concentrations and the effects of singular events, such as hurricanes, have not been examined in detail, even though these are evident in the monitoring data and in the model calculations. More work is needed to understand the fate of the NOx-N that is apparently “missing” from the South Central Inshore region, including the effects of tidal circulation and biological uptake. Once these questions are satisfactorily addressed, the results of calculations can be refined to include the effect of water management policies and practices on the seasonal and inter-annual variations in freshwater inflows and nutrient loads.

SECTION 5:
SUMMARY OF THREATS TO BISCAYNE BAY AND BISCAYNE NATIONAL PARK WATER RESOURCES

The following chapter is a summary of a recent assessment of natural resource conditions in Biscayne Bay (Fig 5.1), based on the evaluation of a review/compilation of existing information on Park's natural resources (Harlem et al. 2009). This review of existing data was used to evaluate threats and stressors, and is intended to improve understanding of BNP resources in order to help guide Park management to properly address the identified threats. Threats to the resources of Biscayne National Park are multiple as are gaps in our understanding of the functioning of the Biscayne Bay ecosystem. Harlem et al. (2009) focused on several broad resource components, namely terrestrial resources and aquatic systems including wetlands, canals, bay waters, marine/reef areas and ground waters. Both, biotic and abiotic resource components were considered in the study, and the main objectives of the assessment were:

1. Provide a review/compilation of existing information on BNP natural resources.
2. Provide a list and description of a suite of threats/stressors to these resources.
3. Generate a semi-quantitative estimation and ranking of such threats to defined resource components, and the richness of existing information
4. Identify research needs based on information gaps and degree of threat to said resources.

Figure 5.1: Biscayne National Park. Also shown, canals, ditches and tidal creeks dissecting the mainland west of Biscayne Bay.

HABITAT LOSS AND IMPAIRMENT

Coastal Development

Biscayne Bay's watershed has experienced an enormous expansion in urban development in the last 100 years, from 12,000 people in 1910 to 2,460,000 people in 2010 for Miami-Dade alone (http://www.census.gov/popest/data/index.html). Former wetlands and more recently farm fields have been transformed into residential areas (Figure 5.2). More people near the Park increases impact on resources by augmenting usage of the parklands for recreation, increasing pollution, and further requiring measures to reduce flooding which, in turn, impacts surface and groundwater flows to the Park. Projections of considerable further development to south Miami-Dade County are alarming in the scope and magnitude of sprawl development.

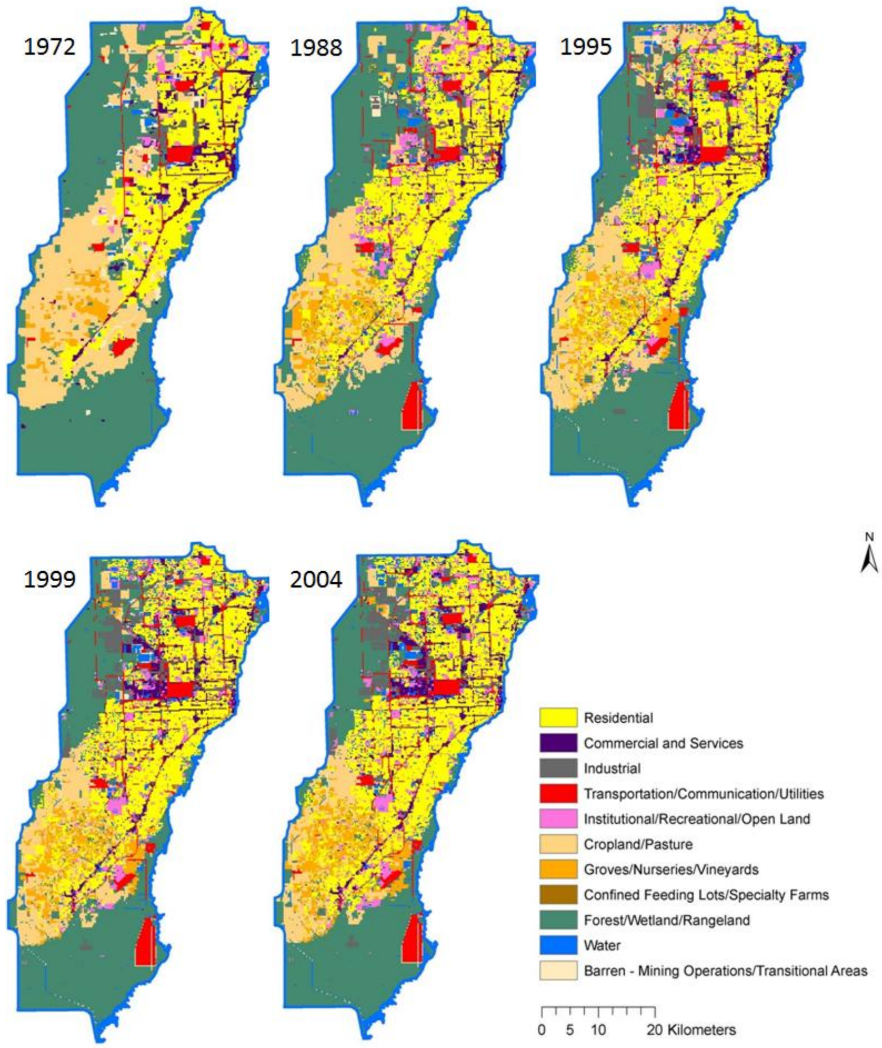

Figure 5.2: Changes in land cover/land use in Miami's Greater Metropolitan area since 1972. Modified after Migliaccio et al (2009).

Channelization/Sheet Flow Barriers

Canals in South Florida were designed to collect surface water and remove it from the landscape thus virtually eliminating sheet flow which once dominated the western BNP shoreline. Road construction produced elevated structures with adjacent canal-like borrow ditches and levee structures which cross the western coast in many places. All these structures are barriers to flow, some affect groundwater, and all fragment the coastal environments into small disconnected parcels (Fig 5.1). This has a negative effect on the wetlands themselves and downstream consequences for those marine/bay ecosystems which depend on both quantity and quality of freshwater entering the estuary, groundwater flow and dynamics of seawater intrusion.

Assessments of perceived impacts of canal and groundwater discharges to southern Biscayne Bay include those of Szmant (1987), Byrne and Meeder (1999), Lietz (1999), Langevin (2000) and Graves et al (2004, 2005). Findings suggest nitrogen-enriched groundwater enters Biscayne Bay through canals and underwater springs. Szmant (1987) reported a change in seagrass community composition near the mouth of C-102 and C-103 and found lower salinities and higher water column nutrient concentrations in the affected areas

Habitat Fragmentation

Habitat fragmentation has both physical and biotic impact. Most fragmentation occurs on the western coastal zone affecting the coastal wetlands and mangrove fringe. This compartmentalization of formerly connected wetlands includes urban areas, canals, roads, and other structures which impede water flow and isolate biota. Therefore habitat fragmentation is a current problem with fair documentation for the terrestrial environments, although its potential impacts on the Bay are only inferred. Dredging and filling for marinas and residential boat access as well as channels dug through shallow water and bridges/causeways are currently a minimal problem in Biscayne National Park, but affects the Bay to the north of the Park.

Power Plants

Electrical generating power plants, all run by Florida Power and Light, are located adjacent to Biscayne National Park. The principal plants are: (1) the Turkey Point Nuclear facility located just west of the Park's SW corner and includes a fossil fuel peaker plant on site; (2) the Cutler Power Plant, located on the shore of Biscayne Bay northwest of the Park; and (3) one fossil fuel peaker plant which has been permitted south of the Princeton canal just west of the Park perimeter. Since 2007, the NPS has expressed concerns about the planned expansion, indicating those plans affect mangrove wetlands within protected areas, and the recharge area which maintains the saltwater barrier line, and would decrease any benefit the CERP Coastal Wetlands restoration could provide once implemented. NPS also pointed out the lands had been previously identified as providing wildlife connectivity, and are frequented by several endangered or threatened species including the Florida panther, indigo snake, wood stork and state listed wading birds. NPS also expressed concerns about the lack of supplies of water to meet the plants needs, disposal of same, archeological issues, and the threats from sea level rise which would leave the facility as an island at some future stage (NPS, 2007).

