United States
Environmental
Protection Agency

Region 4 Science & Ecosystem
Support Division, Water Management Division and Office of
Research and Development

EPA 904-R-01-002
September 2001

EPA

South Florida Ecosystem Assessment: Phase I/II (Summary) – Everglades Stressor Interactions: Hydropatterns, Eutrophication, Habitat Alteration, and Mercury Contamination

Monitoring for Adaptive Management: Implications for Ecosystem Restoration

The South Florida Ecosystem Assessment Project is being conducted by the United States Environmental Protection Agency Region 4 in partnership with the Florida International University Southeast Environmental Research Center, FTN Associates Ltd., and Battelle Marine Sciences Laboratory. Additional cooperating agencies include the United States Fish and Wildlife Service, the National Park Service, the United States Geological Survey, the Florida Department of Environmental Protection, the South Florida Water Management District, and the Florida Fish and Wildlife Conservation Commission. The Miccosukee Tribe of Indians of Florida and the Seminole Tribe of Indians allowed sampling to take place on their federal reservations within the Everglades.

EPA 904-R-01-002
September 2001

SOUTH FLORIDA ECOSYSTEM ASSESSMENT:

Phase I/II – Everglades Stressor Interactions: Hydropatterns, Eutrophication, Habitat Alteration, and Mercury Contamination

(Summary)

by

Q. J. Stober[1], K. Thornton[2], R. Jones[3], J. Richards[4], C. Ivey[3], R. Welch[5], M. Madden[5], J. Trexler[4], E. Gaiser[3], D. Scheidt[6] and S. Rathbun[7]

[1]Project Manager, U.S. Environmental Protection Agency, Region 4, Science and Ecosystem Support Division, Athens, GA; [2]FTN Associates, Ltd., Little Rock, AR; [3]Florida International University, Southeast Environmental Research Center, Miami, FL; [4]Florida International University, Department of Biological Sciences, Miami, FL; [5]University of Georgia, Department of Geography, Center for Remote Sensing and Mapping Science (CRMS), Athens, GA; [6]U.S. Environmental Protection Agency, Region 4, Water Management Division, South Florida Office, West Palm Beach, FL; [7]University of Georgia, Department of Statistics, Athens, GA

ACKNOWLEDGEMENTS

Participants in USEPA Region 4 Everglades Assessment Project

USEPA Region 4 Program Offices

APTMD
J. Ackerman
L. Anderson-Carnahan
D. Dubose
L. Page

ORC
P. Mancusi-Ungaro

SESD
A. Auwarter
G. Bennett
B. Berrang
M. Birch
J. Bricker
G. Collins
D. Colquitt
J. Davee
C. Halbrook
R. Howes
P. Kalla
D. Kamens
B. Lewis
P. Mann
W. McDaniel
P. Meyer
D. Norris
M. Parsons
B. Noakes
B. Pruitt
J. Scifres
S. Sims
T. Slagle
T. Stiber
D. Smith
M. Wasko

WMD
M. Flexner
H. Johnson
J. Negron
D. Powell
E. Sommerville

USEPA - Office of Research and Development

NHEERL
K. Summers
T. Olsen

NERL-RTP
R. Linthurst
J. Messer
R. Stevens
R. Bullock
J. Pinto

NERL-ATHENS
R. Araujo
C. Barber
L. Burns
N. Loux

Florida International University-SERC

A. Alli
M. Bascoy
N. Black
Y. Cai
D. Diaz
A. Edwards
C. Ivey
R. Jaffe
A. Jelensky
W. Loftus
J. Lopez
P. Lorenzo
I. MacFarlane
L. Scinto
R. Taylor
J. Thomas
C. Ugarte

University of Georgia

S. Rathbun
A. Homsey

University of Florida

P. Frederick

Florida Department of Environmental Protection

T. Atkeson

Florida Fish & Wildlife Conservation Commission

T. Lange

South Florida Water Management District

L. Fink
D. Rumbold

Contractors

J. Maudsley, Mantech
B. Heinish, Mantech
L. Dorn, Mantech
M. Weirich,Mantech
D. Stevens, Mantech
S. Ponder, ILS
B. Simpson, ILS
K. Simmons, ILS
S. Pilcher, ILS
J. Benton, FTN Assoc, Ltd.
B. Frank, FTN Assoc, Ltd.
L. Gandy, FTN Assoc, Ltd.
C. Laurin, FTN Assoc, Ltd.
L. Lewis, FTN Assoc, Ltd.
D. Lincicome, FTN Assoc, Ltd.
J. Malcolm, FTN Assoc, Ltd.
S. Phillips, FTN Assoc, Ltd.
M. Ruppel, FTN Assoc, Ltd.
N. Siria, FTN Assoc, Ltd.
K. Thornton, FTN Assoc., Ltd.
E. Crecelius, Battelle Marine Sciences
B. Lasorsa, Battelle Marine Sciences

Funding for this Regional Environmental Monitoring & Assessment (REMAP) Project was provided by the United States Environmental Protection Agency Region 4 South Florida Office, West Palm Beach; the Office of Water; the Office of Research and Development; and the United States Department of Interior, National Park Service.

EXECUTIVE SUMMARY
South Florida Ecosystem Assessment
What Did We Learn?

Things Are Changing; But The Issues Are The Same!
What does this mean?

Over the past 8 years, the US Environmental Protection Agency (EPA) Region 4 has been conducting an ecosystem assessment of the South Florida Everglades ecosystem in conjunction with the Florida Department of Environmental Protection, US Geological Survey, South Florida Water Management District, Florida International University, other universities, and the private sector. Over this time period, there has been a significant decrease in nutrient concentrations and mercury contamination throughout the ecosystem. Change, however, is not a trend. Continued monitoring will be required to determine if these concentrations continue to decrease through time. What was clear at the beginning of the study, and is still clear, is the need for integrated management of the ecosystem. Hydropattern modifications, nutrient loadings and eutrophication, habitat alteration, and mercury contamination are all interrelated. These problems cannot be managed independently!

EPA Region 4 initiated the South Florida Ecosystem Assessment Project in 1993. The Project used a statistical survey design to sample the South Florida ecosystem from Lake Okeechobee in the north to Florida Bay in the south, from the Miami urban area on the east to Big Cypress on the west (Figure 1). Within this 2.5 million acre area, a variety of measurements were made on samples taken from water, soil, sediment, plants (both the algae and the standing plants like sawgrass and cattails), floc (organic debris on the soil) and mosquitofish. These samples were taken in canals (1993-1995) and throughout the marsh (1995-1996, 1999) in both wet (rainy) and dry seasons. Because the marsh was sampled in 1995-96 and again in 1999, it was possible to detect changes that had occurred in some marsh constituents during this period. The South Florida Ecosystem Assessment has been an innovative research, monitoring, and assessment Project that has produced a number of significant findings with management implications.

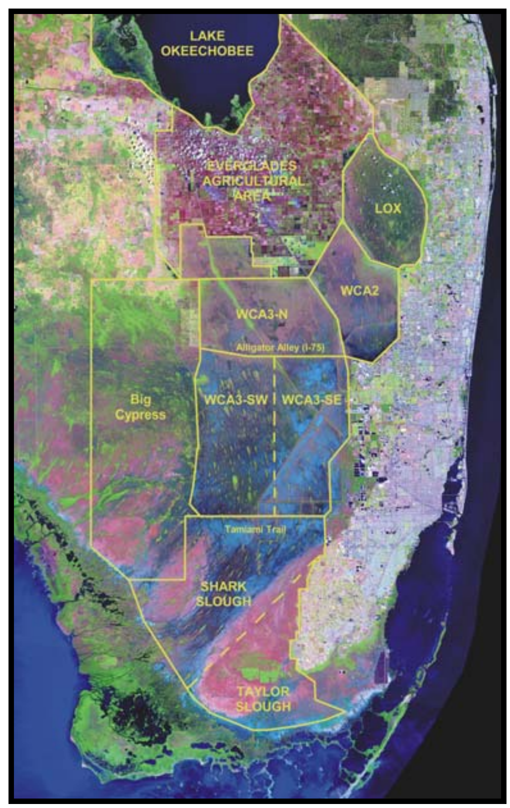

Figure 1. USGS satellite image of South Florida: light areas on the east indicate urban areas; dark areas in the center are the remnant Everglades; the red area at the top is the Everglades Agricultural Area and the western part of the image is Big Cypress National Preserve.

Findings

Some of the significant findings from the Project are that:

Ø Hydropattern modifications and the water requirements to cover different marsh areas can be estimated with a simple surface area-volume relationship. Long and short hydropattern areas can also be determined using this relationship. The plant species distributions observed in the study reinforced and supported these hydropatterns. Water changes from dry to completely flooded are necessary to sustain a pulsed ecosystem like the Everglades.

Ù There are significant north to south gradients, from Lake Okeechobee to Florida Bay, in total phosphorus, total organic carbon, and sulfate (Figure 2) in the ecosystem. These gradients affect eutrophication and mercury contamination throughout the Everglades. These gradients also are affected by hydropattern modifications. These factors are all interrelated.

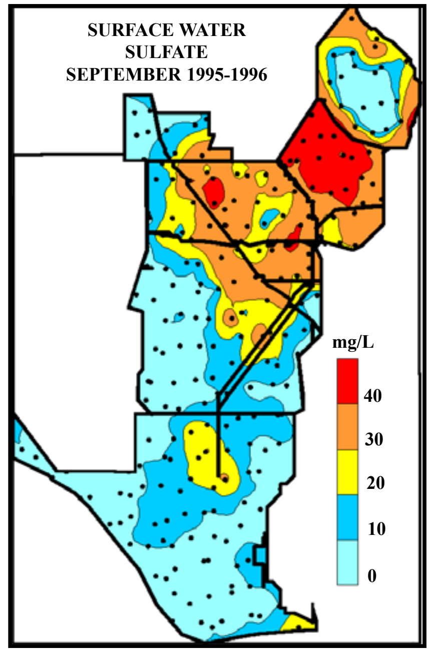

Figure 2. Under the right conditions, sulfate can stimulate sulfate-reducing bacteria to convert inorganic mercury to the toxic organic form of mercury. Note the strong north to south gradients in sulfate concentrations during a wet season.

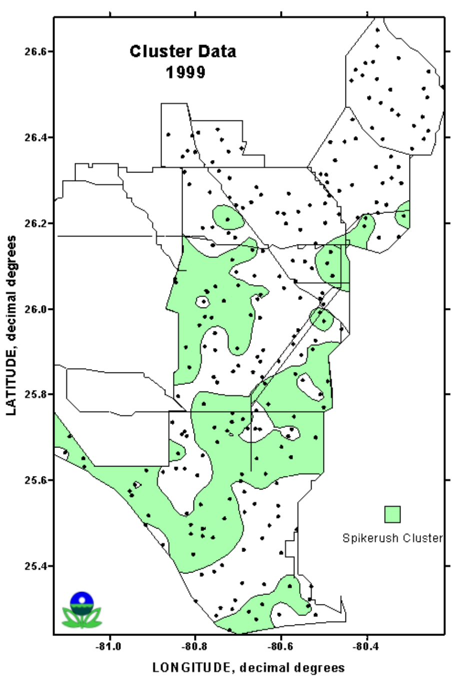

Figure 3. Spikerush community distributions showing areas of the marsh with low total phosphorus concentrations in soil and intermediate to long hydroperiod. Spikerush distributions might be good indicators for assessing the success of restoration.

Ú Total phosphorus (nutrient) concentrations were significantly lower throughout the marsh in 1999 compared to 1995-96. Continued monitoring will be needed to determine if this change represents a decreasing trend in total phosphorus concentrations.

Û The distribution of different aquatic plant species (i.e., macrophytes) throughout the marsh provide good indicators of:

- **hydropattern -** water lily (*Nymphaea odorata*)/ purple bladderwort (*Utricularia purpurea*) indicate stable water slough habitat (i.e., long hydroperiod).
- **low soil phosphorus -** spikerush (*Eleocharis cellulosa*) (Figure 3) is found in soils with low phosphorus concentrations and intermediate to long hydroperiod.
- **high soil phosphorus -** cattail (*Typha domingensis*) is found in soils with high phosphorus concentrations.

In addition, the change in some plant characteristics also were associated with variations in soil phosphorus concentrations. Broad leaves and short petioles in arrowhead (*Sagittaria lancifolia*) were associated with high soil phosphorus concentrations. Narrow leaves and long petioles in arrowhead were associated with low soil phosphorus concentrations.

Ü There is a “hot spot” of mercury contamination in mosquitofish located in the southwestern part of Water Conservation Area 3 below Alligator Alley (Figure 4). The area north of Alligator Alley has high methylmercury concentrations in the water and soil, but low mercury concentrations in the mosquitofish. The area south of Tamiami Trail in Everglades National Park has low methylmercury concentrations in the water and soil, but relatively high mercury concentrations in the mosquitofish.

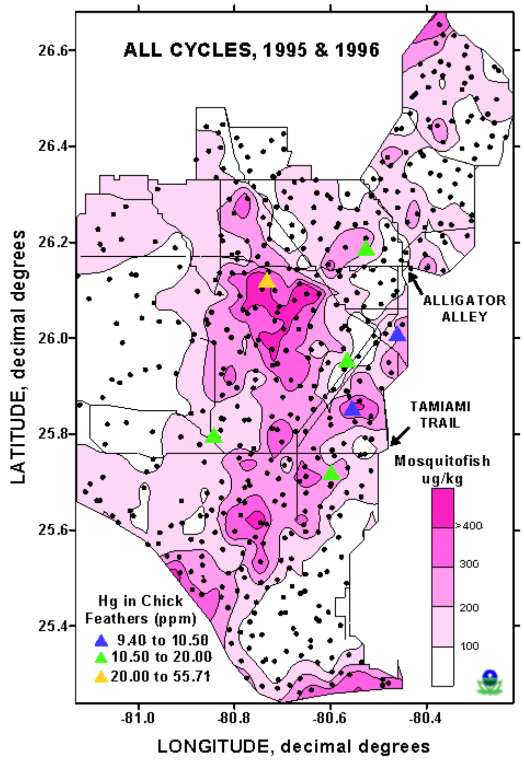

Figure 4. The hot spot is the same for total mercury in both mosquitofish and great egret chick feathers. Largemouth bass and algae mercury concentrations are also high in this hot spot.

Ý Mercury concentrations in the water and in mosquitofish were significantly lower throughout the marsh in 1999 compared to 1995-96 (Table 1). Water and mosquitofish mercury concentrations corresponded with changes in atmospheric wet deposition.

Þ Both top-down and bottom-up controls in the ecosystem explain the observed effects of nutrient loading, and mercury contamination. High chemical (nutrient, TOC, SO_4, S^{2-}) concentrations exert a bottom-up control on ecosystem responses in the northern area. Biological interactions exert a top-down control on ecosystem responses in the low nutrient southern area. The mercury “hot spot” is in the transition zone between these two areas where both bottom-up and top-down interactions occur.

Table 1. Change in total mercury mass (kg) in different media from 1995 to 1999 over the study area. Mercury contamination appears to be decreasing in the ecosystem during the wet season.

Media	1995	1996	1999
Atmospheric Wet Deposition	153	116	146
Water	6.0	4.7	3.8
Mosquitofish	0.64	0.41	0.39

A reasonable question to ask, given these findings, is “So What?” Why are these findings important and what are the implications for management?

Management Implications

Ø Wetlands, by definition, are water driven systems and the water regime drives all other interactions in the wetland. Modifying the water regime will affect everything else in the Everglades ecosystem. Fluctuating water levels are an integral part of the pulsed Everglades ecosystem. These fluctuations need to be maintained and managed.

Ù Distributions of plant species, such as water lily, spikerush, and cattail, and plant characteristics, such as arrowhead leaf widths, are cost effective indicators for assessing the success of the restoration effort because they reflect hydropattern modifications and changes in soil phosphorus concentrations.

Ú Mosquitofish are good indicators for assessing change in mercury contamination because they are found throughout the marsh, have a short life span, and respond quickly to changes in mercury concentrations. The change in atmospheric deposition might correspond with decreased mercury emissions, but it also relates to less rainfall in 1996 and 1999 compared to 1995.

Û Restoration efforts related to managing the water regime, controlling nutrient loading, minimizing habitat alteration, and reducing mercury contamination must proceed together. These factors are all interrelated and must not be managed independently.

Ü Consistent, long-term monitoring is the only way of evaluating the success of the restoration effort. It appears the nutrient management practices and mercury emission reductions have contributed to a decrease in phosphorus concentrations and mercury contamination. However, only continued monitoring will tell if these changes represent a real decreasing sustainable trend and whether management practices are influencing the trend. Statistical survey monitoring networks complement on-going monitoring programs and should be integrated into the Comprehensive Everglades Restoration Plan.

For More Information, Please Contact

Dr. Jerry Stober
US EPA Region 4 SESD
980 College Station Road
Athens, GA 30605-2700
(706) 355-8705

Additional reports and information can be obtained by visiting
the Region 4 Website at www.epa.gov

CONTENTS

US EPA REGION 4
SOUTH FLORIDA ECOSYSTEM ASSESSMENT

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ac-ft = acre feet
ug/m2 = microgram per meter squared
% OM = percent organic matter
cm = centimeter
ft = foot
km = kilometer
mi = mile
kg/yr = kilogram per year
ppm = parts per million (mg/L)
ppb = parts per billion (ug/L)
ppt = parts per trillion (ng/L)
mg/kg = milligram per kilogram (ppm)
ug/kg = micrograms per kilogram (ppb)
uMol/hr = micromoles per hour
kg = kilogram
m = meter

Hg = mercury
Hg0 = elemental mercury
HgII = inorganic mercury
MeHg = methylmercury

ACME = Aquatic Cycling of Mercury in the Florida Everglades

AFDW = Ash Free Dry Weight

APTMD = Air, Pesticides, and Toxics Management Division

BAF = Bioaccumulation Factor

BMPs = Best Management Practices

CERP = Comprehensive Everglades Restoration Program

culm = the stem of a grass-like plant

EAA = Everglades Agricultural Area

EMAP = Environmental Monitoring and Assessment Program

ENP = Everglades National Park

FDEP = Florida Department of Environmental Protection

FIU SERC = Florida International University Southeastern Environmental Research Center

GIS = Geographic Information System

LOX = Loxahatchee National Wildlife Refuge

NAWQA = National Water Quality Assessment Program

NERL – Athens = National Exposure Research Laboratory - Athens, GA

NHEERL - RTP = National Health and Environmental Exposure Research Laboratory - Research Triangle Park, NC

NPS = National Park Service

ORC = Office of Regional Counsel

peri = Periphyton

PS = Periphyton (soil)

PU = Periphyton (utricularia)

REMAP = Regional Environmental Monitoring and Assessment Program

S^2 = Sulfide

SESD = Science and Ecosystem Support Division

SFWMD = South Florida Water Management District

SFWMM = South Florida Water Management Model

SRB = Sulfate Reducing Bacteria

STAs = Stormwater Treatment Areas

TP = Total Phosphorus

US EPA = United States Environmental Protection Agency

USGS = United States Geological Survey

WCA = Water Conservation Area

WMD = Water Management Division

INTRODUCTION

The United States Environmental Protection Agency (US EPA) Region 4 South Florida Ecosystem Assessment Project is an innovative, long-term research, monitoring, and assessment project. Its ultimate goal is to inject sound scientific information into management decisions on the Everglades ecosystem and its restoration.

The South Florida Ecosystem Assessment Project has a five-fold purpose:

1) Contribute to the South Florida Everglades Restoration Program by monitoring the condition and trends in the Everglades ecosystem.

2) Assess the effects and potential risks due to mercury contamination in the South Florida ecosystem, specifically on fish, wading birds, and other biota, as part of the South Florida Mercury Science Program.

3) Assess the effects and potential risks from other environmental stresses such as hydropatt modification, habitat alteration, phospho-rus loading, and eutrophication on the Everglades ecosystem (Figure 1).

4) Improve monitoring design and ecological assessments for evaluating the relative risks of environmental stressors acting on the Everglades ecosystem.

5) Provide scientifically credible information on a regular basis that contributes to management decisions on Everglades restoration issues.

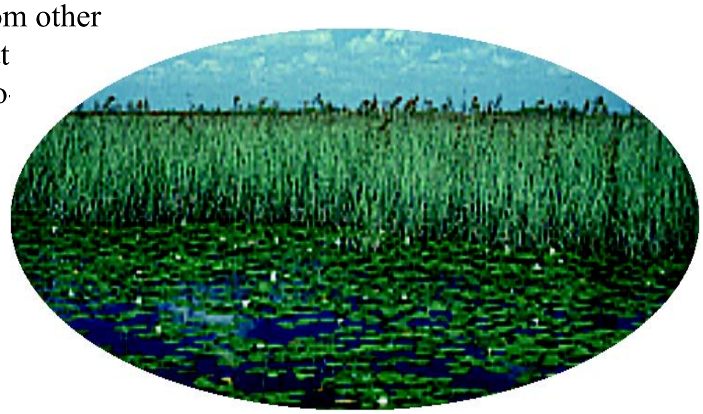

Figure 1. Numerous environmental issues threaten the South Florida Everglades "River of Grass," including mercury contamination.

Working in partnership with Florida International University, Southeast Environmental Research Center; the State of Florida Department of Environmental Protection; Florida Fish and Wildlife Conservation Commission; South Florida Water Management District; United States Geological Survey; United States National Park Service; industry; and other organizations; United States EPA Region 4 Science and Ecosystem Support Division has been monitoring the condition of the South Florida ecosystem since 1993.

This is the fifth assessment report on the issues affecting the Everglades ecosystem. This report expands on the US EPA report series (Stober et al. 1995, Stober et al. 1996, Stober et al. 1998, Scheidt et al. 2000, and Stober et al. 2001). Data are presented for the entire freshwater Everglades marsh system.

This report summarizes the results of the comprehensive Phase I (1995-96) and Phase II (1999) marsh sampling efforts which included assessing:

- hydropattern modifications in the system and responses during dry and wet seasons, based on six sampling events,
- plant community responses, including both periphyton and macrophytes, and habitat alterations associated with nutrient loading and hydropattern changes,
- changes in nutrient concentrations in water and soil over time,
- current status of mercury contamination,
- identification of mercury sources,
- mechanisms controlling mercury contamination,
- biological availability and uptake of methylmercury through the food chain,
- the relative risks from these stressors, and
- the management implications and the interactions of these issues.

South Florida Everglades

The Florida Everglades is one of the largest freshwater marshes in the world. The marsh is a rich mosaic of sawgrass, wet prairies, sloughs, and tree islands (Figure 2). Just over 100 years ago, this vast wilderness encompassed over 4,000 square miles, extending 100 miles from the shores of Lake Okeechobee south to Florida Bay. The intermingling of temperate and Caribbean flora created habitat for a variety of fauna, including Florida panthers, alligators, and hundreds of thousands of wading birds. The unique and timeless nature of the Everglades was described by Marjory Stoneman Douglas (1947) in her classic work, *The Everglades: River of Grass*.

Figure 2. Numerous environmental issues threaten the Everglades "River of Grass," such as water management, soil loss, water quality degradation, and habitat alteration.

A Troubled River

During the last century, however, the "River of Grass" has become a troubled river. The Everglades ecosystem has been altered by extensive agricultural and urban development (Figure 3). Today, 50% of the historic Everglades wetland has been drained. South Florida's expanding human population of nearly 6 million continues to encroach on this ecosystem's water and land. This human population is projected to increase to 20 million people in just a little over 20 years.

Figure 3. Residential development on former Everglades wetlands.

