## PUBLICATIONS FOR SALE

by the *Florida Academy of Sciences*

Complete sets. Broken sets. Individual numbers. Immediate delivery. A few numbers reprinted by photo-offset. All prices strictly net. Prices quoted include domestic postage. Some issues may not be available. All are $20 per volume or $5 per issue, except for symposium issues.

PROCEEDINGS OF THE FLORIDA ACADEMY OF SCIENCES (1936–1944)
Volumes 1–7
QUARTERLY JOURNAL OF THE FLORIDA ACADEMY OF SCIENCES (1945–1972)
Volumes 8–35
FLORIDA SCIENTIST (1973–)
*Florida's Estuaries—Management or Mismanagement?—Academy Symposium*
FLORIDA SCIENTIST 37(4)—$5.00
*Land Spreading of Secondary Effluent—Academy Symposium*
FLORIDA SCIENTIST 38(4)—$5.00
*Solar Energy—Academy Symposium*
FLORIDA SCIENTIST 39(3)—$5.00 (includes do-it-yourself instructions)
*Anthropology—Academy Symposium*
FLORIDA SCIENTIST 43(3)—$7.50
*Shark Biology—Academy Symposium*
FLORIDA SCIENTIST 45(1)—$8.00
*Future of the Indian River System—Academy Symposium*
FLORIDA SCIENTIST 46(3/4)—$15.00
*Second Indian River Research Symposium—Academy Symposium*
FLORIDA SCIENTIST 53(3)—$15.00
*Human Impacts on the Environment of Tampa Bay—Academy Symposium*
FLORIDA SCIENTIST 58(2)—$15.00

Please send payment with order. If required, an invoice will be sent on purchases over $20 from a recognized institution. Please include Florida sales tax if shipped to a Florida address, unless a copy of a valid Florida Consumer's Sales Tax Certificate is enclosed.

ISSN: 0098-4590

# Florida Scientist

Volume 69 | 2006 | Supplement 2

CONTENTS

Charlotte Harbor NEP Special Issue of *Florida Scientist:*
*"Lessons Learned from Transferring Science to Watershed Management"*

2005 Watershed Summit: Lessons Learned Transferring Science to Watershed Management
Lisa B. Beever 3
Seagrass Coverage Changes in Charlotte Harbor, Florida ........
Catherine A. Corbett 7
Seagrass Species Composition and Distribution Trends in Relation to Salinity Fluctuations in Charlotte Harbor, Florida ........
Jaime M.Greenawalt-Boswell, Jason A. Hale, Katie S. Fuhr and Judith A. Ott 24
Development of Water Quality Targets for Charlotte Harbor, Florida using Seagrass Light Requirements ........
Catherine A. Corbett and Jason A. Hale 36
Chlorophyll *a* and its use as an Indicator of Eutrophication in the Caloosahatchee Estuary, Florida ........
Peter H. Doering, Robert H. Chamberlain and Kathleen M. Haunert 51
Comparison of Light Limiting Water Quality Factors in Six Florida Aquatic Preserves ........
Judith A. Ott, Renee M. Duffey, Stephanie E. Erickson, Katie S. Fuhr, Bobbi A. Rodgers and Melynda A. Schneider 73
Preliminary Observations of Estrogenic Activity in Surface Waters of the Myakka River, Florida ........
Heather Cox, Sara Mouzi and James Gelsleichter 92
Pesticides in Southwest Florida Waterways - A Report Card ........
Judith M. Hushon 100
Five Years of the Southwest Florida Frog Monitoring Network: Changes in Frog Communities as an Indicator of Landscape Change ........
E. Corrie Pieterson, Lindsay M. Addison, Jorge N. Agobian, Brenda Brooks-Solveson, John Cassani and Edwin M. Everham III 117
Spotted Seatrout (Family Sciaenidae) Growth as an Indicator of Estuarine Conditions in San Carlos Bay, Florida ........
Stephen A. Bortone, Alfonse J. Martignette, and Justin P. Spinelli 127
Habitat Evaluation in Coastal Southwestern Florida: A Policy Decision Model for the Blue Crab, *Callinectes sapidus* ........
Tomma K. Barnes, Frank J. Mazzotti, Leonard G. Pearlstine and Aswani K. Volety 140
A Simulation of the Hurricane Charley Storm Surge and its Breach of North Captiva Island
Robert H. Weisberg and Lianyuan Zheng 152
A Preliminary Evaluation of Awareness, Knowledge, and Attitude in Environmental Education Specialists, Instructors, Students, and Parents in Southwest Florida ........
Ernesto Lasso de la Vega 166

## FLORIDA SCIENTIST

QUARTERLY JOURNAL OF THE FLORIDA ACADEMY OF SCIENCES

Editor: Dr. Dean F. Martin    Co-Editor: Mrs. Barbara B. Martin
Institute for Environmental Studies, Department of Chemistry, University of South Florida,
4202 East Fowler Avenue, Tampa, Florida 33620-5250
Phone: (813) 974-2374; e-mail: dmartin@mail.cas.usf.edu
Business Manager: Dr. Richard L. Turner
Department of Biological Sciences, Florida Institute of Technology,
150 West University Boulevard, Melbourne, Florida 32901-6975
Phone: (321) 674-8196, e-mail: rturner@fit.edu
http://www.floridaacademyofsciences.org

The *Florida Scientist* is published quarterly by the Florida Academy of Sciences, Inc., a non-profit scientific and educational association. Membership is open to individuals or institutions interested in supporting science in its broadest sense. Applications may be obtained from the Executive Secretary. Direct subscription is available at $45.00 per calendar year.

Original articles containing new knowledge, or new interpretations of knowledge, are welcomed in any field of science as represented by the sections of the Academy, viz., Biological Sciences, Conservation, Earth and Planetary Sciences, Medical Sciences, Physical Sciences, Science Teaching, and Social Sciences. Also, contributions will be considered which present new applications of scientific knowledge to practical problems within fields of interest to the Academy. Articles must not duplicate in any substantial way material that is published elsewhere. Contributions are accepted only from members of the Academy and so papers submitted by non-members will be accepted only after the authors join the Academy. Instructions for preparations of manuscripts are inside the back cover.



Published by The Florida Academy of Sciences, Inc.
Printing by Allen Press, Inc., Lawrence, Kansas

## INSTRUCTION TO AUTHORS

This information is available at two web sites:
(1) **IES site:** http:www.chuma1cas.usf.edu (click on "Centers and Institutes", then select "Institute for Environmental Studies", then select "Florida Scientist").

(2) **FAS site:** http://www.floridaacademyofsciences.org (select "Florida Scientist").

It is possible to search for papers and abstracts of papers for the past six years: Go the FAS site (above), select "Allen Press". When the link is complete, select "Advanced Search" and follow the directions.

The Florida Academy of Sciences Web page, indicated above, allows interested persons to join the Florida Academy of Sciences and pay dues.

## FLORIDA ACADEMY OF SCIENCES INSTITUTIONAL MEMBERS

Florida Fish & Wildlife Conservation Committee
- Lakeland
- Ocala
- Olustee
- Panama City
- West Palm Beach

U.S. Fish and Wildlife Service
- Panama City

Membership applications, subscriptions, renewals, and changes of address should be addressed to the Executive Secretary, Florida Academy of Sciences, Orlando Science Center, 777 East Princeton St., Orlando, FL 32803. Phone: (407) 514-2079

Send purchase orders, payments for reprints and publication charges, orders for back issues and other journal business matters to the Business Manager, Dr. Richard L. Turner, Department of Biological Sciences, FIT, 150 W. University Blvd., Melbourne, FL 32901-6975 [(321) 674-8196; e-mail rturner@fit.edu].

# Florida Scientist

**QUARTERLY JOURNAL OF THE FLORIDA ACADEMY OF SCIENCES**

DEAN F. MARTIN, *Editor* BARBARA B. MARTIN, *Co-Editor*

Volume 69 2006 Number 00S2

## GUEST EDITORS

CATHERINE A. CORBETT, Charlotte Harbor National Estuary Program
PETER H. DOERING, South Florida Water Management District
ERNEST D. ESTEVEZ, Mote Marine Laboratory

DEDICATION—The 2005 Charlotte Harbor Watershed Summit and this special issue are dedicated to three members of the Charlotte Harbor science community who are no longer with us and are sorely missed:

- James R.E. Smith, whom for years almost single-handedly kept Charlotte Harbor's science committees in coffee and donuts, the staff of the NEP office well read, the public well-informed—and who would certainly have preferred to remain anonymous
- Amy Remley, Environmental Scientist, who dedicated her career to the protection, restoration, and management of our marine, estuarine, and freshwater ecosystems and whose goal it was to leave this world a little bit better than it was before she got here. She succeeded.
- Richard Novak, friend to resource managers, boaters and fisher-folk alike, and without whose energy and drive, the Boca Grande Pass Clean-up and Charlotte Harbor Boater's Guide, would not have come to fruition.

The region greatly appreciates these three individuals' dedication to protecting the resources of Charlotte Harbor and informing its residents. Their actions will have lasting impacts on the harbor and its residents for many years to come.

ACKNOWLEDGMENTS—The Charlotte Harbor National Estuary Program and the guest editors of this special issue greatly appreciate the diligent efforts of the contributors to this publication. It is through their hard work and dedication that this special issue is possible.

This special issue is based largely on the authors' contributions presented at the 2005 Charlotte Harbor Watershed Summit at Edison College in Punta Gorda. Sponsorship for the workshop was essential for the success of the workshop and in bringing researchers and citizens together for this triennial conference. Accordingly, we thank Edison College; Sarasota, Manatee and DeSoto Counties; Bonita Bay Group; Friends of Myakka River, Inc.; Peace River/Manasota Regional Water Supply Authority; Southwest Florida Water Management District; Tampa Bay Regional Planning Council; Jelks Family

Foundation; Janicki Environmental, Inc.; EarthBalance; The Myakka Conservancy, Inc.; Barrier Island Park Society; Sierra Club Calusa Group; and Mosaic.

Technical reviews were conducted by multiple scientists on each contributed manuscript. We thank the following individuals for generously donating their time and expertise to this endeavor: Brad Robbins (Mote Marine Laboratory), Charles Kovach (Florida Department of Environmental Protection), Chris Anastasiou (Southwest Florida Water Management District), Don De Angelis (U.S. Geological Survey), Ernesto De La Vega (Lee County Hyacinth Control), Frank Sargent (Southwest Florida Water Management District), Gerold Morrison (Environmental Protection Commission of Hillsborough County), Jason Hale (Charlotte Harbor Environmental Center), Michael Shirley (Rookery Bay National Estuarine Research Reserve), Ron Miller (U.S. Geological Survey), Stephen Bortone (Sanibel-Captiva Conservation Foundation Marine Laboratory), Theresa Bert (Florida Wildlife Research Institute), Gordon Hu (South Florida Water Management District), Donald Balz (Louisiana State Univeristy), Michael D. Murphy (Florida Fish and Wildlife Conservation Commission), Chad Bebee (Florida Department of Environmental Protection), Chung Chen Wu (National Oceanographic and Atmospheric Administration), Charles Paxton (National Oceanographic and Atmospheric Administration), Karen Bickford, Davis Daiker (Florida Department of Agriculture and Consumer Services), Tiziana Schiliro' (University of Torino, Italy), Kyu-Hyuck Chung (Sungkyunkwan University, Korea), Lori J. Morris (St. Johns Water Management District), David A. Tomasko (Southwest Florida Water Management District), David W. Ceilley (Conservancy of Southwest Florida), Katie Fuhr (City of Naples, FL), Roy R. "Robin" Lewis III (Lewis Environmental Services, Inc.), Aaron Adams (Mote Marine Laboratory), Susan K. Jacobson (University of Florida), Linda Cronin Jones (University of Florida), Linda Weir (North American Amphibian Monitoring Program, USGS Patuxent Wildlife Research Center), Catherine A. Corbett (Charlotte Harbor National Estuary Program), Ernest D. Estevez (Mote Marine Laboratory), and Peter H. Doering (South Florida Water Management District).

We greatly appreciate the assistance of Richard L. Turner, Business Manager of the Florida Academy of Sciences, John H. Trefry, Academy President, and the Academy Council. A special thanks goes to the Editors of the *Florida Scientist*, Dean F. Martin and Barbara B. Martin, who always offered support and encouragement and without whom this special issue would not have come about. It was a pleasure working with them on this effort.

The Charlotte Harbor National Estuary Program is a partnership of citizens, elected officials, resource managers and commercial and recreational resource users working to improve the water quality and ecological integrity of the greater Charlotte Harbor watershed. A cooperative decision-making process is used within the program to address diverse resource management concerns in the 4,400 square mile study area. Many of these partners also financially support the Program, which, in turn, affords the Program opportunities to fund projects such as this publication. The entities that have financially supported the program include the following: U.S. Environmental Protection Agency; Southwest and South Florida Water Management Districts; Florida Department of Environmental Protection; Florida Coastal Zone Management Program; Peace River/Manasota Regional Water Supply Authority; Polk, Sarasota, Manatee, Lee, Charlotte, DeSoto and Hardee Counties; Cities of Sanibel, Cape Coral, Fort Myers, Punta Gorda, North Port, Venice and Fort Myers Beach; and the Southwest Florida Regional Planning Council.

# 2005 WATERSHED SUMMIT: LESSONS LEARNED TRANSFERRING SCIENCE TO WATERSHED MANAGEMENT

Lisa B. Beever

Charlotte Harbor National Estuary Program, Fort Myers, FL

The Charlotte Harbor National Estuary Program (CHNEP) hosted a Watershed Summit on February 15–17, 2005 to highlight the latest research which has implications for management decisions. Our theme was Lessons Learned in Transferring Science to Watershed Management. The research falls into the broad categories outlined in the CHNEP Comprehensive Conservation and Management Plan (CCMP): fish and wildlife habitat, water quality, and hydrology.

The Charlotte Harbor Watershed Summit is an important step in the CHNEP process of bringing public and private stakeholders together to discuss ongoing studies and critical environmental issues facing the region. The Summit held in 2005 was an opportunity to review progress since the first Watershed Summit held in 2002 and to discuss current and emerging issues and research affecting the Charlotte Harbor watershed. CHNEP also held a symposium/conference in 1997.

CHNEP is one of 28 National Estuary Programs (NEPs) which focus on estuarine and watershed health; all were created pursuant to section 320 of the Clean Water Act. CHNEP is among the youngest of the NEPs and one of four in Florida. The CHNEP study area covers 4,400 square miles, seven counties, and eight distinct watersheds.

We have found that the major management characteristics that affect this program are:

- A Variety of Regional Partnerships
- Outstanding Research Efforts
- Ability to Communicate Findings across geographic, institutional, and professional boundaries
- Interest of decision-makers to use the best available science
- Committed citizens and professionals.

The CHNEP approach to management decisions is not that science leads to resulting management decisions but that science forms a foundation on which to base management decisions. For example, research can include status, trends, geographic distribution of resources and effects, variability, direct impacts, models, environmental indicators, and complex interactions. Findings from these increasingly complex studies paint broad pictures for decision-makers. Decision-makers are faced with accepting or rejecting standard practices, issuing public information, funding restoration alternatives, and adopting legislation and regulations. General principles and findings are invaluable to these choices.

In that spirit, the Summit was arranged from a management perspective. The Summit themes were:

- Identifying Potential Environmental Issues
- Transferring Findings to Management
- Using Indicators to Improve Management
- Accounting for Variability in Nature
- Appling Findings to Models.

The decision-making process is driven by identifying potential issues and analyzing alternatives, solutions, and costs. Through the alternatives evaluation process research findings are most important to decision-makers.

Indicators are important to communicate the effects of current management practices to both citizens and decision-makers. Designing and implementing appropriate indicators is both a science and an art. For National Estuary Programs, using indicators to improve management is a basic aspect.

Presentations discussing the impacts of the 2004 hurricane season on Charlotte Harbor and its watersheds could seemingly fall outside the realm of the central theme. However, Charlotte Harbor is a variable system with inter-annual changes in water quality, river flows, and seagrass coverage. A specific session was dedicated to natural variability and the difficulty that arises in determining conclusive research results and, in turn, management programs.

These topics generally reflect a number of steps used in resource management but are not inclusive. For instance, sessions dedicated to designing and maintaining a monitoring or research program to respond to specific management questions or methods of analyzing results are not addressed.

*Identifying potential environmental issues*—The process of identifying environmental issues in the first place is the first critical step. It is a basic tenant of the environmental planning process. Without the identification of possible issues in the first place, no management changes can be effected. The approach to identifying potential issues can be taken at two scales: identification of broad patterns that can be used to focus attention where warranted and research on specific concerns that are not captured sufficiently in broader approaches.

Broad sweeping issues identification such as the US EPA Coastal Conditions Report and the Conservancy of Southwest Florida's Estuaries Report Card are critical as a first cut to understanding potential issues. These types of reports are useful to providing citizens and decision-makers information on severity and extent of problems which must be addressed. In addition, it provides information on management decisions which have yielded benefits to the environment.

Surveys of the public are useful to obtain user perspectives. The general public is a source of information on conditions on the ground and concerns which decision-makers need to address. Surveys of human impact such as changes in seagrass scarring are used by the CHNEP to inform management decisions.

Ecoestrogens and pesticides are difficult and expensive to assess but methods are needed to determine if waterways are being contaminated. Inexpensive methods to identify potential issues presented at the Summit included using a benthic invertebrate calibration to assess watersheds and using optical brighteners to determine sources of fecal coliform in the environment.

*Transferring monitoring and research results to management*—Monitoring is a long term investment if it is to be useful. It is difficult for decision-makers to make long term funding commitments to monitoring; however, monitoring is critical to understanding long-term trends.

Water quality measurements in the CHNEP study area is a multi-agency effort. Partners have made efforts to share data to have more robust results. One of the more remarkable programs is the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network (CHEVWQMN). Water quality data are collected by trained citizen volunteers who are able to collect samples concurrently, so that single and comparative snapshot of water quality can be gathered. These data are combined with agency data to determine water quality impairments under state rule. Total Maximum Daily Loads (TMDLs) and Basin Management Action Plans (BMAPs) are in turn developed. The ability to single out chronic water quality impairments is tremendously useful for restoration planning, stormwater design, and better standards.

The invasion of exotic pest plants and nuisance exotic animals warrants monitoring. Surveying the effects of invasive exotic animals on wetland functions, the relationship of habitat quality on nonnative fish colonization, and the identification of newly identified exotic species, such as the Nile monitor lizard, in the area are all critical to management decisions. For example, highlighting the problem of the Nile monitor lizard in Cape Coral prepared the City of Sanibel to program funding for eradication within days of the first confirmed identification of the Nile monitor lizard on the island city.

The USGS has monitored water flows within the study area since the 1930's. Since then more streams have been monitored by water management districts and other agencies. The information has been invaluable in understanding historic water flows and establishing Minimum Flows and Levels (MFLs) pursuant to state regulation.

*Use of environmental indicators to monitor and improve management*—Broadening monitoring efforts, both geographically and by scale, increases the effectiveness of original effort. For example, the water management districts have mapped seagrass coverage regularly to evaluate change. The Charlotte Harbor Aquatic Preserve Program increased the value of the original program by collecting transect data to evaluate species composition, epiphytic relationships over time, and depth. By having a better understanding of these very complex relationships in select areas, better management decisions can be made with the context of the overall mapping effort.

The Frog Listening Network was started in the Tampa Bay region. The methods of citizen training and monitoring were applied in southwest Florida through the program Frog Watch.

Various bioindicators are being investigated in the CHNEP study area. Observing the condition of various animal species can highlight the impacts of complex, inter-linked changes in water quality, hydrology, and habitat. Sharks, red mangrove crabs, spotted seatrout, and sawfish were investigated.

*Accounting for variability in nature*—Variability in nature is a confounding aspect of relating findings to citizens and elected officials. Often the exception to the rule can stymie efforts to improve management. Exceptional events such as the impacts of Hurricane Charlie changed and accelerated identified trends. Some of these changes could be predicted. Drastic drops in oxygen changed faunal assemblages in the northern Charlotte Harbor estuary.

*Applying monitoring and research results to models as a tool for better management*—Properly calibrated mathematical models can represent the possible impacts of proposed management decisions. Modeling the environment is difficult but advances are being made. The Everglades Restoration efforts have advanced the development of models in southwest Florida, particularly for effects of management decisions on blue crabs, oysters, and slough systems.

Development of hydrodynamic models of the estuaries has long been an ambitious goal of the CHNEP. Advances are being made by linking the estuaries with the Gulf of Mexico circulation models, improving bathymetric mapping, and integrating water quality parameters into the models.

Availability of Geographic Information Systems (GIS) and relational databases is improving an overall vision for restoration strategies in the CHNEP study area and beyond. The Lee County Master Mitigation Plan has synthesized the knowledge of resource managers working in Lee County. This work has been used for the CHNEP Restoration Plan, Southwest Florida Feasibility Study, and Everglades Restoration. The Southwest Florida Water Management District expanded this work to support their own restoration efforts. Because of the GIS and relational database formats, matching restoration needs with mitigation funding and grant funding requirements becomes easier.

*The future*—CHNEP has committed to host a Watershed Summit every three years. The information that is summarized by our partners at these conferences is utilized in our own decision-making process. These decisions include selection of format and content for public outreach, selection of needed research projects to support future decisions, choice of restoration projects, and recommendations for legislation and rules. The representatives on our various committees take information that we have developed or summarized back to there own organizations. In this way, knowledge grows and decisions are improved.

Florida Scient. 69(00S2): 3–6. 2006
Accepted: March 10, 2006

# SEAGRASS COVERAGE CHANGES IN CHARLOTTE HARBOR, FL

CATHERINE A. CORBETT

Charlotte Harbor National Estuary Program,
1926 Victoria Avenue, Fort Myers, FL 33901

ABSTRACT: *Seagrass areal coverage is estimated through seagrass polygon maps created almost biennially in Charlotte Harbor, Florida by photo-interpreting aerial photographs. This effort reports and analyzes coverage data for 1982–2003 for Upper and Lower Charlotte Harbor regions and 13 seagrass segments. Analyses did not detect trends in Upper or Lower Charlotte Harbor regions from 1982–2003. The Placida and Pine Island segments displayed increasing trends from 1982–2003, while the Peace River segment demonstrated a decreasing trend. From 1988–2003 the Placida segment displayed an increasing trend in areal extent, while the nearby South Harbor segment demonstrated a decreasing trend. Several segments demonstrated trends in seagrass polygon classification from "patchy" to "continuous" or vice versa, whereas these segments displayed no trend in areal extent. Relatively large changes occurred between the 1996 and 1999 mapping events, potentially a result of above-average rainfall with the 1997–1998 El Niño. This effort proposes that the changes may also be resultant in part from changes in the timing of data acquisition. Despite regional stability in seagrass coverage, declining water quality in some areas and the potential for future declines in others give reason for concern for the long-term maintenance of seagrass coverage in the Charlotte Harbor area.*

*Key Words:* Seagrass coverage, seagrass extent, Charlotte Harbor, estuaries, seagrass maps

CHARLOTTE Harbor, one of Florida's largest estuaries, is located in southwest Florida near Sarasota and Tampa Bays. The Charlotte Harbor estuarine complex includes numerous interconnected estuaries from northern Coastal Venice and Lemon Bay south to Estero Bay. The Charlotte Harbor watershed extends approximately 210 km (130 mi) from the northern headwaters of the Peace River to southern Estero Bay. Three large rivers, the Peace (6,090 km$^2$ basin), the Myakka (1,560 km$^2$ basin) and the Caloosahatchee River (3,570 km$^2$ basin extending to Moore Haven), serve as the major sources of freshwater to the Charlotte Harbor estuary (Hammett, 1990).

Resource managers in the south Florida region, including Indian River Lagoon and Tampa and Sarasota Bays, have focused on seagrass meadows as environmental indicators of coastal environmental conditions. Managers have established systematic coverage maps and fixed transect monitoring to estimate changes in the extent and species composition and abundance of seagrass beds over time. Through seagrass coverage mapping efforts, a 46% loss of seagrass coverage in Tampa Bay from 1950 to 1982 followed by a 24% increase from 1982 to 1996 was documented (Tomasko et al., 2005). A similar trend in Sarasota Bay was documented with a 28%

loss from 1950 to 1988 followed by a 19% increase from 1988 to 1996 (Tomasko et al., 2005). These trends are thought resultant from changes in water quality and policies regulating pollutant loads (see Tomasko et al., 2005).

The Southwest and South Florida Water Management Districts (WMDs) have photo-interpreted 1:24,000 aerial photographs to develop seagrass polygon maps for Upper and Lower Charlotte Harbor approximately every 2 years since 1988 and 1999, respectively, and these data are reported by regions, Upper and Lower Charlotte Harbor, and by 13 seagrass segments (FIG. 1). Also, the Florida Department of Environmental Protection Aquatic Preserves monitor seagrass species composition and abundance annually at 55 fixed transects throughout Charlotte Harbor and Lemon and Estero Bays, documenting six species of seagrasses: *Halodule wrightii* (Ascherson), *Thalassia testudinum* (Banks ex König), *Syringodium filiforme* (Kützing), *Halophila englemanni* (Ascherson), *Halophila decipiens* (Ostenfeld) and *Ruppia maritima* (Linnaeus).

Previous analyses demonstrated that seagrass coverage estimates in Upper Charlotte Harbor are stable since 1988 (Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett and Madley, *In Press*). However, losses in seagrass areal extent have been documented in Charlotte Harbor. Harris and co-workers (1983) compared seagrass extent derived from 1946 to 1951 black and white photographs to data derived from 1982 color photographs and documented a 29% decrease in seagrass, from 33,572 ha (82,959 acres) to 23,672 ha (58,495 acres) between 1945 and 1982, excluding Lemon and southern Estero Bays. All areas within the Charlotte Harbor study area demonstrated losses, ranging from 6–87%; however, the effort determined that over 57% of the total Charlotte Harbor region-wide loss was located solely within the Pine Island Sound, Matlacha Pass and San Carlos Bay segments (FIG. 1) of the Lower Charlotte Harbor region (Harris et al., 1983). Losses in Pine Island Sound alone accounted for more than 40% of the 29% region-wide loss. A subsequent effort, Corbett and co-workers (2005), reported seagrass extent through 2002, excluding Lemon and Estero Bays, and documented an overall 6% decrease between 1982 and 1999, from 23,127 ha in 1982 to 21,802 ha in 1999. The majority of the loss from 1982 to 1999 was found in the Lower Charlotte Harbor region within the Matlacha Pass, San Carlos Bay and Caloosahatchee River segments. During the same time period, the Pine Island Sound segment demonstrated an increase of 631 ha (Corbett et al., 2005).

Whereas water clarity and resultant changes in seagrass coverage in Tampa and Sarasota Bays have been linked to nutrient loads (see Tomasko et al., 2005 for references), coverage changes in Charlotte Harbor were largely attributed to other causes. Harris and co-workers (1983) credited the majority of the decreases from the 1940s to 1982 to the dredging of the Intracoastal Waterway and Sanibel Bridge construction in the Lower Charlotte Harbor region in the 1940s and 1960s. The authors also noted an overall decrease in seagrasses in the deep edges of seagrass beds and the deeper portions of the harbor and conjectured this loss was a result of decreasing water clarity from anthropogenic impacts. Corbett and co-workers (2005) observed some variability between sampling events in seagrass coverage estimates within the Upper Charlotte Harbor region and that this inter-mapping variability

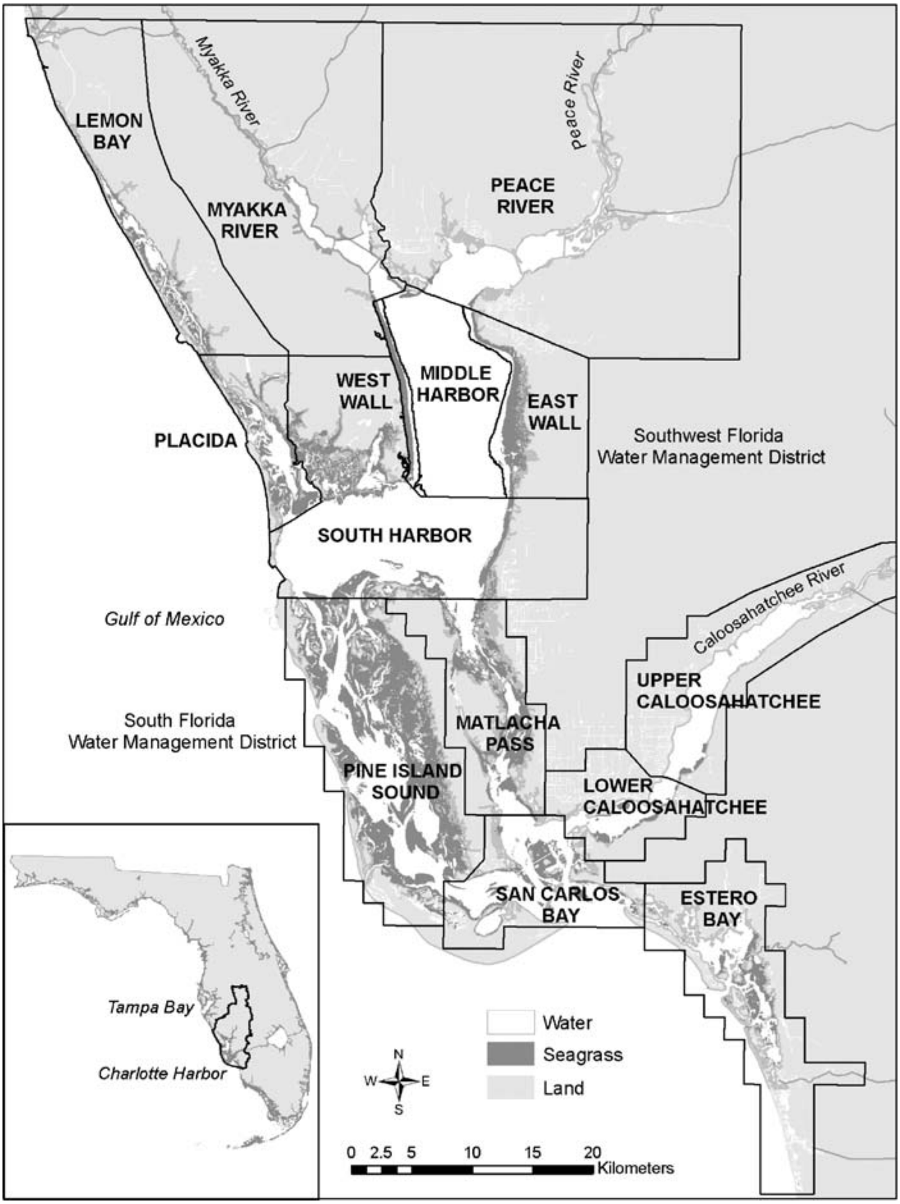



FIG. 1. Upper and Lower Charlotte Harbor Seagrass Segments. Seagrass Segments & 1999 Areal Coverage Provided by SWFWMD and SFWMD.

probably stemmed from inter-annual changes in freshwater inflows from the 3 major tributaries. The authors postulated the decreases detected in the 1999 mapping effort probably stemmed from the 1997–1998 El Nińo event, during which above average rainfall resulted in high inflows of stormwater runoff. In turn, salinity stress and

TABLE 1. Seagrass datasets for Charlotte Harbor and Lemon and Estero Bays.

| Dataset | Date of Aerial Photography Acquisition |
|---|---|
| 1982 | April 1982 |
| 1988 | October 1988 |
| 1992 | March 1, 1993 |
| 1994 | Upper Charlotte Harbor on March 1, 1995 |
| | Lemon Bay in January 1995 |
| 1996 | Upper Charlotte Harbor on April 24 and May 8–9, 1997 |
| | Lemon Bay on January 31 and May 8, 1997 |
| 1999 | Upper Charlotte Harbor December 1, 1999 |
| | Lower Charlotte Harbor December 9 and 26, 1999 |
| 2001 | January 9–10, 2002 |
| 2002 | January 2003 |
| 2003 | January 12–13, 2004 |

reduced water clarity from increased dissolved organic matter (Dixon and Kirkpatrick, 1999; Tomasko and Hall, 1999), likely caused a die-back of above-ground biomass before the 1999 mapping event (Corbett et al., 2005; Tomasko et al., 2005). Thus, changes in nutrient loads have not been linked to seagrass coverage changes in Charlotte Harbor.

Nonetheless, recent analyses of water quality data for Charlotte Harbor and Lemon and Estero Bays demonstrate a reason for concern for the future maintenance of seagrass extent and compel further scrutiny of seagrass coverage estimates. Analyzing water quality collected though 2001, Janicki Environmental Inc. (2003) documented increasing total suspended solids in Lower Charlotte Harbor and Upper Charlotte Harbor and increasing turbidity in Lower Charlotte Harbor. As suspended matter in the water column can at times account for over half of light attenuation in Charlotte Harbor (McPherson and Miller, 1987; McPherson and Miller, 1994; Dixon and Kirkpatrick, 1999), the increasing trends of these constituents give reason for a more thorough evaluation of seagrass coverage estimates. In addition, previous trend analyses for seagrass coverage estimates in Upper Charlotte Harbor (i.e., Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005), failed to analyze data by individual seagrass segment. Corbett and co-workers (2005) completed a change analysis comparing 1982 to 1999 data by region and seagrass segment but did not undertake a trend analysis by individual segment. This effort, therefore, updates previous analyses by reporting 2002 and 2003 coverage data for the Charlotte Harbor area and then examines the data for trends by region and by seagrass segment.

METHODS—*Seagrass maps*—In Upper Charlotte Harbor, the Southwest Florida Water Management District (SWFWMD) has created seagrass polygon maps to estimate seagrass coverage on a roughly biennial basis since 1988, while the South Florida Water Management District (SFWMD) initiated efforts within their jurisdiction of Lower Charlotte Harbor in 1999. The two Districts use approximately the same methodologies in their mapping efforts differing only slightly in the minimum mapping units, map accuracy standards and classification of "patchy" versus "continuous" seagrass coverage (see Corbett et al., 2005 for explanation).

Existing seagrass datasets and the dates of aerial photography acquisition are listed in Table 1. Seagrass maps are produced through a multi-step process by photo-interpreting 1:24,000 aerial photographs using stereoscopes or analytical stereo plotters (for details see Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; SWFWMD, 2006; Corbett and Madley, *In Press*; Tomasko and Greening, *In Press*). Maps are checked for accuracy by post-production field verification, and both WMDs require a photo-interpretation classification accuracy of over 90%. Seagrass signatures are divided into two classes: 9116 "continuous" coverage (approximately 75%–100% seagrass cover visible within a polygon) and 9113 "patchy" (approximately 25%–75% seagrass cover visible within a polygon). Both polygon classes are combined for 911 "total" seagrass coverage. Other map categories are polygons with approximately 0–25% seagrass cover, classified as 6510 "tidal flat" or 5400 "open water" depending on depth. Non-vegetated areas that are periodically exposed or are capable of supporting seagrass, defined as approximately 2 meters in depth or shallower, are classified as "tidal flat"; they are usually found on the shallower edges of seagrass beds, either along the shoreline or on the crest of a seagrass bed (SWFWMD, 2006). Lastly, 7100 "beaches other than swimming" are isolated strands of non-vegetated sand found along mangrove and spoil islands (SWFWMD, 2006).

The 1982 data were collected by the Florida Fish and Wildlife Conservation Commission in April 1982 using similar methods to SWFWMD in 1988 that included field verification of signatures; however, seagrass coverage was classified to three categories (i.e., sparse, dense, patchy) (see Harris et al., 1983 for details). Because the 1982 polygon classifications are not easily comparable to subsequent mapping efforts harbor-wide, the 1982 data are not included in the analysis of "patchy" and "continuous" coverage described below. Also, the 1982 data did not include Lemon or southern Estero Bays, and because of this, analysis of 1982 Lemon and Estero Bays areal extent is not included here. Data for the Caloosahatchee River are reported for the Lower Caloosahatchee River segment (FIG. 1) only.

*Data analysis*—All statistical analyses were completed using Statistica® v 7.0, with the significance level of $\alpha$=0.05. All trend analyses were completed using linear regression analysis (i.e., Pearson r). Mann-Whitney U tests were performed to compare 1988–1996 coverage data with 1999–2003 coverage data.

*Total seagrass coverage*—Seagrass areal extent data were first examined by combining the "patchy" (9113) and "continuous" (9116) polygon categories for total areal extent, called "total", for each mapping effort. A mean-error plot was created of the mean areal extent by seagrass segment for 1982–2003 (1988–2003 for Estero and Lemon Bays). To account for differences in the segments such as segment size and water depth, a uniform estimate of potentially-available seagrass habitat for each segment was made by adding the "tidal flat" (6510) coverage to the "total" seagrass coverage. The plot was then created for the ratio of "total" seagrass coverage to this estimate of "available habitat" by segment.

"Total" seagrass areal extent data for the Upper and Lower Charlotte Harbor regions, excluding Estero and Lemon Bays, were examined for temporal trends for 1982–2003 data by linear regression analysis. "Total" seagrass areal extent data for the 13 individual seagrass segments were also examined for trends for 1982–2003 data by linear regression analysis. For comparison purposes with the "patchy" and "continuous" analyses described below, linear regression analysis was also performed on 1988–2003 "total" seagrass areal extent data by segment.

*Polygon category comparisons*—Seagrass data for each seagrass segment were next analyzed by polygon category, "patchy" and "continuous", for each sampling effort between 1988–2003. The 1982 data were not used in these analyses. Linear regression analysis was performed on "patchy" and "continuous" data separately for each seagrass segment for 1988–2003 to look for temporal trends in coverage by polygon categories.

Next, to quantify changes in the relationship of seagrass coverage mapped as "patchy" or "continuous", the percent of "total" areal extent mapped as "patchy" and then "continuous" was determined by segment and sampling effort from 1988–2003. A mean-error plot of mean percent "continuous" coverage by segment was created. These data were then analyzed by seagrass segment for trends between 1988–2003 using linear regression analysis. For comparison purposes, the linear regression analyses were also performed on data collected by SWFWMD in Tampa Bay for 1988–2003 for the following segments: Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, Boca Ciega Bay, Lower Tampa Bay, Terra Ciea Bay and Manatee River.

TABLE 2. Seagrass coverage in hectares by region and by segment by year since 1982. These coverages reflect segment boundary changes made in 2003 by the SWFWMD and SFWMD.

| Year | Lemon Bay | Upper Charlotte Harbor: Placida | South Harbor | West Wall | East Wall | Middle Harbor | Myakka River | Peace River | Subtotal (Except Lemon Bay) |
|---|---|---|---|---|---|---|---|---|---|
| 1982 | | 957 | 3,544 | 665 | 1,548 | 70 | 218 | 397 | 7,399 |
| 1988 | 1,055 | 1,416 | 3,710 | 580 | 1,372 | 50 | 161 | 158 | 7,448 |
| 1992 | | 1,384 | 3,662 | 490 | 1,361 | 50 | 130 | 167 | 7,244 |
| 1994 | 1,067 | 1,344 | 3,659 | 671 | 1,416 | 60 | 189 | 196 | 7,535 |
| 1996 | 1,054 | 1,460 | 3,648 | 790 | 1,371 | 76 | 203 | 232 | 7,781 |
| 1999 | 1,049 | 1,503 | 3,340 | 699 | 1,452 | 62 | 191 | 109 | 7,356 |
| 2001 | 1,046 | 1,531 | 3,313 | 699 | 1,454 | 64 | 185 | 138 | 7,384 |
| 2003 | 1,110 | 1,625 | 3,488 | 646 | 1,315 | 43 | 118 | 106 | 7,341 |
| Mean | 1,064 | 1,402 | 3,545 | 655 | 1,411 | 60 | 174 | 188 | 7,436 |

| Year | Lower Charlotte Harbor: Pine Island Sound | Matlacha Pass | San Carlos Bay | Caloosahatchee River | Estero Bay | Subtotal (Except Estero Bay) |
|---|---|---|---|---|---|---|
| 1982 | 9,857 | 3,247 | 2,420 | 242 | | 15,766 |
| 1999 | 10,483 | 2,456 | 1,504 | 1 | 1,008 | 14,445 |
| 2002 | 10,647 | 2,784 | 1,768 | 42 | 975 | 15,241 |
| Mean | 10,329 | 2,829 | 1,898 | 95 | 991 | 15,151 |

*Time series comparison*—To determine if seagrass coverage estimates were significantly different between 1988–1996 and 1999–2003, a Mann-Whitney U test was performed on "total" seagrass coverage by segment and by region for 1988–1996 and 1999–2003 periods. A Mann-Whitney U test was also performed on the percent "continuous" coverage by segment to compare 1988–1996 and 1999–2003 percent "continuous" coverage data.

RESULTS—*Seagrass coverage*—Table 2 lists estimates of "total" seagrass areal for 1982–2003, and Table 3 lists coverage estimates for "patchy" and "continuous" categories by segment for 1988–2003. The spatial extents of several segments within the Upper Charlotte Harbor region were modified in 2003 by SWFWMD; thus, the data reported in Table 2 differ slightly from earlier efforts (i.e., Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett and Madley, *In Press*).

The ratio of seagrass coverage to available seagrass habitat appeared different in several segments as did seagrass polygon classifications. The most notable result was that the Peace River and Estero Bay segments displayed reduced mean areal extent to available habitat ratios with mean values less than 0.5 (FIG. 2), and the Myakka River, Lemon Bay and Middle Harbor segments displayed ratios less than 0.75. The segments in the Lower Charlotte Harbor region along with the Estero Bay segment generally displayed a greater percentage of seagrass coverage mapped as "continuous" than those segments in the Upper Charlotte Harbor region and the Lemon Bay segment (FIG. 3), which, in turn, had a larger percentage mapped as "patchy".

"Total" areal extent for the Upper Charlotte Harbor region did not demonstrate a trend from 1982 to 2003 (FIG. 4). Mean seagrass coverage in Upper Charlotte Harbor during 1982 to 2003 was 7,436 hectares, and the difference in coverage

TABLE 3. "Patchy" seagrass coverage in hectares by segment from 1988–2003. "Continuous" coverage is in parentheses.

| | | Upper Charlotte Harbor | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Lemon Bay | Placida | South Harbor | West Wall | East Wall | Middle Harbor | Myakka River | Peace River |
| 1988 | 673 (382) | 804 (612) | 2,423 (1,287) | 357 (223) | 1,175 (197) | 42 (8) | 132 (29) | 157 (2) |
| 1992 | | 853 (530) | 2,455 (1,207) | 303 (188) | 1,215 (147) | 49 (1) | 105 (25) | 167 (0) |
| 1994 | 541 (525) | 853 (491) | 2,721 (937) | 432 (239) | 1,245 (171) | 58 (2) | 159 (29) | 190 (7) |
| 1996 | 510 (544) | 948 (512) | 2,587 (1,061) | 555 (235) | 1,248 (123) | 72 (4) | 173 (29) | 200 (32) |
| 1999 | 383 (667) | 761 (742) | 1,713 (1,626) | 395 (304) | 1,231 (221) | 61 (1) | 171 (20) | 109 (0) |
| 2001 | 291 (755) | 654 (877) | 1,468 (1,845) | 382 (317) | 1,078 (376) | 63 (1) | 163 (23) | 138 (0) |
| 2003 | 484 (626) | 763 (862) | 1,249 (2,239) | 377 (268) | 929 (385) | 43 (0) | 118 (0) | 106 (0) |
| Mean | 480 (583) | 805 (661) | 2,088 (1,457) | 400 (253) | 1,160 (231) | 56 (2) | 146 (22) | 152 (6) |

| | Lower Charlotte Harbor | | | | |
|---|---|---|---|---|---|
| Year | Pine Island Sound | Matlacha Pass | San Carlos Bay | Caloosahatchee River | Estero Bay |
| 1999 | 773 (9,710) | 193 (2,263) | 112 (1,393) | 0 (1) | 105 (903) |
| 2002 | 696 (9,951) | 218 (2,566) | 230 (1,538) | 10 (33) | 65 (909) |
| Mean | 735 (9,830) | 206 (2,414) | 171 (1,465) | 5 (17) | 85 (906) |

estimates between consecutive sampling events was less than 500 hectares. The data for the Lower Charlotte Harbor region also did not demonstrate a trend. Mean areal extent for the 3 mapping efforts in Lower Charlotte Harbor was 15,151 hectares.

Temporal trends were found in several individual seagrass segments when analyzing "total" areal coverage for the 1982 to 2003 period. The Placida and Pine Island segments displayed significant increasing trends estimated to be 26 and 39 hectares per year, respectively, while the Peace River segment demonstrated a significant decreasing trend at a loss approximating 11 hectares per year. The South Harbor segment also demonstrated a decreasing trend from 1982 to 2003 at an estimated rate of 12 hectares per year (FIG. 5), but the trend was not significant ($p=0.15$).

Table 4 lists the results from all trend analyses of 1988–2003 data. From 1988 to 2003, the Placida segment demonstrated a significant increasing trend estimated at 15 hectares per year, while the nearby South Harbor segment displayed a significant decreasing trend at an approximate rate of 25 hectares per year. The South Harbor segment displayed a relatively dramatic loss of 308 ha between the 1996 and 1999 mapping events (FIG. 5). The segment also exhibited a significant decreasing trend from 1988 to 1996 at an approximate rate of 8 hectares per year and an increasing trend that was not significant from 1999 to 2003. A relatively dramatic loss of coverage between the 1996 and 1999 sampling events was also apparent in the Peace River segment. Between 1996 and 1999, coverage declined 53%, while from 1988 to 1996, coverage for the Peace River demonstrated an increasing trend at an approximate rate of 9 hectares per year that was not significant ($p=0.09$). Overall, from 1988 to 2003 the Peace River displayed a decreasing trend that was not significant ($p=0.25$).

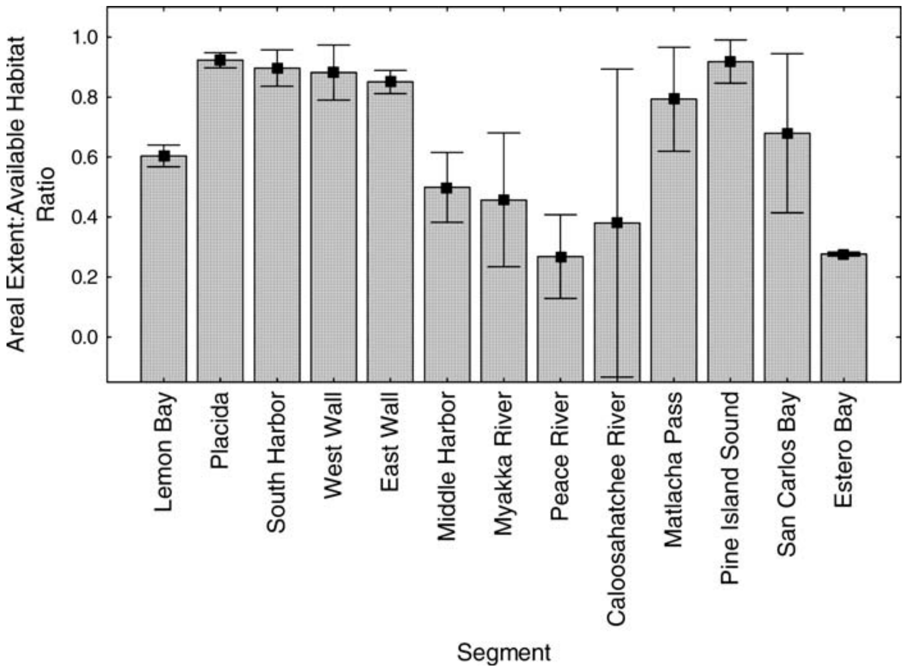



FIG. 2. Mean Areal Extent to Available Habitat Ratio by Segment from 1982 to 2003. Horizontal Bars represent ±0.95 standard deviation.

*Polygon category comparisons*—Linear regression analysis of "patchy" and "continuous" polygons in Upper Charlotte Harbor for 1988–2003 documented trends in several seagrass segments in Upper Charlotte Harbor (Table 4). Four segments, Lemon Bay, Placida, South Harbor and West Wall, displayed significant increasing trends in "continuous" coverage, while the East Wall demonstrated an increasing trend that was not significant ($p=0.06$). The South Harbor segment demonstrated the greatest rate of change with an increase estimated at 68 hectares per year in "continuous" coverage. The South Harbor and Lemon Bay segments demonstrated concomitant significant decreasing trends in "patchy" coverage; the rate of these decreases was approximately 93 hectares and 20 hectares per year, respectively. Three other segments, Placida, Peace River and East Wall, demonstrated decreasing trends in "patchy" coverage also, but these trends were not significant. The Myakka River segment demonstrated a small decreasing trend in "continuous" coverage that was not significant ($p=0.07$) (Table 4) and by 2003 displayed no "continuous" coverage (Table 3). The Middle Harbor and Peace and Myakka River segments also demonstrated no "continuous" coverage in 2003.

An interesting pattern emerges when reviewing these findings and the relationship between "patchy" and "continuous", represented as percent "patchy" or percent "continuous" coverage. The Lemon Bay and South Harbor segments demonstrated significant increasing trends in percent "continuous" coverage and

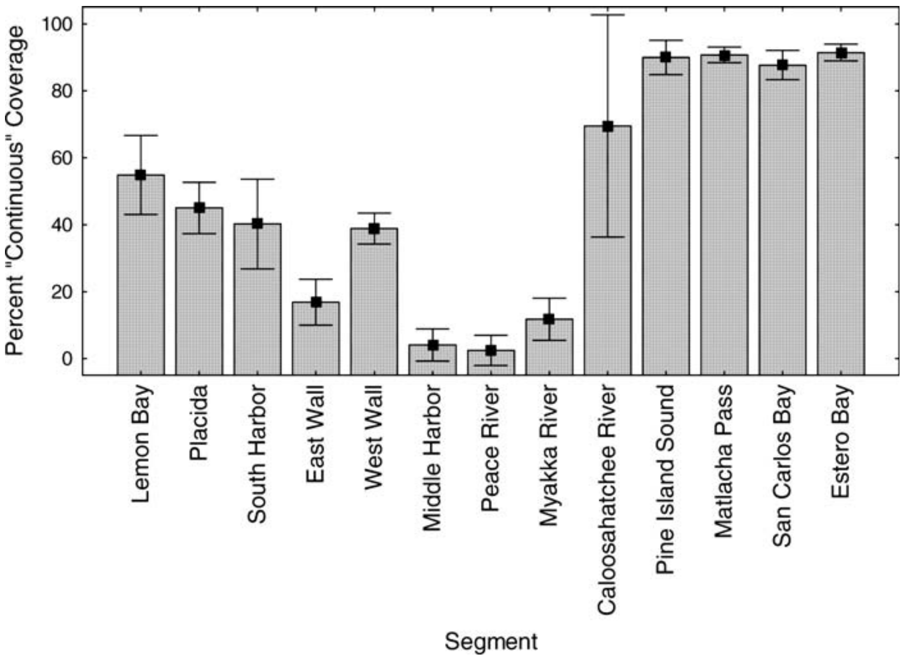



FIG. 3. Mean Percent "Continuous" Coverage by Segment from 1988 to 2003. Horizontal Bars represent ±0.95 standard deviation.

resultant concomitant decreasing trends in percent "patchy". The Placida and East Wall segments demonstrated a similar phenomena, but trends for these segments were not significant ($p=0.09$ and $p=0.06$, respectively). A relatively large increase in percent "continuous" coverage occurred between the 1996 to 1999 sampling events (FIG. 6). Analyses demonstrated the reverse relationship between percent "patchy" and "continuous" for the Middle Harbor and Myakka River segments (Table 4). More than 80% of seagrass coverage in both these and the Peace River segments were classified as "patchy", and in 2003 all 3 segments displayed 100% "patchy" coverage (FIG. 7).

Nonetheless, as mentioned above, only the Placida and South Harbor segments demonstrated "total" coverage trends for the same time period, increasing and decreasing, respectively (Table 4). The South Harbor segment displayed significant trends in all analyses: declining trends in "total", "patchy" and percent "patchy" seagrass coverage and increasing trends in "continuous" coverage and the percent "continuous" coverage. The Placida segment demonstrated significant increasing trends in "total" seagrass coverage and "continuous" coverage. Several of the remaining segments, Lemon Bay, Middle Harbor and Myakka River displayed significant trends in percent "patchy" and percent "continuous" with no concomitant "total" coverage trend. Thus, these data demonstrated a change in the relationship of "patchy" to "continuous" categories.

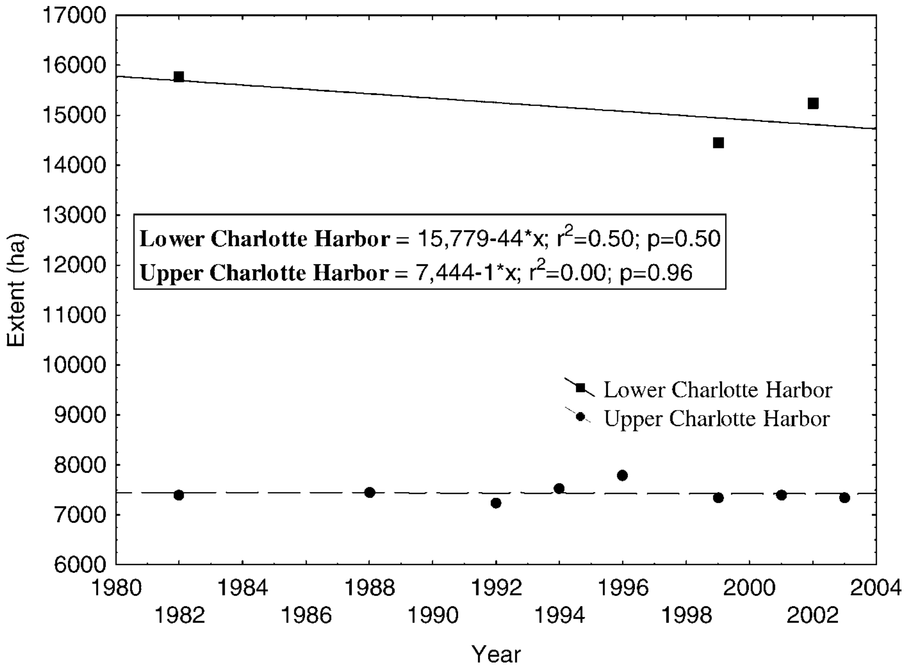



FIG. 4. Areal Extent by Region, excluding Lemon and Estero Bays, from 1982 to 2003.

Results from the analyses of Tampa Bay "total", "patchy", "continuous", percent "patchy" and percent "continuous" coverage data from 1988 to 2003 displayed that only one segment, Terra Ciea Bay, of the 7 segments analyzed demonstrated a significant trend in polygon coverage classification without a concomitant overall coverage trend. The pattern in changing coverage classification without overall coverage trends that was found in several segments in Upper Charlotte Harbor was, therefore, not widespread in Tampa Bay.

*Time series comparisons*—"Total" coverage estimates for 1988–1996 in the Placida, South Harbor and Peace River segments were significantly different from 1999–2003 estimates. The mean coverage for the Placida segment was greater in the 1988–1996 period than the 1999–2003 period, while the opposite was true for the South Harbor and Peace River segments. Percent "continuous" coverage during 1988–1996 was significantly different in all 7 segments in Upper Charlotte Harbor and the Lemon Bay segment from 1999–2003. Lower mean percent "continuous" coverage was detected in 1988–1996 for the Lemon Bay, Placida, South Harbor, West Wall and East Wall segments than in 1999–2003, while the opposite relation was found in the Peace and Myakka Rivers and Middle Harbor segments.

DISCUSSION—Past research has documented that dissolved and suspended matter account for over 90% of light attenuation in Charlotte Harbor (e.g., McPherson

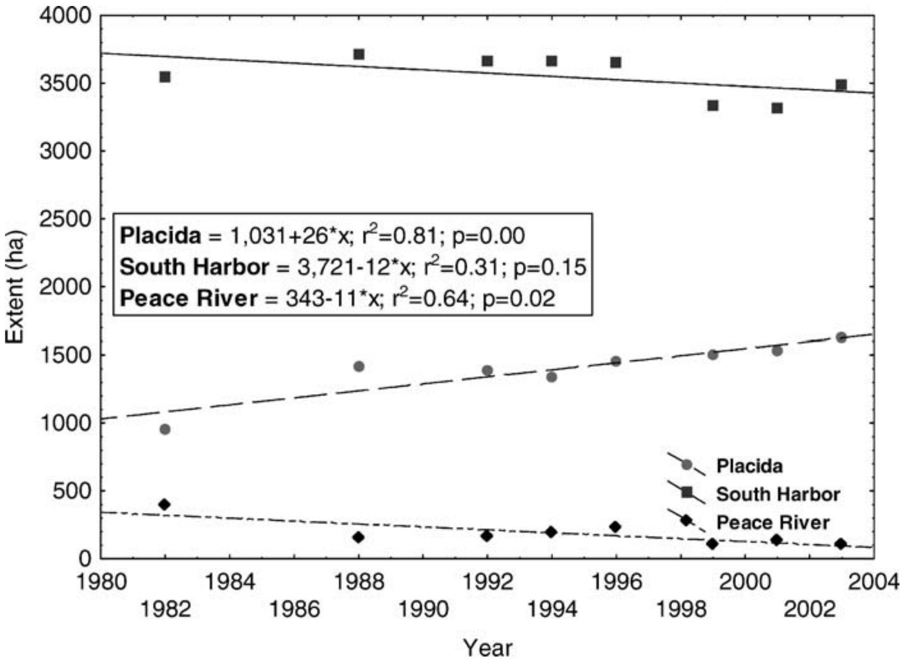



FIG. 5. Areal Extent for Placida, South Harbor and Peace River Segments from 1982 to 2003.

and Miller, 1987; Dixon and Kirkpatrick, 1999) and that water clarity in Charlotte Harbor is strongly, positively associated with salinity (McPherson and Miller, 1987; McPherson and Miller, 1994; Dixon and Kirkpatrick, 1999; Tomasko and Hall, 1999). In turn, water clarity is largely a factor of basin runoff and flows from the three major tributaries (McPherson and Miller, 1987; Doering and Chamberlain, 1999; Tomasko and Hall, 1999). Dixon and Kirkpatrick (1999) found that the maximum depths of seagrass beds in Charlotte Harbor generally increase with increasing distance from the mouths of the 3 tributaries. The analysis in this effort comparing "total" seagrass coverage to available habitat across segments corroborates these previous efforts. Mean areal extent in the river segments, the Peace, Myakka and potentially the Caloosahatchee, appeared lower with respect to available seagrass habitat than in those segments farther away from the tributaries in general. However, Estero Bay also displayed a low mean areal extent to available habitat ratio which suggests that environmental conditions, such as poor water clarity, within this segment are not beneficial for seagrass meadows, a condition that may be worsening. For instance, Janicki Environmental Inc. (2003) found increasing turbidity, total suspended solids and other analytes within the Estero Bay basin.

Similar to previous recent analyses of seagrass coverage estimates for the Upper Charlotte Harbor region (i.e., Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005), seagrass areal extent in the Upper and Lower Charlotte Harbor regions appeared stable in this analysis. This effort did not find a trend in seagrass coverage for 1982 to 2003 for the Upper or Lower Charlotte Harbor region, and estimates for

TABLE 4. Estimated annual rates of change from 1988 to 2003 for seagrass coverage by segment in Upper Charlotte Harbor, expressed as hectares per year or percent by year. Significance levels are enclosed in parentheses with trends significant at p<0.05 shown with an asterisk.

| Segment | "Total" Coverage (ha) | "Patchy" Coverage (ha) | "Continuous" Coverage (ha) | Percent "Patchy" | Percent "Continuous" |
|---|---|---|---|---|---|
| Lemon Bay | +2 (p=0.43) | −20 (p=0.05)* | +21 (p=0.02)* | −2 (p=0.03)* | +2 (p=0.03)* |
| Placida | +15 (p=0.02)* | −9 (p=0.25) | +24 (p=0.05)* | −1 (p=0.09) | +1 (p=0.09) |
| South Harbor | −25 (p=0.03)* | −93 (p=0.02)* | +68 (p=0.04)* | −2 (p=0.03)* | +2 (p=0.03)* |
| West Wall | +9 (p=0.25) | +2 (p=0.73) | +7 (p=0.05)* | 0 (p=0.30) | 0 (p=0.30) |
| East Wall | +1 (p=0.81) | −14 (p=0.14) | +15 (p=0.06) | −1 (p=0.06) | +1 (p=0.06) |
| Middle Harbor | 0 (p=0.86) | +1 (p=0.56) | 0 (p=0.05)* | +1 (p=0.04)* | −1 (p=0.04)* |
| Peace River | −4 (p=0.25) | −4 (p=0.16) | 0 (p=0.85) | 0 (p=0.81) | 0 (p=0.81) |
| Myakka River | 0 (p=0.96) | +1 (p=0.60) | −1 (p=0.07) | +1 (p=0.02)* | −1 (p=0.02)* |

the Upper Charlotte Harbor region demonstrated differences between sampling events no greater than 500 hectares. Therefore, existing seagrass coverage estimates demonstrated that region-wide seagrass coverage for Charlotte Harbor was stable between 1982 and 2003.

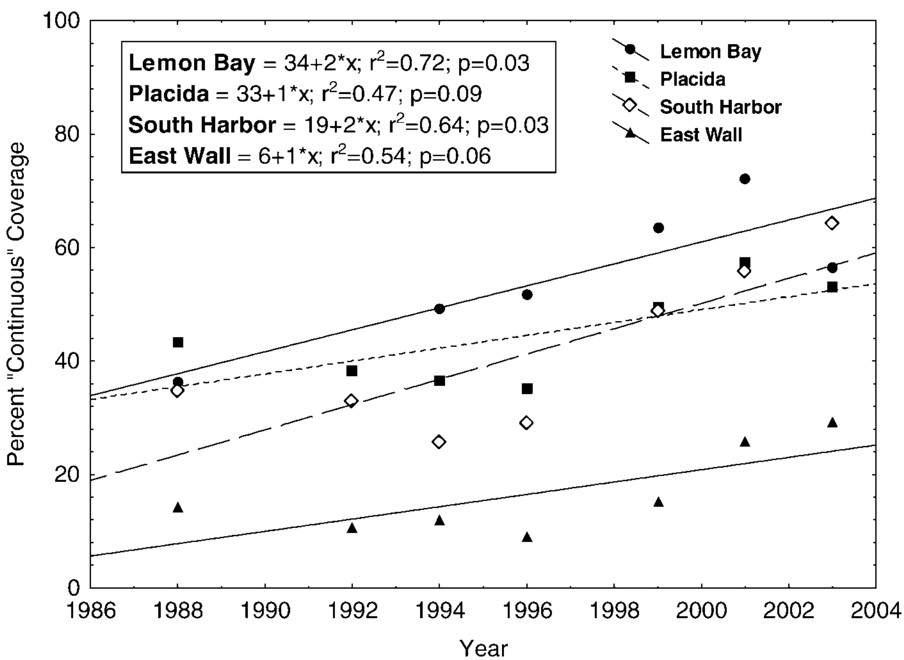



FIG. 6. Percent "Continuous" Coverage in Selected Segments from 1988 to 2003.

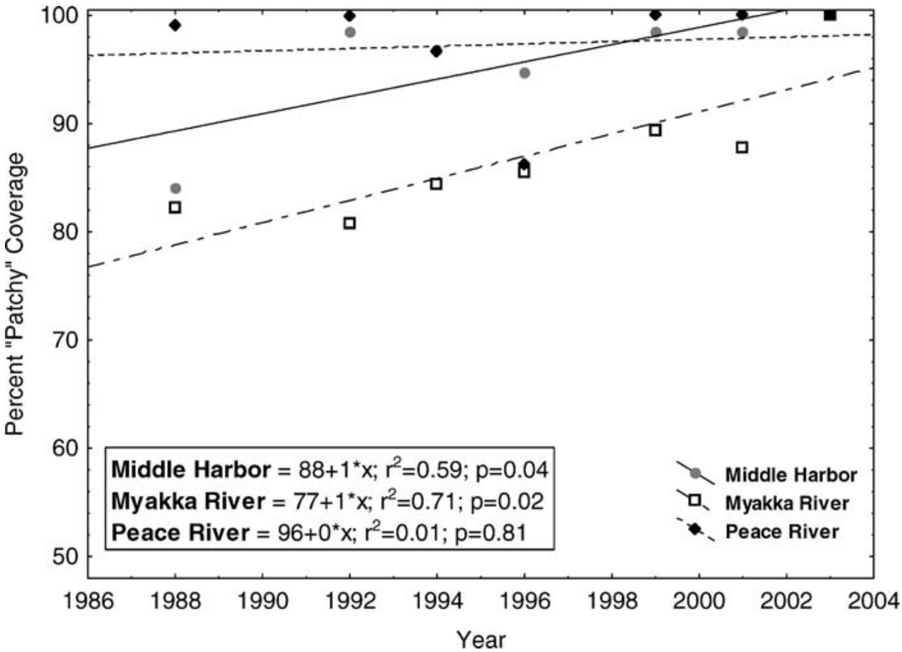



FIG. 7. Increases in Percent "Patchy" Coverage from 1988 to 2003.

Nonetheless, within individual seagrass segments of Charlotte Harbor, there appears to be changes in areal extent and/or classification. Significant trends in seagrass coverage were documented in several segments, such as increasing trends in the Pine Island Sound and Placida segments from 1982 to 2003. The Peace River segment demonstrated an overall significant decreasing trend from 1982 to 2003, but further analysis showed that losses in coverage between the 1982 and 1988 as well as between 1996 and 1999 sampling events could explain that overall trend. Seagrass coverage in the Peace River declined 60% and 53% during those time periods, respectively, while between the 1988 and 1996 periods, the Peace River demonstrated an increasing trend. In addition, the South Harbor segment demonstrated a significant decreasing trend in seagrass coverage from 1988 to 2003. While some of this trend can be explained by a relatively large loss of coverage between the 1996 and 1999 sampling events, this segment also displayed a negative coverage trend between 1988 and 1996.

The 1997–1998 El Niño event occurred between the 1996 and 1999 sampling events and may explain why seagrass coverage in the Peace River and South Harbor segments demonstrated relatively large losses during this time period. Above average rainfall that accompanied the 1997–1998 El Niño resulted in winter and springtime flows as much as 20 times the long-term averages (Dixon and Kirkpatrick, 1999). In turn, salinity stress and reduced water clarity from increased dissolved organic matter (Dixon and Kirkpatrick, 1999; Tomasko and Hall, 1999), likely caused a die-back or sloughing of aboveground biomass documented in the

1999 seagrass maps (Corbett et al., 2005; Tomasko et al., 2005). Conversely, record drought conditions between the 1999 and 2002 seagrass mapping events for Lower Charlotte Harbor probably produced the increase in seagrass coverage documented in the 2002 SFWMD seagrass maps.

Several segments in the Upper Charlotte Harbor region demonstrated trends in "patchy" and "continuous" classification categories. Four segments showed significant increasing trends in "continuous" coverage, and a fifth showed an increasing trend that was not significant. Two of these also showed significant increasing percent "continuous" coverage, while two other segments demonstrated increasing trends that were not significant. Of these segments, only the Placida segment demonstrated a concomitant significant increasing trend in "total" coverage. Moreover, the South Harbor segment demonstrated a concomitant significant *decreasing* trend in "total" coverage. This pattern of increasing "continuous" polygon classification without a simultaneous increase in areal coverage trend seems to signify a "filling in" of gaps between seagrass meadows, although a review of the aerial photographs from which these data are derived is needed for conclusive evidence. The majority of these segments demonstrate a relatively dramatic change between the 1996 and 1999 mapping efforts (FIG. 6). In addition, five segments displayed a higher percent "continuous" coverage in 1999–2003 than in 1988–1996.

The pattern described above—trends in polygon classification with a lack of simultaneous trend in overall coverage—might be indicative of natural variability within the coastal Charlotte Harbor ecosystem or potential evidence of an environmental disturbance. The mosaic of seagrass, oyster bar and unvegetated patches within the coastal Charlotte Harbor landscape probably shifts as environmental constraints, such as salinity, light availability and other water quality variables, vary over time.

Still another likely reason for the significant trends described herein is intersampling differences in aerial photograph acquisition. Between 1988–1996, the data for 2 seagrass maps in the Upper Charlotte Harbor region (i.e., 1992 and 1994) were derived from aerial photography taken in early March, which is towards the end of the seagrass dormant season generally (Robbins, 2006; Ott, 2006), and as late as April and early May for a third dataset (i.e., 1996) (Table 1). Between 1999–2003, the data for the seagrass maps were derived from aerial photography taken in early December or early January, generally the beginning of the seagrass dormant season (Robbins, 2006; Ott, 2006). Tomasko and Hall (1999: FIGS. 6, 8 and 9) found lower *T. testudinum* short shoot density, areal blade biomass and areal blade productivity values in March 1996 than in December 1995. Dixon and Kirkpatrick (1999: FIGS. 12 and 13) also found lower short shoot density in March/April 1998 than December 1997/January 1998 for both *T. testudinum* and *H. wrightii*. Tomasko and Hall (1999) found that *T. testudinum* areal blade biomass and areal blade productivity varied by location and date and that areal productivity was positively related to both water temperature and salinity. A cluster of low areal productivity was documented during low water temperatures ($<20°C$) and intermediate to high salinities (15-35 PPT), and these data were collected from all sample sites during the winter to early spring of 1995–1996 (Tomasko and Hall, 1999). Thus, it is reasonable to expect that the timing of data collection (i.e., aerial photograph acquisition) will have a significant impact on seagrass extent estimates. Indeed, this analysis found that all Upper Charlotte Harbor segments along with Lemon Bay demonstrated significant differences in percent "continuous" coverage between the 1988–1996 and 1999–2003 periods, and three segments displayed significant differences between the periods in areal extent as well.

There have been multiple efforts (references in Robbins, 1997) to quantify the sources of error in the creation of seagrass maps, such as digitization methods and photographic interpretation of habitat categories (see Robbins, 1997; Kurz, 2002; Meehan et al., 2005 for discussion). Seagrass polygons are classified as "patchy" or "continuous" based upon the amount of seagrass coverage within each polygon, and this process is subject to inter and intra-operator error (see Robbins, 1997; Kurz, 2002; Meehan et al., 2005). To reduce these errors, instead of drawing completely new seagrass polygons for each seagrass map, samplers in the southwest Florida region use the previous seagrass map's digital coverage as a baseline and delineate any changes to seagrass extent for the current effort. The size and/or classification of an individual polygon change from sampling event to sampling event, depending on environmental conditions prior to aerial photograph acquisition.

In turn, if above ground biomass is lower in March and April than in December and early January, the trends in changing polygon classifications found herein may not indicate a change in habitat fragmentation. Instead, the coverage within the polygons changed perhaps due to the shift in timing of aerial photograph acquisition to earlier in the "dormant" season. Increasing trends in percent "continuous" coverage without a concomitant coverage trend may be a result of the reclassification of "patchy" polygons in the 1988–1996 datasets to "continuous" in the 1999–2003 because the data for the latter maps were acquired at the beginning of the seagrass dormant season rather than towards the end as in the 1988–1996 datasets. Noteworthy then, is that the Middle Harbor and Peace and Myakka River segments displayed more percent "continuous" coverage in the 1988–1996 datasets than in the 1999–2003 datasets.

Nonetheless, this analysis may suggest potential reasons for concern for the long-term maintenance of seagrass coverage in Charlotte Harbor and a need for further study of seagrass meadows in the region and those factors, such as salinity and water clarity, affecting this essential resource. An important first step would be to review the aerial photographs used to create the seagrass polygon maps to view those areas that displayed losses (i.e., Peace River and South Harbor segments) to determine where the losses occurred. The aerial photographs can be used to verify if seagrass beds within "patchy" polygons are coalescing in those segments that demonstrate polygon classification changes so one may determine if seagrass patch sizes are increasing and habitat fragmentation decreasing or if the classification shifts are potentially due to sampling changes. The aerial photographs can document whether the spatial boundaries of the 13 seagrass segments could better incorporate proper hydrologic, water quality and other ecological variables. For instance, the boundaries of South Harbor segment should probably be changed so those seagrass beds along the East Wall are incorporated into the East Wall segment and those along the northern tip of Pine Island be separate from those in the Cape Haze area. The Placida segment demonstrated an increasing trend in seagrass coverage during the same time period that the nearby South Harbor segment displayed a decreasing trend, and a change to the segment spatial boundaries to reflect *in situ* seagrass bed boundaries might address these opposing trends within the 2 contiguous segments.

Water quality is declining in several areas of Charlotte Harbor and faces potential future declines in many others, raising concerns for the long-term maintenance of seagrass coverage. Total suspended solids are increasing in both Upper Charlotte Harbor and Lower Charlotte Harbor, and turbidity and nutrient levels in Lower Charlotte Harbor show increases through 2001 (Janicki Environmental Inc., 2003). At the same time, the Charlotte Harbor region is facing rapid urbanization pressure along the coast and more intensive landuse changes in its watershed which may result in degraded water quality. In addition, increases in rainfall and freshwater inflows over the previous several decades are projected for the near future (Kelly, 2004), and in turn, pollutant loads that are strongly associated with stormwater runoff will also increase (Tomasko et al., 2005). To understand the impacts of these changes and best protect aquatic resources, it is imperative that resource managers in the Charlotte Harbor region maintain seagrass coverage and species composition and distribution monitoring into the future. In addition, the region should consider developing water quality management strategies protective of seagrass meadows.