WATER QUALITY

Water quality issues of concern for Biscayne Bay and Biscayne National Park are primarily caused by their proximity to Miami Metropolitan area, home to more than 2.4 million people, and also to agricultural activities in the Homestead area, and even to agriculture south of Okeechobee Lake whose nutrients pesticides, and agro-chemicals may be transported along the canal network and brought south to the Biscayne Bay basin. All waters in Biscayne Bay are Class III, whose designated use is recreation and propagation and maintenance of a healthy, well-balanced population of fish and wildlife. Biscayne Bay is also a designated Outstanding Florida Water (OFW). Main water quality issues are: water turbidity); nutrient loading and enrichment, bacterial enrichment, chemical compounds derived from runoff, pesticides, and industrial and stormwater pollutants (Lietz and Meyer 2006; http://www.miamidade.gov). Canal inflow is the primary loading mechanism for pollutants to the bay followed by subsurface runoff from the shallow, highly permeable Biscayne Aquifer, which allows rapid movement of groundwater with direct subsurface connection to the bay and canals (Klein and Hull 1978; Lietz 1999; Alleman et al. 1995). Caccia and Boyer (2007) identified atmospheric deposition as an important contributor to nutrient enrichment.

Contaminated runoff and groundwater have been identified as major sources of pollutants (pathogens and toxicants) to the Dade County canal system (Long et al., 1999, 2000, 2002, 2005), which finally reach the Bay. Polluted waters have been exposed to leachates from agricultural fields, landfills and municipal dumps, through atmospheric deposition of pollutants derived from combustion sources, agricultural applications, industrial discharges and vehicle emissions, and finally from direct disposal and point sources. Three groups of contaminants have been consistently targeted when environmental assessments of Biscayne Bay are conducted: trace metals, chlorinated pesticides, polychlorinated biphenyls (PCBs) and polynuclear aromatic hydrocarbons (PAHs).

Early studies of pollution were focused on the impact of raw sewage from open sewers and septic tanks (Wakefield 1939; Moore et al. 1955; McNulty 1956). The Mowry Canal had elevated phenol levels (Cheesman 1989) and the bay north of Rickenbacker Causeway was more affected by chemical contamination and toxicity than to the south of the causeway (Long et al. 1999). Organophosphates have been detected in sediments at three sites including Military and North Canals (Cantillo and Lauenstein 2004), but sediments in open areas of the park have generally low toxicity. Lidz (2002) reported initial results of surface sediment samples analyzed for heavy metals and concluded that deformed benthic foraminifera were common near the landfill (Black Point area).

NOAA conducted intensive regional surveys to describe the incidence, severity, and spatial extent of adverse biological effects associated with chemical contamination in Biscayne Bay in 1995. Results showed high levels of sediment contamination and severe toxicity in several peripheral canals and tributaries, notably the lower Miami River. The 1995 data also showed sporadic low-level occurrence of sediment toxicity in southern Biscayne Bay. From 1999 results it is apparent that contaminant plumes and associated toxicity do not appear to extend seaward of the mouth of the canals in an appreciable manner. Concentrations of contaminants in the sediments in open areas of Biscayne and Manatee Bays are generally low (Cantillo and Lauenstein 2004)

Nutrient enrichment

Nutrient loading in Biscayne Bay is correlated to population density (Caccia and Boyer 2007), agriculture and storm events (Briceño et al. 2010; Migliaccio and Castro 2009). Additionally, climatic cycles and events seem to affect nutrient loading to the bay with increases in loading rates during wetter years (Caccia and Boyer 2007). Surface waters from the three most important land-cover types in Biscayne Bay watershed, agricultural, urban and wetland cover, have different chemical characteristics. NOx concentrations are higher in agricultural than in urban or wetland areas; concentrations of ammonia, TP, and Chla tend to be higher in urban areas than in wetland or agricultural areas; and TON concentrations are higher in wetland and urban areas than in agricultural areas (Britt and Cheesman 1992; Lietz 1999; Haag et al. 1999; US DOI NPS. 2003; Caccia and Boyer 2007; Migliaccio et al. 2008). Given the oligotrophic nature of these waters the system responds very rapidly to small nutrient enrichment, especially to increases of phosphorous, the limiting nutrient (Brand 1988, 2001).

Turbidity

Most turbidity in Biscayne Bay is produced by re-suspension of bottom sediments, both naturally and anthropogenically generated. Natural agents of resuspension are water currents (tidal driven), wind-produced waves (climate related) and extreme events (storms and hurricanes). Anthropogenic re-suspension occurs when boats are grounded and from boat wakes, as well as from canal discharges. Storm induced turbidity is the principal mechanism for re-suspension along the reef tract. The area north of BNP adjacent to Key Biscayne is affected by high turbidity from the Miami River, caused by re-suspended flocculants (Harlem, 1979). Turbidity problems in Biscayne National Park are reasonably well understood with good data on the sources as well as the effects on organisms. As long as dredging projects are restricted and boat usage regulated, this problem will be minimized. Turbidity in northern sections of the Bay has been a long term problem and is likely to get worse as the downtown Miami area continues to grow and the seaport is expanded.

Microbial contamination

Miami-Dade County beaches are regularly tested and other sites are occasionally tested for microbial contamination. Typical microbial groups of concern include fecal coliforms, enterococci, *Clostridium perfringens*, and coliphage and known pathogens such as *Escherichia coli*, *Serratia marcescens*, and human enterovirus. Endemic problems are largely confined to areas north of BNP and may not relate to conditions within the Park. High concentration of fecal coliform bacteria in the C-8 (Biscayne) Canal, the C-7 (Little River) Canal, the C-6 (Miami River), C-6 (Miami River) Lower Segment, and the C-6 (Miami) Canal, within the Biscayne Bay Basin, have rendered these waterbodies impaired. Threats posed by microbes are not only for humans but for biota in general. Four bacteria have been previously implicated in coral disease, *Aurantimonas coralicida*: white plague (type II) (Richardson et al. 1998), *Serratia marcescens*: white pox (Patterson et al. 2002), *Vibrio shilonii*: bleaching (Kushmaro et al. 1997), and *Vibrio coralliilyticus*: bleaching and necrosis (Ben-Haim and Rosenberg 2002), although the cause of such infections is not uniquely linked to a specific pathogen (Polson et al. 2008). Studies of pathogens attached to atmospheric particulates suggest that deposition of fungi and bacteria to the Park from outside by aerosol means is quite likely to occur. Some concerns have been raised for this to be a driving force for the coral declines seen in recent years but proof is inconclusive. Microbial contamination from terrestrial sources does occur and is a potential problem for Biscayne National Park. Given that data is sparse so the threat is inferential.

Pesticides and herbicides

Key et al. (2003) examined pesticides attributed to contaminated canal discharge levels in grass shrimp and found correlation between reduced levels of acetylcholinesterase enzyme and canal chemicals at Military and North Canals. Cantillo and Lauenstein (2004) analyzed samples from South Biscayne Bay and Manatee Bay for contaminated marine sediment. Eight types of pesticide were found in seawater samples including atrazine, metolachor, CEAT, CIAT (metabolized herbicides), chlorpyrifos, diazinon, malathion, and 4,4'DDE (DDT metabolite). The majority was found at highest levels at the upstream sites associated with the canal network, at the mouths of the canals. Metolachlor was present at all sites sampled. Two sites, Princeton Canal mouth and Florida City Canal mouth had high levels of ethoxylates which can be an endocrine disruptor. Carriger and Rand (2008) assessed the aquatic risk caused by atrazine, metolachlor, malathion, chlorpyrifos and endosulfan in south Biscayne Bay and found that atrazine was the most frequently detected pesticide but only at low levels. Harman-Fetcho et al. (2005) studied pesticides associated with agricultural runoff to the canal network and found that there were seasonal variations and that harvest season when endosulfan is commonly used had a higher hazard potential. Seba (1969) reported pesticides associated with surface microlayers in Biscayne Bay were related to atmospheric transport and deposition.