Issues

The Everglades changed dramatically as drainage canals were dug and agricultural and urban development increased in the 20th century. Most of the remaining Everglades are in Loxahatchee National Wildlife Refuge, Everglades National Park, or the Water Conservation Areas (WCAs) (Figure 4). Today, Everglades National Park includes only one-fifth of the original river of grass that once spread over more than 2 million acres. One-fourth of the historic Everglades is now in agricultural production within the 1,000-square-mile Everglades Agricultural Area (EAA) (Figure 4), where sugar cane and vegetables are grown on fertile peat soils. Big Cypress National Preserve protects forested swamp resources within the Everglades watershed (Figure 4). Although half of the 16,000-square-mile Everglades watershed is in public ownership, there are a number of environmental issues that must be resolved to restore and protect the Everglades ecosystem, including eutrophication (Figure 5); mercury contamination of gamefish, wading birds, the endangered Florida panther (Figure 6), and other top predators; habitat alteration and loss; hydropattern modification; water supply

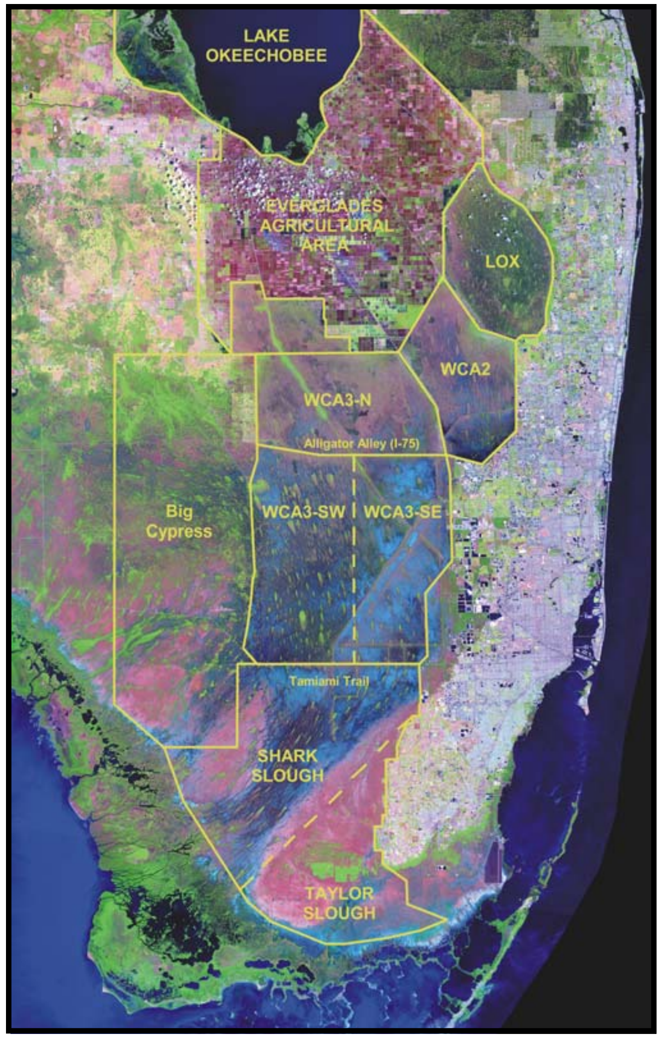

Figure 4. USGS satellite image of South Florida: light areas on the east indicate urban areas; dark areas in the center are the remnant Everglades; the red area at the top is the Everglades Agricultural Area and the western part of the image is Big Cypress National Preserve.

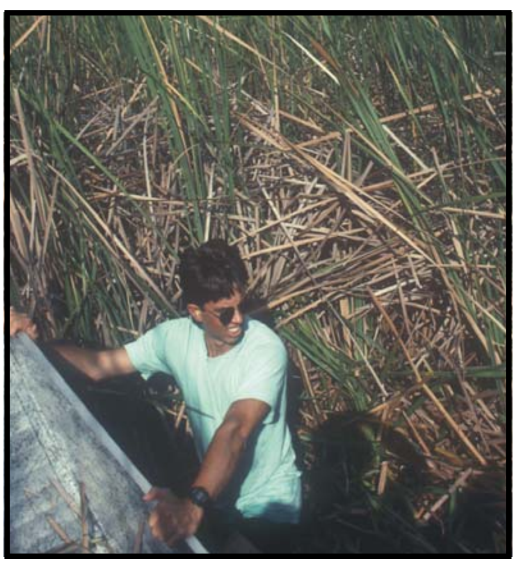

Figure 5. Eutrophication promotes cattail expansion. Cattails are an invasive species.

Figure 6. A Florida panther, which is an endangered species, might have died from mercury toxicity in 1989.

conflicts; protection of endangered species; and introduction and spread of nuisance exotic species (McPherson et al., 2000). Many of these problems were discussed in previous EPA Region 4 publications, *South Florida Ecosystem Assessment: Interim Report* (Stober et al. 1996) and *South Florida Ecosystem Assessment: Phase I Final Technical Report* (Stober et al. 1998, 2 volumes), *South Florida Ecosystem Assessment: Everglades Water Management, Soil Loss, Eutrophication and Habitat* (Scheidt et al. 2000) and *South Florida Ecosystem Assessment: Phase I/II – Everglades Hydropattern, Eutrophication, Habitat and Mercury Contamination Final Technical Report* (Stober et al. 2001, 2 volumes), of which this report is a summary. These problems are interrelated. In fact, the problems may have been aggravated because each problem was managed independently.

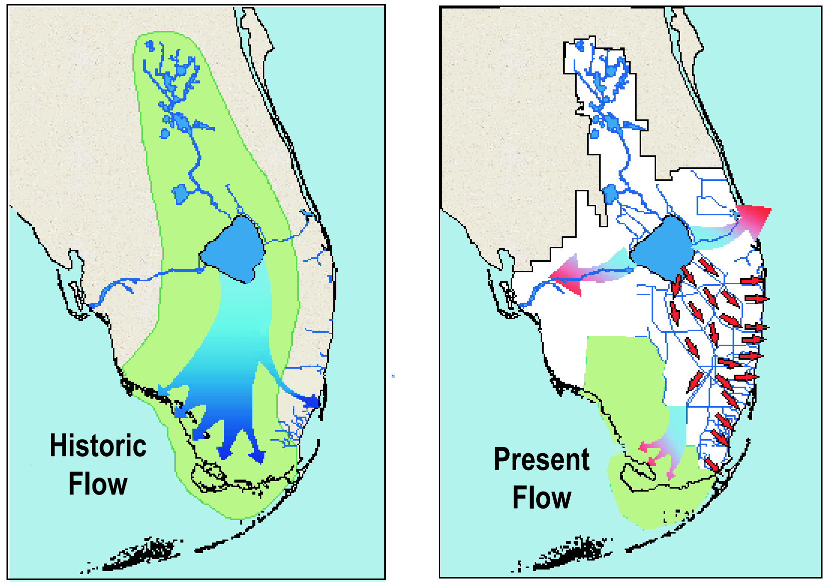

Figure 7. Historic flow pattern (left) and present flow patterns (right) through the South Florida system. Water movement is highly managed through the canals and water control structures.

Hydropatterns

Clearly, the greatest change that occurred in the Everglades ecosystem was "draining the swamp"; changing the natural hydropattern, or the depth, timing and distribution of surface water (Figure 7). Wetland systems, by definition, are driven by water. Canal drainage systems, levees, flood control structures, and water supply diversions have collectively contributed to large-scale changes in the Everglades ecosystem. The US Army Corps of Engineers and the South Florida Water Management District in their comprehensive review study of the Central and Southern Florida Project (1999) are evaluating the modification of canals and levees to return the hydropattern to a more natural regime. Determining the natural flow regime and hydropattern and subsequently implementing the required flows in the Everglades is a major restoration activity. Hydropattern modification represents one of the greatest issues facing the Everglades ecosystem.

Figure 8. Extensive canal systems and water management have modified the natural hydropattern.

Habitat Alteration

Over 1 million acres of the original "River of Grass" have been drained and altered for other uses since the turn of the 20th century (Figure 8). In addition to the habitat lost, much of the remaining habitat has been altered because of unnatural flooding and drying, ground water removal, or similar perturbations. This habitat alteration is still ongoing as the population of South Florida continues to expand. Unlike eutrophication and mercury contamination, habitat loss is irreversible with certain land uses. In addition, habitat alteration aggravates other environmental problems, and these interactions are poorly understood.

Eutrophication

Nutrient loading from the Everglades Agricultural Area and urban areas has significantly increased nutrient concentrations, particularly phosphorus, in the downstream Water Conservation Areas and the Everglades National Park. This has resulted in major eutrophic impacts on these wetland systems (Figure 5). Among the progressive Everglades eutrophic impacts are increased water and soil phosphorus content, changed periphyton communities, increased mass of oxygen-demanding organic matter, loss of dissolved oxygen in water, loss of native sawgrass plant communities, loss of important wading bird foraging habitat, and conversion of wet prairie plant communities to cattails. These collective changes are systemic and impact the structure and function of the aquatic system. The Florida Department of Environmental Protection (FDEP) has concluded that eutrophication of the Everglades results in the violation of four Florida water quality standards to protect fish and wildlife and creates an imbalance in the natural population of aquatic flora and fauna, with a resulting loss in biological integrity. Some eutrophic impacts, such as periphyton community changes, are thought to be short-term (day-months) and reversible if nutrient additions can be significantly decreased. Other impacts are considered longer-term (years-decades), such as loading peat soil with excess phosphorus that triggers the loss of native plant communities and foraging habitat. There are still many marsh areas where natural water phosphorus concentrations are less than 10 parts per billion (ppb). A combination of agricultural best management practices and construction of over 47,000 acres of wetlands (Stormwater Treatment Areas) are being implemented in an attempt to control phosphorus loadings. The effectiveness of these controls in reducing nutrient concentrations to near historic levels, however, is not yet known.

Mercury Contamination

One of the more insidious problems facing the Everglades is mercury contamination. Over 2 million acres in South Florida are under fish consumption advisories or bans because of mercury contamination in top predator fish such as largemouth bass, bowfin, and oscar. These fish consumption advisories are for human consumption of fish. The human population can change its eating preferences and choose other species of fish or other food to eat. Unfortunately, fish and wildlife that have a diet of mercury contaminated fish do not change their diets because of fish consumption advisories. Mercury concentrations in an endangered Florida panther within Everglades National Park were high enough to either have killed or contributed to its death in 1989. Wading bird populations are about one-fifth of their abundance in the 1930s. Wading bird (Figure 9) mercury concentrations in certain Everglades areas in the early 1990s were at or above levels generally considered to be toxic. Mercury contamination might have been a factor in their decline.

Figure 9. Everglades wading bird populations significantly declined during the 1900s.

Many of the other ecological issues in South Florida—nutrient loading, hydropattern modification (Figure 8), habitat alteration—contribute to the mercury problem, and all these issues are embedded in the South Florida Ecosystem Restoration effort. This report discusses the mercury contamination problem in South Florida in relation to these other issues. Specifically, the discussion focuses on

- Where and why the mercury problem exists,
- Mercury sources to the Everglades ecosystem,
- Changes in mercury contamination levels over time,
- Mercury uptake through the food web, and
- Management implications of mercury contamination in South Florida.

Interactions Among Issues

None of the issues discussed previously are independent of the others. They are all intertwined, each problem affecting the others. Addressing these issues requires a large-scale perspective. Integrated and holistic studies of the multiple issues impacting the Everglades need to compare the risks associated with all impacts and their interactions. The US EPA South Florida Ecosystem Assessment effort is a project that provides a foundation for addressing these issues and contributes to the Comprehensive Everglades Restoration Plan (CERP, or the Plan).

Ecosystem Restoration

Among the federal and state Everglades restoration efforts in progress are the EAA phosphorus control program and projects to restore water delivery (and ecology) throughout the Everglades. The present US EPA South Florida Ecosystem Assessment effort evaluates the integral impacts of several important restoration issues and provides a critical, science-based foundation for future ecosystem assessment and restoration design. Long-term monitoring will provide critical baseline information to evaluate the progress of ecosystem restoration. More importantly, continued monitoring is the only way to evaluate the effectiveness of management strategies undertaken to improve ecological conditions.

US EPA REGION 4 SOUTH FLORIDA ECOSYSTEM ASSESSMENT PROJECT

The Region 4 South Florida Ecosystem Assessment Project uses the US EPA (1998) ecological risk assessment framework as a foundation for injecting scientifically sound information into the decision-making process (Figure 10). The mercury contamination issue is guided by seven policy-relevant questions.

1. What is the magnitude of the problem?
2. What is the extent of the problem?
3. Is it getting better, worse, or staying the same over time?
4. What is causing the problem?

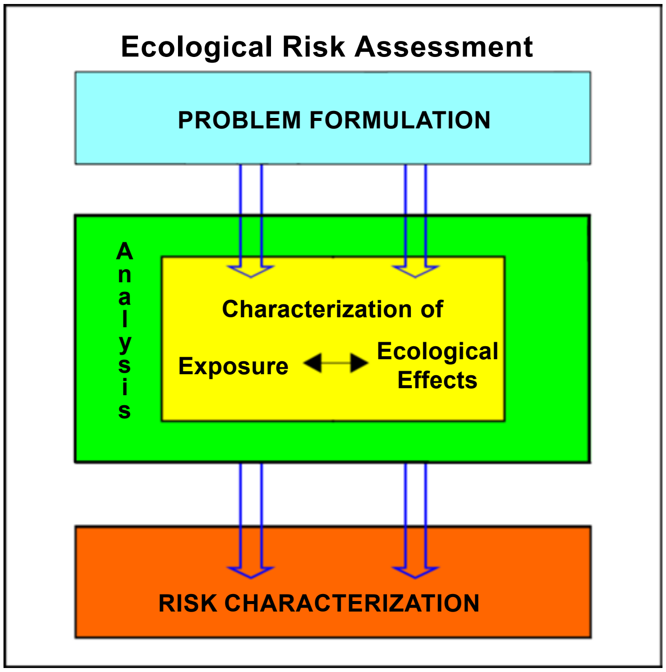

Figure 10. Ecological Risk Assessment Framework. Ecological risk assessment is a way of determining the likelihood of adverse ecological effects from a pollutant such as mercury.

5. What are the sources of the problem?
6. What is the risk to the ecological resources?
7. What can we do about it?

These seven questions are equally applicable for all the environmental problems in the Everglades. These problems include eutrophication, hydropattern modification, habitat alteration, mercury contamination and exotic species introductions.

To begin answering these seven questions, the Region 4 project used a statistical, probability-based sampling (see sidebar) strategy to select sites for sampling. A key advantage of probability-based sampling is that it allows one to estimate with known confidence and without bias, the current status and extent of indicators for the condition of ecological resources (Thornton et al. 1994, Stevens 1997). Also, indicators of pollutant exposure and habitat condition can be used to identify associations between human-induced stressors and ecological condition. This design has been reviewed by the National Academy of Sciences, and the US EPA has applied it to lakes, rivers, streams, wetlands, estuaries, forests, arid ecosystems, and agro-ecosystems throughout the United States (Olsen et al. 1999, US EPA 1995).

Probability Samples: Foundation For Regional Risk Assessment

Probability samples are samples where every member of the statistical population has a known chance of being selected and where the samples are drawn at random. The project used a statistical survey design in selecting its probability samples so that the samples were drawn in direct proportion to their occurrence in the population, whether it was EAA or WCA canals, sawgrass or cattail marshes, or soil type. Consequently, the measurements can be used to estimate the proportion (extent) and condition of that resource in South Florida. As important, each site is selected so it represents that resource in an unbiased manner. The sampling design is not biased to favor one marsh type over another (e.g., sampling only the marshes next to a road because it was easier, or selecting a canal because it looked good or bad). The risk to any of the ecological resources from the multiple environmental threats in South Florida is a direct function of the extent and magnitude of both the threat and the ecological effects. Probability samples permit us to estimate both magnitude and extent of problems for the entire marsh and canal ecosystems. Probability samples, therefore, provide the foundation for ecological risk assessment in South Florida.

Samples were collected from south of Lake Okeechobee to the mangrove fringe on Florida Bay and from the ridge along the urban, eastern coast into Big Cypress National Preserve on the west. The distribution of 200 canal stations is shown in Figure 11 while the distribution of 750 marsh stations is shown in Figure 12. The stations represent the ecological condition in over 750 miles of canals and over 3,000 square miles of marsh. Canals were sampled in September 1993 and 1994, and May 1994 and 1995. Some of these results have been reported in previous documents. Marshes were sampled in April 1995, May 1996 and 1999, and September 1995, 1996 and 1999. This corresponds to three dry (April and May) and three wet (September) seasons for the marsh system over a five-year period. Big Cypress National Preserve was not sampled in 1999 in order to place all the effort on the central flow-way of the Everglades marsh, which is the focus of this report. The sample collection included surface water (Figure 13), marsh soil (Figure 14), fish (Figure 15), and algae at each site during each sampling period. Porewater, floc, periphyton species composition, sawgrass and cattail tissue, macrophyte species, and plant community composition from ground sampling and aerial photo interpretation for each site were added in 1999. The comprehensive multimedia design of this project included over 60 laboratory analytical procedures. In addition to the canal and marsh sampling, mercury was also sampled biweekly at 7 canal flow control structures to estimate mercury loading from runoff into the Everglades during a 3-year period from 1994-96.

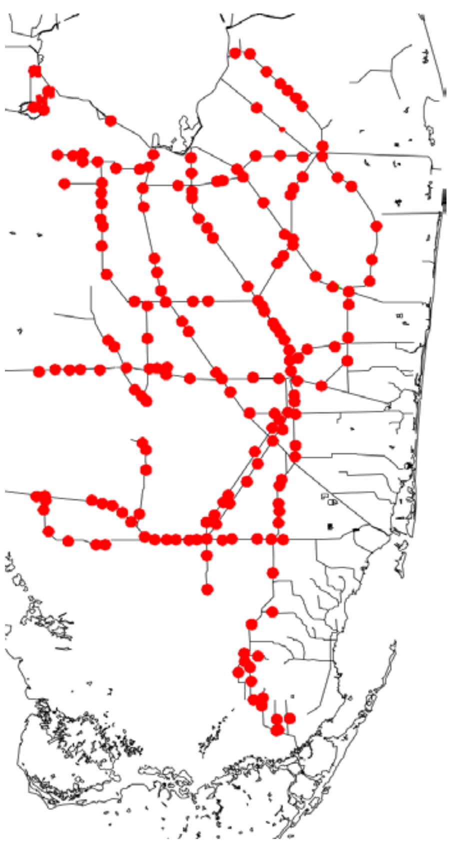

Figure 11. 200 sampling sites are located on over 750 canal miles.

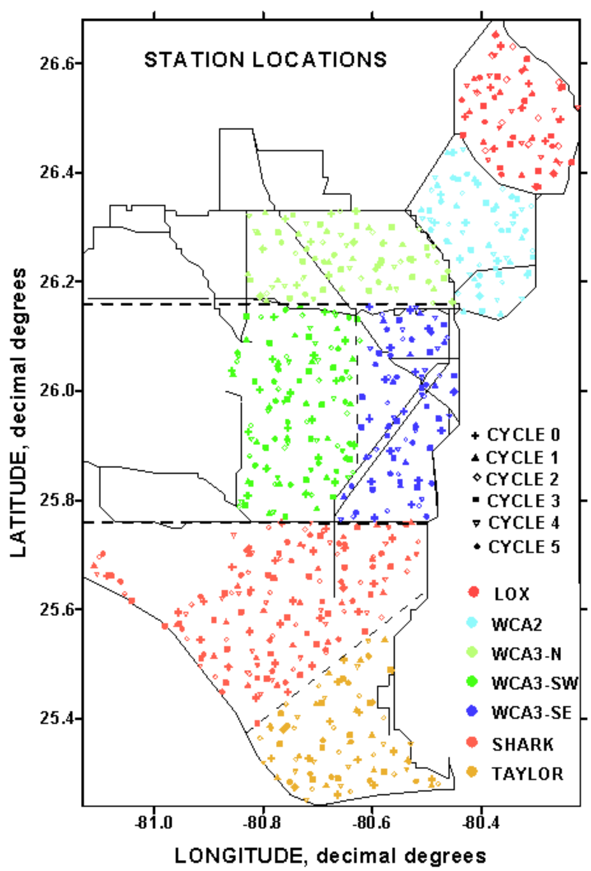

Figure 12. 750 sampling sites are located in over 2 million marsh acres.

Figure 13. Helicopters and air boats were used for sampling the marsh.

Figure 14. Soil cores were collected at each of the marsh sites and analyzed for mercury, nutrients, and other constituents.

Figure 15. Mosquitofish were sampled because they are common in both the canals and the marsh.

This study permits a synoptic look at the ecological condition in all of the freshwater Everglades marsh and most of the freshwater canal system in South Florida from Lake Okeechobee to the mangrove system. This large-scale perspective is critical in predicting the impacts of different factors, such as mercury and phosphorus distributions throughout the canals and marsh, habitat alteration, or hydropattern modification on the entire system rather than at individual locations or in small areas. Looking only at isolated sites in any given area and extrapolating to South Florida can give a distorted perspective. The statistical sampling approach permits quantitative estimates, with known confidence, about population characteristics, such as acres of marsh in cattails, percent of the marsh with fish mercury concentrations greater than a proposed predator protection level, or percent of canal miles with total phosphorus concentrations greater than the initial control target concentration of 50 ppb.

Parameters measured at each site can be used to answer questions on multiple issues including

- Mercury contamination (e.g., mercury in water, soil, algae, and fish).
- Eutrophication (e.g., total phosphorus concentrations, cattail, other macrophyte species, and periphyton distributions).
- Habitat alteration (e.g., plant community distribution throughout the Everglades).
- Hydropattern modification (e.g., water depth at all sites).

Study information is contributing to decisions not only on mercury contamination, but also on the other major problems facing ecosystem restoration in South Florida.

The study provides information critical to the South Florida Ecosystem Restoration design and evaluation of whether its precursor and ecological success criteria are being achieved (Table 1).

Table 1. Example Everglades Ecosystem Restoration success indicators (Science Subgroup, 1997).

Problem	Success Indicators
Water Management	Reinstate system-wide natural hydropatterns and sheetflow
Habitat Alteration	Increased spatial extent of habitat and wildlife corridors
Eutrophication	Reduced phosphorus loading
Mercury Contamination	Reduce top carnivore mercury body burden
Endangered Species	Recovery of threatened/endangered species
Soil Loss	Restore natural soil formation processes and rates

The next sections assess hydropattern modification, habitat alteration, eutrophication and mercury contamination based on the sampling program in canals and marshes from 1993 to 1999. A weight-of-evidence approach was used in this assessment. Not all the information needed to provide definitive answers for each of the seven policy-relevant questions is known, but providing information on an interim basis and incrementally increasing our knowledge permits this information to be used in upcoming and future decisions concerning Everglades restoration.

For the sake of clarity in understanding the interaction of these issues, this report describes the ecosystem by dividing the central north to south flow-way into seven subareas. These subareas (Figure 4) are from north to south: The Arthur R. Marshall Loxahatchee National Wildlife Refuge or Water Conservation Area 1 (WCA1 or Lox); Everglades Water Conservation Area 2 (WCA2); Everglades Water Conservation Area 3 north of Alligator Alley (WCA3-N); Everglades Water Conservation Area 3 Southeast of Alligator Alley (WCA3-SE); Everglades Water Conservation Area 3 Southwest of Alligator Alley (WCA3-SW); WCA3-SE and WCA3-SW indicate an east-west gradient in the central part of this system; Everglades National Park south of Tamiami Trail is divided into Shark River Slough (SRS) and Taylor Slough (TS) by striking a line from northeast to southwest along the leading edge of a low geological ridge of cap rock in the system. The interaction of the issues among these seven subareas is the substance of this report.

HIGHLIGHTS

Hydropatterns

The "River of Grass" was so named because the original Everglades was a slowly moving river, flowing from Lake Okeechobee in the north to Florida Bay in the south. Urban expansion on the east and the construction of canals and levees to store and drain water have significantly altered the natural hydrologic regime of the Everglades. The original Everglades, however, was not always inundated. Understanding the hydrometeorology patterns is important to understanding nutrient and mercury loading and transport in the system. The term hydropattern refers to the depth, duration of flooding, timing, and distribution of freshwater flows. It includes the concept of hydroperiod, which is the amount of time each year that the ground is covered with water, as well as the spatial distribution of water.

There are distinct seasonal patterns of precipitation and inundation in the subtropical Everglades. Precipitation follows a cyclic pattern with May-October being the rainy wet season and November-April being the dry season (Figure 16). This pattern is opposite that in most temperate areas where the wet seasons are during the winter and the dry seasons are during the summer. The sampling events in this study were near the end of the dry (April, May) season and the wet (September) season. Stormwater discharge patterns lag the rainfall, but also indicate the seasonal swing from wet to dry periods (Figure 17). Even though the hydrology of the Everglades is highly managed, there are still characteristic hydropatterns that follow the precipitation patterns.