ACKNOWLEDGMENTS—Jason Hale and Jaime Greenawalt provided statistical advice, and Frank Sargent assisted with seagrass mapping methods. Ralph Montgomery, Brad Robbins and David Tomasko responded to a plethora of questions and always offered encouragement. The data used in this effort were made available through the dedicated work of numerous individuals: David Tomasko, Tomma Barnes, Peter Doering, Kris Kaufman, Kevin Madley, Frank Sargent, Tom Reis, Ray Kurz and others, including Avineon, Inc. and Photo Science, Inc. staff who created the seagrass maps. In addition, members of the Seagrass Working Group for the southwest Florida coast, most notably Brad Robbins, Holly Greening, Judy Ott and Aaron Adams, provided thoughtful insight and encouragement. Three anonymous reviewers and the guest editors provided invaluable constructive and insightful comments that greatly improved this effort.

## LITERATURE CITED

CORBETT, C. A., P. H. DOERING, K. A. MADLEY, J. A. OTT, AND D. A. TOMASKO. 2005. Issues with using seagrass as an indicator of ecosystem condition. Pp. 229–245. *In*: BORTONE, S. A. (ed.), Estuarine Indicators. CRC Press, Boca Raton, FL.

——— AND K. A. MADLEY. *In Press*. Charlotte Harbor Estuarine Complex. Pp. 283–315. *In*: WIGGINS, L. M. (ed.), Gulf of Mexico Seagrass Status and Trends. USGS Scientific Investigations Report.

DIXON, L. K. AND G. J. KIRKPATRICK. 1999. Causes of light attenuation with respect to seagrasses in upper and lower Charlotte Harbor, Report to Southwest Florida Water Management District, SWIM Program and Charlotte Harbor National Estuary Program. Available from the Southwest Florida Water Management District, SWIM Program, Tampa, FL and Charlotte Harbor National Estuary Program, Fort Myers, FL.

DOERING, P. H. AND R. H. CHAMBERLAIN. 1999. Water quality and the source of freshwater discharge to the Caloosahatchee Estuary, FL. Water Res. Bull. 35: 793–806.

HAMMETT, K. M. 1990. Land use, water use, streamflow and water quality characteristics of the Charlotte Harbor inflow area, Florida. Water Supply Paper 2359-A. Prepared in cooperation with the Florida

Department of Environmental Regulation. U.S. Geological Survey, Tallahassee, FL. Available from USGS, Tampa, FL.

HARRIS, B. A., K. D. HADDAD, K. A. STEIDINGER AND J. A. HUFF. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida, Final Report. Florida Department of Natural Resources. Available from Florida Fish and Wildlife Conservation Commission-Florida Marine Research Institute, St. Petersburg, FL.

JANICKI ENVIRONMENTAL INC. 2003. Water quality data analysis and report for the Charlotte Harbor National Estuary Program, August 27, 2003. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

KELLY, M. H. 2004. Florida river flow patterns and the Atlantic Multidecadal Oscillation. Report to the Ecological Section, Southwest Florida Water Management District. Available from the Southwest Florida Water Management District, Brooksville, FL.

KURZ, R. C., D. A. TOMASKO, D. BURDICK, T. F. RIES, K. PATTERSON, AND R. FINCK. 1999. Recent trends in seagrass distributions in southwest Florida coastal waters. Pp. 157–166. *In*: S. BORTONE (ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Marine Science Series, CRC Press, Boca Raton, FL.

———. 2002. Seagrass mapping accuracy issues. *In*: H. GREENING (ed.), Seagrass Management: It's Not Just Nutrients! 2000 Aug 22–24; St. Petersburg, FL. Available from the Tampa Bay Estuary Program, St. Petersburg, FL.

MCPHERSON, B. F. AND R. L. MILLER. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, southwestern Florida. Estuar. Coast Shelf Sci. 25: 721–737.

——— AND R. L. MILLER. 1994. Causes of light attenuation in Tampa Bay and Charlotte Harbor, southwestern Florida. Water Res. Bull. 30(1): 43–53.

MEEHAN, A. J., R. J. WILLIAMS, AND F. A. WATFORD. 2005. Detecting trends in seagrass abundance using aerial photographic interpretation: Problems arising with the evolution of mapping methods. Estuaries. 28(3): 462–472.

OTT, J. A. 2006. Florida Department of Environmental Protection-Charlotte Harbor Aquatic Preserves, Punta Gorda, FL. Pers. Commun.

ROBBINS, B. D. 1997. Quantifying temporal change in seagrass areal coverage: The use of GIS and low resolution aerial photography. Aqua. Bot. 58: 259–267.

———. 2006. Mote Marine Laboratory, Sarasota, FL. Pers. Commun.

SWFWMD. 2006. GIS Data Distribution. Southwest Florida Water Management District Website: SWIM Library of Available Seagrass GIS files and Metadata. http://www.swfwmd.state.fl.us/data/gis/libraries/swim.htm.

TOMASKO, D. A., C. A. CORBETT, H. S. GREENING, AND G. E. RAULERSON. 2005. Spatial and temporal variation in seagrass coverage in southwest Florida: Assessing the relative effects of anthropogenic nutrient load reductions and rainfall in four contiguous estuaries. Mar. Poll. Bull. 50: 797–805.

——— AND H. S. GREENING. *In Press*. Tampa Bay and Saint Joseph Sound. Pp. 246–267. *In*: WIGGINS, L. M. (ed.), Gulf of Mexico Seagrass Status and Trends. USGS Scientific Investigations Report.

——— AND M. O. HALL. 1999 Productivity and biomass of the seagrass *Thalassia testudinum* along a gradient of freshwater influence in Charlotte Harbor, Florida. Estuaries. 22(3A): 592–602.

Florida Scient. 69(00S2): 7–23. 2006
Accepted: March 10, 2006

# SEAGRASS SPECIES COMPOSITION AND DISTRIBUTION TRENDS IN RELATION TO SALINITY FLUCTUATIONS IN CHARLOTTE HARBOR, FLORIDA

Jaime M. Greenawalt-Boswell[1], Jason A. Hale[2], Katie S. Fuhr[3], and Judith A. Ott[4]

[1]Sanibel-Captiva Conservation Foundation, Marine Laboratory,
900A Tarpon Bay Rd. Sanibel, FL 33957
[2]Charlotte Harbor Environmental Center, Watershed Resource Center,
10941 Burnt Store Rd., Punta Gorda, FL 33955
[3]City of Naples, Natural Resources Division, 280 Riverside Circle, Naples, FL 34102
[4]Department of Environmental Protection, Charlotte Harbor Aquatic Preserves (CHAP),
12301 Burnt Store Rd., Punta Gorda, FL 33955

Abstract: *Seagrass species composition and distribution reflect environmental changes, making these measures potentially useful estuarine indicators. An annual seagrass transect and quadrat monitoring survey program including 50 locations in Charlotte Harbor, Florida, began in 1999. This six-year data set was analyzed in conjunction with a monthly water quality monitoring program covering the same time period to examine trends in seagrass species composition and distribution. Analyses of the maximum depth of seagrass distribution for each transect did not indicate any large-scale changes in seagrass depth distribution. This suggests a stable overall area of seagrass distribution in the Charlotte Harbor area during the study period. However, abundance of* Halodule wrightii *and* Thalassia testudinum *has significantly declined, along with the overall frequency of seagrass occurrence among quadrats. Finally, the distribution of the three dominant seagrass species,* H. wrightii, T. testudinum, *and* Syringodium filiforme, *appear to be influenced by low, wet-season salinity and high variation. This study highlights the value of research into seagrass species abundance and distribution on a meter-to-meter scale to recognize the effects of water quality or environmental variables such as salinity on a small scale, prior to large scale loss.*

*Key Words:* Salinity, salinity variability, water quality, *Syringodium filiforme*, *Thalassia testudinum*, *Halodule wrightii*, species shift

The human population in Florida is increasing rapidly, with over a five-fold rise over the fifty-year period 1950–2000 (Dawes et al., 2004). Along with this rise in population and development of the coast lines comes anthropogenic affects on the coastal estuaries. As in many other areas around the world (Short and Wyllie-Echeverria, 1996), large-scale, wide-spread seagrass losses from anthropogenic degradation of water quality have occurred along the west coast of Florida within the last century, including up to a 46% loss in Tampa Bay, and a 28% loss in Sarasota Bay (Tomasko et al., 2005).

A state-wide loss of 3 million acres, an estimated 60% of historical seagrass coverage, corresponds to this increase in Florida's population (Dawes et al., 2004). Despite this large loss of habitat, seagrass beds continue to cover a large portion of the shallow coastal zone of Southwest Florida (Tomasko et al., 2005; Corbett, 2006), providing critical habitat to fish and invertebrates (Green and Short, 2003). Moreover, seagrass beds act as sediment stabilizers (Duarte et al., 1999), are an important food source, and contribute greatly to the nutrient cycle (Phillips and Meñez, 1988) in near-shore coastal ecosystems. The importance of seagrasses to the ecological function of the coastal estuaries highlights the need to understand the factors limiting this natural resource.

Seagrass depth distribution is limited by the amount of light reaching the benthos (Duarte, 1991; Gallegos and Kenworthy, 1996), while the seagrass species composition is also strongly influenced by the long-term salinity regime (Iverson and Bittaker, 1986; Montague and Ley, 1993; Fourqurean et al., 2003). Nutrient loading, often linked to population growth and the resultant decline in water clarity, is one of the leading causes of seagrass loss worldwide (Short and Wyllie-Echeverria, 1996) by limiting the depth at which seagrasses receive adequate light for sustained growth. For example, predicted increases in nitrogen loading into the Northwest portion of Charlotte Harbor, Lemon Bay, could potentially cause a reduction in *Thalassia testudinum* (Banks ex König) depth limit by 24% by 2010 (Tomasko et al., 2001).

Such large scale losses are detectable with aerial photography used to estimate total seagrass coverage. However, maps based on aerial photographs are not sensitive enough to discriminate small scale changes in seagrass species distribution (e.g., Frazer and Hale, 2001), particularly when seagrass meadows are composed of several species, as is often the case along the west coast of Florida (Iverson and Bittaker, 1986; Staugler and Ott, 2001; Frazer and Hale, 2001; Hale et al., 2004). Seagrass species composition and percent-cover are a reflection of biotic and abiotic environmental characteristics, thus making these measures potential indicators of estuarine health (Phillips and Meñez, 1988; Fourqurean et al., 2003; Hunt and Doering, 2005). Furthermore, species-specific seagrass responses to certain water quality variables are predictable (Fourqurean et al., 2003).

Fixed transects, monitored on an annual basis, provide information on percent-cover and species composition, allowing year-to-year comparison and detection of change (e.g., Morris and Virnstein, 2004). Long-term quantitative data on species composition and percent-cover were not available for the Charlotte Harbor area prior to 1999. This paper examines seagrass species abundance, distribution, and meadow composition data collected annually over a six year period (1999–2004) in conjunction with monthly water quality data collected over the same time period. The study (a) describes trends in seagrass abundance and distribution over time, (b) defines the trends in species-specific distribution associated with specific salinity regimes, and (c) characterizes seagrass trends and salinity variability by hydrologic management regions.

MATERIALS AND METHODS—*Study site*—This study was conducted in five designated aquatic preserves of Greater Charlotte Harbor, on the Southwest coast of Florida: Lemon Bay Aquatic Preserve, Gasparilla Sound-Charlotte Harbor Aquatic Preserve, Cape Haze Aquatic Preserve, Pine Island Sound Aquatic Preserve, and Matlacha Pass Aquatic Preserve. The preserves are divided into ten hydrologic

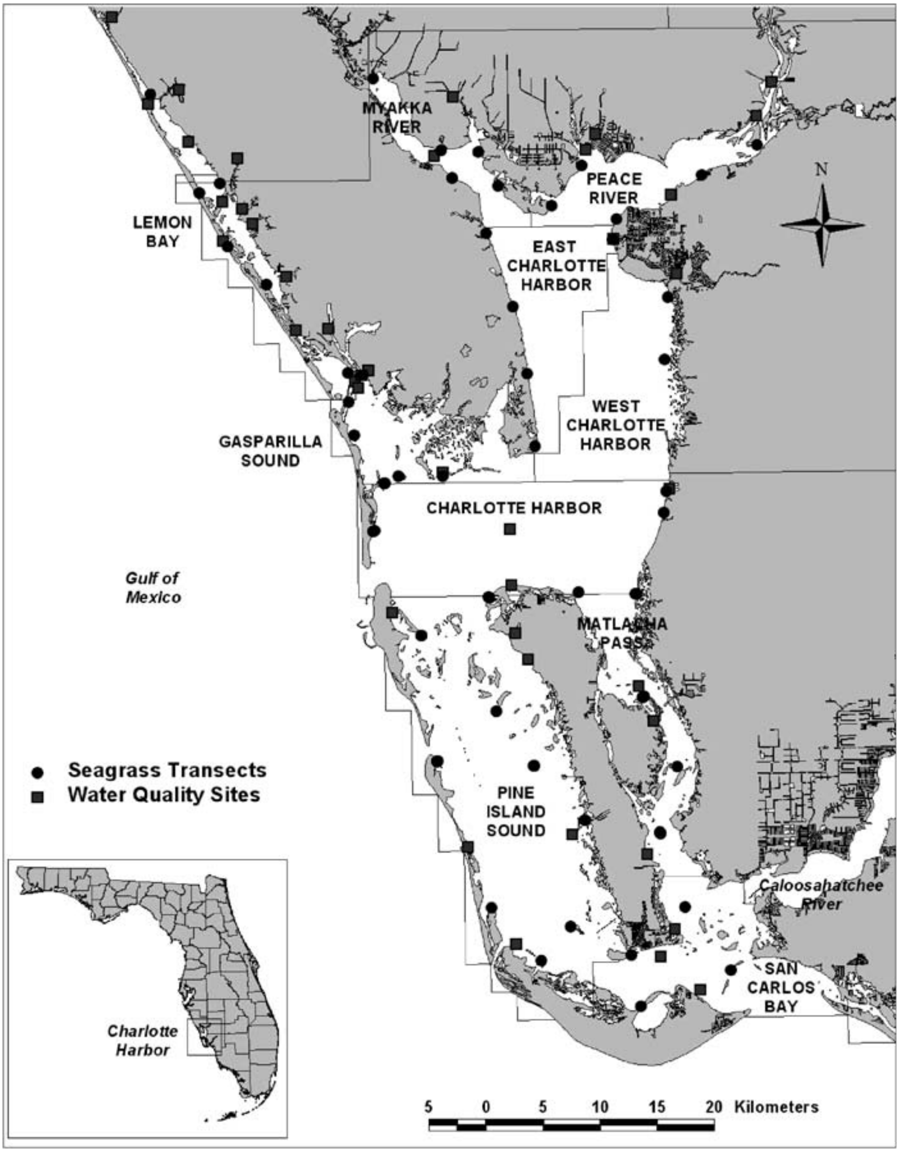



FIG. 1. Map of Greater Charlotte Harbor, on the Southwest coast of Florida, depicting water quality sites, seagrass transect sites, and hydrologic management areas of the Charlotte Harbor Aquatic Preserves.

management regions (FIG. 1). These aquatic preserves – covering more than 165,000 acres (66,773 hectares) – harbor six species of seagrass, three of which are common: *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (Kützing) (manatee grass), and *Halodule wrightii* (Ascherson) (shoal grass).

*Seagrass transects*—Transect monitoring began in 1999 and has continued to the present. Annual samplings are conducted every fall (September–December) to characterize seagrass health at the end of its growing season (Staugler and Ott, 2001). The locations of the 50 transects were chosen to reflect a variety of seagrass bed sizes and, where possible, have a steep depth gradient to facilitate determination of a distinct offshore bed edge. Transects were widely distributed to span the five designated aquatic preserves. Beginning at the near-shore bed edge, transects extend to the offshore bed edge, perpendicular to shore.

Quadrats were typically located every 50 m along transects beginning at the edge of the seagrass bed, except on relatively short transects (<50 m), where they were spaced every 10 m. In addition, quadrats were located at the end of the seagrass beds. Each year approximately 350 quadrats were surveyed among all transects. Of those sampled, 192 quadrats were sampled consistently for each year of the study period (1999–2004).

The data collected at each quadrat and used in these analyses consists of: water depth (in cm, and corrected to mean water), presence/absence of seagrass species, and a modification of the Braun-Blanquet (BB) percent-cover class estimate of abundance (Braun-Blanquet, 1965) (i.e., 0 = no vegetation, 0.1 = solitary shoot, 0.5 = <1%, 1 = 1–5%, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–100%) for each species present.

*Salinity data*—Salinity data, provided by the Charlotte Harbor Volunteer Water Quality Monitoring Network, a program initiated and supported by the CHAP since 1998, were collected on the first Monday of every month at sunrise from 36 fixed sites distributed throughout the Greater Charlotte Harbor estuaries (FIG. 1).

*Analyses*—Analyses to examine the depth of the deep edge of persistent seagrass beds, used 38 transects with abundance data collected for all years during the 1999–2004 study period. A non-parametric repeated-measures ANOVA (i.e., Friedman test) was used to test for differences in deepest depth of seagrass occurrence among years. When a significant difference among years was detected, pair-wise analyses were performed to determine if the changes were significant between consecutive years ($p < 0.05$).

Seagrass species composition and percent-cover class (BB) collected at quadrats sampled all six years ($n = 192$) were examined for annual variation by species. Only quadrats sampled all years were used in these analyses so as not to bias data. A non-parametric repeated-measures ANOVA (i.e., Friedman test) was used to test for differences in percent-cover class among years. When there were significant differences among years, pair-wise analyses were done to determine if the changes were significant between consecutive years ($p < 0.05$).

Seagrass occurrence was characterized by the number of quadrats containing a single seagrass species, a mix of multiple seagrass species, or no seagrass, and was calculated for each year of data. Regression analyses were used to determine if there was a temporal trend in the frequency of occurrence of these three categories throughout the study area. The temporal variation in seagrass species composition was examined by comparing the percent of quadrats exhibiting changes in composition among years. Hence, the types of quadrat composition change were analyzed as a change in the presence or absence of seagrass (or seagrass species), and grouped into four mutually exclusive categories: no change in composition, loss of seagrass (i.e., change from seagrass to no seagrass present), gain of seagrass (i.e., change from no seagrass to seagrass present), and species shift. These categories were used to detect patterns specific to individual hydrologic regions.

Monthly salinity averages, combining all sites throughout the Greater Charlotte Harbor study area during the study period were analyzed to determine the wettest and driest months immediately preceding the seagrass evaluation beginning in September. Salinities from the three consecutive driest months and three consecutive wettest months were averaged for each location for each year to provide estimates of the average high and low salinity values at each site throughout the study area. The average salinity for the wet months and dry months were used to represent each of the sample locations.

Salinity data from each year and from each season (wet and dry) were interpolated and contoured; salinity contour intervals were set at 1 psu. Seagrass transect locations were overlaid onto the contour shapefiles and were assigned the salinity values of the nearest contour line, providing estimates of the wet and dry-season salinity for each of the 50 seagrass transect locations for each of the six study years. The coordinates of the beginning of the transects were used to represent the transect, and corresponding quadrat locations in GIS analyses. Descriptive statistics were calculated for each of the three dominant seagrass

TABLE 1. Descriptive statistics of salinity (psu) in the ten hydrologic management areas throughout the study period (1999–2004).

| | Peace River | Myakka River | East Charlotte Harbor | West Charlotte Harbor | Charlotte Harbor | Gasparilla Sound | Lemon Bay | Matlacha Pass | Pine Island Sound | San Carlos Bay |
|---|---|---|---|---|---|---|---|---|---|---|
| N | 60 | 60 | 24 | 60 | 60 | 60 | 72 | 48 | 108 | 48 |
| Min. | 4 | 5 | 14 | 10 | 11 | 22 | 16 | 9 | 18 | 19 |
| Max. | 34 | 33 | 36 | 37 | 38 | 38 | 39 | 38 | 41 | 37 |
| Mean | 20.07 | 17.98 | 24.42 | 24.47 | 29.10 | 32.21 | 30.63 | 24.88 | 32.52 | 29.67 |
| Std. Dev | 8.68 | 9.39 | 7.63 | 7.94 | 6.82 | 4.40 | 5.79 | 7.75 | 4.51 | 5.71 |
| C.V. | 0.43 | 0.52 | 0.31 | 0.32 | 0.23 | 0.14 | 0.19 | 0.31 | 0.14 | 0.19 |

species, *Halodule wrightii*, *Thalassia testudinum*, and *Syringodium filiforme* to define the salinity in which they were found in the study area. Descriptive statistics of the salinity data were also calculated for each of the ten hydrologic management regions. Analysis of variance was used to test for significant difference in salinity among years and regions. Follow up pair-wise analyses were done using Tukey's test.

All statistics were done using Systat v 9.0, using the significance level of $\alpha = 0.05$. The GIS program ArcGIS v 9.0 (with the Spatial Analyst extension) was used for salinity interpolation, contouring, and spatial relates.

RESULTS—There were a few examples of transects in the Peace River and Myakka River hydrologic management areas where complete loss of seagrass persisted for several years. When these transects did support seagrass it was generally of less than 5% cover and consisted of one of two species: *Halodule wrightii* or *Ruppia maritima* (Linnaeus). The Peace River site furthest upstream exhibited only a single sparsely covered quadrat in 1999 and was devoid of seagrass throughout the remainder of the study period. The adjacent site, further downstream, exhibited only two quadrats with sparse abundance in 1999 and 2003. The transect furthest upstream in the Myakka River supported seagrasses in 4 of 6 years. The next transect downstream supported seagrass in all years except 2001. The Peace River and Myakka River regions had significantly lower salinities than all other regions, and the highest coefficient of variation (Table 1).

All other transects were classified as "persistent" beds, meaning they exhibited at least some seagrass cover during each sampling event. There were no significant differences in the deepest occurrence of seagrasses in persistent beds over the six-year study period.

There were significant decreases in seagrass abundances among years as measured by categorical Braun-Blanquet scores of *Halodule wrightii* and *Thalassia testudinum* (FIG. 2). Significant declines in *H. wrightii* occurred between 2000 and 2001, and between 2001 and 2002. In contrast, the decline in *T. testudinum* occurred gradually over time, with no significant differences between consecutive years, but an overall difference among years. The year of highest abundance, 2000, for all three species was also the year of highest average salinity.

There was a significant increase in the number of quadrats without seagrass, while the number of quadrats with a single species of seagrass significantly declined. The number of quadrats with more than one species remained relatively steady (FIG. 3).

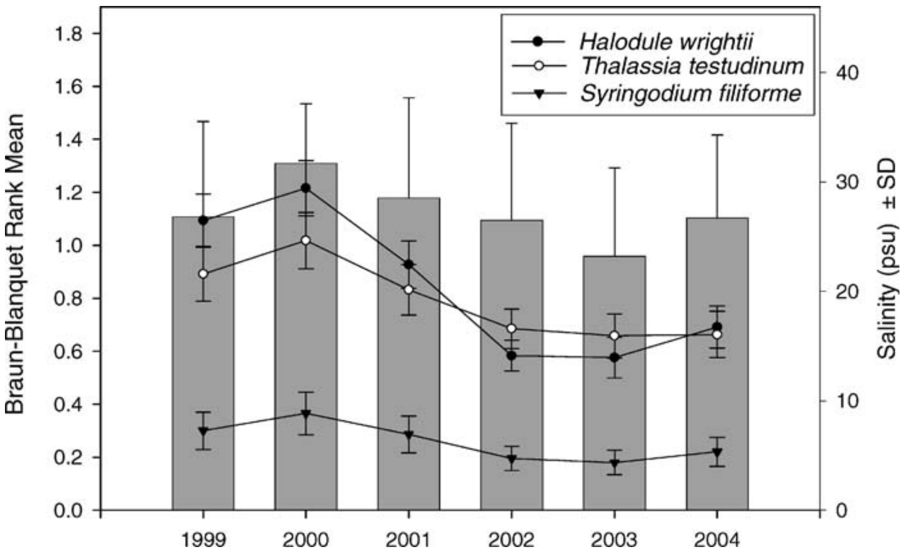



FIG. 2. The mean Braun-Blanquet percent-cover score (± standard error) for three seagrass species, and the mean salinity (± standard deviation) over the six-year study period. Salinity is represented by bars, seagrass is represented by lines.

Most quadrats (66%) did not exhibit any changes in presence, absence, or species composition between consecutive years. In fact, 55.2% of the quadrats had the same species composition in 1999 and 2004, while 23.4% of quadrats with grass lost all abundance at some point during the study, 15.1% gained grass after having none previously, and 6.3% maintained seagrass presence, but experienced a shift in species. These changes in composition were grouped by hydrologic regions (FIG. 4). The northeast portion of the study area (i.e., Peace River, Myakka River, East Charlotte Harbor, and West Charlotte Harbor) experienced a net loss of seagrass. Charlotte Harbor and Gasparilla Sound showed net increases in seagrass. Conditions in the remaining regions (i.e., Lemon Bay, Pine Island Sound, San Carlos Bay, and Matlacha Pass) remained relatively stable. In addition, seagrass stability appears to correspond to low salinity variation, while loss of seagrass corresponds to regions of high salinity variation (Table 1).

Patterns in salinity data were used to define the wet and dry month categories used for analyses (FIG. 5). The average salinity of the dry months (April, May, and June) were consistently above 25 psu. The beginning of the wet season (July, August, and September) was signified by consistently sharp declines in salinity between June and July. Although October also demonstrated low salinity values, this month was not used in analyses because it does not reflect conditions prior to seagrass data collection beginning in September. *Halodule wrightii* is the most common species in areas with the widest range of salinities, while *Syringodium filiforme* is found generally only in areas of consistently higher and less variable salinity (FIG. 6, Table 2).

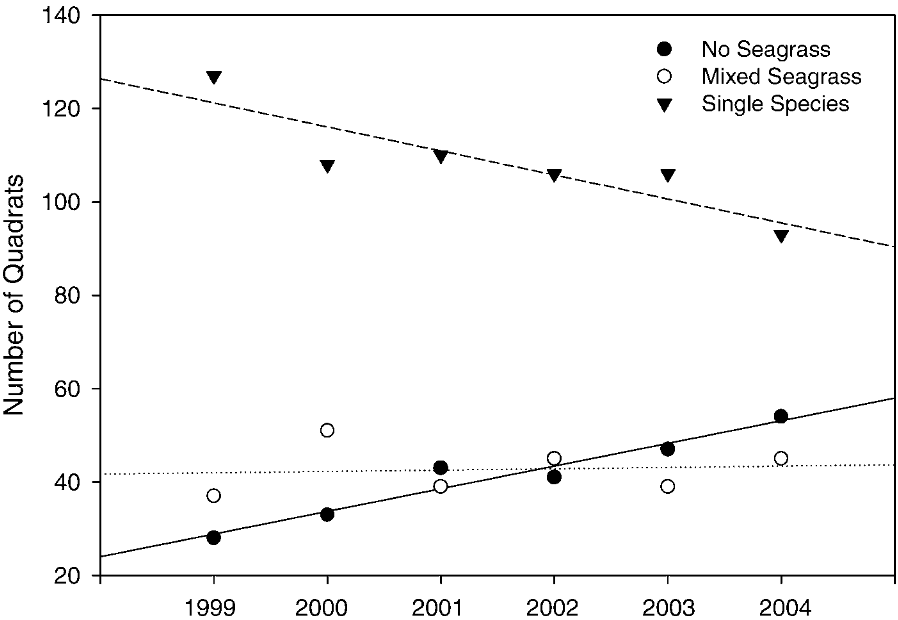



FIG. 3. Regression analyses of number of quadrats for the three categories; no seagrass, mixed seagrass, and single species over the six-year study period. Frequency of no seagrass quadrats increased significantly over time ($y = 4.86x + 24$; $R^2 = 0.93$), while frequency of single seagrass species quadrats decreased significantly over time ($y = -5.14x + 126.3$; $R^2 = 0.78$).

DISCUSSION—Transect survey and aerial survey programs were initiated in the Greater Charlotte Harbor area to detect large-scale changes in seagrass spatial distribution over time. Aerial surveys from the same region show relatively stable spatial distribution of seagrass beds since the initiation of regularly conducted surveys in the 1980s (Tomasko et al., 2005; Corbett, 2006), and analysis of maximum depth of seagrass distribution in this study found no wide-spread shifts in the Charlotte Harbor area. Thus, on a watershed scale, both methods suggest that the overall areal extent of seagrass coverage has been stable over their respective time periods. However, both surveys have identified the Peace River as an area of seagrass loss (see Corbett, 2006 for discussion).

In contrast to areal coverage and transect-level surveys, quadrat surveys were used to detect small-scale changes, such as shifts in species composition and decreasing seagrass abundance. These data suggest that there has been a significant reduction in the percent-cover of *Halodule wrightii* and *Thalassia testudinum* over the six-year study harbor wide, corresponding to salinity fluctuations over the same time period. Productivity of *T. testudinum* has been shown to be reduced significantly at salinities lower than 10 psu in the Charlotte Harbor watershed (Tomasko and Hall, 1999; Doering and Chamberlain, 2000). Growth of this species ceases at salinities at or below 6 psu, even under laboratory conditions with ample light (Doering and Chamberlain, 2000).

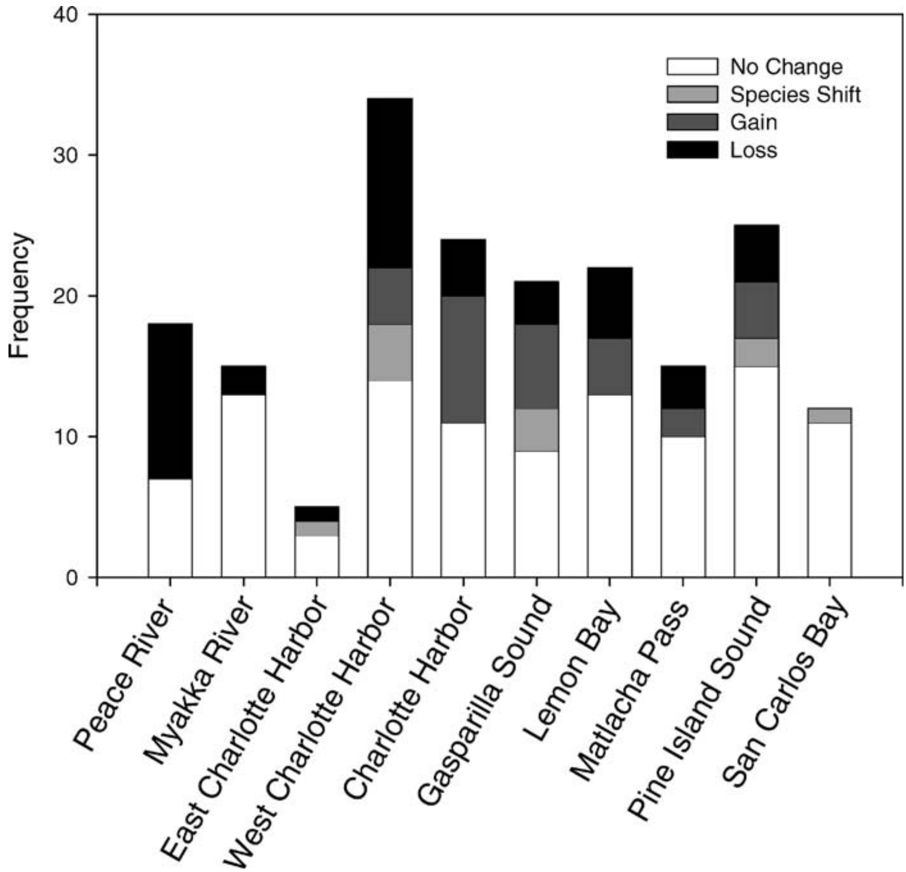



FIG. 4. Frequency of quadrats surveyed over the entire study period, exhibiting *no change, species shift, gain of seagrass,* and *loss of seagrass*, grouped by estuarine region reflecting how composition compared at the beginning and end of the study period.

Low salinities may account for some of the overall loss of seagrass on the meter scale, i.e., quadrat-to-quadrat. As the percentage of quadrats without seagrass has increased, the number of quadrats containing a single seagrass species has decreased. In contrast, multi-species quadrats show some inter-annual variability, but are generally stable over time. The types of changes vary when viewed across all ten hydrologic areas and highlight that the northeast region of the study area, which experiences high salinity variation, is the most unstable.

Numerous researchers have hypothesized a number of now familiar causes behind changes in seagrass communities. Natural weather patterns occurring across many years or decades, such as droughts and periods of above average rainfall, change estuarine salinity conditions, which in turn influence seagrass composition (Cho and Poirrier, 2005). Overloading of seagrass beds with organic matter, whether natural or anthropogenically induced, may also cause die-off as a result of sulfide

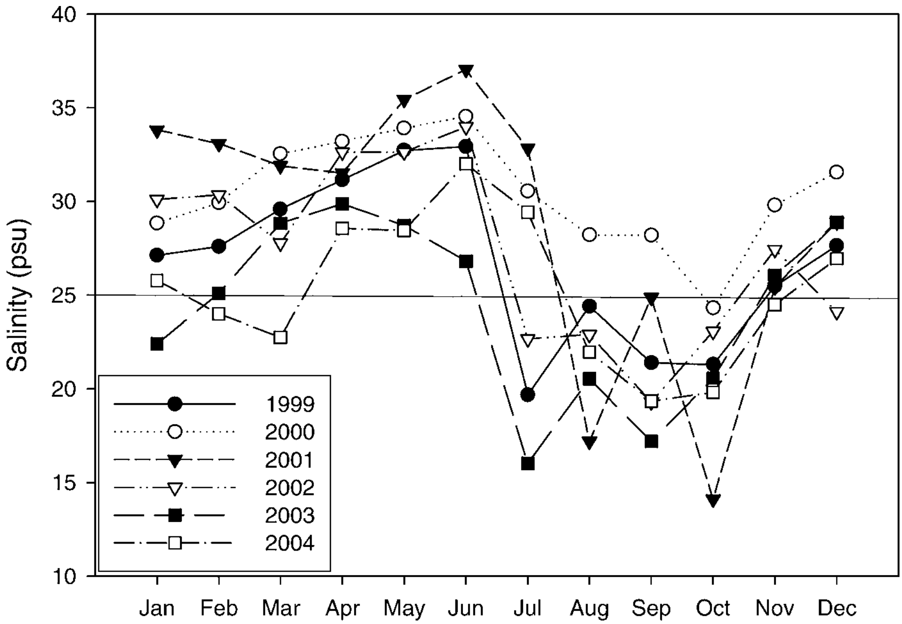



FIG. 5. Average monthly salinity throughout the year for the six-year study period.

toxicity (Morris and Virnstein, 2004). Another cause of seagrass decline may be overcrowding and stress (partially due to hyper-salinity), hypothesized to have triggered a massive seagrass die-off in Florida Bay (Zieman et al., 1999). Lastly, Hale and co-workers (2004) found that species composition changes may have been caused by widespread anthropogenic nutrient loading to the near-shore environment north of Tampa.

In many cases, the causes of seagrass loss cannot be determined, in part due to the lack of data on pre-existing conditions of seagrass and water quality. In some cases, where annual monitoring has been in place and managers have documented trends in species composition prior to seagrass loss (Morris and Virnstein, 2004), researchers were able to more thoroughly assess the causes of change.

Pairing the dependent seagrass variables from quadrat surveys with water quality is useful to describe the conditions in which each species is found within a specific estuary and will allow for future comparison. Temporally extensive water quality data, collected at least monthly, were imperative for summarizing the full range of conditions influencing seagrass composition. Numerous water quality variables influence seagrass composition and distribution (Fourqurean et al., 2003). Spatially and temporally explicit environmental data are essential to determine possible causes of change within seagrass beds.

We chose characteristics of the salinity regime for analysis because of the repeated examples of salinity minimum, range, or variability influencing the abundance and distribution of seagrass species (Montague and Ley, 1993; Tomasko and Hall, 1999; Ziemann et al., 1999; Cho and Poirrier, 2005). Salinity (<20 psu)

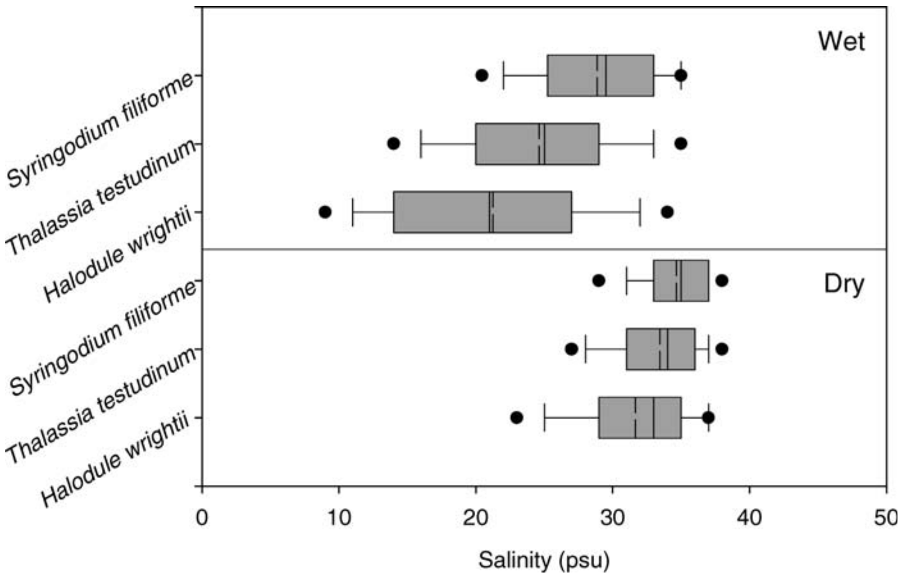



FIG. 6. Box and whisker plots depicting the mean ( - ), median (- -), 75th percentile, and 95th percentile of salinity during the wet and dry seasons at sites where each of the respective seagrass species were found.

has been positively correlated with water clarity in the northeast portion of our study area (Tomasko and Hall, 1999) and negatively correlated with dissolved matter, one of the contributing factors to light attenuation throughout the study area (McPherson and Miller, 1987). Therefore, although other water quality factors (e.g., color, turbidity, and nutrients) were not considered in these analyses, salinity is used as a proxy for the influence of freshwater flow.

Montague and Ley (1993) also reported relationships between seagrass abundance and variability in salinity, and noted changes in species dominance in areas with high salinity variability. Similarly, the results of our study help define the effects that changes in freshwater flow have on seagrass species composition. For

TABLE 2. Descriptive statistics of salinity (psu) during the wet and dry seasons at quadrats containing each species of seagrass.

| | *Halodule wrightii* | | *Syringodium filiforme* | | *Thalassia testudinum* | |
|---|---|---|---|---|---|---|
| | Dry Season Salinity | Wet Season Salinity | Dry Season Salinity | Wet Season Salinity | Dry Season Salinity | Wet Season Salinity |
| N | 1228 | 1228 | 208 | 208 | 699 | 699 |
| Mean | 31.60 | 21.20 | 34.70 | 28.90 | 33.40 | 24.60 |
| Std. Error | 0.12 | 0.23 | 0.19 | 0.32 | 0.13 | 0.23 |
| Std. Dev | 4.48 | 7.94 | 2.72 | 4.67 | 3.48 | 6.14 |
| C.V. | 0.14 | 0.37 | 0.08 | 0.16 | 0.10 | 0.25 |

example, if salinity means or variation changes to the extent that a certain species or percent-cover of seagrass cannot be supported, one of three outcomes may be hypothesized: a shift in dominant species, a decrease in percent-cover, or coverage may be lost altogether. The results presented here demonstrate less stability and lower species diversity in hydrologic regions with highly variable salinity regimes (e.g., Peace River and Myakka River). This study, along with a study by Fourqurean and co-workers (2003) in Florida Bay, demonstrates the wider salinity tolerance of *Halodule wrightii* as compared to the other two dominant seagrass species (i.e., *Thalassia testudinum* and *Syringodium filiforme*). We therefore hypothesize that altered flow leading to higher than normal salinity variation will lead to an overall decline in seagrass abundance and diversity, with a community predominantly composed of *H. wrightii*.

Seagrass species composition and distribution data, collected through transect and quadrat monitoring, have unique and complimentary uses, especially when analyzed in conjunction with one another and with water quality data. Such analyses allow a fuller interpretation of trends on several spatial scales, and can provide an enhanced understanding of estuarine processes. While the Greater Charlotte Harbor estuaries generally show stability in the overall area of seagrass coverage, there is significant thinning and localized loss of single species at the quadrat level of analysis.

ACKNOWLEDGMENTS—The authors thank two anonymous reviewers, the editors of this special addition, and Dr. Steve Bortone, Dr. Rick Bartleson, and Michael Hannan of the Sanibel-Captiva Conservation Foundation for critical review of the manuscript. We also thank the numerous volunteers and employees of the Florida Department of Environmental Protection who contributed time and effort to the seagrass and water quality data collection. Funding for the data collection was provided by the Florida Department of Environmental Protection, funding for analyses was provided by the Sanibel-Captiva Conservation Foundation, and the Charlotte Harbor Environmental Center.

## LITERATURE CITED

BRAUN-BLANQUET, J. 1965. Plant sociology: the study of plant communities. Authorized english translation of Pflanzensoziologie 1932. Translated, revised, and edited by George D. Fuller and Henry S. Conard, 1st ed. McGraw-Hill, New York, NY.

CHO, H. J. AND M. A. POIRRIER. 2005. Response of submersed aquatic vegetation (SAV) in Lake Pontchartrain, Louisiana to the 1997–2001 El Niño southern oscillation shifts. Estuaries. 28(2):215–225.

CORBETT, C. A. 2006. Seagrass coverage changes in Charlotte Harbor, FL. Florida Scient. 69 (00S2): 7–23.

DAWES, C. J., R. C. PHILLIPS, AND G. MORRISON. 2004. Seagrass Communities of the Gulf Coast of Florida: Status and Ecology. Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute and the Tampa Bay Estuary Program, Available from Tampa Bay Estuary Program, St. Petersburg, FL.

DOERING, P. H. AND R. H. CHAMBERLAIN. 2000. Experimental studies on the salinity tolerance of turtle grass, *Thalassia testudinum*. Pp. 81–98. *In*: BORTONE, S. A. (ed.), Seagrasses: Monitoring, Ecology, Phyiology, and Management. CRC Press, Boca Raton, FL.

DUARTE, C. M. 1991. Seagrass depth limits. Aquat. Bot. 40:363–377.

———, E. BENAVENT, AND M. DEL CARMEN SÁNCHEZ. 1999. The microcosm of particles within seagrass *Posidonia oceanica* canopies. Mar. Ecol. Prog. Ser. 181:289–295.

FOURQUREAN, J. W., J. N. BOYER, M. J. DURAKO, L. N. HEFTY, AND B. J. PETERSON. 2003. Forecasting responses of seagrass distributions to changing water quality using monitoring data. Ecol. Appl. 13(2):474–489.

FRAZER, T. K. AND J. A. HALE. 2001. Changes in the abundance and distribution of submersed aquatic vegetation along Florida's Springs Coast: 1992–1999. Final Report. Southwest Florida Water Management District, Available from Southwest Florida Water Management District, Surface Water Improvement and Management Program, Tampa, Florida.

GALLEGOS, C. L. AND W. J. KENWORTHY. 1996. Seagrass depth limits in the Indian River Lagoon (Florida, U.S.A.): Application of an optical water quality model. Estuar. Coast. Shelf S. 42, 267–288.

GREEN, E. P. AND F. T. SHORT. 2003. World Atlas of Seagrasses. Univ. California Press, Berkeley and Los Angeles, CA.

HALE, J. A., T. K. FRAZER, D. A. TOMASKO, AND M. O. HALL. 2004. Changes in the distribution of seagrass species along Florida's central Gulf Coast–Iverson and Bittaker revisited. Estuaries. 27(1):36–43.

HUNT, M. J. AND P. H. DOERING. 2005. Significance of considering multiple environmental variables when using habitat as an indicator of estuarine condition. Pp. 211–227. *In*: BORTONE, S. A. (ed.), Estuarine Indicators. CRC Press, Boca Raton, FL.

IVERSON, R. L. AND H. F. BITTAKER. 1986. Seagrass distribution and abundance in Eastern Gulf of Mexico coastal waters. Estuar. Coast. Shelf S. 22:577–602.

MCPHERSON, B. F. AND R. L. MILLER. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, South-western Florida. Estuar. Coast. Shelf S. 25:721–737.

MONTAGUE, C. L. AND J. A. LEY. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in northeastern Florida Bay. Estuaries. 16(4):703–717.

MORRIS, L. J. AND R. W. VIRNSTEIN. 2004. The demise and recovery of seagrass in the Northern Indian River Lagoon, FL. Estuaries. 27(6):915–922.

PHILLIPS, R. C. AND E. G. MEÑEZ. 1988. Seagrasses. Smithsonian Contributions to the Marine Sciences No. 34. Smithsonian Institution Press, Washington, D.C.

SHORT, F. T. AND S. WYLLIE-ECHEVERRIA. 1996. Natural and human-induced disturbance of seagrasses. Environ. Conserv. 23(1):17–27.

STAUGLER, E. AND J. OTT. 2001. Establishing Baseline Seagrass Health Using Fixed Transects in Charlotte Harbor, FL. Technical report (1). Florida Department of Environmental Protection Charlotte Harbor Aquatic Preserves, Available from the Florida Department of Environmental Protection, Punta Gorda, FL.

TOMASKO, D. A., C. A. CORBETT, H. S. GREENING, AND G. E. RAULERSON. 2005. Spatial and temporal variation in seagrass coverage in Southwest Florida: assessing the relative effects of anthropogenic nutrient load reductions and rainfall in four contiguous estuaries. Mar. Poll. Bull. 50(2005): 797–805.

———, D. L. BRISTOL, AND J. A. OTT. 2001. Assessment of present and future nitrogen loads, water quality, and seagrass (*Thalassia testudinum*) depth distribution in Lemon Bay, Florida. Estuaries. 24(6A):926–938.

——— AND M. O. HALL. 1999. Productivity and biomass of the seagrass *Thalassia testudinum* along a gradient of freshwater influence in Charlotte Harbor, Florida. Estuaries. 22(3A):592–602.

ZIEMAN, J. C., J. W. FOURQUREAN, AND T. A. FRANKOVICH. 1999. Seagrass die-off in Florida Bay: Long-term trends in Abundance and growth of turtle grass, *Thalassia testudinum*. Estuaries. 22(2B):460–470.

Florida Scient. 69(00S2): 24–35. 2006
Accepted: March 10, 2006

*Biological Sciences*

# DEVELOPMENT OF WATER QUALITY TARGETS FOR CHARLOTTE HARBOR, FLORIDA USING SEAGRASS LIGHT REQUIREMENTS

CATHERINE A. CORBETT[1] AND JASON A. HALE[2]

[1]Charlotte Harbor National Estuary Program, Fort Myers, FL
[2]Charlotte Harbor Environmental Center, Punta Gorda, FL

ABSTRACT: *Owing to the catastrophic loss of seagrasses after the 1950s, resource managers in several southern Florida estuaries established water clarity targets to restore seagrass coverage to historical conditions or maintain existing coverage. Recently, analyses of water quality data suggest declining water clarity in some areas of Charlotte Harbor, which may lead to the dramatic impacts to seagrass ecosystems similar to those in other estuaries in Florida. Therefore, resource management strategies for Charlotte Harbor should consider minimum water clarity standards to conserve seagrass resources for the future. This effort provides an optical model to set water quality targets for color, turbidity and chlorophyll* a *that maintain percent-light-at-depth requirements to achieve the maximum seagrass depth distribution presently observed in seagrass transect monitoring. Analysis of recently-collected water quality data show that in all regions of the harbor, dry season water quality in general met the percent-light-at-depth goals proposed in this effort but less than half the data met the goals during the wet season. The methods proposed here can be refined to better incorporate seasonal and spatial changes in water clarity variables but are an important first step in establishing resource-based water quality targets for the Charlotte Harbor region.*

*Key Words:* Charlotte Harbor, seagrass, water clarity, estuaries, optical model, chlorophyll, TSS, turbidity, color, light attenuation

IN southwest Florida, substantial research and restoration efforts have focused on seagrass meadows as an environmental indicator for coastal environmental conditions. Charlotte Harbor, FL is contiguous to the northwest with Lemon, Sarasota and Tampa Bays where seagrass management strategies focus on nutrient load and phytoplankton concentration reductions. Charlotte Harbor confronts different issues, and phytoplankton concentrations do not have as large an influence on light attenuation in Charlotte Harbor as dissolved and suspended matter (McPherson and Miller 1987; Dixon and Kirkpatrick 1999). Also, analyses of seagrass coverage data demonstrate that seagrass coverage in Upper Charlotte Harbor is stable since 1988 (Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett, 2006). Seagrass management strategies in the Charlotte Harbor region have not focused on nutrient load reductions, and currently, resource managers have not established restoration goals for seagrass coverage.

In Tampa Bay, where historical losses have been linked to both direct and indirect impacts, resource managers have set goals for restoring seagrass coverage to approximately ninety-five percent of the coverage present in 1950. Reductions in nitrogen loads since 1982 have led to reduced phytoplankton concentrations and increased water clarity, a cascade of effects which has allowed increases in seagrass extent (Johansson, 1991; Johansson and Ries, 1997; Lewis et al., 1998; Johansson and Greening, 1999). Increases in seagrass coverage is also a restoration objective for seagrass managers in Sarasota Bay, where recent increases (1988–1996) may be linked to decreased nitrogen loads to the bay by the City of Sarasota and Manatee and Sarasota counties (Kurz et al., 1999). In both Tampa and Sarasota Bays, water clarity and quantity of light reaching the tops of seagrass blades is related to nitrogen loading and its effects on phytoplankton populations (cited in Tomasko et al., 2005); thus, seagrass restoration strategies in these areas have focused on nitrogen load reductions.

Lemon Bay, a comparatively small estuary that connects Sarasota Bay to the north to the Venice inlet and Charlotte Harbor in the south, is included within the larger Charlotte Harbor estuarine complex. It is very similar to Tampa and Sarasota Bays in that its water clarity is strongly tied to phytoplankton levels and nitrogen loads (Tomasko et al., 2001). Phytoplankton biomass was calculated to contribute 12 to 39% of light attenuation within the water column with a mean percent of 29%, and depth distribution of seagrasses in Lemon Bay is largely a factor of chlorophyll *a* concentrations (Tomasko et al., 2001). Seagrass mapping efforts have not documented trends in seagrass coverage in Lemon Bay since 1988 (Tomasko et al., 2001; Tomasko et al., 2005). Nonetheless, estimated nitrogen loads to the bay have increased an estimated 59% from historical levels and are expected to increase further with future urbanization (Tomasko et al., 2001; Tomasko et al., 2005). Thus, seagrass management strategies within Lemon Bay region also focus on nutrient load reductions.

South of Lemon and Sarasota Bays along the southwest Florida coast lies the Charlotte Harbor estuarine complex, which includes a number of interconnected estuaries. The Charlotte Harbor watershed extends approximately 210 km (130 mi) from its northern headwaters of the Peace River to southern Estero Bay, and three large rivers, the Peace, Myakka and Caloosahatchee Rivers are the major sources of freshwater (Hammett, 1990). Relative to Tampa, Sarasota and Lemon Bays to its northwest, Charlotte Harbor is strongly influenced by the freshwater inflows from its large watershed. One result of this large watershed is that the water clarity of the harbor is greatly influenced by dissolved and suspended matter from the watershed, as opposed to the dominant influence of phytoplankton found in Tampa and Lemon Bays. Using data collected in Charlotte Harbor, McPherson and Miller (1987) found that non-chlorophyll suspended matter (including detritus, cellular material and minerals) accounts for an average of 72% of light attenuation in the water column, color (dissolved organic matter) accounts for 21% and phytoplankton chlorophyll for only 4%. Dixon and Kirkpatrick (1999) found that color, turbidity and chlorophyll accounted for 66%, 31% and 4% of light attenuation. Hence, there are clear differences in the components of water column light attenuation between Charlotte Harbor and Tampa Bay.

Six species of seagrass are found within the Charlotte Harbor region: *Halodule wrightii* (Ascherson), *Thalassia testudinum* (Banks ex König), *Syringodium filiforme* (Kützing), *Halophila englemanni* (Ascherson), *Halophila decipiens*

(Ostenfeld) and *Ruppia maritima* (Linnaeus). Harris and co-workers (1983) documented a 29% harbor-wide decrease in seagrass coverage from 1940s to 1982 and postulated some of this loss resulted from seagrasses receding from deeper depths because of decreasing water clarity resulting from hydrologic changes and increased pollutant loads. From 1982 to 1999, Charlotte Harbor as a whole demonstrated a 6% decrease in seagrass extent, with 77% of that loss located in the Lower Charlotte Harbor region (Corbett et al., 2005). Subsequently, from 1999 to 2003 seagrass areal extent displayed increases in the Lower Charlotte Harbor region, and no significant trend was found in the Upper Charlotte Harbor region since 1982 (Corbett, 2006). However, analyses of water quality data demonstrate significant increases in total suspended solids in the Lower Charlotte Harbor and Upper Charlotte Harbor regions and increasing turbidity and nutrients in the Lower Charlotte Harbor region (Janicki Environmental Inc., 2003). Thus, resource management strategies in this area may need to focus on the long-term maintenance of seagrass coverage. This study presents an optical model which can be used to establish water clarity goals to maintain percent-light-at-depth requirements to achieve seagrass maximum depth distribution by segment within the Charlotte Harbor estuarine complex. The water clarity goals proposed in this effort are meant to maintain the present seagrass coverage and depth distribution into the future.

METHODS—The Florida Fish and Wildlife Conservation Commission-Fisheries Independent Monitoring Program and the Coastal Charlotte Harbor Monitoring Network divide Charlotte Harbor into 12 hydrologic segments for their fisheries and water quality sampling programs (FIG. 1). Using the methodology described below, we developed water quality goals specific for each segment.

*Maximum depth of seagrass distribution*—We calculated the annual mean maximum depth distribution of seagrass per segment based on the results of 50 fixed-transects monitored throughout Charlotte Harbor and Lemon Bay since 1999 and 5 additional transects in Estero Bay started in 2002. Each transect consists of a fixed line, determined by a compass heading and marked with PVC stakes, extending from the shoreward seagrass edge out to the deep edge of the meadow where seagrass was sparse or no longer existent. Program researchers collect depth measurements, seagrass species abundance (Braun-Blanquet cover scale [Braun-Blanquet, 1965]), blade length, sediment type and epiphyte coverage and type at 50-meter intervals along each transect (or 10-meter intervals for transects shorter than 50 m) from shore to edge of bed (Staugler and Ott, 2001). Depth measurements are adjusted to mean water depth by adjusting the tide level observed in the field to mean water based on the 12 National Oceanographic and Atmospheric Administration (NOAA) tide stations located throughout the study area (Staugler and Ott, 2001). There are several transects for each segment; we used the greatest value of the segment's mean maximum depths by year for 1999–2004 or 2002–2005 as the target depth. There were no comparable transect data for the Tidal Caloosahatchee River segment, so we used a goal of 1 meter based upon vertical scan hydro-acoustic research by Chamberlain (2005).

*Percent light at depth*—Using published analyses, we estimated percent-light-at-depth targets required to achieve the estimated seagrass maximum depth distribution in each segment. Numerous estimates for percent-light-at-depth requirements of seagrass exist, and depending on the species composition of a bed, these estimates indicate a wide range of surface irradiance requirements reaching the deep edge of grass beds. For instance, Gallegos and Kenworthy (1996) cite a general range of 10–30% for efforts documenting requirements of seagrass in other estuaries and 23–37% in Indian River Lagoon, Florida for *H. wrightii* and *S. filiforme*, specifically. Grasses in Charlotte Harbor require between 15–30% photosynthetically active radiation (PAR) penetrating to depth (Dixon, 2000).

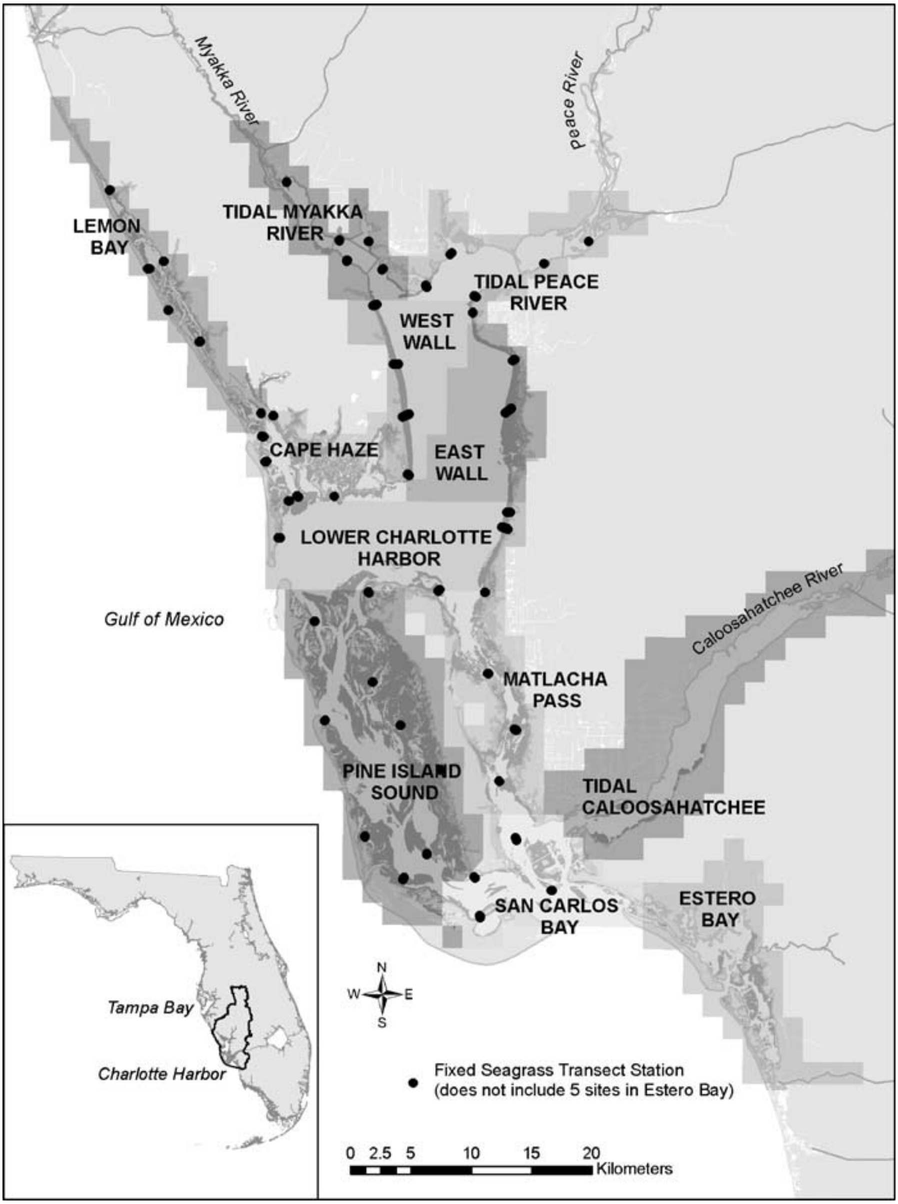



FIG. 1. Charlotte Harbor Segments and Seagrass Transect Monitoring Stations, excluding Estero Bay stations.

Tomasko and Hall (1999) found an average 23% subsurface irradiance reaching all study sites but documented declines in productivity of *T. testudinum* during the study period. Of the species of seagrass in Charlotte Harbor, *T. testudinum* may have the highest light requirements. Greenawalt (2005) determined that *S. filiforme* is found in areas with generally lower percent light at depth than *H. wrightii* and *T. testudinum*, while Chamberlain theorizes that *H. wrightii* extends deeper and is found in areas with lower light conditions than *T. testudinum* (Chamberlain, 2005). We propose a percent-light-at-depth goal of 25% subsurface irradiance, which is on the high end of the estimate in Dixon (2000), an estimate specific to Charlotte Harbor, and higher than the annual average found in Tomasko and Hall (1999).

*Light attenuation coefficient*—To calculate a water clarity target, we used the Lambert-Beer Law:

$$\%\ \text{light at depth}/100 = e^{-k^*z} \tag{1}$$

where the percent light at depth is the estimated minimum amount of subsurface incident light required by seagrasses, *e* is the base of the natural logarithm, k is the light attenuation coefficient (in m-1), and z equals the measured or estimated deep edge depth of seagrass distribution in meters. To use an example of the San Carlos Bay segment in the Lower Charlotte Harbor region (Table 2), inserting a percent-light-at-depth target of 25% PAR and depth of 2.21 meters, we get the following equation:

$$0.25 = e^{-k^*2.21} \tag{1a}$$

$$\ln(0.25) = \ln(e^{-k^*2.21}) \tag{1b}$$

$$-1.4 = -k^*2.21 \tag{1c}$$

$$k = 0.63$$

*Partial contributions to light attenuation*—Light attenuation in the water column is caused by scattering and absorption of light by water quality constituents (Kirk, 1983). For management purposes, light requirements of grass beds can be translated into concentrations of these constituents that meet the specified light availability target (Gallegos and Kenworthy, 1996). To do this, we adapted an optical model derived by McPherson and Miller (1994: eq. 8) which describes total light attenuation as the sum of three partial light attenuation components: color, chlorophyll *a* and turbidity:

$$K_d = 0.014^*C_2 + 0.062^*C_3 + 0.049^*C_4 + 0.30 \tag{2}$$

Where $K_d$ equals the light extinction coefficient at depth, $C_2$ is water color in Pt-Co units, $C_3$ is turbidity in NTU and $C_4$ is chlorophyll *a* in micrograms per liter. The chlorophyll *a* coefficient was derived from measurements using a fluorometric detector (see McPherson and Miller (1994) for complete discussion).

To determine the maximum concentration of each partial light attenuation component that meets a given rate of light attenuation (calculated from the percent-light-at-depth target), set two components to zero and solve for the third, color in this case:

$$0.63 = 0.014^*C_2 + 0.062^*(0) + 0.049^*(0) + 0.30 \tag{2a}$$

$$0.33 = 0.014^*C_2 \tag{2b}$$

$$C_2 = 24\ \text{Pt-Co}$$

*Line of constant attenuation*—To demonstrate the use of this method in describing water clarity with respect to seagrass depth limits, we compared the constants calculated above to seasonal water quality data collected for the coastal Charlotte Harbor and Lemon Bay regions, with these "targets" overlaid. This produced a line of constant attenuation for variable concentrations of the water quality parameters, given our percent-light-at-depth goal. Water quality data points located above this line identify instances when water clarity did not meet the projected targets.

Monthly water quality data from surface water samples collected between 2002 to 2005 were provided by the Coastal Charlotte Harbor Monitoring Network for 12 segments (Table 1). Additional monthly water quality data were provided by Lee County for the Pine Island Sound, Matlacha Pass, San Carlos Bay, Caloosahatchee River and Estero Bay segments as there was a shorter period of record for these areas using only the Coastal Charlotte Harbor Monitoring Network data. All data were divided into "wet" and "dry" seasons, defined as data collected during the months of July–October and November–June, respectively. Salinity data analyses support this delineation (see Greenawalt et al., 2006).

TABLE 1. Water quality data period of record by region.

| Segment | Period of Record |
|---|---|
| Lemon Bay | 11/02–6/05 |
| Cape Haze | 11/02–6/05 |
| West Wall | 11/02–6/05 |
| East Wall | 11/02–6/05 |
| Tidal Peace River | 11/02–6/05 |
| Tidal Myakka River | 11/02–6/05 |
| Lower Charlotte Harbor | 4/02–12/04 |
| Matlacha Pass | 3/02–10/04 |
| San Carlos Bay | 3/02–10/04 |
| Pine Island Sound | 5/03–10/04 |
| Estero Bay | 4/03–10/04 |
| Tidal Caloosahatchee River | 1/04–12/05 |

*Nomographs*—Lastly, for comparison purposes we plotted chlorophyll *a* and turbidity concentration goals for specified depths and color values in terms of optical depth, k-z. In this step, we defined our 25% subsurface irradiance objective as our target optical depth of 1.4 (see *Light Attenuation Coefficient* section above). This allowed us to use any combination of depth (z) and attenuation coefficient (k) that equaled 1.4 (e.g., $k = 0.7$ and $z = 2$ m) to derive multiple lines of constant attenuation.

For the selected optical depths, 0.5, 0.75, 1.0, 1.5, 2.0 and 2.5, we plotted our target chlorophyll *a* and turbidity concentrations, given a range of color values in 10-step increments. This process allows one to determine a combination of the maximum color and chlorophyll *a* or color and turbidity concentrations for a depth of interest that meets our minimum light objective. Similar plots of turbidity and color given a specified range of chlorophyll *a* concentrations or chlorophyll *a* and color given a specified turbidity range could also be developed.

RESULTS—Target seagrass bed depths by segment are shown in Table 2 and range from 0.81 meters in the Tidal Peace segment to 2.21 meters in the San Carlos Bay segment. These goals reflect current maximum depth distributions by segment.

"Target" concentrations for partial light attenuation coefficients for each segment are also shown in Table 2. Maximum turbidity "targets" range from 5 NTU to 23 NTU, while chlorophyll *a* maximums range from 7 μg/L to 29 μg/L.

A comparison of wet and dry season water quality data from the Lower Charlotte Harbor segment suggests how water quality parameters differ by season. Generally, most data points fall within the line of constant attenuation and, in turn, meet or exceed required goals to produce minimum water clarity for each pair of parameters in the dry season, November through June (FIG. 2). In contrast, approximately half of the data collected during the wet season fall outside the line of constant attenuation and would not meet minimum water clarity goals to provide 25% subsurface irradiance at the target maximum seagrass depth distribution for this segment (FIG. 3). Similar results were found for the other 11 segments as well.

Nomographs of chlorophyll *a* and color as well as turbidity and color demonstrate that as color values rise, the concentrations of the other partial constituents must simultaneously decrease to meet our optical depth goal (FIGS. 5 and 6). The graphs also demonstrate that as depths increase from 0.5 to 2.5, the concentrations of all 3 partial constituents must then decrease. It follows then that

TABLE 2. Mean maximum seagrass depth distribution and water clarity constants by region. Stars represent target seagrass depths. Extinction coefficients ($K_d$) were determined using the 25% subsurface irradiance goal and the target maximum grass bed depth by region. Each partial attenuation component was then determined by setting the other 2 components to zero and using the optical model equation derived by McPherson and Miller (1994).

| | Mean Maximum Depth by Year | | | | | | | | Maximum Color | Maximum Turbidity | Maximum Chlorophyll |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | $K_d$ | (Pt-Co) | (NTU) | *a* (µg/L) |
| Lemon Bay | 1.44 | 1.57 | 1.51 | 1.38 | 1.85* | 1.56 | | 0.75 | 32 | 7 | 9 |
| Cape Haze | 1.48 | 1.67 | 1.63 | 1.78 | 1.6 | 1.83* | | 0.76 | 33 | 7 | 9 |
| Lower Charlotte Harbor | 1.51* | 1.41 | 1.07 | 1.13 | 1.3 | 1.3 | | 0.92 | 44 | 10 | 13 |
| West Wall | 1.13 | 1.41* | 1.2 | 1.36 | 0.92 | 1.41* | | 0.98 | 49 | 11 | 14 |
| East Wall | 1.08 | 1.21 | 0.97 | 1.26 | 1.3* | 1.12 | | 1.07 | 55 | 12 | 16 |
| Tidal Myakka | 0.88* | 0.85 | 0.55 | 0.83 | 0.62 | 0.79 | | 1.58 | 91 | 21 | 26 |
| Tidal Peace | 0.81* | 0.79 | 0.77 | 0.74 | 0.79 | 0.73 | | 1.71 | 101 | 23 | 29 |
| Pine Island Sound | 1.71 | 1.63 | 1.58 | 1.56 | 1.69 | 1.82* | | 0.76 | 33 | 7 | 9 |
| Matlacha Pass | 1.03 | 1.46* | 1.22 | 1.34 | 1.12 | 1.35 | | 0.95 | 46 | 10 | 13 |
| San Carlos Bay | 1.7 | 1.64 | 1.74 | 1.87 | 2.07 | 2.21* | | 0.63 | 24 | 5 | 7 |
| Estero Bay | | | | 1.01 | 1.03* | 1.03* | 0.84 | 1.35 | 75 | 17 | 21 |
| Tidal Caloosahatchee | | | | 1.00* | | | | 1.39 | 78 | 18 | 22 |

the deeper our depth target, the lower the target concentrations of the partial attenuation constituents must be to meet our light goal.

DISCUSSION—Immediately visible from the "targets" listed in Table 2 are that some of these constants are relatively high. For instance, the chlorophyll *a* values for 6 segments are higher than the Florida water quality standards for chlorophyll *a* of 11 µg/L for marine and estuarine waters. These constants are the maximum potential concentration of the analytes and are acceptable for meeting the percent-light-at-depth goal only when the concentrations for both the other 2 analytes are zero, an unlikely situation except when color is sufficiently high to limit phytoplankton production. Excepting those periods when chlorophyll *a* concentrations are very low due to high color concentrations, the concentrations for all 3 light attenuation components will be greater than zero, thereby requiring concentrations of all 3 components to be less than these maximums to maintain the percent-light-at-depth goal. The "targets" are a necessary step in developing the resulting line of constant attenuation, which denotes the acceptable concentration of a component of light attenuation in relation to the concentrations of the other components. This line allows the concentration for each component to assume any concentration between zero and its target maximum; its value dependent on the concentrations of the other 2 components. This objective is in contrast to many water quality targets that set a discrete maximum for each specific analyte without regard to concentrations of other relevant constituents affecting the targeted outcome.

The results from plotting the derived lines of constant attenuation over water quality data collected in the recent past (i.e., between 2002 and 2005) show that

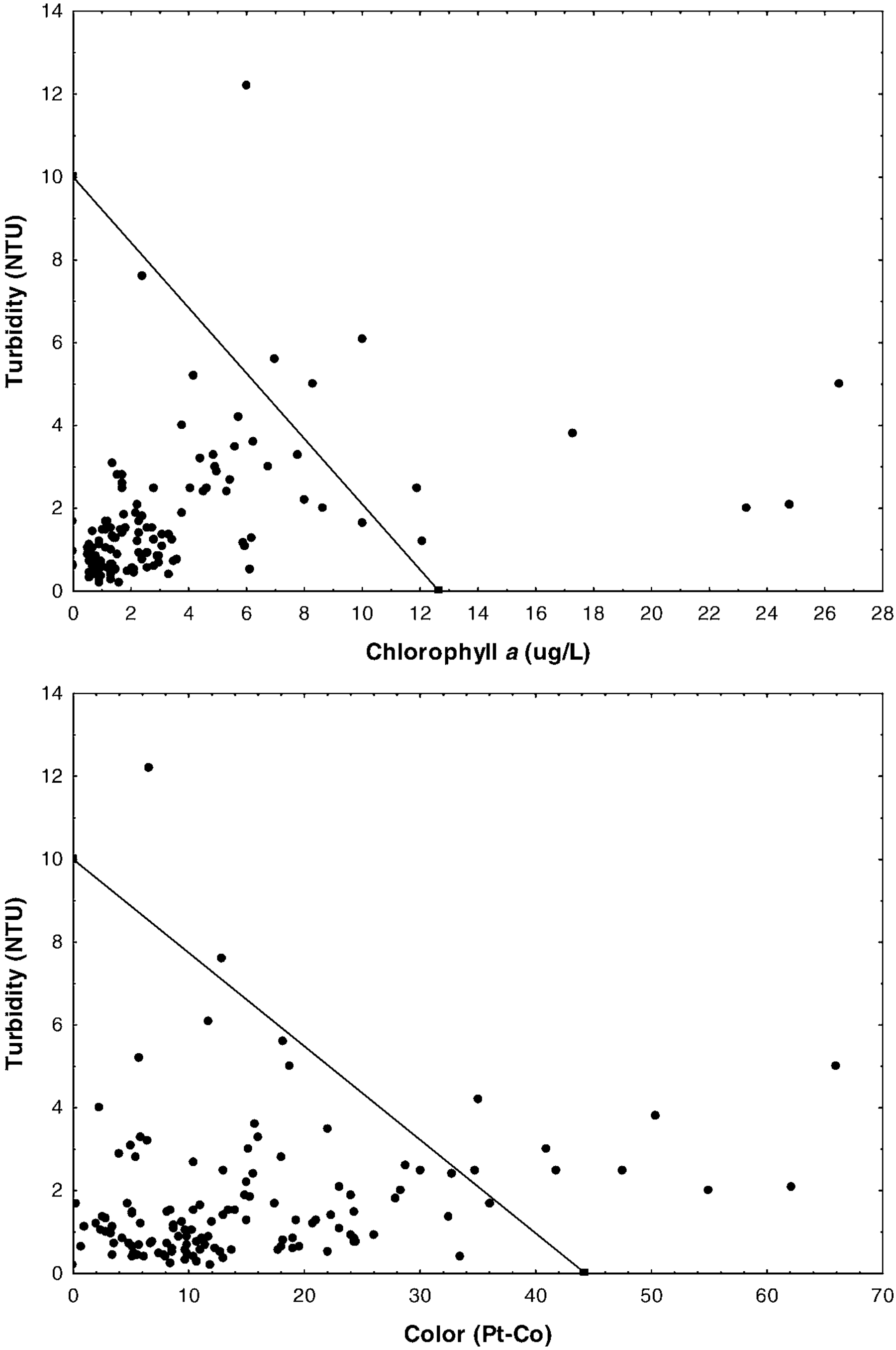
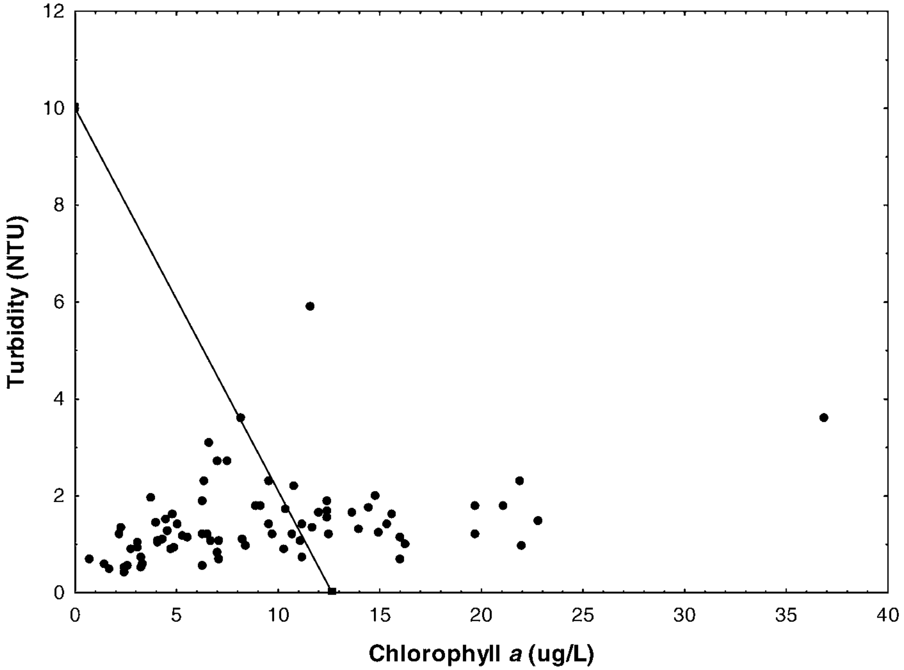



FIG. 2. Instances of dry season water quality which met (below line) or exceeded (above line) water quality goals for chlorophyll *a* and turbidity and color and turbidity in the Lower Charlotte Harbor segment. Data from 4/02–12/04.