Past and present use pesticides and herbicides have been consistently detected in canals and near-shore locations along the southern portions of the bay. For example, atrazine and some of its metabolites are present in almost all water samples collected in the freshwater environments at concentrations up to approximately 100 ng/L and also in coastal areas at lower levels 5-10 ng/L. A similar trend is also evident for the herbicide metolachlor. However, the water quality guidelines for these herbicides are several orders of magnitude above the environmental concentrations thus unlikely to produce detrimental effects. Legacy pesticides, mainly p,p'-DDE (metabolite of DDT) is often found in canal sediments and occasionally in areas immediately adjacent to canal discharge points (Princeton, Military, Mowry, North and Florida City canals and at Black Point Marina). Gardinali et al. (2008c) examined the levels of endosulfan in fish tissues from BNP and Everglades National Parks and reported that endosulfan sulfate is generally present in areas of Everglades National Park near the Homestead Agricultural Area but seldom detected in coastal areas of Biscayne Bay.

Metals

Judge and Curtiss (1977) examined sediment samples from the middle of Biscayne Bay (just north of the park) for heavy metal contamination and found little difference between most areas sampled except for lower values near Fisher Island and a sink for metals in sediments near the mouth of the Miami River. They expressed the concern that south Biscayne Bay may have been polluted by waters from Miami River flowing south under Rickenbacker Causeway. Schroeder and Thorhaug (1980) examined uptake of trace metals into seagrass blades finding higher levels in tissues than in the surrounding water. Miller (1984) analyzed the runoff from several different basins types in South Florida and found the highest lead runoff was from a commercial (shopping center) type basin. Cantillo and Lauenstein (2004) analyzed samples from South Biscayne Bay and Manatee Bay for contaminated marine sediment. The total trace metals (Cu, Zn, Ni, Pb, Cd, Hg, Ag) found in sediments at the mouths of five canals studied indicated toxic conditions were likely. Lidz (2002) reported initial results of surface sediment samples analyzed for heavy metals and concluded that Cu, Pb, and Zn were highest near marinas in the northern parts of the bay, that metal contamination decreased southward and seaward. Among the trace metals, Copper, Arsenic, and Lead have been reported in sediments of the bay at concentrations that are above the national median for the NOAA NS&T Mussel watch program and in some cases above the 85th percentile. However, all the values reported for south Biscayne Bay away from the influences of marinas are below the "probable effects level" (PEL) or the sediment quality assessment guidelines (SQAGs) for coastal sediments used in Florida to assess sediment contamination. With regards to mercury levels in biota, Evans et al. (2008) reported mercury levels in fish samples from Florida Bay and Biscayne Bay with highest values in Crevalle jacks found in south Florida and in other species associated with areas of restricted circulation.

Anti-fouling agents

In the past decade, some non-traditional contaminants have also been reported in the vicinity of BNP. Organotin (TBTs) related antifouling compounds were reported in sediments at the North Canal at Homestead Bayfront Marina and Irgarol 1051, an antifouling booster biocide, has also been reported in many marinas in the bay. All these pollutants are related only to boating activity and transport beyond their localized usage area is not expected. Since TBTs have been banned, Irgarol 1051, in conjunction with copper are contaminants that need to be further monitored with respect to marinas and boatyards. Maxey (2006) analyzed surface water, seagrass, and sediment for the antifouling biocide Irgarol 1051 and its metabolites. Concentrations of Irgarol in surface water and seagrass ranged from N.D. to 1239 ng/L and 2.35 ng/g to 225 ng/g, respectively. Concentrations of Irgarol in sediments were negligible (< 10 ng/g). Bioconcentration factors (BCF) are measurement of the ratio of the chemical concentration in a marine organism compared to that of the surrounding water. BCFs greater than 1000 are considered to be accumulative, while BCFs greater than 5000 are considered highly accumulative. BCF values for Irgarol uptake into seagrass ranged from 60 to 31588. While Irgarol was found at the majority of the marinas sampled, no Irgarol was found at any coral reef, the specie reported to be the most sensitive to Irgarol.

PCBs and PAHs

Lang and coworkers (Lang et al., 2002) reported the abundance and atmospheric deposition of a variety of organic contaminants, including polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), in the Miami metropolitan area. PAHs are commonly present in many sediment samples but their concentrations are relatively low and consistent with background levels in urbanized areas. Marinas, however, represent a deviation of this observation and is common to see sediments in canals and access areas to major marinas to have elevated concentrations of Total PAHs. Litz et al. (2007) reported total PCBs (sigma 73PCBs) present in the highest concentrations and 5 times higher in males dolphins with sighting histories in the northern, metropolitan area of Biscayne Bay than males with sighting histories in the southern, more rural area. All compound classes had higher concentrations in northern animals than in southern and are also high as compared to other studies of estuarine dolphins and may place these animals at risk of reproductive failure and decreased immune function.

CLIMATE CHANGE

Increasing concentrations of greenhouse gases in the atmosphere (carbon dioxide, methane and nitrous oxide) have been shown to be the primary cause of global increase of surface temperatures (IPCC 2007; Karl, et al. 2009), leading to warming of the oceans, melting of ice fields and glaciers, and diverse climatic effects, which for south Florida entail a number of important issues (Table 5.1), such as: sea level rise, changes in rainfall and evaporation patterns affecting the amount of available freshwater and potentially causing prolonged droughts and/or flooding; saltwater intrusion into the coastal aquifers and public water supply; reduction of coastal stormwater release capacity due to sea level rise (SLR); and changes in tropical storm and hurricane activity with increased surge levels (Heimlich et al 2009; Obeysekera 2011)

Sea Level Rise

Because of the sensitivity of vegetation patterns to subtle elevation differences, we can expect the coming sea level rise to have a profound effect on the Park's terrestrial vegetation. Landward (uphill) migration of mangrove is already occurring on the mainland, partly due to anthropogenic changes to the coastal water delivery systems or driven by sea level rise. Wanless (1984) showed the movement of the intertidal zone upward at the Coral Gables Waterway, caused by a slight rise in sea level during the latter half of the 20th Century. However, the current rate of rise is faster and is expected to be the controlling factor on future patterns of terrestrial vegetation as more and more of the low coastal margin of the Park becomes inundated by marine waters. Coronado-Molina et al. (2003) suggested that mangroves on the mainland shore may be better suited to keep up with the sea level rise than those on the Keys, due to higher productivity. Harlem and Meeder (2008) showed that sea level rise of only 1 foot would inundate much of the shoreline of Biscayne National Park at high tide which would alter salinity regimes in the coastal area drastically and favor the westward (inland) migration of saltwater habitats.

One aspect of great concern is the release of sediment and its associated nutrients and pollutants to the marine system as coastlines erode. There are large amounts of the former locked up in coastal sediments which will enter the sea as waves and increased currents attack the existing shore deposits. While moving sediments by currents is a natural phenomenon and most benthic communities are adapted to some amount of sedimentation, the loading potential from rapid sediment adjustments as sea level rises can only be considered a negative impact on Bay and especially on marine/reef ecosystems.

Ocean Acidification

Ocean acidification refers to the ongoing increase in acidity (lowering pH) of the Earth's oceans, caused by the uptake anthropogenic carbon dioxide of (CO_2) from the atmosphere. This pH reduction causes problems for marine organisms which use carbonate molecules (aragonite or calcite) to construct hard body parts or protective shells, skeletons, and tests. Included in the affected groups are molluscs, foraminifera, coccolithophores, crustaceans, starfish, bryozoans, and corals. Octocorals (soft corals) and other marine organisms use calcite for structural support and scleractinian corals use aragonite which is the metastable form of calcium carbonate used to build skeletons. The Park lies in an area that will be least affected by acidification if the models hold true (Guinotte et al. 2006), however, changes in the deep reefs seaward of the Park should be expected in the near term and effects will increase in shallower waters after 2100.