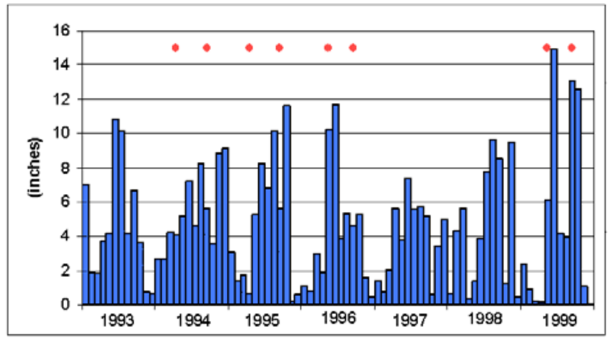

Figure 16. Monthly rainfall (inches) from 1993 to 1999 at pumping station S-8. Months when samples were collected are indicated by a dot.

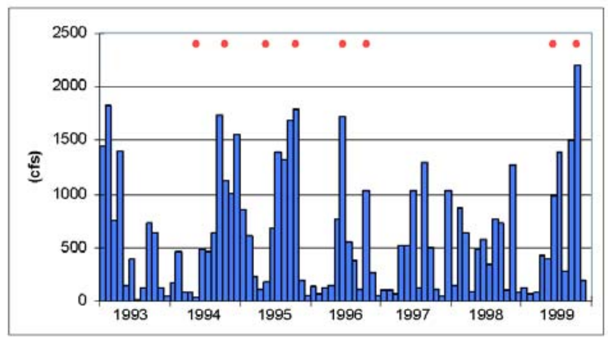

Figure 17. Monthly discharge at S-8, a pumping station that provides flood control for part of the EAA by discharging into the Everglades. Discharge varies from zero to several thousand cfs in response to rain events.

Water depth, and the wet-dry areas of the Everglades, vary significantly throughout the year and among years. Geographically distributed probability samples of water depth taken during each systematic survey found surface water coverage ranged from 44% to 100% of the 5,500 km^2 area of Everglades marsh (Figure 18). Spatial plots of these data for each cycle illustrate a progression of surface water volume increasing from May 1999 < May 1996 < April 1995 < September 1996 < September 1999 < September 1995 which was a record wet season (Figure 19). Long-term, period of record, mean monthly marsh water depths measured at four fixed locations indicate the same seasonal fluctuations, with minimum water levels in April-May and maximum water levels generally in October-November similar to those measured during the 1995, 1996, and 1999 sampling years (Figure 20). During

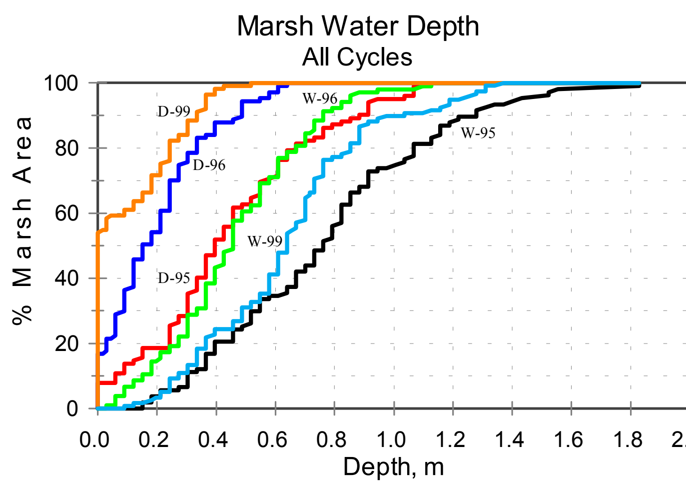

Figure 18. Cumulative distributions of water depths during sampling. W = wet season, D = dry season, No = Year.

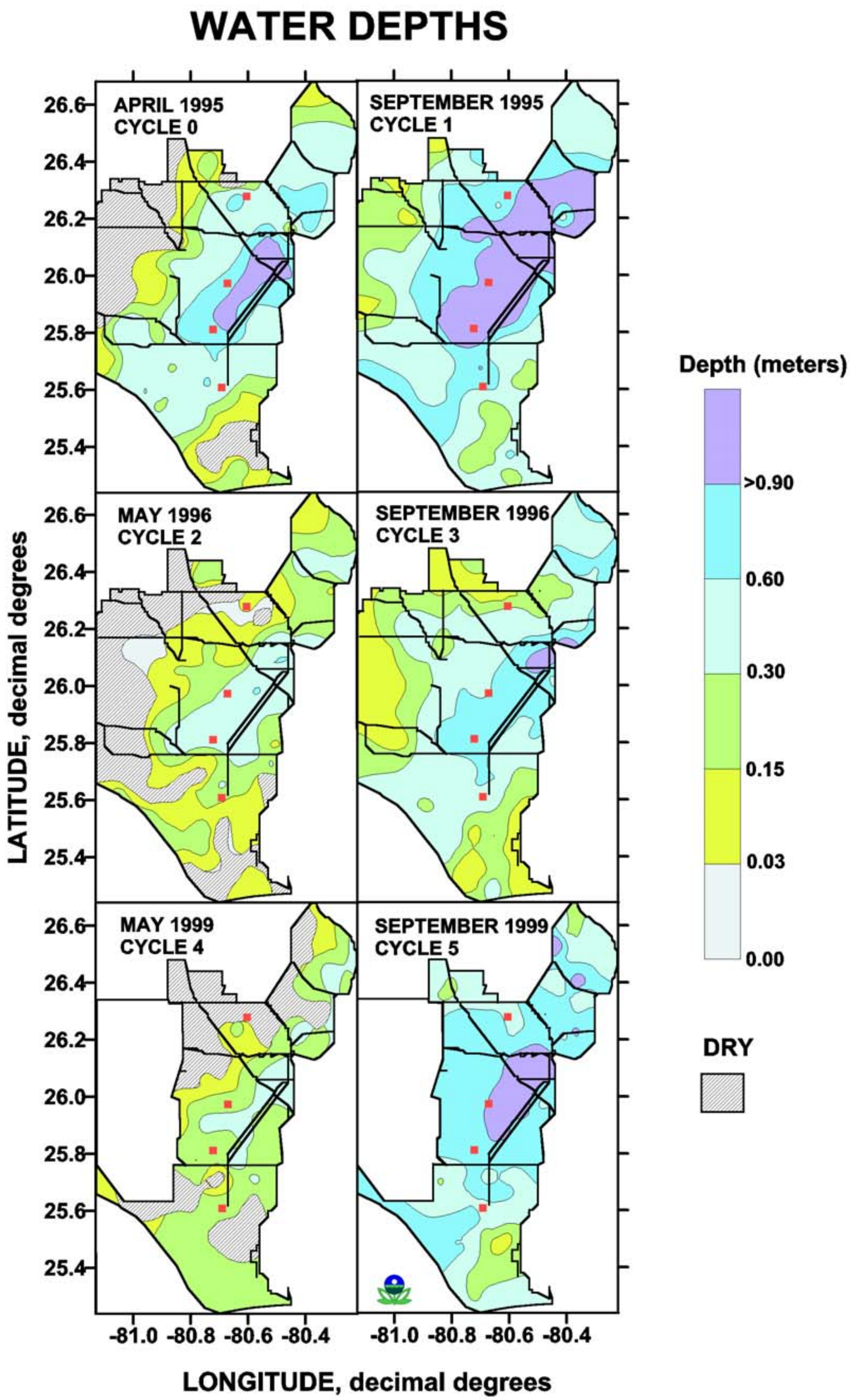

Figure 19. Water depth in the marsh system during the six sampling events. Colored squares indicate the location of water depth gauges used for Figure 20.

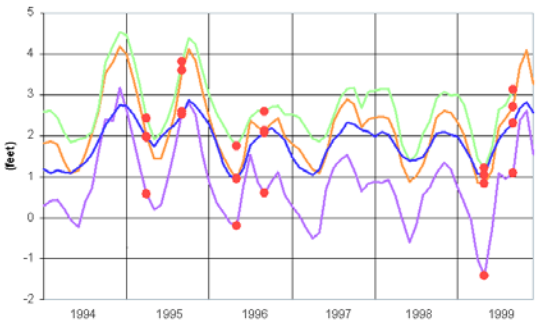

Figure 20. Average monthly water depths measured at gages 3A-NE, 3A-4, 3A-28, and P-33. Dots indicate the water depths at the sampling times in 1995, 1996, and 1999.

April 1999, major areas in the northern part of the system (e.g., WCA-3N) became dry enough that wildfires occurred, burning much of this area. Wildfires are a natural phenomenon in the Everglades during drought years.

Because the sampling design was based on a systematic, probability sample, there was a relatively uniform distribution of sites throughout the system. Surface contouring with spatial statistical software such as SURFER (Golden Software 1999) or ARCVIEW (1996) is compatible with a systematic distribution of points. In addition, the probability samples permit estimates of the surface area associated with each sampling site. Therefore, it is possible to use the measurements taken at sites to characterize conditions, including water depth, for the entire 5500 km^2 area. Using the mean depth computed for the areas inundated during the dry seasons in 1995 - 1999 and the wet season in September 1996, it was possible to estimate the volume of water that was on the marsh at these times because volume is equal to the mean depth multiplied by surface area.

Examination of stage duration curves for gages located in southern WCA3 and northern Shark Slough indicated about 5 inches of water were ponded behind (i.e., north of) Tamiami Trail during the 1999 dry season. A surface water volume to surface area curve for the ecosystem was developed (Figure 21) using Geographic Information System (GIS) techniques for the four driest sampling cycles. The lowest point on the curve is an estimate of the loss of ponding in the system and was determined by subtracting 5 inches from the dry 1999 water levels. The curve illustrates the very large surface area to volume ratio characteristic of this ecosystem. It also indicates that the 5,500 km^2 ecosystem becomes completely inundated with a surface water volume of about 2.9×10^9 m^3. Under extreme drought conditions, such as May 1999, the surface water volume in the marsh declined to about 0.5×10^9 m^3. Elimination of ponding in the system would result in an additional dry area of about 400 km^2 of present slough habitat. The long and intermediate hydropattern area of the marsh occupies about 4200 km^2 with an associated water volume of 1.5×10^9 m^3.

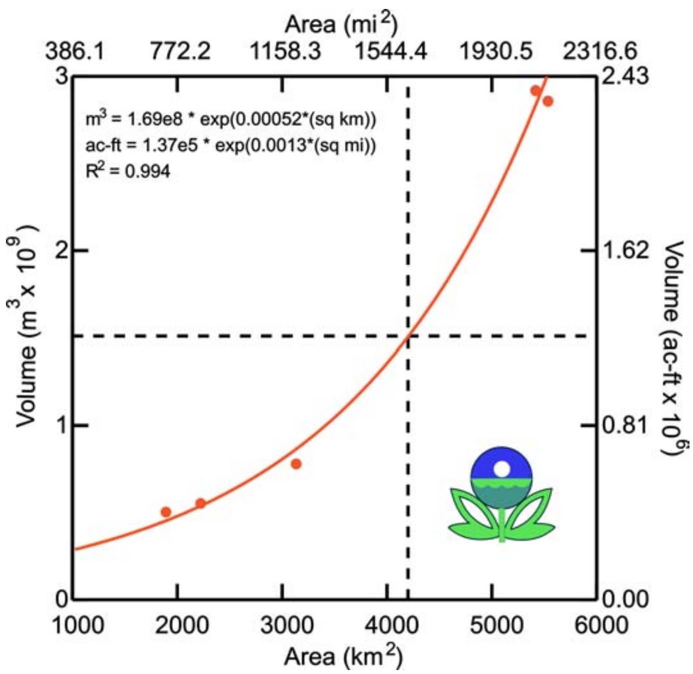

Figure 21. The surface area to volume curve, in both English & metric units, shows how much water (volume) is presently needed to flood given areas of the marsh ecosystem. The area of long hydroperiod marsh is left of the vertical dashed line.

To inundate the additional 1,300 km^2 of marsh required an equivalent volume of water even though the surface area is only about one-third of the longer hydropattern marsh.

Water management to sustain ecological resources will require substantial quantities of water to maintain even minimum habitat coverage during the dry seasons. The short hydropattern portion of the marsh beyond 4,200 km^2 will most likely remain dependent on the wet season rainfall. Due to the present system of levees and canals, ponding in the system occurs primarily in WCA3-SW and WCA3-SE with smaller areas along the southern reaches of Loxahatchee and WCA2 (Figure 22). The surface areas of inundation illustrated show the area without ponding < dry 1999 water level <4,200 km^2 < remaining 1,300 km^2 describing the long, intermediate, short and extremely short hydropatterns, respectively (Figure 22). Drought prone areas are the northern tip of Loxahatchee, WCA3-N and Taylor Slough (See Figure 19, Cycle 4 dry areas). A loss of peat soils occurred in WCA3-N (Davis, 1946, Stober et al. 1998, Scheidt et al. 2000). Water management to establish minimum surface flow in extremely short hydroperiod marshes like WCA3-N will be a considerable challenge. Alternatively, maintenance of ponded slough habitat during drought conditions is critical because the most stable aquatic habitats with a rich flora and fauna occur in these areas. Odum (1971) cites the Everglades as a "fluctuating water ecosystem" or pulsed ecosystem where recurrent drought maintains the system in an early successional stage. He stresses the importance of the seasonal change in water level in maintaining the natural system.

This study provided a synoptic look at the water regime over the entire system during both dry and wet seasons. It spans the range of hydrologic conditions that typically occur in the system and provides a sound baseline for evaluating desired future changes in hydropattern during restoration. It also provided a general surface area to volume relationship (Figure 21) that can be used to quickly evaluate volume requirements for different inundation regimes.

Habitat Alteration

One of the greatest human impacts in South Florida has been to the natural habitat. Over 50% of the historic Everglades wetlands have been converted to urban and agricultural uses. The original habitat was described as a "River of Grass" because of the vast expanses of sawgrass communities. One approach for assessing

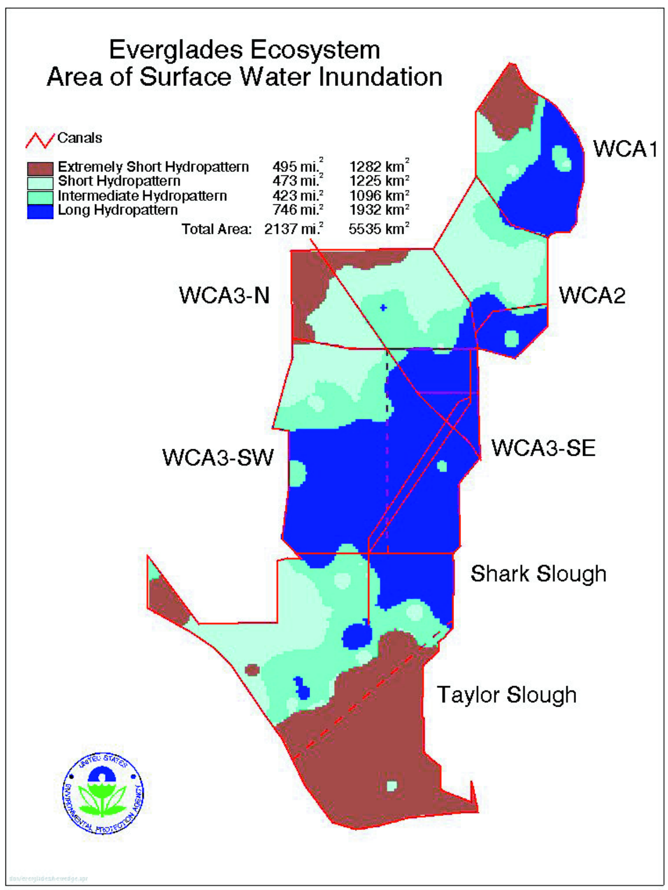

Figure 22. Based on water depths measured during the study, plant community distributions, and comparisons with SFWMM output, the area and contours of long to short hydropattern were estimated with GIS.

current habitat condition, then, would be to characterize the existing plant communities. Three macrophyte studies were completed during 1999 in the Everglades ecosystem, including an aerial photo vegetation assessment, a presence/absence macrophyte community census study, and a macrophyte morphometric/landscape abiotic parameter analysis.

The first study utilized remote sensing and GIS techniques to successfully assess vegetation patterns over the Everglades ecosystem. Analysis of areal summary statistics for 1994-95 indicated general trends such as the diminishing coverage of cattail from north to south ranging from 12 to 17% in the north to 0.4% in the south. It also provided insight into other habitat characteristics. Wet prairie vegetation was found to cover greater percentages of the WCAs than the ENP, while the ENP contained the highest percentage of sawgrass. Randomly selected 1 km^2 plots around each sampling site adequately represented vegetation cover in the Everglades. The average difference in percent cover for vegetation types for the 1 km^2 samples at 250 probability sites compared to full coverage maps of the marsh was 1.5% in ENP Shark Slough (Welch and Madden 1999) and 0.4% in WCA3-N (Rutchey and Vilchek 1999). This effort established a baseline of conditions existing in 1994/1995 when the photographic series was made and a quantitative methodology for efficiently monitoring future vegetation patterns and assessing changes in the Everglades ecosystem over space and time. Capturing this baseline for the entire ecosystem will be important for comparison with future monitoring efforts because a comparable systematic baseline prior to this did not exist. It also allowed characterization of the habitat at the beginning of the 1995 marsh sampling events.

In the second study, a total of 161 taxa were collected during the macrophyte census. One hundred twenty-eight of these taxa were identified to the species level and eight to the genus level, for a total of 136 identified taxa from 250 marsh sites. This second study provided a quantitative evaluation of marsh macrophyte community types and their distributions across the Everglades ecosystem. This quantitative evaluation established a baseline against which to evaluate community change during restoration. Cluster analysis indicated that four major plant community types were found to occur across the entire ecosystem: sawgrass (*Cladium jamaicense*); waterlily (*Nymphaea odorata*)-purple bladderwort (*Utricularia purpurea*); spikerush (*Eleocharis cellulosa*); and cattail (*Typha domingensis*). These communities differ in their hydroperiod, water depth, soil type and nutrient level requirements. The dominant species within each community have different tolerances for soil TP.

Sawgrass is the only community that occurs across the entire ecosystem (Figure 23); the other communities are more localized in their distributions. The sawgrass community type is dominated by *Cladium jamaicense*, with the next most common species present approximately 25% of the time. Thus, although specialized for survival in an oligotrophic environment, sawgrass is a generalist in this ecosystem, occurring across a broad range of hydroperiods, soil types, and soil nutrient levels. A plot of *Cladium jamaicense* culm densities shows not only the ubiquitous distribution across the ecosystem but areas around the EAA and in Taylor Slough where densities are highest in the system (Figure 24).

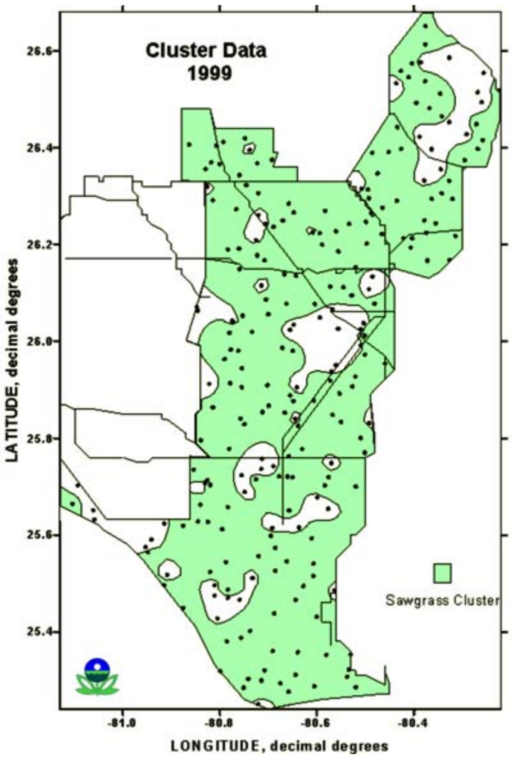

Figure 23. Sawgrass occurs almost everywhere throughout the marsh as indicated by its spatial distribution shown above.

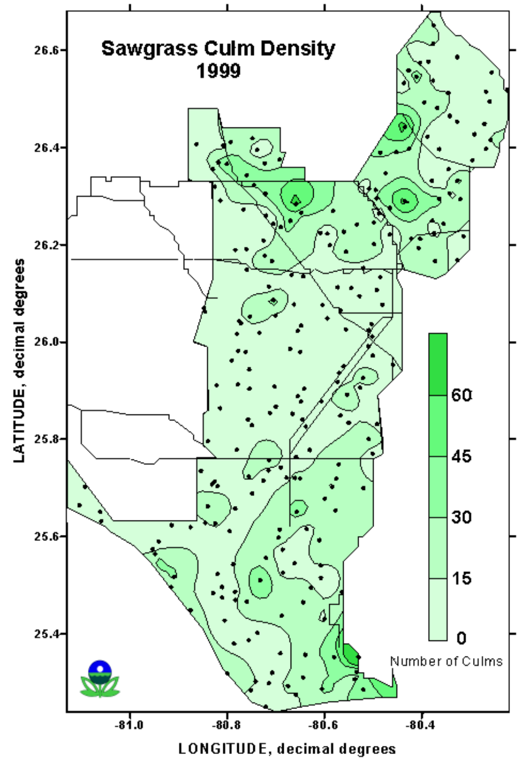

Figure 24. Sawgrass culm densities across the ecosystem.

Although different parts of the ecosystem and different water management subareas share many plant species, these areas do not have equal representation of the major plant communities identified here. The frequency and abundance of these communities differ across the system, indicating that water conditions or ecosystem processes, such as nutrient cycling, vary among the subareas. The water lily-purple bladderwort community (Figure 25) is a very good indicator of stable water slough habitat (i.e., long hydroperiod) in this system, along with its associated communities of aquatic invertebrates and fishes. The distribution of the cattail cluster is also illustrated in Figure 25 where it is largely associated with WCA2, WCA3-N, and the undeveloped part of the EAA. The spikerush community is found in areas of the marsh with low total phosphorus concentrations and intermediate to long hydroperiod (Figure 26). Some communities, for example beakrush (*Rhynchospora tracyi*), which have been noted to be prominent historically in previous work (Loveless 1959, Gunderson 1994), did not appear as distinct communities in our analysis. These differences could represent a historical change in community composition in the ecosystem and/or could be a result of the unbiased quantitative nature of a random survey.

The third 1999 macrophyte study investigated plant morphological changes in relation to abiotic spatial changes across the ecosystem. *Sagittaria lancifolia* (Arrowhead) was found across a broad range of soil TP and soil organic content in the Everglades. We have shown in a parallel study that *S. lancifolia* leaf morphology provides an indication of soil nutrient level and water depth. Plants with broader laminae and shorter petioles are found in sites with higher nutrients, while plants with longer petioles are found in deeper sites with lower nutrients. Although sawgrass was

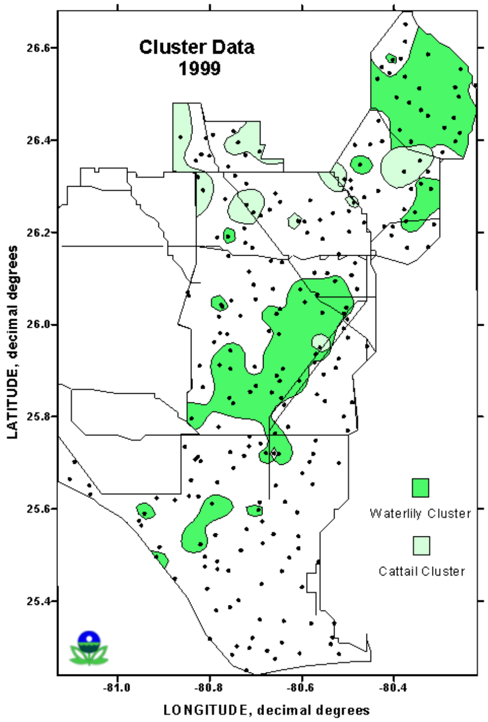

Figure 25. Water lily distributions showing long hydroperiod areas of the marsh and cattail cluster distributions associated with high soil phosphorus.