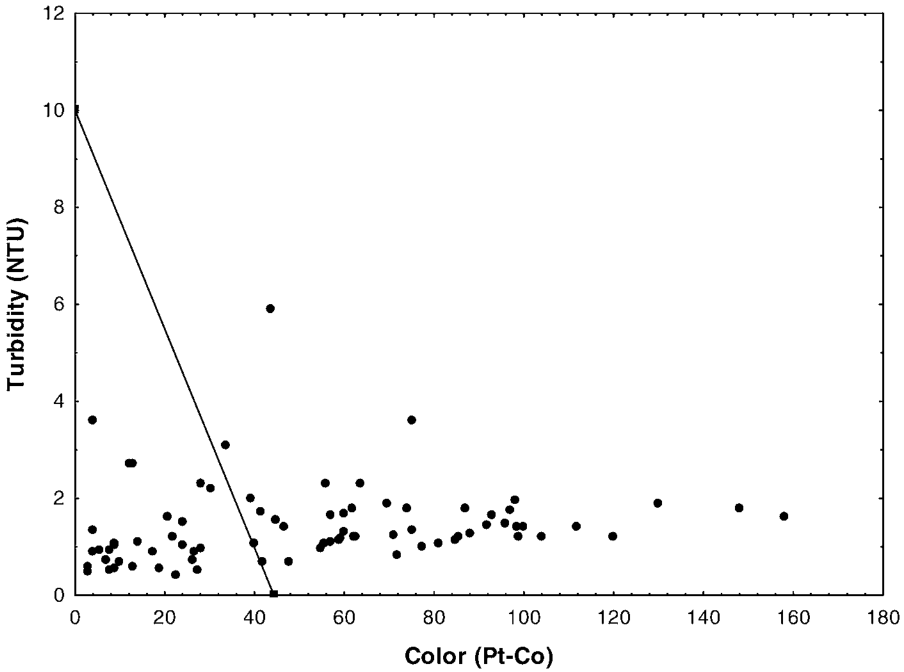




FIG. 3. Instances of wet season water quality which met (below line) or exceeded (above line) water quality goals for chlorophyll *a* and turbidity and color and turbidity in the Lower Charlotte Harbor segment.

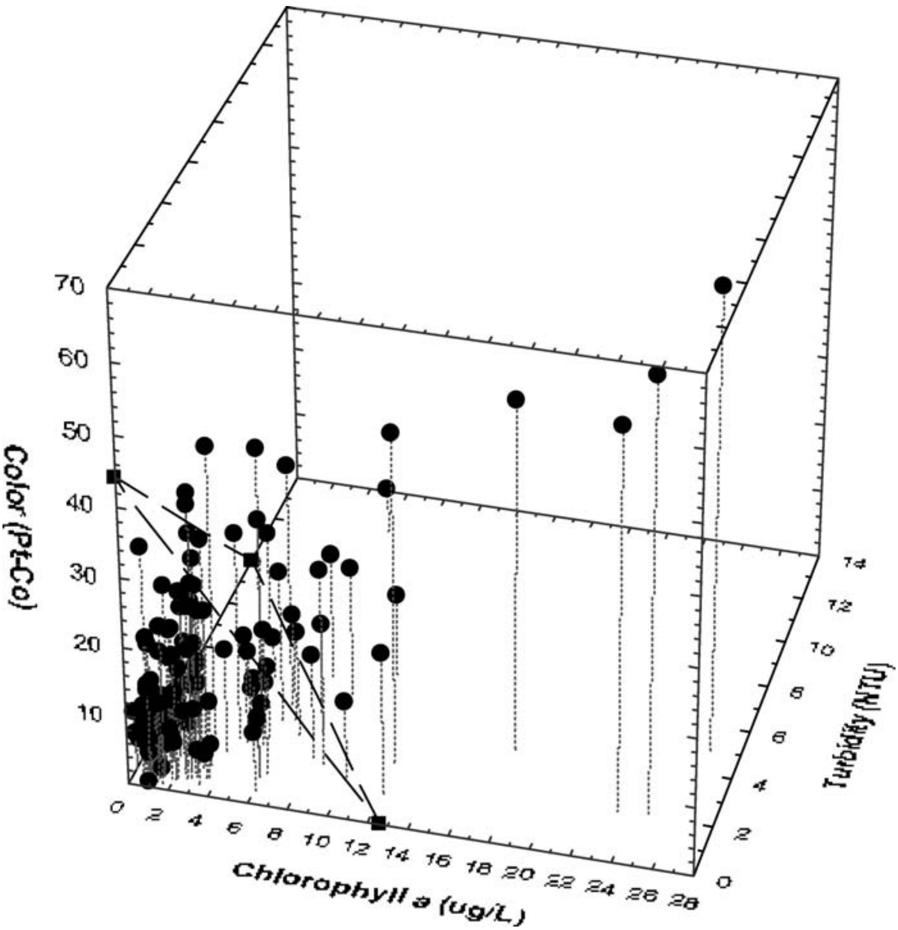



FIG. 4. 3-D Scatterplot with Lower Charlotte Harbor Stratum Dry Season Water Quality. Clarity targets (Table 2) and the line of constant attenuation are overlaid. Water quality data points located above of the line of constant attenuation identify instances when water clarity did not meet these targets.

there are times and locations within each segment that current water quality would not meet the percent-light-at-depth goals proposed in this effort. The locations in which these data were collected may support seagrass if, for instance, they are shallower than the depth target. Also, some data points on the scatterplots may represent locations in which data were collected that are deeper than our depth goal. However, both the light and maximum depth distribution targets are reasonable goals based upon current observations.

Nonetheless, other region-specific maximum depth distribution goals could be developed. The line of constant attenuation and the maximum concentration "targets" are based upon seagrass bed depth goals derived from fixed transect data collected between 1999 and 2005. The depth targets were created using the greatest annual average maximum seagrass deep edge per segment. A different strategy

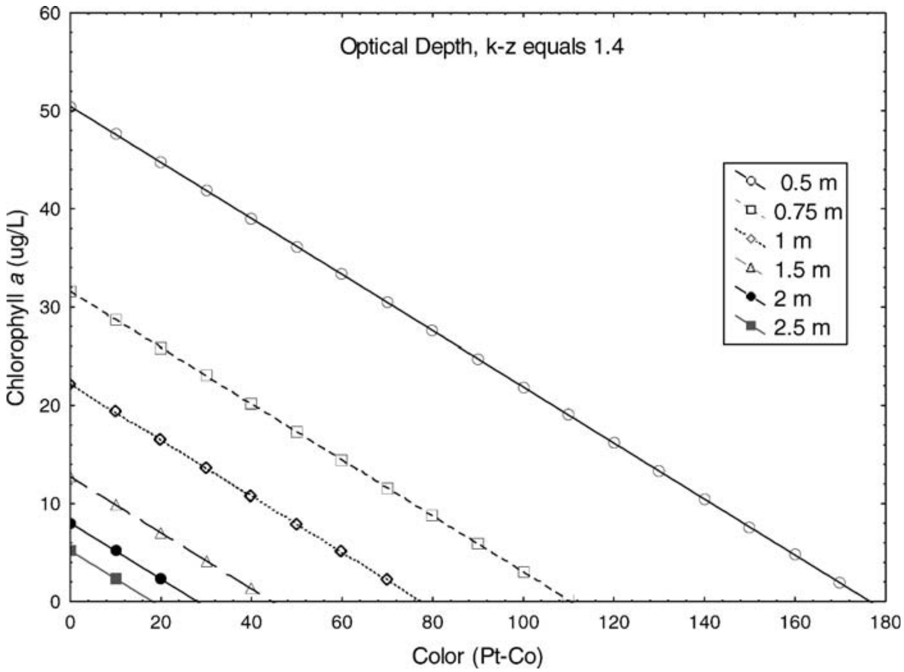



FIG. 5. Nomograph of Chlorophyll *a* Concentrations and Color for Specified Depths. For a given depth, combinations of color and chlorophyll *a* concentrations can reach the values under the line and maintain our light attenuation target.

could use the maximum deep edge value per segment as calculated by the fixed transect data to create water quality goals that would protect the transect with the deepest seagrass bed for each segment or alternatively, the mean annual average maximum seagrass deep edge. A quick review of the nomographs herein will demonstrate how the concentrations of the 3 water clarity components will change depending on depth.

Light requirements of seagrasses within Charlotte Harbor could be refined as well. We used the estimate of 25% subsurface irradiance, but future research may document that more light is needed to be protective of seagrasses. Salinity can affect seagrass photosynthesis (e.g., Torquemada et al., 2005), productivity (Tomasko and Hall, 1999) and abundance (Montague and Ley, 1993). As both Tomasko and Hall (1999) and Dixon and Kirkpatrick (1999) cite salinity stress as possible reasons for reduced *T. testudinum* productivity in this area, seagrasses in Charlotte Harbor would benefit from research to determine actual light requirements based on environmental gradients such as salinity as well as water clarity.

The partial coefficients within this optical model could be refined in several ways. McPherson and Miller (1994) used water quality samples collected in Tampa Bay and Charlotte Harbor to derive the partial attenuation coefficients used in this effort, and the model could be improved by including only data collected from Charlotte Harbor. Also, although other researchers have calculated partial light

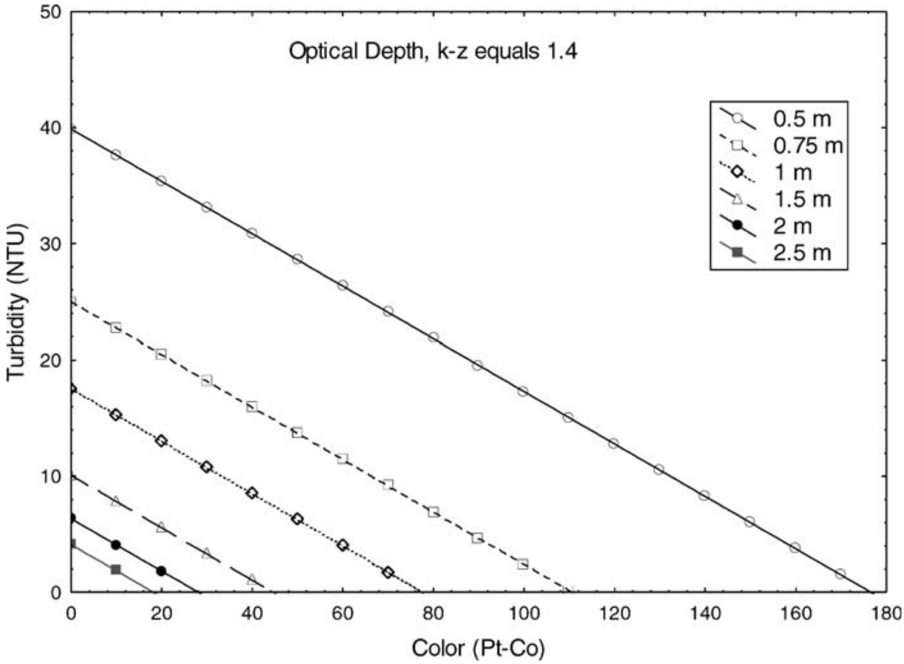



FIG. 6. Nomograph of Turbidity and Color for Specified Depths.

attenuation coefficients to support seagrass growth that differ from those in this effort (e.g., Gallegos and Kenworthy, 1996), the coefficients used here are locally derived and the best available estimates for environmental conditions in Charlotte Harbor.

The "non-algal suspended matter" partial light attenuation coefficient is an important parameter to accurately estimate, as this component is generally responsible for over 50% of light attenuation in these areas (McPherson and Miller, 1987; Dixon and Kirkpatrick, 1999). Furthermore, the actual composition of "non-algal suspended matter", represented by the turbidity term in McPherson and Miller (1994), will differ by segment and by season. Turbidity is a mixture of inorganic suspended matter, such as silt or clay, as well as plankton or other microscopic organisms (APHA, 1985). Turbidity values in Charlotte Harbor are significantly different in dry and wet seasons (Ott and Corbett, 2005), and phytoplankton communities, which also differ from season to season and from region to region, will have a variable impact on light scattering and absorption (see Kirk, 1994 and Jeffrey et al., 1997). However, McPherson and Miller (1987) suggested that re-suspended sediments may largely contribute to the non-algal suspended matter parameter in at least some of the areas in Charlotte Harbor and later estimated its value by accounting for the contribution of chlorophyll to the difference in attenuation between filtered and unfiltered water samples (McPherson and Miller, 1994). Therefore, while this effort uses the best available data appropriate for the Charlotte Harbor region, management strategies incorporating our approach to setting water clarity goals should be prepared to estimate the "non-algal suspended matter" parameter by both season and estuary segment.

The target light attenuation estimate presented here is based upon current seagrass distribution, and the water clarity goals proposed in this effort are meant to maintain the present seagrass coverage and depth distribution into the future. However, recent analysis of water quality data has demonstrated significant increases in total suspended solids in Lower Charlotte Harbor and Upper Charlotte Harbor regions and increasing turbidity in the Lower Charlotte Harbor region (Janicki Environmental Inc., 2003). These water quality constituents, along with dissolved matter, constitute the dominant influences on the light available for seagrass beds in most areas of Charlotte Harbor.

Seagrass coverage in the Upper Charlotte Harbor region is stable since 1988 (Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett, 2006). Nonetheless, if seagrass depth distribution is light limited (Dixon and Kirkpatrick, 1999; Tomasko and Hall, 1999), resource management strategies in this area should focus on the long-term maintenance of present seagrass coverage through the implementation of water clarity targets. If future research efforts determine that seagrass meadows within Charlotte Harbor have indeed receded or catastrophic losses occurred since historic conditions, depth distribution goals reflecting restoration targets could be created from historic data. It should be noted then that water clarity would in turn need to improve to meet those restoration targets. Water quality that meets the goals derived in this effort should allow appropriate water clarity conditions for the maximum depth distribution of seagrass meadows that currently exist.

ACKNOWLEDGMENTS—The authors would like to thank Ron Miller, David Tomasko, Ralph Montgomery and Charles Kovach who provided valuable insight into partial light attenuation components in Charlotte Harbor. Keith Kibbey, Judy Ott, James Evans, Connie Jarvis, Philip Stevens, Patrick Casey, Peter Doering, Katie Fuhr, Dan Quick, Joanne Vernon, Kris Kaufman and other members of the Coastal Charlotte Harbor Monitoring Network supplied water quality data and thoughtful input for this effort. Katie Fuhr, Jaime Greenawalt and Stephanie Erickson provided transect deep edge measurements. Robert Chamberlain and Peter Doering contributed invaluable input into seagrass light requirements and mechanisms into furthering this work. Lisa Beever and Patrick Biber provided much needed support and encouragement. Finally, two anonymous reviewers and the guest editors provided constructive comments that greatly improved this work.

## LITERATURE CITED

AMERICAN PUBLIC HEALTH ASSOCIATION (APHA). 1985. Standard Methods for The Examination Of Water And Wastewater, 16th Ed. American Public Health Association, American Water Works Association, Water Environment Federation publication. APHA, Washington D.C.

BRAUN-BLANQUET, J. 1965. Plant sociology: the study of plant communities. Authorized English translation of Pflanzensoziologie 1932. Translated, revised, and edited by G. D. FULLER AND H. S. CONARD, 1st ed. McGraw-Hill, New York, NY.

CHAMBERLAIN, R. H. 2005. South Florida Water Management District, West Palm Beach, Pers. Commun.

CORBETT, C. A. 2006. Seagrass coverage changes in Charlotte Harbor, Florida. Florida Scient. 69 (00S2): 7–23.

———, P. H. DOERING, K. A. MADLEY, J. A. OTT, AND D. A. TOMASKO. 2005. Issues with using seagrass as an indicator of ecosystem condition. Pp. 229–245. *In*: BORTONE, S. A. (ed.), Estuarine Indicators. CRC Press, Boca Raton, FL.

DIXON, L. K. 2000. Establishing light requirements for the seagrass *Thalassia testudinum*. *In*: BORTONE, S. A. (ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Press, Boca Raton, FL.

——— AND G. J. KIRKPATRICK. 1999. Causes of light attenuation with respect to seagrasses in upper and lower Charlotte Harbor, Report to Southwest Florida Water Management District, SWIM Program and Charlotte Harbor National Estuary Program. Available from the Southwest Florida Water Management District, SWIM Program, Tampa, FL and Charlotte Harbor National Estuary Program, Fort Myers, FL.

GALLEGOS, C. L. AND W. J. KENWORTHY. 1996. Seagrass depth limits in the Indian River Lagoon (Florida, U.S.A.): Application of an optical water quality model. Estuar. Coast Shelf Sci. 42: 267–288.

GREENAWALT, J. M. 2005. Sanibel Captiva Conservation Foundation, Sanibel, FL. Pers. Commun.

GREENAWALT-BOSWELL, J. M., J. A. HALE, K. FUHR, AND J. OTT. 2006. Seagrass species' composition and distribution as estuarine indicators in Charlotte Harbor, FL. Florida Scient. 69 (00S2): 24–35.

HAMMETT, K. M. 1990. Land use, water use, streamflow and water quality characteristics of the Charlotte Harbor inflow area, Florida. Water Supply Paper 2359-A. Prepared in cooperation with the Florida Department of Environmental Regulation. U.S. Geological Survey, Tallahassee, FL. Available from USGS, Tampa, FL.

HARRIS, B. A., K. D. HADDAD, K. A. STEIDINGER, AND J. A. HUFF. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida, Final Report. Florida Department of Natural Resources. Available from Florida Fish and Wildlife Conservation Commission-Florida Marine Research Institute, St. Petersburg, FL.

JANICKI ENVIRONMENTAL INC. 2003. Water quality data analysis and report for the Charlotte Harbor National Estuary Program, August 27, 2003. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

JEFFREY, S. W., R. F. C., MANTOURA, AND S. W. WRIGHT (Eds.). 1997. Phytoplankton pigments in oceanography. UNESCO, Paris.

JOHANSSON, J. O. R. 1991. Long-term trends in nitrogen loading, water quality and biological indicators in Hillsborough Bay, Florida. Pp. 157–176. *In*: S. F. TREAT AND P. A. CLARK (eds.), Proceedings, Tampa Bay Areas Scientific Information Symposium 2. Available from the Tampa Bay Regional Planning Council, St. Petersburg, FL.

——— AND H. GREENING. 1999. Seagrass restoration in Tampa Bay: A resource-based approach to estuarine management. Pp. 279–293 *In*: S. BORTONE (ed.), Subtropical and Tropical Seagrass Management Ecology. CRC Press, Boca Raton, FL.

——— AND T. RIES. 1997. Seagrass in Tampa Bay: Historic trends and future expectations. Pp. 139–150. *In*: S. TREAT (ed.), Proceedings, Tampa Bay Area Scientific Information Symposium-3. Available from the Tampa Bay Regional Planning Council, St. Petersburg, FL.

KIRK, J. T. O. 1983. Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, New York, NY.

——— 1994. 2nd Edition, Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, New York, NY.

KURZ, R. C., D. A. TOMASKO, D. BURDICK, T. F. RIES, K. PATTERSON, AND R. FINCK. 1999. Recent trends in seagrass distributions in southwest Florida coastal waters. Pp. 157–166. *In*: S. BORTONE (ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Marine Science Series, CRC Press, Boca Raton, FL.

LEWIS III, R. R., P. A. CLARK, W. K. FEHRING, H. S. GREENING, R. O. JOHANSSON, AND R. T. PAUL. 1998. The rehabilitation of the Tampa Bay Estuary, Florida, USA, as an example of successful integrated coastal management. Mar. Poll. Bull. 37(8): 468–473.

MCPHERSON, B. F AND R. L. MILLER. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, southwestern Florida. Estuar. Coast Shelf Sci. 25: 721–737.

——— AND R. L. MILLER. 1994. Causes of light attenuation in Tampa Bay and Charlotte Harbor, southwestern Florida. Water Res. Bull. 30(1): 43–53.

MONTAGUE, C. L. AND J. A. LEY. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in northeaster Florida Bay. Estuar. 16(4): 703–717.

OTT, J. A. AND C. A. CORBETT. 2005. Combining fixed station and probabilistic water quality data to identify status and trends for the long-term health and management of the Charlotte Harbor estuaries, Presentation to the 2005 Charlotte Harbor Watershed Summit. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

STAUGLER, E. AND J. A. OTT. 2001. Establishing baseline seagrass health using fixed transects in Charlotte Harbor, Florida: 2 year seagrass monitoring summary 1999–2000, Technical Report (1), Florida Department of Environmental Protection, Charlotte Harbor Aquatic Preserves. Available from Florida Department of Environmental Protection, Punta Gorda, FL.

TOMASKO, D. A., D. L. BRISTOL, AND J. A. OTT. 2001. Assessment of present and future nitrogen loads, water quality, and seagrass (*Thalassia testudinum*) depth distribution in Lemon Bay, Florida. Estuar. 24(6A): 926–938.

———, C. A. CORBETT, H. S. GREENING, AND G. E. RAULERSON. 2005. Spatial and temporal variation in seagrass coverage in southwest Florida: Assessing the relative effects of anthropogenic nutrient load reductions and rainfall in four contiguous estuaries. Mar. Poll. Bull. 50: 797–805.

——— AND M. O. HALL. 1999. Productivity and biomass of the seagrass *Thalassia testudinum* along a gradient of freshwater influence in Charlotte Harbor, Florida. Estuar. 22(3A): 592–602.

TORQUEMADA, Y. F., M. J. DURAKO, AND J. L. SANCHEZ LIZANO. 2005. Effects of salinity and possible interactions with temperature and pH on growth and photosynthesis of *Halophila johnsonii* Eiseman. Mar. Bio. 148: 251–260.

Florida Scient. 69(00S2): 36–50. 2006
Accepted: March 10, 2006

# CHLOROPHYLL *A* AND ITS USE AS AN INDICATOR OF EUTROPHICATION IN THE CALOOSAHATCHEE ESTUARY, FLORIDA

PETER H. DOERING[(1)], ROBERT H. CHAMBERLAIN[(1)], AND KATHLEEN M. HAUNERT[(1)]

[(1)]Coastal Ecosystems Division, South Florida Water Management District, West Palm Beach, Florida 33406

ABSTRACT: *The use of phytoplankton chlorophyll* a *to indicate eutrophication in the Caloosahatchee Estuary and San Carlos Bay was evaluated. Responses of chlorophyll* a *to nutrient loading and freshwater discharge at the Franklin Lock and Dam located at the head of the estuary were examined. Relationships between chlorophyll* a *and dissolved oxygen and light attenuation in the downstream estuary and bay were also investigated. Statistically significant positive correlations with nutrient loading in the lower estuary and San Carlos Bay, significant association between increasing chlorophyll* a *and decreasing dissolved oxygen in bottom waters in the estuary, and positive correlation between light attenuation and chlorophyll* a *in San Carlos Bay argue for the use of chlorophyll* a *to indicate eutrophication. Relationships between chlorophyll* a *and freshwater discharge indicated a flushing or 'wash out' effect. Review of the literature suggested that discharge of dark, colored water enhanced light attenuation. Both effects of discharge would suppress the accumulation of chlorophyll biomass. While chlorophyll* a *might be used to indicate eutrophication in the Caloosahatchee, useful interpretation of the response of this indicator to future reductions in nutrient loading must account for the modulating effects of freshwater discharge exerted through flushing and reductions in light availability.*

*Key Words:* Eutrophication, indicator, chlorophyll *a*

EXCESSIVE fertilization or eutrophication of coastal waters with nitrogen and phosphorus is a continuing world-wide problem (Palmer et al., 2004; Smith et al., 2003; Cloern, 2001; Eyre, 2000). Conceptual understanding of the responses of coastal ecosystems to eutrophication has changed. In a recent review, Cloern (2001) describes three phases in the evolution of this concept. The first emphasized the link between nutrient input, enhanced production of phytoplankton biomass, and the subsequent depletion of dissolved oxygen (e.g. Ryther and Dunstan, 1971). Observation over the past several decades has shown that estuarine systems do not respond generically to enhanced nutrient input. For example, while phytoplankton may bloom in some systems, macroalgae may be favored in others (Harlan, 1995). The Phase II model attempts to explain this diversity of estuarine response. It recognizes a variety of direct responses that can lead to a variety of indirect responses. A good example is the decline of seagrass associated with eutrophication. Increased nutrient supplies lead to increased chlorophyll biomass in the water column (a direct response) that shades out submerged aquatic vegetation (an indirect response, Twilley et al., 1985). Diversity of response is also explained in part by system specific physical and biological attributes or "filters" such as tidal range

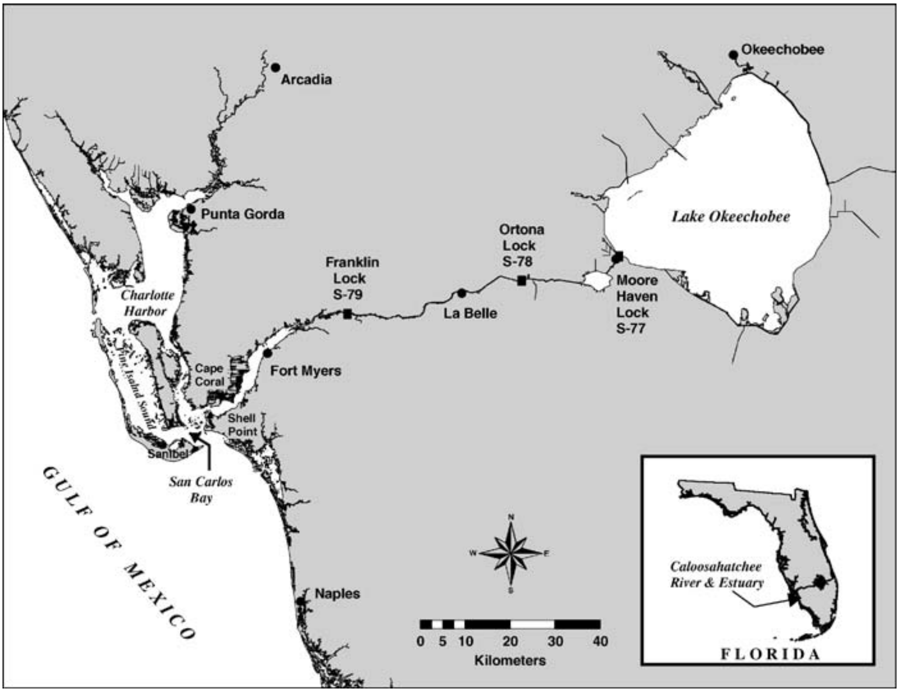



FIG. 1. Location of the Caloosahatchee River and Estuary.

(Monbet, 1992), residence time (Nixon et al., 1996; Welch et al., 1972), and dense populations of filter feeders (Officer et al., 1982; Meeuwig et al., 1998). These attributes can enhance or mask the expression of eutrophication (Cloern, 2001). Understanding how these filters work and how they interact with other stressors is central to the development of the next (Phase III) conceptual model of eutrophication.

The response of phytoplankton biomass to increased nutrient input comprises a major pathway in many conceptual models of eutrophication (Gray, 1992; Harlan, 1995; Smith et al., 1999; Cloern, 2001). Chlorophyll *a*, a measure of phytoplankton biomass, is commonly employed as an indicator of eutrophication (Bricker et al., 1999). Yet, variation in chlorophyll *a* within and between estuarine systems does not always reflect differences in nutrient loading (Tomasko et al., 1996; Cloern, 2001). Use of chlorophyll *a* as an indicator should be considered within the context of our more complex understanding of eutrophication (Phase II, Cloern, 2001).

The Caloosahatchee River and Estuary, located on the southwest coast of Florida, are part of the larger Charlotte Harbor system (FIG. 1). The Caloosahatchee River runs 67 km from Lake Okeechobee to the Franklin Lock and Dam (S-79). S-79 separates the freshwater river from the estuary that terminates 40 km downstream at Shell Point (FIG. 1). The system has been modified. The River has been straightened, deepened and three water control structures have been added. The last, S-79, was completed in 1966 to act in part as a salinity barrier (Flaig and Capece, 1998). The River has also been artificially connected to Lake Okeechobee to convey regulatory releases of water to tide. The estuarine portion of the system has also been modified. Seven automobile bridges and one railroad bridge connect the north and south shores of the estuary. A navigation channel has been dredged and in the 1960's a causeway was built across the mouth of San Carlos Bay. Historic oyster bars upstream of Shell Point have been mined and removed for road construction.

Water quality has been a concern in the Caloosahatchee since the late 1970s and early 1980s. A waste-load allocation study in the Caloosahatchee conducted by the Florida Department of Environmental Regulation concluded that the estuary had reached its nutrient loading limits as indicated by elevated chlorophyll *a* and depressed dissolved oxygen concentrations (DeGrove, 1981). The purpose of this report is to (1) characterize nutrient loading at S-79 and quantify its relationship with chlorophyll *a* in the downstream estuary; (2) evaluate potential nutrient limitation and (3) to evaluate the use of chlorophyll *a* as an indicator of eutrophication in this system.

In keeping with the conceptual evolution of eutrophication described by Cloern (2001), evaluation of chlorophyll *a* as an indicator of eutrophication focused on component relationships of the Phase II model. First, the direct response of chlorophyll *a* to nutrient loading was evaluated. Two indirect responses were also examined: the relationship between chlorophyll *a* concentrations in surface water with oxygen concentrations in bottom water and the relationship between light extinction and chlorophyll *a*. The latter analysis also quantified the contribution of color and total suspended solids to light attenuation in the Caloosahatchee. Finally, the effects of freshwater discharge at S-79 on the downstream distribution of chlorophyll *a* are examined to determine if this parameter may be an important "filter" *sensu* Cloern (2001).

METHODS—*Data sets*—The water quality data evaluated here came from six (6) monitoring programs either conducted or supported by the South Florida Water Management District. All programs monitored the quality of surface waters with samples being taken within the top 0.5 m of the water column using a van Dorn, Kimmerer or similar bottle.

The Caloosahatchee River (CR) program sampled just upstream of the Franklin Lock and Dam (S-79). The program began in January, 1981 and continues to the present. Data from 1981 through June 2003 were analyzed. The frequency of sampling varied throughout the period of record generally being 6–8 times per year but ranging from 3 to 12 (monthly) times per year.

The Caloosahatchee Estuary (CAL) program sampled water quality at 17 stations in the estuary (Shell Point to S-79), San Carlos Bay, Matlacha Pass, and Pine Island Sound. The stations, sampled monthly from December 1985 to May 1989, were all located downstream of S-79. At each station, vertical profiles (0.5 m intervals) of temperature, salinity and dissolved oxygen were obtained electronically using Hydrolab or YSI sonde units.

The Caloosahatchee Estuary High Flow (CALHF) effort sampled monthly at 8 stations from October 1994 to August 1996. Seven stations were located in the estuary and San Carlos Bay, while one was located in freshwater upstream of S-79.

The Center for Environmental Studies (CES) program sampled 7 stations in the estuary (S-79 to Shell Point) and one (1) station upstream of S-79 on a monthly basis from April 1999 to March 2002. Temperature, salinity and dissolved oxygen were measured at 0.5 m below the surface and 0.5 m from the bottom. As of May 2002, the number of stations was reduced to 4, with one upstream of S-79 and the rest in the downstream estuary. This reduced sampling effort continues to the present. Data through June 2003 were used in the analysis.

The Southeastern Environmental Research Center (SERC) program sampled 8 stations in San Carlos Bay, Pine Island Sound, Matlacha Pass and the Gulf of Mexico on a monthly basis beginning in January 1999. The project continues to the present. Data through March 2003 were used in the analysis.

The Environmental Research and Design Program (ERD) sampled 15 sites in the Caloosahatchee Estuary and San Carlos Bay (ERD, 2003). This program was not designed to detect long term trends and therefore was not used in the analysis of water quality or loading. Stations were sampled for two month-long periods in each of three years (2000, 2001, and 2002). Each year one wet season month and one dry season month was sampled. During each sampling month, estuarine stations were occupied 4 times, once every ten days. In addition to vertical profiles of temperature, salinity and dissolved oxygen, vertical profiles of photosynthetically active radiation (PAR) were obtained using a Li-COR PAR Meter with 2 pi deck and submerged collectors.

*Water quality*—In the field, samples for dissolved inorganic nutrients ($NH_4$ = ammonia, NOx = Nitrate + Nitrate, DIN = $NH_4 + NO_X$, DIP = dissolved inorganic phosphorus) and color were passed manually through 0.4 μm membrane filters, using a syringe. Whole water samples were retained for total Kjeldahl nitrogen (TKN), total phosphorus (TP), total suspended solids (TSS) and chlorophyll *a* (Chl *a*). Chlorophyll *a* samples were filtered and analyzed spectrophotometrically in the laboratory within 24 hrs of collection. All samples were stored on ice until their return to the laboratory.

Samples were analyzed using standard methods in the South Florida Water Management District's Water Quality Laboratory or through contracts with private sector laboratories. All laboratories were certified by the National Environmental Laboratory Accreditation Program (NELAP). All nutrient, TSS and dissolved oxygen (DO) concentrations are reported in mg/l, chlorophyll *a* concentrations, corrected for phaeophytin, in μg/l, color in Pt-Co units, salinity (SAL) in parts per thousand and Secchi Disk Depth (SDD) in meters. Total Nitrogen (TN) was calculated as TKN + $NO_X$.

*Calculation of nutrient loads at S-79*—The loads of nutrients delivered to the estuary at the Franklin Lock and Dam (S-79) were calculated by multiplying the daily average discharge of freshwater by the concentration of nutrients in the water. A daily average discharge at S-79 was available from records kept by the SFWMD dating back to the 1960s. Data taken upstream of S-79 from the CR, CALHF and CES programs were used to generate a data set of daily concentrations by linear interpolation between sampling dates. From these data daily, 30-day and annual loads were calculated.

Analysis of loads at S-79 concentrated on temporal trends and sources of variation in the load (concentration or discharge). Temporal trends in annual discharge and loads of total nitrogen and phosphorus from 1981 to 2002 were evaluated using Kendall's Tau b correlation coefficient (SAS, 1989). Trends in daily loads were evaluated as follows. Only loads calculated for days upon which a concentration at S-79 was actually measured were considered. Daily load and concentration data were averaged by year and month to avoid undue influence of any time period. This procedure yielded a daily average load for each month in which S-79 was sampled. Temporal trends were evaluated both with Kendall's Tau b and Spearman's Rank correlation coefficients (SAS, 1989).

Multiple regression was employed to evaluate the contribution of daily discharge and concentration to variation in daily load. Only loads calculated for days upon which a concentration at S-79 was actually measured were considered.

*Water quality in the estuary*—Water quality varies in both time and space. In order to account for spatial variation, the Caloosahatchee system was divided into 4 areas (FIG. 2) each encompassing stations from the various sampling programs summarized below (Table 1). Only data from the CAL, CALHF, CES and SERC programs were used to evaluate trends in water quality. To account for potential differences in detection limits, the detection limits for the CAL program were applied to all data. Values less than the CAL detection limits were set to one half the detection limit.

In each region data were sorted by year and month and then averaged across stations. This produced a set of monthly observations in each region. The data were discontinuous, falling into 3 time periods: December 1985–May 1989 (CAL), November 1994–August 1996 (CALHF) and April 1999–June 2003 (CES, SERC).

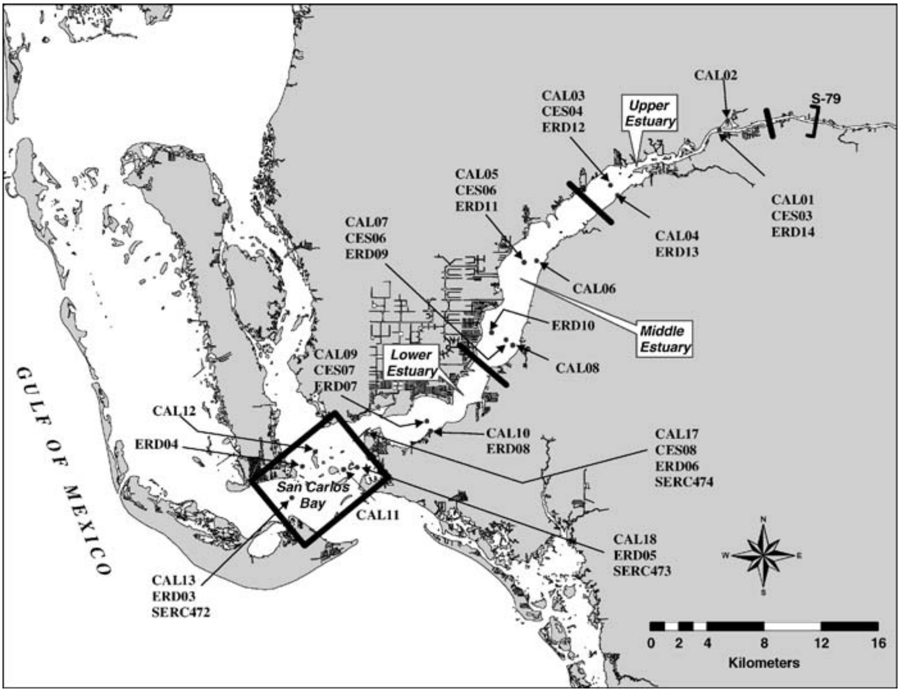



FIG. 2. Location of water quality sampling stations in the Caloosahatchee Estuary and San Carlos Bay.

Statistically, regional differences in water quality parameters were evaluated with the Kruskal-Wallis H test (NPAR1WAY, SAS 1989). This test amounts to a non-parametric one-way analysis of variance on ranked data with region being the treatment factor. If the H test was statistically significant, data were ranked and differences between regions were evaluated using Proc Multtest, with a bootstrap correction of the p-value to account for making multiple t-tests on ranks (equivalent to a Wilcoxon rank-sum test).

The discontinuity of data sets precluded traditional analysis for temporal trends using, for example, Kendall's Tau b. Interpreting differences between periods as temporal trends, even those that increase or decrease progressively from one period to the next, should be done with great caution. It is beyond the scope of this effort to evaluate the data for temporal trends or attempt to explain differences between periods. However, we have compared the three periods for a selected set of water quality parameters relevant to this study (Salinity, TN, DIN, DIP, DIN:DIP, Chl *a*). Differences in water quality between the three periods were evaluated for each region using the same approach as just described with period being the treatment factor. Rain fall and discharge from Lake Okeechobee and to the estuary at S-79 also were summarized for each period. In order to compare periods of different lengths, monthly values during each

TABLE 1. Sampling stations in the four regions of the Caloosahatchee Estuarine System.

| Region of Estuary | Program: CAL, CALHF | CES | SERC | ERD | Km from S-79 |
|---|---|---|---|---|---|
| Upper | 01,02,03,04 | 03,04 | — | 12,13 | 6–14 |
| Mid | 05,06,07,08 | 05,06 | — | 9,10,11 | 14–28 |
| Lower | 09,10,17 | 07,08 | 474 | 6,7,8 | 28–41 |
| San Carlos Bay | 18,11,12,13 | — | 472,473 | 3,4,5 | 41–49 |

period were summed, divided by the number of months in the period and multiplied by 12 to produce a 12 month, periodic average for each time period.

*Nutrient loading and chlorophyll*—The dependence of chlorophyll *a* concentrations in the estuary on loading at S-79 was established by simple linear correlation. Data from stations within each region were averaged by sampling date to produce one observation per region per date. Correlations between concentration in the estuary and the loading that had occurred over the 30 days prior to sampling were calculated.

Other standard correlation and regression techniques applied to the data are described in the results section. All statistical analyses were performed using SAS Version 8 software (SAS, 1989).

*Potential nutrient limitation*—Although providing only a first approximation, comparison of nutrient concentrations with literature values for the half-saturation constant of nutrient uptake by phytoplankton furnishes a measure of nutrient limitation (Fisher et al., 1988). Half-saturation constants range between 0.014 and 0.028 mg/l for DIN and 3.1 and 15.5 μg/l for DIP. Concentrations below these ranges indicate a potential for nutrient limitation (Fisher et al., 1988). As a measure of potential limitation in each region, the proportion of concentration measurement above and below the lower limit of theses ranges were calculated.

*Chlorophyll and dissolved oxygen*—The correlation between chlorophyll *a* concentration in surface waters and dissolved oxygen in bottom waters was examined using data from the CES sampling program. Visual analysis of graphed data was employed to demonstrate dependence over short time scales (weeks). On monthly time scales, linear correlation coefficients were calculated with lags up to 2 months.

*Chlorophyll and light extinction*—Photosynthetically Active Radiation (PAR) data required for the calculation of the light extinction coefficient ($K_d$) was consistently collected only during the ERD study (ERD, 2003). On each sampling date, data were averaged across stations in a region. Stepwise multiple regressions relating variation in the extinction coefficient to chlorophyll *a*, color and total suspended solids were calculated for each region. Statistically, the regression approach identified the water quality parameters that most influence change or variation in light extinction. Following McPherson and Miller (1994), the approach also was used to partition the light extinction coefficient and quantify the contribution of individual water quality parameters to the total light extinction using individual regression coefficients. The concentration of an individual water quality constituent on each sampling date was multiplied by its regression coefficient from the multiple regression equation. The result was divided by the corresponding light extinction coefficient on the same day.

*Chlorophyll and freshwater discharge*—The potential for freshwater discharge at S-79 to influence the distribution of chlorophyll *a* was examined regionally in the same way as the relationship with nutrient loading described above. The effect of discharge on the longitudinal position of maximum chlorophyll *a* in the study area (S-79 to San Carlos Bay) was examined following Doering and co-workers (1994) and Doering and Chamberlain (1999). On each sampling date, the station with the highest chlorophyll *a* concentration was identified along with its distance from S-79. The correlation between the position of the chlorophyll maximum and discharge at S-79 was determined. In addition, the position data were classified into several flow ranges increasing from low to high and analyzed by one-way ANOVA. The treatment was flow range. The flow ranges were based on the salinities they produce in the estuary and the tolerances of estuarine organisms (Chamberlain and Doering, 1998; Doering et al., 2002). Flows less than about 14 $m^3$/sec (500 cfs) do not maintain the full (0–35 ppt) salinity gradient in the estuary. At flows greater than about 79 $m^3$/sec (2800 cfs) salinity declines in the lower estuary impacting marine seagrasses typical of this area. Flows greater than about 127 $m^3$/sec (4500 cfs) lower salinity sufficiently in San Carlos Bay to impact seagrasses there (Chamberlain and Doering, 1998).

Not all the data could be used for this analysis. The CAL and CALHF program sampled the entire study area. The CES and SERC programs sampled the Caloosahatchee Estuary and San Carlos Bay

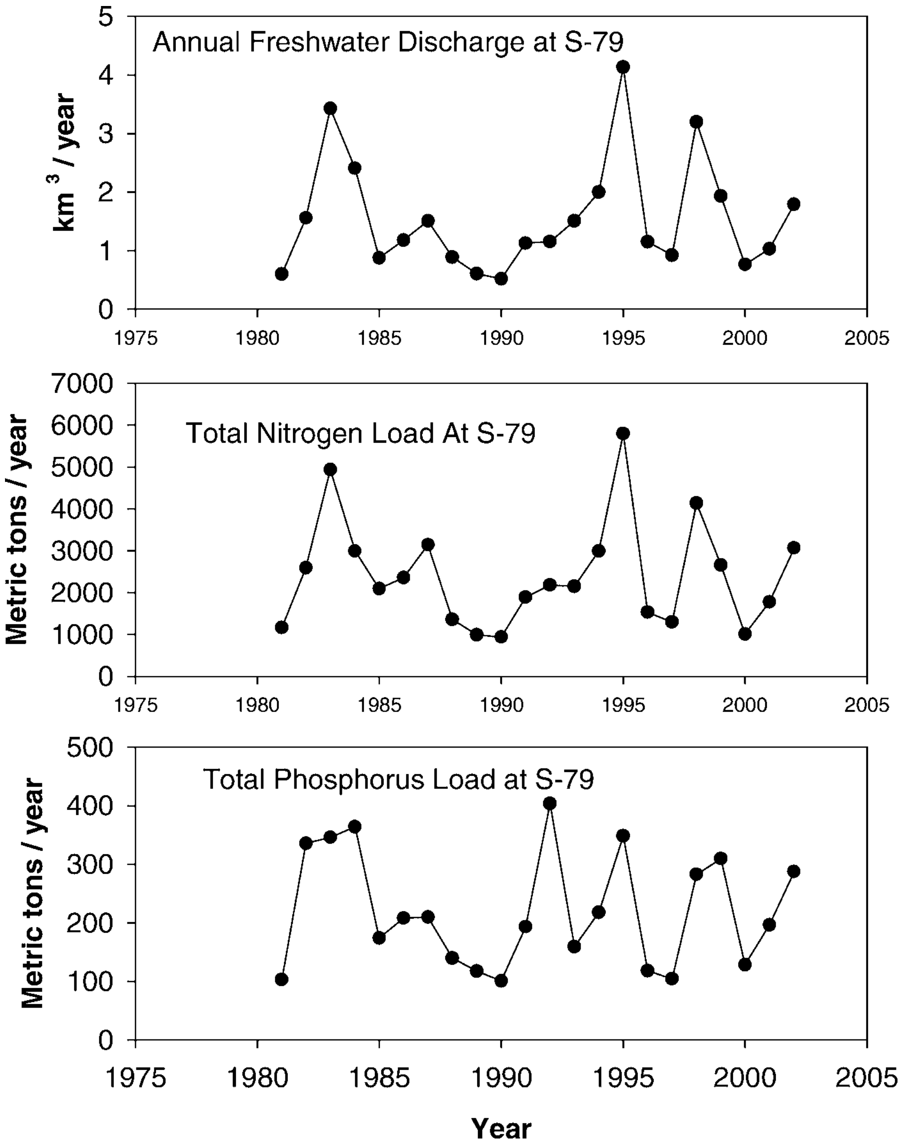



FIG. 3. Annual discharge and annual loading of total nitrogen and phosphorus at S-79.

respectively. In most instances, the two programs sampled their respective areas within a day or two of each other and these were considered as one event. At other times sampling was not so coincidental. Events occurring more than a week apart were eliminated from the analysis.

RESULTS—*Nutrient loading*—Annual discharge of freshwater at S-79 averaged 1.57 $km^3$/yr (1.27 million acre-ft), with a minimum of 0.52 $km^3$ (424 thousand ac-ft) in 1990, a drought year, and a maximum of 4.17 $km^3$ (3.38 million ac-ft) in 1995,

TABLE 2. Fraction of variation in daily loading at S-79 explained by fluctuations in discharge and nutrient concentration. All fractions are statistically significant at $p<0.0001$.

| | Discharge | Concentration | Total Variation |
|---|---|---|---|
| Total Nitrogen | 0.908 | 0.023 | 0.931 |
| Dissolved Inorganic Nitrogen | 0.692 | 0.082 | 0.774 |
| Total Phosphorus | 0.716 | 0.117 | 0.833 |
| Dissolved Inorganic Phosphorus | 0.503 | 0.260 | 0.763 |

a very wet year (FIG. 3). No long term trend in discharge was detected (Kendall Tau b, $p>0.60$). Annual loading of total nitrogen at S-79 averaged 2412 metric tons/year with a minimum of 938 metric tons in 1990 and a maximum of 5801 metric tons in 1995. Over the period 1981 through 2002 there was no general increase or decrease in the annual total nitrogen load ($p>0.8$). Loading of total phosphorus averaged 220 metric tons/year with a minimum of 101 metric tons in 1990 and a maximum of 403 metric tons in 1992. No long term trends were detected ($p>0.8$). The molar ratio of the total N load to the total P load averaged 24.4 and ranged from 12 to 37.

Variation in daily nutrient loads at S-79 was primarily a function of freshwater discharge (Table 2). In multiple regressions, this variable explained between 50 and 90% of the variation in nutrient loads. Concentration explained a significant but substantially smaller proportion of the total variation (range 2–26%).

No long term trends in the daily loads (Table 3) of total nitrogen, total phosphorus, dissolved inorganic nitrogen or dissolved inorganic phosphorus at S-79 were detected. The molar N to P ratio of the daily total nutrient load averaged nearly 30 and the median was 26. The molar ratio of the daily inorganic load averaged about 9.5 over the 22 year period of record with a median of 7.5.

*Differences between periods*—Hydrologic conditions varied between the three sampling periods. Period 2 was the wettest with a 12 month periodic average rainfall of 1.67 m, compared to Period 1 with 1.17 m and Period 3 with 1.45 m. This result is expected given that 1995 was a very wet year (FIG. 3). Period 2 also had the highest 12 month periodic average discharge at S-79 (3.22 $km^3$) with 60% accounted for by discharge from Lake Okeechobee. Discharge at S-79 for Period 1 averaged 1.09 $km^3$/12 months with only 11% being released from Lake Okeechobee. For Period 3, discharge at S-79 averaged 1.55 $km^3$/12 months with 30% being released from Lake Okeechobee.

Salinity reflected these hydrologic conditions in all regions being lower during

TABLE 3. Summary of daily loads at S-79.

| | Daily Load (kg/day) | | | |
|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum |
| Total Nitrogen | 7,018 | 2,618 | 0 | 46,885 |
| Dissolved Inorganic Nitrogen | 1,385 | 567 | 0 | 12,874 |
| Total Phosphorus | 657 | 253 | 0 | 5,141 |
| Dissolved Inorganic Phosphorus | 426 | 157 | 0 | 3,352 |

TABLE 4. Median values for selected water quality parameters during three time periods in four regions of the Caloosahatchee estuarine system. Letters indicate statistical differences between periods at $p<0.05$. Medians with the same letter are not statistically different. DIN:P is the molar ratio of DIN to DIP.

| | | Water Quality Parameter | | | | | |
|---|---|---|---|---|---|---|---|
| Region | Period | SAL | TN | DIP | CHL *a* | DIN | DIN:P |
| Upper Estuary | 1985–1989 | 4.1 a | 1.43 a | 0.08 a | 10.3 | 0.10 | 2.7 b |
| | 1994–1996 | 0.3 b | 1.31 a | 0.04 b | 3.5 | 0.17 | 8.6 a |
| | 1999–2003 | 1.0 a | 1.13 b | 0.06 b | 8.6 | 0.19 | 5.5 a |
| Mid Estuary | 1985–1989 | 13.9 a | 1.30 a | 0.06 a | 8.1 | 0.01 b | 0.4 b |
| | 1994–1996 | 1.0 b | 1.29 a | 0.04 b | 7.3 | 0.09 a | 7.9 a |
| | 1999–2003 | 8.8 a | 0.91 b | 0.04 b | 10.5 | 0.04 a | 3.4 a |
| Lower Estuary | 1985–1989 | 25.3 a | 0.95 a | 0.04 a | 4.7 | 0.01 c | 0.95 c |
| | 1994–1996 | 15.3 b | 0.99 a | 0.03 ab | 5.5 | 0.13 a | 11.7 a |
| | 1999–2003 | 26.8 a | 0.33 b | 0.02 b | 3.6 | 0.03 b | 3.5 b |
| San Carlos Bay | 1985–1989 | 30.7 | 0.83 a | 0.015 a | 3.1 | 0.01 b | 1.9 c |
| | 1994–1996 | 27.9 | 0.83 a | 0.014 ab | 3.4 | 0.15 a | 19.9 a |
| | 1999–2003 | 31.8 | 0.25 b | 0.008 b | 3.4 | 0.01 b | 5.2 b |

Period 2 than at other times (Table 4). The concentration of TN was lower in all regions during Period 3 than at other times. In general, DIP concentrations were highest and DIN concentrations were lowest in Period 1. Chlorophyll *a* did not change. The molar ratio of DIN:DIP was generally lowest during Period 1, highest during Period 2 and intermediate during Period 3 (Table 4).

*Spatial trends in water quality and potential nutrient limitation*—Evaluation of the overall spatial variation in water quality indicated several patterns (Table 5). As expected, median salinity increased from the upper estuary to San Carlos Bay. Many

TABLE 5. Median values of water quality parameters by estuarine region. Letters indicate statistical differences between regions at $p<0.05$. Medians with the same letter are not statistically different. Medians calculated for all three sampling periods combined except for SDD, Color, and TSS. These parameters were measured in San Carlos Bay only during the 1985–1989 and 1994–1996 sampling periods.

| | Region | | | |
|---|---|---|---|---|
| Parameter | Upper Estuary | Mid Estuary | Lower Estuary | San Carlos Bay |
| SAL | 4.1 d | 10.1 c | 22.6 b | 29.4 a |
| TN | 1.26 a | 1.05 b | 0.67 c | 0.55 d |
| DIN | 0.18 a | 0.10 b | 0.07 b | 0.05 c |
| NH4 | 0.038 a | 0.027 b | 0.025 b | 0.026 b |
| NOx | 0.15 a | 0.08 b | 0.04 c | 0.02 d |
| Chl *a* | 10.7 a | 12.7 a | 5.3 b | 4.2 b |
| TP | 0.14 a | 0.13 a | 0.09 b | 0.05 c |
| DIP | 0.07 a | 0.06 b | 0.03 c | 0.02 d |
| TSS | 9.8 b | 15.0 b | 24.8 a | 21.0 a |
| Color | 93 a | 73 a | 42 b | 20 c |
| SDD | 1.05 c | 1.13 bc | 1.33 ab | 1.37 a |

TABLE 6. Potential nutrient limitation. Percentage and (n = number) of measured nutrient concentrations falling below (limiting) and above (not limiting) half-saturation constants for the uptake of DIN (0.014 mg/l) and DIP (3.1 μg/l).

| Region | Nutrient Status | DIN Percent (n) | DIP Percent (n) |
|---|---|---|---|
| Upper Estuary | Limiting | 24% (73) | 2% (7) |
| | Not Limiting | 76% (236) | 98% (302) |
| Mid Estuary | Limiting | 45% (125) | 3% (9) |
| | Not limiting | 55% (152) | 97% (268) |
| Lower Estuary | Limiting | 40% (107) | 4% (10) |
| | Not Limiting | 60% (163) | 96% (260) |
| San Carlos Bay | Limiting | 63% (164) | 17% (45) |
| | Not Limiting | 37% (96) | 83% (215) |

water quality parameters showed an inverse pattern, decreasing from the upper estuary to San Carlos Bay: TN, DIN, $NO_X$, DIP, Color. Others such as TSS and SDD followed the same pattern as salinity, increasing towards the Gulf of Mexico. Concentrations of some parameters (Chl *a*, TP, Color) suggested two regions of differing water quality: an upper and mid estuarine region with higher concentrations and a lower estuary- San Carlos Bay region with lower concentrations.

Potential nutrient limitation as judged by measured DIN and DIP concentrations relative to half-saturation constants for nutrient uptake indicated nitrogen limitation more often than phosphorus limitation (Table 6). Furthermore, the percentage of measurements indicating nitrogen limitation increased progressively from 24% in the upper estuary to 40–45% in the lower and mid-estuary to 63% in San Carlos Bay.

*Nutrient loading and chlorophyll*—The correlation between chlorophyll *a* concentration in the Calooshatchee estuary and the loading of total nitrogen during the 30 days prior to sampling varied spatially (FIG. 4). In San Carlos Bay and the lower estuary, increased loading corresponded to increased chlorophyll *a*. In the mid-estuary the correlation was not significant. In the upper estuary, the relationship was negative with increased loading associated with a reduction in the concentration of chlorophyll *a*. It is worth noting that while TN loading is featured in Figure 4, this does not mean that TN limits the growth of phytoplankton in the Caloosahatchee. Chlorophyll *a* concentrations showed the same regional relationships with DIN loading, DIP loading and TP loading: positive in the lower estuary and San Carlos Bay, not significant in the mid-estuary and negative in the upper estuary (Table 7).

Except in the mid-estuary, these relationships were seasonally robust. In the upper estuary, lower estuary and San Carlos Bay correlations for the wet (November–April) and dry (May–October) seasons showed the same patterns as when all data were considered together. The negative relationship in the upper estuary during the wet season was significant only at the $p<0.10$ level. By contrast, the relationship between loading and chlorophyll *a* in the mid-estuary was positive in the dry season ($r = 0.229$, $p<0.05$) and not significant in the wet season.

*Chlorophyll and dissolved oxygen*—High concentrations of chlorophyll *a* in

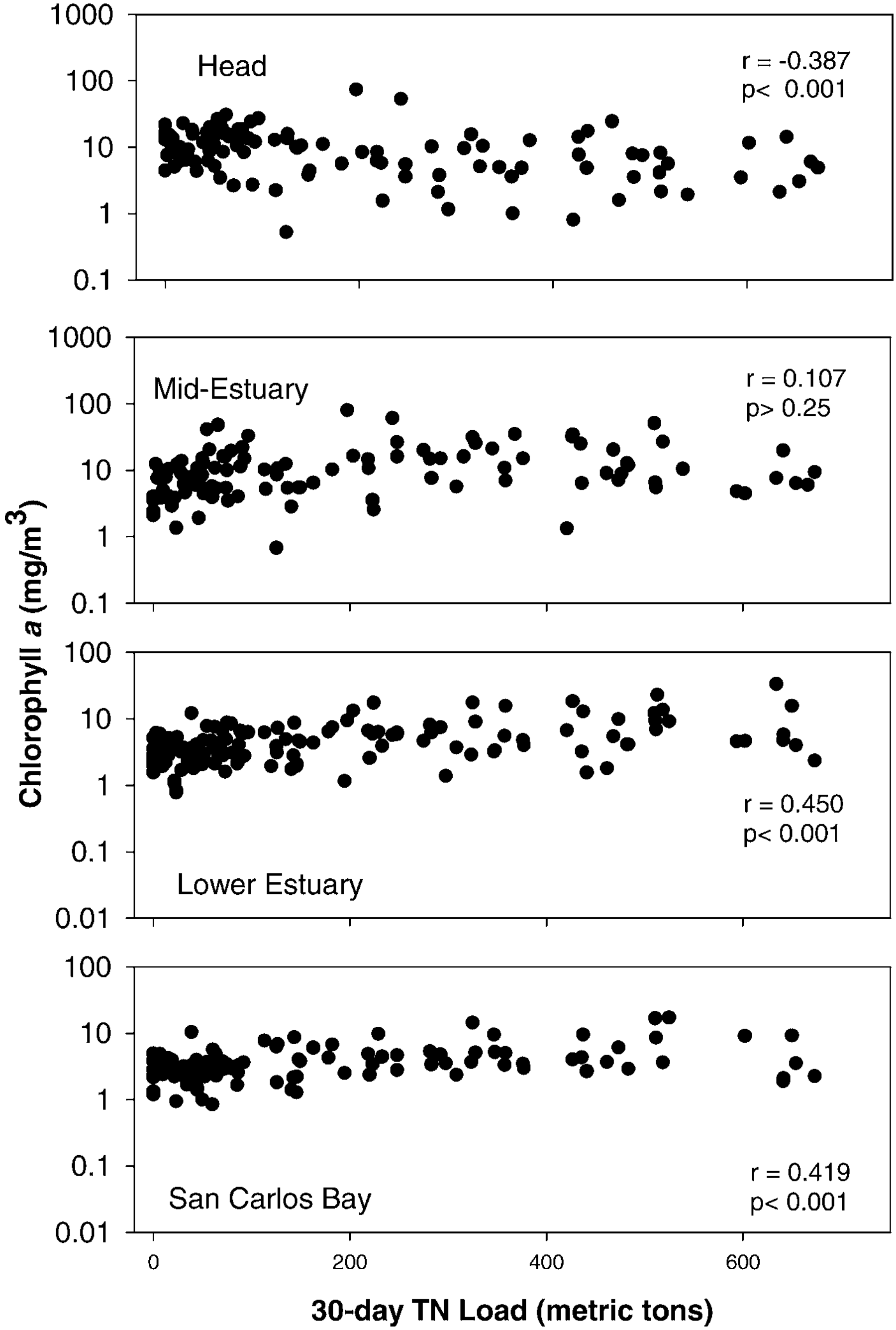



FIG. 4. Concentration of chlorophyll *a* as a function of total nitrogen loading at S-79 for the 30-days prior to sampling. r = Pearson correlation coefficient.

TABLE 7. Correlation between nutrient loading (kg per 30 days prior to sampling) at S-79 and chlorophyll *a* (log10 transformed) in 4 regions of the Caloosahatchee Estuary. * = Pearson correlation coefficients (r) statistically significant at $p<0.05$. n = 114–146 observations.

| Region | DIN Load | TP Load | DIP Load |
|---|---|---|---|
| Upper Estuary | −0.457* | −0.452* | −0.404* |
| Mid Estuary | 0.141 | 0.123 | 0.035 |
| Lower Estuary | 0.492* | 0.508* | 0.528* |
| San Carlos Bay | 0.569* | 0.559* | 0.588* |

surface waters can be associated with low concentrations of dissolved oxygen in bottom waters (0.5 m above bottom) in the Caloosahatchee on short time scales of weeks (FIG. 5). During the month of June 2000, the crash of a chlorophyll *a* bloom coincided with a rapid decline in oxygen in bottom waters. On longer time scales, the high concentrations of chlorophyll *a* may be associated with lower oxygen concentrations one or two months in the future (Table 8).

*Chlorophyll and light extinction*—Photosynthetically Active Radiation (PAR) data required for the calculation of the light extinction coefficient was consistently collected only during the ERD (2003) study. The results of stepwise multiple regressions relating variation in the extinction coefficient to chlorophyll *a*, color and total suspended solids are given in Table 9. Color explained most of the variation in light extinction in the upper, mid and lower estuary. In San Carlos Bay, chlorophyll

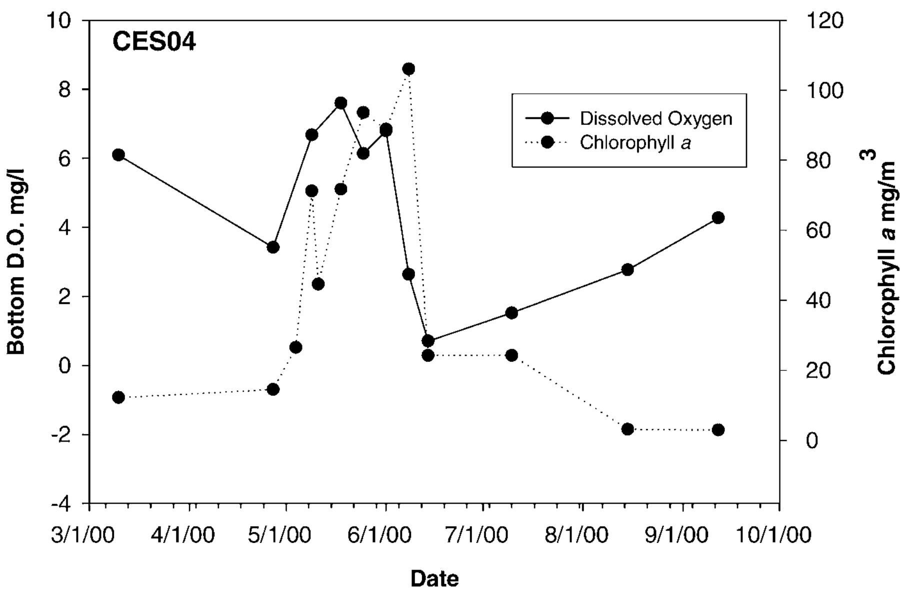



FIG. 5. Time series of chlorophyll *a* and dissolved oxygen in bottom water at station CES04 in the upper estuary (see Figure 2 for location). Note the marked decline in dissolved oxygen following a phytoplankton bloom.

TABLE 8. Correlation between chlorophyll *a* and the concentration of dissolved oxygen (log 10) in bottom waters. Monthly Data from CES Data Set POR: 3/99–4/2002. * $p<0.05$, ** $p<0.01$, $n = 33–35$.

| | Chlorophyll *a* | | |
|---|---|---|---|
| | Lag in Months | | |
| Region | 0 | 1 | 2 |
| Upper Estuary | −0.041 | −0.534** | −0.633** |
| Mid-Estuary | 0.009 | −0.170 | −0.359* |
| Lower Estuary | −0.286 | −0.458** | −0.266 |

*a* explained the majority of variation. The contribution of color to $K_d$ ranged from 20–30% depending on location and chlorophyll *a* from 10–25%. TSS accounted for 17% of the total light extinction in the upper estuary.

*Chlorophyll and freshwater discharge*—Freshwater discharge at S-79 also explained variation in the concentration of chlorophyll *a* in the downstream estuary (FIG. 6). The regional relationships were the same as those for loading: positive in the lower estuary and San Carlos Bay, not significant in the mid-estuary and negative in the upper estuary. In contrast to loading, there was apparent curvature in the relationships with discharge. In the mid and lower estuary and San Carlos Bay the concentration of chlorophyll *a* increased with increasing discharge up to a maximum and then began to decrease. In the mid-estuary this inflection point occurred at a 30-day average discharge of about 85 $m^3$/sec (3000 cfs). To the right of the inflection point, chlorophyll *a* concentration was positively correlated with discharge ($r = 0.384$, $p<0.001$, $n = 90$) and to the left negatively correlated ($r = –0.463$, $p<0.02$, $n = 25$). In the lower estuary ($r = 0.326$, $p<0.01$, $n = 131$) and San Carlos Bay ($r = 0.390$, $p<0.01$, $n = 109$) the concentration of chlorophyll *a* was positively correlated at discharges of less than 127–141 $m^3$/sec (4500–5000 cfs). At higher flows linear correlation coefficients were negative but not statistically significant (lower estuary $r = –0.400$, $p<0.15$, $n = 10$; San Carlos Bay $r = –0.533$, $p<0.12$, $n = 10$).

Analyzing the relationships on a seasonal basis yielded results similar to those for nutrient loading. In the upper estuary, lower estuary and San Carlos Bay both wet

TABLE 9. Mean (± SD) light attenuation coefficient ($K_d$) and percentage of total variation in the light extinction coefficient explained by variation (Var) in color, chlorophyll *a* and total suspended solids (TSS) in stepwise multiple regressions. Also given is the mean (± SD) percentage of light extinction attributable to each parameter calculated from the regression equations. Significance level for entry in the model was $p<0.05$ in all cases except for the Upper Estuary where $p<0.10$.

| | Color | | Chlorophyll *a* | | TSS | | |
|---|---|---|---|---|---|---|---|
| Percentage | Var | $K_d$ | Var | $K_d$ | Var | $K_d$ | Mean $K_d$ |
| Upper Estuary | 13 | 20 ± 13 | 0 | 0 | 11 | 17 ± 12 | 2.91 ± 0.73 |
| Mid-Estuary | 72 | 30 ± 19 | 12 | 12 ± 10 | 0 | 0 | 2.25 ± 0.94 |
| Lower Estuary | 78 | 23 ± 18 | 11 | 10 ± 10 | 0 | 0 | 1.55 ± 0.75 |
| San Carlos Bay | 0 | 0 | 68 | 25 ± 17 | 0 | 0 | 1.21 ± 0.39 |

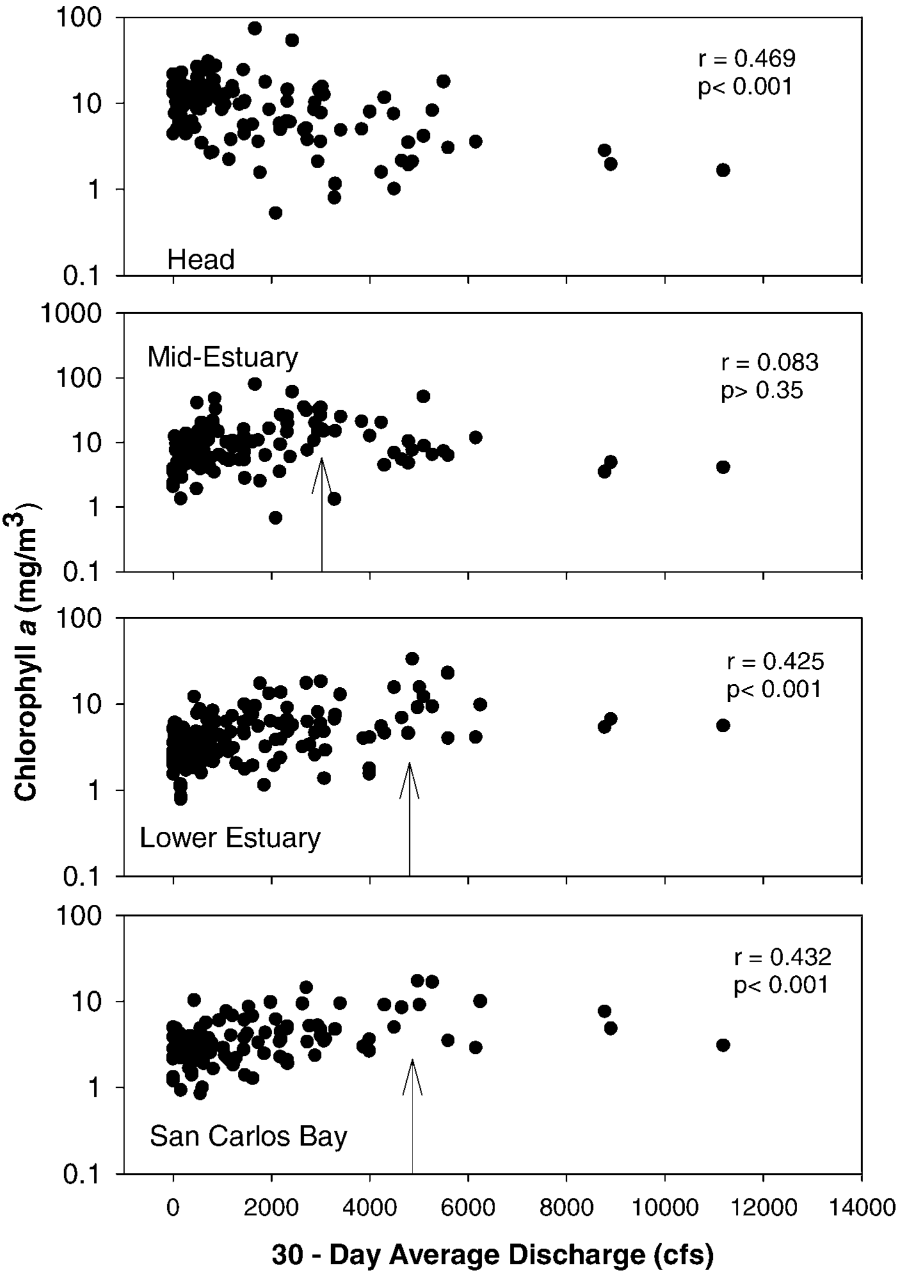



FIG. 6. Concentration of chlorophyll *a* as a function of discharge of freshwater at S-79 for the 30-days prior to sampling. Arrows indicate inflection point. r = Pearson correlation coefficient.