Table 5.1 - Summary of Climate Change Impacts on Southeast Florida's Water Resources (Heimlich et al., 2009)

Climate change impact	Potential threats to fresh water supply	Potential threats of severe flooding	Other effects
Sea level rise	• Saltwater intrusion of aquifer • Inundation of Southernmost Everglades with seawater potentially affecting the Biscayne Aquifer in south Miami-Dade. • Reduced groundwater flow • Reduced fresh water available	• Compromised stormwater drainage systems • Reduced capacity of canals and coastal control structures. • Greater potential for flooding due to heavy rain storms and hurricanes • Reduced groundwater flow • Rising water tables • Reduced soil storage capacity • Increased risk of flooding of coastal and low-lying inland areas	• Barrier islands subject to inundation and washout • Beach erosion • Coastal wetlands and southernmost Everglades encroachment
Changes in rainfall patterns	• Longer, more severe drought during dry season • Greater likelihood of multiyear droughts • Reduced annual rainfall (10-15%) • Increased risk of ground and surface water contamination due to flooding	• Shorter, wetter rainy seasons • More severe rainfall events • Severe flooding during more intense rain events	• Stresses on agriculture, landscaping, and natural systems due to drought
More intense hurricanes	• Increased risk of contamination with seawater due to storm surge,	• Enhanced storm surge • More intense rainfall	• Greater wind and storm surge damage • Beach erosion • Coastal inundation
Higher temperatures	• Increased evapotranspiration reducing water available for urban and natural areas		• Heat stress on ecosystems and marine life • Dehydration of plants and soils • Greater risk of urban fires and wildfires • Hypoxia of coastal waters and algae blooms • Increased risk of insects and insect-borne disease

SECTION 6:
NUMERIC NUTRIENT CRITERIA

An additional task was added to the original NPS-FIU Task Agreement, whose objective was to derive numeric nutrient criteria for all south Florida estuaries and coastal waters, including Biscayne Bay. FIU has been monitoring WQ in South Florida since the early 1990's, hence, expanding the objectives to incorporate all estuaries and coastal waters from North Biscayne Bay, to Pine Island Sound, on the western coast (Fig 6.1) was a natural progression to other tasks in the project.

Among the several reasons for on-going water quality problems in South Florida is the unenforceability of its narrative water quality criteria. Existing Outstanding Florida Waters, anti-degradation, standards and many of the Class III, protection of designated use, standards are non-numeric, making their applicability very limited at best. Thus, there is an immediate need to change their narrative format to a more practical and usable numeric format through the implementation of valid processes and sound statistical methods. The US Environmental Protection Agency (USEPA) and the Florida Department of Environmental Protection (FDEP) are in the process of deriving such numeric nutrient criteria for South Florida estuaries and coastal waters, which must be promulgated by late 2012.

Most of these waters are either within designated National Parks lands or within their influence zones, and considering that it is responsibility of the National Park Service to protect and preserve the natural and cultural resources and values of the National Park System, NPS has a great interest in EPA's and FDEP's efforts for developing t numeric surface water quality criteria for key nutrients.

Water quality of South Florida's estuaries and coasts is the result of a long-term and poorly understood interplay of local, regional and global forcing, drivers, pressures and responses. Monitoring programs render water quality (WQ) snapshots taken during the last 20 years from which researchers attempt to produce not only a motion picture of the past, but a projection of future scenarios. South Florida's coastal and estuarine waters have experienced the impact of anthropogenic interventions since the early 1900's, including major disruptions of its hydrology and also sustained urban and agricultural development (Davis and Ogden, 1994; Hunt et al. 2007; Nuttle et al. 2000; RECOVER 2005). Furthermore South Florida (SoFlo) waters are influenced by distant sources, such as the Gulf of Mexico and the Mississippi River. Hence, SoFlo aquatic ecosystems bear the heritage and signals of these long and sustained influences.

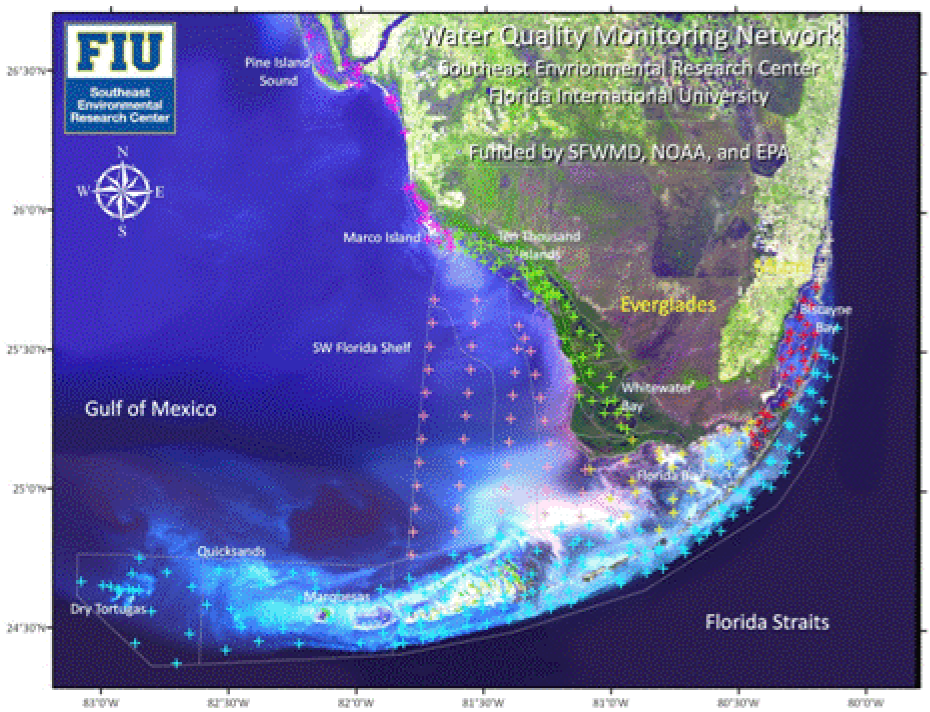

Figure 6.1: Spatial coverage of FIU Water Quality Monitoring Network. (http://serc.fiu.edu/wqmnetwork/).

Given the ecological impacts caused by water management of the Everglades since the last century, the probabilities of finding a pristine water body are meager. Nevertheless, most South Florida estuaries are oligotrophic and practically algal bloom-free, except for some restricted areas (Central Florida Bay and North Biscayne Bay) where occurrence of algal blooms is chronic. The USEPA recommends three types of approaches for setting numeric nutrient criteria, including: reference condition approaches, stressor-response analysis, and mechanistic modeling. This study will apply the second of these approaches and use FIU's water quality monitoring data to describe stressor-response relationships and use this information to derive numeric nutrient criteria. We will first focus our efforts on defining baseline conditions. We will develop water quality targets using information on the relationship between Total Nitrogen (TN) and Total Phosphorous (TP) as causal enrichment variables, and Chlorophyll *a* (CHLa) as initial response variable, given its recognized value as ecological indicator of nutrient enrichment (Boyer et al. 2009).

SEGMENTATION OF SOUTH FLORIDA WATERS

It has been well documented that South Florida estuaries have different water quality characteristics due to differences in geomorphology, water circulation, residence time, soil type in their watershed and bay bottom, benthic communities, and management practices. We evaluated these characteristics and reassessed all previously established subdivisions for Florida Bay, Ten Thousand Islands, Whitewater Bay, Pine Island Sound-Rookery Bay, Florida Keys and Biscayne Bay. After an initial stage of QA/QC, we redefined the Period of Record (POR) for each basin depending upon data availability and variable set completeness for the whole set of biogeochemical parameters (total and dissolved nutrients, CHLa, turbidity, temperature, salinity, DO and light extinction). We then calculated descriptive statistics and performed long-term trend exploration of the redefined POR time-series, to gain insight into patterns of behavior along the POR for all relevant biogeochemical parameters. This exploration was performed with Akritas Thiel-Sen slope calculations and z-scored cumulative sum charts (explained above).