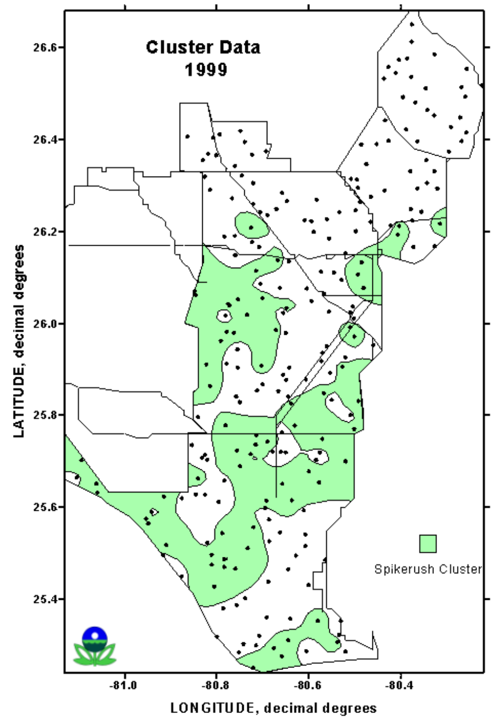

Figure 26. Spikerush community distributions showing areas of the marsh with low total phosphorus concentrations in soil and intermediate to long hydroperiod.

present throughout the Everglades, sawgrass morphology and density varied across the environment, which correlated with changes in soil type, nutrients, and hydroperiod. Controls on variations in density and morphology, as well as patchiness, represent areas for future research.

These data, in conjunction with future monitoring, can be used to predict changes in the distribution of the major macrophyte communities as a result of restoration actions that change water depth. It has also identified potential indicators of low and high phosphorus regimes and long versus short hydropattern areas.

Eutrophication

A phosphorus control program was initiated in the 1990s in order to prevent the further loss of Everglades plant communities and wildlife habitat due to nutrient enrichment. Phase I of the program requires that discharges from the EAA into the Everglades be reduced to 50 ppb or less. Control is to be achieved by a combination of about 47,000 acres of treatment wetlands, referred to as Stormwater Treatment Areas (STAs) (Figure 27) and agricultural Best Management Practices (BMPs). The first STA (about 10% of the Phase I treatment acreage) began discharging in 1994, and the BMPs were required to be fully implemented by 1995. Comparing 1999 with 1995-96 baseline phosphorus concentrations presents an opportunity to look for early changes in total phosphorus concentrations in water and soil. McCafferty and Baker (2000) report a 55% reduction in EAA basin phosphorus load for

WY2000 and a 3 year trend showing a 48% reduction as compared to what would have been expected without BMPs. A clear trend in phosphorus load reductions has resulted following implementation of the BMPs.

The median wet season water total phosphorus concentrations with associated 95% confidence intervals are presented by subarea along the flow path (Figure 28) with the combined 1995-96 data compared with the 1999 data. The 1999 water total phosphorus concentrations indicated that all subareas were about equal to or less than the 1995-96 concentrations with a statistically significant decrease (confidence limits do not overlap) in Taylor Slough. A total phosphorus gradient in water persists in the system with maximum concentrations occurring in WCA3-N. However, even in WCA3-N, the medians declined from 16 to 11.4 ppb over the intervening three year period. Nutrient loading might have increased across the northwestern portions of WCA3-N and WCA3-SW in 1999 (Figure 29), but decreased in other areas. The high concentrations of TP in water observed in WCA3-SE and WCA3-SW during the 1999 dry season might have been from phosphorus mobilization during the wildfire, which burned WCA3-N two weeks prior to sampling. There has been consistent improvement in the spatial extent of wet season TP concentrations in marsh water since 1995. The extent of the marsh area less than 10 ppb in the 1999 wet season had increased to 87% from 41% in 1995 (Table 2).

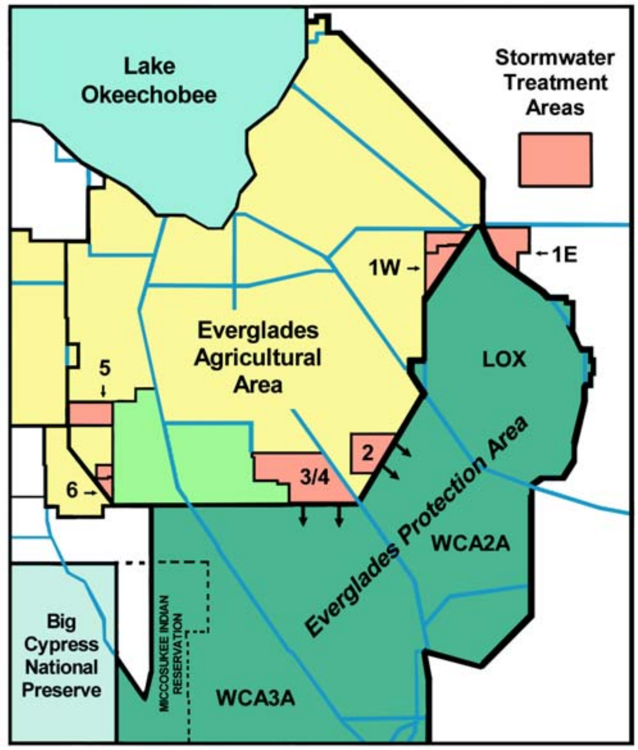

Figure 27. Location of Phase I phosphorus control program stormwater treatment wetlands. In combination with agricultural best management practices they are to decrease phosphorus to 50 ppb or less prior to discharge into the Everglades (from SFWMD).

The median wet and dry season soil concentrations with associated 95% confidence intervals are presented by subarea along the flow path (Figure 30) with the combined 1995-96 data compared with 1999. The floc and layer of periphyton mat, if present on the soil surface, was removed and analyzed separately leaving only the soil material minus large roots, rocks and coarse debris. Some

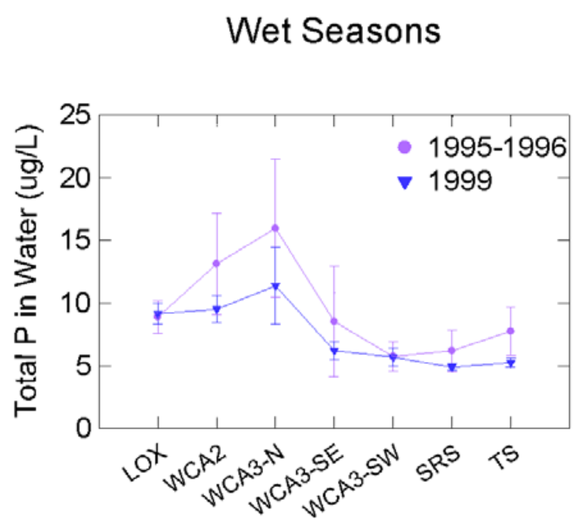

Figure 28. Median wet season water total phosphorus concentrations were lower in the high loading areas of WCA2 and WCA3N during 1999 compared to 1995-96.

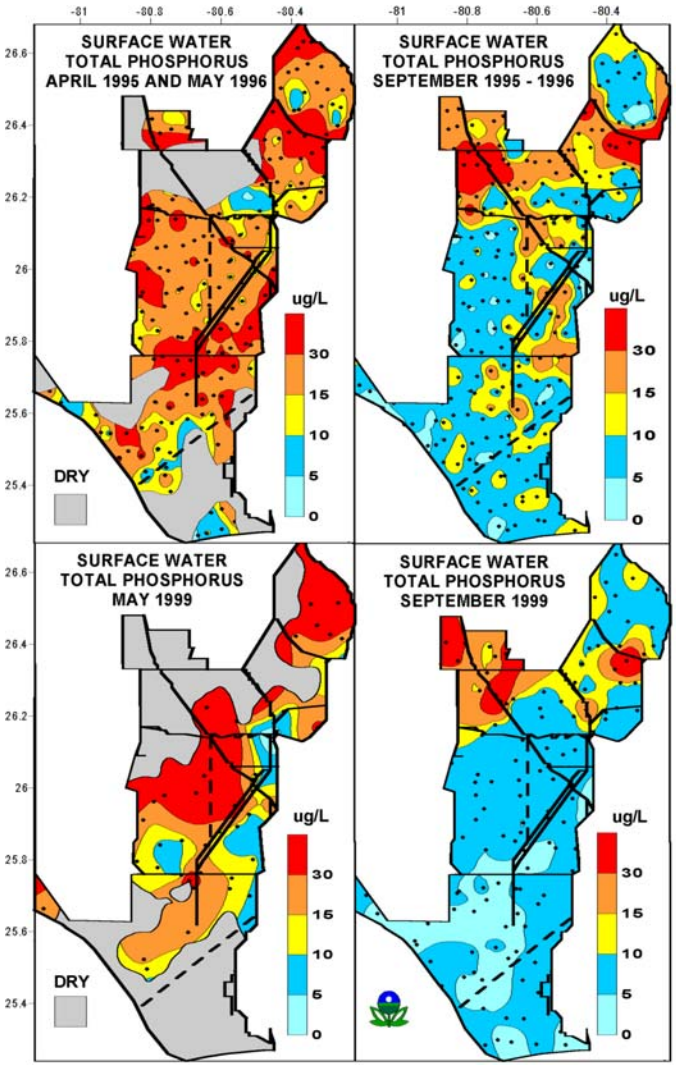

Figure 29. Surface plots of TP measured in surface water during dry (left) and wet (right) seasons in Phases 1 (1995-96) and 2 (1999) showing north-south gradients.

Table 2. Spatial extent (%) of TP in water (wet seasons marsh).

Year	1995	1996	1999
% <10 ppb	41	78	87
% <15 ppb	65	87	93
% >50 ppb	3	2	2

investigations analyze the periphyton mat as part of the soil. Periphyton was analyzed separately to investigate uptake and bioaccumulation of mercury and subsequent transfer to other parts of the food web.

The 1999 data indicate a significant decline in TP soil concentrations in Loxahatchee, WCA3-N, WCA3-SE, WCA3-SW, and Shark Slough. Lowest concentrations were consistently found in Taylor Slough, however, the 1999 decline was not significant. No significant change in soil TP concentration was found in WCA2, the most impacted part of the system. The median soil TP concentrations ranged from 350 to 400 mg/kg, which contributes to a significant increase in the proliferation of cattails in the northern subareas (Figure 31) where most of the stormwater runoff enters the public Everglades from the EAA. The location of the decrease in soil TP observed from 1995-96 to 1999 in the downstream subareas is consistent with expectations. The initial subareas to indicate a response will be those with lower soil concentrations, while the last subareas to show change with reduced TP loading to the system will be the most highly contaminated northern subareas. Figure 31 also shows total phosphorus concentrations in soil for 1995-96 and 1999, indicating the hot spots greater than 600 mg/kg in subareas WCA2 and WCA3-N along with the decline observed in 1999.

Changes in the total mass of phosphorus, by media, from 1995 to 1999 are shown in Table 3. There was a significant decrease in the phosphorus mass in water from 1995 to 1996. Water total phosphorus mass was comparable between 1996 and 1999. There has been a progressive decline in the total mass of phosphorus in the 0-10 cm of soil from 1995 to 1999. The mass of phosphorus in floc, although only measured during 1999, was over 50 times the mass of phosphorus in the water. The floc is a microbially active media that likely plays an important role in phosphorus cycling in the marsh. Little is known about the dynamics in the floc layer.

The changes observed in water and soil TP mass and concentrations from 1995-96 to 1999 require verification by future large scale monitoring due to the dynamic nature of this ecosystem. However, the baseline and tools needed for assessments of system responses have been developed.

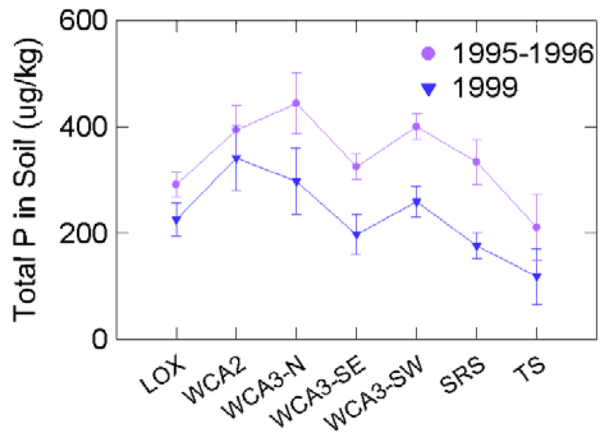

Figure 30. Median soil concentrations of TP (ug/kg dry weight) for wet and dry seasons combined by subarea along the Everglades flow path.

Mercury Contamination

The Regional Environmental Monitoring and Assessment Program (REMAP) was initially designed to address mercury contamination in South Florida.

Assessing the extent and magnitude of mercury contamination and associated factors provides insight into where the contamination might be occurring. The first step was selecting appropriate indicators. Largemouth bass would appear to be a good indicator for mercury contamination. They are a popular sport fish and have high mercury concentrations because they are at the top of the aquatic food chain. Unfortunately, largemouth bass are not found at every sampling site, they live several years and may move over large areas so it is hard to determine exactly where their mercury contamination occurred. They are also harder to sample in the marsh. Largemouth bass monitoring was the responsibility of Florida Fish & Wildlife Conservation Commission.

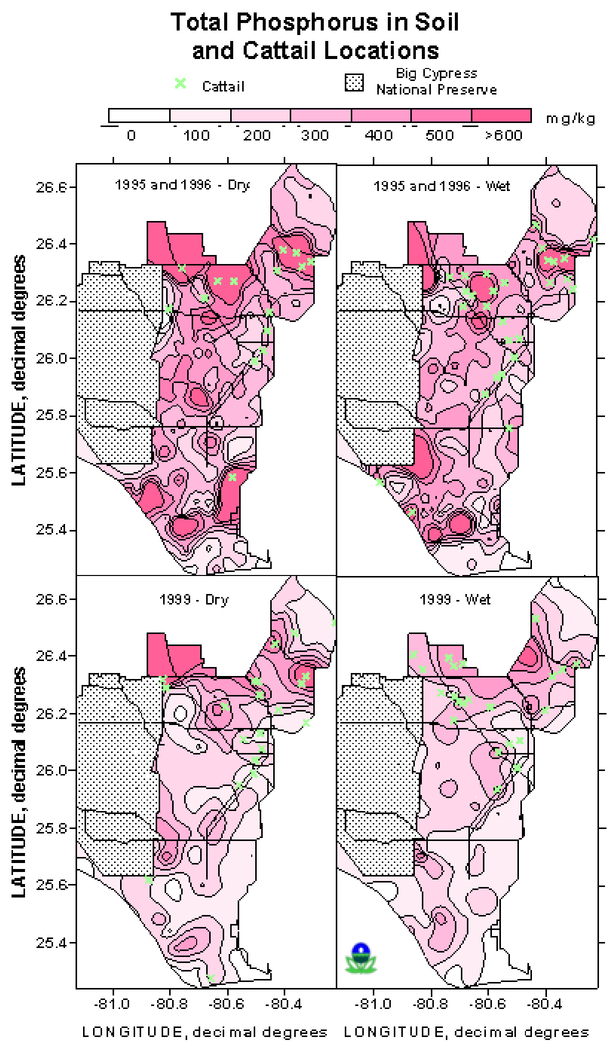

Figure 31. Spatial plots of total phosphorus in soil measured during phases 1 and 2 indicating sites where cattails occurred.

Table 3. Metric tons of total phosphorus, by media and year, in the South Florida ecosystem.

Media	1995	1996	1999
Water	75.2	23.5	24.3
Floc*			1,549
Soil	46,833	39,489	21,281
Macrophytes			

* Assumed floc thickness = 0.1 water depth

Mosquitofish were selected as the indicator fish species because they are common throughout the marsh and canals, can be easily collected at all sampling sites, and are in the food chain for wading birds and sport fish. In addition, a predator protection level of 100 ppb mercury in prey fish has been proposed by the US Fish and Wildlife Service (Eisler, 1987). Since mosquitofish are prey for the largemouth bass, this predator protection level can be used as a criterion to determine potential exposure of largemouth bass and other fish-eating animals to mercury.

Mercury Patterns

The highest baseline Phase I (1995-96) mercury concentrations in fish were found in the marsh (Figure 32). Over half the area in the marsh (62% or over 1 million acres) had mosquitofish with mercury concentrations that exceeded 100 ppb (Figure 32). Only 17% of the canal miles (about 130 miles) had mosquitofish with mercury concentrations that exceeded 100 ppb (Figure 32). There also was a “hot spot” of mercury in mosquitofish and wading birds (Frederick et al. 1997) between Alligator Alley and Tamiami Trail (Figure 33) in subarea WCA3-SW. Alligator Alley and Tamiami Trail are two highways that divide the Everglades into 3 general areas and provide a frame of reference for looking at these spatial patterns. The highest mercury concentration in mosquitofish occurred between Alligator Alley and Tamiami Trail in both the canal and marsh habitats (Figure 34). However, mosquitofish also had high mercury contamination in the marsh south of Tamiami Trail in Shark Slough (Figure 34). The marshes, then, were the primary areas of mercury contamination. Methylmercury was found to exceed 95% of the total mercury in mosquitofish.

The highest concentrations of methylmercury (the form of mercury concentrated in the food chain) in algae, which are plants at the base of the food chain, were also found in the marsh between Alligator Alley and Tamiami Trail.

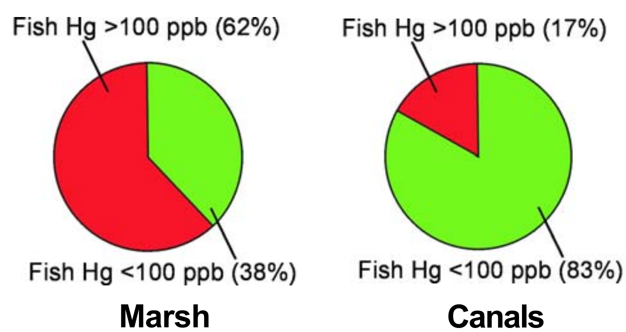

Figure 32. About 62% of the marsh area, compared to 17% of the canal miles, have mosquitofish with mercury concentrations exceeding the proposed predator protection level of 100 ppb.

Similar mercury patterns and their general location were also observed in the monitoring of largemouth bass conducted by Florida Fish & Wildlife Conservation Commission since 1989 (Lange and Richard 2001).

The highest methylmercury concentrations in water, however, were found north of Alligator Alley (Lox, WCA2, and WCA3-N). The methylmercury water concentrations found between Alligator Alley and Tamiami Trail (AA-TT included WCA3-SE and WCA3-SW) were only slightly lower than concentrations north of Alligator Alley (Figure 35). Methylmercury concentrations in water south of Tamiami Trail (TT-S) in Shark Slough were 50 to 60% lower than concentrations found in the other areas to the North.

Other Water Quality Patterns

There were also patterns from north to south in the system for constituents besides mercury. Total phosphorus (Figure 29), total organic carbon (Figure 36), and sulfate (Figure 37), for example, all had steep,

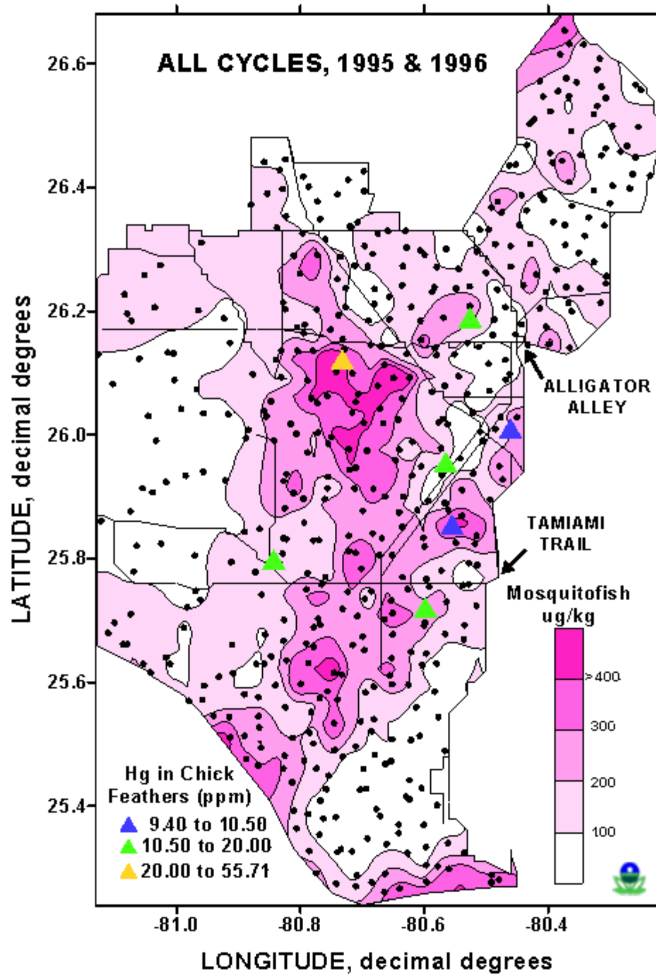

Figure 33. The hot spot is the same for total mercury in both mosquitofish and great egret chick feathers. Largemouth bass and algae mercury concentrations are also high in this hot spot.

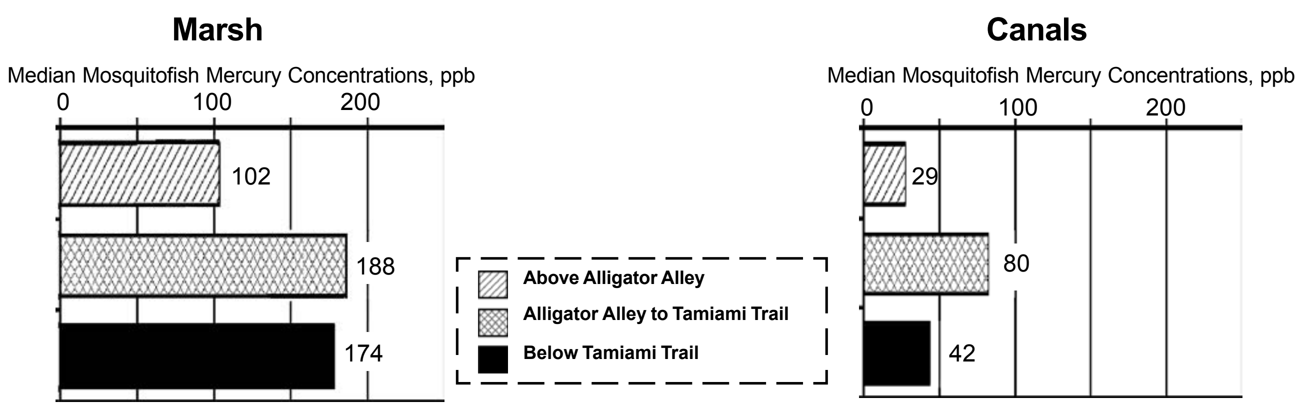

Figure 34. Comparison of marsh and canal mosquitofish mercury distribution from north to south in the Everglades. Note: 100 ppb is proposed predator protection level and the average mosquitofish mercury concentration exceeds this level in all three marsh areas.