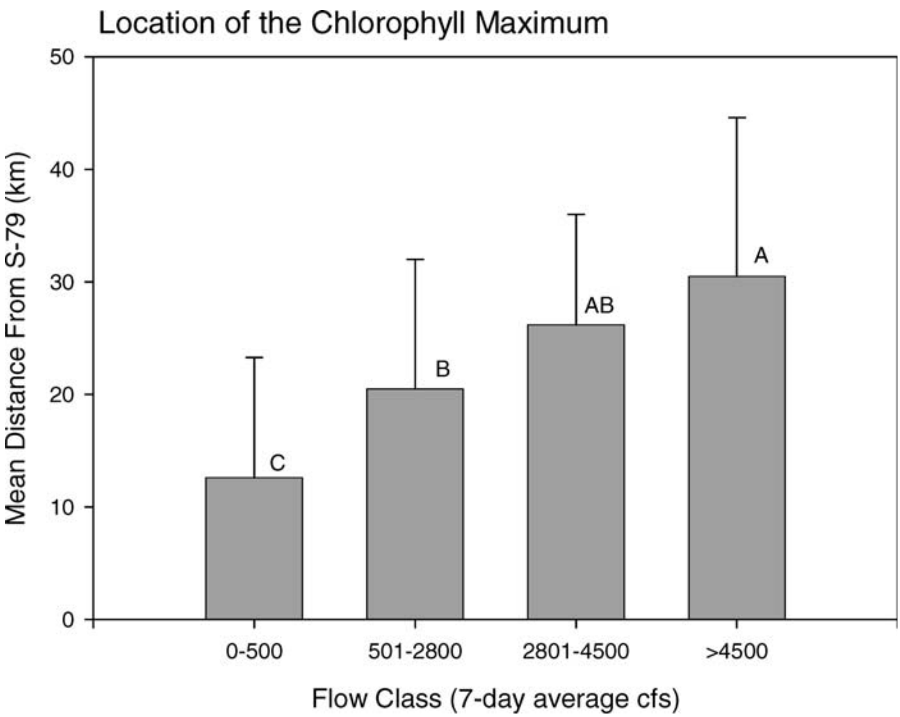



FIG. 7. Mean distance of the chlorophyll *a* maximum downstream of S-79 as a function of freshwater discharge at S-79.

and dry season relationships were the same as the overall. In the mid-estuary, the relationship was weakly positive in the dry season ($r = 0.210$, $p<0.08$) and not significant in the wet season.

The rate of discharge at S-79 also influenced the position of maximum chlorophyll *a* found on a sampling date in the downstream estuary. The correlation between position of the maximum (in km from S-79) and discharge averaged over the 7 days prior to sampling was $r = 0.526$ ($p<0.001$, $n = 91$ sampling events). This pattern is illustrated in Figure 7 where the location data have been classified into several ecologically based flow classes. The mean distance of the chlorophyll maximum from S-79 increased as flow increased.

TABLE 10. Comparison of average daily nutrient loads (kg/day) at S-79. Annualized estimates from the ERD study are the average of the wet and dry season mean daily loads.

| | ERD Study | | | This Study |
|---|---|---|---|---|
| | Wet Season | Dry Season | Annual | Annual |
| TN | 11,051 | 2,408 | 6,730 | 7,018 |
| DIN | 2,476 | 608 | 1,542 | 1,385 |
| TP | 1,040 | 355 | 698 | 657 |
| DIP | 474 | 211 | 343 | 426 |

DISCUSSION—*Nutrient loading*—Annual loads of total nitrogen delivered to the Caloosahatchee at S-79 calculated in this study agree well with those estimated previously by Janicki Environmental (2003). Although the period of record examined here was longer than the Janicki study, agreement is remarkable for the period of overlap (1990–2002). Discharge at S-79 explained most of the variance in loading and the good agreement between studies most likely stems from the use of similar discharge data and similar methods for calculating loads.

Environmental Research and Design (2003) measured nutrient loads at S-79 intermittently during 2000–2002 and derived mean daily estimates for the wet and dry seasons. The ERD study shows that most of the annual nutrient load is delivered during the wet season (Table 9). The annually averaged daily loads reported here fall within the range of seasonal loads reported by ERD (2003). When an annualized daily load is derived from the ERD data, means compare well with this study (Table 9).

The present study examined nutrient loads at S-79 only. There are other prominent nutrient inputs to the Caloosahatchee including waste water treatment facilities (WWTF). In the 1980s and early 1990s, five WWTFs discharged directly into the Caloosahatchee Estuary (Baker 1990). By 2000, the effluent from the Cape Coral plant had been reclaimed and under ordinary circumstances discharges to the Caloosahatchee had ceased.

The ERD (2003) study compared nutrient loading at S-79 with that from the remaining four plants. In general, average daily nutrient loads at S-79 exceeded those from all 4 plants combined by an order of magnitude in both the wet and dry seasons. This is not to say that loading from WWTFs is never important. During drought conditions when no flow and hence no loading occurs at S-79, WWTFs can dominate nutrient loading (ERD 2002).

*Differences between periods*—Hydrologically, the three periods ranged from relatively dry in Period 1 (1986–1989) to relatively wet in Period 2 (1994–1996) with Period 3 (1999–2003) being intermediate and may be viewed as capturing a range of natural variation. There were statistical differences in water quality between periods (Table 4). Whether these differences reflect natural variation or temporal changes caused by other factors remains unknown in the absence of a time series of appropriate length. The question of whether the differences obviated other analyses presented here deserves consideration. Certainly, relationships between nutrient loading or freshwater discharge at S-79 and chlorophyll *a* in the downstream estuary were not affected since all three exhibited no trend over the period of record. Other analyses (dissolved oxygen, light attenuation) relied on smaller data sets taken recently, within Period 3 (1999–2003). The spatial analyses of water quality may have been influenced but results agree with all previous investigations of the system (see below).

*Water quality and nutrient limitation*—The distribution of nutrients and other water quality parameters reported here (Table 5) is similar to those described previously (McPherson and Miller, 1990; Doering and Chamberlain, 1998; Doering and Chamberlain, 1999). The spatial distribution of nutrients and color largely reflects freshwater input at S-79: concentrations are high near the structure and decrease as proximity to clearer ocean water increases. Water clarity as measured by secchi disk showed the same pattern. TSS shows the opposite pattern suggesting a major input of suspended sediment from the Gulf of Mexico (Doering and Chamberlain, 1999; McPherson and Miller, 1990). This pattern also could arise from greater resuspension of sediments in saltier more open regions of the system such as San Carlos Bay and Pine Island Sound.

Understanding nutrient limitation of primary productivity can be considered a keystone of the study of eutrophication (Smith et al., 1999). Restricting the loading of the limiting nutrient(s) should control eutrophication. Eutrophication of the Caloosahatchee has been a concern since the late 1970s and early 1980s. A waste load allocation study conducted by the Florida Department of Environmental Regulation concluded that the estuary had reached its nutrient loading limits as indicated by elevated chlorophyll *a* and depressed dissolved oxygen concentrations (DeGrove, 1981). Nutrient addition experiments conducted in October during high flow conditions indicated nitrogen limitation of phytoplankton growth in the upper reaches and phosphorus limitation in the lower reaches of the Caloosahatchee Estuary. McPherson and Miller (1990) and McPherson and coworkers (1990) concluded that nitrogen was likely the most limiting nutrient in the Charlotte Harbor estuarine system because concentrations of inorganic nitrogen frequently fell below detection limits and atomic ratios (N:P) were generally less than 3:1 and well below the traditionally accepted ratio for balanced uptake by phytoplankton of 16:1 (Day et al., 1989). While the analysis of inorganic nutrient concentrations presented here indicates nitrogen is most likely to limit phytoplankton productivity, potential limitation by phosphorus may also occur, especially in San Carlos Bay (Table 6). Median nutrient ratios (Table 4) were consistent with these conclusions. These ratios were less than 16:1 in all regions during all periods except in San Carlos Bay during Period 2 (DIN:DIP = 19.9). Since the Caloosahatchee River at S-79 is a major source of nutrients to the estuary there is a general increase in the potential for nutrient limitation by either N or P as distance from S-79 increases (Table 6).

*Chlorophyll and eutrophication*—If chlorophyll *a* is a good an indicator of nutrient enrichment or eutrophication in the Caloosahatchee Estuary then both direct and indirect effects consistent with the Phase II (Cloern 2001) model need to be established. Establishing a direct relationship between nutrient loading and chlorophyll *a* concentrations has been problematic for estuarine systems (Nixon and Pilson 1983; Monbet 1992). This may stem from a paucity of data or a weak response to loading (Nixon and Pilson 1983). Monbet (1992) argues that nutrient loadings control nutrient concentrations and the nutrient concentration actually controls phytoplankton standing crop. Statistical analysis of data from the Caloosahatchee demonstrates a direct effect of nutrient input on chlorophyll *a*: on monthly time scales, increases in nutrient loading are associated with increases in chlorophyll *a* concentration in the lower estuary and San Carlos Bay (FIG. 4). In these regions, the relationship is seasonally robust. The expected relationship does not hold in the upper and mid estuarine regions and this is discussed below. In the lower estuary and San Carlos Bay, nutrient loading at S-79 explains only 17–35% of the variability in chlorophyll *a* concentration (FIG. 4, Table 7). While these relationships imply that reducing the nutrient load could decrease chlorophyll *a* in both wet and dry seasons, they are not of predictive significance.

The Phase II conceptual model allows for cascading secondary effects of increased chlorophyll *a* and two were investigated here: effects on dissolved oxygen and light extinction. The classic link between increases in chlorophyll *a* in surface waters and declining oxygen concentrations in bottom waters is amply demonstrated for the Caloosahatchee Estuary by the data presented in Figure 7 and Table 8.

The water quality parameters that influenced light extinction varied spatially in the estuary and San Carlos Bay (Table 9). Suspended solids acounted for 17% of the total in the upper estuary. Non-chlorophyll suspended matter (NSM) can be the major attenuator of light in the Charlotte Harbor system (McPherson and Miller 1987; 1994). We made no attempt to directly measure or calculate the contribution NSM to light extinction. We included TSS as a surrogate in the regression analysis. TSS is not a good indicator of light extinction caused by NSM (McPherson and Miller, 1987), and this may explain why TSS did not appear as a more prominent component of light extinction in the estuary or San Carlos Bay.

Water quality in the Caloosahatchee Estuary is significantly influenced by the tannin stained freshwater input at S-79 (Doering and Chamberlain, 1999). In this region, color accounted for 20–30% of the light attenuation. This estimate agrees well with those (mean 22%, range 4–93%) reported for the greater Charlotte Harbor system by McPherson and Miller (1994).

Chlorophyll *a* accounted for 25% of the light attenuation in San Carlos Bay. While this estimate also agrees with those reported for the greater Charlotte Harbor system by McPherson and Miller (1994, mean 16%, range 0–43%), it exceeds that reported by Dixon and Kirkpatrick (1999) for San Carlos Bay (3%). They found color and turbidity to be most important, respectively accounting for 60% and 37% of light attenuation.

Statistics may help explain the differing results. In our study, color was correlated with light extinction in San Carlos Bay ($r = 0.740$, $p<0.05$) but not selected in a stepwise multiple regression because the correlation with chlorophyll was stronger ($r = 0.824$, $p<0.05$). Nevertheless, based on the linear regression of $K_d$ on color, it can be calculated that color may have accounted for $19 \pm 15\%$ of light attenuation in San Carlos Bay during the ERD study. There also appear to be concentration differences between the two studies. In the Dixon and Kirkpatrick (1999) study color concentrations ranged from 15–60 pcu, with an average of 31.8 pcu and a median of 30 pcu ($n = 6$). In the ERD study Bay wide averages used in the analysis ranged from 0.5–73 pcu with a mean of 14.7 pcu and a median of 11.8 pcu ($n = 24$). On average the concentration of color during the Dixon and Kirkpatrick (1999) study was twice that of the ERD study. Chlorophyll *a* concentrations appeared similar with a median of 5 μg/l , a mean of 6.1 μg/l and range of 2.7–13.4 μg/l for the Dixon and Kirkpatrick study, compared with a median of 4.5 μg/l a mean of 7.5 μg/l and a range of 0.5 to 25.4 μg/l for the ERD study.

The differing results of these studies have important management implications. There are extensive seagrass beds in San Carlos Bay composed primarily of *Thalassia testudinum* Banks ex Konig and *Halodule wrightii* (Acherson) (Chamberlain and Doering, 1998). A comparison of sites in the Charlotte Harbor Estuarine system, including San Carlos Bay, showed that the depth of the deep edge of bed (DDEB) depended on light attenuation (Dixon and Kirkpatrick, 1999). The DDEB decreased as light attenuation increased. The contrasting results above suggest that reductions in chlorophyll *a* attendant with reductions in nutrient loads will not always result in improved light availability in San Carlos Bay.

*Freshwater discharge as a filter*—In the Phase II conceptual model of eutrophication, filters act to modulate the response of an estuary to changes in nutrient loading. For example, San Francisco Bay, a highly turbid estuary, is less responsive to nutrient addition than Chesapeake Bay because light is more often limiting (Cloern, 2001). Turbidity is the filter.

In the Caloosahatchee, chlorophyll *a* responds to both nutrient loading and freshwater discharge at S-79. Because the Caloosahatchee River at S-79 is a major source of nutrients and because freshwater discharge explains much of the variability in nutrient loading at S-79 (Table 2), it is difficult to determine which of the two influence chlorophyll *a*. There is some evidence that freshwater discharge may modulate or "filter" the response of chlorophyll *a* through a 'wash out' effect (Welsh et al., 1972).

In the upper estuary the responses of chlorophyll *a* to nutrient loading and freshwater discharge are both negative. The negative relationship between nutrient loading and chlorophyll *a* in the upper estuary is counter to expectation if nutrient supply were limiting. Being closest to a major source, nutrients are least likely to limit chlorophyll in this region (Table 6). The negative relationship with freshwater discharge observed in this region is consistent with the wash out hypothesis. Finally, changes in horizontal location of the chlorophyll maximum are also consistent with this hypothesis. The maximum occurs in the upper estuary at low discharges (Fig. 7) and moves down stream as discharge increases.

In the mid and lower estuary and San Carlos Bay, chlorophyll *a* – freshwater discharge relationships also exhibit an inflection point that suggests 'wash out'. At higher discharges (85 $m^3$/sec or 3000 cfs in the mid-estuary, 127–141 $m^3$/sec or 4500–5000 cfs in the lower estuary and San Carlos Bay), chlorophyll *a* decreases as discharge increases. This inflection point was not evident in relationships with nutrient loading.

Relationships between chlorophyll *a* and both nutrient loading and freshwater discharge in the mid-estuary varied seasonally, being slightly positive in the dry season and unrelated in the wet season. The lack of a negative relationship in the wet season was due to variability in the data. At lower flows and loadings, both relatively high and low chlorophyll *a* values occurred and these spanned the range observed at higher flows.

The tannic, dark color of freshwater discharge may modulate the response of chlorophyll *a* to enhanced nutrient supply through light limitation. McPherson and coworkers (1990) measured phytoplankton biomass and productivity throughout the Charlotte Harbor system including a station at the near mouth of the Caloosahatchee in San Carlos Bay. They explained the responses of phytoplankton biomass and productivity to freshwater inflow as an interaction between nutrient and light availability. Increased freshwater inflow increases nutrient supply but also increases color, hence decreasing light availability. Phytoplankton biomass and productivity increase where nutrient rich colored water has been diluted enough for light to become sufficiently available. These conditions obtain in the mid-salinity regions of an estuary (McPherson et al., 1990). The present study suggests that "wash out" influences the accumulation of phytoplankton biomass. In the Caloosahatchee, the rate of freshwater inflow comprises another interacting variable. In general, the spatial distribution of chlorophyll *a*, with a peak in the mid-estuary suggests that it is here that conditions most often become favorable for the growth and accumulation of phytoplankton.

This interaction between color and phytoplankton productivity may also determine where and when each of these water quality constituents becomes an important contributor to light extinction. Ultimately, this interaction, moderated by freshwater inflow, may help explain why the contributions of chlorophyll *a* and color to light attenuation appear to vary spatially and temporally between studies conducted in different years.

In summary, correlations between chlorophyll *a* and nutrient loading, dissolved oxygen and light extinction recommend its use as an indicator of eutrophication in the Caloosahatchee Estuary and San Carlos Bay. However, useful interpretation of the response of this indicator to future changes in nutrient loading must account for the modulating effects of freshwater discharge exerted through flushing and reductions in light availability. These modulating effects are especially germane to changes in nutrient loads at S-79 caused by alterations in the rate of freshwater discharge.

ACKNOWLEDGMENTS—We thank Matt Giles, Tammy Lyday, Tomma Barnes and Dan Crean for assistance in the field. We also thank the Lee County Environmental Lab and The Southeastern Environmental Research Center for collecting and analyzing water quality samples. Comments from two anonymous reviewers greatly improved the manuscript.

## LITERATURE CITED

BAKER, B. 1990. Draft Caloosahatchee water quality based effluent limitations documentation (Lee County). Florida Dept. Env. Reg. Water Quality Tech. Ser. 2. No. 121, 18 pp.

BRICKER, S. B., C. G. CLEMENT, D. E. PIRHALLA, S. P. ORLANDO, AND D. R. G. FARROW. 1999. National Estuarine Eutrophication Assessment: Effects of nutrient enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD. 71 pp.

CHAMBERLAIN, R. H. AND P. H. DOERING. 1998. Freshwater inflow to the Caloosahatchee Estuary and the resource-based method for evaluation. Pp. 81–90. *In*: Proceedings of the Charlotte Harbor Public Conference and Technical Symposium; 1997 March 15–16; Punta Gorda, FL. Charlotte Harbor National Estuary Program Technical Report No. 98-02. 274 p.

CLOERN, J. E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecol. Prog. Ser. 210: 223–253.

DAY, J. W., JR., C. A. S. HALL, W. M. KEMP, AND A. YANEZ-ARANCIBIA. 1989. Estuarine Ecology, John Wiley and Sons, New York, 558 pp.

DEGROVE, B. 1981. Caloosahatchee River waste load allocation documentation. Florida Dept. of Env. Reg., Water Quality Tech ser. 2. No. 52 17 pp.

DIXON, L. K. AND G. J. KIRKPATRICK. 1999. Causes of light attenuation with respect to seagrasses in Upper and lower Charlotte Harbor. Final Report. Submitted to: Southwest Florida Water Management District, Surface Water Improvement and Management Program. 7601 US Hwy 301 North, Tampa, Florida.

DOERING, P. H., C. A. OVIATT, J. H. MCKENNA, AND L. W. REED. 1994. Mixing behavior of dissolved organic carbon and its potential biological significance in the Pawcatuck River Estuary. Estuaries 17(3): 521–536.

——— AND R. H. CHAMBERLAIN. 1998. Water quality in the Caloosahatchee Estuary, San Carlos Bay and Pine Island Sound. Pp. 229–240. *In*: Proceedings of the Charlotte Harbor Public Conference and Technical Symposium; 1997 March 15–16; Punta Gorda, FL. Charlotte Harbor National Estuary Program Technical Report No. 98-02.

——— AND R. H. CHAMBERLAIN. 1999. Water quality and the source of freshwater discharge to the Caloosahatchee Estuary, FL. Wat. Resour. Bull. 35: 793–806.

———, R. H. CHAMBERLAIN, AND D. E. HAUNERT. 2002. Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee Estuary, Florida. Estuaries 25(6B): 1343–1354.

ENVIRONMENTAL RESEARCH AND DESIGN. 2002. Caloosahatchee Water quality data collection program. Interpretive report No. 2–Year 2. Prepared for: South Florida Water Management District. 3301 Gun Club Rd. West Palm Beach, FL 33406.

ENVIRONMENTAL RESEARCH AND DESIGN. 2003. Caloosahatchee Water quality data collection program. Final Interpretive Report for Years 1–3. Prepared for: South Florida Water Management District. 3301 Gun Club Rd. West Palm Beach, FL 33406.

EYRE, B. D. 2000. Regional evaluation of nutrient transformation and phytoplankton growth in nine river-dominated sub-tropical east Australian estuaries. Marine Ecol. Prog. Ser. 205: 61–83.

FISHER, T. R., L. W. HARDING, JR., D. W. STANLEY, AND L. G. WARD. 1988. Phytoplankton, nutrients and turbidity in the Chesapeake, Delaware, and Hudson estuaries. Est. Coast. Shelf Sci. 27: 61–93.

FLAIG, E. G. AND J. CAPECE. 1998. Water use and runoff in the Caloosahatchee watershed. Pp. 73–80. *In*: Proceedings Charlotte Harbor Public Conference and Technical Symposium: 1997 March 15–16; Punta Gorda, FL. Charlotte Harbor National Estuary Program Technical Report No. 98-02. 274 p.

GRAY, J. S. 1992. Eutrophication in the sea. Pp. 3–15. *In*: COLUMBO, G., I. FERRARI, V. U. CECCHERELLI AND R. ROSSI (ed.), Marine Eutrophication and Population Dynamics. Olse and Olsen, Fredensborg.

HARLAN, M. M. 1995. Changes in major plant groups following nutrient enrichment. Pp. 173–187. *In*: MCCOMB, A. J. (ed.), Eutrophic Shallow Estuaries and Lagoons. CRC Press, Inc. Boca Raton, FL.

JANICKI ENVIRONMENTAL. 2003. Development of Critical Loads for the C-43 Basin, Caloosahatchee River. Prepared for: Florida Department of Environmental Protection, 2600 Blair Stone Road Tallahassee, Florida 32399-2400. 17 pp.

MCPHERSON, B. F. AND R. L. MILLER. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, southwestern Florida. Est. Coastal Shelf Sci. 25: 721–737.

——— AND R. L. MILLER. 1990. Nutrient distribution and variability in the Charlotte Harbor estuarine system, Florida. Wat. Resour. Bull. 26: 67–80.

——— AND R. L. MILLER. 1994. Causes of light attenuation in Tampa Bay and Charlotte Harbor, Southwestern Florida. Wat. Resour. Bull. 30: 43–53.

———, R. T. MONTGOMERY AND E. E. EMMONS. 1990. Phytoplankton productivity and biomass in the Charlotte Harbor estuarine system, Florida. Wat. Resour. Bull. 26: 787–800.

MEEUWIG, J. J., J. RASMUSSEN, AND R. H. PETERS. 1998. Turbid waters and clarifying mussels: their moderation of Chl:nutrient relations in estuaries. Mar. Ecol. Prog. Ser. 171: 139–150.

MONBET, Y. 1992. Control of phytoplankton biomass in estuaries: A comparative analysis of microtidal and macrotidal estuaries. Estuaries 15(4): 563–571.

NIXON, S. W. AND M. E . Q. PILSON. (1983). Nitrogen in estuaries and marine ecosystems. Pp. 565–648 *In*: CARPENTER, E. J., CAPONE, D. G. (eds.), Nitrogen in the marine environment. Academic Press, New York.

———, J. W. AMMERMAN, L. P. ATKINSON, V. M. BEROUNSKY, G. BILLEN, W. C. BOICOURT, W. R. BOYNTON, T. M. CHURCH, D. M. DITORO, R. ELMGREN, J. H. GARBER, A. E. GIBLIN, R. A. JAHNKE, N. J. P. OWENS, M. E. Q. PILSON, AND S. P. SEITZINGER. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry 35: 141–180.

OFFICER, C., T. J. SMAYDA, AND R. MANN. 1982. Benthic filter feeding: A natural eutrophication control. Mar. Ecol. Prog. Ser. 9: 203–210.

PALMER, M., E. BERNHARDT, E. CHORNESKY, S. COLLINS, A. DOBSON, C. DUKE, B. GOLD, R. JACOBSON, S. KINGSLAND, R. KRANZ, M. MAPPIN, M. L. MARTINEZ, F. MICHELI, J. MORSE, M. PACE, M. PASCUAL, S. PALUMBI, O. J. REICHMAN, A. SIMONS, A. TOWNSEND, AND M. TURNER. 2004. Ecology for a crowded planet. Science 304: 1251–1252.

RYTHER, J. H. AND DUNSTAN, W. M. 1971. Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171: 1008–1013.

SAS INSTITUTE INC. 1989. SAS/STAT User's guide, Version 6, Cary, NC: SAS Institute Inc.

SMITH, S.V., D. P. SWANEY, L. TALAUE-MCMANUS, J. D. BARTLEY, P. T. SANDHEI, C. J. MCLAUGHLIN, V. C. DUPRA, C. J. CROSSLAND, R. W. BUDDEMEIER, B. A. MAXWELL, AND F. WULFF. 2003. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. Bioscience 53: 235–245.

SMITH, V. H., G. D. TILMAN, AND J. C. NEKOLA. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine and terrestrial ecosystems. Environ. Poll. 100: 179–196.

TOMASKO, D. A., C. J. DAWES, AND M. O. HALL. 1996. The effects of anthropogenic enrichment on Turtle Grass (*Thalassia testudinum*) in Sarasota Bay, Florida. Estuaries 19(2B): 448–456.

TWILLEY, R., W. KEMP, K. STAVER, J. COURT STEVENSON, AND W. BOYNTON. 1985. Nutrient enrichment of estuarine submersed vascular plant communities. 1. Algal growth and effects on production of plants and associated communities. Mar. Ecol. Prog. Ser. 23: 179–191.

WELSH, E. B., R. M. EMERY, R. I. MATSUDA, AND W. A. DAWSON. 1972. The relation of periphytic and planktonic algal growth in an estuary to hydrographic factors. Limnol. Oceanogr. 17: 731–737.

Florida Scient. 69(00S2): 51–72. 2006
Accepted: March 10, 2006

# COMPARISON OF LIGHT LIMITING WATER QUALITY FACTORS IN SIX FLORIDA AQUATIC PRESERVES

Judith A. Ott[1], Renee M. Duffey[1], Stephanie E. Erickson[2], Katie S. Fuhr[3], Bobbi A. Rodgers[4], and Melynda A. Schneider[1]

[1]Florida Department of Environmental Protection, Charlotte Harbor Aquatic Preserves, 12301 Burnt Store Road, Punta Gorda, FL 33955
[2]Florida Department of Environmental Protection, Estero Bay Aquatic Preserve, 700-1 Fisherman's Wharf, Fort Myers Beach, FL 33931
[3]City of Naples, Division of Natural Resources, 280 Riverside Circle, Naples, FL 34102
[4]Charlotte Harbor Environmental Center–Cedar Point, PO Box 5197 Englewood, FL 34224

Abstract: *Correlations of Secchi depth to color, turbidity and chlorophyll* a *within and between eight estuaries comprising the Charlotte Harbor estuarine complex were examined. Secchi depth was used as an indicator of light availability for seagrass growth, a primary habitat in the six Florida aquatic preserves in the Charlotte Harbor region. Six years (1998–2004) of monthly water quality data from the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network were examined. Results showed significant differences between the eight estuaries, two seasons and six years for each of the four parameters. Mean Secchi depth values for the eight estuaries ranged from 1.0 m to 1.8 m. Significant correlations were found between Secchi depth and the combination of color, turbidity and chlorophyll* a *in six of the estuaries, explaining 26% to 53% of Secchi depth change. Color was the strongest predictor of Secchi depth in 6 estuaries and turbidity was the greatest predictor in two of the estuaries. Based on the results, additional water quality questions have been posed which will be addressed in pending status and trends analyses of the data. The volunteer water monitoring program enhances resource management and community involvement in the six aquatic preserves in the Charlotte Harbor region.*

*Key Words:* Charlotte Harbor, aquatic preserves, seagrasses, light attenuation, water quality, water clarity, color, turbidity, chlorophyll *a*, estuary

This study examined the correlations of water clarity (as Secchi disc depth) to color, turbidity and chlorophyll *a* (as a measure of phytoplankton) within and between the eight estuaries comprising the Charlotte Harbor estuarine complex in southwest Florida. The three questions asked were: 1) what is the water clarity throughout the estuary region and how does it compare to other Florida estuaries; 2) do color, turbidity and chlorophyll *a* contribute to reductions in water clarity throughout the region; and 3) which of these three factors is the most predictive of water clarity in each estuary.

The aquatic preserves in the region include: Lemon Bay, Gasparilla Sound/ Charlotte Harbor, Cape Haze, Pine Island Sound, Matlacha Pass and Estero Bay. Aquatic preserves are areas of exceptional submerged resources, established by the state legislature to be preserved in natural conditions through resource management, research and education. Effective resource management in the aquatic preserves depends on an accurate assessment of resource health, including submerged resources and water quality. Sustainability of the resources requires identification and prioritization of critical habitat and water quality concerns, locations, trends, sources and needed corrective management actions. Throughout the local aquatic preserves, resource distribution and health, estuary physiography and watershed land use vary widely, requiring the need for thorough water quality monitoring and interpretation. Therefore, resource-based management goals should be developed specifically for each aquatic preserve. Throughout southwest Florida, seagrass distribution and abundance serve as useful indicators of estuarine health (Corbett, et al., 2005; Tomasko, et al., 2005; CHNEP, 2005).

This initial study focused on water clarity as an indicator of light availability for seagrasses. Emphasis was placed on light availability because of its well documented relationship to seagrass health, areal extent and maximum depth of seagrass growth (Miller and McPherson, 1995; Duarte, 2002). Seagrasses comprise one of the largest and most productive submerged habitats in the Charlotte Harbor Aquatic Preserves (FDNR 1983; FDNR 1992; Dawes et al., 2004; Tomasko et al., 2005; Corbett, 2006) and reflect the overall health of the estuaries (Corbett et al., 2005). The average depth at the deep edge of seagrass growth varies throughout the region from approximately 0.8 m near the mouth of the Peace and Myakka Rivers to approximately 1.8 m in Pine Island Sound (Ott et al., 2003).

Light availability for seagrasses was characterized as water clarity measured by Secchi depth (Kirk, 1983; Miller and McPherson, 1995). Previous studies have shown that in southwest Florida primary light attenuating factors in estuaries include color, turbidity and chlorophyll *a* (Dixon and Kirkpatrick, 1999; Kirk, 1983). Therefore, these parameters were used in this study as indicators of light attenuation. In the Charlotte Harbor region, color is a strong indicator of freshwater inflow, and is inversely proportional to salinity (McPherson and Miller, 1987). Turbidity for this study was measured in NTU and includes both algal and non-algal suspended matter (APHA, 1992). Chlorophyll *a*, as measured in μg/l, serves as an indirect measure of phytoplankton abundance (Dixon and Kirkpatrick, 1999) and total nitrogen levels (Tomasko et al., 2001).

Six years (1998–2004) of data for Secchi depth, color, turbidity, and chlorophyll *a* were evaluated. Data used for this study were collected by the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network (CHEVWQMN). The CHEVWQMN is a long term (since 1998), region-wide (66,773 hectares), monthly, fixed station (46 sites) water quality monitoring program. The monitoring program is a partnership of Florida Department of Environmental Protection's (FDEP) Charlotte Harbor Aquatic Preserves (CHAP), Estero Bay Aquatic Preserve (EBAP), the Charlotte Harbor Environmental Center (CHEC), the Charlotte Harbor National Estuary Program (CHNEP), and local citizens. The program's purpose is to collect consistent, technically sound water quality data throughout the six aquatic preserves to determine baseline conditions and trends in habitat health, which will be used to set resource management goals.

METHODS—*Study site*—The Charlotte Harbor estuarine complex is located in southwest Florida. The 46 CHEVWQMN fixed sampling locations are shown in Figure 1. CHEVWQMN sampling sites

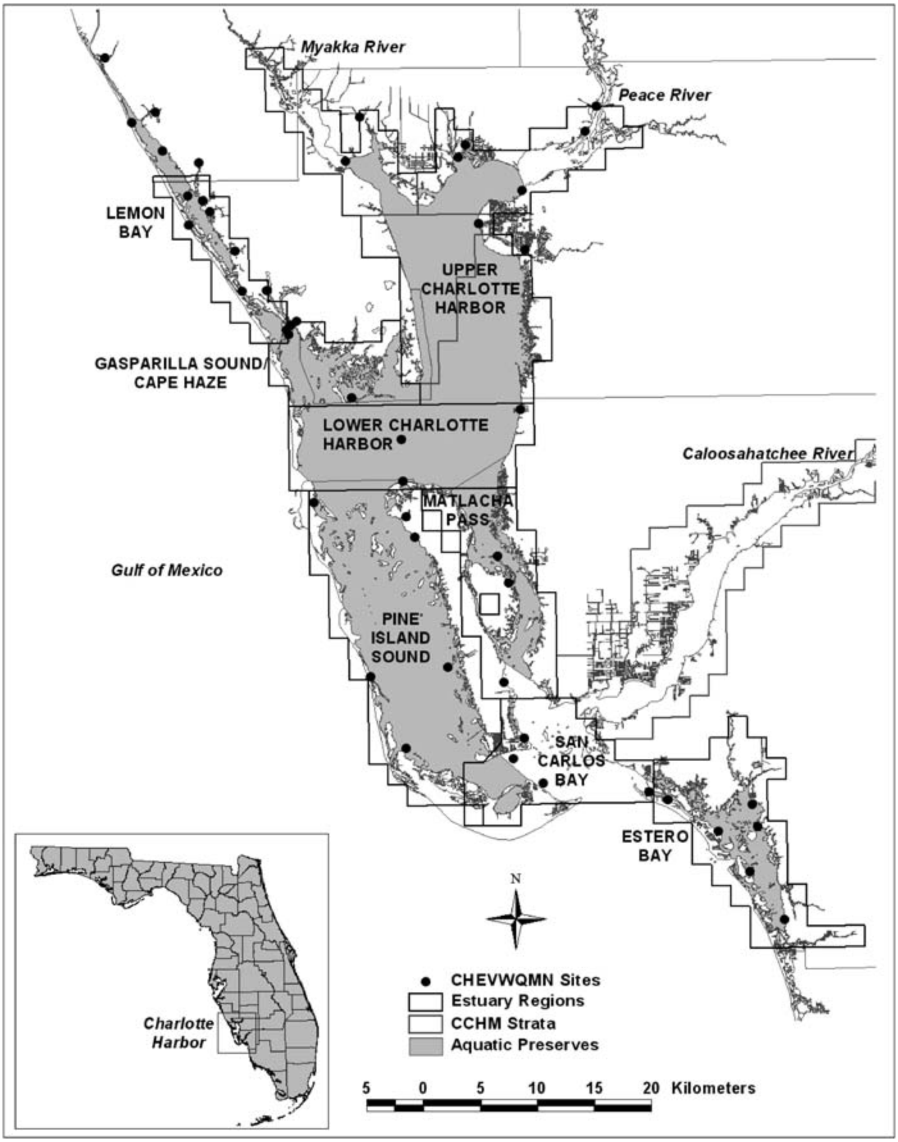



FIG. 1. Sampling Locations of the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network (July 1998–Current).

were grouped into 8 estuary regions based on hydrologic strata established by the interagency Coastal Charlotte Harbor Monitoring Network (CCHMN), to describe homogeneous hydrologic regions (CHNEP, 2004). CHEVWQMN sites, estuaries, CCHMN hydrologic strata and aquatic preserves are summarized in Table 1. Sampling locations emphasize near shore coastal areas, with limited sampling in the open water portions of Charlotte Harbor due to sample transport and travel time constraints. Secchi depth values could not be determined for shallow sites and times when water clarity exceeded water depth.

TABLE 1. Sampling Sites in Each Estuary Region for the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network (July 1998–Current).

| Estuary Region | CHEVWQMN No. of Sites | CCHMN Hydrologic Stratum | Aquatic Preserve |
|---|---|---|---|
| Lemon Bay | 12 | Upper Lemon Bay | Lemon Bay |
| | | Lower Lemon Bay | |
| Gasparilla Sound/Cape Haze | 3 | Cape Haze | Cape Haze |
| | | | Gasparilla S/Charlotte H |
| Upper Charlotte Harbor | 8 | Tidal Myakka R | Gasparilla S/Charlotte H |
| | | Tidal Peace R | |
| | | East Wall Charlotte H | |
| | | West Wall Charlotte H | |
| Lower Charlotte Harbor | 4 | Lower Charlotte H | Gasparilla S/Charlotte H |
| Pine Island Sound | 6 | Pine Island Sound | Pine Island Sound |
| Matlacha Pass | 3 | Matlacha Pass | Matlacha Pass |
| San Carlos Bay | 4 | San Carlos Bay | |
| Estero Bay | 6 | Estero Bay | Estero Bay |
| Total Sites | 46 | | |

*Sampling frequency and period*—CHEVWQMN sampling occurred synoptically each month, within 1 hour of sunrise on the first Monday of each month at all stations simultaneously. The sampling frequency crossed tidal cycles and included the lower Secchi depth and dissolved oxygen values associated with early morning hours. A six year period of monthly dry and rainy season data was used, which included November 1998 through October 2004. The dry season included the months of November through May each year and the rainy season included June through October (Montgomery, 2005).

*Field methods*—Field methods are described in detail in the Comprehensive Quality Assurance Project Plan for the CHEVWQMN (FDEP, 1997). Surface water samples were collected and field measurements were made for 10 physical and chemical parameters which included wind speed and direction, wave height, tide stage, water depth, Secchi depth, temperature, pH, dissolved oxygen and salinity. Water was also collected in clean sample bottles for the following 7 laboratory parameters: chlorophyll *a*, turbidity, color, total phosphorus, total Kjeldahl nitrogen, nitrate/nitrite, and fecal coliform bacteria. The nutrient bottle was pre-acidified. Samples were stored on ice and transported to the laboratory within the maximum holding times. An additional ten percent of field samples were collected for duplicate and blank analyses. Water clarity was measured using a .20 m Secchi disc with a line calibrated at 0.10 m intervals. No depth profiles or bottom samples were collected.

*Laboratory methods*—Laboratory analyses, summarized in Table 2, were conducted by certified laboratories using standard methods (APHA 1992, USEPA 1979). Color was determined by visual

TABLE 2. Certified Laboratories and Analysis Methods Used for the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network (July 1998–Current).

| Analyte | FDEP South Dist Jul 98–Nov 01 | Cape Coral Dec 01–Dec 02 | Tri Tech Jan 03–Dec 03 | FDEP South Dist Jan 04–Current |
|---|---|---|---|---|
| Color | SM 2120 B(1) | SM 2120 B(1) | SM 2120 B(1) | EPA 110.2(2) |
| Turbidity | EPA 180.1(2) | SM 2130 B(2) | EPA 180.1(2) | EPA 180.1(2) |
| Chlorophyll *a* | SM 10200 H(2) | (samples not analyzed) | SM 10200 H(2) | SM 10200 H(2) |

(1) Standard Methods for the Examination of Water and Waste Water, 18th Edition. 1992. AMPHA.
(2) Methods for Chemical Analysis of Water and Wastes. 1979. USEPA.

TABLE 3. Typical Water Quality Values for Florida Estuaries and Suggested Estuary Health Categories.

| Reference | Secchi depth (m)[1][2] | Color (PCU)[1][3] | Turbidity (NTU)[1][4] | Chl *a* (μg/l)[1][5] | Estuary Category |
|---|---|---|---|---|---|
| Typical FL WQ Values[1][6] | ≥1.4 m | ≤10 PCU | ≤1.9 NTU | ≤3.8 μg/l | Above Average |
| Typical FL WQ Values[1][7] | 0.9–1.3 m | 11–25 PCU | 4.1–2.0 NTU | 3.9–7.8 μg/l | Average |
| Typical FL WQ Values[1][8] | <0.8 m | ≥26 PCU | ≥4.2 NTU | >7.9 μg/l | Below Average |
| FL Impaired Waters Criteria[9] | — | — | — | ≥11 μg/l | Impaired |

(1) Typical Water Quality Values for Florida's Lakes, Streams & Estuaries (Hand, 2004).
(2) Based on 69,000 Secchi depth samples, 2,657 stations, 21 Florida estuaries, 1990–2003.
(3) Based on 43,000 color samples, 1,805 stations, 21 Florida estuaries, 1990–2003.
(4) Based on 237,000 turbidity samples, 3,512 stations, 21 Florida estuaries, 1990–2003.
(5) Based on 62,000 chlorophyll *a* samples, 2,338 stations, 22 Florida estuaries, 1990–2003.
(6) Percentile rankings (median values): 70–100% Secchi depth; 0–30% color, turbidity & chlorophyll *a*.
(7) Percentile rankings (median values): 40–69% Secchi depth; 31–60% color, turbidity & chlorophyll *a*.
(8) Percentile rankings (median values): ≤39% of Secchi depth; ≥61% of color, turbidity & chlorophyll *a*.
(9) FL Impaired Waters Criteria. (FDEP, 2002).

comparison using the platinum cobalt method (SM 2120B, EPA 110.2). Turbidity was determined by a turbidity meter, (Hach model number 18900) (EPA 180.1, SM 2130 B). Chlorophyll *a* was determined spectrophotometrically, without pheophytin correction (SM 10200 H). Because of time and funding constraints, chlorophyll *a* analyses were not conducted from December 2001 through Dec 2002. Ten percent of the samples were run as laboratory replicates and blanks.

*Data manipulation and analysis methods*—Data were entered into an Access© data base and reviewed for transcription errors and outliers (greater than 2 standard deviations from mean). Descriptive statistics (medians, means, ranges and standard errors) for each of the eight estuary regions, parameters and seasons were calculated using Excel©. Comparisons of mean values between estuaries, seasons and years for each parameter were made using analysis of variance (ANOVA) with Excel©. Correlations (Pearson's) of chlorophyll *a* to total nitrogen and color to salinity were calculated, with pair wise deletion of missing data points, using SPSS©. Correlations (Pearson's, Spearman's) and regressions between the 4 parameters for each of the estuaries were conducted using Excel© for multiple regressions and using SPSS© for forward stepwise regressions, with list wise deletion of data points. Three dimensional graphs of relationships between color, chlorophyll *a* and turbidity for each estuary were produced using S© software.

*Data interpretation*—As a guide for interpreting water quality values relative to estuary health, median values for each estuary region were compared to typical water quality values for Florida estuaries (Hand, *In Press*; Friedemann et al., 1989). A summary of the ranges of typical values is shown in Table 3. These typical water quality values were based on median values found between 1990 and 2003 in 22 estuaries throughout Florida from more than 1,800 ambient stations and 43,000 samples. For each parameter, median values for each site were used to create a percentile distribution of values found throughout the estuaries and time period sampled. The CHEVWQMN median values for each estuary, as shown in Table 4, were compared to the typical water quality value percentiles. It is recognized that the statewide median values do not take into consideration important geographic and morphological differences in estuaries around the state. However, the values do provide a good overview of the variation of water quality conditions throughout Florida. They also provide information about important parameters, such as turbidity and color, which are not used in other state, regional or national estuary trophic state classification systems such as the Florida Trophic State Index (Friedemann et al., 1989) and NOAA's estuarine eutrophication survey (NOAA, 1996).

TABLE 4. Median and Mean Values for Secchi Depth, Color, Turbidity, and Chlorophyll *a* (November 1998–October 2004).

| | Secchi depth (m)(1) | | | | Color (PCUs)(2) | | | | Turbidity (NTUs)(3) | | | | Chl *a* (μg/l)(4) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Estuary | Median | Mean | SE | n | Median | Mean | SE | n | Median | Mean | SE | n | Median | Mean | SE | n |
| Lemon Bay | 1.1* | 1.1 | 0.02 | 310 | 20* | 25 | 1 | 407 | 2.7* | 3.2 | 0.18 | 408 | 5.2* | 7.4 | 0.45 | 333 |
| Gasparilla S/Cape H | 1.4 | 1.5 | 0.07 | 58 | 15* | 20 | 1.3 | 122 | 3* | 3.5 | 0.28 | 122 | 3.7 | 4.7 | 0.37 | 103 |
| Upper Charlotte H | 0.9* | 1 | 0.02 | 262 | 45* | 66 | 3.2 | 379 | 2.8* | 3.3 | 0.13 | 378 | 6.4* | 9.5 | 0.57 | 310 |
| Lower Charlotte H | 1.5 | 1.8 | 0.09 | 82 | 20* | 27 | 1.7 | 180 | 2.3* | 2.7 | 0.18 | 180 | 4.4* | 5.7 | 0.41 | 148 |
| Pine Island Sound | 1.3* | 1.5 | 0.05 | 130 | 15* | 21 | 1.1 | 289 | 2.8* | 3.9 | 0.21 | 297 | 5.2* | 6.6 | 0.36 | 226 |
| Matlacha Pass | 1.7 | 1.7 | 0.04 | 221 | 25* | 31 | 1.5 | 244 | 2.3* | 2.6 | 0.1 | 244 | 3.6 | 5.3 | 0.46 | 196 |
| San Carlos Bay | 1.4 | 1.5 | 0.04 | 187 | 15* | 21 | 1.3 | 179 | 3.5* | 4.9 | 0.68 | 179 | 4.0* | 5.2 | 0.39 | 146 |
| Estero Bay | 1.1* | 1.2 | 0.04 | 133 | 21* | 28 | 1.4 | 255 | 4.2* | 5.6 | 0.34 | 255 | 4.2* | 5.7 | 0.35 | 201 |
| All Estuaries | 1.2* | 1.3 | 0.02 | 1383 | 20* | 33 | 0.1 | 2064 | 2.8* | 3.7 | 0.09 | 2063 | 4.9* | 6.7 | 0.18 | 1854 |

(1) * values are < 1.4 m Secchi depth found in the most transparent 30% of FL estuaries (Hand, 2004).
(2) * values are > 10 PCU Color found in the least colored 30% of FL estuaries (Hand, 2004).
(3) * values are > 1.9 NTU found in the least turbid 30% of FL estuaries (Hand, 2004).
(4) * values are > 3.8 μg/l Chl *a* found in the healthiest 30% of FL estuaries (Hand, 2004).

RESULTS—*Chlorophyll* a*-nitrogen and color-salinity relationships*—For the region as a whole, chlorophyll *a* and nitrogen were significantly ($p = .01$) positively correlated. In addition color and salinity were significantly ($p = .01$) negatively correlated for each estuary, as well as for the region as a whole. As salinity decreased, color increased.

*Secchi depth*—Secchi depth values varied widely throughout the sampling region and period. ANOVA results for the region as a whole indicated that Secchi depth varied significantly between the 8 estuaries ($p < .0001$), between the 2 seasons ($p < .0001$) and between the 6 years ($p < .0001$). Median and mean Secchi depth values for each estuary are shown in Table 4 and seasonal ranges are shown in Figure 2. Secchi depth values ranged from 0.2 m in Gasparilla Sound/Cape Haze to 3.9 m in San Carlos Bay. The widest range of Secchi depth values occurred in Matlacha Pass in the rainy season, and the narrowest range occurred in Estero Bay during the rainy season. Mean Secchi depth values for each estuary ranged from 1.0 m in Upper Charlotte Harbor to 1.8 m in Lower Charlotte Harbor. Seasonal mean values were significantly different in two of the estuaries: Upper Charlotte Harbor and Matlacha Pass. According to Hand (*In Press*), 30% of Florida estuaries have median Secchi depth values ≥ 1.4 m. Four of the Charlotte Harbor estuaries had median Secchi depth values ≥ 1.4 m, suggesting above average Secchi depth conditions: Gasparilla Sound/Cape Haze, Lower Charlotte Harbor, Matlacha Pass and San Carlos Bay. Forty percent of Florida estuaries have median Secchi depth values < 0.8 m (Hand, *In Press*), but none of the Secchi depth medians in the Charlotte Harbor estuaries were less than 0.8 m.

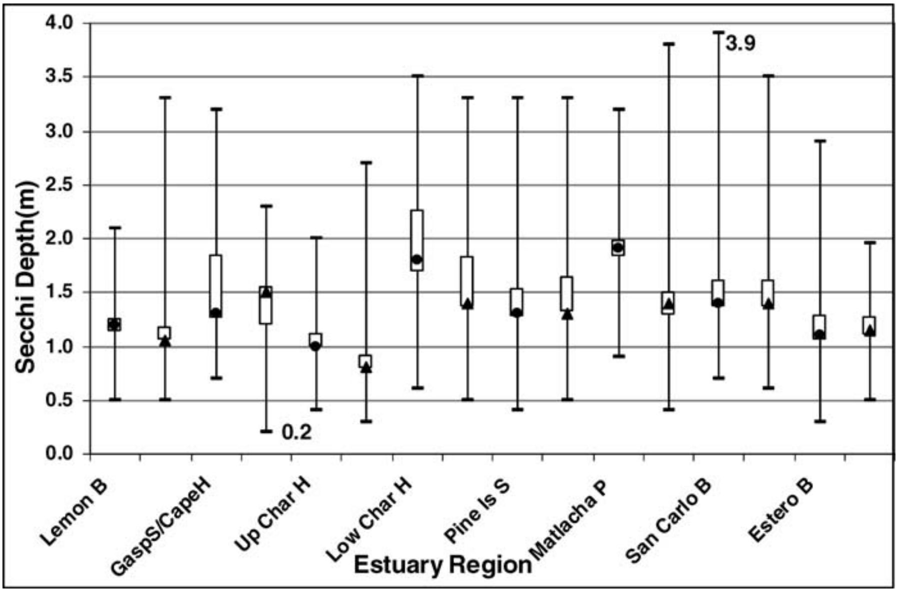



FIG. 2. Seasonal Secchi depth Ranges for Each Estuary Region (November 1998–October 2004). Vertical Bar represents data range. Box represents 95% confidence interval of mean. Symbols represent seasonal medians: ● = Dry Season ▲ = Rainy Season.

*Color*—Color also varied widely throughout the sampling region and period. ANOVA results for the region as a whole indicated that color varied significantly between the 8 estuaries ($p < .0001$), between the 2 seasons ($p < .0001$) and between the 6 years ($p < .0001$). Median and mean color values for each of the estuaries are given in Table 4 and seasonal color ranges are shown in Figure 3. Color values ranged from 3 PCU–400 PCU throughout the sampling area and period. The highest color values were found in Upper and Lower Charlotte Harbor. Mean color values for the estuaries ranged from 20 PCU for Gasparilla Sound/Cape Haze to 66 PCU for Upper Charlotte Harbor. The widest color range was found in Upper Charlotte Harbor for both seasons. Seasonal mean color values were significantly different in all 8 estuaries. According to Hand (*In Press*), 30% of FL estuaries have median color values $\leq$10 PCU, and 40% have color medians $\geq$26 PCU. Seven of the Charlotte Harbor estuaries fell within the intermediate color range of 10–25 PCU. Only Upper Charlotte Harbor had color values greater than 26 PCU, associated with Florida's most highly colored estuaries.

*Turbidity*—Turbidity values varied widely throughout the sampling region and period. ANOVA results for the region as a whole indicated that turbidity varied significantly between the 8 estuaries ($p < .0001$), between the 2 seasons ($p = .03966$) and between the 6 years ($< .0001$). Median and mean estuary turbidity values are given in Table 4 and seasonal ranges are shown in Figure 4. Turbidity values ranged from 1 NTU to 120 NTU, being highest in San Carlos Bay, Lemon

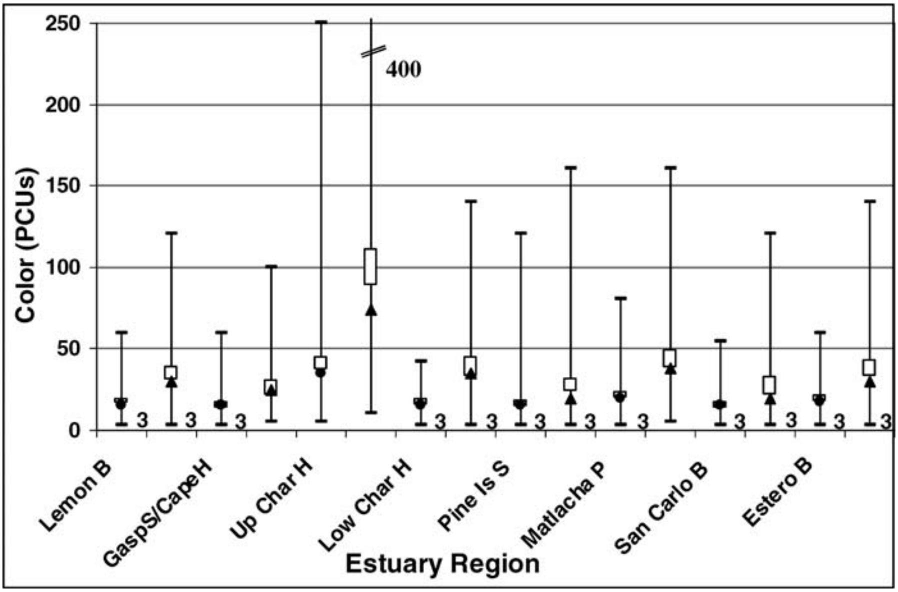



FIG. 3. Seasonal Color Ranges for Each Estuary Region (November 1998–October 2004). Vertical Bar represents data range. Box represents 95% confidence interval of mean. Symbols represent seasonal medians: ● = Dry Season ▲ = Rainy Season.

Bay and Estero Bay. Widest turbidity ranges were found in the San Carlos Bay rainy season, Lemon Bay dry season and Estero Bay dry season. Mean turbidity values for the estuary regions ranged from 2.6 NTU in Matlacha Pass to 5.6 NTU in Estero Bay. Seasonal turbidity means were statistically different in Matlacha Pass and Estero Bay. According to Hand (*In Press*), 30% of Florida estuaries have median turbidity values $\leq$ 1.9 NTU and 40% have turbidity values $>$ 4.2 NTU. Seven of the Charlotte Harbor estuaries had turbidity median values in the intermediate range of 2.0–4.1 NTU, suggesting average conditions relative to Florida estuaries. Only Estero Bay had values exceeding the 4.2 NTU associated with the most turbid 40% of Florida estuaries, suggesting below average conditions.

*Chlorophyll* ~~a~~—ANOVA results for the region as a whole indicated that chlorophyll *a* varied significantly between the 8 estuaries ($p < .0001$), between the 2 seasons ($p = .00013$), and between the 6 years ($p < .0001$). Chlorophyll *a* median and mean estuary values are given in Table 4 and seasonal chlorophyll *a* ranges are shown in Figure 5. Chlorophyll *a* values ranged from 1.0 μg/l to 79.5 μg/l throughout the sampling area and period. Highest values and ranges were found in Lemon Bay, Upper Charlotte Harbor and Matlacha Pass. Mean chlorophyll *a* values ranged from 4.7 μg/l in Gasparilla Sound/Cape Haze to 9.5 μg/l in Upper Charlotte Harbor. Seasonal mean chlorophyll *a* values were significantly different in only one estuary: Pine Island Sound. According to Hand (*In Press*), 30% of Florida estuaries have chlorophyll *a* values $\leq$ 3.8 μg/l and 40% have chlorophyll *a* values $\geq$ 7.9 μg/l.

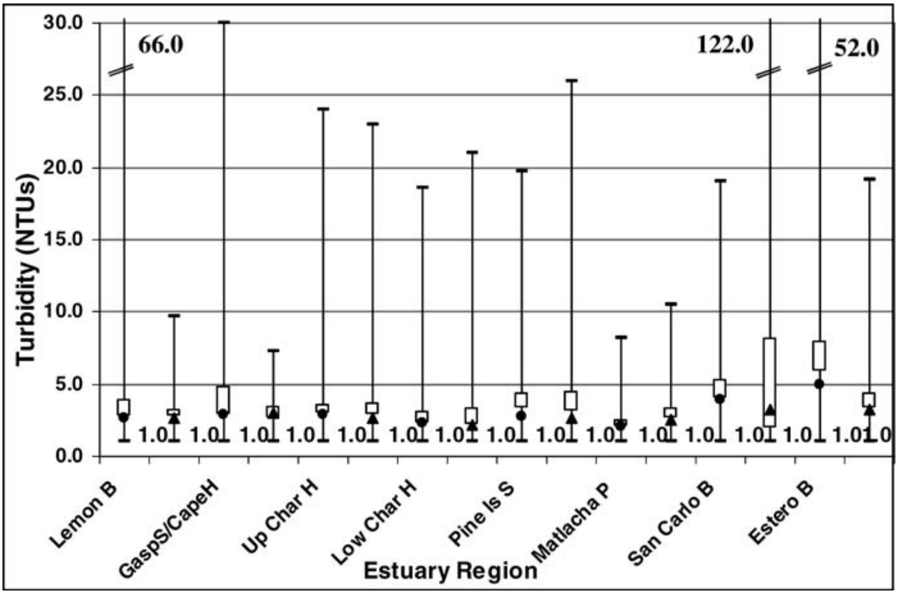



FIG. 4. Seasonal Turbidity Ranges for Each Estuary Region (November 1998–October 2004). Vertical Bar represents data range. Box represents 95% confidence interval of mean. Symbols represent seasonal medians: ● = Dry Season ▲ = Rainy Season.

The Florida Impaired Waters criterion for chlorophyll *a* is $\geq$ 11 μg/l (FDEP, 2002) and the NOAA estuarine eutrophication survey considers values $\geq$ 20 μg/l as "high" (NOAA, 1996). In the Charlotte Harbor region, two estuaries (Gasparilla Sound and Matlacha Pass) had median chlorophyll *a* values associated with the lowest 30% of Florida estuaries, suggesting above average chlorophyll *a* conditions. Chlorophyll *a* median values for the other six estuaries fell within the intermediate range associated with 31–60% of Florida estuaries, suggesting average chlorophyll *a* conditions. While none of the estuaries had median or mean values that exceeded the 11 μg/l Impaired Waters criterion (FDEP 2002), individual values exceeded that criteria at least once in all estuaries and in all seasons.

*Color, turbidity and chlorophyll* a *relationships*—Spearman's correlations between turbidity, color and chlorophyll *a* for each estuary were calculated (Table 5). For all estuaries combined, chlorophyll *a* was significantly correlated to both turbidity ($p < .05$) and to color ($p < .05$). However, turbidity and color were not significantly correlated for the region as a whole. For the individual estuary regions, significant relationships ($p < .05$) between all pairs of the three variables were shown in 3 estuaries: Lemon Bay, Pine Island and Upper Charlotte Harbor. No significant correlations between any pair of the three variables were found in two estuaries: Gasparilla Sound/Cape Haze and Estero Bay. In Lower Charlotte Harbor, chlorophyll *a* was significantly ($p < .05$) related to both turbidity and color, but

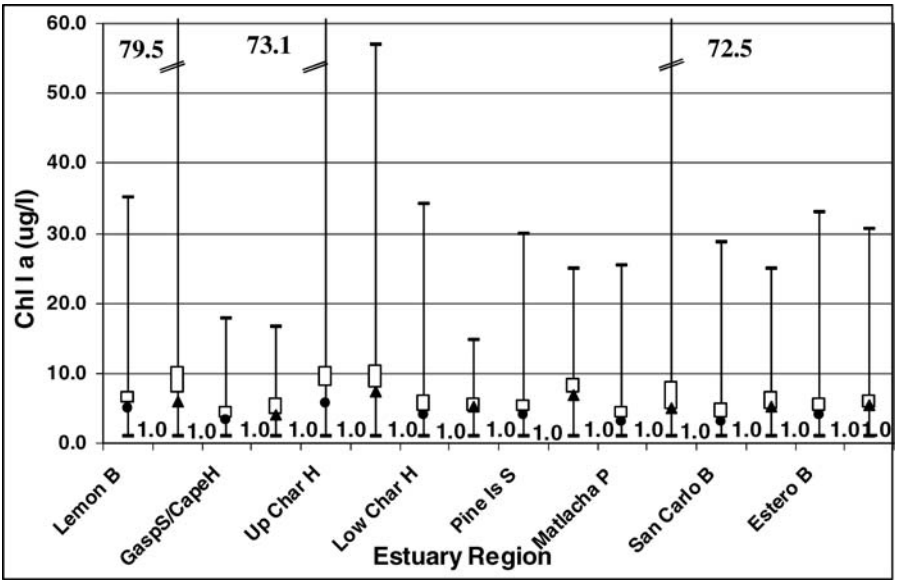



FIG. 5. Seasonal Chlorophyll *a* Ranges for Each Estuary Region (November 1998–October 2004). Vertical Bar represents data range. Box represents 95% confidence interval of mean. Symbols represent seasonal medians: ● = Dry Season ▲ = Rainy Season.

color and turbidity were not related. And, in Matlacha Pass color was significantly ($p < .05$) related to both turbidity and chlorophyll *a* but turbidity and chlorophyll *a* were not significantly related. For visual reference, relationships between color, turbidity and chlorophyll *a* for each estuary are shown in the three dimensional scatter plots given in Figure 6.

*Secchi depth relationships to color, turbidity and chlorophyll* a—Results of multiple regression analyses for Secchi depth compared to color, turbidity and

TABLE 5. Correlations between Turbidity, Color and Chlorophyll *a* for Each Estuary Region (November 1998–October 2004).

| Estuary | Turbidity: Color $R^2$ | Turbidity: Chlorophyll *a* $R^2$ | Color: Chlorophyll *a* $R^2$ |
|---|---|---|---|
| Lemon Bay | 0.121* | 0.144* | 0.292* |
| Gasparilla S/Cape Haze | 0.053 | 0.155 | 0.194 |
| Upper Charlotte Harbor | 0.121* | 0.308* | 0.137* |
| Lower Charlotte Harbor | 0.095 | 0.258* | 0.262* |
| Pine Island Sound | −0.044* | 0.152* | 0.282* |
| Matlacha Pass | 0.271* | 0.107 | 0.221* |
| San Carlos Bay | 0.024 | −0.073 | 0.276* |
| Estero Bay | −0.099 | 0.058 | −0.013 |
| All Estuaries Combined | 0.04 | 0.134* | 0.246* |

* Values are significant at the 0.01 level.

chlorophyll *a* for each estuary are shown in Table 6. Six of the 8 estuaries showed a significant correlation of Secchi depth to color + turbidity + chlorophyll *a*. Only Gasparilla Sound/Cape Haze and San Carlos Bay showed no significant relationship between Secchi and the other 3 parameters collectively. The percent of Secchi depth change explained by the combination of these three variables ranged from 53% for Lower Charlotte Harbor to 26% in Lemon Bay. A stepwise regression was conducted to select the best variable or set of variables that explained the most variation in Secchi depth. Results of the stepwise regression analysis for Secchi depth compared to color, chlorophyll *a* and turbidity for each estuary are shown in Table 7. Only the variables that maximize the explained variability in Secchi depth and have at least a .05 significance level are displayed. For the Charlotte Harbor estuarine complex as a whole, color explained the most variation in Secchi depth (R squared = 0.173), followed by a combination of color and turbidity (R squared = 0.202). For six of the individual estuary regions (excluding Pine Island Sound and Estero Bay) color also explained the most variation in Secchi depth, ranging from 39% in Lower Charlotte Harbor to 4% in San Carlos Bay. In both Pine Island Sound and Estero Bay, turbidity explained the most variation in Secchi depth, with turbidity and color combined explaining all the estimated variation. Chlorophyll *a* was a significant contributor to Secchi depth prediction only in Lower Charlotte Harbor.

DISCUSSION—*General considerations*—The findings of this study were consistent with previous water quality studies in the Charlotte Harbor region (Miller and McPherson 1994; Tomasko et al., 2001; Morrison et al., 2002; Janicki Environmental Inc., 2003), and answered the three initial questions posed. 1) Water clarity, as measured by Secchi depth, varied widely throughout the region and seasons. The lowest Secchi depth mean values, associated with the highest light attenuation, were found in Upper Charlotte Harbor (1.0 m), Lemon Bay (1.1 m) and Estero Bay (1.2 m). Compared to other Florida estuaries, four of the estuary regions had above average Secchi depth conditions associated with the clearest 30% of Florida estuaries (Gasparilla Sound/Cape Haze, Lower Charlotte Harbor and Matlacha Pass). Four of the estuaries studied, as well as the region as a whole, had average water clarity associated with the intermediate 31–60% of Florida estuaries. 2) Color, turbidity and chlorophyll *a* together contributed to light attenuation to varying degrees in the different estuaries within the region. The strongest relationships between water clarity and the combination of color, turbidity and chlorophyll *a* were found in Lower Charlotte Harbor (53%), Matlacha Pass (41%) and Estero Bay (35%). 3) The strongest predictor of water clarity was color in all estuaries except Estero Bay.

Additionally, turbidity was a strong predictor of water clarity in all six estuaries, and in the region as a whole, and was the primary predictor in Estero Bay. Chlorophyll *a* was a significant contributor to Secchi depth prediction only in Lower Charlotte Harbor. Also, both turbidity and chlorophyll *a* showed elevated mean and peak values in some estuaries and seasons. The highest turbidity values occurred in San Carlos Bay, at the mouth of the Caloosahatchee River, during the rainy season.

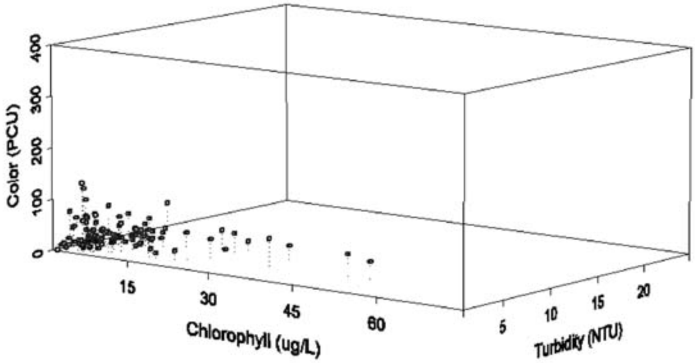
High turbidity values occurred in Lemon Bay and Estero Bay during the dry season; these are the shallower estuaries and windiest months of the study. While none of the mean chlorophyll *a* values for the estuaries exceeded the 11 μg/l Impaired Waters criterion for chlorophyll *a*, significant chlorophyll *a* peaks ($\geq$73 μg/l) occurred in the rainy season in Lemon Bay, Upper Charlotte Harbor and Matlacha Pass and individual monthly values exceeded the 11 μg/l in each season of each estuary.

*Resource management considerations*—Throughout the Charlotte Harbor region, water clarity targets need to be fully developed for each aquatic preserve which will allow long term sustainability and restoration of existing seagrass habitats. Optical models, such as those proposed by Corbett and Hale (2006), can be used to quantify relationships between seagrass light requirements and partial light attenuation associated with color, turbidity and chlorophyll *a* for each specific estuary. Once water clarity targets have been established, efforts are needed to identify and quantify both natural and anthropogenic sources of turbidity and nutrients within the watersheds of each aquatic preserve. Possible sources of elevated turbidity levels in estuaries include freshwater in-flows and resuspension of bottom sediments due to changes in hydrologic regimes (CHNEP, 2005), dredging and filling (Duarte, 2002), and wave and storm action (Preen et al., 1995). For example, high dry season turbidity levels in Lemon Bay, Estero Bay and Gasparilla Sound/Cape Haze may be strongly related to sediment resuspension. Restoration efforts designed to reduce turbidity would be directed most effectively toward restoring natural hydrology and minimizing anthropogenic sources of sediment resuspension.

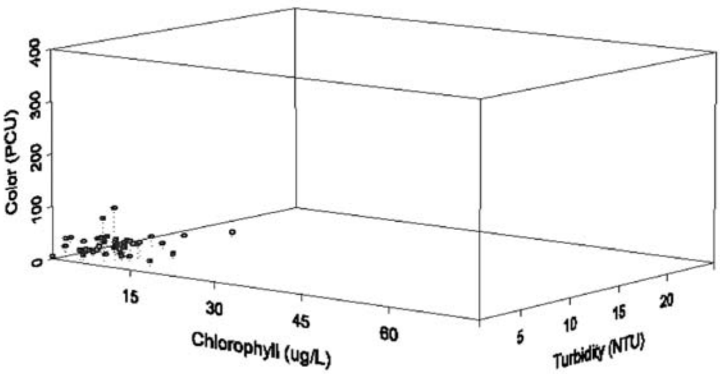
High rainy season turbidity in San Carlos Bay, Matlacha Pass and Pine Island Sound may be more strongly related to freshwater in-flows. Possible sources need to be identified and quantified, but restoration may focus on reestablishing natural hydrologic flow regimes in the tributaries, especially in the Caloosahatchee River. Additional turbidity reductions could be accomplished by reducing storm water velocity and volume through installation of a variety of appropriate retention systems for existing and future impervious areas (Peluso and Marshall, 2002). Water clarity could also be enhanced by reducing chlorophyll *a* values. Elevated chlorophyll *a* values in estuaries are associated with excess nitrogen and phosphorus inputs from anthropogenic sources and resuspension of nutrient rich sediments (Kennish, 2000). Possible nitrogen sources include stormwater runoff, septic tank systems, rainfall and groundwater base flow (Tomasko et al., 2001). Sources of nutrients supporting high rainy season chlorophyll *a* values in Lemon Bay, Upper Charlotte Harbor and Matlacha Pass need to be identified, quantified and remediated through a variety of non-regulatory and regulatory best management practices and approaches.

→

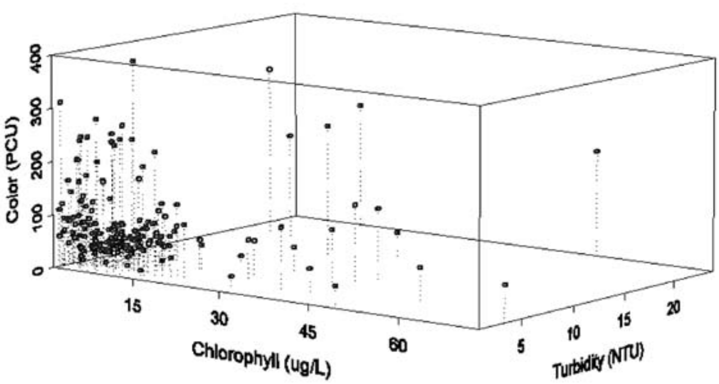
FIG. 6. Color, Turbidity and Chlorophyll *a* Regressions for Each Estuary Region (November 1998–October 2004).




Lemon Bay




Gasparilla Sound/Cape Haze




Upper Charlotte Harbor

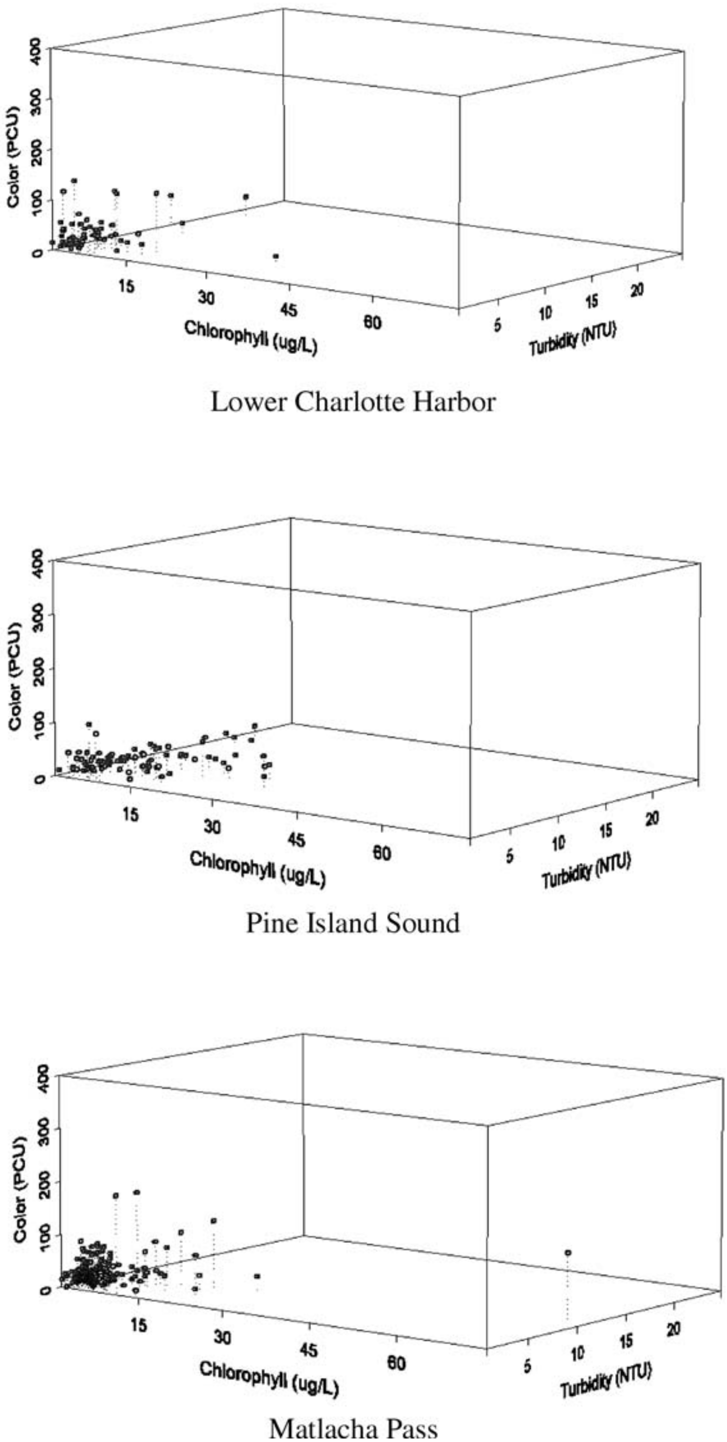
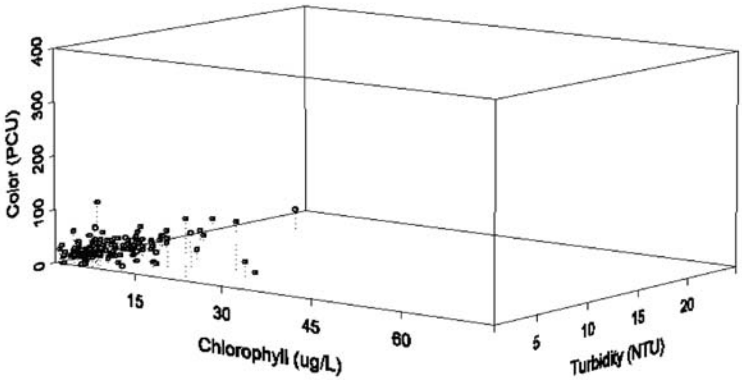
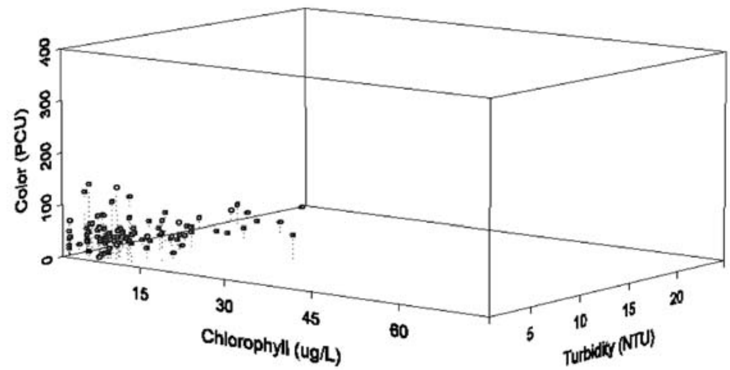


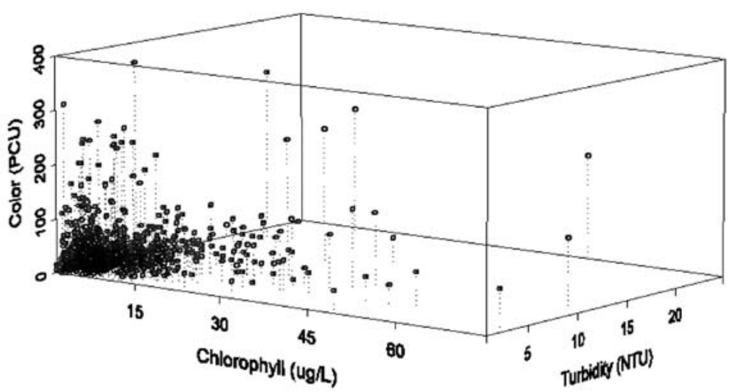

FIG. 6. Continued.