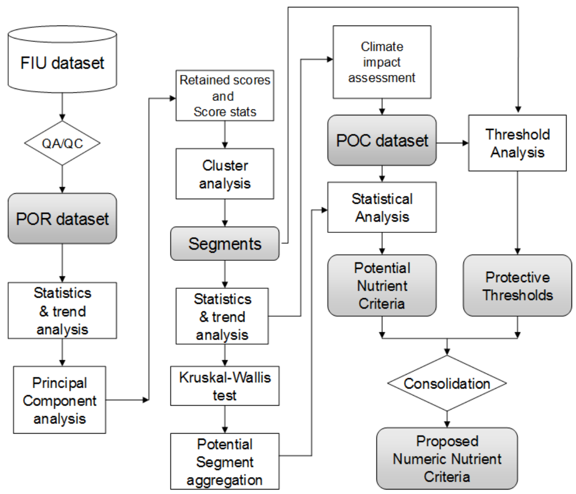

Figure 6.2: Flow diagram illustrating the steps followed in the derivation of Numeric Nutrient Criteria as applied to South Florida coastal and estuarine waters.

A well recognized spatial-temporal variability within estuaries and coastal waters is present in our individual SoFlo basins. This fact called for a holistic approach to basin segmentation to account for variability not only dictated by a given nutrient concentration level, but by the combination of imposed conditions such as: nutrients, water clarity, climate, weather, extreme events, geomorphology, circulation and exchange, and management. As done for Biscayne Bay, basin segmentation was accomplished with an objective classification of station sites combining Principal Component Analysis (PCA) and Hierarchical Clustering methods in tandem. Selected biogeochemical variables (8 to 13) for each of the five basins (Florida Bay, Florida Keys, Whitewater Bay-10,000 Islands, Gulf Shelf and Pine Island-Rookery Bay) were used for PCA. Statistics (mean, standard deviation, median and median absolute deviation) of retained scores from PCA were input into Hierarchical clustering routines. The rationale behind the selection of these statistics was to account not only for level of individual parameter but also for their variability. Then, progressive subdivisions were obtained varying the statistical distance among groups in the cluster tree. Selection of the final number of segments was subjective and knowledge-based. Spatial extension and pattern, geomorphology, water circulation and benthic ecosystem distribution played a major role on the decision. In summary, we statistically characterized and subdivided waters in each basin into what we considered biogeochemically and spatially coherent segments.

We identified 40 water-types for SoFlo coastal and estuarine waters that extend from Biscayne Bay in the east to Dry Tortugas in the southwest and to Pine Island Sound in the northwest (Table 6.1, Fig 6.3). Segment maps were generated placing the separating lines approximately midway in between clustered stations, or followed the FATHOM Model subdivision (Cosby et al. 2005), followed previous subdivisions or were arbitrarily drawn following general geomorphologic patterns. In summary, border lines are site-specific and not the result of systematic spatial statistical analysis.

Non-parametric Mann-Whitney and Kruskal-Wallis tests were used to compare biogeochemical variables among segments, and box-and-whisker plots to summarize descriptive statistics. The former analyses highlighted statistically significant differences among segments, and the later underscored anomalous and probably impacted stations and segments. Sustained high concentration levels would suggest sustained impacted and perhaps impaired conditions – not meeting designated use type. Anomalous stations isolated from permanent sources of human disturbance (urban areas, canal mouths) were interpreted as responding to site-specific natural behavior. On the other hand, eventual occurrence of high nutrient levels would indicate anomalous conditions responding to short-lived disturbances.

Besides those precipitation changes occurring in the early-to-mid nineties from lower to higher precipitation rates which lead to region-wide declines in water nutrients and chlorophyll *a* concentrations (Briceño and Boyer 2010), we compared nutrients time-series with records of storms and hurricanes which affected South Florida during the period 1989-2008. Separate statistics were calculated for before and after identified events to test the nature, duration and magnitude of the impact. After identifying that human and hurricane impacts combined to strongly disturb conditions in northeastern Florida Bay-Southwestern Biscayne Bay since 2005, we discarded data obtained from that area (MBS) during the disturbed period (2005-2008) for statistical calculations. The dataset resulting from this selective process defined the Period of Calculation (POC) dataset to be used for the remaining calculations.

Table 6.1: Aggregation of SoFlo basins into 40 segments resulting from PC/Cluster

Region	No.	Segment	Sub-basin
FLORIDA KEYS (FK)	1	MAR	Marquesas
	2	BKB	Back Bay
	3	BKS	Back Shelf
	4	LK	Lower Keys
	5	MK	Middle Keys
	6	UK	Upper Keys
	7	Offshore	Offshore
FLORIDA BAY (FB)	1	CFB	Central Florida Bay
	2	ECFB	East-Central Florida Bay
	3	NFB	North Florida Bay
	4	CL	Coastal Lakes
	5	SFB	South Florida Bay
	6	WFB	West Florida Bay
WHITEWATER BAY (WWB-TTI)	1	BLK	Black River
	2	CTZ	Coastal Transition Zone
	3	GI	Gulf Islands
	4	IWW	Internal Waterways
	5	MR	Mangrove Rivers
	6	PD	Ponce de Leon
	7	SRM	Shark River Mouth
	8	WWB	Whitewter Bay

Region	No.	Segment	Sub-basin
BISCAYNE BAY (BB)	1	CS	Card Sound
	2	NCI	North central Inshore
	3	NCO	North Central Outer-Bay
	4	NNB	Northern North Bay
	5	SCI	South Central Inshore
	6	SCM	South Central Mid-Bay
	7	SCO	South Central Outer-Bay
	8	SNB	Southern North Bay
	9	MBS	Manatee-Barnes Sound
PINE ISLAND ROOKERY BAY (PIRB)	1	CI	Collier Inshore
	2	EB	Estero Bay
	3	MARC	Marco Island
	4	NPL	Naples Bay
	5	PINE	Pine Island Sound
	6	SCB	San Carlos Bay
	7	COCO	Cocohatchee
SHELF (SHELF)	1	IGS	Inner Gulf Shelf
	2	MGS	Midddle Gulf Shelf
	3	OGS	Outer Gulf Shelf

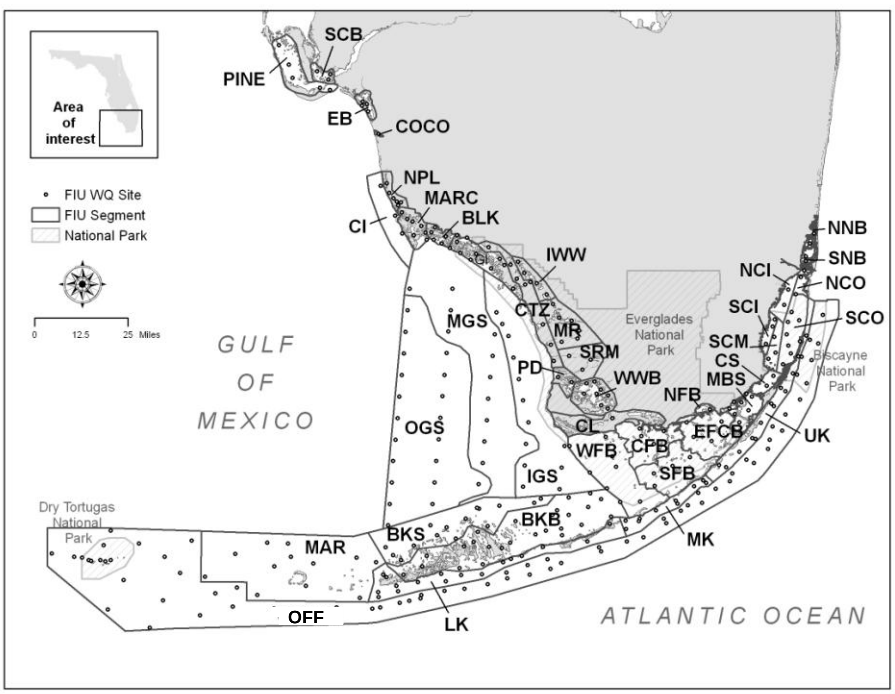

Figure 6.3: Biogeochemical segmentation of South Florida's estuarine and coastal waters.