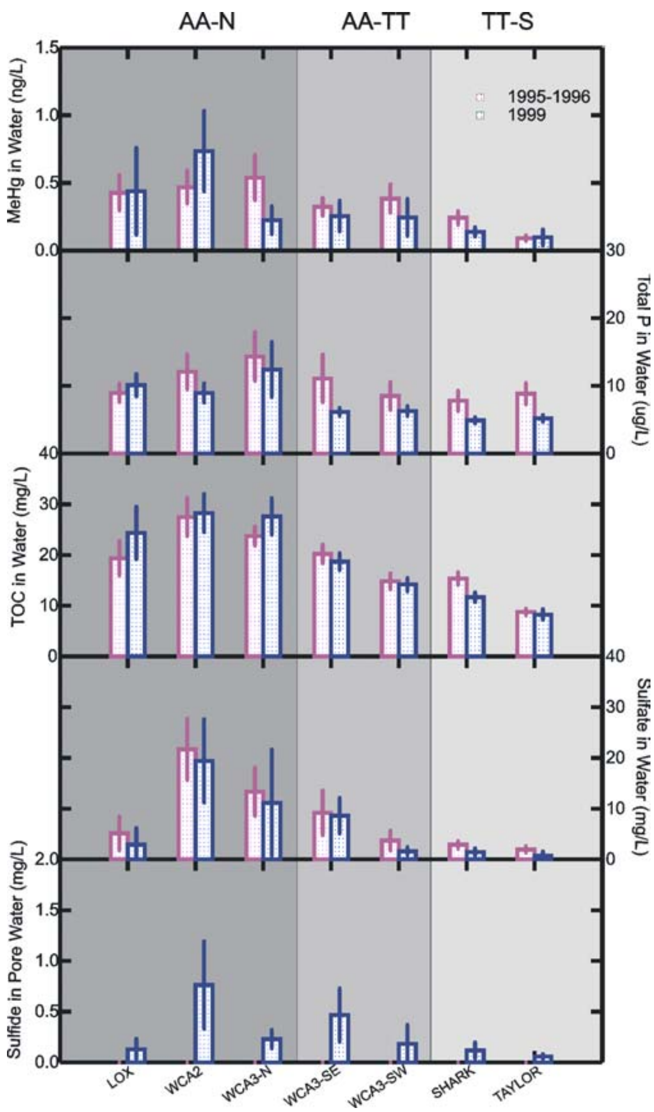

Figure 35. Mean wet season (+-95 C.I.) methylmercury, TP, TOC, and sulfate in surface water and sulfide in soil porewater for phase 1 and 2 by subarea.

decreasing gradients from north to south (Figure 35). Loxahatchee (WCA1) at the top of this system is a rainfall-driven bog with very deep peat soil. There is some transport of EAA discharges into Loxahatchee from the surrounding peripheral canals, but the effects are significantly less than the main stormwater diversion into the flow-way occurring in WCA2. Taylor Slough is a sub-basin at the far south end of this system, which also has very different characteristics than the other Everglades subareas. Generally, it has an extremely short hydroperiod and shallow marl soils.

North to south gradients in the system due to stormwater from the EAA are common, with peak concentrations in WCA2 extending through WCA3-N, WCA3-SE, WCA3-SW and Shark Slough (Figure 35). Sulfide in surface water and porewater was measured during the 1999 sampling seasons (Figure 38), which also showed a steep decreasing gradient from north to south. The spatial footprint of porewater sulfide concentrations showed WCA2 and WCA3-SE were the most impacted subareas with predominant reducing conditions, while sulfide was at background concentrations in WCA3-SW, Shark Slough and Taylor Slough. Differences in porewater sulfide clearly defined the east-west gradient between WCA3-SE and WCA3-SW. Sulfide has important implications in the bioaccumulation of mercury.

Why do we see these gradients and hot spots of methylmercury in water and mercury in fish and birds? Why are mercury concentrations in biota highest between Alligator Alley and Tamiami Trail while the gradients in other constituents are higher north of Alligator Alley?

Causes of Mercury Contamination

For mercury contamination to occur in fish and wildlife, four factors must be present:

1) There must be a source(s) of mercury,

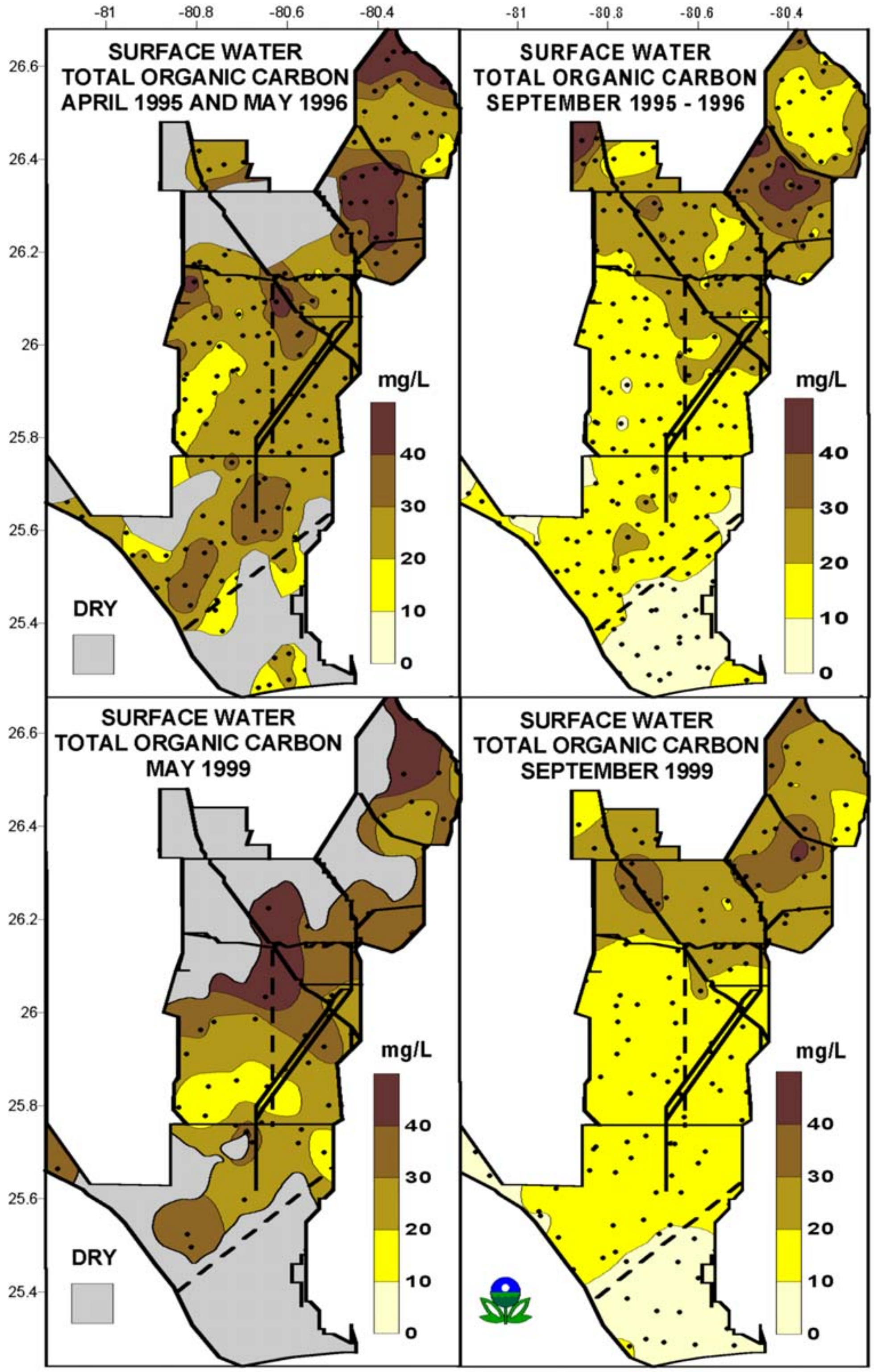

Figure 36. Surface plots of TOC measured in surface water during wet and dry seasons in phases 1 and 2 showing north-south gradients.

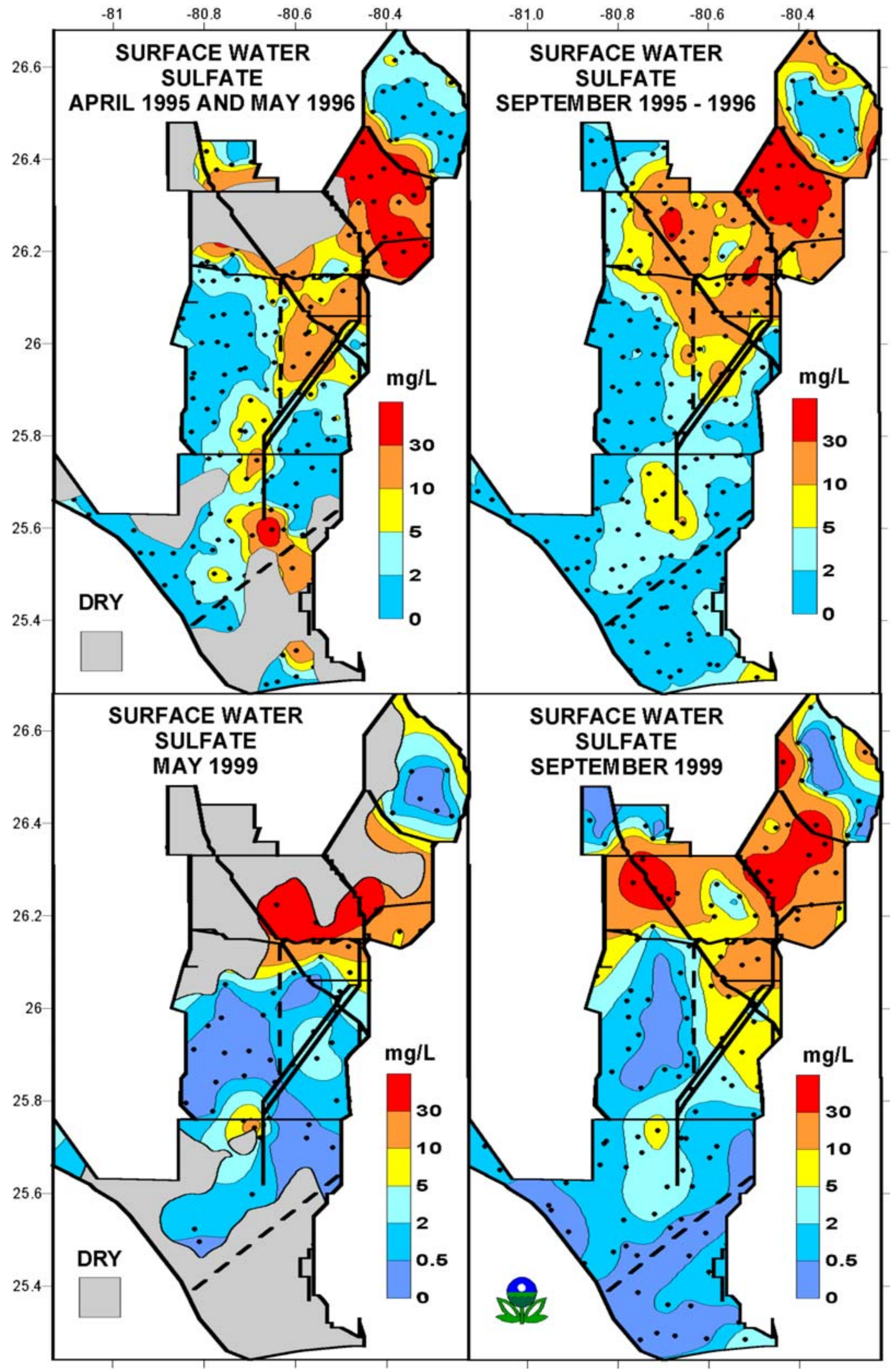

Figure 37. Surface plots of sulfate measured in surface water during wet and dry seasons in phases 1 and 2 showing north-south gradients.

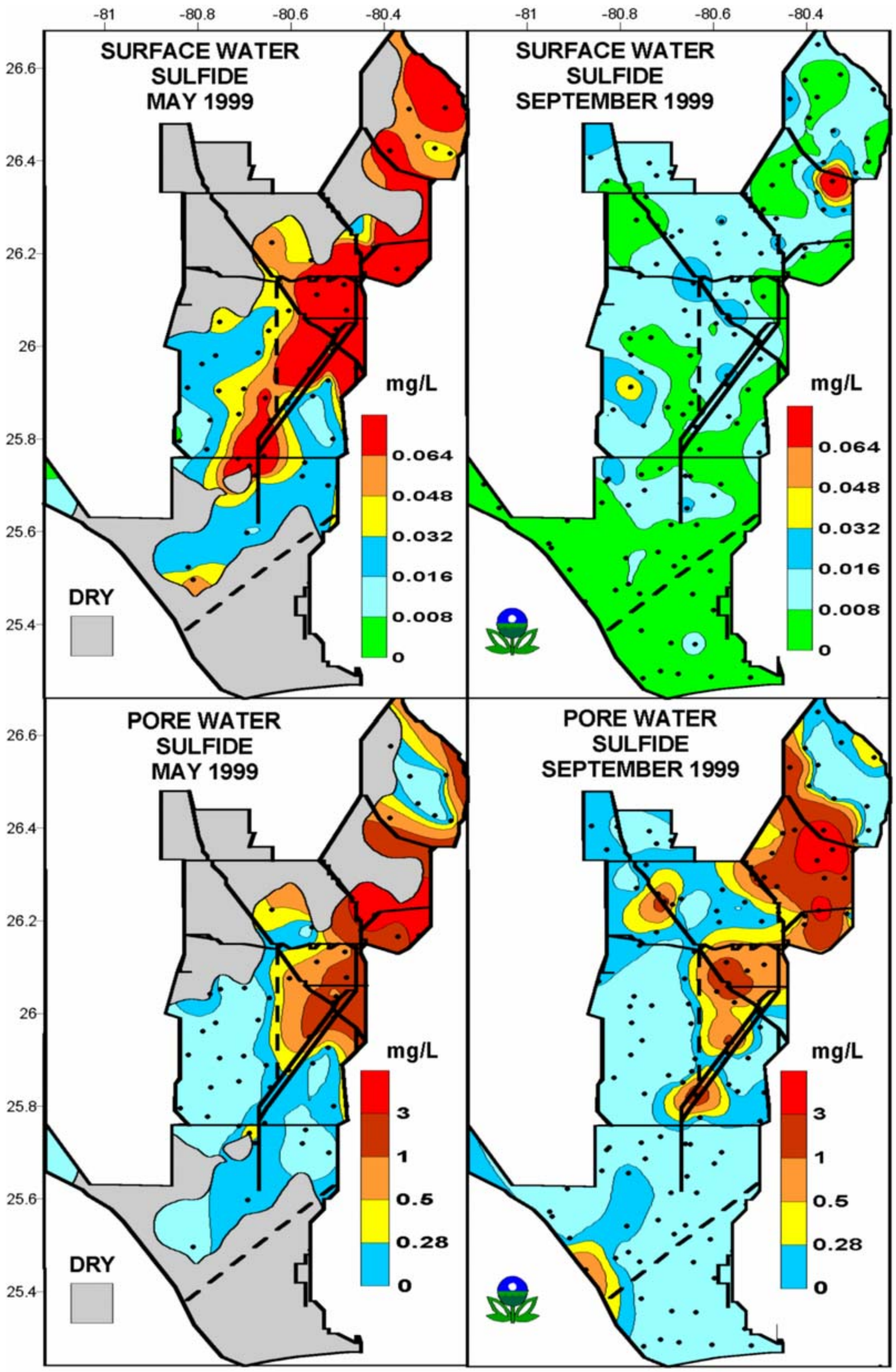

Figure 38. Surface plots of sulfide in surface and porewater during phase 2 wet and dry seasons showing north-south gradients.

2) The right combination of environmental conditions must exist for inorganic mercury to be converted to organic or methylmercury,

3) Methylmercury, the mercury form readily taken up by biological organisms, must be available (unbound) at the base of the food web, and

4) There must be biological uptake and accumulation of methylmercury through the food chain to higher trophic levels.

Once mercury enters the food chain, it increases in concentration or biomagnifies at each higher step or level in the food chain (Figure 39). The highest mercury concentrations are usually found in top predator fish (e.g., largemouth bass), birds, reptiles, and mammals that eat fish or fish-eating animals (e.g., raccoon, Florida panther, respectively).

Given the mercury contamination fish consumption advisories throughout the Everglades ecosystem, obviously all four factors must be present. But, how does this contamination occur in the Everglades?

Mercury Sources

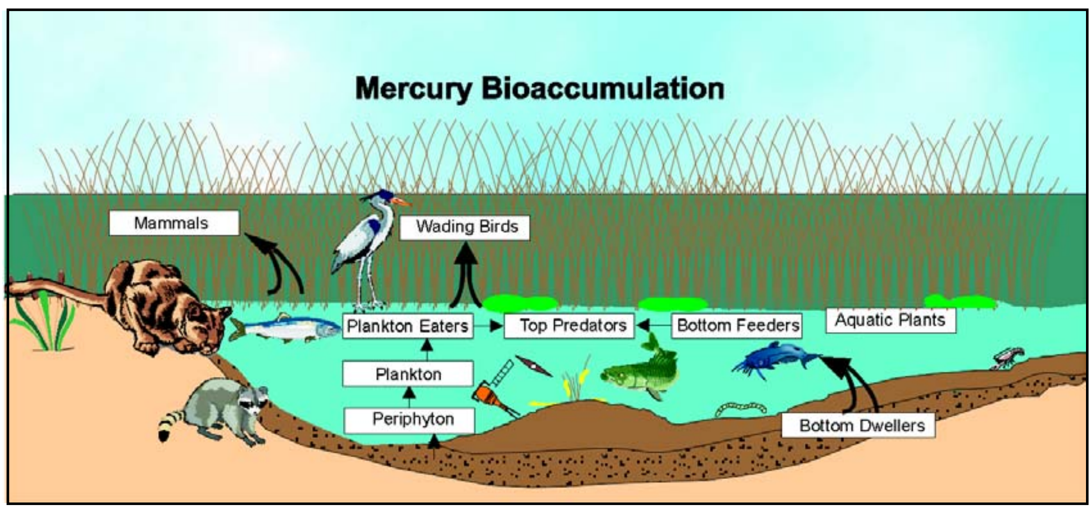

Figure 39. Bioaccumulation of mercury up the food chain from the water to wading birds and the Florida panther. Mercury concentrations in largemouth bass are over 1,000,000 times higher than methylmercury concentrations in water.

There are multiple possible sources contributing mercury to the Everglades ecosystem, including those external to the system:

1) Atmospheric deposition (wet and dry fall) from local and regional sources;

2) Global background, which contributes mercury to the Everglades from international sources primarily via wet deposition;

3) Loading from the Everglades Agricultural Area stormwater; and those internal to the system:

4) Peat decomposition and decay and fires releasing mercury stored in the plant tissue;

5) Weathering and erosion of mercury in rocks (e.g., limestone) in the Everglades ecosystem.

Currently, the magnitude of only three of these sources has been estimated - atmospheric deposition (Figure 40), EAA loading (Figure 41), and global background. Monthly-weighted average atmospheric mercury deposition monitoring data were collected at 10 locations throughout South Florida, including a site to estimate global background (Figure 42) (Guentzel et al., 2001). US EPA and the South Florida Water Management District monitored total mercury concentrations biweekly at the pumps located on the canals surrounding the EAA to estimate the mercury load from the EAA (Stober et al., 1998). Data from these two sources (atmospheric and canals) were used to estimate the annual total mercury loading to the Everglades ecosystem (Table 4). Atmospheric deposition in precipitation contributed from 35 to 70 times the mercury loading to the freshwater Everglades compared to mercury coming from EAA stormwater loadings. The global background site provided one estimate of the amount of the atmospheric total mercury load that was derived from distant or global background sources. Some analyses indicated that global contributions account for between 25 and 40% of the atmospheric load to South Florida. Mercury emission source studies, being conducted by US EPA, indicated that medical and municipal incinerators are major atmospheric mercury emission sources in South Florida (Figure 43). The portion of atmospheric total mercury that is derived from all local and regional sources, estimated from these separate EPA studies, ranged from 60 to 75%, which is consistent with estimates of the global background contributions (Dvonch et al., 1999). These studies are on-going, so more accurate estimates of atmospheric mercury loadings will be available in future reports.

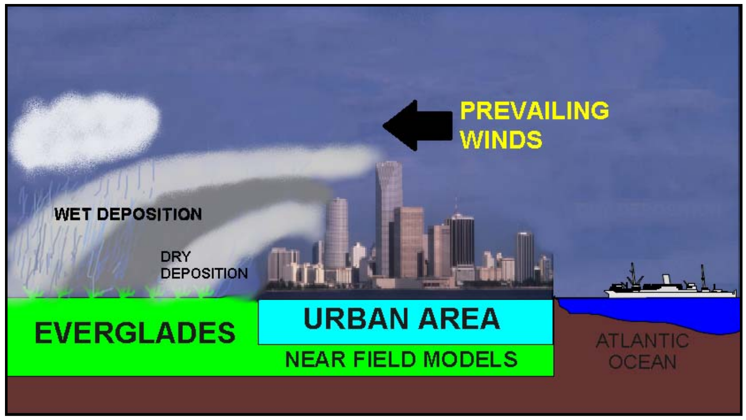

Figure 40. Fate and transport of mercury emissions from the source to the atmosphere with deposition over the marsh.

Figure 41. EAA stormwater discharge contributes nutrients and mercury to the public Everglades.

Table 4. Comparison of atmospheric vs. surface water mercury loading.

Year	Atmospheric Deposition (kg/yr)	EAA Water (kg/yr)
1994	140	2
1995	155	3-4

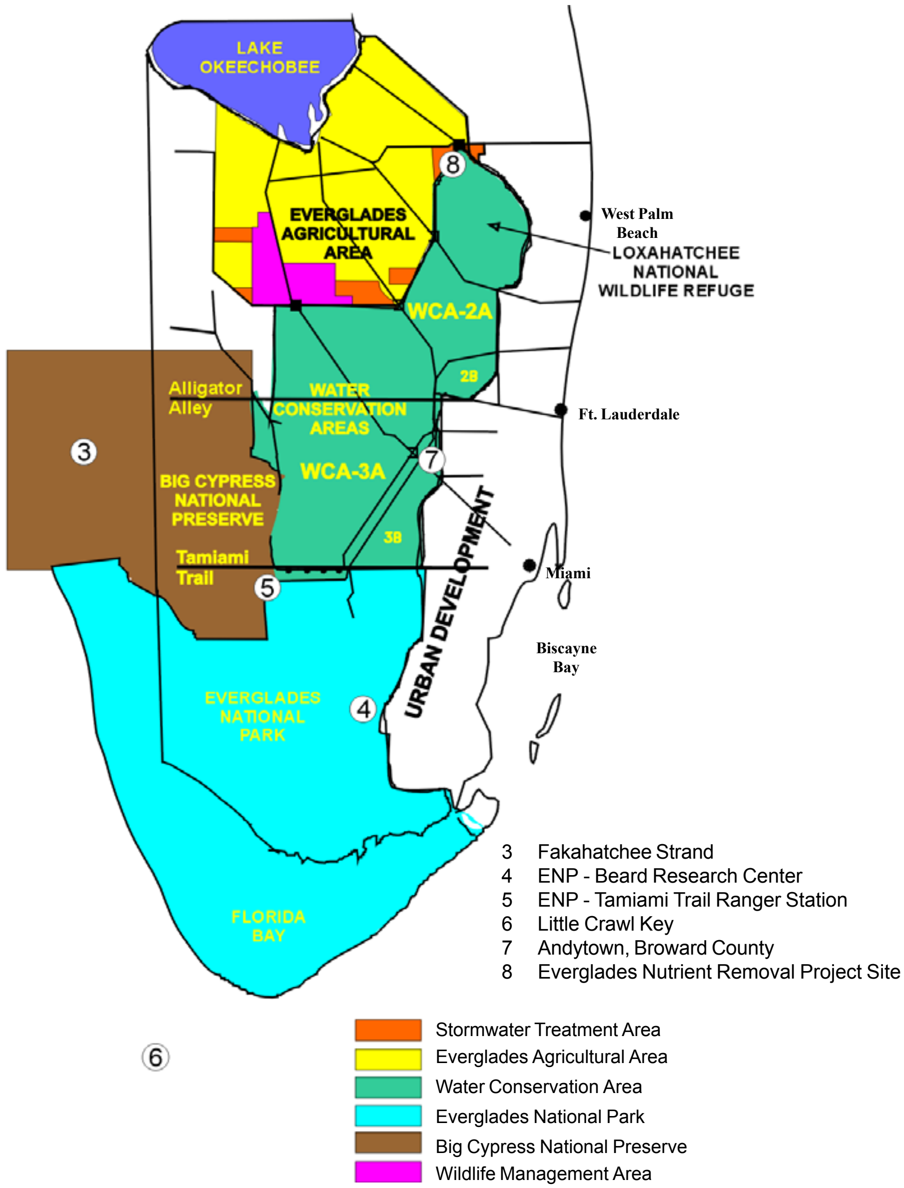

Figure 42. Deposition monitoring locations in the Everglades.