San Carlos Bay




Estero Bay




All Estuaries Combined

FIG. 6. Continued.

TABLE 6. Multiple Regression Analysis between Secchi Depth and Color, Turbidity and Chlorophyll *a* for Each Estuary Region (November 1998–October 2004).

| Estuary | R Squared | Color Coefficient[2] | Turbidity Coefficient[2] | Chl *a* Coefficient[2] | Intercept | Residual SE |
|---|---|---|---|---|---|---|
| Lemon Bay | 0.26* | −0.01* | −0.05* | −0.01 | 1.62 | 0.34 |
| Gasparilla S/Cape Haze | 0.17 | −0.01* | −0.05 | −0.02 | 2.02 | 0.48 |
| Upper Charlotte Harbor | 0.30* | 0.00* | −0.02* | 0.00 | 1.27 | 0.31 |
| Lower Charlotte Harbor | 0.53* | −0.01* | −0.07* | −0.04* | 2.81 | 0.57 |
| Pine Island Sound | 0.32* | −0.01* | −0.07* | −0.01 | 2.06 | 0.51 |
| Matlacha Pass | 0.41* | −0.01* | −0.13* | +0.01 | 2.38 | 0.42 |
| San Carlos Bay | 0.05 | 0.00 | 0.00 | −0.01 | 1.67 | 0.56 |
| Estero Bay | 0.35* | 0.00* | −0.06* | 0.00 | 1.68 | 0.36 |
| All Estuaries Combined | 0.22* | −0.01* | −0.02* | −0.01* | 1.74 | 0.52 |

* Values are significant at 0.05 level.

*Program value*—The CHEVWQMN data have been useful in evaluating water clarity relationships throughout the Charlotte Harbor estuaries based on a uniform, system wide data set. One of the primary values of the monitoring program is the use of consistent field and laboratory procedures throughout the estuary complex which facilitates data analysis. Also, the monthly, synoptic sample collection and long term sampling period allow the data to be used for spatial/temporal comparisons and trend analyses. Additional parameters from the CHEVWQMN, such as salinity, nutrients, dissolved oxygen and fecal coliform bacteria, can further our understanding of relationships between freshwater inflows and water clarity, nutrients, chlorophyll *a* and dissolved oxygen throughout the region. As watershed land use changes occur

TABLE 7. Stepwise Regressions of Secchi Predicted by Color, Turbidity and Chlorophyll *a* (November 1998–October 2004). Predictors that maximize Secchi depth variation shown.

| | Strong to Weak | Predictor | Adjusted $R^2$ | $R^2$ Change | T | Sig Level |
|---|---|---|---|---|---|---|
| Lemon Bay | 1 | Color | 0.161 | 0.161 | −4.9 | <0.01 |
| | 2 | Turbidity | 0.245 | 0.084 | −3.71 | <0.01 |
| Gasparilla S/Cape H | 1 | Color | 0.099 | 0.099 | −2.15 | <.05 |
| Upper Charlotte H | 1 | Color | 0.27 | 0.27 | −8.06 | <0.01 |
| | 2 | Turbidity | 0.298 | 0.028 | −2.66 | <0.01 |
| Lower Charlotte H | 1 | Color | 0.394 | 0.394 | −6.04 | <0.01 |
| | 2 | Chlorophyll *a* | 0.474 | 0.08 | −2.9 | <0.01 |
| | 3 | Turbidity | 0.533 | 0.059 | −2.62 | <.05 |
| Pine Island Sound | 1 | Turbidity | 0.271 | 0.271 | −5.56 | <0.01 |
| | 2 | Color | 0.308 | 0.037 | −2.09 | <.05 |
| Matlacha Pass | 1 | Color | 0.315 | 0.315 | −8.23 | <0.01 |
| | 2 | Turbidity | 0.403 | 0.088 | −4.64 | <0.01 |
| San Carlos Bay | 1 | Color | 0.042 | 0.042 | −2.39 | <.05 |
| Estero Bay | 1 | Turbidity | 0.309 | 0.309 | −6.38 | <0.01 |
| | 2 | Color | 0.348 | 0.04 | −2.34 | <.05 |
| All Estuaries | 1 | Color | 0.173 | 0.174 | −13.5 | <0.01 |
| | 2 | Turbidity | 0.202 | 0.174 | −5.64 | <0.01 |
| | 3 | Chlorophyll *a* | 0.222 | 0.021 | −4.86 | <0.01 |

or resource management practices are implemented, specific, near shore fixed station sampling results can be utilized to measure habitat responses to changes. The CHEVWQMN is a cost effective method of collecting technically sound water quality data. The quality assurance and training activities included in the program design and project management, together with agency laboratory and administrative support, allow for scientifically reliable data to be collected by citizen monitors. The continuity and contributions of the citizen monitors have allowed for a longer term sampling period than would have otherwise been possible. The CHEVWQMN partnership of citizens and agency staff fosters community involvement in aquatic preserve management, and provides the agency with a better understanding of community needs.

*Further investigations*—Pending analyses of the CHEVWQMN data include: 1) quantifying the relationship between water clarity and maximum seagrass depth for each estuary, 2) comparing water clarity measured by Secchi depth to photosynthetically active radiation, 3) conducting trend analyses of key water quality conditions throughout the region, 4) identifying and quantifying natural and anthropogenic sources of turbidity and nutrients throughout the region, 5) determining the relationships between freshwater inflows, total nitrogen, and chlorophyll *a* throughout the region, and 6) identifying non-regulatory best management practices and regulatory actions needed to address the anthropogenic sources of turbidity and nitrogen for each aquatic preserve.

CONCLUSIONS—Seagrasses are an essential submerged habitat within the six Aquatic Preserves in the Charlotte Harbor estuary complex. Sustainability of seagrass habitat depends on maintaining and restoring water clarity, specifically related to color, turbidity and chlorophyll *a*. The 6 year results of the CHEVWQMN water quality data for these four parameters highlighted the wide range of conditions found throughout the region. Based on the analysis results, priority parameters included turbidity and chlorophyll *a* and critical locations included Upper Charlotte Harbor, Lemon Bay and Estero Bay. The study results emphasized the need for further analysis of the CHEVWQMN data to link water clarity to potential contaminant sources, watershed land uses and habitat preservation and restoration activities. The analyses also showed the strong need for development of more effective estuary health condition indices and tools. Immediate needs for the CHEVWQMN include entering the complete database into STORET and answering specific water quality trend and source questions for each aquatic preserve. With assistance from citizen and agency partners, both the CHEVWQMN and CHAP/EBAP long term seagrass monitoring efforts will continue to provide sound science for wise resource management activities.

ACKNOWLEDGMENTS—The authors wish to thank Jason Hale, Charlotte Harbor Environmental Center/Water Resource Center and Ralph Montgomery, PBS&J for extensive statistical support, as well as Joe Hand, FDEP for assistance with typical Florida water quality values. Special recognition is also given to the long term dedication and flexibility of the FDEP South District Laboratory chemists David Winkler and Jennifer Thera, 80 plus citizen water monitors, the Charlotte Harbor National Estuary Program staff Catherine Corbett and Lisa Beever, and Charlotte County Sea Grant Marine Extension Agent Elizabeth Staugler. Finally, sincere gratitude is given to the three anonymous reviewers and the guest editors for their considerable time and constructive comments which significantly improved this work.

## LITERATURE CITED

American Public Health Association (APHA). 1992. Standard Methods for the Examination of Water and Wastewater, 18th Ed. American Public Health Association, American Water Works Association, Water Environment Federation Publication. APHA, Washington, D.C.

Corbett, C. A. 2006. Seagrass coverage changes in Charlotte Harbor, FL. Florida Scient. 69(00S2):7–23.

——— and J. A. Hale. Development of water quality targets for Charlotte Harbor, FL using seagrass light requirements. Florida Scient. 69(00S2):36–50.

———, P. H. Doering, K. A. Madley, J. A. Ott, and D. A. Tomasko. 2005. Issues with using seagrass as an indicator of ecosystem condition. Pp. 229–245. *In*: Bortone, S. A. (ed.), Estuarine Indicators. CRC Press, Boca Raton, FL.

Charlotte Harbor National Estuary Program (CHNEP). 2004. Coastal Charlotte Harbor Monitoring Network Description and Standard Operating Procedures. Technical Report 02–03. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

———. 2005. Environmental indicators for the Charlotte Harbor National Estuary Program. Technical Report 05–01. Available from the Charlotte Harbor National Estuary Program, Ft. Meyers, FL.

Dawes, C. J., R. C. Phillips, and G. Morrison. 2004. Seagrass communities of the Gulf Coast of Florida: status and ecology. Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute and the Tampa Bay Estuary Program. St. Petersburg, FL.

Dixon, L. K. and G. J. Kirkpatrick. 1999. Causes of light attenuation with respect to seagrasses in upper and lower Charlotte Harbor, Report to Southwest Florida Water Management District, SWIM Program and Charlotte Harbor National Estuary Program. Available from the Southwest Florida Water Management District, SWIM Program, Tampa, FL and Charlotte Harbor National Estuary Program, Fort Myers, FL.

Duarte, C. M. 2002. The Future of Seagrass Meadows. Env. Cons. 29(2):192–206.

Florida Department of Environmental Protection (FDEP). 2002. Identification of Impaired Surface Water. Chapter 62–303.353. Available from the Florida Department of Environmental Protection, Tallahassee, FL.

———. 1997. Comprehensive Quality Assurance Plan for the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network. Project Quality Assurance Plan. Available from the Florida Department of Environmental Protection Charlotte Harbor Aquatic Preserves, Punt Gorda, FL.

Florida Department of Natural Resources (FDNR). 1992. Lemon Bay Aquatic Preserve Management Plan, Bureau of Submerged Lands and Preserves, Tallahassee, FL.

Florida Department of Natural Resources (FDNR). 1983. Charlotte Harbor Aquatic Preserves Management Plan, Bureau of Environmental Land Management, Tallahassee, FL.

Friedemann, M. and J. Hand. 1989. Typical water quality values for Florida's lakes, streams and estuaries, Florida Department of Environmental Regulation, Bureau of Surface Water Management. Available from Florida Department of Environmental Protection, Tallahassee, FL.

Hand, J. *In Press.* Typical water quality values for Florida's lakes, streams and estuaries, Florida Department of Environmental Protection, Bureau of Watershed Management. Available from Florida Department of Environmental Protection, Tallahassee, FL.

Janicki Environmental Inc. 2003. Water quality data analysis and report for the Charlotte Harbor National Estuary Program, August 27, 2003. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

Kennish, M. J. (ed.) 2000. Estuary Restoration and Maintenance: The National Estuary Program. CRC Press, Boca Raton, FL.

Kirk, J. T. O. 1983. Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, New York, NY.

MCPHERSON, B. F. AND R. MILLER. 1994. Causes of light attenuation in Tampa Bay and Charlotte Harbor, Southwestern FL, Water Res. Bull. 30(1):43–53.

——— AND R. MILLER. 1987. The Vertical Attenuation of Light in Charlotte Harbor, a Shallow, Subtropical Estuary, South-western Florida. Estaur. Coast. and Sh. Sci. 25:721–737.

MILLER, R. L. AND B. F. MCPHERSON. 1995. Modeling photosynthetically active radiation in waters of Tampa Bay, Florida, with emphasis on the geometry of incident light radiance. Estuar. Coast. Shelf Sci. 40:359–377.

MONTGOMERY, RALPH A. 2005. PBS&J, Port Charlotte, FL. Pers. Communication.

MORRISON, G., R. MONTGOMERY, A. SQUIRES, R. STARKS, E. DEHAVEN AND J. OTT. 2002. Nutrient, chlorophyll *a* and dissolved oxygen concentrations in Charlotte Harbor: Existing conditions and long-term trends, in Proceedings of the Charlotte Harbor Public Conference and Technical Symposium, Charlotte Harbor National Estuary Program, Fort Myers, FL.

NATIONAL OCEANIC AND ATMOSPHERIC ASSOCIATION (NOAA). 1996. NOAA's Estuarine Eutrophication Survey, Vol. 1: South Atlantic region. NOAA Office of Ocean Resources Conservation Assessment, Silver Springs, MD.

OTT, J. A., K. FUHR, AND E. STAUGLER. 2003. Establishing baseline seagrass health in Charlotte Harbor Florida using fixed transects: 1999–2000 seagrass monitoring summary. Section 22. *In*: GREENING, H. (ed.), Submerged Aquatic Habitat Restoration: Issues, Options and Priorities Workshop, March 11–13, 2003, Mote marine Laboratory, Sarasota, FL. CD Rom available from the Tampa Bay Estuary Program, St. Petersburg, FL.

PREEN, A., W. J. LEE LONG, AND R. G. COLES. 1995. Flood and Cyclone Related loss, partial recovery of more than 1000 km2 of seagrass in Hervey Bay, Queensland Australia. Aquat. Bot. 52:3–17.

PELUSO, V. AND A. MARSHALL. 2002. Best Management Practices for South Florida Urban Stormwater Management Systems, SFWMD Technical Publication REG-004, West Palm Beach, FL.

TOMASKO, D. A., C. A. CORBETT, H. S. GREENING, AND G. E. RAULERSON. 2005. Spatial and temporal variation in seagrass coverage in southwest Florida: Assessing the relative effects of anthropogenic nutrient load reductions and rainfall in four contiguous estuaries. Mar. Poll. Bull. 50:797–805.

———, D. L. BRISTOL, AND J. A. OTT. 2001. Assessment of present and future nitrogen loads, water quality, and seagrass (*Thalassia testudinum*) depth distribution in Lemon Bay, Florida. Estuaries. 24(6A):926–938.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA). 1979. Methods for Chemical Analysis of Water and Wastes. EPA-600/4-79-020. USEPA. Cincinnati, OH.

Florida Scient. 69(00S2): 73–91. 2006
Accepted: March 10, 2006

# PRELIMINARY OBSERVATIONS OF ESTROGENIC ACTIVITY IN SURFACE WATERS OF THE MYAKKA RIVER, FLORIDA

Heather Cox[(1)], Sara Mouzi[(2)], and James Gelsleichter[(1)]

[(1)]Elasmobranch Physiology and Environmental Program, Center for Shark Research, Mote Marine Laboratory, 1600 Ken Thompson Parkway, Sarasota, Florida, 34236
[(2)]University of Houston, Houston, Texas, 77204

Abstract: *Environmental pollutants capable of disrupting endocrine function and impairing hormonally regulated processes such as animal reproduction pose significant threats to the health of aquatic wildlife populations. Unfortunately, broad assessments of endocrine-disrupting activity are difficult to perform for large aquatic ecosystems because of the substantial number of hormonally active contaminants and the expense of conducting specific chemical analyses for each of these compounds. This report describes pilot attempts to detect the presence of endocrine-disrupting pollutants in the surface waters of southwest Florida estuaries using the E-SCREEN, a short-term, cell culture bioassay that measures the occurrence and abundance of estrogen-mimicking substances by their ability to induce proliferation in estrogen-sensitive, MCF-7 human breast cancer cells. Using this technique, estrogenic activity was detected in multiple sites in the Myakka River, a major tributary of the Charlotte Harbor estuary. Estrogenic substances appear to occur primarily near areas of significant residential development in the lower portions of this river system. Therefore, it is likely that these contaminants enter the Myakka River via input of stormwater runoff and/or unprocessed sewage, perhaps from overburdened or damaged septic systems.*

*Key Words:* Endocrine disruption, E-SCREEN, xenoestrogens, pollution, Myakka River, Charlotte Harbor, Sarasota County, Charlotte County, Florida

During the past decade, there has been growing concern about the environmental impact of man-made pollutants capable of interacting with the vertebrate endocrine system and impairing hormone-regulated processes, in particular, animal development and reproduction (see National Research Council, 1999 for review). These "endocrine disrupting compounds (EDCs)," as they are commonly referred to, include a number of common anthropogenic pollutants, such as synthetic hormones used in human contraceptives, natural hormones used to promote growth of livestock, organochlorine pesticides, industrial chemicals (e.g., polychlorinated biphenyls), byproducts of pulp and paper production (e.g., dioxins), and breakdown products of plastics and detergents. Few regions in the world have received as much attention as the state of Florida, with regards to the potential effects of these compounds on aquatic wildlife. In fact, exposure to elevated concentrations of EDCs has been linked with reproductive anomalies in several species residing in Florida rivers and lakes including the American alligator (*Alligator mississippiensis* [Daudin]) (Semenza et al., 1997; Guillette et al., 1999; Gunderson et al., 2004), brown bullhead catfish

(*Ameriurus nebuosus* Lesueur) (Gallagher et al., 2001), largemouth bass (*Micropterus salmoides* Lacepède) (Orlando et al., 1999; Sepúlveda et al., 2001; 2002), and mosquitofish (*Gambusia holbrooki* Baird and Girard) (Bortone and Cody, 1999; Parks et al., 2001; Toft et al., 2003). Exposure to some of these pollutants, organochlorine pesticides in particular, has also been implicated as a possible cause of genital disorders in the endangered Florida panther (*Puma concolor coryi* Bangs) (Facemire et al., 1995). Given these concerns, it is important to determine the identities, sources, and concentrations of EDCs in Florida waters so that policies to reduce the release and ecological impacts of these compounds can be developed.

Due to the large number of potential environmental EDCs and the expense of conducting chemical-specific measurements for each of these compounds, it is generally difficult to perform broad assessments of EDC concentrations in large-scale aquatic ecosystems. However, recent studies have demonstrated that a cost-effective approach for identifying elevated concentrations of EDCs in environmental matrices is to use short-term, cell culture bioassays to pre-screen samples for EDC activity prior to performing more specific chemical analyses (Körner et al., 1999; Oh et al., 2000; Furuichi et al., 2004; Schiliró et al., 2004; Soto et al., 2004; Leusch et al., 2005). One of the most commonly used bioassays in such studies is the E-SCREEN, a cell culture technique that is capable of detecting the presence and concentration of compounds that mimic the natural hormones, estrogens, by their ability to stimulate proliferation of estrogen-dependent MCF-7 human breast cancer cells (Soto et al., 1995). Using this method, estrogenic activity has been detected in rivers bordering rural sites in central Korea (Oh et al., 2000) and areas downstream of cattle feedlots in the Elkhorn River, Nebraska (Soto et al., 2004). Based on these studies, this technique shows promise as an effective approach for screening EDC activity in Florida rivers and estuaries, which may accumulate estrogenic compounds as a result of agricultural activity, stormwater runoff, and wastewater discharge.

The present study describes recent efforts to screen for EDC activity in estuarine waters in southwest Florida, a rapidly developing coastal area. In particular, the E-SCREEN bioassay was used to characterize the presence and distribution of estrogenic substances in surface waters of the Myakka River, a tributary of the Charlotte Harbor estuary. This project was a component of a larger study focused on identifying the ecological threats that EDCs pose to the Charlotte Harbor ecosystem and its resident wildlife.

MATERIALS AND METHODS—Surface water samples were obtained from 15 sites along the length of the lower Myakka River between Sarasota and Charlotte counties during a 2-day period in September 2004 (FIG. 1). The sampling period occurred one month after a major hurricane (Hurricane Charley) passed to the east of the Myakka River. Water samples were collected in pre-cleaned, 1-L amber glass bottles and held on ice until returned to the laboratory. Samples were stored at 4°C for a maximum of 2 weeks until processed for extraction of active components.

Samples were measured to 1 L and filtered through 10-μm stainless steel wire mesh for removal of particulate matter. Afterwards, samples were transferred to 2-L glass separatory funnels and active components extracted following methods described in Soto and co-workers (2004). Briefly, each sample was extracted three times with 60 mL of dichloromethane (DCM) with shaking for 2 min. Water and DCM fractions were allowed to separate for 10 min, after which DCM fractions were filtered through a stemmed funnel filled to a depth of ~2 cm with solvent-rinsed sodium sulfate. Filtered extracts were

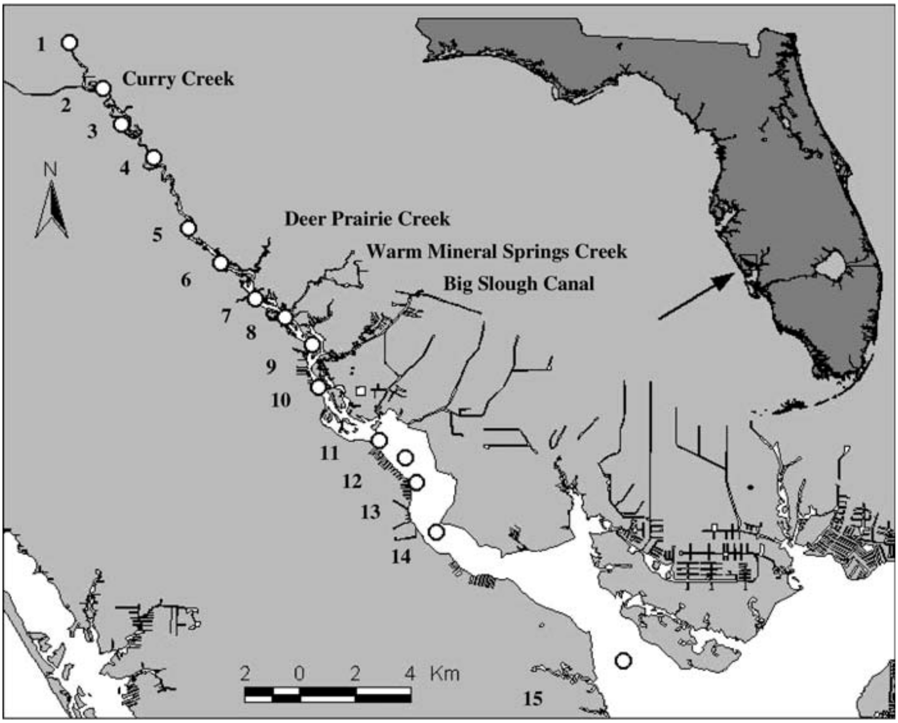



FIG. 1. Map of 15 water collection sites within the central to lower Myakka River, Florida. Nearby tributaries are identified for reference.

combined in a single 500-mL glass bottle and concentrated to a volume of 1–1.5 mL using a RapidVap $N_2$ evaporation system (Labconco, Kansas City, MO). Samples were then transferred to 1.5-mL glass vials and evaporated to near dryness using a gentle stream of nitrogen. Extracts were solvent-exchanged with 1 mL dimethyl sulfoxide (DMSO) and nitrogen was applied for an additional hour to remove residual DCM. Extracts were stored at –20°C until used in the E-SCREEN assay.

Estrogen-sensitive MCF-7 BOS human breast cancer cells (see Villalobos et al., 1995 for a comparison of MCF-7 cell lines) were kindly provided by Drs. A.M. Soto and C. Sonnenschein, Tufts University (Boston, MA). Cells were cultured in Dulbelcco's modified Eagle's medium (DMEM) supplemented with 0.5 I.U./mL penicillin, 50 μg/mL streptomycin (Mediatech, Inc, Herndon, VA), 2.25% sodium bicarbonate, 0.584% L-glutamine, 0.01% sodium pyruvate, and 5% heat inactivated fetal bovine serum (FBS) at 37°C with 5% $CO_2$ and 95% air under saturating humidity.

A miniaturized E-SCREEN assay was developed using the reduction of MTT [(3-(4,5-dimethylthiazolyl-2)-2, 5-diphenyltetrazolium bromide)] as a specific indicator of cell proliferation (Tian et al., 2002). Cells were harvested with phosphate buffered saline (PBS) containing 0.25% trypsin and 0.03% EDTA, re-suspended in 5% FBS DMEM, and plated onto 96-well plates at an initial density of 5,000 cells/well in 200 μL of medium. Following a 24 hour period during which cells adhered to plates, medium was replaced with 100 μL phenol red-free DMEM containing 5% FBS previously treated with dextran-coated charcoal (Sigma-Aldrich, St. Louis, MO) to minimize endogenous estrogenic activity. Cells were exposed to one of four dilutions (0.1–100 pM in DMSO, FIG. 2) of 17β-estradiol ($E_2$, Sigma-Aldrich) or one of four dilutions of sample extracts (equivalent to 1.25–10 μL of river water) for a period of 5 days. Controls were exposed to 0.1% DMSO, the concentration used in all treatment assays. All exposures were performed in triplicate.

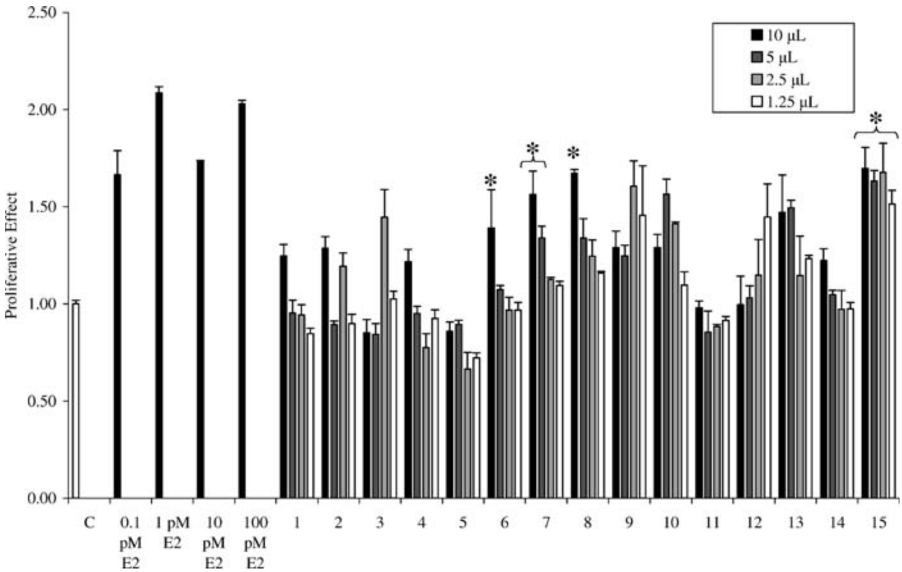



FIG. 2. Cell proliferation in 100-µL cultures of MCF-7 cells exposed to DMSO (control, C), 0.1–100 pM 17β-estradiol (E2), and extract representing the equivalent of 1.25–10 µL of river water obtained from sites 1–15 in the Myakka River. Bars represent means ±SE. *Cells exposed to extracts from sites 6 (10 µL), 7 (5–10 µL), 8 (10 µL), and 15 (1.25–10 µL) exhibited proliferative responses significantly greater than that observed in hormone-free controls (ANOVA with Bonferroni correction, $P < 0.05$).

Following the culture period, 20 µL of 5 mg/mL MTT prepared in 10 mM phosphate buffered saline (PBS) was added to each well. After an incubation period of 4 h, 100 µL of a solubilizing solution (0.01 N HCl/10% SDS in PBS) was added to each well and allowed to react overnight. The following day, optical density of wells was measured at 570 and 630 nm using a microplate reader. MTT is reduced by metabolically active cells to an insoluble purple formazan product, which is released into the culture supernatant by solubilization. Therefore, the degree of color reaction in a microplate well is proportional to cellular activity.

The proliferative effect (PE) of $E_2$ and water extracts was calculated to characterize estrogenic activity (Körner et al., 1999; Oh et al., 2000). The PE is level of cell proliferation induced by $E_2$ or water extracts, respectively, relative to that in estrogen-free controls and was calculated as:

$$PE = OD_{\text{estradiol or water extracts}}/OD_{\text{control}} \quad (1)$$

where $OD_{\text{estradiol or water extracts}}$ refers to the optical density measurements of samples exposed to $E_2$ or water extracts and $OD_{\text{control}}$ refers to the mean optical density of DMSO-exposed controls. Measurements of PE were grouped by sample and compared with the estrogen-free control by one-way ANOVA with Bonferroni error protection to detect the presence of significant estrogenic activity. Since the goal of the larger study was to "pre-screen" numerous (>200) water samples for evidence of water-borne xenoestrogens, the relative potency or estradiol equivalency factor (EEF; Körner et al., 1999) of samples was not calculated because it requires the use of >4 dilutions of each extract and a greater amount of cells than that regularly available. However, EEF measurements will be calculated for sites in which estrogenic activity is consistently detected and presented in future reports.

RESULTS—Significant estrogenic activity was detected in 4 of the 15 water samples obtained from the Myakka River (ANOVA, $P < 0.05$; FIG. 2). Together, these samples appeared to represent two general locations in which elevated concentrations of estrogenic compounds were present. The first region included sites 6, 7, and 8, and lies between two tributaries, Deep Prairie Creek and Warm Mineral Springs Creek. This region lies near the city of Nort Port and is one of few portions of the river within Sarasota County that has experienced a significant degree of coastal development (Southwest Florida Water Management District [SWFWMD], 2004). The second region included site 15 and is located within Charlotte County in the southernmost portion of the river. This region is adjacent to the city of Port Charlotte and is also an area of significant urban development (SWFWMD, 2004). No other sites appeared to possess detectable levels of estrogenic compounds.

DISCUSSION—The results presented in this study demonstrate the presence of significant hormonal activity in portions of the Myakka River within Sarasota and Charlotte Counties. Elevated concentrations of estrogenic substances were detected in multiple water samples obtained from two regions of the river during late summer-early fall, a period of increased precipitation and high river discharge. However, little evidence of estrogenic activity was observed in other locations in the central to lower portions of the river. These findings suggest that estrogen mimics pose low risks to the ecological health of the Myakka River in comparison with other tributaries of the Charlotte Harbor estuary in which widespread estrogenic activity has been consistently detected (e.g., Caloosahatchee River, Cox and Gelsleichter, unpublished data). Nonetheless, future research may be necessary to identify the substances that contribute to estrogenic activity in certain portions of the river given that samples from these regions are occasionally capable of inducing potent biological responses in the E-SCREEN assay.

The presence of significant estrogenic activity in sites 6–8 and 15 is consistent with what is known regarding land usage in these areas (SWFWMD, 2004). The first region is adjacent to a major urban roadway (US 41) and a large residential subdivision in Nort Port, and likely receives nontrivial amounts of both residential discharge and stormwater runoff. The second location is situated near the most developed portion of the entire sampling area, which has been reported to contain a high density of on-site sewage disposal systems (Lipp et al., 2001). In contrast, the region between the northernmost sampling site and sites 6–8 is largely undeveloped because Sarasota County has designated virtually its entire portion of the river a conservation area. The region between sites 6–8 and 15 is also bordered by conservation lands and is only sparsely populated.

Based on the land use patterns described above, wastewater-related compounds likely contribute greatest to estrogenic activity present in the central and southern Myakka River. This category of EDCs includes human-excreted hormones (both natural and synthetic), detergent metabolites, and plasticizers, which together represent nearly 80% of the total organic wastewater contaminants commonly detected in U.S. streams and rivers (Kolpin et al., 2002). Organochlorine pesticides may also be responsible for estrogenic activity in these regions based on the high per acreage application rates of some of these compounds (e.g., endosulfan) in the southwest Florida region. Anabolic agents excreted by livestock (Soto et al., 2004) presumably contribute little to the total estrogenicity of the mid- to lower portions of the river. However, these compounds may be more prevalent in surface waters to the north of the sampling area, where agricultural activity is more concentrated.

Although estrogenic activity in the lower Myakka River is present in areas of significant residential development, its abundance in surface waters may not be directly linked with seasonal changes in human activity. This premise is based on previous studies that have demonstrated elevated concentrations of fecal indicator organisms and human enteroviruses in the surface waters of the lower Myakka River primarily during the less-populated, wet season (Lipp et al., 2001). During such periods, these compounds enter the riverine environment more substantially via increased stormwater runoff and backflow of flooded and/or damaged sewerage systems (Euripidou and Murray, 2004). In consideration of these results, the authors hypothesize that estrogenic contaminants may pose their greatest and, perhaps, only threat to the Myakka River ecosystem during periods of flooding associated with increased precipitation and extreme weather events (e.g., tropical storms, hurricanes). This would be especially true for the lower segment of the sampling area, which experienced significant chemical contamination just prior to September 2004 due to flooding and structural damage caused by Hurricane Charley. Interestingly, an increase in the abundance of fecal organisms may also influence the estrogenic activity of surface waters because they are capable of re-converting inactive conjugates of natural and synthetic estrogens excreted by humans back to their non-conjugated, active form (Ying et al., 2002).

In conclusion, this study has demonstrated the presence of estrogenic EDCs in surface waters of the lower Myakka River near regions of high residential development. Identification of the specific contaminants that contribute to hormonal activity in this region will be necessary in future studies based on the potential health risks that these chemicals pose to wildlife populations. However, given the limited presence of xenoestrogens in this river system, EDC screening in other areas of the Charlotte Harbor ecosystem that consistently possess evidence of estrogenic contamination may be of greater concern at this time. To this end, the present study has also demonstrated the value of the E-SCREEN bioassay as a useful technique for pre-screening Florida waters for evidence of these harmful, yet rarely measured contaminants.

ACKNOWLEDGMENTS—The authors thank L. K. Dixon and J. Perry for their contributions to this study and the guest editor and anonymous reviewers for their assistance in improving this publication. This project was supported by a grant from the Charlotte Harbor National Estuary Program to JG. Additional support for this research was provided by grant from the Mote Scientific Foundation to Mote Marine Laboratory's Charlotte Harbor Initiative. Funding for Sara Mouzi's involvement in this study was provided via National Science Foundation Grant #OCE-0139392 to JG, which supports Mote Marine Laboratory's Research Experience for Undergraduates Program.

## LITERATURE CITED

BORTONE, S. A. AND R. P. CODY. 1999. Morphological masculinization in poeciliid females from a paper mill effluent receiving tributary of the St. Johns River, Florida, USA. Bull. Environ. Contam. Toxicol. 63: 150–156.

EURIPIDOU, E. AND V. MURRAY. 2004. Public health impacts of floods and chemical contamination. J. Public Health (Oxf) 26: 376–383.

FACEMIRE, C. F., T. S. GROSS, AND L. J. GUILLETTE, JR. 1995. Reproductive impairment in the Florida panther: nature or nurture? Environ. Health Perspect. 103 Suppl. 4: 79–86.

FURUICHI, T., K. KANNAN, J. P. GIESY, AND S. MASUNAGA. 2004. Contribution of known endocrine disrupting substances to the estrogenic activity in Tama River water samples from Japan using instrumental analysis and in vitro reporter gene assay. Water Res. 38: 4491–4501.

GALLAGHER, E. P., T. S. GROSS, AND K. M. SHEEHY. 2001. Decreased glutathione S-transferase expression and activity and altered sex steroids in Lake Apopka brown bullheads (*Ameiurus nebulosus*). Aquat. Toxicol. 55: 223–237.

GUILLETTE, L. J., JR., A. R. WOODWARD, D. A. CRAIN, D. B. PICKFORD, A. A. ROONEY, AND H. F. PERCIVAL. 1999. Plasma steroid concentrations and male phallus size in juvenile alligators from seven Florida lakes. Gen. Comp. Endocrinol. 116: 356–372.

GUNDERSON, M. P., D. S. BERMUDEZ, T. A. BRYAN, S. DEGALA, T. M. EDWARDS, S. A. KOOLS, M. R. MILNES, A. R. WOODWARD, AND L. J. GUILLETTE, JR. 2004. Variation in sex steroids and phallus size in juvenile American alligators (*Alligator mississippiensis*) collected from 3 sites within the Kissimmee-Everglades drainage in Florida (USA). Chemosphere 56: 335–345.

KOLPIN, D. W., E. T. FURLONG, M. T. MEYER, E. M. THURMAN, S. D. ZAUGG, L. B. BARBER, AND H. T. BUXTON. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance. Environ. Sci. Technol. 36: 1202–1211.

KÖRNER, W., V. HANF, W. SCHULLER, C. KEMPTER, J. METZGER, AND H. HAGENMAIER. 1999. Development of a sensitive E-screen assay for quantitative analysis of estrogenic activity in municipal sewage plant effluents. Sci. Total Environ. 225: 33–48.

LEUSCH, F. D., H. F. CHAPMAN, W. KÖRNER, S. R. GOONERATNE, AND L. A. TREMBLAY. 2005. Efficacy of an advanced sewage treatment plant in southeast Queensland, Australia, to remove estrogenic chemicals. Environ. Sci. Technol. 39: 5781–5786.

LIPP, E. K., R. KURTZ, R. VINCENT, C. RODRIGUEZ-PALACIOS, S. R. FARRAH, AND J. B. ROSE. 2001. The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. Estuaries 24: 266–276.

NATIONAL RESEARCH COUNCIL. 1999. Hormonally Active Agents in the Environment. National Academy Press, Washington DC.

OH, S. M., S. Y. CHOUNG, Y. Y. SHEEN, AND K. H. CHUNG. 2000. Quantitative assessment of estrogenic activity in the water environment of Korea by the E-SCREEN assay. Sci. Total Environ. 263: 161–169.

ORLANDO, E. F., N. D. DENSLOW, L. C. FOLMAR, AND L. J. GUILLETTE, JR. 1999. A comparison of the reproductive physiology of largemouth bass, *Micropterus salmoides*, collected from the Escambia and Blackwater Rivers in Florida. Environ. Health Perspect. 107: 199–204.

PARKS, L. G., C. S. LAMBRIGHT, E. F. ORLANDO, L. J. GUILLETTE, JR., G. T. ANKLEY, AND L. E. GRAY, JR. 2001. Masculinization of female mosquitofish in Kraft mill effluent-contaminated Fenholloway River water is associated with androgen receptor agonist activity. Toxicol. Sci. 62: 257–267.

SCHILIRO, T., C. PIGNATA, E. FEA, AND G. GILLI. 2004. Toxicity and estrogenic activity of a wastewater treatment plant in Northern Italy. Arch. Environ. Contam. Toxicol. 47: 456–462.

SEMENZA, J. C., P. E. TOLBERT, C. H. RUBIN, L. J. GUILLETTE, JR., AND R. J. JACKSON. 1997. Reproductive toxins and alligator abnormalities at Lake Apopka, Florida. Environ. Health Perspect. 105: 1030–1032.

SEPULVEDA, M. S., W. E. JOHNSON, J. C. HIGMAN, N. D. DENSLOW, T. R. SCHOEB, AND T. S. GROSS. 2002. An evaluation of biomarkers of reproductive function and potential contaminant effects in Florida largemouth bass (*Micropterus salmoides floridanus*) sampled from the St. Johns River. Sci. Total Environ. 289: 133–144.

SEPULVEDA, M. S., D. S. RUESSLER, N. D. DENSLOW, S. E. HOLM, T. R. SCHOEB, AND T. S. GROSS. 2001. Assessment of reproductive effects in largemouth bass (*Micropterus salmoides*) exposed to bleached/unbleached kraft mill effluents. Arch. Environ. Contam. Toxicol. 41: 475–482.

SOTO, A. M., J. M. CALABRO, N. V. PRECHTL, A. Y. YAU, E. F. ORLANDO, A. DAXENBERGER, A. S. KOLOK, L. J. GUILLETTE, JR., B. LE BIZEC, I. G. LANGE, AND C. SONNENSCHEIN. 2004. Androgenic and estrogenic activity in water bodies receiving cattle feedlot effluent in Eastern Nebraska, USA. Environ. Health Perspect. 112: 346–352.

SOTO, A. M., C. SONNENSCHEIN, K. L. CHUNG, M. F. FERNANDEZ, N. OLEA, AND F. O. SERRANO. 1995. The E-SCREEN assay as a tool to identify estrogens: an update on estrogenic environmental pollutants. Environ. Health Perspect. 103 Suppl. 7: 113–122.

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT. 2004. Myakka River Comprehensive Watershed Management Plan. Brooksville, FL. Available online at http://www.swfwmd.state.fl.us/documents/.

TIAN, C.-Y., C.-Q. HU, AND H.-Y. SONG. 2002. Assessment of estrogenic activity of natural compounds using improved E-SCREEN assay. Acta Pharmacol. Sin. 23: 572–576.

TOFT, G., T. M. EDWARDS, E. BAATRUP, AND L. J. GUILLETTE, JR. 2003. Disturbed sexual characteristics in male mosquitofish (*Gambusia holbrooki*) from a lake contaminated with endocrine disruptors. Environ. Health Perspect. 111: 695–701.

VILLALOBOS, M., N. OLEA, J. A. BROTONS, M. F. OLEA-SERRANO, J. M. RUIZ DE ALMODOVAR, AND V. PEDRAZA. 1995. The E-screen assay: a comparison of different MCF7 cell stocks. Environ. Health Perspect. 103: 844–850.

YING, G. G., R. S. KOOKANA, AND Y. J. RU. 2002. Occurrence and fate of hormone steroids in the environment. Environ. Int. 28: 545–551.

Florida Scient. 69(00S2): 92–99. 2006
Accepted: March 10, 2006

# PESTICIDES IN SOUTHWEST FLORIDA WATERWAYS – A REPORT CARD

JUDITH M. HUSHON

Conservancy of Southwest Florida, Naples, Florida

ABSTRACT: *This paper describes a methodology for estimating pesticide hazards in surface water by Water Body ID (WBID). Southwest Florida was selected as the area of interest. The methodology considers agriculture (citrus and row crops), mosquito management, lawn maintenance, and golf course maintenance. For each pesticide, physical chemical properties are used to predict transport and fate in surface water and this is combined with acute toxicity data on fish, aquatic invertebrates, insects, and birds. This together with the quantity of each pesticide used by WBID helps to estimate the relative pesticide hazards for each WBID. Row crops contribute the greatest hazard with tomatoes and bell peppers leading the list followed by citrus, lawn maintenance, mosquito management and finally golf course maintenance. The most hazardous pesticides were: the fumigants methyl bromide and chloropicrin followed by oxadiazon (lawn herbicide), copper hydroxide (agricultural fungicide), permethrin (lawn insecticide), bromacil (lawn herbicide), mancozeb (lawn fungicide), atrazine (lawn herbicide), diuron (agricultural herbicide), chlorothalonil (agricultural and lawn fungicide), and glyphosate (agricultural herbicide). The methodology predicted that the most affected WBIDs lie in the agricultural areas of Collier and Hendry Counties.*

*Key Words:* Pesticides, surface water, WBID, hazard index, relative hazard assessment methodology, mosquito control, lawncare, golf course, agriculture, row crops, citrus

PESTICIDES have many different uses and the impacts from these applications can combine to create significant hazards to those populations that rely on surface water. Pesticides entering southwest Florida waterways predominately come from: agriculture (citrus and row crop), mosquito control, golf courses, and residential lawn maintenance.

The geographic area of interest for this project extends from Charlotte Harbor to Rookery Bay and includes the area to the west of the main Okeechobee/Everglades drainage through the "river of grass." This drainage area is generally hydrologically separate from that for the southeastern two thirds of the state. It includes a number of distinct water drainage basins, designated by distinct water body IDs (WBIDs).

Monitoring of surface water and sediment has been done for the area of interest in the past for a limited set of pesticides. Most of these are no longer in use, though many are still present because of their long environmental half-lives. In Collier County, no surface water data were available, but sediment data for pesticides were available for a variety of locations covering the period 1991 to 1992 under two separate monitoring programs (Grabe, 1993). The bulk of the monitoring looked for aldrin, Delta-BHC, Gamma-BHC, 4,4′-DDD, dieldrin, endosulfan, endosulfan sulfate, endrin, heptachlor and chlordane in surface sediments. While levels above the detection limit were found for all of the above at a number of locations, no levels approached the Florida soil/sediment screening levels. Of the above pesticides, only gamma-BHC (Lindane) and endosulfan are still in use, the rest having being banned.

Gardinali and co-workers (2002) reviewed the historical data on pollutants from urban and agricultural land use, including pesticides. They carried out sampling in June and December 2001 at a variety of coastal and estuarine locations. They also looked for levels of historical pesticides and found chlordanes, endosulfan and DDTs in sediment at levels above the detection limit in Rookery Bay/Henderson Creek, the Everglades/Faka Union Canal and Naples Bay. They found 4,4′-DDE in 62% of their samples, chlorpyrifos in 31% of the samples, and chlordanes in 20% of the samples. Endosulfan (including I, II and endosulfan sulfate) was not found at frequencies above 6%. Only aldrin and chlorpyrifos exceeded concentrations of 1 mg/kg. At one sampling station on the Blackwater River, the level of chlorpyrifos in sediments was well above the national average of 0.269 mg/kg and use of chlorpyrifos has been increasing.

These chlorinated pesticides tend to reside in sediments, and data for surface water concentrations of currently used pesticides have not been found. Based on the findings of the NOAA report (Clark et al., 1993) coupled with the higher percentage of pesticide detections in sediments as reported by Grabe (1993) for Collier County, Shahane (2003b) stated that Collier County is viewed as one of the "hot spots" by the state regulators.

In Charlotte County, the South Florida Water Management District undertook quarterly sampling from 1980 through the present time at three locations on the Caloosahatchee River that empties into Charlotte Harbor (Pfeuffer & Matson, 1980-present). That river receives water from Lake Okechobee as well as numerous other streams and canals. This project looked for the presence in surface water of 63 pesticides, most of which are in current use. Ametryn, atrazine and two of its breakdown products (atrazine desethyl and atrazine desisopropyl), bromacil, norflurazon, and simazine were detected above background levels. Peak concentrations tended to occur in late summer/early fall when rainfall runoff is greatest and when pumping is occurring to clear fields of standing water. Most of these pesticides are associated with sugar cane and citrus which is typical of this area.

These data, or lack thereof, point out that there is an obvious need to determine what pesticides are in use in southwest Florida, the rates at which they are being applied, and the levels to which they are present in local waters and sediments. It is also important to identify those pesticides that represent the greatest hazards to local ecosystems.

This paper describes a methodology that attempts to combine data from a number of sources in a scientific approach to determining the relative risks of various pesticides and the geographical areas (WBIDS) that are most likely to be affected. It will be in these areas that monitoring will most likely detect pesticides and the individual pesticides likely to be present can also be predicted.

MATERIALS AND METHODS—*Schema for assigning relative risk scores*—This exercise is in no way intended to be a quantitative risk assessment, predicting actual exposure levels to individual target species.

Rather, it is designed to be a relative risk estimation method to indicate which water drainage areas are most likely to be impaired due to pesticide use and which pesticides are most likely to be causing the greatest impacts on specific Southwest Florida waterways.

Therefore, a scoring system was devised that relied on physical/chemical properties, aquatic, avian, and insect toxicity tests conducted under laboratory conditions, and information on pesticide chemical usage for the counties in Southwest Florida. This system is based on other systems used by the US Environmental Protection Agency (1992), the Florida Pesticide Review Council of the Florida Department of Agriculture (1986), and the US Department of Energy (Gillett, 1983).

The basic scoring approach involves creating a Hazard Index (HI) that serves as a measure of relative risk and represents the relationship shown in Equation 1:

$$\text{Hazard Index} = \text{Chemical Quantity} \times \text{Environmental Fate} \times \text{Toxicity} \qquad (1)$$

The *Chemical Quantity* term is expressed in terms of pounds of active ingredient per acre times the number of acres to which it is applied. The quantities come from the state agricultural data for the agricultural and mosquito control pesticides, from type of land use for the lawncare pesticides, and from use statistics on a per hole basis for the golf course pesticides. Because estimated actual use data are available, it is possible to compare the relative impacts of the four categories of use.

Because it was impossible to obtain concurrent use data for all categories of use, there will be some discrepancies since use of particular products may increase or decrease over time. There are also trends in shifting land use that may affect actual outcomes. Decisions were also made to assume that all pesticide users in a particular category used the same products since there was no way to differentiate. This will lead to local variations, but overall, the methodology is useful to predict a ranked list of concerns by chemical and by WBID.

The goal of this project is to obtain scores by water drainage areas in Southwest Florida. The approach used to accomplish this varied by use pattern.

*Agriculture*—The Florida State Department of Agricultural Services publishes a survey of agricultural pesticide use every three years (Shahane, 2003a). This publication identified the major crops by county, the pesticides used on each crop, and the quantity of each pesticide used per county. This was extremely useful both in identifying the pesticides used and the differences in pesticides used by crop and region within the state of Florida. The most recent data were for 2002, and these were used for this effort.

*Mosquito control*—Shahane (2003a) also identified the quantities of various mosquito control chemicals used by county in 2002. These included both pre-emergent and larval treatments which were added together to obtain total quantities of pesticides used.

*Golf courses*—Since collective data on golf course pesticide quantities are not available. These values had to be estimated based on a survey of pesticide use by a group of typical golf course superintendents. The locations of the golf courses are known as are the counties in which they are located. There were no golf courses within the portions of Charlotte and Hendry Counties that lie within our study area (courses present in those counties lie outside the study area for this project). Collier County has 75 courses with 1539 holes, Lee County has 75 courses with 1432 holes and Glades County has two golf courses with 45 holes.

A supplier of golf course chemicals in SW Florida provided a list of chemicals and their active ingredients were identified from Material Safety Data Sheets (MSDSs) and labels. Quantities of chemicals for the 152 golf courses in our study area were estimated based on a survey of 15 golf course superintendents in Collier and Lee Counties and knowledge about the sizes and number of holes per course. The data from the 15 courses that responded to the survey were adjusted to take into account the shorter executive courses and averaged on a per hole basis. These averages were used to estimate total pesticide use at the 152 identified golf courses in the study area.

*Lawncare*—The numbers of residences within a WBID were estimated based on County data obtained from the 1999 Florida Geographic Data Library maps showing residential areas and estimating residential density within an area. The scale used was: $<$2 domiciles/acre are considered low density, 2–5 domiciles/acre are considered medium density, and $>$5 domiciles/acre are considered high density.

TABLE 1. Pesticide applicators by housing type.

| | Owner Applied | Service Applied |
|---|---|---|
| Mobile Homes | 100% | 0% |
| Low Density (<2/ac) | 50% | 50% |
| Medium Density (2–5/ac) | 30% | 70% |
| High Density (>5/ac) | 50% | 50% |
| High Density Hi Rise | 0% | 100% |

There are also two types of grass in Southwest Florida, St. Augustine (*Stenotaphrum sedondum*) and bahia (*Paspalum notatum*), each of which requires a unique maintenance regimen. It is assumed that 80% of the lawns are St. Augustine and 20% are bahia grass.

There are two general approaches to lawncare pesticide application: owner applied or lawn service applied. The chemicals used and concentrations in the products vary for the two approaches. The split of these two approaches shown in Table 1 was assumed.

For lawn service applied chemicals, the recommended levels of the chemicals identified by Tru-Green and the large wholesale chemical supplier were used and averaged for each grass type and then combined for a total application pattern.

For the chemicals used by homeowners, active ingredients were noted on the labels of lawncare products sold at Home Depot and Lowe's stores located in SW Florida. For residential applications, it was assumed that a series of lawncare products were used as recommended by the manufacturer as well as one container of spot weed control (herbicide), and one container for insect (aphid, scale, grub, or fire ant) control. Data for all marketed products were averaged and spread over the total number of residences. Application rates were those recommended on the label by the manufacturer.

The lawncare acreage is probably an underestimation of the current residential acreage because of the rapid rate of conversion of agricultural lands to residential lands, especially in the eastern parts of Lee, Collier and Charlotte Counties.

The *Toxicity Score* is dependent on the affected ecological populations; however scores for fish and aquatic invertebrates are averaged since they occupy the same niche. Therefore, one obtains a separate toxicity score for aquatic organisms (Ta), insects (Ti), and birds (Tb). The following is an example of the ordinal scoring schema used for toxicity. Toxicities for fish and aquatic invertebrates were based on 96 hour flow through $LC_{50}$s for fish and 48 hour $LC_{50}$s for the invertebrates as measured in water fleas (*Daphnia magna*). Concentrations less than 1 mg/l received an ordinal score of 7. Concentrations in the 1–10 mg/l range received a score of 3, those in the 10–100 mg/l range a score of 2, those in the 100–1000 mg/l range a score of 1, and those greater than 1000 mg/l a score of 0. Insect toxicity was based on those toxicity ranges regularly reported for honeybee bioassays with a score of 7 being assigned for honey bee toxicity <11 µg/bee, a score of 3 for 24–11 µg/bee, a score of 2 for 25–99 µg/bee and a score of 1 for >100 µg/bee. Bird toxicity was based on mallard, quail, or rat oral $LD_{50}$s, in that order. A score of 7 being assigned for an $LD_{50}$ <5 mg/kg of body weight, a score of 3 for 5–99 mg/kg, a score of 2 for 100–999 mg/kg, a score of 1 for 1000–5000 mg/kg and a score of 0 for >5000 mg/kg.

The *Environmental Fate* term (EF) is computed as shown in Equation 2:

$$EF = W + S + A + BCF + Pw + (0.5 * Ps) \qquad (2)$$

Where

W = water solubility score
S = soil mobility
A = sediment adsorption
BCF = bioaccumulation score
Pw = Persistence in water
Ps = Persistence in soil

The soil persistence score was divided in half because pesticides tilled into deeper soil layers may not reach waterways.

The following schema was used to evaluate environmental fate parameters. Soil mobility and adsorption to sediments were ranked from high to low based on Koc (soil adsorption coefficient). The tendency to bioconcentrate was based on BCF (bioconcentration factor) or log Kow (octanol/water partition coefficient) and ranges from a score of 7 for a log Kow >6 or a BCF >4000 to a score of 0 for a log Kow <3 or a BCF <300. Water solubility was obtained from literature values obtained at approximately ambient temperatures and ranged from a score of 4 for >1000 ppm to a score of 1 for a solubility of <10 ppm. The next set of scores relate to how long a chemical is likely to remain in the aquatic environment and in sandy soil. These scores range from 9 for a half life of >100 days to 0 for a persistence of less than 0.01 day.

These scales are generally logarithmic in nature and were chosen to provide a good spread of values as well as to penalize those chemicals that are particularly persistent, bioaccumulative, or toxic. Chemicals that have these attributes have been demonstrated to be those that are most likely to impact target populations.

To try to evaluate the potential for exposure to a pesticide and the effects on fish, aquatic invertebrates, insects, and birds, specific chemical information was gathered from USEPA Pesticide Fact Sheets, material safety data sheets and pesticide labels. Additional data were obtained from Hazardous Substances Data Bank, Extonet and other electronic sources available from the author upon request. These same sources generally also contain toxicity test data.

*General approach to scoring*—First EF × Toxicity scores were obtained by group (aquatic, insect, bird). These were then normalized to a 100 point scale. Table 2 contains the scores assigned to the raw data and the calculated EF values, the raw EF × Toxicity scores, and the normalized EF × T scores for aquatic life, insects, and birds. These data give an indication of the relative impacts pesticide active ingredients are likely to have in the aquatic environment. Only those chemicals found to have a significant potential impact were included in Table 2, but the number of chemicals actually evaluated in this exercise was much larger.

*Computation of hazard indexes by county*—As stated previously, in EQUATION (1), the Hazard Index is the product of chemical quantity, environmental fate and toxicity. For this project, Hazard Indexes were obtained separately for agricultural, mosquito control, golf course, and residential lawncare pesticides.

For each chemical and use, the chemical quantities and the normalized EF × T scores (aquatic, insect and bird) were multiplied together. These results show the major impacting chemicals by activity and by county for the region of Southwest Florida. These results are shown in Table 3 for agricultural crops; similar tables are available from the author for mosquito control, lawn care and golf course maintenance.

Table 4 contains the percentages of the total pesticide loading across the whole study area represented by each pesticide use category in each of the counties studied. It can be seen that the quantities vary greatly by use.

It is obvious that agriculture dominates the pesticide use with over 84% of the total. This also results in elevated county totals for Collier and Hendry, where most of the agricultural activities occur. Collier has the highest overall county scores because it has both agriculture and a significant residential population. Lee County, which has much less agriculture, has the highest residential lawncare-related pesticide use because its residential area is the greatest.

DISCUSSION—*Pesticides representing the greatest impacts*—Throughout this evaluation, pesticides have been grouped into use categories as fungicides (F), herbicides (H) and insecticides (I). The fact that a pesticide shown in Table 2 may have a particularly high EF × T score does not necessarily mean that it is causing a problem within the study area. This is because potential impacts are caused by a combination of EF × T and the amount used. Sometimes, a lower scoring EF × T pesticide that is used in higher volumes will actually cause greater harm than one with a high EF × T score but with lower use. Many active ingredients in pesticides are included in a wide range of products that are approved by USEPA for a variety

TABLE 2. Pesticide data table including environmental fate and toxicity scores.

| | Soil Mob | Sed Adsorb | BCF | H20 sol | Fish Tox | Inv Tox | Ins Tox | Bird Tox | Ps | Pw | Env Fate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,3-dichloropropene | 3 | 3 | 0 | 4 | 3 | 3 | 7 | 0 | 6 | 3 | 17.5 |
| 2,4-D | 3 | 3 | 0 | 3 | 2 | 3 | 3 | 1 | 6 | 3 | 16.5 |
| acephate | 3 | 3 | 0 | 4 | 7 | 7 | 7 | 2 | 3 | 6 | 16 |
| aldicarb | 3 | 3 | 0 | 3 | 3 | 2 | 7 | 7 | 6 | 6 | 18 |
| atrazine | 3 | 2 | 0 | 2 | 2 | 3 | 1 | 1 | 6 | 9 | 17.5 |
| basic copper sulfate | 1 | 1 | 3 | 4 | 7 | 7 | 1 | 1 | 6 | 6 | 18 |
| bifenthrin | 1 | 1 | 7 | 1 | 7 | 7 | 7 | 1 | 6 | 6 | 19 |
| bromacil | 3 | 3 | 0 | 3 | 3 | 1 | 1 | 0 | 9 | 6 | 21 |
| carbaryl | 3 | 3 | 0 | 3 | 7 | 7 | 7 | 2 | 6 | 3 | 16.5 |
| chloropicrin | 3 | 3 | 0 | 3 | 7 | 7 | 1 | 3 | 3 | 3 | 13.5 |
| copper hydroxide | 3 | 3 | 1 | 1 | 7 | 7 | 1 | 1 | 6 | 6 | 17 |
| diazinon | 1 | 1 | 1 | 1 | 7 | 7 | 7 | 7 | 6 | 3 | 11.5 |
| dicofol | 1 | 1 | 2 | 1 | 7 | 7 | 1 | 1 | 6 | 9 | 15.5 |
| diuron | 2 | 1 | 0 | 2 | 7 | 7 | 1 | 0 | 9 | 9 | 18.5 |
| endosulfan | 1 | 1 | 1 | 1 | 7 | 7 | 3 | 2 | 9 | 3 | 14.5 |
| ethion | 1 | 1 | 3 | 1 | 3 | 7 | 3 | 0 | 9 | 9 | 19.5 |
| glyphosate | 1 | 1 | 0 | 4 | 2 | 2 | 1 | 1 | 6 | 6 | 15 |
| lambda-cyhalothrin | 1 | 1 | 7 | 1 | 7 | 7 | 3 | 0 | 6 | 3 | 17.5 |
| malathion | 3 | 3 | 0 | 3 | 7 | 7 | 7 | 1 | 3 | 6 | 15 |
| mancozeb/maneb | 2 | 2 | 0 | 1 | 3 | 7 | 1 | 0 | 3 | 3 | 9.5 |
| methomyl | 3 | 3 | 0 | 3 | 3 | 2 | 7 | 1 | 6 | 9 | 19.5 |
| methyl bromide | 3 | 3 | 0 | 2 | 3 | 3 | 7 | 3 | 6 | 6 | 17 |
| monosodium methane arsenate (MSMA) | 1 | 1 | 7 | 2 | 7 | 7 | 7 | 1 | 9 | 9 | 24.5 |
| naled | 3 | 3 | 0 | 4 | 7 | 7 | 3 | 1 | 3 | 6 | 16 |
| norflurazon | 1 | 1 | 0 | 2 | 3 | 2 | 1 | 1 | 6 | 6 | 13 |
| oxadiazon | 1 | 1 | 7 | 1 | 7 | 3 | 1 | 1 | 9 | 6 | 22 |
| pentachloronitrobenzene | 1 | 1 | 7 | 1 | 7 | 7 | 0 | 1 | 9 | 3 | 20.5 |
| permethrin | 1 | 1 | 7 | 1 | 7 | 7 | 7 | 0 | 6 | 6 | 19 |
| simazine | 3 | 2 | 0 | 1 | 1 | 3 | 1 | 0 | 6 | 3 | 13.5 |
| sulfur | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 6 | 6 | 12 |
| thiophanate-methyl | 3 | 3 | 0 | 2 | 3 | 3 | 1 | 0 | 6 | 3 | 15.5 |

of uses. Therefore, it is also important to sum the use of each pesticide active ingredient across uses to estimate its potential impact.

Table 5 contains the data on potential pesticide impacts across uses by pesticide for those with the highest risks. Table 5 is coded to show increasing levels of risk. There are only two chemicals with extremely high risk and these are chloropicrin and methyl bromide, both which are only used as fumigants on agricultural crops. These highly toxic fumigants are applied to the soil prior to planting to sterilize it against nematodes, bacteria, fungi, and insects such as grubs, cutworms and wire-worms. The fumigated area is immediately covered with a tarpaulin to avoid evaporation and drift. The high usage volumes also affect the HI score and elevate it further. These two pesticides alone account for 63.35% of the total calculated risk (see last column on Table 5). There is international legislation under the Montreal Protocol to reduce levels of methyl bromide released to the atmosphere where it is

TABLE 3. Hazard indexes by county for highest impact agricultural pesticides.

| Chemical | Use | Charlotte HI Total | Collier HI Total | Glades HI Total | Hendry HI Total | Lee HI Total |
|---|---|---|---|---|---|---|
| basic copper sulfate | F | 0 | 605,250 | 0 | 807,000 | 0 |
| chloropicrin | O | 0 | 2,189,734 | 0 | 2,919,645 | 0 |
| chlorothalonil | F | 0 | 122,105 | 0 | 162,806 | 0 |
| copper hydroxide | F | 0 | 77,089 | 0 | 102,785 | 0 |
| methyl bromide | O | 0 | 3,246,847 | 0 | 4,329,129 | 0 |
| Total Cucumber | | 0 | 6,384,443 | 11 | 8,512,591 | 0 |
| chlorpyrifos | I | 258,047 | 95,993 | 17,191 | 463,472 | 76,096 |
| copper hydroxide | F | 1,675,054 | 623,118 | 111,595 | 3,008,525 | 493,962 |
| diuron | H | 272,465 | 101,286 | 18,139 | 488,944 | 80,292 |
| ethion | I | 377,855 | 140,562 | 25,173 | 678,657 | 111,427 |
| fenbutatin-oxide | I | 60,165 | 22,381 | 4,008 | 108,062 | 17,742 |
| glyphosate | H | 273,500 | 101,742 | 18,221 | 491,227 | 80,653 |
| norflurazon | H | 65,056 | 24,201 | 4,334 | 116,845 | 19,185 |
| sulfur | F | 516,770 | 192,238 | 34,428 | 928,159 | 152,392 |
| Total Grapefruit | | 3,852,519 | 1,433,061 | 257,227 | 6,918,998 | 1,136,027 |
| aldicarb | I | 1,036,348 | 1,909,946 | 566,807 | 5,201,139 | 566,807 |
| basic copper sulfate | F | 192,673 | 355,088 | 105,378 | 966,971 | 105,378 |
| bromacil | H | 219,590 | 404,696 | 120,100 | 1,102,062 | 120,100 |
| carbaryl | I | 735,295 | 1,355,117 | 402,152 | 3,690,237 | 402,152 |
| chlorpyrifos | I | 239,992 | 442,295 | 131,258 | 1,204,452 | 131,258 |
| copper hydroxide | F | 2,464,191 | 4,541,399 | 1,347,732 | 12,367,078 | 1,347,732 |
| dicofol | I | 227,908 | 420,025 | 124,649 | 1,143,806 | 124,649 |
| diuron | H | 1,670,433 | 3,078,537 | 913,605 | 8,383,430 | 913,605 |
| ethion | I | 183,041 | 337,336 | 100,110 | 918,630 | 100,110 |
| glyphosate | H | 1,209,074 | 2,228,272 | 661,275 | 6,068,000 | 661,275 |
| iprodione | F | 24,507 | 45,165 | 13,403 | 122,992 | 13,403 |
| mefenoxam | F | 24,645 | 45,420 | 13,479 | 123,688 | 13,479 |
| norflurazon | H | 178,717 | 329,369 | 97,745 | 896,933 | 97,745 |
| paraquat | H | 48,521 | 89,421 | 26,537 | 243,511 | 26,537 |
| pyridaben | I | 32,578 | 60,040 | 17,818 | 163,500 | 17,818 |
| simazine | H | 298,147 | 549,473 | 163,065 | 1,496,318 | 163,065 |
| sulfosate | H | 56,268 | 103,700 | 30,775 | 282,396 | 30,775 |
| sulfur | F | 257,262 | 474,123 | 140,703 | 1,291,124 | 140,703 |
| Total Oranges | | 9,268,587 | 17,081,613 | 5,069,347 | 46,516,421 | 5,069,239 |
| chloropicrin | O | 0 | 12,884,460 | 0 | 23,621,509 | 0 |
| copper hydroxide | F | 0 | 1,130,546 | 0 | 2,072,667 | 0 |
| mancozeb/maneb | F | 0 | 623,947 | 0 | 606,278 | 0 |
| methomyl | I | 0 | 258,166 | 0 | 473,304 | 0 |
| methyl bromide | O | 0 | 38,876,181 | 0 | 71,272,999 | 0 |
| Total Peppers | | 0 | 54,008,016 | 500 | 98,476,950 | 0 |
| methyl bromide | O | 0 | 2,206,466 | 0 | 1,427,713 | 778,753 |
| Total Squash | | 0 | 2,206,699 | 0 | 1,427,960 | 778,835 |
| chloropicrin | O | 0 | 71,474,984 | 0 | 28,244,147 | 8,069,756 |
| chlorothalonil | F | 0 | 3,762,502 | 0 | 1,486,795 | 424,799 |
| copper hydroxide | F | 0 | 7,486,655 | 0 | 2,958,436 | 845,267 |
| diquat | H | 0 | 128,565 | 0 | 50,804 | 14,515 |
| endosulfan | I | 0 | 1,038,213 | 0 | 410,262 | 117,218 |
| imidacloprid | I | 0 | 205,351 | 0 | 81,147 | 23,185 |

TABLE 3. Continued.

| Chemical | Use | Charlotte HI Total | Collier HI Total | Glades HI Total | Hendry HI Total | Lee HI Total |
|---|---|---|---|---|---|---|
| mancozeb/maneb | F | 0 | 3,810,423 | 0 | 1,505,732 | 430,209 |
| methamidophos | I | 0 | 235,865 | 0 | 93,205 | 26,630 |
| methomyl | I | 0 | 542,183 | 0 | 214,250 | 61,214 |
| methyl bromide | O | 0 | 233,047,662 | 0 | 92,091,415 | 26,311,833 |
| Total Tomatoes | | 0 | 322,495,708 | 406 | 127,437,873 | 36,410,821 |
| 1,3-dichloropropene | O | 392,873 | 622,672 | 0 | 1,015,939 | 327,722 |
| Total Watermelon | | 406,615 | 640,649 | 0 | 1,045,269 | 337,184 |

considered an ozone depleting substance. This has the potential to reduce the use on agricultural fields in southwest Florida and to reduce the overall potential risk from pesticide exposure significantly.

The agricultural pesticides of greatest concern, following methyl bromide and chloropicrin are: copper hydroxide, diuron, glyphosate, aldicarb, mancozeb, captan, chlorothalonil, and sulfur. For mosquito control, no chemicals reach the levels of risk posed by the agricultural pesticides, but naled, malathion and permethrin are still of concern. The lawncare chemicals representing the greatest risk are: oxadiazon, pentachloronitrobenzene, bifenthrin, atrazine and mancozeb. The golf course chemical use is so greatly reduced due to integrated pest management techniques that only monosodium methane arsenate, and acephate are of potential concern. The use categories (herbicide, insecticide, fungicide and fumigant for the above listed chemicals of potential concern are included in Table 5.

Many of these high use pesticides are designated by the USEPA (2003) as Restricted Use Products or RUPs. This means that they must only be applied by trained operators and records of exposure must be maintained as required by 40 CFR 152 Subpart I. Generally only those pesticides felt to represent a risk to applicators or the environment are designated as RUP. The pesticides that have been designated as RUP are indicated with an asterisk in the second column of Table 5.

Only those pesticides indicated as High, Medium-High or Medium Risk should be considered for inclusion in the follow-on monitoring program since they represent the greatest potential risks to the environment. It should be pointed out that copper hydroxide and sulfur may represent more significant hazards than this method identifies because they contain elements that are not further degraded in the environment and which will be cumulative and persistent.

TABLE 4. Percent of total pesticide use across study area by activity.

| County | Agriculture | Lawncare | Mosquito Control | Golf Course Maintenance | County Totals |
|---|---|---|---|---|---|
| Charlotte | 1.58 | 0.29 | 0.26 | 0.00 | 2.13 |
| Collier | 44.80 | 1.34 | 0.96 | 0.48 | 47.58 |
| Glades | 0.59 | 1.30 | 0.00 | 0.01 | 1.91 |
| Hendry | 32.37 | 0.08 | 0.00 | 0.00 | 32.44 |
| Lee | 4.91 | 9.76 | 0.83 | 0.43 | 15.94 |
| Use Totals | 84.24 | 12.78 | 2.05 | 0.93 | 100 |

TABLE 5. Total HIs by pesticide by activity.

| Chemical | RUP | Agriculture | Mosquito | Lawncare | Golf Course | Total | % |
|---|---|---|---|---|---|---|---|
| 1,3-dichloropropene | | M | | | | M | 0.24 |
| 2,4-D | | P | | M | LM | M | 0.12 |
| acephate | | P | | M | M | M | 0.55 |
| aldicarb | * | M | | | | M | 0.94 |
| atrazine | * | P | | MH | P | MH | 1.89 |
| basic copper sulfate | | M | | | | M | 0.32 |
| bifenthrin | * | LM | | MH | P | MH | 2.17 |
| bromacil | | M | | | | M | 0.21 |
| carbaryl | | M | | LM | LM | M | 0.79 |
| chloropicrin | * | H | | | | H | 15.35 |
| chlorothalonil | * | M | | M | LM | MH | 1.33 |
| chlorpyrifos | * | M | | | LM | M | 0.34 |
| copper hydroxide | | MH | | | | MH | 4.32 |
| diazinon | * | LM | | M | | M | 0.92 |
| dicofol | | M | | | | M | 0.22 |
| diuron | | MH | | | | MH | 1.61 |
| endosulfan | | M | | | | M | 0.17 |
| ethion | * | M | | | | M | 0.30 |
| glyphosate | | MH | | LM | LM | MH | 1.29 |
| lambda-cyhalothrin | * | P | | M | P | M | 0.16 |
| malathion | | P | M | LM | | M | 0.35 |
| mancozeb/maneb | | M | | MH | P | MH | 2.12 |
| methomyl | * | M | | | | M | 0.17 |
| methyl bromide | * | H | | | | H | 48.00 |
| MSMA | | LM | | | M | M | 0.19 |
| naled | | P | M | | | M | 0.90 |
| norflurazon | | M | | | | M | 0.19 |
| oxadiazon | | | | MH | LM | MH | 8.03 |
| PCNB | | | | MH | | MH | 3.91 |
| permethrin | * | LM | M | | | M | 0.19 |
| simazine | * | M | | | | M | 0.29 |
| sulfur | | M | | | | M | 0.42 |
| thiophanate-methyl | | | | M | LM | M | 0.37 |

H = High Hazard, MH = Med-High Hazard, M = Medium Hazard, LM = Low-Med Hazard, P = Present.