NUMERIC NUTRIENT CRITERIA

As a contribution to the regulatory process under way for the derivation of numeric criteria by the USEPA and FDEP, we have: (1) Sub-divided the six major South Florida basins into forty spatially-coherent water-types (segments). This classification has been adopted by both agencies with minor modifications; and (2) we have derived a series of protective nutrient thresholds to be considered in the derivation of protective numeric nutrient criteria.

The USEPA recommends three types of approaches for setting numeric nutrient criteria (USEPA 2001, 2010): (1) reference condition approaches; (2) stressor-response analysis; and (3) mechanistic modeling. The reference conditions approach entails the existence of undisturbed segments of reference, something not to be found in South Florida after over a century of continuous human intervention. A suggested alternative is to select the less impacted station or segment complying with its designated use as reference, but given the recognized site-specific response to nutrient variability that characterizes estuaries, there is no guarantee that the extrapolations would be correct.

The stressor-response approach requires cause-effect data (i.e. nutrient-dose experiments), and that information is mostly absent or very scarce for relevant South Florida biotic components such as phytoplankton biomass (Brand 1986; Brand et al. 1991) or ambiguous for major benthic primary producers (seagrass, epiphytes, macroalgae, and benthic microalgae) (Armitage et al. 2005; Ferdie and Fourqurean 2004; Herbert and Fourqurean 2008). Findings from a handful of studies in Florida Bay indicate that N addition had little effect on any benthic primary producers throughout the bay, and P-induced alterations of community structure were not uniform and did not always agree with expected patterns of P-limitation (Armitage et al. 2005). Nutrient-dose experiments of seagrass meadows suggest that upon enrichment, Halodule wrightii replaces Thalassia testudinum (Fourqurean et al 1995), and total epiphyte and epiphyte chlorophyll loads were significantly, but weakly, correlated with phosphorus availability (Frankovich and Fourqurean 1997). Likewise, the responses of benthic communities to

N and P enrichment in the coral reefs of the Florida Keys vary appreciably between nearshore and offshore habitats, and responses were species-specific. Nutrient addition at nearshore sites increased the relative abundance of macroalgae, epiphytes, and sediment microalgae.

Ferdie and Fourqurean (2004) and Fourqurean (2008) used *in situ* nutrient enrichment experiments in seagrass beds in the Florida Keys and Florida Bay. Results from their analysis of N and P concentration in *T. testudinum* leaves lead them to suggest a preliminary relationship between nutrient enrichment and a drift of the N:P ratio towards a value of 30 (similar to a Redfield Ratio). Meeder and Boyer (2001) studied areas within and adjacent to Biscayne National Park and documented a strong correlation between elevated NH_4^+ concentrations with a decrease in *Thalassia*, an increase in *Halodule* and fast growing algae, and an increase in filamentous algae cover near Black Creek.

Given the uncertainties and lack of conclusive dose experiments, we focused our approach on water quality monitoring datasets for two causative (phosphorus and nitrogen) and one response (chlorophyll a) variables. This selection finds support on abundant literature worldwide documenting nutrient influx as the primary cause of algal blooms (Sparrow et al. 2007), by either natural events such as river plumes, storms and upwelling (Fujita et al. 1989, Longhurst 1993, Grimes and Kingsford 1996, Oke and Middleton 2001, Fitzwater et al. 2003, Moisander et al. 2003, Wieters et al. 2003, Yin 2003, Carstensen et al. 2004, Hodgkiss and Lu 2004, Yin et al. 2004, Beman et al. 2005, Furnas et al. 2005), or urban runoff and sewage (Smith et al. 1981, Hodgkiss and Lu 2004, Lapointe et al. 2004, Carruthers et al. 2005; Sparrow et al. 2007)

The relationship between nutrients and phytoplankton biomass (i.e. CHLa) in South Florida waters has been widely reported (Brand 1986; Fourqurean et al 1993; Rudnick et al. 1999, 2006, 2007**;** Boyer and Briceño 2007; Briceño and Boyer 2008, 2010; Boyer et al. 2009), so CHLa seems to be a reasonable proxy to assess nutrient enrichment. The selection of these parameters finds support on a preliminary assessment of FIU's dataset indicating a positive correlation between both nutrients and CHLa, especially TP, the recognized main limiting nutrient region-wide (Brand 1988;

Brand et al 1991; Boyer et al 1999; Fourqurean et al 1993; Szmant and Forrester 1996; Fourqurean and Robblee 1999; Hoyer et al 2002; Boyer 2006; Boyer et al. 2009).

Threshold Analysis

In this report, we adopt the definition of ecological threshold of Andersen et al. (2008) who stated …"*an ecological threshold is the critical value of an environmental driver for which small changes can produce an abrupt shift in ecosystem conditions, where core ecosystem functions, structures and processes are essentially changed between alternative states*". Nutrient (TN, TP) concentration thresholds for each segment were derived by identifying concentrations that were associated with sudden and sustained increases (shifts) between CHLa alternative states. CHLa z-scored cumulative sums were plotted along either TP or TN gradients, mimicking nutrient dose-experiment results. These graphs, constructed as described in Appendix 4, illustrate the cumulative reaction of phytoplankton biomass to nutrient enrichment, highlight the main threshold(s), and provide information to assess the potential health status of phytoplankton communities in the water column.

Andersen et al. (2008) give an excellent description of driver:response scenarios and the resulting regime shifts as shown in Fig 6.4. Panel (a) illustrates a regime shift when the driver is linearly mediated to the ecosystem state response, and steps appear only in the time series. Panel (b) shows a regime shift in ecosystem state after the driver exceeds a threshold. The jump appears in the time series of the response. Panel (c) shows a hysteresis loop linking the response to the environmental driver causing shifts between two alternative states. The Zcusum charts along the lower row precisely display the location of the threshold in every case.

There is a wide variety of patterns in Zcusum charts for South Florida waters reflecting the complexity of these ecosystems as shown in a transect from SCI to ocean (OFF) waters (Fig 6.5). In SCI CHLa seems to respond positively to nutrient enrichment, although the pattern for TN is rather complex and the first important CHLa reaction (shift) to increasing TN values occurs well below the median TN concentration. This complexity reflects the dynamics of SCI, strongly affected by canal inputs, sudden changes in salinity and nutrient concentrations, and perhaps different assemblages of

CHLa producers. For TP at SCI there is a CHLa increasing pattern (“V-shaped” Zcusum) and a threshold location way below the median TP concentration. Further east, in SCM, both TN and TP seem to share the control on phytoplankton biomass production, although the CHLa pattern is better developed for TN than for TP. Also notice that for values just above the median TP concentration the relationship reverses and CHLa declines. In SCO, more affected by oceanic exchange, TN and TP play inverse roles on CHLa production with TN positively correlated and TP negatively correlated to CHLa, and a potential threshold at relatively low TP concentration. The TP threshold for SCI, SCM and SCO is the same, 0,004 mg/l TP. Finally, in oceanic waters to the east and above the reef track (OFF) CHLa is positively correlated to TN and TP. These relationships underscore both, the compartmentalization of Biscayne Bay waters and the complexity of the exchange between relatively nutrient-rich freshwaters and nutrient-poor oceanic waters.