All plants and rocks contain small concentrations of mercury. When the plants decompose or decay and when rocks erode and weather, this mercury re-enters the mercury cycle in the system. There are no precise estimates of the amount of mercury derived from these two sources. However, Scheidt et al. (2000) estimated up to 3 feet of peat loss in the public Everglades over the past 50 years (Figure 44). One of the questions that arises is "where did this mercury go?" The answer to this question is unknown. However, because mercury is a volatile element, it could have entered the atmosphere and become part of the global background, or perhaps redeposited in marsh water or sediment and again taken up by plants. Better estimates of mercury source contributions will be available in the future. For now, it is clear that atmospheric emissions from human activities (e.g., incinerators) are an important source of mercury in the Everglades ecosystem.

Figure 43. Waste incinerators are one of the sources of atmospheric mercury.

Simply having a mercury source, however, does not mean that mercury will become a concentrated contaminant in the ecosystem. The right combination of conditions also must exist for mercury to be converted to a form that can be bioaccumulated and biomagnified through the food chain.

Explaining the Environmental Patterns

For mercury to be converted from an inorganic to an organic form that can contaminate biological organisms, the right combination of environmental conditions must occur. The seven subareas of the Everglades that have been identified have different environmental conditions and characteristics. These different environmental conditions affect both the methylation (conversion from inorganic to organic mercury) and the mercury bioaccumulation processes. These differences probably contribute to the development of the mercury hot spot between Alligator Alley and Tamiami Trail in WCA3-SW. Comparing the differences among environmental conditions in these areas can help explain why there are differences in mercury contamination across the ecosystem. A conceptual model which consolidated the seven subareas into three larger areas can help explain the interactions among different constituents (Figure 45). It is these interactions that result in the mercury responses and patterns that were observed and are discussed with broad general statements for each subarea.

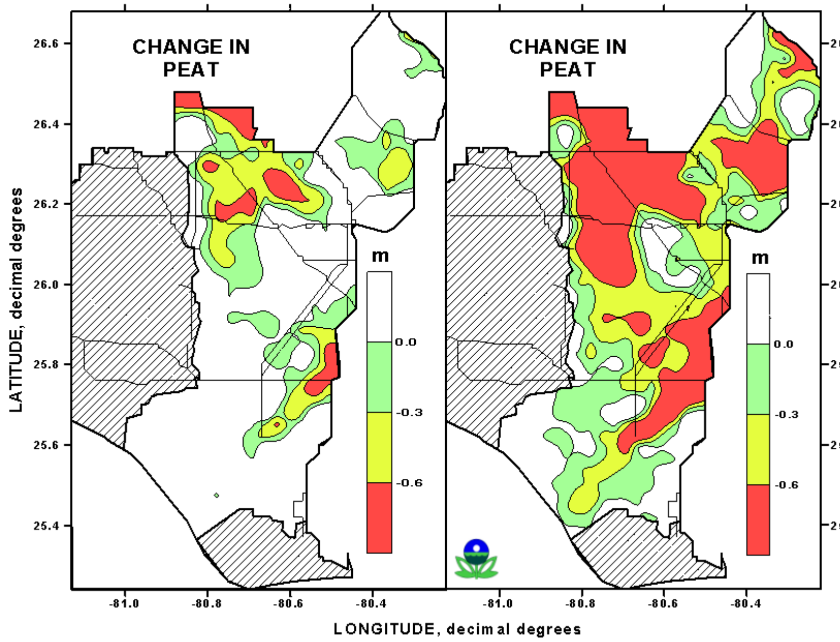

Figure 44. Subsidence estimates (1945-1996) indicate that peat has been lost in portions of the public Everglades. Minimum estimates of peat change are shown on the left with maximum estimates shown on the right. The answer to the question "Where did the mercury tied up in this peat go?' is unknown.

North of Alligator Alley

Discharge from the EAA controls most constituent concentrations in WCA2, WCA3-N and WCA3-SE (Figure 45). Total organic carbon, total phosphorus, and sulfate concentrations in water are high in these subareas (Table 5). Dissolved oxygen concentrations, however, can be low or zero in both the water and soil in this area. This is important because sulfate reducing bacteria (SRB), an important type of bacteria that methylates or converts inorganic mercury to organic mercury, only live in environments without oxygen. There is a lot of sulfate available in

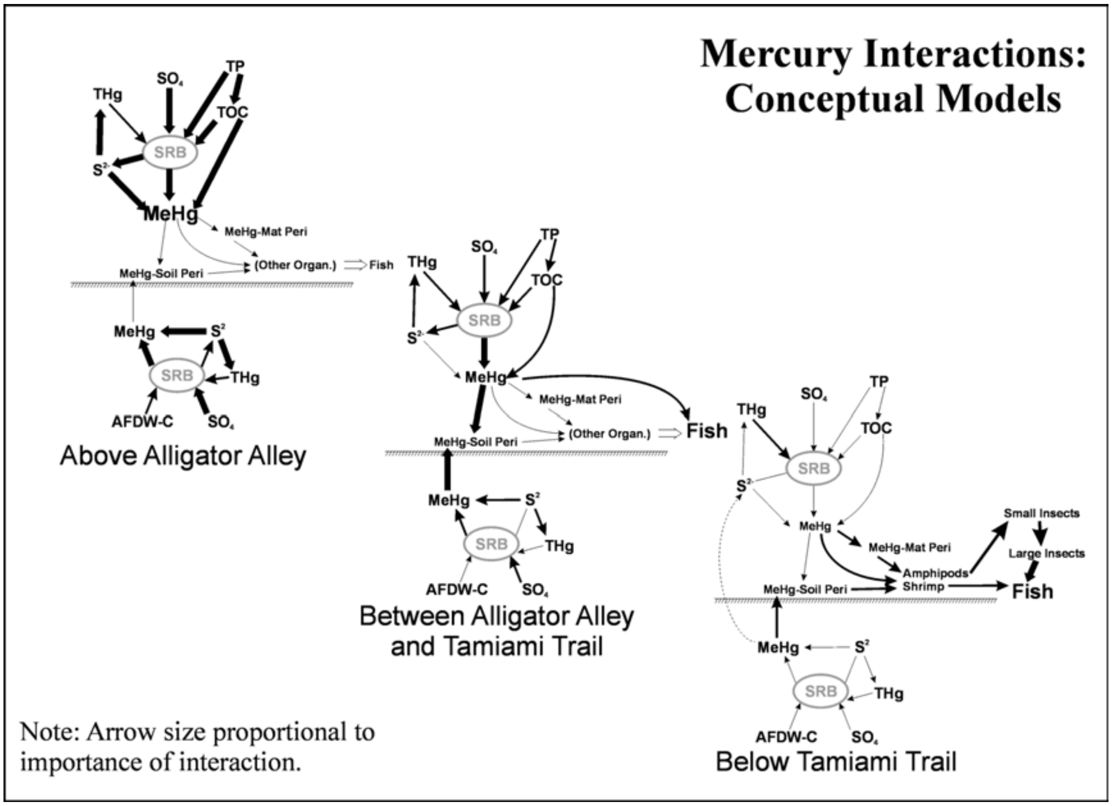

Figure 45. Above Alligator Alley, chemical concentrations (TOC, SO_4, S^{2-}) are high and bind inorganic and methylmercury making it less biologically available. Below Tamiami Trail, chemical concentrations are low, methylmercury is readily bioavailable, and food web complexity magnifies mercury through the food chain. Between the Alley and the Trail, there are dynamic chemical and biological interactions resulting in the "hot spot" of mercury contamination. SRB = sulfate reducing bacteria.

these areas for these bacteria to use in their growth. In addition, there is a lot of organic carbon that also serves as an energy source for these and other bacteria. The spatial pattern of high sulfide concentrations in soil porewater validates the presence of reducing conditions prevalent in WCA2 and WCA3-SE. An important interaction between marsh drying and sulfate in soil was found (Figure 37) by observation of a large increase in sulfate in 1999. As water depth declines and soil is exposed to drying, sulfide is oxidized to sulfate that is available upon reflooding to stimulate the growth of sulfate reducing bacteria and methylmercury production. The highest methylmercury concentrations in water were found in Lox, WCA2, and WCA3-N (Table 5). Higher total phosphorus concentrations cause the plants to grow and also produce a lot of organic matter. Bacterial decay and decomposition of the organic matter from the EAA take the oxygen out of the water. With high concentrations of organic carbon and sulfate as food, there is a lot of production of methylmercury by the sulfate-reducing bacteria which results in high methylmercury concentrations in water north of Alligator Alley. The complex interactions of sulfate/ sulfide on control of microbial methylation hot spots in the Everglades have also been reported by Orem et al. (1999), Bates et al. (1998), Bates et al. (1999), Orem et al. (2000), and Krabbenhoft et al. (2000 and 2001).

Mosquitofish mercury concentrations were lower in LOX, WCA2, WCA3-N and WCA3-SE than in WCA3-SW and Shark Slough even though surface water methylmercury concentrations were higher (Figure 49). There are several possible explanations for why the fish mercury con-

Table 5. Median marsh and canal water quality in three Everglades zones.

	North of Alligator Alley			Alligator Alley to Tamiami Trail			South of Tamiami Trail		
Constituents	**Marsh 1995-1996**	**Marsh 1999**	**Canal 1995-1996**	**Marsh 1995-1996**	**Marsh 1999**	**Canal 1995-1996**	**Marsh 1995-1996**	**Marsh 1999**	**Canal 1995-1996**
Total Phosphorus, ppb (ug/L)	18	10	83	11	7.4	26	10	5.3	14
Total Organic Carbon, ppm (mg/L)	29	28	25	20	18	21	16	11	10
Sulfate, ppm (mg/L)	15	11	34	<2	1.4	5	<2	0.7	9
Methylmercury, ppt (ng/L)	0.4	0.4	0.2	0.4	0.3	0.2	0.2	0.1	0.1

centrations were lower in the northern subareas.

First, although the sulfate reducing bacteria need organic carbon and sulfate as a substrate, organic carbon and the reduced form of sulfate (sulfide) can also both bind inorganic mercury and methylmercury (Cai et al. 1999; Cai 1999; Aiken et al. 2000; Reddy et al. 1999; Lu and Jaffe 2001). This binding can make the inorganic mercury less available to the sulfate reducing bacteria and the methylmercury less available for biological uptake. The net result could be less methylmercury in the food chain.

Another reason for lower fish mercury concentrations could be a different food chain in the eutrophic subarea north of Alligator Alley compared with the food chain in WCA3-SW and Shark Slough to the south (Kendall et al. 2000). For mercury contamination to occur in higher trophic levels, there must be bioaccumulation through the food chain. The amount of organic carbon discharged from the Everglades Agricultural Area or produced by plants because of higher total phosphorus concentrations may overwhelm the capacity of the system to handle the volume of organic material. Dissolved oxygen concentrations are low or zero. This condition is not tolerated by many invertebrates and fish. The food chain, therefore, could be altered in this area so that mercury is not efficiently accumulated to the higher trophic levels. Much of the plant matter produced probably falls to the bottom and decays or rots. Many of the organisms living in this area might feed on this decaying plant matter where the mercury is either bound by the organic matter, or it is demethylated and converted back to an inorganic form. Those organisms that can tolerate these conditions, however, might proliferate and grow faster. This increased mass and number of organisms might dilute the concentration of methylmercury in any one organism, resulting in reduced bioaccumulation in the food chain. The inorganic mercury formed by demethylation reactions could also be bound as sulfide in this high sulfate, highly reducing environment.

Finally, much of this area dries during the dry season so there will be less habitat for aquatic organisms, fish, and wildlife, including wading birds that feed on these organisms. The exact pathways and processes that are occurring in this area are not fully known, but similar processes do occur in other wetland ecosystems.

Alligator Alley to Tamiami Trail

Total organic carbon, sulfate, and total phosphorus loadings from the EAA have been assimilated in WCA2, WCA3-N, and WCA3-SE resulting in concentrations of these constituents that are significantly lower in the southern subareas (WCA3-SW, Shark Slough and Taylor Slough). Water methylmercury concentrations, however, are comparable to those north of Alligator Alley for several reasons. First, there is an unknown amount of downstream transport of methylmercury in the water from upstream. Second, because the organic carbon and sulfide concentrations are lower, there is less binding of total mercury and methylmercury. However, there are relatively high porewater sulfide concentrations in WCA3-SE establishing an additional sharp gradient from east to west in WCA3 (Figure 38). Structural equation modeling or path analysis (Duncan 1975, Hoyle 1995, StatSoft Inc. 2000) of multiple interacting variables by subarea identified the importance of TOC in WCA3-SE and sulfate in the adjoining subarea WCA3-SW, which constitutes the highly active interface between the more heavily impacted northern subareas and the less affected subareas to the south. More inorganic mercury is available for the sulfate reducing bacteria and more methylmercury is available for uptake and bioaccumulation through the food web (Figure 39). Third, there is a significant increase in periphyton mats throughout this area (Figure 46). Although phosphorus concentrations have diminished, these concentrations can still stimulate production of periphyton. These periphyton mats (Figure 47) become so thick that the interior of the mat becomes anoxic or devoid of oxygen during darkness. At night, when there is no oxygen production by the periphyton, the sulfate reducing bacteria in the thick periphyton mats (Figure 47) methylate mercury (Cleckner et al. 1998, Cleckner et al. 1999). The methylmercury is then taken up by the growing periphyton. The methylation rates measured as part of the US Geological Survey studies were some of the highest methylation rates that have been observed in any aquatic ecosystem (Gilmour et al. 1998). These higher rates probably reflect the warmer temperatures in the Everglades waters.

Because this system is not overwhelmed by the loading of material from the EAA, the food chain is more complete. There are additional pathways for both the uptake of methylmercury by plants and for the transfer of this methylmercury to higher levels in the food chain. The highest mercury concentrations in mosquitofish are found in this area

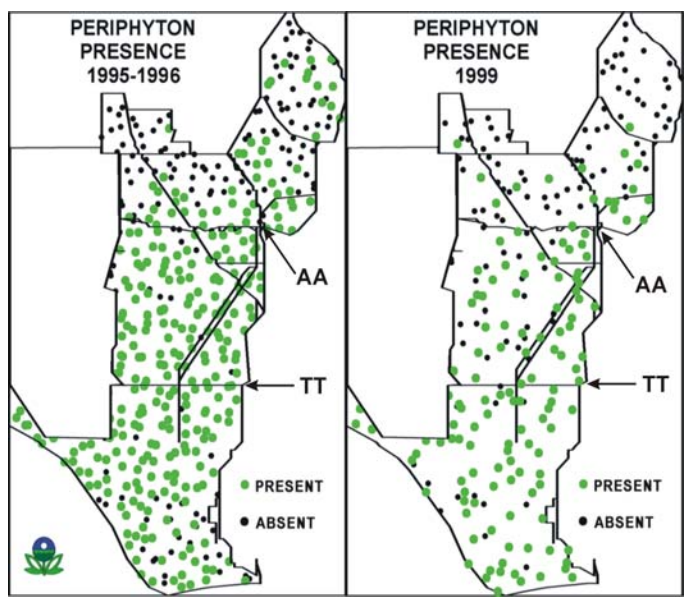

Figure 46. Periphyton mats were found more often in 1995-1996 than 1999, but were more frequent south of Alligator Alley in both periods.

(WCA3-SW and Shark Slough). In fact, this is the area with the mosquitofish and large mouth bass (Lange et al. 2000) mercury hot spot (Figure 48) (Stober et al. 1996). Periphyton concentrations were also high in this hot spot.

A large part of this area also remains wet during the dry season and offers significant habitat for wading birds as feeding, roosting, and nesting sites. This is probably why there are high mercury concentrations in wading bird nestlings in this area (Figure 48) (Frederick and Spalding, 2000). Unfortunately, the exact processes controlling wading bird mercury concentrations are not fully understood.

Figure 47. Periphyton mats can be stimulated to grow by total phosphorus loading and become so dense that the mat interior becomes anaerobic and mercury methylation occurs inside the mat.

South of Tamiami Trail

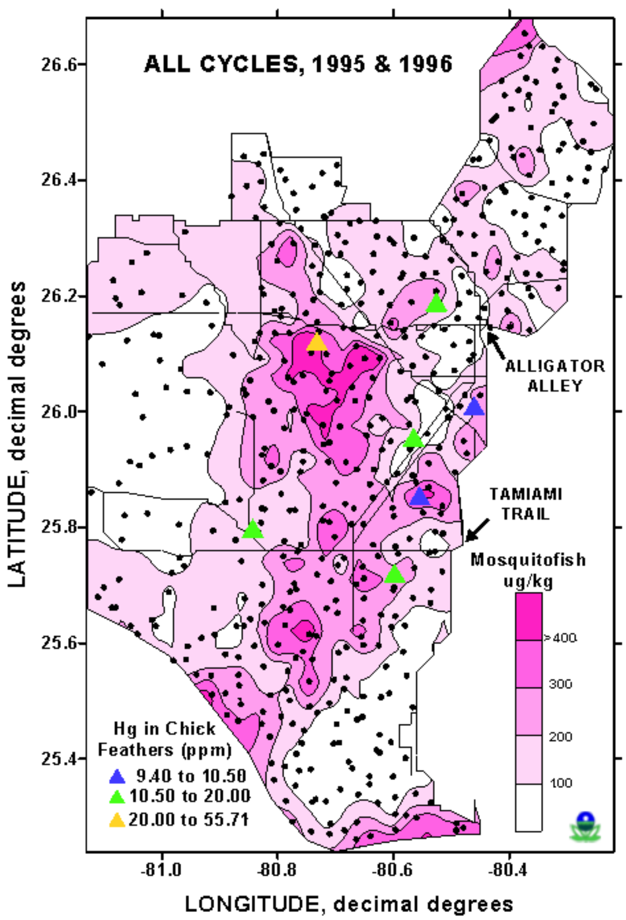

Figure 48. The hot spot is the same for total mercury in both mosquitofish and great egret chick feathers (Frederick et al. 1997).

Aside from the interior of Loxahatchee, concentrations of all constituents are lowest south of Tamiami Trail in Shark and Taylor Sloughs, except for total mercury in fish (Figure 45, Table 5). The methylmercury, although significantly lower in concentration, is probably more biologically available than in the subareas to the north. Organic carbon and sulfide concentrations are significantly lower and bind less of the methylmercury produced. Therefore, the methylmercury present should be more available for uptake and accumulation by biological organisms.

The mosquitofish mercury concentrations in Shark River Slough in the Everglades National Park are almost as high as the fish mercury concentrations found in the WCA3-SW hot spot below Alligator Alley (Figure 49).

The food chain is probably more complete in this area so there is greater accumulation and biomagnification through multiple links in the food web (Figure 39) (Loftus et al. 2000). This area had the highest observed bioaccumulation factors (BAF) for mercury of any of the three areas—one million times higher mercury concentrations in mosquitofish when compared to the water methylmercury concentrations. Much of this area also dries during the dry season and many of the wading bird nesting and roosting sites have been disrupted because of changes in hydropattern and urban and agricultural development on the eastern edge of the Everglades National Park.

Top Down vs Bottom Up

"Top down" versus "bottom up" is a concept used to explain how control of patterns and processes in aquatic systems changes during eutrophication or as nutrient loading to a system increases (Carpenter et al., 1985 and 1995). Some of these ecological attributes are compared between oligotrophic and eutrophic systems in Table 6. The comparison is relevant because eutrophication, in part, affects mercury contamination patterns and processes; the concept is an analog for mercury contamination; and the Everglades ecosystem shows the entire gradient from eutrophic in the north to oligotrophic in the south.

Oligotrophic systems can be viewed as "top-down" controlled ecosystems. Nutrient cycles are tightly coupled because nutrients are limiting, biotic-abiotic interactions control the response of the ecosystem and the variability in biomass production is relatively small, varying by a factor of only 4 to 5 over a year (Table 6). Oligotrophic systems usually have a seasonal renewal of nutrients, such as during the rainy season. The predictability of the response of oligotrophic ecosystems is relatively low because there are multiple factors that control the interactions among biotic and abiotic constituents and these are not understood very well.

Eutrophic systems can be viewed as "bottom-up" controlled ecosystems because nutrient cycles are leaky and decoupled from higher levels in the food chain. Physical factors such as inflow, hydrodynamic mixing and sedimentation

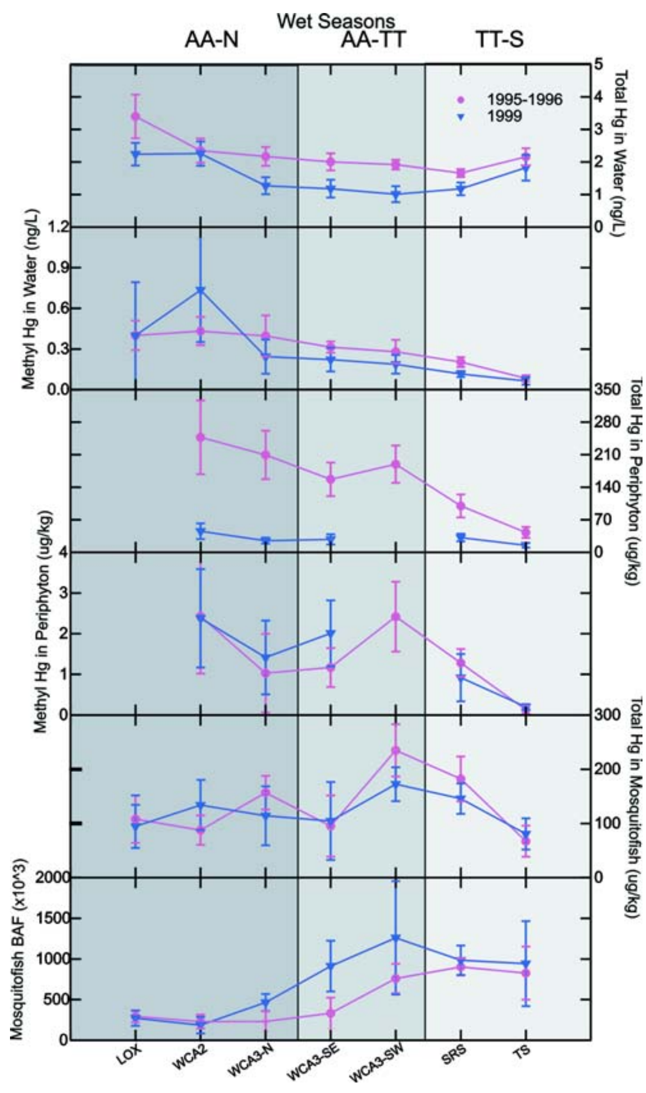

Figure 49. Median wet season concentrations and 95% C.I. for total and methylmercury in water and periphyton (soil, floating, utricularia associated), total mercury in mosquitofish and the bioaccamulation factor by subarea for phase 1 (1995-96) and phase 2 (1999).

Table 6. Comparison of processes and patterns between oligotrophic and eutrophic systems.

Ecological Attribute	**Oligotrophic Systems**	**Eutrophic Systems**
Controlling Factors	"Top-down"	"Bottom-up"
Nutrient Cycling	Tightly coupled nutrient cycles-algae-grazers-microbes, regenerated in water column	Loose nutrient cycling–decoupled from higher food chain, supplied from inflow, sediment cycling
Forcing Functions	Biotic-abiotic interactions	Physical factors–inflow, hydrodynamic mixing
Temporal Patterns	Relatively small biomass variability	Large biomass variability
Nutrient Requirements	Seasonal renewal	Continuous supply
Predictability	Low–multivariate relationships among biomass and controlling factors not well understood	High–statistical relationships between nutrient loads and biomass

control system responses, and there typically are large variations in biomass production, varying by over an order of magnitude throughout a year (Table 6). Nutrients are supplied primarily through inflows and are relatively continuous throughout the year. The predictability of the system response is relatively high. Statistical relationships between nutrient loads and biomass can be developed (i.e., Vollenweider-type nutrient loading models (Vollenweider 1976)).