*Determination of potential impacts by water drainage area*—The distribution of pesticide use within each Southwest Florida county was obtained separately for each type of application, but was then divided into water drainage areas using the ArcView™ Geographic Information System (GIS). Southwest Florida had Water drainage area delineations are available from several sources. For this project, the water drainage maps from the Florida State Department of Environmental Protection were used. These maps were merged and boundary discrepancies minimized for use on this project so they would cover the 5-county Southwest Florida water drainage area. It should be pointed out that a number of the WBIDs span county borders which is logical since the boundary lines are generally straight and do not follow waterways in this part of the state.

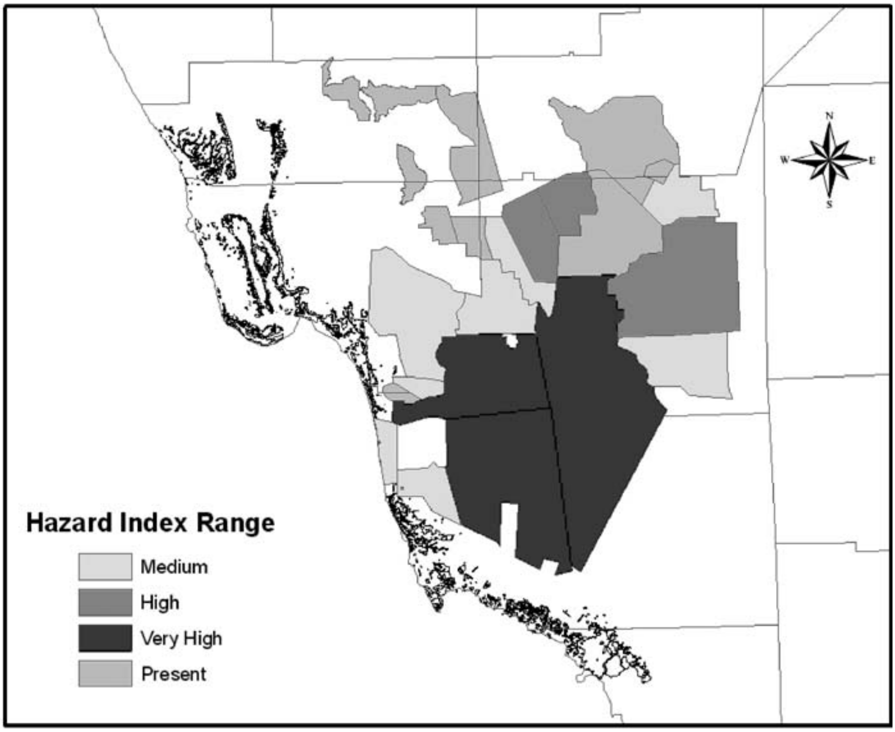



FIG. 1. Drainage areas of greatest concern for pesticides used in row crop agriculture.

GIS technology was also used to locate the various pesticide usage areas and to estimate the usage by water drainage area for each type of application on a county basis.

*Agriculture*—The US Department of Agriculture's Regional Agricultural Agent had significant experience covering the region in question and knew all of the farms, where they were located, the crops grown, and acreages by crop (McAvoy, 2004). The percentage of the total area for each crop was estimated for each water drainage area by overlaying the farm location and drainage area maps. The quantity of each major agricultural pesticide was calculated by water drainage area by County and is available from the author. The Agricultural Agent was also asked to review the State data on pesticides used by crop to see whether these data appeared consistent with his experience; and they were.

In addition, digitized county maps provided by Florida Geographic Data Library (1999) with layers showing farm locations for citrus and other row crops were used. Agricultural areas were split into two separate subcategories: citrus (oranges & grapefruit) and row crops (tomatoes, peppers, squash, cucumbers, watermelon). These two agricultural crop types have very different pesticide use patterns and so splitting them is logical. Figure 1 demonstrates the potential impacts of agricultural pesticide use on row crops by WBID. For citrus, there is one WBID of high concern (3261C which straddles Collier and Hendry Counties) and three WBIDs of moderate concern (2041 (Charlotte County), 3259B (Collier County) and 3259X (Collier, Lee, and Hendry Counties)).

*Mosquito control*—Areas of mosquito control were obtained from for the Collier Mosquito Control District (2004) from their web site. Similarly, Charlotte data were available at their website. Data for Lee County were obtained from their mosquito control department and application areas and rates were said to approximate the population distribution so that was used as a surrogate. No spraying is done in Hendry or Glades counties. These data were then added as a GIS layer and used to estimate the percentage the total spraying, and therefore of chemical use, could be allocated to each drainage area.

Table 6 contains the mosquito pesticide use relative risks by WBID and Figure 2 shows the WBIDs potentially affected. Most of the treated areas in Charlotte County were outside our study area. Only four WBIDs were identified as being of low potential concern: 3258C (Lee County), and 3259B, 3259I and 8064 (Collier County).

*Golf courses*—Each of the 152 golf courses identified during our survey was located on a base map using its address as a locator. Based on the data obtained for the 15 courses that participated in our survey, a typical per hole average application of chemicals was obtained. This was then multiplied by the total number of holes within each water drainage area. Amounts of chemicals were reduced by 15% for executive courses. Table 6 contains the golf course pesticide use relative risks by WBID. The greatest impacts are in Collier and Lee Counties which have the highest concentration of courses. Only two WBIDs (3259B & 3259C in Collier County) were indicated as potentially affected, and these are of low-measurable concern.

*Lawncare*—The GIS was used to estimate the total lawncare use by pesticide by water discharge area. This is shown in Table 6. The WBIDs potentially affected by residential lawncare use are all only of low potential concern and include: 3235J (Lee & Hendry Counties), 3235M (Glades & Hendry Counties), 3240A,B,C & E (Lee County), 3240I & J (Lee County), 3235J (Lee & Hendry Counties), 3235M (Glades & Hendry Counties), 3255 (Hendry County), 3258 C & E (Lee County), 3259 B, C, D, E, F, H & I (Collier County), and 8064 (Collier County).

*Combined impacts from all sources by WBID*—Because the HI scores for all activities are computed on the basis of pounds of active ingredient per acre, and are based on the same normalized EF $\times$ T scores, they can be summed across different uses within the same water drainage area. Table 6 contains the total relative risk data from all sources by WBID and the summed results are displayed in Figure 3. Several WBIDs that were below concern for any particular use pattern became of low concern when all patterns were combined: 2092 (Lee County), 3235D (Lee, Charlotte, Glades & Hendry Counties), 3235I (Lee & Hendry Counties), 3240L (Lee & Charlotte Counties), 3258F (Lee & Collier Counties), 3258G & H (Lee County), and 3259A (Lee & Collier Counties).

TABLE 6. Priorities for sampling by chemical and by WBID.

| WBID | Counties | 1,3-dichloropropene | 2,4-D | acephate | aldicarb | atrazine | basic copper sulfate | bifenthrin | bromacil | carbaryl | chloropicrin | chlorothalonil | copper hydroxide | diazinon | dicofol | diuron | endosulfan |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2041 | Charlotte | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3235B | Glades | M | M | M | | MH | M | MH | | M | H | M | MH | M | | | M |
| 3235J | Lee/Hendry | | M | M | | MH | | MH | | M | | M | | | | | |
| 3235L | Hendry | M | | | M | | M | | M | M | H | M | MH | M | M | MH | M |
| 3235M | Glades/Hend | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3235N | Hendry | M | | | M | | M | | M | M | H | M | MH | M | M | MH | M |
| 3237A | Glades | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3237B | Glad/Hend | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3237D | Glad/Hend | M | | | | | M | | | | H | M | MH | M | | | M |
| 3240A | Lee | | M | M | | MH | | | | M | | M | | | | | |
| 3240B | Lee/Char | | M | M | | MH | | MH | | M | | M | | | | | |
| 3240C | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3240E | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3240J | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3240K | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3255 | Hendry | | M | M | | MH | | MH | | M | | M | | | | | |
| 3258B | Lee | M | M | M | | MH | M | MH | | M | H | M | MH | M | | | M |
| 3258C | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3258E | Lee | | M | M | | MH | | MH | | M | | M | | | | | |
| 3259B | Collier | M | M | M | M | MH | M | MH | M | M | H | M | MH | M | M | MH | M |
| 3259C | Collier | M | M | M | | | M | | | M | H | M | MH | M | | | M |
| 3259D | Collier | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3259E | Collier | | M | M | | MH | | MH | | M | | M | | | | | |
| 3259F | Collier | | M | M | | MH | | MH | | M | | M | | | | | |
| 3259H | Collier | M | M | M | | MH | M | MH | | M | H | M | MH | M | | | M |
| 3259I | Collier | | M | M | | MH | | MH | | M | | M | | | | | |
| 3259L | Collier | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3259M | Collier | | | | M | | M | | M | M | | | MH | | M | MH | |
| 3259X | Col/Lee/Hend | M | | | M | | M | | M | M | H | M | MH | M | M | MH | M |
| 3261C | Collier/Hend | M | | | M | | M | | M | M | H | M | MH | M | M | MH | M |
| 3267 | Hendry | M | | | M | | M | | M | M | H | M | MH | | M | MH | M |
| 8064 | Collier | | M | M | | MH | | MH | | M | | M | | | | | |

TABLE 6. Continued.

| WBID | Counties | ethion | glyphosate | lambda-cyhalothrin | malathion | mancozeb | methomyl | methylbromide | MSMA | naled | norflurazon | oxadiazon | pentachloronitro-benzene | permethrin | simazine | sulfur | thiophanate methyl |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2041 | Charlotte | M | MH | | | | | | | | M | | | | M | M | |
| 3235B | Glades | | MH | M | M | MH | M | H | | | | MH | MH | M | | M | M |
| 3235J | Lee/Hendry | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3235L | Hendry | M | MH | | M | MH | M | H | | | M | | | M | M | M | |
| 3235M | Glades/Hendry | M | MH | | | | | | | | M | | | | M | M | |
| 3235N | Hendry | M | MH | | M | | M | H | | | M | | | M | M | M | |
| 3237A | Glades | M | MH | | | | | | | | M | | | | M | M | |
| 3237B | Glad/Hend | M | MH | | | | | | | | M | | | | M | M | |
| 3237D | Glad/Hend | | MH | | M | MH | M | H | | | | | | M | | M | |
| 3240A | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3240B | Lee/Char | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3240C | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3240E | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3240J | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3240K | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3255 | Hendry | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3258B | Lee | | MH | M | M | MH | M | H | | | | MH | MH | M | | M | M |
| 3258C | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3258E | Lee | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3259B | Collier | M | MH | M | M | MH | M | H | M | M | M | MH | MH | M | M | M | M |
| 3259C | Collier | M | MH | | M | MH | M | H | M | | | MH | | M | | M | M |
| 3259D | Collier | M | MH | | M | | | | | | M | | | | M | M | |
| 3259E | Collier | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3259F | Collier | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3259H | Collier | | MH | M | M | MH | M | H | | | | MH | MH | M | | M | M |
| 3259I | Collier | | MH | M | M | MH | | | | | | MH | MH | | | | M |
| 3259L | Collier | M | MH | | | | | | | | M | | | | M | M | |
| 3259M | Collier | M | MH | | | | | | | | M | | | | M | M | |
| 3259X | Col/Lee/Hend | M | MH | | M | MH | M | H | | | M | | | M | M | M | |
| 3261C | Collier/Hend | M | MH | | M | MH | M | H | | | M | | | M | M | M | |
| 3267 | Hendry | M | MH | | | MH | | H | | | M | | | | M | M | |
| 8064 | Collier | | MH | M | M | MH | | | | M | | MH | MH | | | | M |

H = High Hazard, MH = Med-High Hazard, M = Medium Hazard.

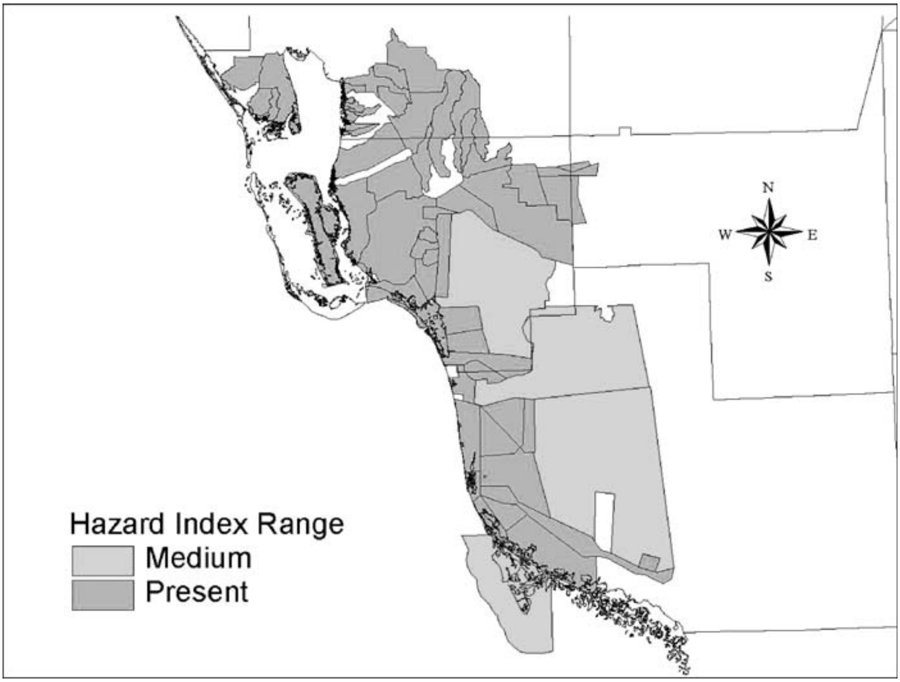



FIG. 2. Drainage areas of greatest concern for pesticides used in mosquito control.

CONCLUSIONS—The impacts of the evaluated activities appear to have the potential to impact the aquatic environment in the following order:

Agriculture >>> Lawncare >> Mosquito Control > Golf Course Management

This pattern was shown in Figure 4. Within the Agriculture category, row crops have a greater potential impact than citrus crops on a chemical use per acre basis. When the potential impacts of the individual row crops are evaluated, the following order emerges:

Tomatoes > Green peppers >> Watermelons > Cucumbers > Squash

Collier and Hendry Counties have the greatest concentrations of agricultural areas and hence the greatest potentials for impacts. Collier County also has the added concern of large residential areas adding in the lawncare, golf course maintenance and mosquito prevention activities.

From Figure 4 it becomes apparent that the impacts on the aquatic environment are greatest followed by those on insects and birds. Many pesticides target insects, but when runoff to aquatic habitats occurs, the fish and invertebrates are adversely affected. Birds are less affected because their diet does not tend to come all from one water body and they also tend to eat a variety of biota.

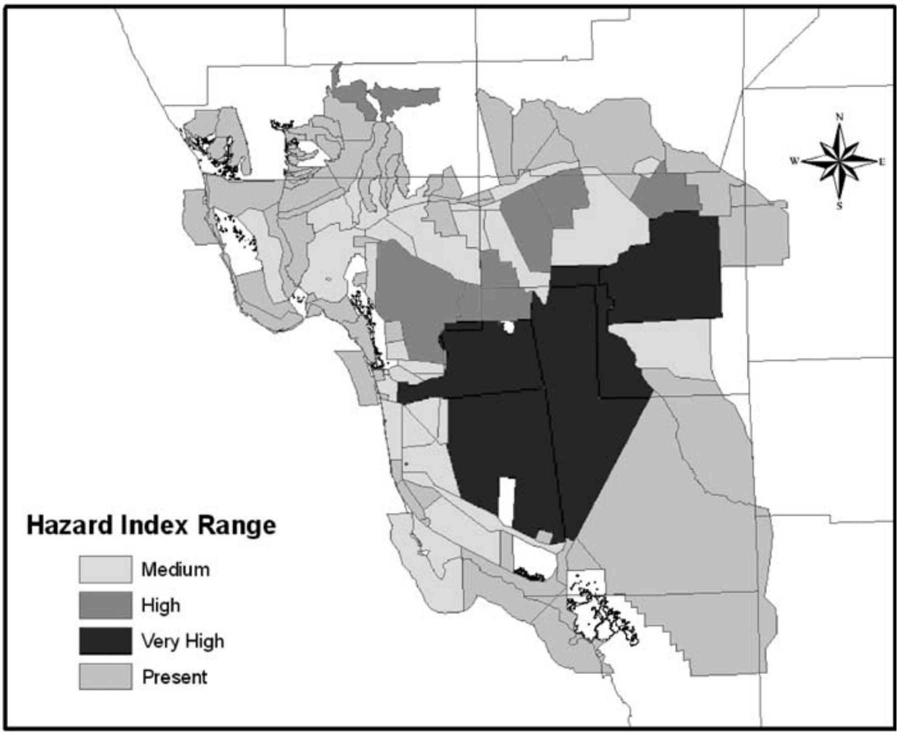



FIG. 3. Drainage areas of greatest concern for pesticides for all uses combined.

*What next?*—This exercise has been purely predictive based on literature values and reported and estimated application rates for a wide variety of pesticides used in agriculture, mosquito control, golf course maintenance, and residential lawncare. However, it has indicated the need for confirmatory monitoring of pesticides likely to represent the greatest threats and the water drainage areas most likely to be affected in Southwest Florida.

To confirm these predictions, sampling of surface water and sediment is required. Because the greatest runoff of pesticides occurs during the rainy season (in August–September), this is the optimal sampling time. The second best time is shortly after the first heavy rain following the dry season (April). Table 6 contains a matrix of the pesticides of potential concern by WBID where high levels of potential impacts are predicted and can be used to establish priorities for monitoring. The WBIDs indicated with a High or Medium-High Risk are the first priority. This prioritization can be used to select chemicals for inclusion in a monitoring program depending on the available funding level.

Ideally confirmatory sampling should include both water column and sediment samples at the same location at several points along the waterway within the selected WBID. Sampling points should be located downstream of identified stormwater outfalls. If high levels are identified at a sampling point, follow-up sampling to more

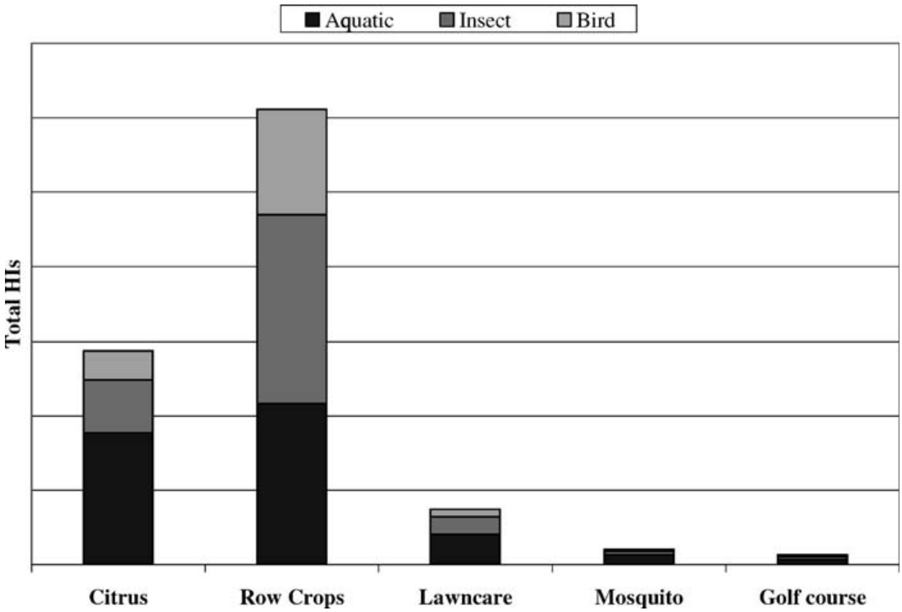



FIG. 4. Hazard impacts on ecological populations by type of use.

closely define the local situation may be required. It may also be desirable to sample some of the same points in the spring as well as in the fall.

If the sampling activities confirm the presence of levels of pesticides that raise environmental concerns, ways of reducing these potential impacts should be sought.

ACKNOWLEDGMENTS—Gary Davis, Conservancy of Southwest Florida for his guidance and knowledge of data sources; my reviewers and guest editors for their helpful comments and guidance.

## LITERATURE CITED

CHARLOTTE COUNTY ENVIRONMENTAL SERVICES. 2004. http:/www.charlottecountyfl.com/Environmental Services/buggs/mosquito1.html

CLARK, J. R., M. A. LEWIS, AND A. S. PAIT. 1993. Pesticide Inputs and Risks in Coastal Wetlands. Environ. Toxicol. Chem. 12:2225–2233.

COLLIER COUNTY MOSQUITO CONTROL DISTRICT. 2004. http://www.collier-mosquito,org/districtmap.asp

FLORIDA PESTICIDE REVIEW COUNCIL. 1986. Pesticide Assessment Procedure: An evaluation procedure based on pesticide and hydrogeologic factors developed for selective pesticide monitoring of groundwater in Florida.

GARDINALI, P., Y. CAI, R. JAFFEE, AND J. BOYER. 2002. Effects of Increased Urban and Agricultural Land use on the Anthropogenic Loading to Southwest Florida Estuaries: Volume 1—Technical Report. Prepared for the Environmental Services Division, Pollution Control Department, Collier County, Florida, Southeast Environmental Research Program and Department of Chemistry, Florida International University, OE-148, Miami, FL.

FLORIDA GEOGRAPHIC DATA LIBRARY. 1999. Geoplan Center, University of Florida.

GILLETT, J. W. 1983. A comprehensive pre-biologic screen for ecotoxicologic effects. Environ. Toxicol. Chem. 2:463–576.

GRABE, S. 1993. Sediment quality in Collier County estuaries, 1990–1991. Report PC-AR-93-07. Pollution Control Department, Collier County, Florida.

MCAVOY, G. 2004. Regional Vegetable/Horticulture Extension Agent III, Hendry County Cooperative Extension Service, University of Florida, Pers. Commun.

PFEUFFER, R. AND F. MATSON. 1980-present. Pesticide Monitoring Project Reports, South Florida Water Management District. available at www.sfwmd.gov/org/ema/envmon/wqm/pest/pestindex.html.

SHAHANE, A. 2003a. Summary of Agricultural Pesticide Use in Florida: 1999–2002. Bureau of Pesticides, Florida Department of Agriculture and Consumer Services, Tallahassee, Florida.

———. 2003b. Florida Department of Agriculture and Consumer Services, Tallahassee, Florida. Pers. Commun.

USEPA. 1992. Inventory of exposure-related data systems sponsored by federal agencies. EPA/600/R-92/078, Office of Research and Development, Washington, DC.

———. June 2003. Restricted Use Products (RUP) Report. http://www.epa.gov/opprd001/rup/rupjun03.htm.

Florida Scient. 69(00S2): 100–116. 2006
Accepted: March 10, 2006

# FIVE YEARS OF THE SOUTHWEST FLORIDA FROG MONITORING NETWORK: CHANGES IN FROG COMMUNITIES AS AN INDICATOR OF LANDSCAPE CHANGE

E. Corrie Pieterson[1], Lindsay M. Addison[1], Jorge N. Agobian[1], Brenda Brooks-Solveson[1], John Cassani[2], and Edwin M. Everham III[1]

[1]Florida Gulf Coast University, 10501 FGCU Blvd. S. Ft. Myers, FL 33965-6565
[2]Lee County Hyacinth Control District, PO Box 60005, Ft. Myers, FL 33936

Abstract: *Amphibians have been shown to be important indicators for environmental change, particularly changes in water quality. The Southwest Florida Amphibian Monitoring Network was established in 2000 to collect long-term data on frog communities in southwest Florida. Twenty-two routes of 12 stops each are monitored monthly during the rainy season. Wind, temperature, humidity, sky condition, and habitat changes are recorded at each stop. Frog presence and abundance is indicated by calling intensity, which is tabulated using a three-level intensity code. Using data from the Network, frog communities were summarized, and factors that may explain differences in frog communities among sites and over time were investigated using measures of biological diversity, community classification, and community ordination. The data show an increased calling intensity in the exotic Cuban treefrog (*Osteopilus septentrionalis*), and a shift to native frog species requiring more permanent water. Continued monitoring may aid in understanding implications of altered hydroperiods and amphibian responses to restoration efforts. This type of citizen scientist database provides opportunities to investigate trends in environmental change on a landscape scale.*

*Key Words:* Amphibians, frog communities, citizen science

Amphibian populations have been identified as declining worldwide, and these declines have been identified as indicators of environmental stress (Barinaga, 1990; Wake, 1991; Vial and Saylor, 1993). Explanations for declines in amphibian populations vary from regional habitat change and environmental stress to global environmental change (Blaustein et al., 1994; Pechmann and Wilber, 1994; Blaustein and Wake, 1995). These declines generated interest in long-term data on amphibian populations and resulted in the establishment of volunteer networks that monitor amphibian populations using shared protocols to facilitate comparisons (NAAMP, 2005; DAPTF, 2005).

Although the southwest Florida region has one of the most rapidly growing human populations in the state (Smith, 2005), little has been reported on the impacts of urban sprawl on local amphibian populations. Development in southwest Florida often results in modified hydrology. Historically, human modifications to the landscape have resulted in increased runoff and loss of wetlands (Tang et al., 2005). Current regulations require wetland mitigation and retention of water (Gutrich and

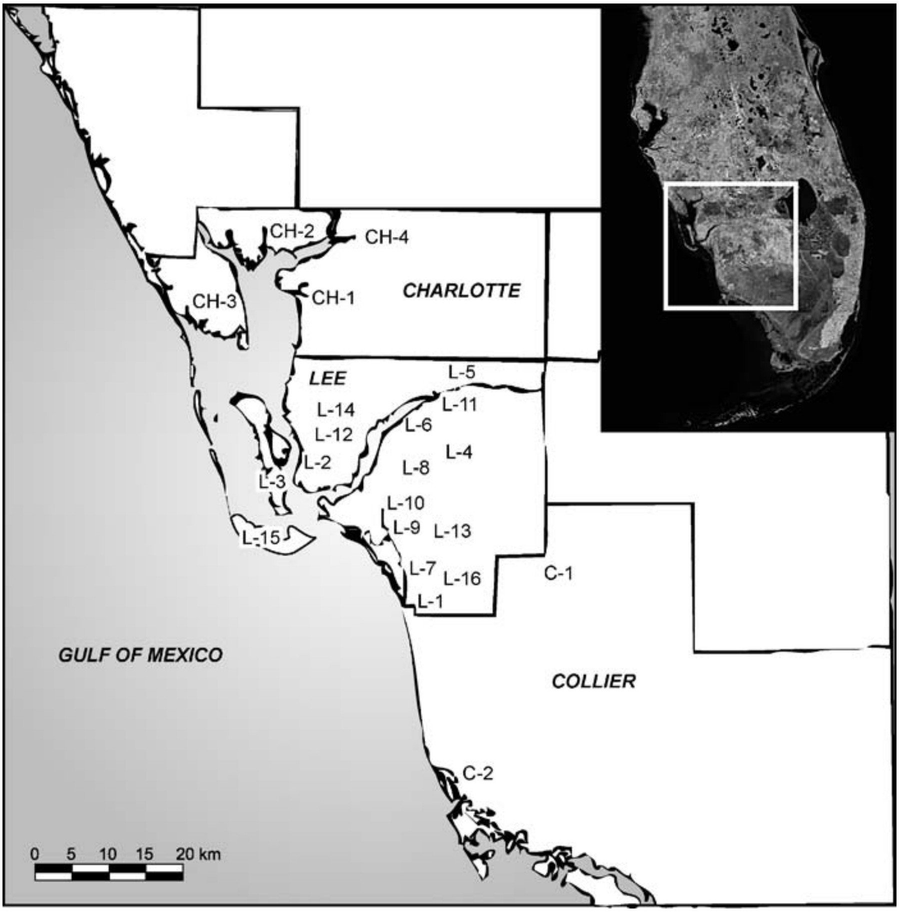



FIG. 1. Frog monitoring routes in the Southwest Florida Amphibian Monitoring Network (Frog Watch).

Hitzhusen, 2004). Native wetlands are restored through removal of invasive exotic plants, but water retention is commonly accomplished through the construction of deeper ponds (Mitsch and Day, 2004).

In 2000, the Southwest Florida Amphibian Monitoring Network (Frog Watch) was established. By 2004, the network had grown to 22 routes in Charlotte, Lee, and Collier Counties (Fig. 1), with a database of almost 6000 observations. This report analyzes the first five years of data. The goals of this analysis were to 1) investigate changes in frog communities, 2) explore the data set for patterns in space and time, and 3) examine the efficacy of citizen science in providing data to investigate landscape level changes over time.

MATERIALS AND METHODS—The 22 routes have up to 12 stops and are monitored monthly during the rainy season (June–September). Following protocols established by the North American Amphibian

Monitoring Program (NAAMP), at each stop on each route volunteers record temperature, humidity, wind speed, degree of cloud cover, and precipitation. In addition, changes to adjacent habitat are recorded (NAAMP, 2005; Frog Watch, 2005).

The routes were established by citizen science volunteers who agreed to act as route leaders. Each route leader selected the stops along his or her route, usually near home or work. Although not a fully randomized process, this did result in a geographically diverse set of routes across all three counties, through a variety of habitats.

At each stop, volunteers listen for three minutes and record the species and intensity of any frog calls heard during that time. The intensity of calls is quantified using scaled values of 1 for small groups of individuals whose calls do not overlap, 2 for small groups where there is some overlap of calls between individuals of a species, and 3 for a chorus of overlapping calls. Volunteer-based surveys that rely solely on frog calls as a means of identification have been found to accurately represent species richness and diversity, provided the sampling effort is sufficiently robust (de Solla et al., 2005). Frog Watch volunteers are trained to use the same method on each route. Therefore, it is possible to make comparisons of the presence and abundance of species over time and across different routes.

Because some routes had a greater number of stops than others, and because in some cases some routes were not visited in each of the four sampling months, it was necessary to normalize the recorded call intensities. The normalization process involved summing the total call intensity recorded for each species for a particular route. The sums were then divided by the number of times that measurements were made at each route, taking into account both the number of stops and the number of dates that the route was visited. This process may disproportionately under-report some species whose calling phenology does not include all months sampled, and may disproportionately over-represent species with louder calls, where a smaller population may appear to reach a calling intensity of three. Since the analyses involve comparisons of communities between years, the normalization procedure should be an appropriate method for incorporating the calling intensities in the analyses.

As route leaders changed through time, additional routes were added and some routes were abandoned. When comparing changes in biotic communities by route through time, the routes included in the analyses were limited to those with consistent data collection, resulting in analyses that utilized fewer than the total 22 routes.

The percent change in normalized calling intensity over time was calculated. Normalized calling for each species in 2000 were compared to the normalized calling intensities in 2004 for routes that were sampled both years. A percent change (positive or negative) was then calculated.

To compare frog communities at the landscape level, a variety of biological diversity indices were calculated following Ludwig and Reynolds (1988). These diversity measures included the Shannon Weaver Index, Simpson Index, modified Hill's Ratio, Menhinick Index, and Pielou Index. Measures of richness versus evenness were then used to create a community ordination space.

Bray-Curtis similarity indices were calculated for polar ordination (Ludwig and Reynolds, 1988) of the route data summarized from 2000 through 2004, using the normalized calling intensity as a measure of species abundance. A polar ordination for 12 routes was constructed comparing the data collected in 2001 with the data collected in 2004. These years were used because they shared 12 routes, whereas 2000 and 2004 had only six routes in common. Therefore, comparing data from 2001 and 2004, rather than 2000 and 2004, resulted in an increased sample size. This ordination was used to examine shifts within the ordination space over time.

Finally, a principal component analysis (PCA) was used to examine the frog communities, using the normalized calling intensity for routes from 2000 through 2004. PCA determines the component that accounts for the most variability within the data. Each succeeding component then accounts for the most remaining variability. This ordination process creates a variability ranking of all the analyzed components. Primer 5.2.9 software was used to carry out the PCA (Whitman et al., 2004).

RESULTS—The changes in percent calling intensity from 2000 to 2004 (Fig. 2) indicate both increases and decreases in native species' population sizes and an increasing population of exotics. However, the majority of native species show a decline in calling intensity. The increase in exotics is driven principally by

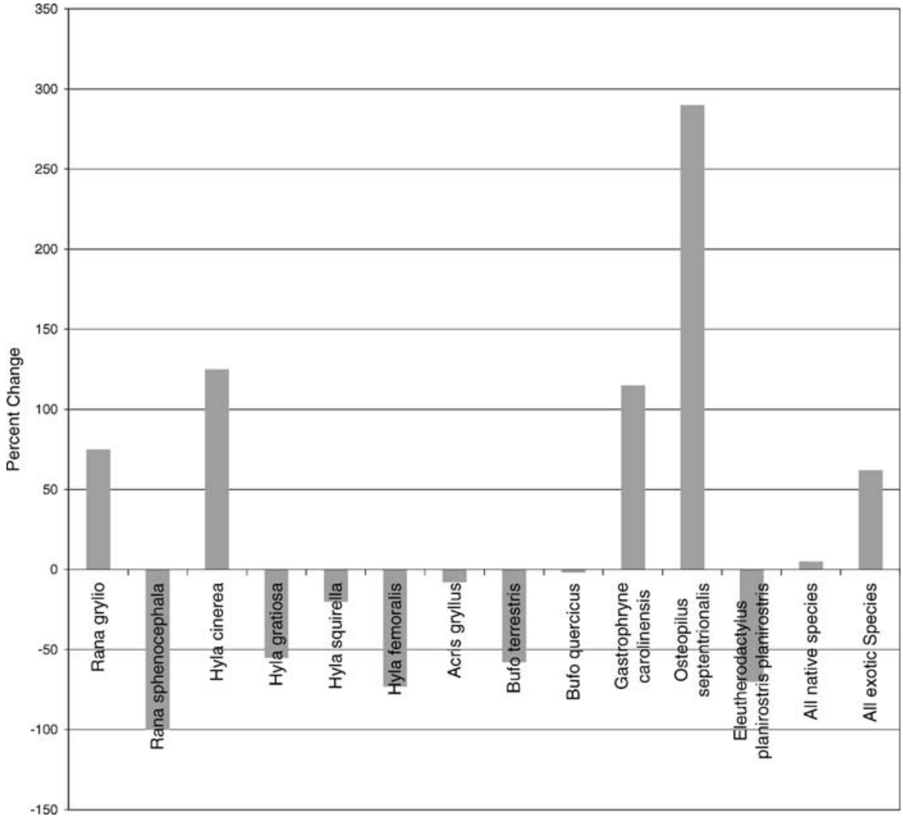



FIG. 2. Percent change in frog species from 2000 to 2004. Only species with a summed calling intensity of at least 50 in both years are included. Data is limited to routes sampled both years. All stops on all routes are pooled, so no error bars can be calculated.

a large increase in the calling intensity of *Osteopilus septentrionalis* (Duméril and Bibron).

An ordination space was created using the modified Hill's ratio as a measure of species evenness and the Menhinick Index as a measure of species richness (Ludwig and Reynolds, 1988). The modified Hill's ratio responds with lower values as a single species becomes more dominant. In Figure 3, the outlier routes include L-5, CH-3, and C-1 in decreasing order, separated along the evenness axis. The frog community in L-5, the rural community of Alva, is dominated by *Osteopilus septentrionalis*. *Hyla cinerea* (Schneider) is a dominant species in both CH-3 and C-1, although these routes are within a residential community and the area around Corkscrew Swamp Sanctuary (an old-growth cypress swamp preserve), respectively.

Bray-Curtis similarity indices, calculated from the normalized calling intensities, were used to create the ordination space in Figure 4. The first axis is defined by the dissimilarity between L-13, near Six-Mile Cypress Slough Preserve (a preserved cypress swamp) and L-14, a residential area in North Fort Myers. The

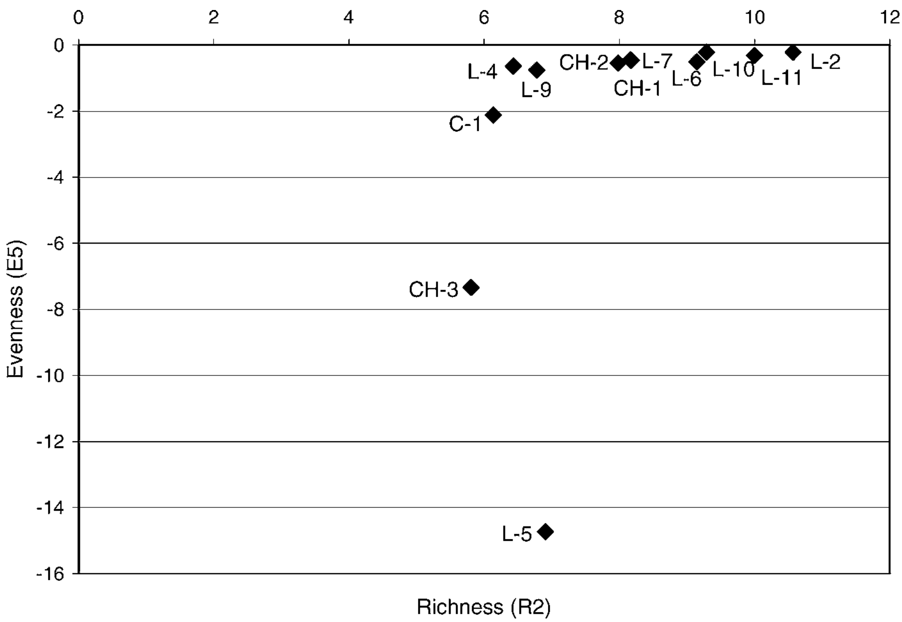



FIG. 3. Richness and evenness 2001 to 2004. Ordination of all routes using the normalized calling intensity for species abundance and calculating the modified Hill's ratio for evenness and the Menhinick Index for richness.

second axis includes two clusters. At the top of the ordination space is C-1, CH-3, and L-16, a development in Charlotte County, the route along Corkscrew Swamp Sanctuary, and the route through the Corkscrew Regional Ecosystem Watershed (a public land trust with extensive upland and wetland preserve areas), respectively. The first two were identified as outliers in the biodiversity ordination (Fig. 3) due to *Hyla cinerea* dominance. The cluster at the bottom of the ordination, L-2 (north Cape Coral), L-10 (Fort Myers), and L-3 (Pine Island) are, again, a mix of intensities of human activity, but may all have more limited permanent water habitats. It appears that this ordination separates the routes first based on human impacts and second on wetland habitat, which may indirectly relate to human activity.

The degree of change in communities is represented in Figure 5. Both of the routes showing the greatest change, L-10 in Fort Myers and L-7 around Florida Gulf Coast University, are areas of rapid human development. The two routes that changed the least through the five years of sampling, CH-2 in Charlotte County and L-6 in North Fort Myers, are also human-impacted landscapes, but are more stable and not undergoing the same degree of rapid growth, as indicated by the "changes to adjacent habitat" route data collected by volunteers.

The results of the PCA ordination (Fig. 6) show some similarities to previous ordinations. C-1 and CH-3 are again outliers, as they were in both the diversity ordination and the polar ordination. The first PCA axis accounts for 49.7% of the total variance in the data set. The species that are most important to the creation of

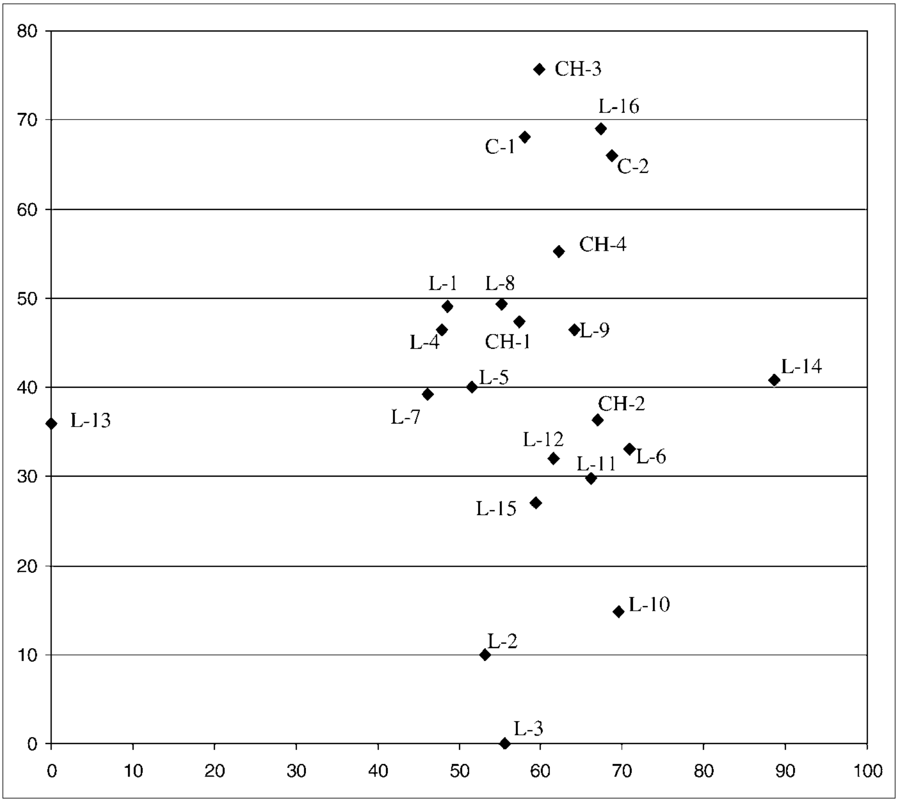



FIG. 4. Polar ordination of all routes – 2001 through 2004 data. Bray-Curtis percent similarities were calculated using normalized calling intensity for species abundances. Outlier routes L-13, L-14, CH-3, and L-3 define the boundaries of the ordination space for this data set. Each axis represents the two sampling units with the greatest dissimilarity. The other sampling units are plotted within this ordination space relative to their similarity to the four outliers.

this axis are *Hyla cinerea*, *Rana grylio* (Stejneger), and *Acris gryllus dorsalis* (Harlan), two of which may indicate the importance of more permanent water bodies. The second principal component accounts for an additional 28.4% of the variance and is loaded most heavily by *Osteopilus septentrionalis*, indicating the importance of exotics in differentiating among routes. L-5 (the rural community of Alva) becomes an outlier, as it was in the biodiversity ordination.

DISCUSSION—This initial analysis of the frog monitoring data for southwest Florida clearly indicates shifts in the species abundances as quantified by calling intensity, demonstrating the applicability of data collected by citizen scientists.

The majority of native species show a decline in calling intensity, with only a few species showing an increase in calling intensity. One of these, *Rana grylio*, is dependent on more permanent water (Ashton and Ashton, 1988), while another, *Hyla cinerea*, is common in wetlands (Ashton and Ashton, 1988). Declining species

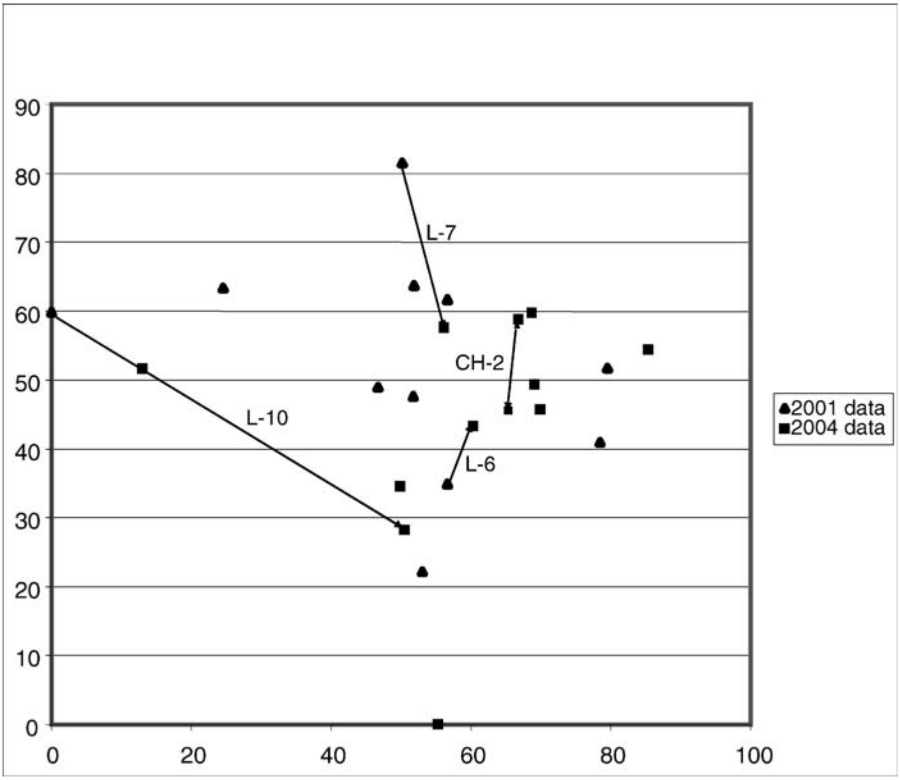



FIG. 5. Polar ordination – 2001 and 2004 data. Normalized calling intensity was used for species abundances. Data from 2001 and 2004 were treated as unique sampling units. Pairs of data points for any particular route show the magnitude of change in the ordination space for that route. The two routes with the greatest change (L-10 and L-7) and the two routes with the smallest change (L-6 and CH-2) are shown. Each axis represents the two sampling units with the greatest dissimilarity. The other sampling units are plotted within this ordination space relative to their similarity to the four outliers.

included those requiring intact upland systems such as *Hyla femoralis* (Bosc in Daudin) and *Bufo terrestris* (Bonnaterre) (Ashton and Ashton, 1988), whereas *Rana sphenocephala utricularia* (Harlan), another declining species, is common in permanent water habitats (Ashton and Ashton, 1988). Both shifts may be tied to human modifications of the landscape.

In southwest Florida, changes to the frog populations seem to be related to local human modifications of the landscape rather than to global changes, which would be expected to create more landscape-level impacts. While some frog species are able to establish metapopulations across isolated landscapes, many others can be severely affected by habitat fragmentation (Ficetola and DeBernardi, 2004). Lesbarrères and co-workers (2003) also found that anuran communities located near highways rather than in undisturbed areas suffered a significant reduction in heterozygosity, making them more vulnerable to bottleneck effects and extinction.

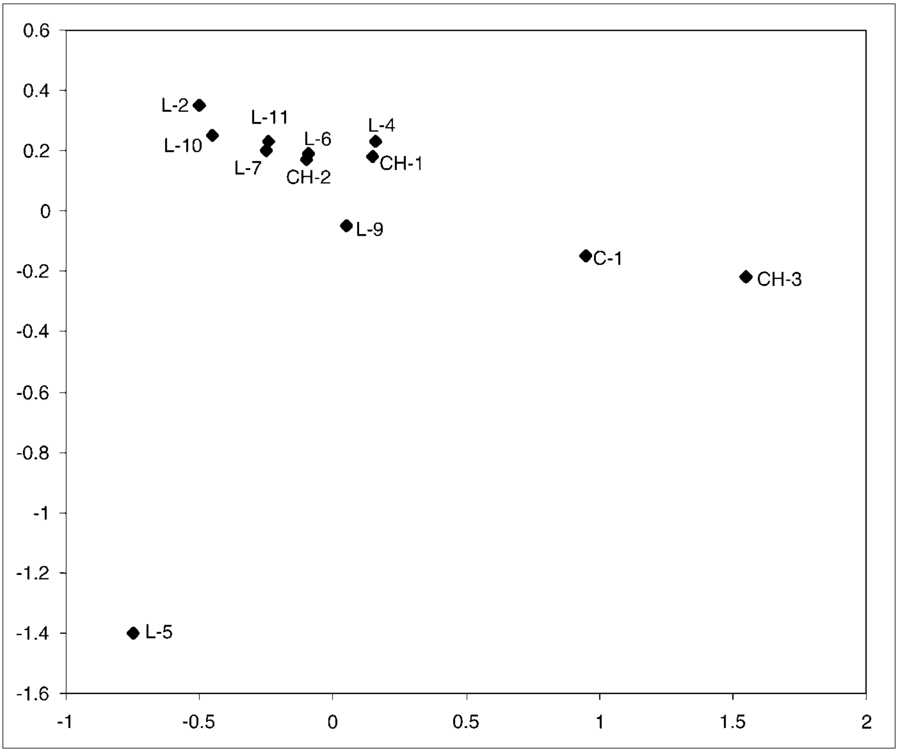



FIG. 6. PCA analysis of routes sampled in 2001 and 2004. Normalized calling intensity was used for species abundances.

These inferences must be considered in light of several inherent limitations. Chief amongst these are the small sample size, which was exacerbated by the fact that several routes had to be eliminated because they were not sampled on a regular basis. In addition to the route sampling irregularity, some routes were shifted to different locations during the course of the study, necessitating their removal from the analysis. Finally, several assumptions were built into the normalization process: that the calling intensity was directly related to the abundance of each species; that the relationship between calling intensity and abundance is the same for all species; and that differences in species' breeding phenology did not affect sampling. In addition, the routes were analyzed as a whole; therefore, fluctuations at individual stops could have been undetected or may have canceled one another out. However, the analyses were not limited to community comparisons that rely only on presence and absence data, because this would have resulted in the loss of additional information available by incorporating calling intensity. Nelson and Graves (2004) reported a positive relationship between calling intensity and population size, but their study was limited to a single species, *Rana clamitans* (Latreille in Sonnini de Manoncourt and Latreille), and the relationship tended to be weaker at higher population densities. Further long-term monitoring, resulting in increased sampling size may help to resolve these uncertainties.

An unforeseen difficulty encountered during the monitoring is directly attributable to human landscape change. During the first five years of monitoring, traffic volumes increased along most routes. Many animal species communicate in settings with substantial levels of background noise, but the effects of the noise on frog communication are not well known. Wollerman and Riley (2002) found that moderate levels of background noise reduced the ability of gravid female *Hyla ebraccata* (Cope) to detect or discriminate between males' calls. Additionally, increasing traffic noise may interfere with the ability of volunteers to detect frog calls. Background noise may play an important part in frog calling dynamics and will bear further research. For the data collection sheets used by Frog Watch volunteers, the following index for traffic noise was added to the standard NAAMP protocols: 0 – no traffic noise, 1 – only distant traffic noise, 2 – intermittent traffic with the majority of the time quiet, 4 – fairly constant traffic noise with some gaps but the majority of the time with traffic, and 5 – constant traffic.

There are additional opportunities to investigate the relationships between environmental factors such as time, weather, habitat, and calling intensities using this data. Often, illuminating these relationships requires larger datasets over longer periods of time. Citizen science monitoring efforts can provide these data in cost-effective ways.

ACKNOWLEDGMENTS—The authors would like to acknowledge the efforts of the over 70 people who have participated in the Southwest Florida Amphibian Monitoring Network. Without their efforts, the data for this manuscript would not exist. These efforts were supported by the Charlotte Harbor National Estuary Program, and the Whitaker Center at Florida Gulf Coast University. The authors wish to give special thanks to Ellen Lindblad for taking over leadership of the Network. The authors would also like to acknowledge the careful reading and helpful comments of two anonymous reviewers and guest editors, whose suggestions vastly improved the article.

## LITERATURE CITED

ASHTON, R. E. AND P. S. ASHTON. 1988. Handbook of Reptiles and Amphibians of Florida Part Three: The Amphibians. Windward Publishing, Inc. Miami, FL.

BARINAGA, M. 1990. Where have all the froggies gone? Science 247(4946):1033–34.

BLAUSTEIN, A. R. AND D. B. WAKE. 1995. The puzzle of disappearing amphibian populations. Sci. Am., 272(4):52–57.

———, D. B. WAKE, AND W. P. SOUSA. 1994. Amphibian declines: judging stability, persistence, and susceptibility of populations to local and global extinctions. Conserv. Biol., 8(1):60–71.

DAPTF. 2005. Declining Amphibian Populations Task Force. http://www.open.ac.uk/daptf/index.htm

FICETOLA, G. F., AND F. DE BERNARDI. 2004. Amphibians in a human-dominated landscape: the community structure is related to habitat features and isolation. Biol. Conserv. 119:219–230.

FROG WATCH: SOUTHWEST FLORIDA AMPHIBIAN MONITORING NETWORK. 2005. http://www.frogwatch.net.

GUTRICH, J. J. AND F. J. HITZHUSEN. 2004. Assessing the substitutability of mitigation wetlands for natural sites: estimating restoration lag costs of wetland mitigation. Ecol. Econ. 48:409–424.

LESBARRÈRES, D., A. PAGANO, AND T. LODÉ. 2003. Inbreeding and road effect zone in a Ranidae: the case of agile frog, *Rana dalmatina* Bonaparte, 1840. C. R. Biologies 326:S68–S72.

LUDWIG, J. J., AND J. F. REYNOLDS. 1988. Statistical Ecology: A Primer on Methods and Computing. John Wiley & Sons. New York, NY.

MITSCH, W. J. AND J. W. DAY, JR. 1988. Thinking big with whole-ecosystem studies and ecosystem restoration – a legacy of H. T. Odum. Ecol. Model. 178:133–155.

NAAMP. 2005. North American Amphibian Monitoring Network. http://www.pwrc.usgs.gov/NAAMP/other/.

NELSON, G. L. AND B. M. GRAVES. 2004. Anuran population monitoring: comparison of the North American Amphibian Monitoring Program's calling index with mark-recapture estimates for *Rana clamitans*. J. Herpetol. 38(3):355–359.

PECHMANN, J. H. K. AND H. M. WILBUR. 1994. Putting declining amphibian populations in perspective: natural fluctuations and human impacts. Herpetologica 50(1):65–84.

SMITH, S. K. 2005. *Florida Population Growth: Past, Present, and Future.* University of Florida Bureau of Economic and Business Research. http://www.bebr.ufl.edu/Articles/FloridaPop2005.pdf

SOLLA, S. R., DE, L. J. SHIROSE, K. J. FERNIE, G. C. BARRETT, C. S. BROUSSEAU, AND C. A. BISHOP. 2005. Effect of sampling effort and species detectability on volunteer based anuran monitoring programs. Biol. Conserv. 121:585–594.

TANG, Z., B. A. ENGEL, B. C. PIJANOWSKI, AND K. J. LIM. 2005. Forecasting land use change and its environmental impact at a watershed scale. J. Environ. Manage. 76:35–45.

VIAL, J. L. AND L. SAYLOR. 1993. The status of amphibian populations: a compilation and analysis. IUCN/SSC Declining Amphibian Populations Taskforce. Working Document No. 1.

WAKE, D. B. 1991. Declining amphibian populations. Science 253(5022):680.

WHITMAN, R. L., M. B. NEVERS, M. L. GOODRICH, P. C. MURPHY AND B. M. DAVIS. 2004. Characterization of Lake Michigan coastal lakes using zooplankton assemblages. Ecol. Indic. 4(4):277–286.

WOLLERMAN, L. AND R. H. WILEY. 2002. Background noise from a natural chorus alters female discrimination of male calls in a neotropical frog. Anim. Behav. 63:15–22.

Florida Scient. 69(00S2): 117–126. 2006
Accepted: March 10, 2006

# SPOTTED SEATROUT (FAMILY SCIAENIDAE) GROWTH AS AN INDICATOR OF ESTUARINE CONDITIONS IN SAN CARLOS BAY, FLORIDA

Stephen A. Bortone, Alfonse J. Martignette, and Justin P. Spinelli

Marine Laboratory, Sanibel-Captiva Conservation Foundation, Sanibel, FL

Abstract: *Life history characters of the spotted seatrout (*Cynoscion nebulosus*) have tremendous potential to discern trends in environmental conditions within and among estuaries. The species is widely distributed (i.e., from North Carolina to Mexico), is both commercially and recreationally important, and rarely leaves its home estuary. Thus, the estuarine conditions to which a population was subjected while growing could affect changes in its life history features such as growth. About 400 spotted seatrout were collected from April through July 2003 from the San Carlos Bay area of the southern portion of Charlotte Harbor in southwest Florida. Otolith sections were examined with enhanced imagery to facilitate recording age and annulus increments from the otolith. There was a significant relationship between otolith radius and fork length that differed between sexes. A comparison of back-calculated size at Age 1 for four year classes (1999–2002) indicated that there were significant differences in growth between year classes. Initial time-series analysis indicated the potential effects of seagrass density and salinity on fish growth. Salinity conditions are artificially manipulated in this estuary and this action may be responsible for the differences in growth rates observed for both males and females among year classes.*

*Key Words:* Growth, estuaries, otolith, seagrass, salinity, time-series, spotted seatrout

The spotted seatrout (*Cynoscion nebulosus* (Cuvier) – a fish species in the croaker and drum family Sciaenidae) is one of the preferred food and game fishes within its native distribution that includes estuarine conditions along coastal areas of the southeastern portion of the USA, including the Gulf of Mexico. It is found chiefly within estuaries and has a strong affinity for seagrasses where it feeds on fishes and small crustaceans (see Bortone, 2003a for a complete compilation of its life history).

Northern American estuaries, including Charlotte Harbor, have become areas of rapid human population growth and development. Development along estuarine shorelines has resulted in stress through hydrologic alterations, water-quality degradation, and habitat loss (Kennish, 1991). Environmental managers must be vigilant to ensure that estuarine and coastal waters do not become so degraded that the normal biological function of these estuarine ecosystems becomes impaired. Similarly, estuarine-restoration efforts should have target goals that seek to re-establish the biological function of disturbed systems to approach or, hopefully, regain normal, undisturbed levels of biological integrity (Bortone, 2003b; Bortone et al., 2005).

After careful evaluation of several indigenous species, it became apparent that the spotted seatrout is particularly suited as a sentinel in detecting environmental stress to estuarine ecosystems along the warm temperate coast of North America (Bortone and Wilzbach, 1997a; Bortone, 2003b). The spotted seatrout is an exceptional fish among estuarine sport fish in that it generally spends its life within the confines of a single estuary. In addition, the spotted seatrout is a relatively long-lived species (often up to 10 years); thus, it is subjected to the conditions of a single estuary for an extended period and, therefore, can serve as a time-series monitor of estuarine conditions. It feeds on fishes and crustaceans found among seagrasses and thus serves as an important trophic link with the estuary (Bortone, 2000). It attracts considerable public attention as an important sport and food fish with significant landings throughout its range but especially in Lee County, Florida (Bortone and Wilzbach, 1997b). Lastly, the spotted seatrout has the attention of the scientific community as evidenced by the substantial database of life history information on the species (Johnson and Seaman, 1986; Bortone et al., 1997).

This project was initiated to develop an estuarine bio-indicator capable of discerning the environmental stressors and their degree of impact on the overall environmental conditions in the southern portions of the Charlotte Harbor estuarine ecosystem. Establishing a fully documented biological indicator would allow those concerned with the biological integrity of these estuarine waters to evaluate trends and determine the stressors that affect the functional attributes of the ecosystem.

The basic biology of the spotted seatrout (they are also known as specks, trout, and speckled trout) was recently summarized in a volume dedicated to establishing its life history parameters as potential metrics to assess the environmental conditions within an estuary (Bortone, 2003c). A host of biological characters are potentially available to serve this purpose. For example, reproductive condition (Brown-Peterson, 2003), genetic differentiation (Gold et al., 2003), and parasite infestation (Blaylock and Overstreet, 2003), among others, are biological features that could prove useful in providing characters that would allow an assessment of environmental stressors. However, growth is reflective of a metabolic component of this species that is intimately interwoven with its environment that includes water quality, habitat conditions, salinity regimes and the abundance of predators, prey, and conspecifics (Murphy and McMichael, 2003).

Bedee and co-workers (2003) and DeVries and co-workers (2003) clearly demonstrated the utility of using growth features of spotted seatrout to compare different estuaries. This study takes their concept further and makes use of comparative growth rates among spotted seatrout to monitor potential environmental stressors through time in the southern portions of the Charlotte Harbor estuarine ecosystem.

MATERIALS AND METHODS—About 400 spotted seatrout were captured using hook-and-line in an area limited to San Carlos Bay and portions of lower Pine Island Sound (FIG. 1) in the southern portions of Charlotte Harbor from April through July 2003. Upon capture, fish were placed on ice and returned to the laboratory where they were labeled by date and field-collection number, and frozen. Later, fish were thawed, the sex was determined, and each fish was measured for fork length (FL) to the nearest mm.

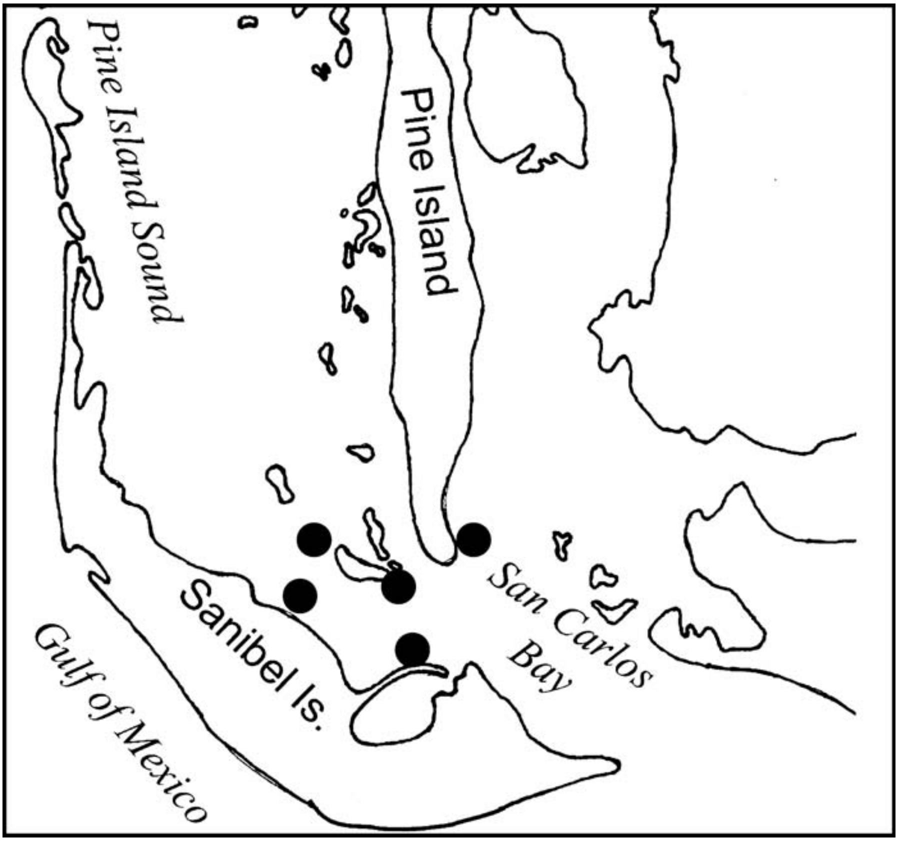



FIG. 1. Map of the study area. Filled circles indicate the specific sampling locations for spotted seatrout.

Otoliths were removed from thawed fish and prepared for analysis following the methods of Bedee and co-workers (2003) with the following two exceptions: 1) Crystal Bond® was used to affix otoliths to microscope slides for sectioning; and 2) Flo-Texx® (Lerner Laboratories) mounting media was used to affix the otolith sections to the microscope slides. The Image-Pro® Express image analysis system (Version 4.5.1.3) was used to record measurements from the otolith image. Each otolith was sectioned in cross section at its mid-point.

Since only one fish was recorded at Age 5 or older, only fish aged 1–4 were used in this study. The size at capture, otolith radius, and annular radii for each fish were used to back-calculate the size at annulus formation. The equation used was:

$$L_i = a + (L_c - a) \times (O_i/O_c) \quad (1)$$

where $L_i$ = the fork length (FL in mm) of the fish when it became age $i$, a = the y-axis (fork length) intercept of the relationship between otolith radius (abscissa) and fork length (ordinate), $L_c$ = size of fish (FL in mm) at capture, $O_i$ = distance in mm from central core of otolith to the distal edge of the annulus at age $i$, and $O_c$ = otolith radius in mm.

Time-series analyses were conducted to relate environmental conditions in the estuary with fish growth, by determining time-lagged measures of association (i.e., correlation coefficients) in annual fish growth to environmental features in the estuary. Time-series analyses (i.e., ARIMA – AutoRegressive, Integrated Moving Average) were conducted using the back-calculated size at age one for each year class (dependent variable) versus several environmental variables (independent variables) using the SPSS® statistical program package (Version 8.0). In the lower Charlotte Harbor area, few environmental data were available as annual parameters collected corresponding to the year classes examined here (i.e., 1999–2002) Environmental variables that were available for inclusion in the time-series analyses, however, were salinity and species-specific, seagrass density.

Annual conductivity parameters (overall average, average daily minimum, average daily maximum and overall standard deviation) as a surrogate for salinity were used as relative indicators of water quality. Conductivity data were obtained from the South Florida Water Management District's water-quality monitoring probe near the Sanibel Causeway at the entrance of San Carlos Bay. Species-specific seagrass densities were obtained chiefly from the Florida Department of Environmental Protection Agency's Burnt Store Road facility in Punta Gorda, Florida. The seagrass density estimates were based on Braun-Blanquet measures of percent cover averaged from five transects in lower Charlotte Harbor surveyed annually each fall.

RESULTS—*Age and growth*—Although more than 400 fish were captured during this study, only 295 (161 males and 134 females; FIG. 2) were used for age determination. Nearly 100 fish could not be reliably aged for a variety of reasons. Sometimes both otoliths from some individuals were damaged during extraction, sectioning, or mounting and, therefore, no age or growth could reliably be determined. Each otolith was read at least twice by two investigators. Otoliths that were problematic were read a third time by a third investigator. If agreement was not attained then that fish was excluded from ageing. It was assumed that exclusion or inclusion of data from an otolith was not biased with regard to age or growth of a particular fish.

The mean (±SD, min-max, number) size of males was 293.75 (±36.37, 217–420, 161) mm FL and females was 321.36 (±51.08, 228–557, 134) mm FL. The relationship between the otolith radius and length was determined separately for each sex using regression analysis (FIG. 3). While both regression lines showed a positive correlation, the lines were significantly different ($p \leq 0.05$) from each other with regard to both slope and y-axis intercept. Consequently, all analyses were conducted separately for each sex, using the respective slope and y-intercept information.

All fish used in the analyses were captured after March 2003. The literature indicates that spotted seatrout generally deposit the annulus in the early spring of each year (Murphy and McMichael, 2003). The bar chart (FIG. 4) indicates that the marginal increment increased after March. All fish used for aging here were captured beginning in April.

Annual growth and overall total mortality can be determined by examination of the actual and back-calculated size data presented in Table 1. Size at annulus formation was determined separately for each sex: males – 251, 294, 331, and 373 mm FL; and females – 260, 324, 354, and 443 mm FL for ages 1–4, respectively. Generally, females were larger and grew faster than males at each age at annulus formation. The decline in the number of fish at each subsequent age is indicative of total mortality and is presented here as supplemental population information. Males displayed a classic and typical decline where the most abundant year class was

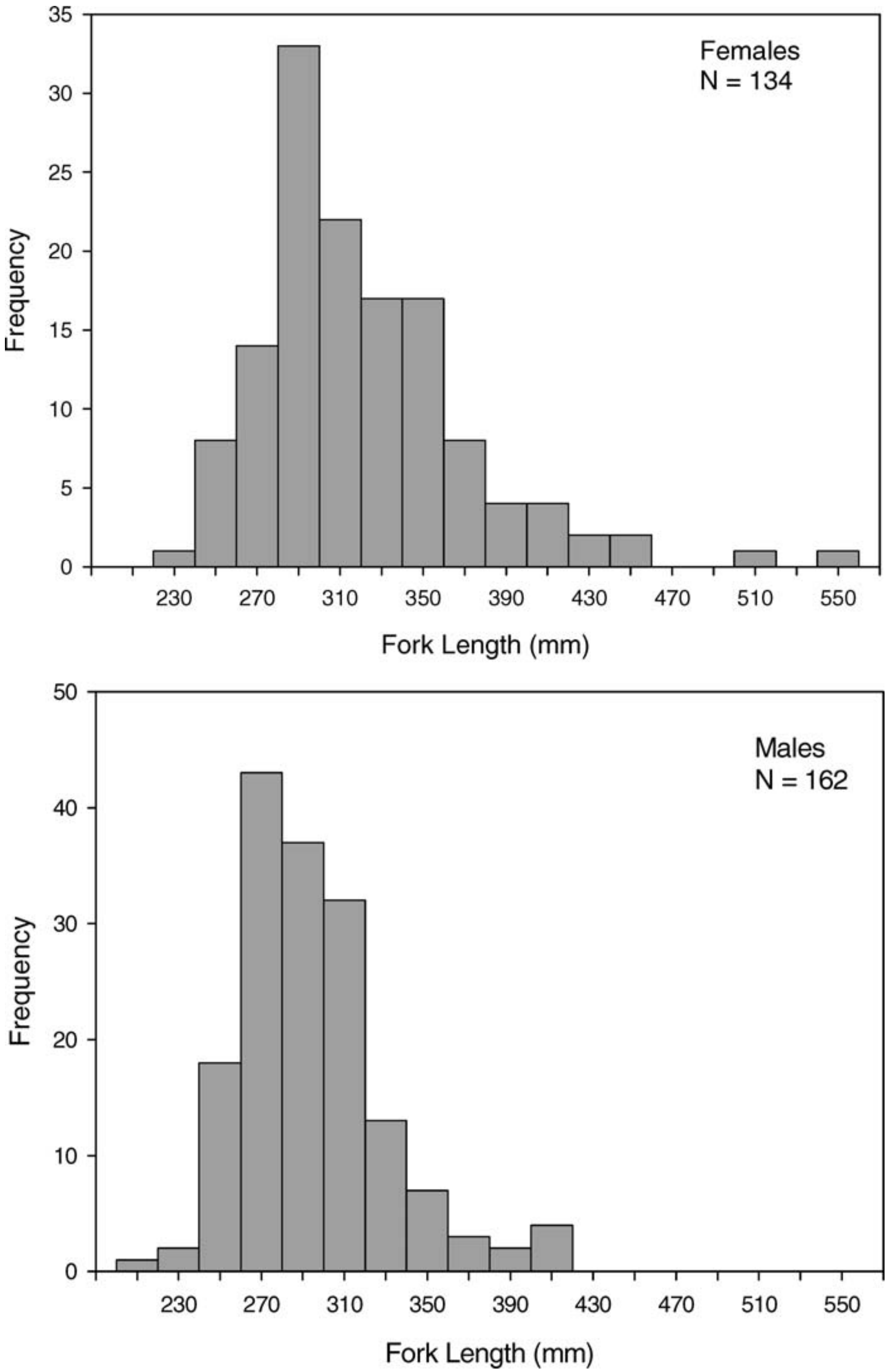



FIG. 2. Length-frequency histogram of all females (above) and males (below) examined during this study.

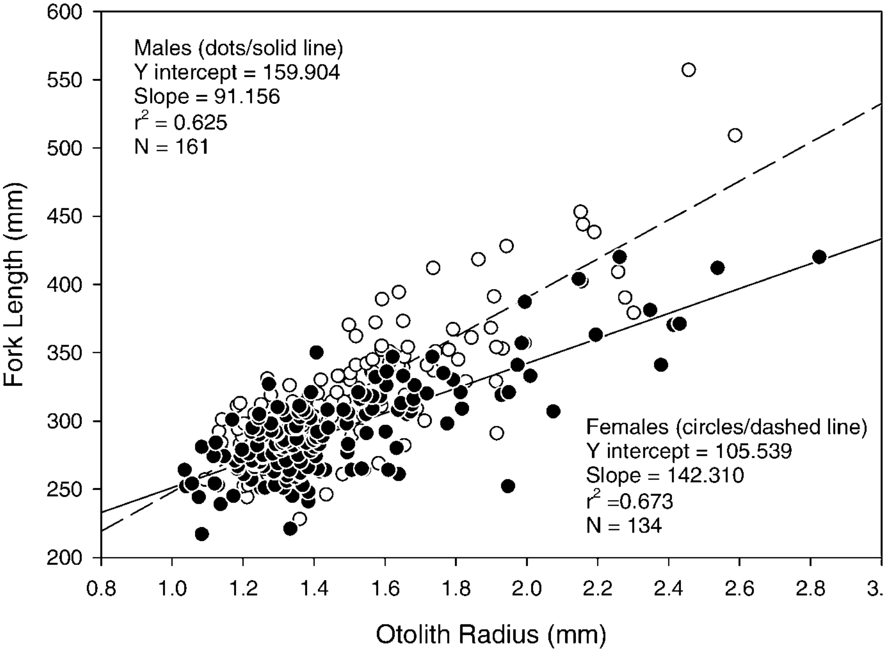



FIG. 3. Scatter diagram of otolith radii and fork lengths (both in mm) for male (dots/solid line) and females (circles/dashed line).

age-group 1 and the decline asymptotically approached the abscissa. A slightly different profile was observed among females. Age-group 2 was proportionately more abundant, or concomitantly, age-group 1 was slightly underrepresented among the data. An age-length key to fish-size classes (Table 2) indicates considerable size overlap with regard to size within an age-group for each sex.