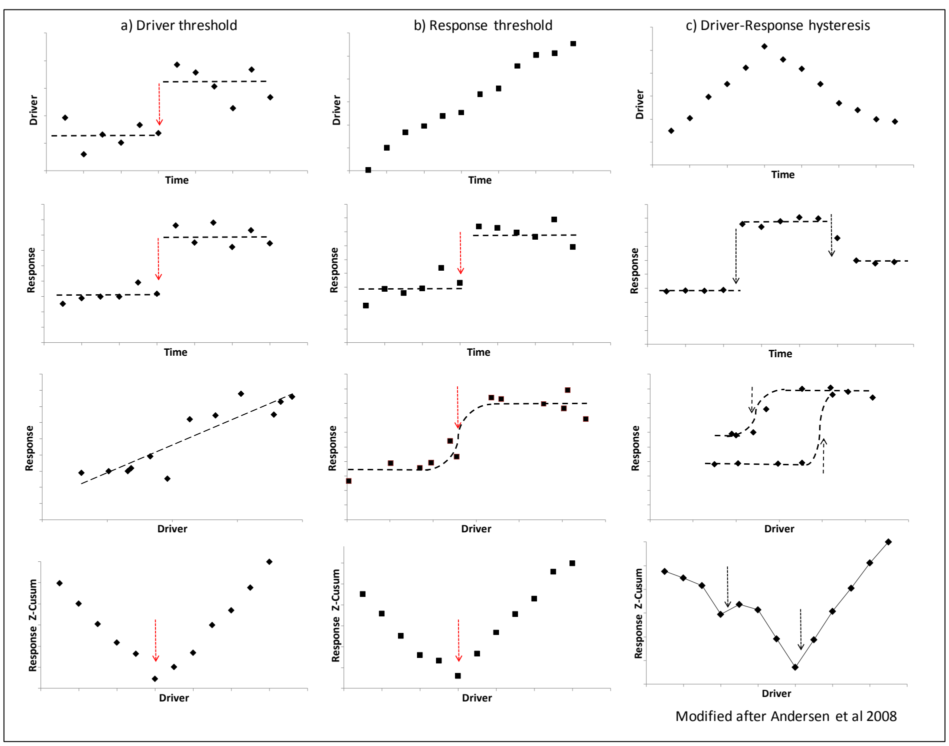

Figure 6.4: Selected relations driver:response and their resulting regime shifts: (a) smooth pressure–status relationships, (b) threshold-like state responses and (c) bistable systems with hysteresis. Modified after Andersen et al. 2008.

The relative location of the median nutrient concentration within the Zcusum chart and its relation to the threshold position deserve special consideration. As shown in Figure 6.5 median TN and median TP are above the CHLa thresholds, suggesting the initiation of bloom conditions below median nutrient levels in the water column. Furthermore, in all instances the median nutrient concentrations fall on the above-average branch of the CHLa Zcusum chart (positive slope branch), indicating that median nutrient concentrations are associated to above average CHLa production. Finally, relationships for the overall region show that median TN and median TP are above the CHLa thresholds almost everywhere. Those relationships suggest the initiation of bloom conditions below median nutrient levels in the water column. Bloom conditions simply means significant increase in biomass (Legendre 1990), abundance (Lapointe 1999), or population size (Smyda 1997; Carstensen et al 2004; Sparrow 2007). In our case, the beginning of bloom conditions indicated by the threshold correspond to the first sudden, significant and sustained CHLa increase.

Criteria

Although coastal and estuarine waters in South Florida have been affected by human intervention and nutrient enrichment (Davis and Ogden 1994) most waterbodies remain under oligotrophic-mesotrophic conditions, and most seem to meet with their designated use. These characteristics have lead regulators to suggest numeric criteria designed to maintain the current data distribution hoping to protect those uses in the future (FDEP 2011). Our long-term trend analysis indicate that there are periods of nutrient enrichment and associated water quality deterioration (i.e. algal blooms) which may be linked to management practices, disturbances and/or climate variability. Hence, statistics derived from the overall dataset, which includes these “anomalous” periods, will be biased towards above “baseline” conditions.

Defining baseline conditions for each station or segment is a complicated task given the specific characteristics of each site, but we have determined important TN and TP concentration thresholds separating what seems to represent nutrient baseline conditions from those conditions that may foster significantly increased phytoplankton biomass (CHL-a) in the water column. Such increases (blooms) may result from seasonal nutrient enrichment or from environmental disturbances in general, so the threshold may be envisioned as the mean baseline condition to guarantee a protective nutrient level in the long run.

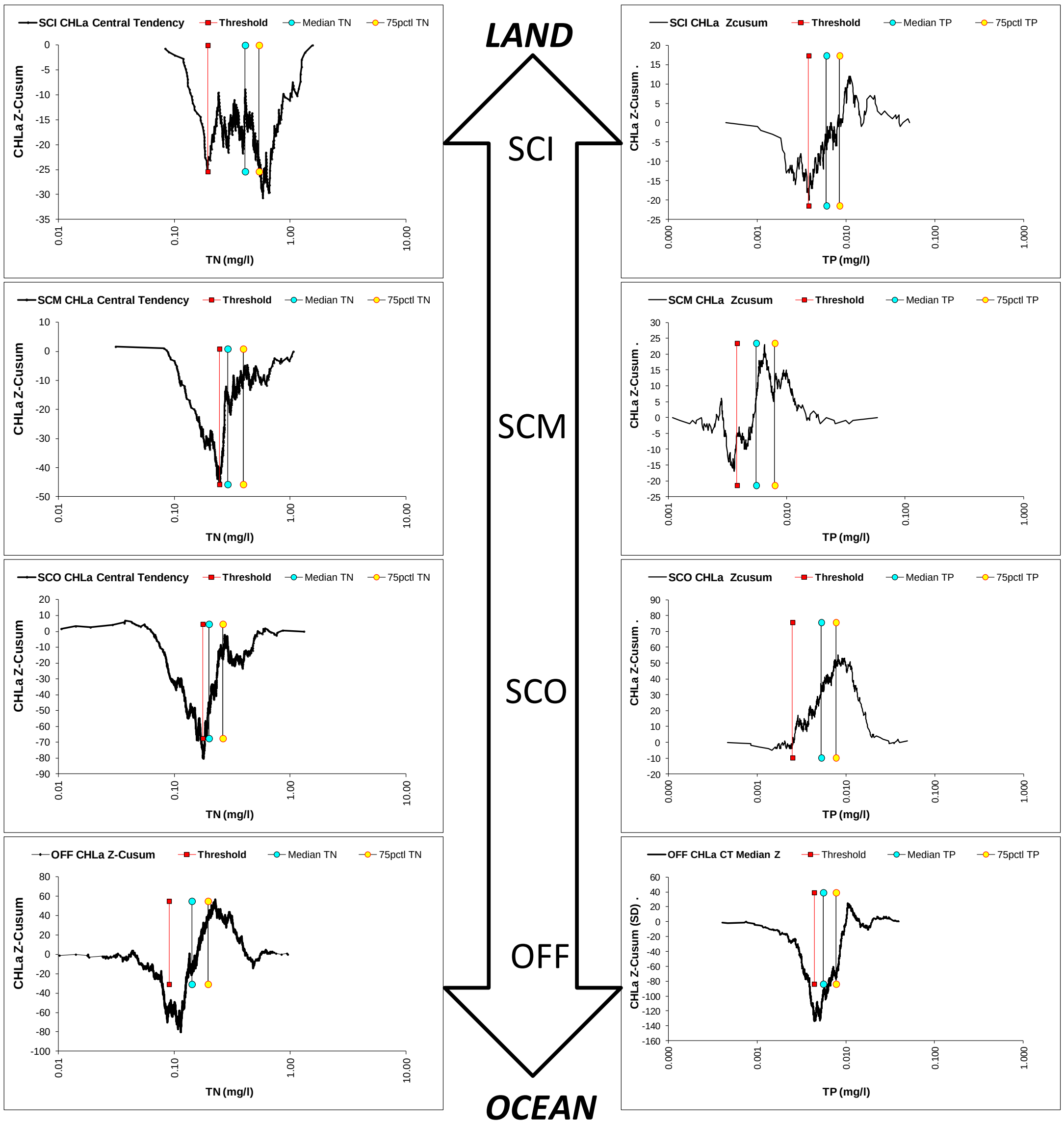

Figure 6.5: Chlorophyll-a Zcusum charts along TN and TP gradients for a West-East transect in South-central Biscayne Bay. "V-shape" charts indicate increasing CHLa concentration and "peak-shape" charts indicate declining trend. Red, blue and yellow vertical markers are located at threshold, median and 75th percentile of nutrient concentrations, respectively.