A statistical analysis technique called structural equation modeling or path analysis was used to evaluate some of the linkages among factors such as water depth, different chemical constituents [e.g., total organic carbon (TOC), total phosphorus (TP), sulfate, total mercury (THg) and methyl mercury (MeHg)] in both water and soil, and different biological assemblages, such as soil periphyton or mat periphyton and mosquitofish. Path analysis or structural equation modeling estimates the strength of the associations or linkages among different constituents simultaneously, by evaluating the patterns in variability among constituents. This is a different approach than is used in standard regression analyses, but it can be a powerful approach for looking at relationships among many variables, such as there are in the Everglades ecosystem. If the association between two different factors or variables, such as between TP and TOC was estimated to be 1.0, this would indicated there was a strong relationship between the two variables. If this estimated association was 0.0, it would indicate there was no relationship between the two variables. Estimating these path coefficients, then, provides an indication of the strength of the relationship among variables and can indicate which pathways are statistically significant. These pathways and the strength of the associations and direction (positive in blue and negative in red) are shown in Figures 50 through 52.

North of Alligator Alley (except for Loxahatchee), the marsh is eutrophic. Chemical constituent concentrations are high (e.g., TP, TOC, SO_4), and chemical interactions appear to control mercury bioavailability and bioaccumulation (i.e., bottom-up) (Figure 50). The food web in this eutrophic area is likely very different from other areas in the marsh.

Between the Alley and the Trail, the system is in transition between a eutrophic and oligotrophic ecosystem. Productivity is still stimulated by nutrients, but chemical interactions and interferences with methylmercury bioavailability and bioaccumulation have decreased. Methylmercury concentrations are high, and mosquitofish mercury concentrations are at their greatest values. Food webs are likely more tightly coupled, contributing to the elevated fish mercury concentrations. Transition areas typically are dynamic and have characteristics of both eutrophic and oligotrophic ecosystems (Figure 51).

South of Tamiami Trail, the marsh is oligotrophic, chemical constituent concentrations are low, and biotic-abiotic interactions are likely much more tightly coupled (i.e., top-down) (Figure 52). Although methylmercury concentrations in water are low, more of this methylmercury is likely biologically available and, therefore, bioaccumulated and biomagnified through the food web. The methylmercury BAF (Figure 49) is significantly higher in this area than in the north.

Understanding some of the eutrophication processes helps our understanding of mercury contamination. For example, the path analyses indicated that the area between Alligator Alley and Tamiami Trail was dynamic, with multiple pathways and interactions among chemical constituents and methylmercury concentrations in water and soil, periphyton and fish (Figure 51). North of Alligator Alley, where the system was eutrophic and chemical constituent concentrations were high, the pathways were simple (Figure 50). South of Tamiami Trail, where the system is oligotrophic, the

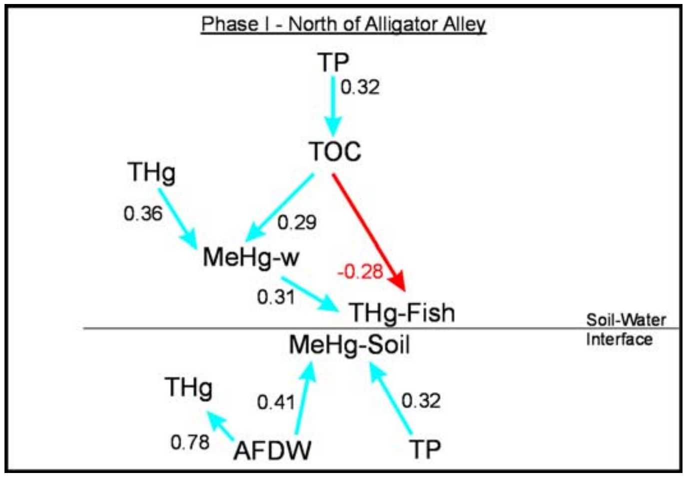

Figure 50. Chemical interactions dominate in the area north of Alligator Alley. Blue lines represent positive interactions; red lines negative interactions. The strength of the interactions is indicated by the numbers with 1.0 being the strongest interaction and 0 being no interaction. Simple linkages among constituents and chemically dominated linkages are typical of eutrophic systems. (Note: AFDW = ash free dry weight).

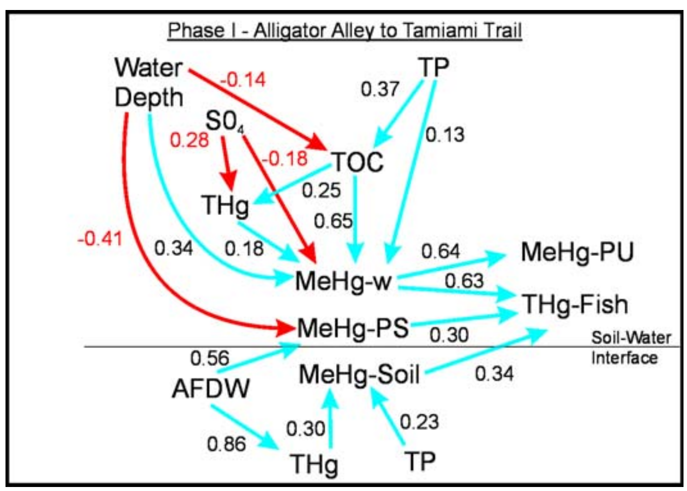

Figure 51. The system is highly dynamic between Alligator Alley and Tamiami Trail with significant positive (blue) and negative (red) interactions among the chemical and biological factors such as floating periphyton (PU) and soil periphyton (PS). These interactions are part of the reason the hot spot occurs in this area.

pathways are relatively complex, with both floc and water methylmercury concentrations associated with fish mercury concentrations. Structural equation modeling indicated that both detrital and autotrophic pathways contribute to fish mercury concentrations (Figure 52). Brumbaugh et al. (2001) also found that fish mercury concentrations were strongly correlated with water methylmercury concentrations in a national study of 21 National Water Quality Assessment Program (NAWQA) watersheds.

Changes in Mercury Contamination

Atmospheric emissions of mercury began to decline from municipal solid waste incinerators in the late 1980s. This was followed in the early 1990s by further restrictions on medical waste incinerators that resulted in an overall 95% decline in mercury emissions in South Florida through 1999 (FDEP). The marsh spatial monitoring data collected in this study were generated during the mid and late 1990 when atmospheric emission rates in South Florida were thought to have declined from around 100 to 10 ug/m^3. However, precipitation, and therefore wet deposition, also declined from 1995 to 1996, with 1999 being a drought year. One approach for assessing change in an atmospheric contaminant is to consider change across large spatial areas, or over an entire ecosystem over long periods of time. This approach smooths out the noise in the signal that occurs because of small temporal and spatial scale variations, and helps reveal changes in the underlying signal.

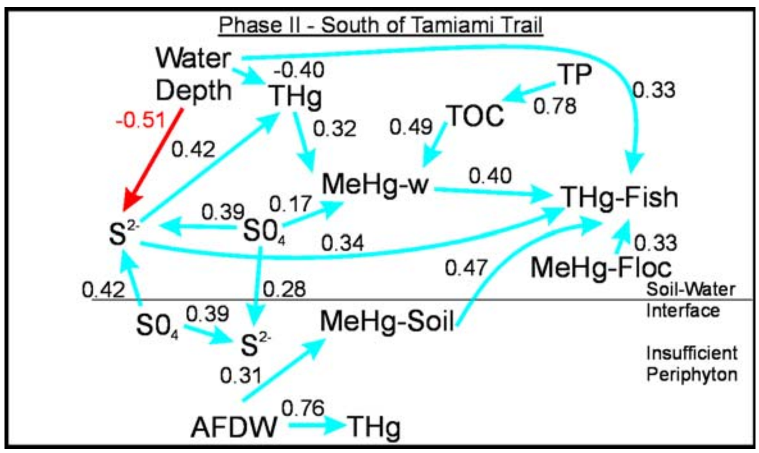

Figure 52. In the oligotrophic area south of Tamiami Trail, the food webs are complex, and the linkages are almost all positive. A small increase in nutrients, sulfate, or inorganic mercury will likely result in increased mercury in fish because of the complex food webs and biological magnification of mercury through the food chain.

Mass estimates were calculated for total and methylmercury by media and by year to assess possible changes in the distribution of mercury in the South Florida ecosystem from 1995-96 to 1999 (Tables 7 and 8). These mercury distributions and their change over time can indicate possible effective management actions for implementation as part of the restoration efforts. The total mercury mass in wet deposition, water, floc, soil, periphyton, and fish are shown in Table 7. There has been a decrease in total mercury wet deposition to the system from 1995 to 1999. In addition, there has been a statistically significant decrease in soil total mercury mass between the 1995-96 period and 1999. There was a corresponding decrease in total mercury in water and fish during this same period. Periphyton mercury mass was highly variable among years, reflecting the relative distribution of periphyton throughout the system.

The thickness of the floc layer was difficult to accurately measure in the field. The floc layer thickness typically varied from about 0.01 to 0.1 (i.e., 1 - 10%) of the water depth. Floc mercury mass estimates, therefore, were estimated as a range. Even assuming the minimum thickness, total mercury mass in floc exceeded that in the water and periphyton by at least 2-fold and might have exceeded it by over an order of magnitude. Other studies have included the floc and soil periphyton as part of the soil measurements so this component of the ecosystem and its role in mercury cycling has been confounded with soil estimates and processes. Future studies might consider separating the floc from the soil and studying the dynamics of the floc-sediment interactions and the floc-microbial-microcrustacean interactions.

A methylmercury mass estimate was also calculated for the system (Table 8). Methylmercury mass decreased during 1996 and 1999 in water, periphyton, and fish compared with the methylmercury mass estimates for 1995. Soil methylmercury mass decreased between 1995 and 1996, but increased significantly in 1999. Floc methyl mercury masses ranged from being comparable to the methylmercury mass in water to having an order of magnitude more mass than water and about 5 times the methylmercury mass found in periphyton. As indicated above, the thickness of the floc layer varied from 0.01 to 0.1 times the water depth. The floc layer has not been adequately studied and could be a major pathway for mercury methylation, uptake and bioaccumulation in the ecosystem.

Table 7. Total mercury estimated by media on a total mass (kg) and areal basis (g/m², in parentheses) for the three wet season monitoring years.

Media	1995	1996	1999
Wet Deposition	153.3 (27.7)	116.1 (21.0)	146.5 (26.5)
Water	6.0 (1.1)	4.7 (0.8)	3.8 (0.7)
Floc			658 (123)+
			65.8 (10)++
Soil	11,559 (2,090)	11,078 (2,006)	9,232 (1,665)
Periphyton (Combined)	39.2 (7)	152.3 (29)	24.5 (5)
Mosquitofish	0.64 (10.12)	0.41 (10.07)	0.39 (6.07)

+ Assumes floc thickness = 0.1 water depth ++ Assumes flock thickness = 0.01 water depth

Similar changes were noted in constituent concentrations over time. Wet season results collected during the September rainy season are presented in Table 9. Wet season samples were collected during the period of maximum atmospheric deposition and with sheetflow occurring throughout the system. The median concentrations of total mercury in surface water showed a significant decline from 1.96 ng/L in 1995-96 to 1.43 ng/L in 1999, a 27% decrease. This decline is illustrated in Figure 49 showing that the 1999 total mercury in water was equal to or less than the 1995-96 baseline across all subareas. The lack of change in WCA2 could be due to the input from the downstream transport of total mercury from the EAA while the remaining subareas were responding mainly to atmospheric deposition. Over the same time period, methylmercury in water declined from 0.275 to 0.174 ng/L, a decrease of 37%. The methyl to total mercury ratio in water ranged from 0.145 to 0.163, showing no significant change over the same time period.

Table 8. Methyl mercury, by media, expressed on a total mass (kg) and an areal basis (μg/m^2, in parentheses) for the three wet season monitoring years.

Media	1995	1996	1999
Water	1.76 (0.32)	1.02 (0.18)	0.79 (0.14)
Floc			9.2 (1.7)+
			0.9 (0.17)++
Soil	62.2 (11.2)	56.9 (10.3)	128.9 (23.3)
Periphyton (Combined)	3.8 (0.7)	2.8 (0.5)	1.29 (0.23)
Mosquitofish	0.64 (0.12)	0.41 (10.07)	0.39 (0.07)

Subarea wet season median methylmercury concentrations in water in 1999 were equal to or less than those measured in 1995-96 except in WCA2 which may also have been receiving an unknown amount of methylmercury from the EAA (Figure 49). Median methylmercury concentrations in soil by subarea increased in 1999, with higher concentrations to the north. Most of the areas with highest soil concentrations of methylmercury were located in the WCAs closest to the EAA where the soil had been dried during the previous season (Figure 53). Median total mercury in all periphyton types decreased significantly in 1999 while median methylmercury concentrations remained at similar levels as those in 1995-96.

A comparison of dry season mercury concentrations is strongly influenced by the degree of dry down in the marsh (Table 10). The 1995-96 dry seasons were relatively wet (8% and 17% dry surface area, respectively) in comparison to the 1999 dry season in which 54% of the marsh surface area was exposed to drying. The median total mercury concentrations in water in 1995-96 were identical in both the dry and wet seasons at 1.96 ng/L (Table 10). Dry season surface water median total mercury concentrations increased to 3.30 ng/L in 1999. Dry season methylmercury in surface water was found to reach medians of 0.578 and 0.723 ng/L in 1995-96 and 1999, respectively (Table 10) followed by declines in the subsequent wet seasons to 0.275 and 0.174 ng/L in 1995-96 and 1999, respectively (Table 9). There was no significant change in total or methylmercury in wet season soil, however, dry season soil concentrations of total mercury decreased 15%, while methylmercury increased 18%. Median methylmercury concentrations in periphyton were not substantially different between seasons or years. The water constituent concentrations, which increase with seasonal dry down of the marsh and decrease with the onset of the rainy season, represent a pattern to which this ecosystem is exposed on an annual basis.

The South Florida Everglades ecosystem is a pulsed system that is maintained by wetting and drying (Odum, 1971). The fluctuating water levels are part of the regular, but acute, physical perturbations under which the system evolved. The dry season drawdown speeds aerobic decomposition of accumulated organic matter, transforms some reduced species such as sulfide back to oxidized species such as sulfate, and concentrates aquatic species such as the mosquitofish and invertebrates in smaller areas where they are preyed on by other fish, terrestrial mammals (e.g., raccoon), and wading birds. The

Table 9. Freshwater Everglades Ecosystem wet season median concentrations of total and methylmercury by media.

Parameter	1995-96	C.I.	N	1999	C.I.	N	% Change
Surface Water (ng/L)							
HgT	1.96	1.9-2.13	207	1.43	1.28-1.58	112	-27
MeHg	0.275	0.229-0.305	207	0.174	0.127-0.245	100	-37
Ratio MeHg:HgT	0.145	0.127-0.161	207	0.163	0.11-0.188	99	12
Soil (ug/kg)							
HgT	130	110-140	207	130	120-140	113	NS
MeHg	0.40	0.32-0.50	180	0.38	0.27-0.58	113	NS
Floc (ug/kg)							
HgT				157	130-179	100	
MeHg				0.79	0.48-1.69	84	
Periphyton (ug/kg)							
HgT	151	125-185	76	27.34	22.5-31.8	55	-82
MeHg	1.21	1.05-1.65	130	1.145	0.74-1.82	55	NS
Mosquitofish (ug/kg)							
HgT (Wet + Dry)	163	149-180	350	123	107-140	151	-24
		% Exceedance					
(100 ppb)	68	63-73	350	60	52-68	151	-12
		% Exceedance					
(200 ppb)	40	35-45	350	20	13-26	151	-50
BAF x 10^5	5.3	3.9-6.7	196	7.5	5.9-9.4	99	43

NS = not significant, CI = 95% confidence interval, N = number, BAF = Bioaccumulation Factor

nutrients, sulfate, and other constituents released during the dry season contribute to productivity and other processes such as mercury methylation during the wet season. The pulsed nature of the ecosystem is an integral part of the life histories of many species such as the wood stork. The wood stork breeds when the water levels are falling and small fish on which it feeds are concentrated in the pools. If the water level remains high during the normal dry season, or fails to rise in the wet season, the wood stork does not nest (Kahl 1964). Changing the water level fluctuations can affect both the distribution

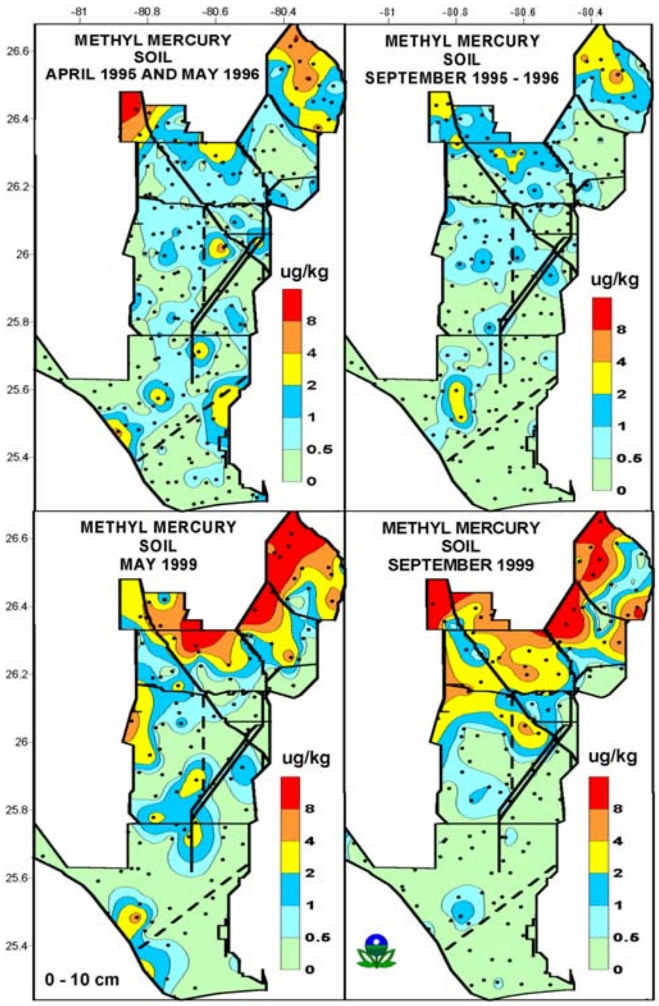

Figure 53. Surface plots of methylmercury measured in soil during wet and dry seasons in phases 1 and 2 showing north-south gradients.

and nesting of wading birds within the system and has likely been a major contributor to the decrease in wading bird populations and concentrating the nesting and feeding areas around the mercury hot spot in WCA3-SW (Frederick et al. 1998, Rumbold 2000).

The mosquitofish can integrate mercury exposure across both wet and dry season conditions, so combined wet/dry season results are presented. Total mercury concentrations in trophic level 3 mosquitofish *(Gambusia holbrooki)* were lower in 1999 especially in the mercury hot spot (WCA3-SW). However, these differences were not significant in a subarea by subarea comparison (Figure 49). Analysis of total mercury concentrations in mosquitofish across the entire study area showed a decline in median concentration of 24% from 1995-96 to 1999. A reduction of 12% in the fish exceeding the 100 ug/kg concentration was evident (i.e., 68% exceedance in 1995-96 to a 60% exceedance in 1999), however, there was a 50% decrease (40 to 20%) in fish exceeding 200 ppb. There was a greater decline in the fish with higher mercury concentrations (Table 9).

The wet season BAF in mosquitofish across the entire ecosystem ranged from a median of 5.3×10^5 in 1995-96 to 7.5×10^5 in 1999 indicting a 43% increase. However, analysis by subarea showed a strong gradient from north to south ranging from 2×10^5 to 1×10^6 (Figure 49). The dry season median BAFs were significantly lower than the wet season with 3.0×10^5 in 1995-96 and 2.0×10^5 in 1999 due to the extremely high concentrations of methylmercury in water. The BAF gradient was still apparent in the dry season but shifted to the south.

The Florida Fish and Wildlife Conservation Commission has monitored mercury in large-mouth bass fillets since 1990 showing a 66% decline in mercury concentrations over this period at a canal location in southern WCA3 (Lange et al. 2000). Fredrick and Spalding (2000) showed a 50% decline in mercury concentrations in great egret nestling feathers from 1994 to 2000 in WCA3 colonies. The area of the marsh with >100 ppb total mercury in mosquitofish has remained about the same during the 1995, 1996, and 1999 wet seasons at 60, 59, and 62%, respectively. Most of the decline in mosquitofish mercury concentrations has occurred in these fish with

Table 10. Ecosystem dry season median concentrations of total and methylmercury by media.

Parameter	1995-96	C.I.	N	1999	C.I.	N	% Change
Surface Water (ng/L)							
HgT	1.96	1.64-2.34	178	3.30	2.44-3.91	50	68
MeHg	0.578	0.573-0.717	177	0.723	0.458-0.966	50	25
Ratio MeHg:HgT	0.341	0.279-0.399	176	0.217	0.170-0.266	50	-36
Soil (ug/kg)							
HgT	130	114-140	207	110	93-116	112	-15
MeHg	0.44	0.33-0.62	187	0.52	0.31-0.84	103	18
Floc (ug/kg)							
HgT				171	152-221	49	
MeHg				0.20	0.20-1.31	46	
Periphyton (ug/kg)							
HgT	54.73	50.03-56.09	143	31.64	25.25-40.3	72	-42
MeHg	2.24	1.71-2.78	135	1.29	0.884-1.72	73	-42
Mosquitofish (ug/kg)							
HgT (Wet + Dry)	163	149-180	350	123	107-140	151	-24
		% Exceedance					
(100 ppb)	68	63-73	350	60	52-68	151	-12
		% Exceedance					
(200 ppb)	40	35-45	350	20	13-26	151	-50
BAF x 10^5	3.0	2.5-3.6	152	2.0	1.1-2.7	39	-34

NS = not significant, CI = 95% confidence interval, N = number, BAF = Bioaccumulation Factor

above 200 ppb whole body concentration in WCA3-SW. Reduction of the maximum mercury concentrations in prey fish has apparently been responsible for the downward trends in top predator total mercury concentrations in this system.

The previous data and observations indicate that wet season changes in mercury concentrations in water, and prey fish correspond to changes in atmospheric deposition. If deposition declines due to local emission controls, these changes can probably be detected by the large scale changes in water and mosquitofish mercury concentrations. With continued local diligence, a management goal of approximately 100 ppb in prey fish species appears to be practically achievable. Mercury concentrations in largemouth bass fillets declined to about 650 ppb in 1999 (Lange et al. 2000). It appears that if the mosquitofish hot spot continues to decline to 100 ppb that the largemouth bass may reach the FDEP criterion level of 500 ppb. However, to achieve the US EPA (2001) methylmercury human health water quality criterion of 300 ppb in fish will require that the concentrations in mosquitofish must decline to approximately 60 ppb across the marsh assuming bioaccumulation increase per trophic level of five times. To achieve this level may not be possible in this very reactive ecosystem, and may well require additional, significant reductions in emissions of mercury to the air at all three spatial scales: locally (within south Florida), regionally (statewide and adjacent states), and internationally. Scientific debate continues regarding the relative importance to mercury deposition from emissions sources at the three scales. Currently, controls on waste combustion (important in South Florida) have been implemented, and EPA is pursuing regulations to reduce mercury from coal fired boilers at electric utilities (important regionally). To reach the goal of very low deposition may require voluntary efforts beyond regulations, as well as obtaining international agreements to reduce mercury emissions which can be transported on a global scale.

Risk Assessment

Structural equation models were used to estimate the change in fish tissue mercury that might result from reductions in total mercury, sulfate, total organic carbon, and/or total phosphorus inputs to the system and subsequent changes in the bioaccumulation of methylmercury within the ecosystem. These results were then coupled with the ecological risk assessment analyses conducted by Rumbold (2000) to evaluate any risk reductions that might occur at higher trophic levels within the South Florida ecosystem. As indicated previously, mercury concentrations in mosquitofish decreased from 1995 to 1999. More importantly, the greatest decline occurred in mosquitofish with mercury concentrations exceeding 200 ppb. There was a corresponding decrease in risk to top predators consuming mosquitofish as a major part of the diet of the predator or the prey that were feeding on mosquitofish and subsequently consumed by the predator. The risk reduction was greatest when mosquitofish were the major portion of the predators diet.