A pair-wise bar-chart for size of males and females for each year class at age one were derived from the back-calculated size at age one for each of the four year classes (FIG. 5). Again, females tended to attain a larger size at annulus formation than males for each year class. Interestingly, for both males and females, the longest fish were from the most recent year class (2002). The shortest fish were males from the 1999 and 2000 year classes and females from the 2000 year class. This may indicate Lee's Phenomenon (Gutreuter, 1987) where earlier back-calculated lengths tend to be shorter in older fish. However, it should be noted that length of females for year classes 1999 and 2002 were not statistically different ($p > 0.05$). The results of a One-Way Analysis of Variance and Tukey's post-hoc test) for size at age 1 for each year class (sexes analyzed separately) indicated that fish from year-class 2002 were significantly longer ($p < 0.05$) than fish from year-class 2001 and 2000 among females. Fish from year-class 2002 were significantly longer than fish from year-classes 2001 and 2000 among males as well. Fish of both genders from year-class 2000 were shorter at age-1 annulus formation than fish from all other year classes, but this difference was not statistically significant at $p < 0.05$) in all cases.

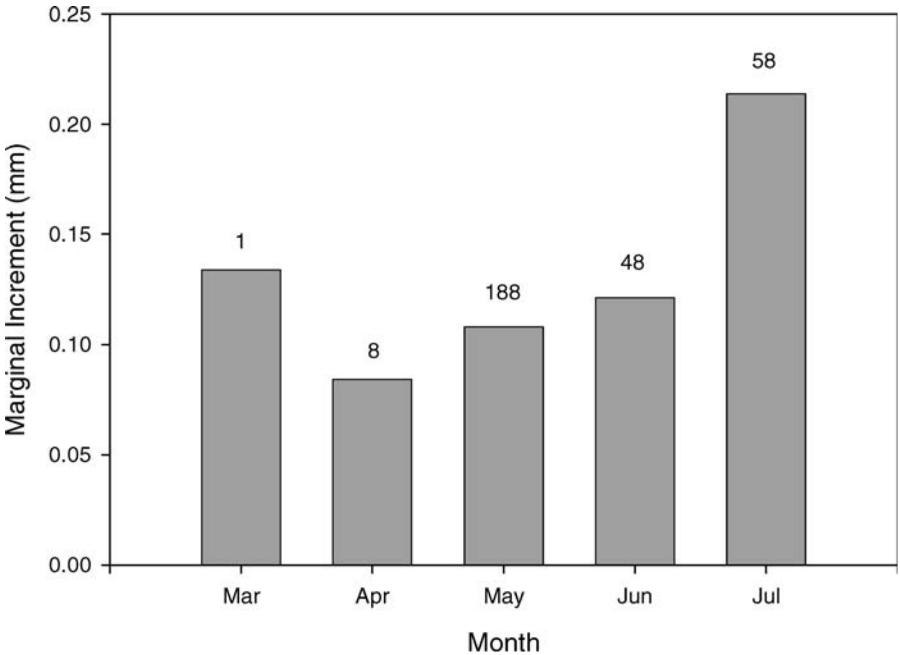



FIG. 4. Bar graph of marginal increment, by month, of all fish examined. Numbers above bars indicate number of fish examined.

*Environmental associations*—Densities (Braun-Blanquet percent cover) for each of three species of seagrass from the lower portion of Pine Island Sound and San Carlos Bay were used, along with evidence of salinity, as measures of habitat condition (Table 3). Results of the time-series analyses (summarized in Table 4) produced correlation coefficients that indicated the degree of association between the dependent (size at age 1) and independent (species-specific seagrass densities and conductivity parameters) variables between all possible years for which there were data. Because there were data for only four years, none of the associations were

TABLE 1. Summary of fork length (mm) statistics (actual and back-calculated) by age for male and female spotted seatrout captured during this study.

| | | Actual Age | | | | | Back-calculated | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Age | Mean | Min. | Max. | SD | No. | Mean | Min. | Max. | SD | No. |
| Males | 1 | 278.43 | 217 | 336 | 22.09 | 113 | 251.11 | 194 | 323 | 24.48 | 161 |
| | 2 | 310.25 | 265 | 350 | 21.15 | 28 | 293.72 | 251 | 338 | 19.97 | 48 |
| | 3 | 337.00 | 307 | 387 | 25.10 | 10 | 330.91 | 297 | 379 | 25.17 | 20 |
| | 4 | 368.60 | 252 | 420 | 51.73 | 10 | 373.30 | 328 | 413 | 34.10 | 10 |
| Females | 1 | 288.38 | 228 | 333 | 22.91 | 68 | 260.14 | 201 | 323 | 23.02 | 134 |
| | 2 | 338.43 | 269 | 428 | 29.34 | 48 | 324.06 | 245 | 418 | 29.54 | 66 |
| | 3 | 371.00 | 291 | 438 | 42.45 | 12 | 354.39 | 189 | 460 | 72.76 | 18 |
| | 4 | 457.33 | 379 | 557 | 66.33 | 6 | 443.23 | 364 | 539 | 67.41 | 6 |

TABLE 2. Age-Length (FL in mm) key for spotted seatrout captured in 2003 relative to sex.

| Class Size | Age Group | | | | Total | Age Group | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| FL (mm) | 1 | 2 | 3 | 4 | Female | 1 | 2 | 3 | 4 | Male |
| 200 | | | | | | 1 | | | | 1 |
| 220 | | | | | | | | | | |
| 240 | 1 | | | | 1 | 2 | | | | 2 |
| 260 | 8 | | | | 8 | 17 | | | | 17 |
| 280 | 13 | 1 | | | 14 | 40 | 3 | | | 19 |
| 300 | 28 | 4 | 1 | | 33 | 32 | 5 | | | 37 |
| 320 | 13 | 8 | 1 | | 22 | 18 | 11 | 3 | | 32 |
| 340 | 5 | 13 | | | 18 | 3 | 6 | 3 | 1 | 69 |
| 360 | | 13 | 4 | | 17 | | 3 | 3 | 4 | 10 |
| 380 | | 7 | | 1 | 8 | | | 1 | 1 | 2 |
| 400 | | 1 | 3 | 1 | 5 | | | | | 5 |
| 420 | | | 3 | | 3 | | | | 4 | 4 |
| 440 | | 1 | | | 1 | | | | | 1 |
| 460 | | | | 2 | 2 | | | | | 2 |
| 480 | | | | | | | | | | |
| 500 | | | | 1 | 1 | | | | | 1 |
| 520 | | | | | | | | | | |
| 540 | | | | | | | | | | |
| 560 | | | | 1 | 1 | | | | | 1 |
| Totals | 68 | 48 | 12 | 6 | 134 | 113 | 28 | 10 | 10 | 161 |

statistically significant, nevertheless, several associations were high (i.e., $> |0.75|$) and these deserve comment.

During the first year, female growth was positively associated with the density of the seagrass *Halodule wrightii* (Ascherson) (shoal grass) from the preceding year and positively with *Syringodium filiforme* (Kützing) (manatee grass) density from the preceding year and negatively with the same year.

During the first year of growth for each year class, female growth was positively associated with salinity from the preceding year. There was little evidence that minimum salinity was related to female growth during their first year; however, maximum salinity was positively associated with growth of females during their first year for each year class. Variation in water conditions, as measured by the annual standard deviation in conductivity, was somewhat associated with female growth during the concurrent year for each year class.

Growth among males, during the first year of life for each year class showed similar patterns to those described for females. A positive association was determined for both *H. wrightii* and *S. filiforme* density from the preceding year, while a negative association of *Thalassia testudinum* (Banks ex König) (turtle grass) density occurred with male growth from the two years proceeding the first year of growth for males. The initial year of growth among males was positively associated with salinity the year before.

DISCUSSION—The observed monthly increase in marginal increment after April indicates that the annulus is generally deposited in early spring for this species in

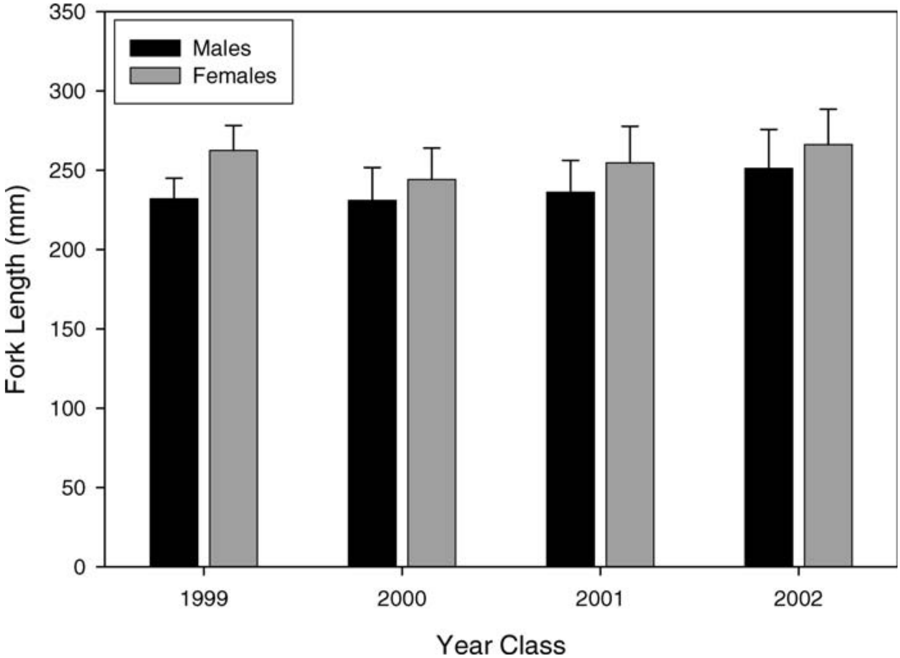



FIG. 5. Bar graph comparing back-calculated size (fork length in mm) at age 1 for the year classes 1999–2002. Males and females separately.

Florida waters (Murphy and Taylor, 1994) and helps validate the use of otoliths in determining age for the spotted seatrout in this area.

Males and females grew differently, with females generally growing faster and attaining a larger size at an equivalent age. Differences in growth between sexes (as observed in the relationship between otolith radius and length) indicated that each sex should be treated separately in all analyses. While outwardly cumbersome, analyzing sexes separately allows the advantage in offering a test by congruence

TABLE 3. Summary data for the variables used in the Time-Series analysis for each respective year class. Fish lengths are FL in mm, seagrass species are density estimates based on cover (Braun-Blanquet).

| | Year Class | | | |
|---|---|---|---|---|
| Variable | 1999 | 2000 | 2001 | 2002 |
| Male FL (mm) | 231.97 | 230.93 | 232.32 | 251.11 |
| Female FL (mm) | 262.53 | 244.28 | 254.72 | 266.39 |
| *H. wrightii* | 0.78 | 1.23 | 1.63 | 0.96 |
| *S. filiforme* | 1.47 | 2.75 | 3.65 | 1.43 |
| *T. testudinum* | 1.41 | 2.06 | 1.38 | 1.33 |
| Average Conductivity | 46751 | 48415 | 51228 | 48675 |
| Minimum Conductivity | 34315 | 37589 | 35846 | 38395 |
| Maximum Conductivity | 52699 | 54104 | 55680 | 53863 |
| Cond. Stand. Dev. | 3932 | 2996 | 4297 | 3722 |

TABLE 4. Summary of Time-Series analyses of size at age 1 in spotted seatrout relative to seagrass species density and salinity parameters recorded for years 1999–2002 in San Carlos Bay. Underlining indicates associations greater than |0.75|. Salinity average is measured as average annual salinity (generally measured daily), salinity minimum is the average monthly minimum, salinity maximum is average monthly maximum, and salinity standard deviation (SD) is based on all data.

| Dependent Variable | Independent Variable | Lag Time (years) | | | | |
|---|---|---|---|---|---|---|
| | | −2 | −1 | 0 | +1 | +2 |
| Male Size | *H. wrightii* | 0.15 | 0.86 | −0.16 | −0.33 | −0.14 |
| | *S. filiforme* | 0.23 | 0.77 | −0.39 | −0.34 | −0.05 |
| | *T. testudinum* | 0.74 | −0.21 | −0.56 | −0.16 | 0.25 |
| | Salinity Avg | −0.04 | 0.91 | 0.18 | −0.28 | −0.26 |
| | Salinity Min | 0.36 | 0.08 | 0.62 | −0.07 | −0.17 |
| | Salinity Max | 0.06 | 0.90 | 0.08 | −0.30 | −0.22 |
| | Salinity SD | −0.67 | 0.47 | 0.19 | 0.03 | −0.20 |
| Female | *H. wrightii* | 0.15 | 0.84 | −0.55 | −0.48 | 0.47 |
| | *S. filiforme* | 0.19 | 0.71 | −0.69 | −0.40 | 0.60 |
| | *T. testudinum* | 0.51 | −0.10 | −0.88 | 0.54 | 0.18 |
| | Salinity Avg | 0.02 | 0.92 | −0.24 | −0.61 | 0.27 |
| | Salinity Min | 0.28 | 0.36 | −0.13 | 0.20 | −0.51 |
| | Salinity Max | 0.09 | 0.91 | −0.38 | −0.55 | 0.33 |
| | Salinity SD | −0.46 | 0.28 | 0.57 | −0.70 | 0.21 |

of any observed trends detected for one sex. Previous studies on spotted seatrout have also found that females grow faster than males (Mercer, 1984) although the difference may not be significant during the first year of growth (Murphy and McMichael, 2003).

Murphy and McMichael (2003) summarized the growth of spotted seatrout throughout their range for which there are data. Comparisons with other studies should be done with caution as sometimes size-at-age data are reported as standard length as opposed to total length and fork length (these are equivalent in spotted seatrout) and authors do not always indicate which measure for length was used. With this caveat, an inspection of back-calculated lengths at age (Murphy and McMichael, 2003) indicates that male spotted seatrout from San Carlos Bay in the Charlotte Harbor system seem to grow faster than other male spotted seatrout in other areas of the eastern Gulf of Mexico. We found that the back-calculated size for the first four years of age (251, 293, 331, and 373) were similar to the sizes (237, 305, 345, and 384) reported for Charlotte Harbor by Murphy and Taylor (1994) while Moffett (1961) reported slower growth among males from Fort Myers, Florida (i.e., 156, 245, 302, and 364, ages 1–4 respectively).

Moffett (1961) reported females at age of annuli 1–4 as 160, 248, 313, and 377, respectively, for Fort Myers whereas Murphy and Taylor (1994) reported sizes as 242, 357, 434, and 495 mm TL in Charlotte Harbor. Here, female spotted seatrout were observed to be 288, 388, 371, and 457 mm TL for their back-calculated size at annulus formation. Our study results are more similar to the growth observed for both sexes by Murphy and Taylor (1994) but much faster than that observed by Moffett (1961) for Fort Myers. These differences could be due to methodological differences in aging fish, differences in back-calculation protocols, or real differences in growth rates taken over different time periods.

Comparisons of size at a similar age are facilitated by using back-calculated size at annulus formation data. Assuming some feature such as Lee's Phenomenon was not acting to invalidate comparisons, this technique allows ready comparison among previous year classes. One of the objectives of this study was to relate environmental conditions in the estuary to growth parameters. In this study, it was inviting to make the assumption that there may have been environmental factors affecting the slower growth (size at age) observed for both males and females for year-class 2000. This year was environmentally significant in the Caloosahatchee River/Estuary in that extreme conditions of salinity, caused by excessive releases of fresh water from Lake Okeechobee followed by a complete cessation of releases of water from the Lake. It is tempting to speculate that the observed differences in growth among spotted seatrout were caused by extremes in the salinity regime. Lowest salinities were recorded in 1999 and the greatest variance was recorded in 2001. The advantage of initiating such a database on spotted seatrout growth is that we now have a basis upon which to compare future responses of fish growth to extreme salinity conditions.

The time-series analysis indicated some interesting associations between environmental conditions, as measured by seagrass density and salinity, and growth during the first year of life for both males and females for each year class. Faster growth was preceded by higher densities of *H. wrightii* and *S. filiforme* and higher average salinities. One should interpret these findings with some caution as the apparent association found here does not necessarily indicate causation. Green (1979) indicated that strong correlations in Time-Series analysis could represent causative relationships but, oppositely, they could also result from similar responses to the same unmeasured, natural rhythms. As with any time-series analysis, there should be many replicates of natural cycles and concomitant fish growth responses to make statements regarding causation. Nevertheless, the model presented here indicates that it is possible to speculate on subsequent year-class growth based on seagrass density information or salinities.

There is an indication here that higher salinities favor faster growth among spotted seatrout preceding their first year of life (or conversely, lower salinities precede slower growth). The inevitable implication for management is that increasing the average salinity of the estuary through reductions in freshwater discharges may lead to higher growth rates among spotted seatrout. However, more evaluation is needed before this becomes an acceptable management action. Alternatively, it may be that seagrass density, as influenced by salinity, could be the factor controlling spotted seatrout growth. We have no way, at this time, to separate the potentially interactive or co-variant effects of these factors. Similarly, we are aware that many other factors can influence fish growth. Some of these factors include: food availability and condition, predation pressure, and fishing mortality. This study was unable to obtain sufficient year-specific data on these factors for our analysis here. It could be assumed, however, that since there were few changes in fishing regulations during the years examined, that fishing pressure was relatively constant during the period of interest. Similarly, the area was not subjected to major hurricanes or storms during this period. Obversely, red tide is known to occur in the area and could have affected fish growth.

From the final posed hypotheses we offer the question: Are differences in spotted seatrout growth reflective of differences in estuarine condition over time? This is the very premise of the current research effort. With only a few years of data (both with regard to fish growth and environmental data) with which to conduct the analyses, the hypothesis that environmental differences in the estuary can be observed in the growth rate among an estuarine-resident fish like the spotted seatrout is not rejected. Continued examination of the relationship between growth and the environment is warranted. If this hypothesis continues to stand after further examination, then growth rates of spotted seatrout can serve as a valuable indicator of estuary conditions. Furthermore, knowledge of this relationship could also provide environmental managers with a gauge to determine the effects of efforts to restore estuaries.

The data on age and growth offered in these study results are important. They help form a baseline for assessing future trends in age and growth in this ecologically and economically important species, both within and between estuaries. To be fully evaluated, consideration should also be given to other factors that may influence growth (such as food availability, genetic differences, etc.) The data presented here lend credence to the idea that some features or factors in the estuary are associated with seatrout growth. With a longer-term database, it may one day be possible to predict fish growth in the estuary through evaluation of a few pertinent environmental features. Eventually, it may even be possible to affect growth in some fish species through manipulation of controllable environmental features, such as salinity. Longer-term trends in age and growth may allow us to detect long-term, global-scale phenomena related to factors related to global climate change. One such rule is the Moran Effect (Hudson and Cattadori, 1999; Ripa, 2000; Koenig, 2002; Stenseth et al., 2002) that implies common biological trends may be detected across a wide spatial scale if subjected to a generally widespread stressor such as climate change. While such a feature was not detected here, the baseline information is accumulating through data gathered by studies such as this to be able to make such determinations.

ACKNOWLEDGMENTS—We thank Jaime Greenawalt (Sanibel-Captiva Conservation Foundation) and Judy Ott (Florida Department of Environmental Protection) for providing data on seagrass density. Kathy Haunert (South Florida Water Management District) kindly provided conductivity data. We thank Chad Bedee (Florida Department of Environmental Protection) for assistance with age determination. Michael Hannan offered suggestions which improved the manuscript. We thank Michael Murphy (Florida Fish and Wildlife Research Institute) for helpful discussions regarding age and growth in spotted seatrout. We also appreciate the comments provided by the anonymous reviewers. Support for this study was provided through a grant to SAB from the Charlotte Harbor National Estuary Program.

## LITERATURE CITED

BEDEE C. D., D. A. DEVRIES, S. A. BORTONE, AND C. L. PALMER. 2003. Estuary specific age and growth of spotted seatrout in the northern Gulf of Mexico. Pages 57–77. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

BLAYLOCK, R. B. AND R. M. OVERSTREET. 2003. Diseases and parasites of the spotted seatrout. Pages 197–225. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

BORTONE, S. A. (ed.). 2000. Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Press. Boca Raton, Florida. 318 pages.

——— (ed.). 2003a. The Biology of the Spotted Seatrout. CRC Press, Boca Raton, Florida.

———. 2003b. Spotted seatrout as a potential indicator of estuarine condition. Pages 295–298. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press, Boca Raton, Florida.

———. 2003c. Introduction. Pages 1–3. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press, Boca Raton, Florida.

———, W. A. DUNSON, AND J. M. GREENAWALT. 2005. Fishes as estuarine indicators. *In*: S. A. BORTONE (ed.). Estuarine Indicators. CRC Press. Boca Raton, Florida.

——— AND M. A. WILZBACH. 1997a. Spotted seatrout as an important sentinel for the condition of Florida's estuaries. Up Close and Environmental – July 1997, 1(1):1–2.

——— AND M. A. WILZBACH. 1997a. Status and trends of the commercial and recreational landings of spotted seatrout (*Cynoscion nebulosus*): South Florida. Florida Center for Environmental Studies, Tech. Ser. 2:1–47. Florida Atlantic University (Northern Palm Beach Campus).

———, M. A. WILZBACH, AND C. D. BEDEE. 1997. An indexed bibliography to the biology and life history of the spotted seatrout (*Cynoscion nebulosus*). Florida Center for Environmental Studies, Tech. Ser. 1:i–iii, 1–74. Florida Atlantic University (Northern Palm Beach Campus).

BROWN-PETERSON, N. J. 2003. The reproductive biology of the spotted seatrout. Pages 99–133. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

DEVRIES, D. A., C. D. BEDEE, C. L. PALMER, AND S. A. BORTONE. 2003. Pages 79–98. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

GOLD, J. R., L. B. STEWART, AND R. WARD. 2003. Population structure of spotted seatrout (*Cynoscion nebulosus*) along the Texas Gulf Coast., as revealed by genetic analysis. Pages 17–29. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

GREEN, R. H. 1979. Sampling Design and Statistical Methods for Environmental Biologists. John Wiley & Sons, New York.

GUTREUTER, S. 1987. Considerations for estimation and interpretation of annual growth rates. *In*: SUMMERFELT, R. C. AND HALL, G. E. (eds.), Age and Growth of Fish. Iowa State University Press, Ames.

HUDSON, P. J. AND I. M. CATTADORI. 1999. The Moran Effect: a cause of population synchrony. Trends in Ecology and Evolution 14:1–2.

JOHNSON, D. R. AND W. SEAMAN, JR. 1986. Species profiles: life histories and environmental requirements of costal fishes and invertebrates (South Florida) – spotted seatrout. U.S. Fish and Wildlife Service, Biol. Rep. 82(11.43). U.S. Army Corps of Engineers, TR EL-82-4. 18 pp.

KENNISH, M. J. 1991. Ecology of Estuaries: Anthropogenic Effects. CRC Press. Boca Raton, Florida.

KOENIG, W. D. 2002. Global patterns of environmental synchrony and the Moran Effect. Ecography 25:283–288.

MERCER, L. P. 1985. A biological fisheries profile for spotted seatrout, *Cynoscion nebulosus*. North Carolina Department of Natural Resources and Community Development, Special Scientific Report 40:1–87.

MOFFETT, A. W. 1961. Movements and growth of spotted seatrout, *Cynoscion nebulosus*, in west Florida. State of Florida Board of Conservation, Technical Series 36:35pp.

MURPHY, M. D. AND R. H. MCMICHAEL, JR. 2003. Age determination and growth of spotted seatrout, Cynoscion nebulosus (Pisces: Sciaenidae). Pages 41–56. *In*: S. A. BORTONE (ed.). The Biology of the Spotted Seatrout. CRC Press. Boca Raton, Florida.

——— AND R. G. TAYLOR. 1994. Age, growth, and mortality of spotted seatrout in Florida waters. Trans. Amer. Fish. Soc. 123:482–497.

RIPA, J. 2000. Analysing the Moran effect and dispersal: their significance and interaction in synchronous population dynamics. Oikos 89:175–187.

STENSETH, N. C., A. MYSTERUD, G. OTTERSON, J. W. HURRELL, K-S, CHAN, AND M. LIMA. 2002. Ecological effects of climate fluctuations. Science 297:1292–1296.

Florida Scient. 69(00S2): 127–139. 2006
Accepted: March 10, 2006

# HABITAT EVALUATION IN COASTAL SOUTHWESTERN FLORIDA: A POLICY DECISION MODEL FOR THE BLUE CRAB, *CALLINECTES SAPIDUS*

TOMMA K. BARNES[1,2], FRANK J. MAZZOTTI[3], LEONARD G. PEARLSTINE[3], AND ASWANI K. VOLETY[4]

[1]South Florida Water Management District, Fort Myers, Florida, 33901
[2]Oceanographic Center, Nova Southeastern University, Dania Beach, Florida, 33004
[3]Ft. Lauderdale Research and Education Center, University of Florida, Ft. Lauderdale, Florida, 33314
[4]Division of Marine and Ecological Sciences, Florida Gulf Coast University, Fort Myers, Florida, 33965

ABSTRACT: *A stressor response model in the form of a habitat suitability index was created for blue crab to quantify impacts of alternative management actions and to assist managers in policy decisions. The model simulates system response by examining impact of freshwater input into southwest Florida estuaries and is being used to help bring together research and monitoring components within southwest Florida ecosystems as part of the Comprehensive Everglades Restoration Plan. The model uses both a larval-component index and spawning female component index and has been incorporated into a geographic information system to portray responses spatially and temporally to facilitate policy decisions. This habitat suitability stressor response model can be applied at other locations using information from the literature, expert knowledge and available local field data and can be easily modified or refined as additional data becomes available. This study examines four hydrological scenarios: a target flow, 2000 base, and 2050 with and without Comprehensive Everglades Restoration, on the habitat suitability of the estuary for blue crabs. The model indicates that preferred flow frequency distribution and the future conditions with Comprehensive Everglades Restoration Plan have higher habitat suitability values than existing or future without Comprehensive Everglades Restoration Plan conditions.*

*Key Words:* Alternative assessment, blue crab, *Callinectes sapidus*, forecasting model, habitat suitability index, stressor response, Comprehensive Everglades Restoration Plan

HUMAN activity has altered function of natural ecosystems throughout the world (Rapport et al., 1985; Maltby and Dugan, 1994). In areas where impacts are minimal or reversible, natural recovery may be possible. In more heavily-impacted regions, ecological restoration is required. The historic Florida's Everglades, once an expansive and ecologically productive system (Davis and Ogden, 1994), was often described as a free-flowing river of grass (Douglas, 1947). Today, it is fragmented and hydrologically altered (Light and Dineen, 1994; Ogden et al., 2005a; Ogden et al., 2005b), which has led to loss of sheet-flow across the system (Science Coordination Team, 2003) and into estuaries (McIvor et al., 1994), loss of spatial extent (Gunderson and Loftus, 1993), and deteriorated water quality (Ogden et al., 2005a; Ogden et al., 2005b).

The Comprehensive Everglades Restoration Plan (CERP) developed by the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD) includes a series of restoration projects that focus on the quality, quantity, timing, and distribution of water in the Everglades ecosystem (U.S. Army Corps of Engineers and South Florida Water Management District, 1999). Everglades restoration is a large effort and is being implemented through a series of eight expedited projects, together called Acceler8. The C-43 West Reservoir (an Acceler8 project and a component of a larger restoration effort for the Caloosahatchee River and estuary) focuses on storing regulatory releases from Lake Okeechobee and stormwater runoff. Removing surplus water will reduce excess water flow to the estuary during the wet season and provide essential flows during the dry season. The project will consist of an above-ground reservoir located along the Caloosahatchee River with a maximum storage capacity of 197 million cubic meters (160,000 acre-feet).

The pre-construction effort for such a project involves attaining a series of sequential objectives necessary to arrive at a selected restoration plan (Yoe and Orth, 1996). Two critical objectives of this process are evaluation of alternative restoration plans and comparison of the effects of each alternative. In the evaluation step, each individual restoration alternative is assessed and its effects are quantified and judged. For the C-43 West Reservoir Project, the evaluation protocol chosen here is a forecasting model.

Forecasting models bring together data resulting from research and monitoring studies within ecosystems and place them into an adaptive management framework for evaluation of alternative plans. In an integrated approach that includes both passive and active adaptive management a forecasting model is used to simulate system response for alternative plan evaluation and is validated by monitoring programs to measure actual system response (Barnes and Mazzotti, 2005). Monitoring can then feed back as a passive adaptive management tool for calibration of the forecasting model. Directed research driven by model uncertainties is an active adaptive management strategy for reducing uncertainties in the model (Ogden et al., 2003; Barnes and Mazzotti, 2005).

For the C-43 West Reservoir Project, the forecasting model is a set of habitat suitability models for individual species, which relate stressors to the habitat of each organism. Each forecasting model component is being applied to multiple restoration alternatives with the assumption that, as stress level on the ecosystem changes for each alternative, so will extent and quality of suitable habitat. Another assumption is that habitat suitability is related to distribution and abundance of the species (or life stage) modeled (Klopatak and Kitchens, 1985). This assumption should be tested and models modified as appropriate (Flather et al., 1992).

Criteria for selecting focal species were based on their ecological, recreational, and/or economical importance, as well as their well-established linkage to stressors of management interest (Barnes, 2005). An additional criterion for focal species selection was the relevance of a species to engage the public concern as to the outcomes of restoration projects. The habitat suitability models created for the C-43 West Basin Reservoir Project include the blue crab (*Callinectes* *sapidus* Rathbun), spotted seatrout (*Cynoscion nebulosus* Cuvier), eastern oyster (*Crassostrea virginica* Gmelin), seagrass (*Thallassia testudium* Banks & Soland. ex Koenig and *Halodule wrightii* Aschers.), and wild celery (*Vallisneria americana* Michx.). This paper presents the process that was used to develop a habitat suitability model for the blue crab and demonstrates its use for the assessment of restoration alternatives in the Caloosahatchee estuary, Florida.

The blue crab is an estuarine-dependent crustacean that supports a crab-trap fishery in the Caloosahatchee River and estuary (FWC, 1997). Its life history involves a complex cycle of planktonic, nektonic, and benthic stages which occur throughout the estuarine-near-shore marine environment in a variety of habitats. The blue crab is one of the more abundant estuarine macro-invertebrates and supports valuable commercial and recreational fisheries along the Atlantic and Gulf coasts where it plays a crucial role in estuarine food webs, providing prey for many species and is in turn a voracious predator on other species (Laughlin, 1982; Van Den Avyle and Fowler, 1984; Van Engel, 1987; Mansour, 1992).

Blue crabs are a highly prized commodity to consumers. In the state of Florida, fishing effort increased significantly in the 1980's and 1990's while landings have fluctuated (Guillory et al., 2001; Murphy et al., 2001). During 1998–2000, the highest reported landings on Florida's Gulf coast were in Lee County (Murphy et al., 2001). In 2004–05 the number of licensed crabbers in Lee County, Florida was 118 (FWC, 2005a) and in 2004 over 70,300 kg (155,000 pounds) of blue crab were harvested (FWC, 2005b). This fishery expends a large effort and yields large numbers of crabs for local and distant consumers while providing a valuable local economic employment opportunity (Wasno, 2006).

METHODS—*Model development and application*—Habitat Suitability Indices (HSI) used here were developed by choosing specific life stages with the most limited, restricted, or tightest range of suitable conditions, to capture the highest sensitivities of organisms to environmental changes associated with planned restoration activities. Each stressor metric was portrayed spatially and temporally across aquatic systems of the study area at a scale appropriate to blue crabs. The blue crab HSI model was incorporated into a geographic information system (GIS) to portray responses spatially and temporally. As a result, the model was capable of describing a response surface of habitat suitability values that vary spatially according to stressor levels throughout the estuary and temporally according to temporal patterns in stressor variables. Much of the temporal variation observed was caused by the temporal pattern of important stressor inputs, such as water salinity and temperature.

Adult blue crabs tolerate a very wide range of estuarine conditions (Perry and McIlwain, 1986). Therefore, it was determined that limiting variables for successful blue crab habitat are the more restricted conditions necessary for blue crab recruitment. As a result, two components (i.e., larval settlement (megalopae) and spawning females) were chosen to determine habitat suitability of blue crabs recruitment in the Caloosahatchee Estuary. Variables used to estimate habitat suitability for larval settlement were salinity, temperature, and flow. To estimate habitat suitability for spawning females, salinity and temperature were included in the model. Each variable can be weighted ($w$) with regard to importance; however, the sum of the weights must be equal to one.

$$\text{Blue Crab } \textit{Larval Component Index} = (\text{Salinity}^{w} * \text{Temperature}^{w} * \text{Flow}^{w}) \quad (1)$$

$$\text{Blue Crab } \textit{Spawning Female Component Index} = (\text{Salinity}^{w} * \text{Temperature}^{w}) \quad (2)$$

$$\text{HSI}_{\text{June}-\text{October}} = (\textit{Larvae Component Index}^{w} + \textit{Spawning Female Component Index}^{w}) \quad (3)$$

$$\text{HSI}_{\text{March}-\text{May, Nov, Dec}} = (\textit{Spawning Female Component Index}) \quad (4)$$

TABLE 1. Environmental requirements taken principally from peer reviewed scientific literature and used to create HSI curves.

| Variable | Value |
|---|---|
| Blue Crab: Larvae (Megalopae) Salinity | Optimal – >30‰ (Costlow 1967) |
| | Range – 10‰ to 40‰ (Costlow 1967) |
| | Most at >20‰ (Perry 1975) |
| Blue Crab: Larvae (Megalopae) Temperature | Optimal – 25°C |
| | Range – 21.5°C–34.5°C (Costlow 1967) |
| Blue Crab: Spawning Female Salinity | Range 21‰–35‰ |
| | (Costlow and Bookhout 1959; Sulkin and Epifanop 1975; Bookhout et al., 1976; Sulkin et al., 1976; Steele and Bert 1994) |
| Blue Crab: Spawning Female Temperature | Range 16°C–25°C (Steele and Bert 1994) |

Values for these environmental requirements were taken principally from peer reviewed scientific literature (Table 1) and adjusted for local conditions using expert knowledge and local data. Adjusted values were then used to create the individual suitability indices (FIG. 1) that drive the model. The suitability indices are represented as line graphs, where the Y axis is in a scale of 0–1 to represent the suitability of each variable value and the X axis is the range of values for the variable being modeled. The values range from 0 to 1 indicates unfit to ideal habitat, respectively.

In the blue crab model, habitat suitability was calculated monthly as the weighted geometric mean of the individual suitability indices for each of the environmental variables. Because the geometric mean is derived from the product of variables rather than the sum (as in the arithmetic mean) and has the property that if any individual variable was unsuitable for species success (i.e., the value of the variable is zero) then the entire index went to zero. An annual index was then calculated as the average (arithmetic mean) of monthly indices. For blue crab recruitment indices, the annual mean was obtained by averaging monthly index values calculated from June through October, corresponding with local spawning and settlement activity in southwest Florida estuaries. Suitable habitat was then aggregated for purposes of reporting into four categories as "poor", "good", "better" and "best". Habitat units are reported both monthly and annually as area of suitable habitat in each habitat category.

Model output was designed to provide information through numerical values as well as visual aids that allow users to rapidly explore and compare mapped results. The user interface was created with flexibility to adjust input and their weighted importance. Versatility allows, for instance, variable weighting for the impact that monthly water temperatures can have on a species habitat. This is valuable because the same temperature may have a different effect on a species habitat affinity during different seasons. The flow component is also capable of change by the user just by entering the total number of maximum flow days per month. Flow is important during the months when larval growth occurs. For example, if there are more than five consecutive days of high flow, then there is an increased likelihood of reduced survivability. Each component can be weighted to give it more or less importance in the calculation of the HSI. With each change in the maximum flow days per month and/or component weight a new simulation is performed, creating a new display. The total HSI value for any location is displayed in chart form and numerically for each individual component by clicking on the displayed map at any location. Users may also view each individual month's results by selecting the particular month.

Input data for the model came from multiple sources. Salinity data for the HSI models were obtained using an estuary-salinity regression model and a spatial interpolator post processor (Story, 2005). The regression model uses daily flows at the Franklin Lock and Dam structure (S-79), the boundary between freshwater and estuarine portions of the Caloosahatchee River. The regression model is based on 19 fixed sampling stations within the estuary and is post processed into a grid using inverse distance weighting with barriers (Story, pers comm., 2005). This produces a grid of salinity values for different flow

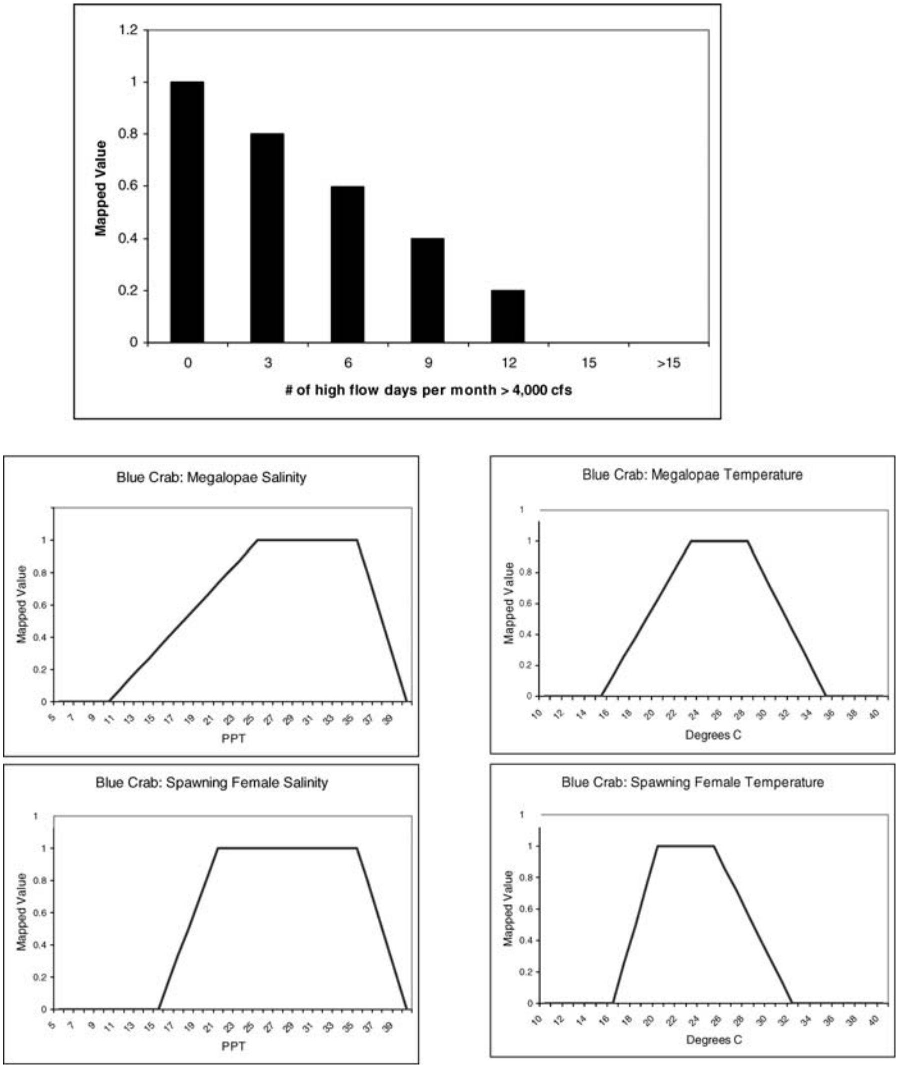



FIG. 1. Suitability index diagrams created for the blue crab using data from Table 1 (adjusted for local conditions).

alternatives. Flow values at S-79 can be obtained from several different regional-scale hydrodynamic models. Substrate, bathymetry, and temperature data were obtained through previous projects (Avineon, 2003; Hansen and Perry, 2003; Tetra Tech, 2004).

Four initial hydrologic scenarios have been evaluated for the C-43 West Reservoir Project. Flow at S-79 was obtained using the South Florida Water Management Model (SFWMM) (MacVicar et al., 1984; SFWMD, 1997), a landscape scale computer model that simulates regional hydrology on a daily basis at a scale of 10.36 $km^2$ (four square miles; i.e., $2 \times 2$ model). The SFWMM uses climatic data for the 1965–2000 period of hydrologic conditions which includes drought and wet periods. SFWMM model output was then run through the Caloosahatchee Estuary Salinity Regression Model and Spatial Interpolator Post

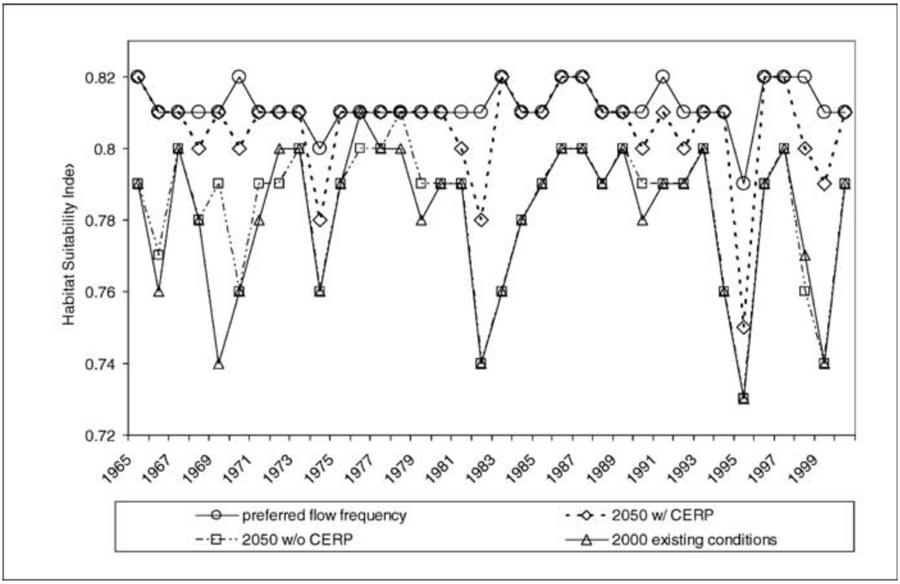



FIG. 2. Modeling results for yearly average blue crab settlement habitat suitability for 20 years comparing the preferred flow frequency for the Caloosahatchee Estuary, the 2000 existing conditions, 2050 condition without the Comprehensive Everglades Restoration Plan projects and 2050 conditions with Comprehensive Everglades Restoration Plan as defined by the Comprehensive Everglades Restoration Plan Final Integrated Feasibility Report (USACE and SFWMD, 1999).

Processor (Story, 2005). Four sets of grids were generated from daily flows at S-79 from the following sources:

1) Preferred flow frequency distribution for the Caloosahatchee Estuary (PFF) based on providing a full range of salinity along its longitudinal axis that is supportive of naturally occurring estuarine biota (SFWMD, 2003). This represents a target condition.
2) Existing conditions (2000).
3) Future conditions (2050) without any Comprehensive Everglades Restoration Plan projects.
4) Future conditions (2050) with the Comprehensive Everglades Restoration implemented.

RESULTS—The results are displayed in Figure 2. The models have the capability of displaying results as average yearly HSI or average yearly habitat units. For the purpose of this paper, we have used average HSI values. The model indicates that preferred flow frequency distribution and the future conditions with CERP have higher HSI values than existing or future without CERP conditions. Figure 3 is a graphic comparison of the 2050 with CERP and 2050 without CERP, showing average HSI value distribution in the Caloosahatchee Estuary using 1998 hydrology, and with CERP conditions having a higher distribution of "best" HSI values.

DISCUSSION—Ultimate selection of restoration alternatives depends on evaluation of a suite of factors including national and regional economic development, cost, real estate, fish and wildlife, cultural resources, and water quality. When

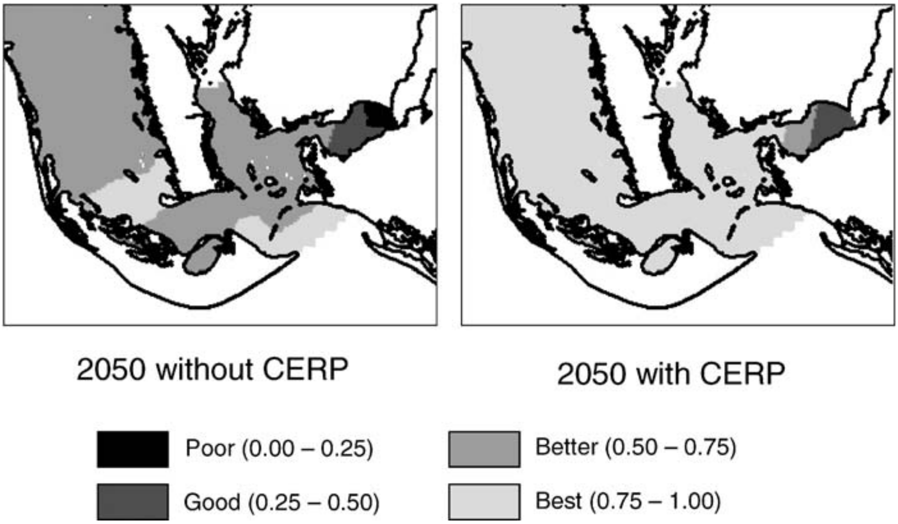



FIG. 3. Comparison of 2050 conditions with the implementation of Comprehensive Everglades Restoration Plan (USACE and SFWMD, 1999) and 2050 condition without the any Comprehensive Everglades Restoration Plan projects. Maps show average habitat suitability in the Caloosahatchee Estuary for hydrology year 1998.

possible, benefits from each alternative should be quantified into appropriate units such as dollars or habitat units (Yoe and Orth, 1996). In many cases, evaluations are made through informal and subjective processes or by using best professional judgment. This can make quantification of benefits difficult. The use of quantifying tools can assist significantly in this process.

HSIs (USFWS, 1981) and other habitat assessment models have become a common methods for environmental evaluations and, in ecosystem restoration projects, are often used as a first approximation toward quantifying relationships between ecosystem changes due to land and water management practices and their effects on specific species (Turner et al., 1995; Mladenoff et al., 1997; Elliot et al., 1999; Curnutt et al., 2000; Larson et al., 2003; Tarboton et al., 2004). More than 150 HSI models were published by the U.S. Fish and Wildlife Service as part of the Habitat Evaluation Procedures; a planning and evaluation technique that focuses on the habitat requirements of fish and wildlife (US Fish and Wildlife Service, 1980).

The series of models created for the C-43 West Reservoir Project build on these and other existing models, when available. For the blue crab, no pre-existing model was identified. A GIS based HIS model for blue crab was created for use in the Caloosahatchee estuary by resource managers. This model has several advantages over previous HSI models in the integration of GIS into the model for easy visualization and the adaptation of HSI values to suit local conditions in southwest Florida.

An advantage of this type of forecasting model is that it can be developed in early stages of a project using scientific literature, expert knowledge, and field data. By optimizing the models to local conditions and physiological adaptations to local environments, the C-43 blue crab HSI can better capture the sensitivities of organisms in the Caloosahatchee Estuary, and allow managers to better distinguish between and quantify benefits of restoration alternatives. In addition, the incorporation of the C-43 HSIs into a GIS interface makes overall interpretation of results easier for managers and allows them to display details for any specific location within the estuary.

Another advantage of the blue crab model is that it can be easily transferred and applied to other estuaries by incorporating local variables or conditions, collected through monitoring or mapping programs. Using this type of local focus can assist in transforming somewhat generic assessments into a more refined site or project specific analyses.

When choosing restoration alternatives, it needs to be kept in mind that HSI models are only simplifications of reality and that there are limitations to using this type of tool such as:

1. Other factors affecting habitat suitability may have been ignored or omitted due to lack of baseline/input data.
2. HSIs do not predict the population dynamics of the organisms modeled only the quality of their habitat.
3. HSIs only give a snapshot in time (monthly or yearly value) and do not incorporate spatial or temporal aspects of species habitat relations (Turner et al., 1995).

As a result, managers should not depend on HSI models alone for selection of restoration or management alternatives, but should incorporate HSIs with monitoring and research plans. Because different ecosystem indicators can respond to management scenarios or restoration alternatives in different ways and at different times, large scale restoration projects such as the C-43 West Reservoir Project should not depend on results of a single model. Instead, multiple models for a suite of species, with different habitat requirements, response times and scales should be used in conjunction with monitoring and research components.

Model verification, calibration, and validation must also be considered and are often misconstrued. Verification is the internal examination of the model and can be done throughout the model development process. Calibration, in the case of HSI models, can be done by addressing scientific uncertainties within the model through research and adjusting the HSI curves accordingly. Research is a key component of active adaptive ecosystem management (Barnes and Mazzotti, 2005). Scientific uncertainties have been reduced by using peer reviewed scientific literature. Spatial uncertainties, such as grid size or resolution of input layers, may also be present. Uncertainties may also be present where we have used regional data to estimate a local response. This occurs in geographic regions where there is a lack of scientific data on the organism being modeled and may increase with distance from the source data. Validation is the process of using the HSI models to make predictions of how restoration will affect the habitat of a specific species or suite of species, and through monitoring, confirm the predictions. This is the passive adaptive process (Barnes and Mazzotti, 2005). Monitoring results can also be used to fine-tune the HSI graphs.

In the case of the blue crab model HSI, the model does not predict if blue crab settlement is actually occurring, it only examines the suitability of the habitat for settlement at any given point in time. Whether or not settlement is actually occurring is beyond the scope of this model. If it is found through monitoring that they are not, settlement failure then becomes a research question.

Results from four model runs for the blue crab not only show that the preferred flow frequency and 2050 with CERP hydrologic conditions produce higher HSIs, but they also show more consistent HSI value from year to year. Actual blue crab populations are dependent on what has happened in the estuary in previous years; if settlement conditions are poor one year, the following year there may be a decrease in the population of spawning females and in turn a decrease in larvae for settlement (Tagatz, 1965). This may not apparent in the model results, which strictly look at habitat value for average conditions of the year.

CONCLUSION—A HSI model for the blue crab integrated with GIS for visual display was developed. This model is optimized for use in the Caloosahatchee estuary but can be applied to other estuaries by adjusting variable values to mimic local condition of those estuaries. This model will enhance decision making by resource managers by providing a tool that is based on empirical data rather than informal judgments or professional opinion.

ACKNOWLEDGMENTS—The authors would also like to thank Peter Doering, along with the anonymous reviewers and the guest editors for their helpful suggestions. Their diligence and helpful suggestions significantly improved the quality of this manuscript. We would also like to thank Kevin Chartier for his help with the model development, model runs, and graphics. The project was supported by the South Florida Water Management District, University of Florida and the U.S. Army Corp of Engineers.

## LITERATURE CITED

AVINEON. 2003. Seagrass Mapping Project Final Report contract PC P2201325 submitted to the South Florida Water Management District. Available from the South Florida Water Management District, Lower West Coast Service Center, Fort Myers, FL.

BARNES, T. K. 2005. Caloosahatchee Estuary Conceptual Ecological Model. Wetlands 25(4):884–897.

——— AND F. J. MAZZOTTI. 2005. Using conceptual models to select ecological indicators for monitoring restoration and management of estuarine ecosystems. Pp. 493–50. *In*: BORTONE, S. A. (ed.), Estuarine Indicators, CRC Press, Boca Raton, FL.

BOOKHOUT, C. G., J. D. COSTLOW, JR. AND R. MONROE. 1976. Effects of methoxchlor on larval development of mud-crab and blue-crab. Water Air Soil Poll. 5:349–365.

COSTLOW J. D., JR. 1967. The effects of salinity and temperature on survival and metamorphosis of megalops of the blue crab, *Callinectes sapidus* Rathbun. Helgoland. Wiss. Meer. 15:84–97.

——— AND C. G. BOOKHOUT. 1959. The larval development of *Callinectes sapidus* Rathbun reared in the laboratory. Bio. Bull. 116(3):373–396.

CURNUTT, J. L., J. COMISKEY, M. P. NOTT, AND L. J. GROSS. 2000. Landscape-based spatially explicit species index models for Everglades restoration. Ecol. Appl. 10:1849–1860.

DAVIS, S. M. AND J. C. OGDEN. 1994. Toward ecosystem restoration. Pp. 769–796. *In*: DAVIS, S. M. AND J. C. OGDEN (eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Boca Raton, FL.

DOUGLAS, M. S. 1947. The Everglades: River of Grass (revised ed., 1988), Pineapple Press, Sarasota, FL.

ELLIOTT, C. R. N., M. J. DUNBAR, I. GOWING, AND M. C. ACREMAN. 1999. A habitat assessment approach to the management of groundwater dominated rivers. Hydrol. Process. 13(3):459–475.

FLATHER, C. H., S. H. BRADY, AND D. B. INKLEY. 1992. Regional habitat appraisals of wildlife communities: a landscape-level evaluation of a resource planning tool using avian distribution data. Landscape Ecol. 7:137–147.

FWC. 1997. Florida Fish and Wildlife Conservation Commission Marine Fisheries Information Systems, Fish and Wildlife Research Institute, St. Petersburg, FL. http://www.floridamarine.org.

———. 2005a. Florida Fish and Wildlife Conservation Commission Marine Fisheries Information Systems 2004 Annual Landings Summary *Preliminary report 8/1/2005*. Fish and Wildlife Research Institute, St. Petersburg, FL. http://www.floridamarine.org.

———. 2005b. Florida Fish and Wildlife Conservation Commission Marine Fisheries Information Systems 2004–2005 License/Permit Summary. Fish and Wildlife Research Institute, St. Petersburg, FL. http://www.floridamarine.org.

GUILLORY, V., H. PERRY, P. STEELE, T. WAGNER, W. KEITHLY, B. PELLEGRIN, J. PETTERSON, T. FLOD, B. BUCKSON, L. HARTMAN, E. HOLDER, AND C. MOSS. 2001. The Blue Crab Fishery of the Gulf of Mexico, United States: A Regional Management Plan. Gulf States Marine Fisheries Commission, Ocean Springs, MS. http://www.gsmfc.org/pubs/IJF/Blue_Crab_FMP_2001.pdf.

GUNDERSON, L. H. AND W. F. LOFTUS. 1993. The Everglades. Pp. 191–255. *In*: MARTIN, W. H., S. G. BOYCE, AND A. C. ECHTERNACHT (eds.), Biodiversity of the Southeastern United States/Lowland Terrestrial Communities. John Wiley & Sons, NY.

HANSEN, M. AND G. PERRY. 2003. Estero Bay to Charlotte Harbor bathymetric survey USGS Final Report contract C-13105-WO01 submitted to the South Florida Water Management District. Available from the South Florida Water Management District, Lower West Coast Service Center, Fort Myers, FL.

KLOPATEK, J. M. AND J. M. KITCHINGS. 1985. A regional technique to address land use changes and animal habitats. Environ. Conserv. 12:343–354.

LARSON, M. A., W. D. DIJAK, F. R. THOMPSON, III, AND J. J. MILLSPAUGH. 2003. Landscape-level Habitat Suitability Models for Twelve Wildlife Species in Southern Missouri. General Technical Report NC-233. St. Paul, MN: U.S. Dept of Agriculture, Forest Service, North Central Research Station. 51p.

LAUGHLIN, R. A. 1982. Feeding habits of the blue crab, *Callinectes sapidus* Rathbun, in the Apalachicola estuary, Florida. Bull. Mar. Sci. 32:807–822.

LIGHT, S. S. AND J. W. DINEEN. 1994. Water control in the Everglades: A historical perspective. Pp. 47–84. *In*: DAVIS, S. M. AND J. C. OGDEN (eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Boca Raton, FL.

MACVICAR, T., T. VAN LENT, AND A. CASTRO. 1984. South Florida Water Management Model Documentation Report, Technical Publication 84-3. Available from the South Florida Water Management District, West Palm Beach, FL.

MALTBY, E. AND P. J. DUGAN. 1994. Wetland ecosystem protection, management, and restoration: An international perspective. Pp. 29–46. *In*: DAVIS, S. M. AND J. C. OGDEN (eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Boca Raton, FL.

MANSOUR, R. A. 1992. Foraging ecology of the blue crab, *Callinectes sapidus* Rathbun, in lower Chesapeake Bay. PhD Dissertation. College of William and Mary, Williamsburg, VA.

MCIVOR, C. C., J. A. LEY, AND R. D. BJORK. 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: A review. Pp. 117–146. *In*: DAVIS, S. M. AND J. C. OGDEN (eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Boca Raton, FL.

MLADENOFF, D. J., R. C. HAIGHT, T. A. SICKLEY, AND A. P. WYDEVEN. 1997. Causes and implications of species restoration in altered ecosystems. A spatial landscape projection of wolf population recovery. Bioscience 47:21–31.

MURPHY, M. D., C. A. MEYER, AND A. L. MCMILLEN-JACKSON. 2001. A Stock Assessment for Blue Crab, *Callinectes sapidus*, in Florida Waters. Report to the Florida Fish and Wildlife Commission Division of Marine Fisheries, July 9, 2001. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute, St. Petersburg, FL. http://www.floridamarine.org.

OGDEN, J. C., S. M. DAVIS, T. K. BARNES, K. J. JACOBS, AND J. H. GENTILE. 2005a. Total System Conceptual Ecological Model. Wetlands 25(4):955–979.

OGDEN, J. C., S. M. DAVIS, K. J. JACOBS, T. K. BARNES, AND H. E. FLING. 2005b. The use of conceptual ecological models to guide ecosystem restoration in south Florida. Wetlands 25(4):795–809.

———, S. M. DAVIS, AND L. A. BRANDT. 2003. Science strategy for a regional rcosystem monitoring and assessmentpProgram. Pp. 135–163. *In*: BUSCH, D. E. AND J. C. TREXLER (eds.), Monitoring Ecosystems. Island Press, Washington, D.C.

PERRY, H. M. 1975. The blue crab fishery in Mississippi. Gulf Res. Rep. 5(1):39–57.

——— AND T. D. MCILWAIN. 1986. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Gulf of Mexico): Blue Crab. U. S. Fish Wildl. Serv. Biol. Rep. 82(11.55). U.S. Army Corps of Engineers, TR EL-82-4. 21 pp.

RAPPORT, D. J., H. A. REGIER, AND T. C. HUTCHINSON. 1985. Ecosystem behavior under stress. Am. Nat. 125:617–640.

SCIENCE COORDINATION TEAM. 2003. The role of flow in the Everglades ridge and slough landscape. South Florida Ecosystem Restoration Task Force, Miami, FL. http://www.sfrestore.org.

SOUTH FLORIDA WATER MANAGEMENT DISTRICT. 1997. DRAFT Documentation for the South Florida Water Management Model, Hydrologic Systems Modeling Division, Planning Department, SFWMD, West Palm Beach, FL. http://www.sfwmd.gov.

———. 2003. Existing Legal Sources for the Caloosahatchee Estuary at the Franklin Lock and Dam (S-79). Coastal Ecosystems Division unpublished report. Available from the South Florida Water Management District, West Palm Beach, FL.

STEELE, P. AND T. M. BERT. 1994. Population ecology of the blue crab, *Callinectes sapidus* Rathbun, in a subtropical estuary: Population structure, aspects of reproduction, and habitat partitioning. Fla. Mar. Res. Pub. (51):1–24.

STORY, G. 2005. US Army Corp of Engineers Jacksonville District, Jacksonville, FL. Pers. Commun.

SULKIN, S. D. AND C. E. EPIFANIO. 1975. Comparison of rotifers and other diets for rearing early larva of the blue crab, *Callinectes sapidus* Rathbun. Estuar. Coast. Mar. Sci. 3:109–113.

SULKIN, S. D., E. S. BRANSCOMB, AND R. E. MILLER. 1976. Induced winter spawning and culture of larvae of the blue crab, *Callinectes sapidus* Rathbun. Aquaculture 8:103–113.

TAGATZ, M. E. 1965. The fishery for blue crabs in the St. Johns River, Florida, with special reference to fluctuation in yield between 1961 and 1962. U.S. Fish and Wildlife Service Spec. Sci. Rep. Fish. 501:1–11.

TARBOTON, K. C., M. M. IRIZARRY-ORTIZ, D. P. LOUCKS, S. M. DAVIS, AND J. T. OBEYSEKERA. 2004. Habitat Suitability Indices for Evaluation Water Management Alternatives. South Florida Water Management District Office of Modeling Technical Report, West Palm Beach, FL. www.sfwmd.gov.

TETRA TECH, INC. AND JANICKI ENVIRONMENTAL, INC. 2004. Compilation, Evaluation, and Archiving of Existing Water Quality Data for Southwest Florida. Final Report Contact No. DACW 17-02-D-0009, May 5, 2004. Submitted to US Army Corp of Engineers Jacksonville District. Available from US Army Corp of Engineers Jacksonville District, Jacksonville, FL.

TURNER, M. G., G. J. ARTHAUD, R. T. ENGSTROM, S. J. HEJL, J. LIU, S. LOED, AND K. MCKELVEY. 1995. Usefulness of spatially explicit population models in land management. Ecol. Appl. 5(1):12–16.

U. S. ARMY CORPS OF ENGINEERS AND SOUTH FLORIDA WATER MANAGEMENT DISTRICT. 1999. Central and Southern Florida Project Comprehensive Review Study Final Integrated Feasibility Report and Programmatic Environmental Impact Statement April 1999. U. S. Army Corp of Engineers, Jacksonville District, Jacksonville, FL. www.evergladesplan.org.

U. S. FISH AND WILDLIFE SERVICE. 1980. Habitat Evaluation Procedures (HEP). USDI Fish and Wildlife Service Division of Ecological Services. ESM 102. http://www.fws.gov/policy/ESMindex.html.

———. 1981. Standards for the development of habitat suitability index models for use in the habitat evaluation procedures. Report ESM 103, Interagency Interdisciplinary Development Group, Division of Ecological Services, U.S. Fish and Wildlife Service, US Department of the Interior, Washington, DC.

VAN DEN AVYLE, M. J. AND D. L. FOWLER. 1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic): Blue Crab. U.S. Fish and Wildlife Service, Publication FWS/OBS-82/11. 19, 16 pp.

VAN ENGLE, W. A. 1987. Factors affecting the distribution and abundance of the blue crab in Chesapeake Bay. Pp. 177–209. *In*: MAJUMDAR, S. K., L. W. HALL, JR., AND H. M. AUSTIN (eds.), Contaminant and Management of Living Chesapeake Bay Resources. The Pennsylvania Academy of Sciences, PA.

WASNO, R. M. 2006. Lee County Extension Agent, Florida Sea Grant, Fort Myers, Florida, FL, Pers. Comm.

YOE, C. E. AND K. D. ORTH. 1996. Planning Manual. IWR Report 96-R-21. U.S. Army Corp of Engineers, Water Resources Support Center, Alexandria, VA. http://www.iwr.usace.army.mil/iwr/pdf/96r21.pdf.

Florida Scient. 69(00S2): 140–151. 2006
Accepted: March 10, 2006

# A SIMULATION OF THE HURRICANE CHARLEY STORM SURGE AND ITS BREACH OF NORTH CAPTIVA ISLAND

Robert H. Weisberg and Lianyuan Zheng

College of Marine Science, University of South Florida,
140 7th Avenue South, St. Petersburg, FL 33701

Abstract: *A high resolution, three-dimensional numerical circulation model with flooding and drying capabilities is used to simulate the Hurricane Charley storm surge in the Charlotte Harbor vicinity. The model-simulated surge is in sufficiently good agreement with observations at four stations for which data exist to allow us to use the model to explain the surge evolution and to account for the inlet breach that occurred at North Captiva Island. Despite Charley being a Saffir-Simpson category 4 hurricane the surge was only of nominal magnitude and hence the damage, while severe, was primarily wind-induced. We explain the relatively small surge on the basis of the direction and speed of approach, the point of landfall to the south of Boca Grande Pass and subsequent translation up the estuary axis, and the collapse of the eye radius as the storm came ashore. These inferences are based on lessons learned from hypothetical hurricane storm surge simulations for Tampa Bay. Under other approach scenarios the potential for hurricane storm surge in the Charlotte Harbor may be catastrophic.*

*Key Words:* Hurricane Charley, storm surge, numerical simulation, inlet breach.

On August 13, 2004 Hurricane Charley made landfall near North Captiva Island, traveled up the Charlotte Harbor estuary, and made landfall again at Punta Gorda, as the first of four devastating hurricanes to sweep across the State of Florida that year. Wind damage was severe for both the coastal and the inland communities that came under Charley's path. However, despite its Saffir-Simpson scale rating of category 4 the damage by storm surge was modest. Here we provide a simulation of the Hurricane Charley storm surge and explain, in view of the storm's strength, why the surge was relatively small. We also account for the breach at North Captiva Island that resulted in a new inlet being cut there (Fig. 1).

Storm surge refers to the rise in sea level that may accompany a severe storm. Surges, or conversely sea level depressions, may result from both tropical and extra-tropical storms. Storm surges are generally associated with tropical storms since these tend to have the strongest winds causing the largest surges. Yet, observations show either higher or lower than normal sea levels, especially in fall through spring months, when extra-tropical systems (synoptic scale weather fronts) regularly transit the Florida peninsula. These weather-induced sea level variations come about by a number of processes that require explanation in order that the more severe instances of hurricane storm surge may be understood.

Sea level varies due to tides, seasonal steric effects, atmospheric pressure, and winds. Other deep-ocean influences may also be felt locally through the propagation of planetary waves (e.g., Sturges and Hong, 2001), or by long gravity waves in the

FIG. 1. Coastline of the North Captiva Island on September 21, 2001 (left panel) and on August 16, 2004 (right panel) after Hurricane Charley made landfall (A. Sallenger, personal communication).

case of a Tsunami. Here we concern ourselves with astronomical tides, seasonal steric effects, atmospheric pressure, and winds. Tides are well represented for the west coast of Florida by existing tidal models, e.g., for the full Gulf of Mexico in the ¼° resolution global model of Tierney and co-workers (2000) and for the west Florida shelf in the higher resolution regional model of He and Weisberg (2002). Steric effects are due to seasonal heating and cooling that alters seawater density and hence the water volume. This amounts to about plus or minus 20 cm for the Gulf of Mexico, with the highest (lowest) elevations occurring in late summer (winter).

Atmospheric pressure affects sea level through the "inverted barometer effect" by amount equal to 1 cm per mbar of pressure variation. Thus if pressure decreases locally sea level will rise, and this adjustment occurs rapidly through long gravity wave propagation at speed $(gH)^{1/2}$, where g is the acceleration of gravity and H is the water depth. Typical pressure fluctuations are a few mbar, and even under the most extreme hurricanes the inverted barometer effect is only about 100 cm so this alone cannot account for observed surges.

Wind effects arise by both the along shore and across shore components of wind stress, with their relative importance depending on the water depth and the duration over which the wind blows. In deep water, and due to the Earth's rotation, the net transport of water by the wind occurs at a 90° angle to the right (in the northern hemisphere) of the wind. If this transport impinges on a coast, water will pile up along the coast. Thus an along shore component of wind stress will cause a storm surge (depression) if the coast is to the right (left) of the wind. For instance, in advance of cold fronts, when the winds are from the south, we see higher than normal tides on the west coast of Florida, and, conversely, on the trailing side of cold fronts, when the winds are from the north, we see lower than normal tides.

Since these wind-normal transports are a consequence of the Earth's rotation (via the Coriolis force) it takes about a pendulum day ($2\pi/f = 12$ hr/sin$\phi$), or about 1 day along the west coast of Florida (since the latitude $\phi$ is about 30°) to set up the response. The amount by which sea level may rise depends on the magnitude of the along shore current produced by the along shore winds. The relevant force balance is between the pressure force due to the across shore slope of the sea surface, $\eta_x$, and the Coriolis force due to the along shore current, v. Thus $fv = \rho g \eta_x$, where $\rho$ is the water density and f is the Coriolis parameter. Even under very strong winds it is rare for v to exceed about 100 cm/s because of bottom friction, and, consequently, if the slope begins about 100–200 km offshore the surge by the along shore wind stress component may be about 60–120 cm. Moreover, the winds must blow for about a day for this to be fully realized. So while the along shore component of wind stress accounts for the sea level surges of a few feet, as synoptic weather fronts go by, it can only account for a portion of the surge by tropical storms. Here the onshore component of wind stress is the main culprit.

The across shore component of wind stress increases in importance as the water depth decreases since this bottom stress diminishes the Coriolis tendency for transport to be to the right of the wind. Hence winds blowing onshore over shallow water will pile water up along the coast, and conversely. The force balance is between the pressure gradient force due to the across shore slope of the sea surface and the vertical stress gradient. Thus $\rho g \eta_x = \tau_z$, where $\tau_z$ is the vertical stress gradient. Integrating over depth results in $\rho g H \eta_x = \tau^w - \tau^b$, where the superscripts, w and b, denote wind and bottom stresses, respectively. This shows that the across shore sea surface slope is directly proportional to the wind stress and inversely proportional to the water depth. The shallower the water, the larger the sea surface slope, and the farther upslope the larger the surge. Hence broad, shallow continental shelves, and especially long estuaries, are more prone to large surge than narrow, deep continental shelves. It also takes a certain amount of time to drive water from one point to another, thereby establishing the surface slope, so winds must blow over a given region for several hours to develop the slope and hence the storm surge.

In summary, a storm surge comes about by atmospheric pressure, along shore wind stress, and across shore wind stress. For extra-tropical systems the first two are generally the most important, whereas for tropical systems it is the last of these that accounts for the bulk of the storm surge. Not mentioned yet, nor quantitatively treated herein, are the wind induced surface gravity waves whose effects add to the storm surge.

With storm surge entailing several contributors that are each geometry and time scale dependent, its simulation cannot be generalized. Required are three elements: 1) a physics-based model, 2) a supporting data set on water depths and land elevations, and 3) wind and surface pressure fields to drive the model. Elevations and water depths alone are insufficient since sea level does not rise and fall uniformly. Surge is the highly localized impact of surface slopes by the factors discussed above, and since surge is mostly in response to wind, the winds must be sufficiently accurate to drive the model. All three of these elements are available for the Hurricane Charley simulation. We use the finite volume coastal ocean model

(FVCOM) with flooding and drying capabilities developed by Chen and co-workers (2003). The model grid is overlain on a South Florida Water Management District (SFWMD), merged bathymetric/topographic data set provided by T. Liebermann (personal communication, 2004). For winds and pressure we combine available data with an analytical expression for the structure of a hurricane (Holland, 1980) since there are never enough data to fully specify the wind field for any given storm.

Section 2 describes the model and its implementation for Hurricane Charley. The evolution of the modeled surge is given in Section 3 along with comparisons to the existing data. It is here that we also provide the mechanism by which an approximate 450 m wide breach occurred on North Captiva Island. Section 4 discusses these findings in the light of what we learned from previous Tampa Bay region simulations and offers a set of conclusions.

Model Description and Configuration—There are basically three types of numerical model constructs that may be used for simulating storm surges: finite difference, finite element, and finite volume, all differing in how they organize their grids and how they solve the governing equations of motion. The FVCOM, a finite volume model, combines the attributes of both finite difference and finite element models. As in finite element models it uses a non-overlapping unstructured triangular mesh for high horizontal resolution where needed, but it solves the hydrodynamic equations by finite-differences, using a flux calculation integrated over each grid control volume. This assures the conservation of mass, energy, salt, and heat in both the individual grid cells and over the entire computational domain, even for long integrations. An application of the FVCOM to the baroclinic, three-dimensional and time dependent circulation of the Tampa Bay estuary is given by Weisberg and Zheng (2006a), and Weisberg and Zheng (2006b) used the FVCOM for hypothetical hurricane storm surge simulations of Tampa Bay, results of which will be discussed in section 4.

The FVCOM domain used here (Fig. 2) extends from the Mississippi River delta in the north to the Florida Keys in the south, with an open boundary arching in between. Model resolution increases from the deep-ocean toward the Charlotte Harbor region. The highest resolution of about 80 m (a zoomed-in view is also provided in Figure 2) is centered on the barrier islands, where Hurricane Charley initially made landfall. Within the estuary the resolution is less than 300 m, and the lowest resolution is about 20 km along the open boundary. The reason for a large model domain is to allow for running different hurricane scenarios for storms approaching from different directions. For the transition from ocean to land the model domain extends landward to the 10 m elevation contour. A total of 63077 triangular cells with 31821 nodes comprise the horizontal, and 31 uniformly distributed sigma coordinate layers comprise the vertical. The model grid is superimposed on the 30 m resolution SFWMD, merged bathymetric/topographic data set (Fig. 3). We use mean sea level as a datum, and we set the sea wall height at 1.2 m elevation. Therefore a minimum 1.2 m surge is required to cause flooding in this model. While the model is capable of baroclinic simulations we ran it with constant density for the hurricane storm surge simulations since observations show that high winds and heat flux rapidly lead to vertically well-mixed density. Three-dimensionality nevertheless remains important since this determines the bottom stress.