Hence, we propose the development of protective nutrient criteria that include two limits: LT-L (Long-Term Limit) and UP-L (Upper Limit). The LT-L is the expected nutrient concentration in a water body at which no adverse effects would be expected or the effects would be insignificant for the type of designated use. The LT-L is equal to the nutrient threshold or to the median nutrient concentration if the threshold is larger than the median. The UP-L is a nutrient upper bound concentration of the LT-L that accounts for natural variability in nutrient drivers, for example annual seasonality and climatic variability. The UP-L is the 80th upper confidence limit of a normal distribution with mean equal to the threshold and standard deviation equal to the nutrient’s standard deviation for the segment under consideration. This limit allows one exceedence in three consecutive years. The Type I error rate for both limits is about 10 percent. A summary of the calculated criteria is presented in Table 6.2.

Table 6.2: Total Phosphorous (TP) and Total Nitrogen (TN) median, Long-Term Limit (LT-L) and Upper-Limit (UP-L) concentrations for South Florida coastal and estuarine waters.

Basins	Segment	TN median	TN LT-L	TN UP-L	TP median	TP LT-L	TP UPL
FK	MAR	0.165	0.126	0.213	0.007	0.007	0.011
	BKB	0.219	0.182	0.292	0.007	0.007	0.010
	BKS	0.200	0.163	0.276	0.009	0.008	0.012
	LK	0.178	0.178	0.270	0.006	0.005	0.008
	MK	0.185	0.147	0.244	0.006	0.004	0.007
	OFF	0.142	0.113	0.198	0.006	0.004	0.008
	UK	0.158	0.125	0.201	0.005	0.003	0.007
BB	CS	0.277	0.205	0.307	0.006	0.004	0.008
	MBS	0.534	0.476	0.656	0.006	0.004	0.007
	NCI	0.290	0.290	0.397	0.005	0.004	0.008
	NCO	0.244	0.235	0.344	0.006	0.005	0.009
	NNB	0.257	0.189	0.304	0.010	0.007	0.012
	SCI	0.421	0.421	0.598	0.006	0.004	0.007
	SCM	0.292	0.244	0.382	0.006	0.004	0.008
	SCO	0.209	0.187	0.283	0.005	0.004	0.007
	SNB	0.254	0.153	0.246	0.008	0.005	0.008
FB	CFB	0.869	0.869	1.331	0.015	0.012	0.025
	ECFB	0.613	0.449	0.652	0.006	0.004	0.009
	NFB	0.614	0.664	0.882	0.009	0.005	0.010
	SFB	0.571	0.520	0.781	0.007	0.007	0.012
	WFB	0.323	0.222	0.408	0.012	0.012	0.025
	CL	1.090	1.050	1.399	0.036	0.028	0.042
WWB-TTI	BLK	0.357	0.339	0.474	0.046	0.035	0.050
	CTZ	0.514	0.474	0.674	0.030	0.024	0.037
	GI	0.375	0.335	0.488	0.033	0.024	0.037
	IWW	0.556	0.516	0.732	0.028	0.022	0.032
	MR	0.619	0.579	0.795	0.019	0.012	0.021
	PD	0.437	0.398	0.561	0.019	0.012	0.019
	SRM	0.617	0.577	0.879	0.018	0.012	0.021
	WWB	0.690	0.651	0.927	0.020	0.017	0.027
PIRB	CI	0.213	0.150	0.235	0.026	0.021	0.034
	EB	0.264	0.239	0.351	0.041	0.038	0.056
	MARC	0.254	0.214	0.321	0.037	0.035	0.049
	NPL	0.264	0.222	0.331	0.039	0.031	0.045
	PINE	0.255	0.220	0.347	0.038	0.036	0.056
	SCB	0.318	0.318	0.516	0.055	0.037	0.068
	COCO	0.389	0.316	0.479	0.049	0.043	0.059
SHELF	IGS	0.230	0.190	0.298	0.014	0.011	0.020
	MGS	0.208	0.134	0.223	0.014	0.012	0.017
	OGS	0.181	0.181	0.262	0.013	0.011	0.015

RECOMMENDATIONS

A century of drainage modification has altered the natural cycle of freshwater inflows into the Biscayne Bay. Freshwater wetlands in the watershed have been reduced drastically and transformed into agricultural or urban areas, while the metropolitan area extended even into the bay proper. Nutrient enrichment due to urban development has preferentially affected North BB, and agriculture has impacted WQ especially in Central and South BB. In spite of these transformations, Biscayne Bay waters are still oligotrophic and nurture abundant tropical and temperate fish species and prolific benthic communities dominated by seagrass meadows and sponges (Browder et al. 2005; Alleman, et al. 1995; Lirman et al. 2003, 2008).

Threats posed to BB ecosystems are diverse, some are natural while other are anthropogenic, some are unstoppable (i.e. SLR) while other may be managed and/or neutralized (i.e. sprawl urban development). Recent reports from the U.S. Global Climate Change Science Program (Karl, et al. 2009) indicate that global average sea level may rise more than 2 feet by 2100, while local weather patterns would change causing significant impacts on coastal South Florida (Table 5.1). Hence, any policy or action plan to protect BNP natural resources must be conceived within the framework of an increasing sea level and global warming scenario. On the other hand, managing the effects of sea level rise will require adapting human activities with policies, programs and actions so communities, economies and ecosystems cope with climate change (Lausche, 2009).

The following are summarized recommendations derived from the literature synthesis and analysis of this research, intended to protect BNP natural resources within the framework of climate change:

- Little is known regarding species responses to climate change in South Florida. Nevertheless, ecosystem resilience and capacity for adaptation may be improved by maintaining or restoring large-scale connectivity of ecological networks (core areas, corridors, buffer zones and restoration areas), especially in those areas affected by habitat fragmentation.

- The region nearest BNP has recently seen an enormous expansion in urban development as former farm fields have been converted into residential developments. Projections of considerable further development to south Miami-Dade County are alarming in the scope and magnitude of development planned for the Park perimeter. Coastal development is an existing threat to the Park which will only become worse through time.
- BNP should assure the acquisition of the necessary private and public land to make initiatives like RECOVER viable. This project is intended to provide a more natural overland flow into BB by diverting runoff and redistributing it through a spreader canal system into the coastal wetlands, but will also help upstream ecosystem migration as sea level rises.
- Four tightly interconnected domains need to be protected to guarantee sustainability of BNP resources: freshwater marshes, mangrove forest, seagrass meadows and coral reefs.
- Especial protection should be given to ecosystems characterized by high rates of C-fixation, such as mangrove forest.
- Maintain coral reefs and mangrove forest as natural barriers to storm surge, and consider assisted colonization of key species
- Perform comprehensive monitoring programs including data derived from satellite and ground observations of vegetation and faunal communities, key indicator species, WQ, land-use and cover, climate variables, and hydrology. Monitoring methodologies should be standardized and data format should be compatible with regional and national databases
- Perform periodic water quality monitoring to ensure compliance with WQ regulations within BNP and its watershed
- Contribute to the derivation and upgrading of protective numeric nutrient criteria for both, fresh and coastal/marine waters.
- Contribute to fill knowledge gaps, especially those on effects of nutrient enrichment on SoFlo aquatic ecosystems, by partnering research programs with universities and research centers

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