Given the model, supported by high-resolution bathymetry and topography, hurricane storm surge simulation requires sufficiently accurate atmosphere forcing fields (winds and pressure). We used the analytical expression for the structure of a prototypical hurricane developed by Holland (1980) since actual measurements over the evolution of any storm are sparse and error prone. This prototypical hurricane construct requires information on the eye radius, the central pressure, and the maximum wind speed, and these information, along with the storm track, were obtained at three-hour intervals from the National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center (NHC) website. We further modified the storm track for consistency with local Doppler radar images. Figure 4 shows the track, eye radii, central pressures and maximum wind speeds employed, and Figure 5 gives an example of the prototypical hurricane wind and pressure distributions corresponding to the time when the eye passed over Punta Gorda, Florida. Such distributions were calculated for every model time step (at 20 sec

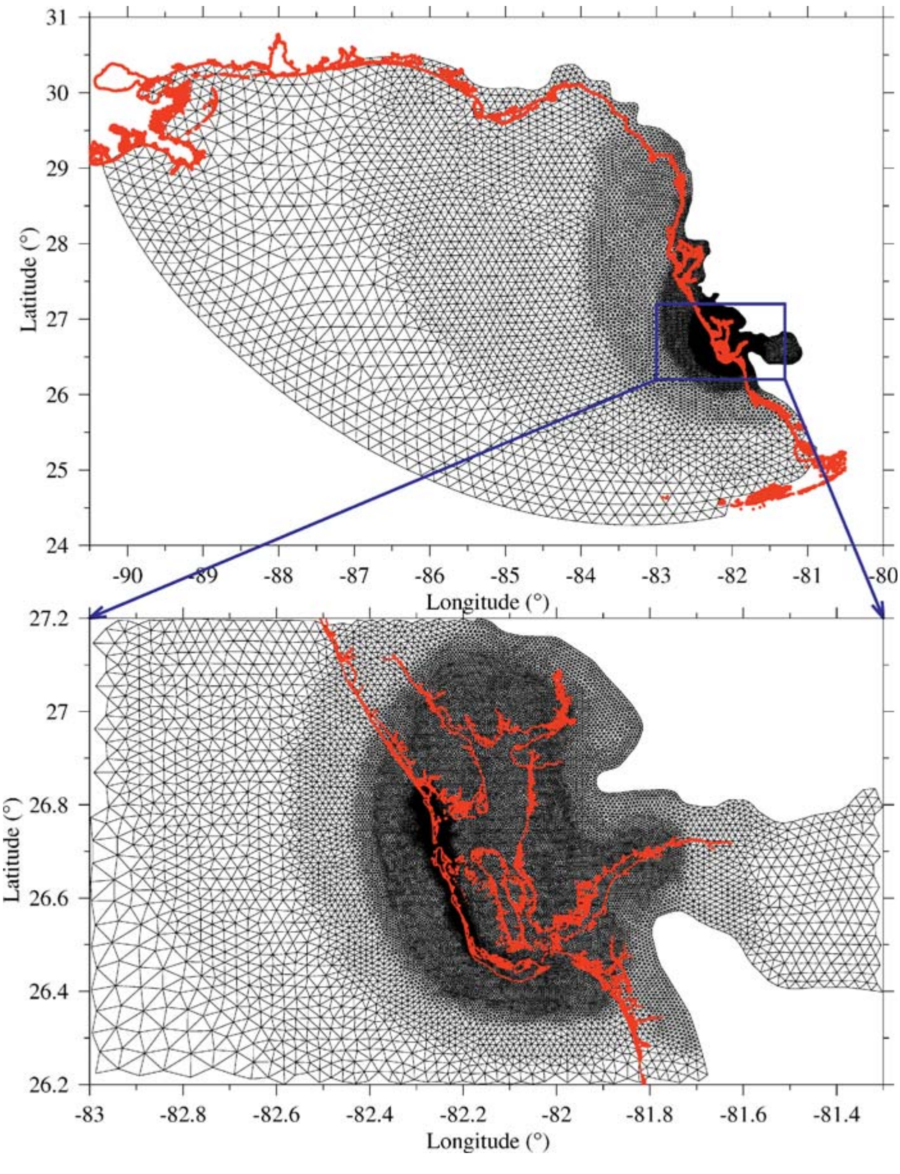



FIG. 2. The non-overlapping, unstructured triangular grid used in this simulation (upper panel) and its zoomed view focusing on Charlotte Harbor vicinity (lower panel).

intervals) by linearly interpolating between the three-hourly NOAA NHC data. In this way we were able to model the Hurricane Charley surge using winds and pressure that systematically varied as the storm approached and transited across the Charlotte Harbor region. Drawbacks to this approach are that the Holland (1980) prototypical storm is symmetric, whereas asymmetries occur in nature, and the actual winds contain a background field on which the storm is superimposed. These are of particular note after the storm passes since in the wake of a storm there tends to be a continuation of winds feeding it as it progresses away.

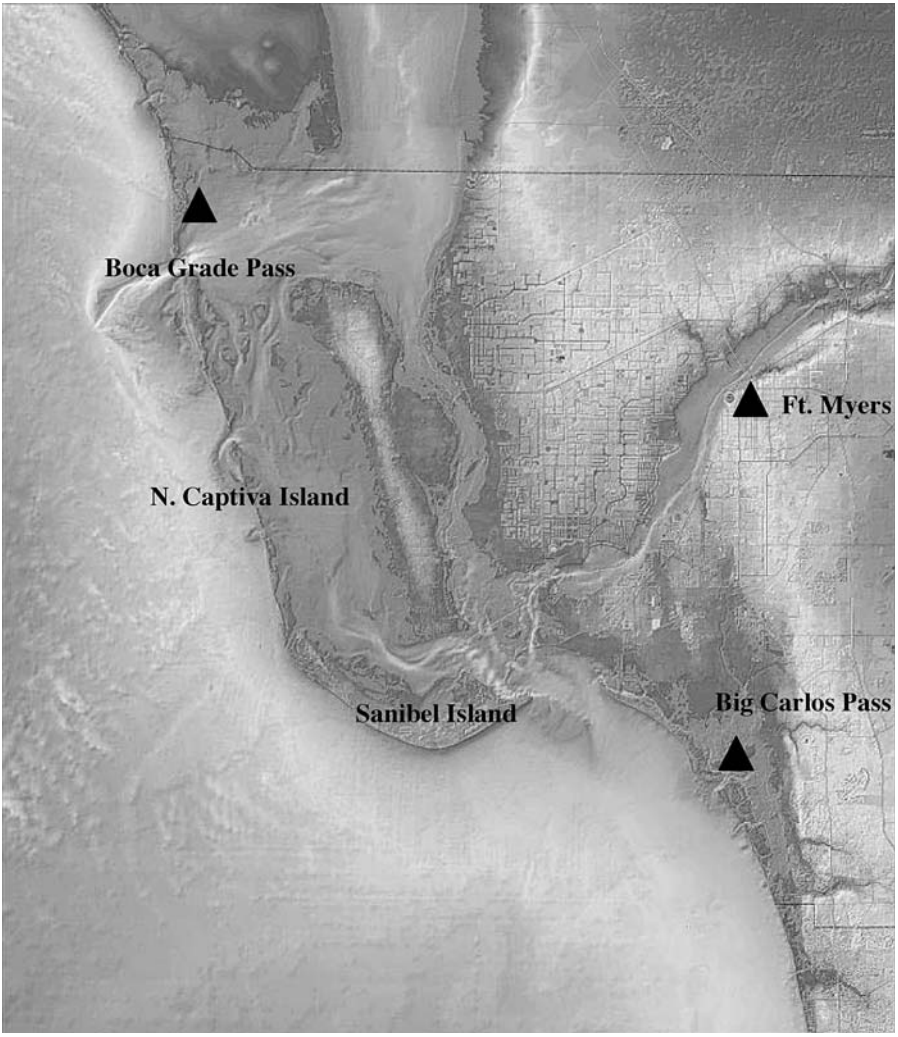



FIG. 3. The 30-m resolution bathymetric and topographic image. Triangles denote observed sea level stations used (Peace River station beyond image range).

HURRICANE CHARLEY STORM SURGE SIMULATION—The start time for the model run is 0300 UTC on August 13, 2004, when Hurricane Charley was positioned south of Cuba, and the end time is 2400 UTC on August 13, 2004, when the hurricane was positioned 140 km northeast of the study region. All future times will be referenced to UTC (local daylight savings time minus four hours). The model sea levels and currents were initialized as zero since the hurricane started far way from the model domain. Hurricane Charley entered the Gulf of Mexico at 1200 with an eye radius, central pressure, and maximum wind speed of 27.5 km, 967 mbar, and 48.8 m/s, respectively. At 1500 the hurricane veered right toward Charlotte Harbor

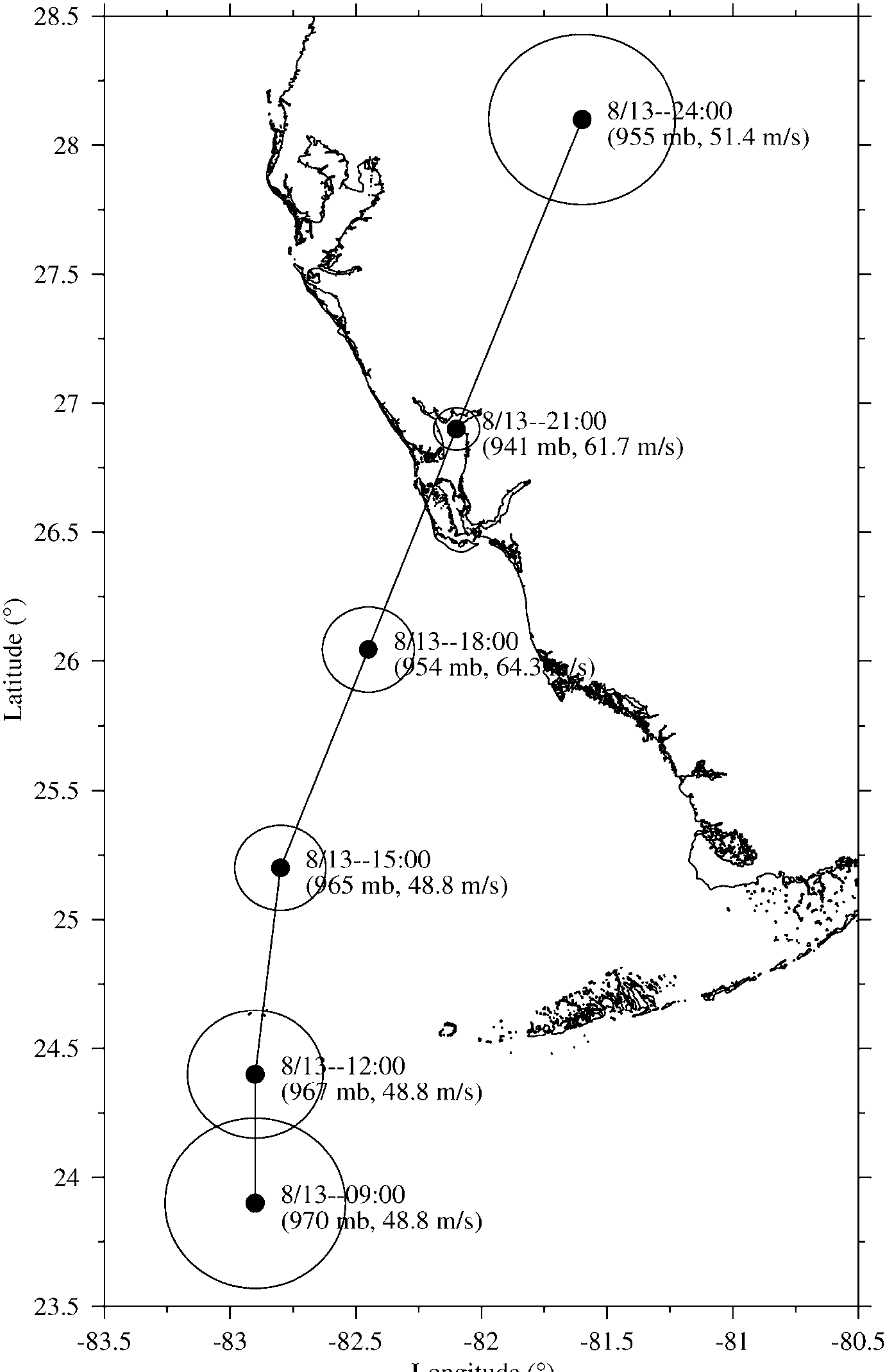



FIG. 4. The Hurricane Charley track along with eye radii, central pressures, and maximum wind speeds provided from NOAA NHC website.

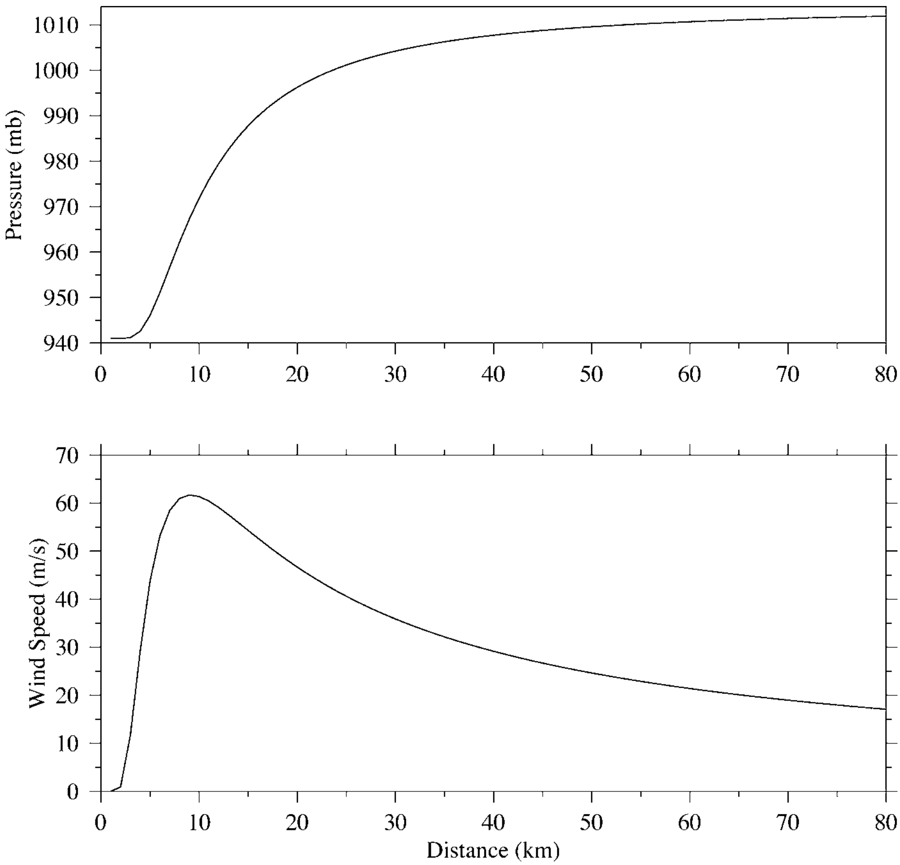



FIG. 5. Distributions of pressure (upper panel) and wind speed (lower panel) as a function of radial distance from the hurricane eye. These distributions are corresponding to the time when hurricane eye passes over Punta Gorda.

and started to intensify to category 4. From 1800 to 2100 the winds remained about the same while the eye radius decreased and the central pressure dropped to 10 km and 941 mbar, respectively. During this interval it made landfall near North Captiva Island, proceeded up the axis of the estuary, and passed over Punta Gorda.

Hurricane Charley moved very rapidly across the study region, taking about three hours to transit 100 km. Figure 6 shows the model simulated sea level evolution from 1900 to 2130 in half-hourly snapshots. Areas of sea level set up (storm surge) and set down are evident, but nowhere is the storm surge very large. The largest surge of about 250 cm occurred near Ft. Myers Beach at 2030. Beginning at 1900 when the hurricane eye is some 35 km southwest of North Captiva Island sea level is first set down on by about 100 cm in advance of the storm since the winds are directed offshore, and some draining is found around the shallow Pine Island Sound region. It is only within the hurricane eye where sea level is elevated by about 60 cm due to the

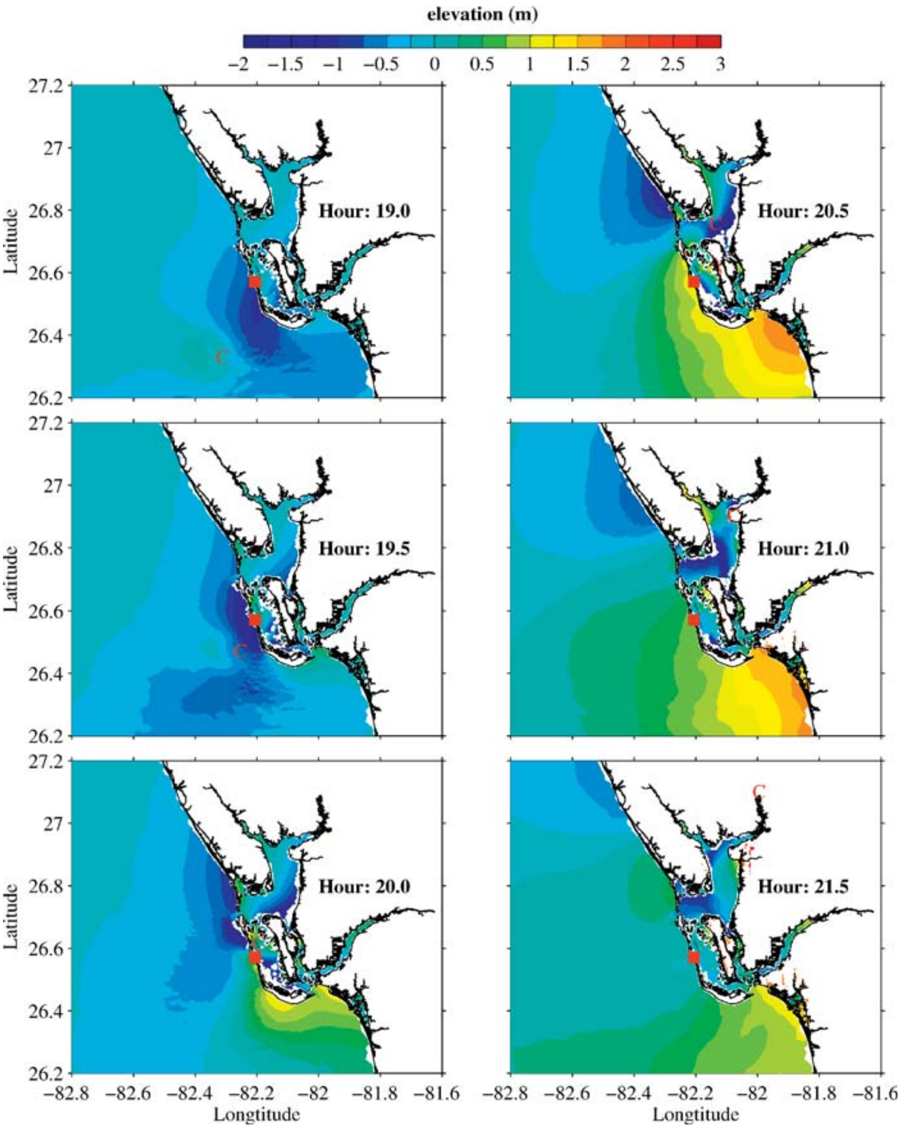



FIG. 6. Model simulated sea level evolution from 1900 to 2130 in half-hourly snapshots. The C denotes the hurricane eye location, and the filled square denotes the breach location on North Captiva Island.

inverted barometer effect. By 1930 the hurricane eye is within 15 km of landfall, additional draining occurs on both sides of the Captiva Islands and on the sound side of Sanibel Island. It is at this time when the maximum sea level depression of about 200 cm occurs on the gulf side of North Captiva Island, whereas sea level is increased on the sound side by approximately 50 cm, generating a seaward directed sea level gradient across the barrier island. Farther south from the hurricane eye we see sea level beginning to rise as winds blow onshore there. For example, the sea level at San Carlos Pass increases to about 50 cm.

Landfall occurred at 2000, at which time Figure 6 shows sea level to be elevated everywhere along the coast to the south of the eye, particularly at Sanibel (150 cm) and Ft. Myers Beach. To the north of the eye and within most of the Charlotte Harbor estuary sea level is set down, particularly on the east side with draining there, in Pine Island Sound, and on the gulf side of Cayo Costa Island. Some surge is beginning on the west side of the estuary, however.

By 2030 we see a significant change when the hurricane eye moves about half way up the axis of the estuary. The entire Captiva/Sanibel barrier island complex now has about a 100 to 150 cm surge, with the local maximum at North Captiva Island (the maximum recall is near Ft Myers Beach). More draining occurs on the east side of the estuary, and surge, although small, increases on the west side. Landfall at Punta Gorda occurs at 2100, but with a very small eye radius. With winds acting over a smaller region the surge offshore diminishes, and by 2130 sea level in this simulation is returning toward normal.

Explanations for why the Hurricane Charley storm surge was relatively small and also why an inlet was cut at North Captiva Island are both straight forward. Before providing these, however, it is important to lend some credibility to the analyses by comparing simulated with observed sea level elevations. Recorded data with sea level measures that are resolved by our model are limited to four stations: Ft Myers, Big Carlos Pass, Peace River, and Boca Grande Pass. The locations are shown in Figure 3. Data from the Ft. Myers gauge, located in the Caloosahatchee River, are provided by NOAA. The Big Carlos Pass data are from a University of South Florida, Coastal Ocean Monitoring and Prediction System station that was coincidentally deployed a few weeks prior to the event. The Peace River and Boca Grande Pass data are from US Geological Survey gauges. Because we simulated storm surge relative to mean sea level, adjustments must be made to correct for tide gauge datum, astronomical tides, and seasonal steric elevations. Datum corrections are based on tide gauge site surveys relative to the North American Vertical Datum of 1983, or NAVD83. Records of long enough duration were available at the Ft. Myers and Big Carlos Pass stations to perform a tidal harmonic analysis in order to subtract the astronomical tides from the record. Shorter records from the Peace River and Boca Grande Pass stations were not amendable to detiding so we adjusted our model datum to conform with the tidal phase at the time of maximum surge. Tides are not a major factor for two reasons. First the tidal range in the Charlotte Harbor vicinity is generally small and August 13, 2004 corresponded to neap tide. For all gauges we also made adjustment for the seasonal steric sea level obtained from an analysis of ten years of detided data. For the Hurricane Charley time period this amounted to 10 cm.

Figure 7 shows the resulting comparisons. Three time series are shown for the Ft. Myers and Big Carlos Pass stations: observed, datum adjusted sea level; detided sea level, or surge; and the simulated surge adjusted for the seasonal steric effect. Two time series are shown for the Peace River and Boca Grande Pass stations: observed, datum adjusted sea level, and the simulated surge adjusted for both the

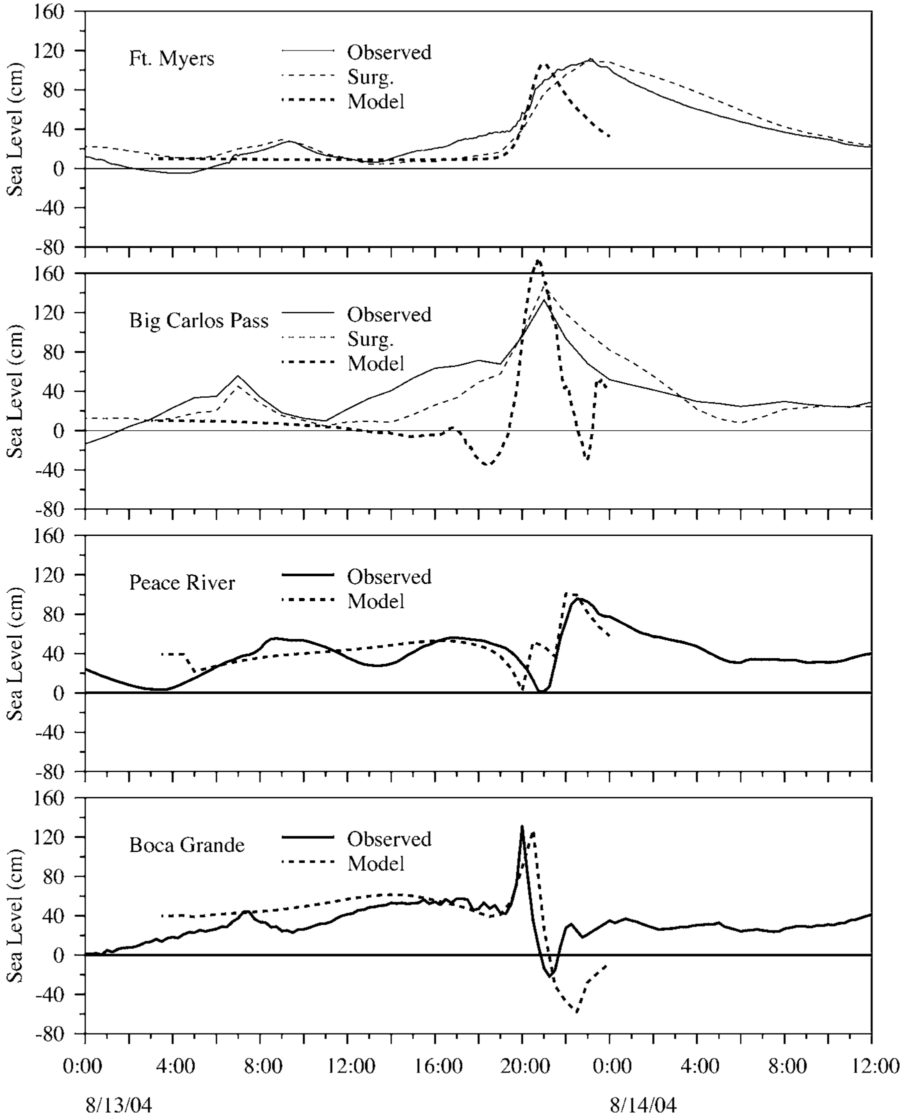



FIG. 7. Time series comparisons for observed and simulated sea levels at Ft. Myers, Big Carlos Pass, Peace River, and Boca Grande Pass. The thin-dashed lines are observed, detided sea levels; the solid lines are observed sea levels; and the thick-dashed lines are the simulated sea levels.

seasonal steric effect and the astronomical tidal elevation at the time of maximum surge. At each of these stations the maximum surge and the time of occurrence agree fairly well. Quantitatively, the differences between observed and simulated surges are –4 cm at Ft. Myers, 23 cm at Big Carlos Pass, 10 cm at the Peace River, and 5 cm at Boca Grande Pass, where positive (negative) denotes a model overestimate (underestimate). The time differences between observed and simulated surges are

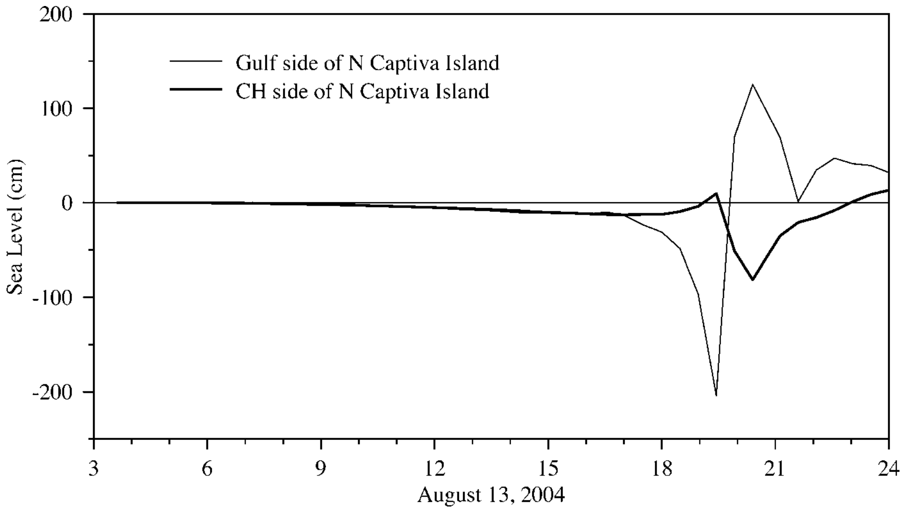



FIG. 8. Model simulated sea level time series sampled on the gulf (grey line) and sound sides (dark line) of the location in North Captiva Island where an inlet breach occurred.

less than one hour except at the Ft. Myers station, where the difference is about two hours. At Ft. Myers and Big Carlos Pass sea level remains elevated after the simulated surge abates. This may be a consequence of two factors. First, as mentioned earlier, hurricane winds tend to be asymmetric, with strong winds remaining in the wake of the storm that are not included in the simulation. Second, the simulation makes no provision for fresh water drainage. Despite these drawbacks the agreements in the maximum surge magnitudes and times (the two most important factors in storm surge prediction) between observed and simulated surges suggests that our Hurricane Charley storm surge simulation is sufficiently accurate. These results find additional support in the Florida State Emergency Operations Center website (http://floridadisaster.org/eoc/Charley04.asp), which states that the highest surge plus tide (and plus the steric sea level adjustment) was about 10–13 ft from Vanderbilt Beach (north of Naples) to the Lee County line. This agrees with our simulated estimate there of about 250 cm, or about 8.5 ft. The difference may easily be accounted for by wind wave run up not included in the model.

Given the veracity of the simulation we can now use it to explain the breach of North Captiva Island. Figure 8 shows model simulated sea level time series sampled on the gulf and sound sides of the location that was breached. As the hurricane approached and passed over this region we see an initially small depression of sea level on both sides followed by a large (200 cm) depression on the gulf side. Within an hour the sea level gradient across the island reversed such that the surge on the gulf side was 125 cm and the depression on the sound side was 90 cm. In total there was a sea level difference of more than 200 cm across a very narrow low-lying strip of island. This allowed for flow across the barrier island driven by a very large horizontal pressure gradient force. Once the breach began, sand transport then very rapidly eroded the barrier island, resulting in the new, 450 m wide inlet (Fig. 1).

DISCUSSION AND CONCLUSIONS—Having simulated the evolution of the Hurricane Charley storm surge and establishing some degree of credibility by comparing the simulation with observations it remains to explain why the surge was relatively small given the category 4 nature of the hurricane. There are five reasons for this that we developed based on simulations of hypothetical hurricanes making landfall in the Tampa Bay vicinity [Weisberg and Zheng (2006b), available at http://ocgweb.marine.usf.edu]. Using the same model strategy we considered the storm surges due to category 2 and 4 hurricanes, approaching Tampa Bay from different directions, at different speeds of approach, and making landfall at different locations. All of these factors are of importance to the evolution and magnitude of the surge. The point of landfall is important since, with winds blowing counterclockwise around the hurricane eye, the surge by onshore-directed winds occurs to the south of the eye for the west coast of Florida. North of the eye the winds are directed offshore and sea level is depressed. The speed of approach is important since it takes a finite amount of time to transport water from one point to another. Fast moving storms may yield lesser surge than slow moving storms since there may not be sufficient time to fully set up the sea surface slope that comprises the surge. The direction of approach enters in two ways. First, if the storm approaches from the south the affect of offshore-directed winds in advance of the eye initially sets sea level down. Hence when surge occurs it begins from a condition of depressed sea level. To the contrary, if the storm approaches from the north, sea level is set up directly. Hence surge magnitude increases for the west coast of Florida as the angle of approach rotates from southeast to northwest. Second, should the storm move up the axis of the estuary the tendency is to lower sea level on one side and raise sea level on the other side, effecting a redistribution of water mass in the estuary, versus a net increase in water mass. Finally, the physical dimension of the storm is also highly relevant. Large eye radii storms have large winds extending over larger areas than small eye radii storms.

All of these factors tended to mitigate storm surge for Hurricane Charley. The eye radius collapsed to a very small value (less than 10 km) as it made landfall, the storm approached from the southerly quadrant and proceeded directly up the axis of the Charlotte Harbor estuary, it moved very swiftly (about 18 kts), and it made landfall to the south of the largest pass, namely Boca Grande Pass. Thus despite its category 4 status, the size, approach speed, approach direction and movement up the estuary axis, and point of landfall all led to the relatively small surge.

In summary we applied a three-dimensional, high-resolution, finite-volume coastal ocean model with flooding and drying capabilities (the FVCOM of Chen et al., 2003) to simulate the Hurricane Charley storm surge in the Charlotte Harbor vicinity and to account for the new inlet breach at North Captiva Island. The model was supported by high-resolution, SFWMD bathymetry and topography data, and it was driven with prototypical hurricane wind and pressure distributions (Holland, 1980) using a NOAA NHC supplied storm track along with the eye radii, maximum wind speeds, and central pressures observed along the track. Comparisons with observed data, after appropriate adjustments for astronomical tides referenced to NAVD83 datum and seasonal steric effects, demonstrated the veracity of the simulation.

A 450-m wide new inlet that was cut across the narrowest portion of North Captiva Island was attributed to a sufficiently large gulf to sound directed sea level gradient that set up as the eye transited the island to the north of the breach. The region of largest storm surge (about 250 cm in our simulation and slightly larger than this in anecdotal emergency management narratives) occurred to the south of the Charlotte Harbor region near Ft. Myers Beach. The surge within the Charlotte Harbor estuary was relatively small in view of Hurricane Charley's category 4 status, and we attributed this finding to the direction and speed of approach, the point of landfall to the south of Boca Grande Pass, the translation of the hurricane up the estuary axis, and the compact eye radius. Despite this relatively small hurricane storm surge event (Hurricane Charley damage was primarily wind generated), we caution that the Charlotte Harbor region is highly susceptible to severe storm surge under other conditions. Had Hurricane Charley approached more slowly, from a more westerly to northwesterly direction and made landfall to the north of Boca Grande Pass with a larger eye radius, the storm surge would also have been catastrophic. These findings are based on simulations performed for prototypical category 2 and 4 storms conducted for the Tampa Bay region (Weisberg and Zheng, 2006b). Finally, while not included in these simulations wind waves also add to the storm surge and to the destructive power thereof.

ACKNOWLEDGMENTS—Support was provided by the U.S. Geological Survey, requisition #4-2090-1478 and by the Office of Naval Research, grant #N00014-02-1-0972 and N00014-05-1-0483. A. Sallenger (USGS Center for Coastal Studies, St. Petersburg, FL) provided helpful discussions along with Figure 1. C. Chen (University of Massachusetts, Dartmouth) graciously shared the FVCOM code. T. Liebermann (South Florida Water Management District) provided the bathymetric and topographic data. J. Donovan (University of South Florida) assisted with computer related matters. Finally, we thank our peer reviewers and the guest editors for their constructive comments and suggestions.

## LITERATURE CITED

CHEN, C. S., H. D. LIU, AND R. C. BEARDSLEY. 2003. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. J. Atmos. Oceanic Technol. 20: 159–186.

HE, R. Y. AND R. H. WEISBERG. 2002. Tides on the West Florida Shelf. J. Phys. Oceanogr. 32: 3455–3473.

HOLLAND, G. J. 1980. An analytic model of the wind and pressure profiles in hurricanes. Mon. Wea. Rev. 108: 1212–1218.

LIEBERMANN, T. 2004. South Florida Water Management District, Ft. Myers, FL, Pers. Commun.

STURGES, W. AND B. G. HONG. 2001. Decadal variability of sea level. Pp. 165–179. *In*: DOUGLAS, B. C., M. S. KEARNEY AND S. P. LEATHERMAN (eds.), Sea Level Rise: History and Consequences. Academic Press, San Diego.

TIERNEY, C. C., L. H. KANTHA, AND G. H. BORN. 2000. Shallow and deep water global ocean tides from altimetry and numerical modeling. J. Geophys. Res. 105: 11259–11277.

WEISBERG, R. H. AND L. Y. ZHENG. 2006a. Circulation of Tampa Bay driven by buoyancy, tides, and winds, as simulated using a finite volume coastal ocean model. J. Geophys. Res., 111, C01005, doi:10.1029/2005JC003067.

——— AND L. Y. ZHENG. 2006b. Hurricane storm surge simulations for Tampa Bay. Submitted to Estuaries.

Florida Scient. 69(00S2): 152–165. 2006
Accepted: March 10, 2006

# A PRELIMINARY EVALUATION OF AWARENESS, KNOWLEDGE, AND ATTITUDE IN ENVIRONMENTAL EDUCATION SPECIALISTS, INSTRUCTORS, STUDENTS, AND PARENTS IN SOUTHWEST FLORIDA

Ernesto Lasso de la Vega

Division of Ecological Studies and Social Sciences, College of Arts and Science,
Florida Gulf Coast University, 10501 FGCU Blvd S., Fort Myers, FL 33965-6565

Abstract: *Environmental education has been part of the curriculum in Southwest Florida public schools. Curriculum objectives, such as environmental awareness, knowledge, and attitude, have been investigated in the literature as ways to improve the overall behavior of future citizens toward the environment. The purpose of this study was to conduct a preliminary evaluation of the aforementioned objectives among the following groups: environmental education specialists, high school instructors, high school students, and the parents of the corresponding students in three Southwest Florida counties. The returned surveys represented responses from 27 environmental education specialists, 15 high school instructors, 224 high school students, and 222 parents. This study found significant differences among the groups regarding the levels of environmental awareness, knowledge, and attitude. The environmental education specialists scored the highest for these components as compared to the lowest levels presented by parent awareness, parent attitude, and high school student knowledge. In addition, demographic factors such as socioeconomic status and preference of leisure activities resulted in differences among the groups. This study presents an alternative for the usually independent evaluation of awareness, knowledge, and attitude as an appropriate approach to the evaluation of environmental curriculum objectives.*

*Key Words:* Attitude, knowledge, awareness, environmental education, high school, evaluation

Environmental education (EE) has interested school systems, local communities, the private sector, and local governments. These organizations request that schools include EE in the curriculum of K-12 education, but a plan to establish an EE curriculum that unifies an effective approach to teaching environmental education is lacking (Wilke, 1997). Most programs, according to the North American Association of Environmental Educators (NAAEE) (Ballard and Pandya, 1990), rely on a series of environmental activities that can be incorporated into any course within an existing curriculum. Such approaches are called "an interdisciplinary infusion of environmental topics" and typically crowd an already full curriculum (Disinger, 1997).

The Intergovernmental Conference on Environmental Education: Tbilisi (USSR) (UNESCO, 1978) recommended in the Tbilisi Declaration the primary goals and objectives of an environmental education curriculum as follow: (a) awareness, (b) knowledge, (c) attitudes, (d) skills, and (e) participation. While these objectives have been cited by many authors in the last decade (Callicott and Rocha, 1996; Gough, 1997; Palmer, 1998; Athman and Monroe, 2000; Day and Monroe, 2000), not all authors agree upon the relative importance of the objectives. However, there are recurring objectives that are mentioned frequently in the literature, specifically *awareness, knowledge*, and *attitude* (Hungerford and Peyton, 1994; Palmer, 1998).

These three components affect students throughout their lives, both inside and outside the classroom. According to the NAAEE, awareness is an important goal in EE between kindergarten and 3rd grade. Knowledge is an important goal from 3rd through 9th grade, and attitude is important throughout the entire educational career (Ballard and Pandya, 1990).

Research has been conducted to evaluate these objectives in EE focusing mostly on the level of knowledge and attitude in students (e.g., Armstrong and Impara, 1990, 1991; Gigliotti, 1992; Knapp, 1996; Zimmermann, 1996; Salmivalli, 1998; Worsley and Skrzypiec, 1998; Ma and Bateson, 1999), instructors (e.g., Shuman and Ham, 1997; Moseley et al., 2002), both students and parents (e.g., Musser and Diamond, 1999; Rovira, 2000), and adults alone (e.g., Schahn and Holzer, 1990; Arcury and Christianson, 1993; Van Es et al., 1996; Morrone et al., 2001; Cottrell, 2003). Sometimes attitude has been interpreted as behavior (e.g., Pooley and O'Connor, 2000), whereas awareness has been interpreted as concern (e.g., Krause, 1993), or distinctively as different (e.g., Hausbeck et al., 1992). Despite the apparent difference in terminology a broad consensus generally accepts the principles, goals and objectives of the Tbilisi Declaration (Palmer, 1998 p. 135).

For the purpose of this study the definitions of awareness, knowledge, and attitude (AKA) are in accordance with the Tbilisi Declaration as follows. Awareness is to help social groups and individuals acquire an awareness of and sensitivity to the total environment and its allied problems. Knowledge is to help social groups and individuals gain a variety of experience in, and acquire a basic understanding of, the environment and its associate problems. Attitude is to help social groups and individuals acquire a set of values and feelings for the environment, and the motivation for actively participating in environmental improvement and protection (UNESCO, 1978 pp. 26–27).

The purpose of this study was to evaluate the levels of the three components among participants involved with EE curriculum in high schools in Southwest Florida. This evaluation measured the levels of AKA among EE specialists, high school instructors who teach components of EE in their curriculum, senior high school students enrolled in their classes, and the parents of these students. In addition, the study explores how well socioeconomic, demographic, and personal background factors account for differences in the levels of AKA.

METHODS—The study was conducted during the spring semester of the 2003–2004 school year with volunteers involved with EE in Lee, Charlotte, and Hendry counties. Surveys were distributed after the corresponding counties' school boards granted permission. The same survey was used to compare findings among the participants. To optimize the rate of return the study utilized distribution and collection methods recommended by Dillman (2000). No remuneration was granted to the participants except in cases where extra credit was given to students for completing the survey and returning it on time.

TABLE 1. Number of surveys distributed and returned per county and number of high schools and H.S. students per county. Stars represent data from the Florida Department of Education (2003).

| Group | County | Number of H.S. per County* | Number of H.S. Students per County* | Surveys Issue | Surveys Returned | % Return |
|---|---|---|---|---|---|---|
| EE specialists | no distinction | | | 55 | 27 | 49 |
| H.S. instruct. | Lee | | | 12 | 10 | |
| | Charlotte | | | 3 | 3 | |
| | Hendry | | | 2 | 2 | |
| Subtotal | | | | 17 | 15 | 88 |
| H.S. students | Lee | 10 | 16500 | 277 | 167 | |
| | Charlotte | 4 | 6500 | 50 | 30 | |
| | Hendry | 2 | 3000 | 38 | 27 | |
| Subtotal | | | | 365 | 224 | 61 |
| Parents | Lee | | | 277 | 167 | |
| | Charlotte | | | 50 | 30 | |
| | Hendry | | | 38 | 25 | |
| Subtotal | | | | 365 | 222 | 61 |
| Total | | | | 802 | 488 | 61 |

*The participants*—Four volunteer groups participated in the study. The first group, (EE specialists) consisted of representatives and coordinators of EE programs in their respective schools. The second group (H.S. instructors) consisted of educators of senior level courses who introduced environmental concepts in the curriculum of their discipline. These instructors were science teachers or teachers of other subjects. The third group (H.S. students) consisted of students willing to participate in the study from the instructors' classes. They returned the survey anonymously in a return envelope along with the answers of the fourth group. The fourth group (Parents) consisted of one of the legal guardians of each participating student.

A total of 802 surveys were issued among the sample population. Fifty-five surveys were issued to the EE specialists using the mail distribution system of the school board of Lee County. The responses of H.S. instructors, H.S. students and parents were collected from five high schools from a total of ten located in Lee County, one high school from a total of four in Charlotte County, and one from a total of two high schools in Hendry County. Table 1 presents details of the numbers of surveys distributed and returned in the study along with the corresponding number of schools and population of students per county enrolled in 2002–2003 according to the Florida Department of Education (2003).

*The instrument*—The evaluation tool was developed by adapting surveys and questionnaires from Dunlap and co-workers (2000), La Trobe and Acott (2000), Morrone and co-workers (2001), Marcinkowski (1997), and Bogan and Kromrey (1996). These studies were selected because of their contemporary content and their reported reliability.

The survey used in this study consisted of 80 questions (81 for parents' instruments) with four different modalities of questions: (1) four point Likert response scale, (2) true/false questions (agree or disagree), (3) multiple choice questions, and (4) selection of the proper response. Questions relevant to measuring AKA were similar in all participants' surveys. Questions regarding demographic information were the same except in those cases which characterize the group of the participant (see Lasso de la Vega (2004) for complete discussion).

*Awareness*—The first set of questions measured the influences of the family and authoritative figures regarding environmental issues. The scores ranged from 1 = Never, 2 = Seldom, 3 = Often, to 4 = Very Often. High scores indicated a person with strong influences and extensive degree of awareness. The second set of questions measured perception of local environmental conditions or issues in Southwest

*Please indicate how often you have had the following experiences by circling the option that best represents you.*
1 = Never 2 = Seldom 3 = Often 4 = Very Often

1. Participating in outdoor experiences such as camping and fishing.
2. Having your parents or grandparents encourage you to care for the environment.
3. Having a teacher encourage you to care for the environment.
4. Watching television programs with an environmental message.

*Please indicate how you feel local environmental issues have become since you have lived here.*
1 = Much Worse 2 = Worse 3 = Better 4 = Much Better

1. The water quality in your local streams, rivers, and lakes.
2. The level of pollution or waste produced by nearby businesses, farms, and industries.
3. The misuse of chemicals such as fertilizers and pesticides.
4. The number of exotic animals and plants.

*Please indicate how concerned you are about the following environmental issues in Southwest Florida.*

1 = Not concerned at all
2 = Somewhat concerned
3 = Concerned
4 = Very concerned

1. The conditions of wetlands and nature preserves.
2. Water shortage.
3. Solid waste management.
4. Endangered species.

FIG. 1. Examples of questions in the survey inquiring about Awareness.

Florida. The scores ranged from 1 = Much Worse, 2 = Worse, 3 = Better, to 4 = Much Better. Scores in this group of questions described a general perception without compromising the knowledge of those surveyed. The third set of questions measured the level of concern about environmental issues. Scores ranged from 1 = Not Concerned at all, 2 = Somewhat Concerned, 3 = Concerned, to 4 = Very Concerned. High scores indicated a person with strong concerns about diverse environmental issues. Examples of the questions measuring awareness are presented in Figure 1.

*Attitude*—The next set of questions measured the respondent's balance between social responsibility and environmental interest, government regulations, and political actions taken to protect the environment. The survey measured attitude using questions modified from Dunlap and co-workers (2000) with a four point Likert response scale (1 = Strongly Disagree, 2 = Disagree, 3 = Agree, and 4 = Strongly Agree) to measure the attitudes toward the environment. The questions alternate statements that classify a participant's attitude from a pro-environmental to an anthropocentric point of view following methodology described by Dunlap and co-workers (2000). Examples of the questions measuring attitude are presented in Figure 2.

*Knowledge*—Another series of questions measured respondents' basic ecological concepts and knowledge of regional issues. These questions measured knowledge using true/false (1 = Agree or 2 = Disagree) questions. Two multiple-choice questions asked participants to choose from a list of nine, the first and second most important environmental issues facing Southwest Florida. Answers for this section of the instrument were compared to the rankings from responses of surveys with the same questions given to a panel of research biologists, university instructors of environmental science, government planners, and officials. Examples of the questions measuring knowledge are presented in Figure 3.

The rest of the instrument measured the participant's demographics. These questions were intended to determine the following demographic characteristics: (1) present urbanicity, (2) antecedent urbanicity,

*Please indicate how much you agree or disagree with the following statements.*
1 = Strongly Disagree  2 = Disagree  3 = Agree  4 = Strongly Agree

1. We are approaching the limit of the number of people the Earth can support.
2. Humans have the right to modify the natural environment to suit their needs.
3. When humans interfere with nature it often produces disastrous consequences.
4. Science and technology can overcome any environmental problem.
5. Humans are severely abusing the environment.
6. The Earth has plenty of natural resources if we just learn how to develop them.
7. Plants and animals have as much right as humans to exist.
8. The balance of nature is strong enough to cope with the impacts of modern industrial nations.
9. Despite our special abilities humans are still subject to the laws of nature.
10. The so-called "ecological crisis" facing humankind has been greatly exaggerated.
11. The Earth has very limited room and resources.
12. Humans were meant to rule over the rest of nature.
13. The balance of nature is very delicate and easily upset.
14. Maintaining economic growth is more important than protecting the natural environment.
15. If things continue on their present course, we will soon experience a major ecological catastrophe.

FIG. 2. Examples of questions in the survey inquiring about Attitude. Adapted from Dunlap et al. (2000).

(3) years living in Southwest Florida, (4.1) field of instruction (for EE specialists and H.S. instructors only), (4.2) field of interest (for H.S. students only), (4.3) career orientation (for parents only), (5) entertainment preferences, (6) gender, (7) ethnicity, and (8) socioeconomic status (for parents only). Questions measuring demographic information are presented in Figure 4. Socioeconomic information was collected from the parent group only. The scale of annual income was: <$15,000, between $15,000 and $29,999, between $30,000 and $44,999, between $45,000 and $59,999, and >$60,000.

DATA ANALYSIS—Data were entered into a research database utilizing the *Statistical Package for the Social Sciences: Graduate Pack 11.0 for Windows* (SPSS

*Do you Agree or Disagree with each of the following statements?*
1 = Agree  2 = Disagree

1. Saving endangered plant species is just as important as saving endangered animal species.
2. The most effective way to save an endangered animal is to establish a large enough reserve for it to live and reproduce.
3. As the population in an area increases, the potential for pollution decreases.
4. Manatees should be protected because they control the water hyacinth.
5. Most water for human consumption in Florida comes from rivers and lakes.

1. What do you think is the single most important environmental issue facing Southwest Florida? *Please circle one.*

| | | |
|---|---|---|
| a. Water pollution | b. Endangered species | c. Exotic plants or animals |
| d. Wetland destruction | e. Water shortage | f. Air pollution |
| g. Unlimited development | h. Solid waste | i. Other _____ |

2. What is the 2nd most important environmental issue facing Southwest Florida? *Please circle one.*

| | | |
|---|---|---|
| a. Water pollution | b. Endangered species | c. Exotic plants or animals |
| d. Wetland destruction | e. Water shortage | f. Air pollution |
| g. Unlimited development | h. Solid waste | i. Other _____ |

FIG. 3. Examples of questions in the survey inquiring about Knowledge.

1. Which of the following alternatives characterize your living area?

a. Rural (not so populated) b. Urban (very populated)

2. Which of the following alternatives characterize where you grew up?

a. Rural (not so populated) b. Urban (very populated)

3. How many years have you lived in Southwest Florida?

a. less than 5 years b. 5 and under 10 years
c. 10 and under 20 years d. More than 20 years

4.1 What curriculum do you teach regularly? (EE Specialist and HS Instructors only)

a. Science b. Social science
c. Arts d. Literature
e. Math g. Other: ___.

4.2 What career field are you interested? (Student only)

a. Science b. Social science
c. Arts d. Literature
e. Math f. Undecided
g. Other: ___.

4.3 What category will describe your career orientation? (Parent only)

a. Social services b. Business
c. Agro business d. Health services
e. Education f. Government
g. Construction / development h. Other: ___.

5. Which is your most preferred activity for entertainment?

a. Sports
b. Outdoor activities such as camping, fishing, boating, etc.
c. Indoor activities such as reading, watching TV, computers, etc.
d. Social activities
e. Gardening
f. Other: ___.

FIG. 4. Questions regarding the Demographics of the participants.

Inc., 2001). Significance for the statistical measures was determined at the 0.05 alpha level. A comparison of the participating groups regarding the levels of awareness, knowledge, and attitude was conducted using a multiple comparison one-way analysis of variance (ANOVA). In order to determine how well socioeconomic, demographic, and personal background factors account for differences in the levels of AKA, multiple comparison one-way ANOVA tests were performed for each nominal independent variable (socioeconomic, demographic, and personal background factors) and the dependent variables (awareness, knowledge, and attitude) among the groups. *Post hoc* multiple comparison analyses using the Scheffé test was conducted when variables presented significant differences.

RESULTS—*Awareness, knowledge, and attitude*—The mean percentages of AKA for the four groups are presented in Table 2. Environmental education specialists scored higher than the other groups regarding awareness, knowledge, and attitude. The results of the ANOVA showed a significant difference on the levels of

TABLE 2. Mean percentage of awareness knowledge and attitude (standard deviation) and significant differences for EE Specialists, H.S. Instructors, H.S. Students, and Parents.

| Group | Number | Awareness | Knowledge | Attitude |
|---|---|---|---|---|
| EE Spec. | 27 | 69 (7.9) | 70 (12.1) | 78 (10.0) |
| H.S. Instr. | 17 | 61 (17.0) | 69 (21.2) | 73 (22.2) |
| H.S. Stud. | 226 | 64 (13.4) | 58 (19.3) | 69 (14.8) |
| Parents | 224 | 59 (19.8) | 58 (24.0) | 64 (21.8) |

dependent variables, awareness ($F_{3,490} = 5.12$, $p \leq 0.05$), knowledge ($F_{3,490} = 4.11$, $p \leq 0.05$), and attitude ($F_{3,490} = 7.02$, $p \leq 0.05$) for the participating groups. An examination of the *post hoc* analysis revealed significant differences between the mean of AKA for the specific groups. Parents displayed lower mean percentage levels of awareness (59%) than the H.S. students (64%) and the EE specialists (69%). Similar findings were found for the mean percentage of attitude for the parents (64%) when compared to higher scores of the H.S. students (69%) and the EE specialists (78%). With respect to knowledge, the *post hoc* analysis revealed significant differences when comparing only the lowest levels among the H.S. students' scores (58%) and the highest levels among EE specialists (70%). There were no significant differences between the AKA levels of the EE specialists and the H. S. instructors. The *post hoc* analyses are summarized in Table 3.

*Socioeconomic, demographic, and personal background*—A summary of the differences among the demographic variables in respect to AKA across the groups is presented in Table 4. The analysis of variance using income as an independent variable and the percentages for AKA in the parents group did not present a significant difference for awareness ($F_{4,176} = 0.78$, $p > 0.05$) or knowledge ($F_{4,176} = 2.35$, $p > 0.05$). However, there was a significant difference for attitude ($F_{4,176} = 4.28$, $p \leq 0.05$). Further examination of the *post hoc* analysis revealed that parents with an annual income of <\$15,000 scored significantly lower in attitude level (59%) when compared to those parents with an annual income between \$15,000 and \$29,999 (70%), between \$30,000 and \$44,999 (70%), and >\$60,000 (73%).

There was no significant difference when comparing entertainment activities with levels of awareness ($F_{5,457} = 1.65$, $p > 0.05$) among the participant groups. However, there was a significant difference for knowledge ($F_{5,457} = 3.29$, $p \leq 0.05$) and attitude ($F_{5,457} = 4.14$, $p \leq 0.05$). The *post hoc* analysis for the mean difference of knowledge revealed that the difference resides among the scores of those who prefer outdoor activities (68%) with higher scores than those who prefer social activities (59%) as forms of entertainment. The *post hoc* analysis also showed that levels of attitude in individuals who found gardening (77%) as the choice of entertainment scored higher attitude levels than those who chose sports (69%) as a form of entertainment. There was no significant difference when comparing gender and urbanicity with awareness, knowledge, and attitude among all the participant groups.

DISCUSSION—This study was limited by the lack of estimation of an appropriate

TABLE 3. Post Hoc multiple comparisons analysis for AKA across the 4 groups. Stars represent significance at the 0.05 alpha level.

| Dependent Variable | (I) Group | (J) Group | Mean Difference (I − J) | Std. Error | Sig. |
|---|---|---|---|---|---|
| Awareness | EE Specialist | H.S. Instructor | 8.2 | 5.1 | 0.47 |
| | | H.S. Student | 5.8 | 3.4 | 0.39 |
| | | Parent | 10.6* | 3.4 | 0.02 |
| | H.S. Instructor | EE Specialist | −8.2 | 5.1 | 0.47 |
| | | H.S. Student | −2.3 | 4.2 | 0.96 |
| | | Parent | 2.4 | 4.2 | 0.95 |
| | H.S. Student | EE Specialist | −5.8 | 3.4 | 0.39 |
| | | H.S. Instructor | 2.3 | 4.3 | 0.96 |
| | | Parent | 4.7* | 1.6 | 0.03 |
| | Parent | EE Specialist | −10.6* | 3.4 | 0.02 |
| | | H.S. Instructor | −2.4 | 4.2 | 0.95 |
| | | H.S. Student | −4.7* | 1.6 | 0.03 |
| Knowledge | EE Specialist | H.S. Instructor | 1.2 | 6.6 | 0.99 |
| | | H.S. Student | 12.5* | 4.4 | 0.04 |
| | | Parent | 12.0 | 4.4 | 0.06 |
| | H.S. Instructor | EE Specialist | −1.2 | 6.6 | 0.99 |
| | | H.S. Student | 11.3 | 5.4 | 0.22 |
| | | Parent | 10.8 | 5.4 | 0.25 |
| | H.S. Student | EE Specialist | −12.5* | 4.4 | 0.04 |
| | | H.S. Instructor | −11.3 | 5.4 | 0.22 |
| | | Parent | −0.5 | 2.0 | 0.99 |
| | Parent | EE Specialist | −12.0 | 4.4 | 0.06 |
| | | H.S. Instructor | −10.8 | 5.4 | 0.25 |
| | | H.S. Student | 0.5 | 2.0 | 0.99 |
| Attitude | EE Specialist | H.S. Instructor | 5.1 | 5.7 | 0.85 |
| | | H.S. Student | 9.2 | 3.8 | 0.11 |
| | | Parent | 14.4* | 3.8 | 0.01 |
| | H.S. Instructor | EE Specialist | −5.1 | 5.7 | 0.85 |
| | | H.S. Student | 4.1 | 4.6 | 0.85 |
| | | Parent | 9.3 | 4.6 | 0.25 |
| | H.S. Student | EE Specialist | −9.2 | 3.8 | 0.11 |
| | | H.S. Instructor | −4.1 | 4.6 | 0.85 |
| | | Parent | 5.2* | 1.7 | 0.03 |
| | Parent | EE Specialist | −14.4* | 3.8 | 0.01 |
| | | H.S. Instructor | −9.3 | 4.6 | 0.25 |
| | | H.S. Student | −5.2* | 1.7 | 0.03 |

sample population based on census data for the three counties under study. For this reason, results and conclusions cannot be extrapolated to the general population of EE specialists, H.S. instructors, H.S. students, and parents in Southwest Florida. Also, no attempt was made to analyze data regarding the following demographics: antecedent urbanicity, years living in Southwest Florida, field of instruction (EE specialists and H.S. instructors), field of interest (students), career orientation (parents), and ethnicity. However, results regarding the level of AKA did indicated significant differences in AKA among EE specialists, H.S. instructors, H.S. students,

TABLE 4. Summary of the differences among all demographic variables in respect to AKA across the groups. Stars represent significance at the 0.05 alpha level.

| Demographic | Awareness | Knowledge | Attitude |
|---|---|---|---|
| Income (Parents only) | $F_{4,176} = 0.78$ | $F_{4,176} = 2.35$ | $F_{4,176} = 4.28$* |
| Enter. Activity | $F_{5,457} = 1.65$ | $F_{5,457} = 3.29$* | $F_{5,457} = 4.14$* |
| Gender | $F_{1,463} = 0.16$ | $F_{1,463} = 1.30$ | $F_{1,463} = 0.70$ |
| Urbanicity | $F_{1,462} = 0.13$ | $F_{1,462} = 0.34$ | $F_{1,462} = 0.50$ |

and parents within this study. Among the groups studied, the EE specialists scored the highest in the three objectives (AKA). This result does not come as a surprise since research has shown that environmental experience plays an important role in the means to make responsible environmental decisions (Tikka et al., 2000; Morrone et al., 2001). Madsen (1996) concluded that knowledge, beliefs, and commitment are necessary components when addressing environmental concerns. It is likely that EE specialists demonstrated higher levels of experience with and commitment to environmental issues, resulting in higher levels of AKA. When comparing the EE specialists with the H.S. instructors there was no significant difference in the results for AKA. These results suggest positive implications in terms of curriculum implementation as knowledge and attitude are directly related to the process of teaching (Moseley et al., 2002).

*Awareness*—Hausbeck and co-workers (1992) studied awareness along with environmental knowledge in high school students and concluded that the scores for awareness were higher than the scores for knowledge. They linked these results to the relatively easy access to information by electronic media, where awareness and concern can be picked up with little substantive knowledge. The present study shows similar results where H.S. students' levels of awareness were higher than their levels of knowledge.

*Knowledge*—Measurements of knowledge in this study revealed no significant differences between the higher levels scored by the EE specialists and scores of the H.S. instructors. This suggests that in this study H.S. instructors who incorporate environmental topics into their classes are knowledgeable of environmental subjects. These findings are encouraging since a study by the National Environmental Education and Training Foundation (NEETF) indicated that overall knowledge about the environment in the U.S. is often erroneous factually and persistent in misinformation (1998). The report also concluded, however, that Americans are concerned about the environment.

*Attitude*—The level of attitude presented by the H.S. students in this study was significantly higher when compared to the levels of their corresponding parents. Villacorta and co-workers (2003) developed the Motivation Towards the Environment Scale (MTES) and found that individuals were more likely to engage in autonomous environmental behaviors if: (a) their parents had shown an interest in their developing attitudes about the environment, (b) their peers supported their freedom to make decisions about the environment, and (c) if they had concern for their community. The findings of Villacorta and co-workers (2003) are supported by the results of this study. Awareness and attitude between H.S. students and parents appear similar, with the lowest level of awareness and attitude presented by the parent scores. However, there were no significant differences between H.S. students and the H.S. instructors' levels of AKA. This suggests that positive influence may be higher by the H.S. instructors than by the parents with regards to AKA.

*AKA with respect to demographics*—Several studies have investigated factors that may play a role in affecting AKA (Dunlap et al., 2000; Rovira, 2000; Tikka et al., 2000; Zelezny et al., 2000; Morrone et al., 2001). The present study explores four demographic components: income (for parents only), entertainment activities, gender, and urbanicity. Differences among the parents' income were present only for levels of attitude. Lower levels of attitude were found in the lowest income range (<\$15,000) as compared to parents with higher income. These findings are consistent with a qualitative study by Rovira (2000) who found differences in responsiveness to environmental programs according to the influences of social factors that include income and social position.

Regarding gender, the present study revealed no significant difference between sexes across the groups, which contrasts with conclusions found by three previous studies. The conclusions in these studies were that women have stronger environmental attitudes than men (Zelezny et al., 2000), women are more likely than men to state that current laws and regulations do not go far enough towards the protection of the natural environment (NEETF, 1998), and that women expressed greater concerns for the biosphere (Stern and Dietz, 1994).

This study showed no significant difference between living in urban versus rural communities across the groups. These findings disagree with conclusions found by Albrecht and co-workers (1982), who concluded that lower levels of attitude toward the environment were present in a population of farmers than metropolitan residents.

This study suggests that levels of knowledge and attitude differ when comparing activities for entertainment. Those who preferred outdoor activities showed higher scores in knowledge than those who preferred social activities. In addition, individuals who found gardening the choice of entertainment scored higher attitudes levels than those who chose sports. These results are similar to those published by Palmberg and Kuru (2000). The attitudes of young students (ages 11 and 12 yrs.) with different levels of outdoor experience such as camping, hiking or fishing were compared. They found a strong and clearly definable positive relationship to nature in those students with outdoor experiences, along with better social behavior and higher moral judgment.

*Implications for environmental education*—These findings have positive implications regarding the status of EE programs in Southwest Florida. EE specialists and H.S. instructors know their subjects and show a positive attitude towards the environment as related to environmental issues. High school students show higher levels of attitude and awareness towards the environment when compared to their parents. And although the level of knowledge among students is lower when compared to the EE specialist, there is no difference in the level of attitude and awareness.

Madsen (1996) explained that environmental awareness, knowledge, and commitment are necessary to achieve environmental protection and restoration. Madsen emphasized that the public must have a basic grasp of environmental problems. Leaders in the field of environmental education must not only have extensive knowledge and understanding of environmental problems, but must have environmental awareness to solve these problems. They must be committed "to initiate action, based upon knowledge and understanding" (Madsen, 1996, p. 73).

Ultimately, this process rests in the hands of well-educated communities that can train their new generations toward becoming responsible environmental citizens. Curriculum theorists, including John Dewey, have long advocated the solution of social problems, along with the development of responsible members of a democracy, as the foundations of curriculum (Pinar et al., 1995). Therefore, the role of an education system is to assume this responsibility for educating environmentally literate citizens.

ACKNOWLEDGMENTS—I would like to express my gratitude to Dr. Larry Holt, Dr. Marcella Kysilka, Dr. Stephen Sivo, Dr. Kay Allen, Dr. Win Everham, and Dr. Amy Hadley. Their expertise and guidance were invaluable during this study. A special thank you to all the participants in this study, especially Cynthia L. Bear and Dr. Charles O'Connor, School District of Lee County, Environmental Education Department, and all the environmental education specialists for their outstanding effort in promoting environmental education. In addition, I would like to thank the anonymous reviewers and guest editors for the suggestions that improved this paper. Finally, I would like to acknowledge funding provided by the Charlotte Harbor National Estuary Program.

## LITERATURE CITED

ALBRECHT, D., G. BULTENA, E. HOIBERG, AND P. NOWAK. 1982. The new environmental paradigm scale. J. Environ. Educ. 13: 39–43.

ARCURY, T. AND E. CHRISTIANSON. 1993. Rural-urban differences in environmental knowledge and actions. J. Environ. Educ. 25: 19–25.

ARMSTRONG, J. AND J. IMPARA. 1990. The effect of order of test administration on environmental attitudes. J. Environ. Educ. 21: 37–40.

———. 1991. The impact of an environmental education program on knowledge and attitude. J. Environ. Educ. 22: 36–40.

ATHMAN, J. AND M. MONROE. 2000. Elements of Effective Environmental Education Programs. Retrieved February 15, 2006 from http://www.rbff.org/uploads/Resources_bestpractices/julieathman_paper.pdf.

BALLARD, M. AND M. PANDYA. 1990. Essential Learnings in Environmental Education. North American Association for Environmental Education, Troy, OH.

BOGAN, M. AND J. KROMREY. 1996. Measuring the environmental literacy of high school students. Florida J. Educ. Resear. 36: 61–72.

CALLICOTT, J. B. AND F. J. ROCHA. 1996. Earth Summit Ethics: Towards a Reconstructive Postmodern Philosophy of Environmental Education. Albany State Univer. of New York Press, Albany, NY.

COTTRELL, S. 2003. Influence of socio demographics and environmental attitudes on general responsible environmental behavior among recreational boaters. Environ. Behav. 35: 347–375.

DAY, B. R. AND M. C. MONROE. 2000. Environmental Education & Communication for a Sustainable World. Handbook for International Practitioners. Academy for Educational Development, Washington, DC.

DILLMAN, D. 2000. Mail and Internet Surveys, the Tailored Design Method. 2nd ed., John Wiley & Son, Inc., New York, NY.

DISINGER, J. F. 1997. Environment in the K-12 curriculum: an overview. Pp. 23–45. *In*: R. J. WILKE (ed.), Environmental Education, Teacher Resource Handbook. A Practical Guide for K-12 Environmental Education. Corwin Press, Inc., Thousand Oaks, CA.

DUNLAP, R., K. VAN LIERE, A. MERTIG, AND R. JONES. 2000. Measuring endorsement of the new ecological paradigm: a revised NEP scale. J. Soc. Issues 56: 425–442.

FLORIDA DEPARTMENT OF EDUCATION. 2003. Enrollment Size of Florida's Public Schools 2003-20F. Retrieved February 15, 2006 from http://www.firn.edu/doe/eias/eiaspubs/pdf/enroll.pdf.

GIGLIOTTI, L. 1992. Environmental attitudes: 20 years of change? J. Environ. Educ. 24: 15–26.

GOUGH, A. 1997. Education and the Environment: Policy, Trends and the Problems of Marginalization. Australian Education Review No. 39. The Australian Council for Educational Research Ltd., Melbourne, Australia.

HAUSBECK, K., L. MILBRATH, AND S. ENRIGHT. 1992. Environmental knowledge, awareness and concern among 11th grade students: New York State. J. Environ. Educ. 24: 27–34.

HUNGERFORD, H. AND R. PEYTON. 1994. Procedures for Developing an Environmental Education Curriculum. UNESCO-UNEP, International Environmental Education Program. Retrieved on February 15, 2006 from http://unesdoc.unesco.org/images/0013/001304/130454eo.pdf.

KNAPP, D. 1996. Evaluating the impact of environmental interpretation: a review of three research studies. *In*: Coalition for Education in the Outdoors Research Symposium Proceedings (Bradford, Woods, Indiana, January 12–14, 1996). (ERIC Document Reproduction Services No. ED413132).

KRAUSE, D. 1993. Environmental consciousness: an empirical study. Environ. Behav. 25: 126–143.

LA TROBE, H. AND T. ACOTT. 2000. A modified NEP/DSP environmental attitude scale. J. Environ. Educ. 32: 12–20.

LASSO DE LA VEGA, E. 2004. Awareness, Knowledge, and Attitude About Environmental Education: Responses from Environmental Specialists, High School Instructors, Students, and Parents. Ed.D. Dissert. University of Central Florida. Orlando, FL. Retrieved on February 15, 2006 from http://www.lee.k12.fl.us/dept/plan/Research/Lasso%20de%20la%20Vega_Ernesto_R_200412_EdD.pdf.

MA, X. AND D. BATESON. 1999. A multivariate analysis of the relationship between attitude toward science and attitude toward the environment. J. Environ. Educ. 31: 27–32.

MADSEN, P. 1996. What can universities and professional schools do to save the environment? Pp. 71–91. *In*: J. B. CALLICOTT AND F. J. DA ROCHA (eds.), Earth Summit Ethics: Toward a Reconstructive Postmodern Philosophy of Environmental Education. Albany State Univer. of New York Press, Albany, NY.

MARCINKOWSKI, T. 1997. Assessment in environmental education. Pp. 144–197. *In*: R. WILKE (ed.) Environmental Education, Teacher Resources Handbook, a Practical Guide for K-12 Environmental Education. Corwin Press, Inc., Thousand Oaks, CA.

MORRONE, M., K. MANCL, AND K. CARR. 2001. Development of a metric to test group differences in ecological knowledge as one component of environmental literacy. J. Environ. Educ. 32: 33–42.

MOSELEY, C., K. REINKE, AND V. BOOKOUT. 2002. The effect of teaching outdoor environmental education on preservice teachers' attitudes toward self-efficacy and outcome expectancy. J. Environ. Educ. 34: 9–15.

MUSSER, L. AND K. DIAMOND. 1999. The children's attitudes toward the environmental scale for preschool children. J. Environ. Educ. 30: 23–30.

NEETF. 1998. The National Report Card on Environmental Knowledge, Attitudes and Behaviors: the Seventh Annual Survey of Adult Americans. (ERIC Document Reproduction Services No. ED433214).

PALMBERG, I. AND J. KURU. 2000. Outdoor activities as a basis for environmental responsibility. J. Environ. Educ. 31: 32–38.

PALMER, J. 1998. Environmental Education in the 21st Century: Theory, Practice, Progress and Promise. Routledge, New York, NY.

PINAR, W., W. REYNOLDS, P. SLATTERY, AND P. TAUBMAN. 1995. Understanding Curriculum: an Introduction to the Study of Historical and Contemporary Discourses. Peter Lang, New York, NY.

POOLEY, J. AND M. O'CONNOR. 2000. Environmental education and attitudes: emotions and beliefs are what is needed. Environ. Behav. 32: 711–724.

ROVIRA, M. 2000. Evaluating environmental education programs: some issues and problems. Environ. Educ. Resear. 6: 143–155.

SALMIVALLI, M. 1998. Children's environmental response inventory among Finnish adolescents. J. Environ. Educ. 29: 49–54.

SCHAHN, J. AND E. HOLZER. 1990. Studies of individual environmental concern: the role of knowledge, gender, and background variables. Environ. Behav. 22: 767–787.

SHUMAN, D. AND S. HAM. 1997. Toward a theory of commitment to environmental education teaching. J. Environ. Educ. 28: 25–32.

SPSS, INC. 2001. SPSS Graduate Pack 11.0 for Windows, 11th ed., SPSS, Inc., Chicago, IL.

STERN, P. AND T. DIETZ. 1994. The value basis of environmental concern. J. Soc. Issues 26: 4–20.

TIKKA, P., M. KUITUNEN, AND S. TYNYS. 2000. Effects of educational background on students' attitudes, activity levels, and knowledge concerning the environment. J. Environ. Educ. 31: 12–19.

UNESCO. 1978. Intergovernmental Conference on Environmental Education: Tbilisi (USSR), 14–26 October 1997. Final Report. UNESCO Press, Paris, France. Retrieved on February 15, 2006 from http://unesdoc.unesco.org/images/0003/000327/032763eo.pdf.

VAN ES, J., D. LORENCE, G. MORGAN, AND J. CHURCH. 1996. "Don't know" responses in environmental surveys. J. Environ. Educ. 27: 13–18.

VILLACORTA, M., R. KOESTNER, AND N. LEKES. 2003. Further validation of the motivation toward the environment scale. Environ. Behav. 35: 486–505.

WILKE, R. J. (ed.) 1997. Environmental education, teacher resource handbook. A practical guide for K-12 environmental education. Corwin Press, Inc., Thousand Oaks, CA.

WORSLEY, A. AND G. SKRZYPIEC. 1998. Environmental attitudes of senior secondary school students in South Australia. Glob. Environ. Change 8: 209–225.

ZELEZNY, L., P. CHUA, AND C. ALDRICH. 2000. Elaborating on gender differences in environmentalism. J. Soc. Issues 56: 443–457.

ZIMMERMANN, L. 1996. The development of an environmental values short form. J. Environ. Educ. 28: 32–37.

Florida Scient. 69(00S2): 166–178. 2006
Accepted: March 10, 2006