Several uncertainties remain in gaining a complete understanding of the spatial mercury mass balance across the Everglades ecosystem. There is little doubt that atmospheric wet and dry deposition accounts for a major part of the input of mercury to the ecosystem, but it is unclear how much of the atmospheric deposition is re-volatilized. Lindberg et al. (2001) compared the mercury flux data from open water surface to cattails and sawgrass and found the “transpiration” of Hg^o from these aquatic macrophytes the single largest flux of mercury in the ecosystem. The summer daytime emission rates from cattails and sawgrass were 31 and 17 $ng/m^2/hr$, respectively and he reported that incubation studies on soil and lacunal gas both suggested that the source of mercury flux from vegetation was the soil. If deposition and volatilization/transpiration are approximately in balance any other source such as stormwater from the EAA or anthropogenic air emissions could become a net addition and of much more importance than currently appreciated. The relative importance of the soil as a mercury source via transpiration in contrast to the mercury deposited from the atmosphere to the water column has not been determined.

What are the conditions that lead to mercury methylation and mobilization? Microbial degradation or chemical reactions within the aquatic environment have not been thoroughly worked out to determine the relative flux of soil mercury to the water as opposed to transpiration and deposition from the atmosphere to the water. The data seem to support that low redox conditions created by high phosphorus enrichment combined with wet/dry cycles leads to methyl mercury mobilization, however, in the presence of high sulfate and total organic carbon the amount of methyl mercury which is not bound and available for bioaccumulation has not been quantified. We think this probably explains why the hot spot for bioaccumulation is not the same as the site of maximum methyl mercury formation. Unbound methyl mercury in the water column appears to be most available to bioaccumulation by the foodweb. The role of sunlight in photoreduction, photooxidation and methyl mercury degradation has not been quantitatively investigated. The abiotic formation of methyl mercury has received little attention in the Everglades and may be significant. With the strong north-south chemical gradients much remains to be developed before a spatial mercury flux model can be developed for the Everglades ecosystem. Improved integration with the numerous process study results could provide a more comprehensive understanding of this ecosystem.

Synthesis

Although there are differences in constituents, methylmercury concentrations and fish bioaccumulation factors among the subareas in the South Florida Everglades ecosystem, there are also several unifying themes that emerge from analysis and study of the large-scale patterns measured by the US EPA Region 4 monitoring program when considered in concert with mercury work of other agencies and scientists:

Ø Hydropattern modifications and the water requirements to cover different marsh areas can be estimated with a simple surface area-volume relationship. Long and short hydropattern areas can also be determined using this relationship. The plant species distributions observed in the study reinforced and supported these hydropatterns. These water changes from dry to completely flooded are necessary in sustaining a pulsed ecosystem like the Everglades.

Ù There are significant north to south gradients, from Lake Okeechobee to Florida Bay, in total phosphorus, total organic carbon, and sulfate in the ecosystem. These gradients affect eutrophication and mercury contamination throughout the Everglades. These gradients also are affected by hydropattern modifications. These factors are all interrelated.

Ú Total phosphorus (nutrient) concentrations were significantly lower throughout the marsh in 1999 compared to 1995-96. Continued monitoring will be needed to determine if this change represents a decreasing trend in total phosphorus concentrations.

Û The distribution of different aquatic plant species (i.e., macrophytes) throughout the marsh provide good indicators of:

- **hydropattern -** water lily (*Nymphaea odorata*)/purple bladderwort (*Utricularia purpurea*) indicate stable water slough habitat (i.e., long hydroperiod).
- **low soil phosphorus -** spikerush (*Eleocharis cellulosa*) is found in soils with low phosphorus concentrations.
- **high soil phosphorus -** cattail (*Typha domingensis*) is found in soils with high phosphorus concentrations.

In addition, the change in some plant characteristics also were associated with variations in soil phosphorus concentrations. Broad leaves and short petioles in arrowhead (*Sagittaria lancifolia*) were associated with high soil phosphorus concentrations. Narrow leaves and long petioles in arrowhead were associated with deep water and low soil phosphorus concentrations.

Ü There is a "hot spot" of mercury contamination in mosquitofish located in the southwestern part of Water Conservation Area 3 south of Alligator Alley. The area north of Alligator Alley has high methylmercury concentrations in the water and soil, but low mercury concentrations in the mosquitofish. The area south of Tamiami Trail in Everglades National Park has low methylmercury concentrations in the water and soil, but relatively high mercury concentrations in the mosquitofish.

Ý Mercury concentrations in the water and in mosquitofish were significantly lower throughout the marsh in 1999 compared to 1995-96. Water and mosquitofish mercury concentrations corresponded to changes in atmospheric wet deposition.

Þ Both top-down and bottom-up controls in the ecosystem are needed to explain the effects of nutrient loading and mercury contamination. High chemical (nutrient) concentrations exert a bottom-up control on ecosystem responses in the northern area. Biological interactions exert a top-down control on ecosystem responses in the low nutrient concentration southern area. The mercury "hot spot" is in the transition zone between these two areas where both bottom-up and top-down interactions occur.

POLICY AND MANAGEMENT IMPLICATIONS

Seven management and policy-relevant questions guided this project. One of the primary objectives of this project was to provide scientifically sound information to answer these questions and contribute to management decisions on the South Florida Everglades ecosystem. This is an interim assessment so not all of these questions can be fully answered, but at least partial answers can be provided for each question. Based on the findings noted above, the management implications are:

Ø Wetlands, by definition, are water driven systems and the water regime drives all other interactions in the marsh. Modifying the water regime will affect everything else in the Everglades ecosystem. Fluctuating water levels are an integral part of the pulsed Everglades ecosystem. These fluctuations need to be maintained and managed.

Ù Distributions of plant species such as water lily, spikerush, and cattail, and plant characteristics such as arrowhead leaf widths are good indicators for assessing the success of the restoration effort because they reflect hydropattern modifications and changes in soil phosphorus concentrations.

Ú Mosquitofish are good indicators for assessing change in mercury contamination because they are found throughout the marsh, have a short life span, and respond quickly to changes in mercury concentrations. The change in measured atmospheric wet deposition might correspond with decreased mercury emissions, but it also could be a result of less rainfall in 1996 and 1999 compared to 1995.

Û Restoration efforts related to managing the water regime, controlling nutrient loading, minimizing habitat alteration, and reducing mercury contamination must proceed together. These factors are all interrelated and must not be managed independently (Figure 54).

Ü Consistent, long-term monitoring is the only way of evaluating the success of the restoration effort. It appears the nutrient management practices and mercury emission reductions have already contributed to a decrease in phosphorus concentrations and mercury contamination. But, only continued diagnostic monitoring will tell if these changes represent a sustained decreasing trend. Statistical survey monitoring networks complement on-going monitoring programs and should be integrated into the Comprehensive Everglades Restoration Plan.

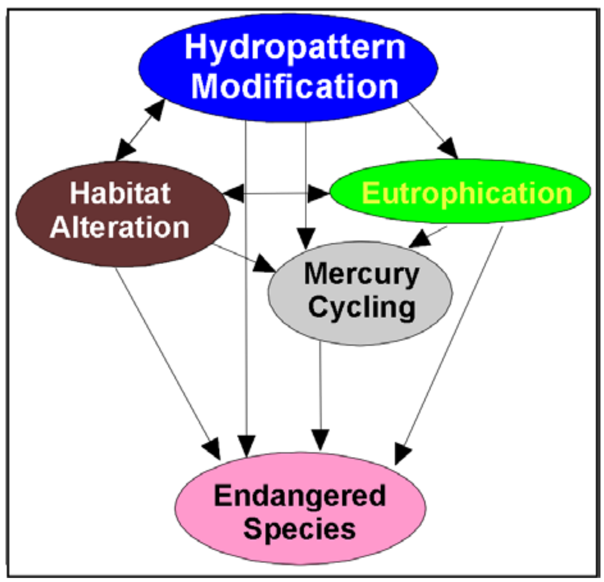

Figure 54. Restoration issues are highly interdependent and must be addressed together.

THE FUTURE

US EPA Region 4 completed the baseline sampling cycles in canals (1993-95) and marshes from 1995 through 1996. That information was analyzed and reported in 1998 followed by adjustments in the monitoring network to emphasize the marsh. The phase II 1999 marsh monitoring effort was carried out during comparative dry and wet seasons to begin the trend monitoring assessment. This information has been used not only to answer the seven policy relevant questions identified for mercury, but also to answer similar questions related to the other environmental problems threatening the Everglades ecosystem. For example, plant communities were monitored using both remote sensing and field techniques during Phase II to determine not only their role in mercury methylation, but also their response to total phosphorus changes and hydroperiod. This information can be used to evaluate the effectiveness of the BMPs and Stormwater Treatment Areas in reducing phosphorus loading to the ecosystem. The comprehensive sampling design of this project has allowed an integration of interacting variables across the entire ecosystem that has not been duplicated by any other project. Additional monitoring is essential to determine the variability in the seasonal and annual patterns, interactions of controlling variables and the effect of this variability on future management decisions. Continued monitoring will increase the ability to make statements about subareas in the Everglades ecosystem under different water management regimes, and will minimize the time required to detect changes from adaptive management actions because it will take advantage of the information already collected. Monitoring and iterative comparative ecological risk assessments must continue into the future to help improve our scientific understanding of the interactions among constituents and management actions.

This monitoring is beginning to provide information on emerging trends in environmental problems and will permit an evaluation of the effectiveness of any policy and management strategy implemented to fix these problems. Consistent, long-term monitoring is the only approach that can be used to assess the success and performance of management practices.

The US EPA, a member of the South Florida Ecosystem Restoration Task Force, is contributing to other studies being conducted as part of the restoration effort including the on-going mercury biogeochemistry and bioaccumulation process studies being conducted by the USGS. For example, the Region 4 Ecosystem Assessment Project has identified critical study areas in South Florida where process research is needed to better understand the interrelationships among hydropattern modifications, nutrient additions, and mercury cycling in the Everglades ecosystem. This project is also providing complementary monitoring information for simultaneous studies of atmospheric mercury emissions, and subsequent mercury transport and deposition in South Florida. In addition, the US EPA is working with the SFWMD, the US National Park Service, the US Army Corps of Engineers, and Florida Department of Environmental Protection in order to better understand the Everglades so it can be protected and restored.

REFERENCES

Aiken, G., M. Reddy, M. Ravichandran and J.N. Ryan. 2000. Interactions between Dissolved Organic Matter and Mercury. (Abstract) Greater Everglades Ecosystem Science Conference, Hosted by: The Science Coordination Team: a Committee of the South Florida Ecosystem Restoration Task Force and Working Group. Naples, FL.

ArcView GIS 3.1. 1996. Environmental Systems Research Institute Inc., 380 New York St., Redlands, CA.

Bates, A.L., W.H. Orem, J.W. Harvey, and E.C. Spiker. 1999. Sources of sulfate to the northern Everglades, Florida, USA: ES&T (In Press).

Bates, A.L., E.C. Spiker, and C.W. Holmes. 1998. Speciation and isotopic composition of sedimentary sulfur in the Everglades, Florida, USA: Chemical Geology, v. 146, p. 155-170.

Brumbaugh, W.G.., D.P. Krabbenhoft, D.R. Helsel, and J.G. Wiener. 2001. USGS National Pilot Study of Mercury Contamination of Aquatic Ecosystems along Multiple Gradients: Bioaccumulation in Fishes. (Abstract) Workshop on the Fate, Transport, and Transformation of Mercury in Aquatic and Terrestrial Environments, May 8-10, 2001. West Palm Beach, FL.

Cai, Y. 1999. A Simple Model for Improvement of Accuracy in size Distribution Measurements of Dissolved Organic Carbon in Natural Waters Using Ultrafiltration Techniques. Water Research. 33, 3056-3060.

Cai, Yong, R. Jaffe, and R. Jones. 1999. Interaction of Mercury with Dissolved Organic Carbon/ Colloids in the Everglades Surface Water. Applied Geochemistry. 14: 395-407.

Carpenter, S.R., D.L. Christensen, JJ Cole, K.L. Cottingham, X. He, J.R. Hodgson, J.F. Kitchell, S.E. Knight, M.L. Pace, D.M. Post, D.E. Schindler, and N. Voichick. 1995. Biological control of eutrophication in lakes. Env. Sci. Tech. 29: 784-786.

Carpenter, S.R., J.F. Kitchell, and J.R. Hodgson. 1985. Cascading trophic interactions and lake productivity. Bioscience 35: 634-639.

Cleckner, L.B., C.C. Gilmour, J.P. Hurley, and D.P. Krabbenhoft. 1999. Mercury methylation in periphyton of the Florida Everglades. Limnology and Oceanography. 44(7): 1815-1825.

Cleckner, L.B., P.J. Garrison, J.P. Hurley, M.L. Olson, and D.P. Krabbenhoft. 1998. Trophic transfer of methylmercury in the northern Everglades. Biogeochemistry. 40: 347-361.

Davis, J.H. 1946. The Peat Deposits of Florida: Their Occurrence, Development, and Uses. Geological Bulletin No. 30. Florida Geological Survey. Tallahassee, FL. 247 pp.

Douglas, Marjory Stoneman. 1947. The Everglades: *The River of Grass.* Banyan Books. Sarasota, FL.

Duncan, O.D. 1975. Introduction to Structural Equation Models. Academic Press. New York.

Dvonch, J.T., J.R. Graney, G.J. Keeler, and R.K. Stevens. 1999. Use of Elemental Tracers to Source Apportion Mercury in South Florida Precipitation. Environmental Science and Technology, 33: 4522-4527.

Eisler, R. 1987. Mercury Hazards to Fish, Wildlife and Invertebrates: A Synoptic Review. Biological Report 85(1.10), Contaminant Hazard Reviews, Report No. 10, US Fish and Wildlife Service, Department of the Interior.

Frederick, P.C., M.G. Spalding, M.S. Sepulveda, G. Williams, S. Bouton, H. Lynch, J. Arrecis, S. Lorazel, and D. Hoffman. 1997. Effects of Environmental Mercury Exposure on Reproduction, Health, and Survival of Wading Birds in the Florida Everglades. Final Report to Florida Department of Environmental Protection, Tallahassee, FL and US Fish and Wildlife Service, Atlanta, GA. 206 pp.

Frederick, P.C., M.G. Spalding, M.S. Sepulveda, G.E. Williams Jr., L. Nico and R. Robbins. 1999. Exposure of Great Egret Nestlings to Mercury Through Diet in the Everglades of Florida. Environmental Toxicology and Chemistry. 18: 1940-1947.

Frederick, P. and M. Spalding. 2000. Temporal and geographic influences in mercury exposure in wading bird colonies across Florida. Ann. Meeting South Florida Mercury Science Program, Tarpon Springs, FL. May 8-11, Abstract.

Gilmour, C.C., G.S. Riedel, M.C. Ederington, J.T. Bell, J.M. Benoit, G.A. Gill and M.C. Stordal. 1998. Methylmercury concentrations and production rates across a trophic gradient in the northern Everglades. Biogeochemistry. 40: 327-345.

Golden Software, Inc. 1999. Surfer 7 Contouring and 3D Surface Mapping for Scientists and Engineers, 809 14th St., Golden, CO.

Guentzel, J.L., W.M. Landing, G.A. Gill, and C.D. Pollman. 2001. Processes Influencing Rainfall Deposition of Mercury in Florida. Environmental Science and Technology, 35: 863-873.

Gunderson, L.H. 1994. Vegetation of the Everglades: Determinants of Community Composition: Everglades--the Ecosystem and its Restoration, S.M. Davis and J.C. Ogden (Eds), St. Lucie Press, Delray Beach, FL. Chapt 13, pp. 323-340.

Hoyle, R. 1995. Structural Equation Modeling: Concepts, Issues and Applications. Sage Publications, Beverly Hills, CA.

Kahl, M.P. 1964. The food ecology of the wood stork. Ecol. Monogr. 34: 97-117.

Kendall, C., S.R. Silva, C.C.Y. Chang, R.F. Dias, P. Garrison, T. Lange, D.P. Krabbenhoft, and Q.J. Stober. 2000. Spatial Changes in Redox Conditions and Food Web Relations at Low and High Nutrient Sites in the Everglades. (Abstract) Greater Everglades Ecosystem Science Conference. Hosted by: The Science Coordination Team: A Committee of the South Florida Ecosystem Restoration Task Force and Working Group, Naples, FL.

Krabbenhoft, D.P., M.L. Olson, J. DeWild, C.C. Gilmour, W.H. Orem, G.R. Aiken, C. Kendall. 2000. Aquatic Cycling of Mercury in the Everglades (ACME) Project: Synopsis of Phase I Studies and Plans for Phase II Studies (Abstract) Greater Everglades Ecosystem Science Conference. Hosted by: The Science Coordination Team: A Committee of the South Florida Ecosystem Restoration Task Force and Working Group, Naples, FL.

Krabbenhoft, D.P., C.C. Gilmour, W.H. Orem, G.R. Aiken, M.L. Olson, J.F. DeWild, S.D. Oluud, A. Heyes, G.S. Riedel, J.T. Bell, H. Lerch, J.M. Benoit, and S. Newman. 2001. (Abstract) Interfacing Process-Level Research and Ecosystem-Level Management Questions: Aquatic Cycling of Mercury in the Everglades (ACME) Phase II. (Abstract) Workshop on the Fate, Transport, and Transformation of Mercury in Aquatic and Terrestrial Envrionments. May 8-10, 2001. West Palm Beach, FL.

Lange, T. and D. Richard. 2001. Interactions of Trophic Position and Habitat with Mercury Bioaccumulation in Florida Everglades Largemouth Bass. (Abstract) Workshop on the Fate, Transport, and Transformation of Mercury in Aquatic and Terrestrial Environments. May 8-10, 2001. West Palm Beach, FL.

Lange, T., D. Richard, and H. Royals. 2000. Long-term trends of mercury bioaccumulation in Florida's largemouth bass. Ann. Meeting South Florida Mercury Science Program, Tarpon Springs, FL, May 8-11, Abstract.

Lindberg, S.E., T. Meyers, J. Clanton, and w. Dong. 2001. Evaluation on Environmental Factors Affecting Gaseous Hg Emission from Subtropical Vegetation in the Florida Everglades. (Abstract) Workshop on the Fate, Transport, and Transformation of Mercury in Aquatic and Terrestrial Environments. May 8-10, 2001. West Palm Beach, FL.

Loftus, W.F., J. Trexler, and R. Jones. 2000. (Abstract) Mercury Transfer Through an Everglades Aquatic Food Web. Greater Everglades Ecosystem Restoration Science Conference. Hosted by: The Science Coordination Team: A Committee of the South Florida Ecosystem Restoration Task Force and Working Group. Naples, FL.

Loveless, C.M. 1959. A Study of the Vegetation of the Florida Everglades. Ecology, 40(1): 1-9.

Lu, Xiaoqiao and R. Jaffe. 2001. Interaction Between Hg(II) and Natural Dissolved Organic Matter: A Fluorescence Spectroscopy Based Study. Water Research, Vol. 35, No. 7, pp. 1793-1803.

McCafferty, R. and W. Baker. 2000. An Analysis of Changes in Basin-Wide and Farm-Scale Phosphorus Loading from the Everglades Agricultural Area Due to Implementation of Best Management Practices. (Abstract) Greater Everglades Ecosystem Restoration Science Conference. Hosted by: The Science Coordination Team: A Committee of the South Florida Ecosystem Restoration Task Force and Working Group, Naples, FL.

McPherson, B.F., R.L. Miller, K.H. Haag, and A. Bradner. 2000. Water Quality in Southern Florida, Florida, 1996-98. US Geological Survey Circular 1207. 32 pp.

Odum, E.P. 1971. Fundamentals of Ecology. W.B. Saunders Company. P. 268ff.

Olsen, A.R., J. Sedransk, D. Edwards, C.A. Gotway, and W. Ligget. 1999. Statistical Issues for Monitoring Ecological and Natural Resources in the United States. Environmental Monitoring and Assessment, vol. 54, p. 1-45.

Orem, W.H., A.L. Bates, H.E. Lerch, M. Corum, and A. Boylan. 1999. Sulfur Contamination in the Everglades and its Relation to Mercury Methylation. US Geological Survey Program on the South Florida Ecosystem. Proceedings of South Florida Restoration Science Forum, May 17-19, 1999, Boca Raton, FL.

Orem, W.H., H.E. Lerch, A.L. Bates, M. Corum, M. Chrisinger, and R.A. Zielinski. 2000. Nutrient and Sulfur Contamination in the South Florida Ecosystem: Synopsis of Phase I Studies and Plans for Phase II Studies. Greater Everglades Ecosystem Restoration Task Force and Working Group, Naples, FL.

Reddy, M.M., G.R. Aiken, and P.F. Shuster. 1999. Mercury-Dissolved Organic Carbon Interactions in the Florida Everglades: A Field and Laboratory Investigation. (Abstract) US Geological Survey Program on the South Florida Ecosystem, Proceedings of South Florida Restoration Science Forum, May 17-19, 1999, Boca Raton, FL.

Rumbold, D. 2000. Assessment of Methylmercury Risk to Three Species of Wading Birds in the Florida Everglades. (Abstract) Greater Everglades Ecosystem Restoration Science Conference. Hosted by: The Science Coordination Team: A Committee of the South Florida Ecosystem Restoration Task Force and Working Group. Naples, FL.

Rutchey, K. and L. Vilchek. 1999. Air Photo Interpretation and Satellite Imagery Analysis Techniques for Mapping Cattail Coverage in a Northern Everglades Impoundment. Photogrammetric Engineering and Remote Sensing, 65(2): 185-191.

Scheidt, D., Q.J. Stober, R. Jones, and K.W. Thornton. 2000. South Florida Ecosystem Assessment: Water Management, Soil Loss, Eutrophication and Habitat. EPA 904-R-00-003. USEPA Region 4 Science and Ecosystem Support Division and Water Management Division; Office of Research and Development. Athens, GA. 45 p. http://www.epa.gov/region4/sesd/reports/

Science Subgroup. 1997. Ecologic and Precursor Success Criteria for South Florida Restoration. Report to the Working Group of the South Florida Ecosystem Restoration Task Force. Planning Division. United States Army Corps of Engineers. Jacksonville, FL. http://sfrestore.org/

StatSoft, Inc. 2000. Electronic Textbook. www.statsoftinc.com/textbook/stsepath.html

Stevens, D.L., Jr. 1997. Variable Density Grid-Based Sampling Designs for Continuous Spatial Populations. Environmetrics vol. 8, p. 167-195.

Stober, Q.J., D. Scheidt, R. Jones, K.W. Thornton, R. Ambrose, and D. France. 1996. South Florida Ecosystem Assessment: Monitoring for Ecosystem Restoration. Interim Report. EPA 904-R-96-008. USEPA Region 4 Science and Ecosystem Support Division and Office of Research and Development. Athens, GA. 26 p. http://www.epa.gov/region4/sesd/sflea/sfleair.html

Stober, Q.J., R.D. Jones, and D.J. Scheidt. 1995. Ultra Trace Level Mercury in the Everglades Ecosystem. A Multi-Media Canal Pilot Study. Water, Air and Soil Pollution. 80: 991-1001.

Stober, Q.J., D. Scheidt, R. Jones, K.W. Thornton, L.M. Gandy, D. Stevens, J. Trexler, and S. Rathburn. 1998. South Florida Ecosystem Assessment: Monitoring for Ecosystem Restoration. Final Technical Report-Phase I. EPA 904-R-98-002. USEPA Region 4 Science and Ecosystem Support Division and Office of Research and Development. Athens, GA. 285 p. plus appendices. http://www.epa.gov/region4/sesd/reports/epa904r98002.html

Stober, Q.J., K. Thornton, R. Jones, J. Richards, C. Ivey, R. Welch, M. Madden, J. Trexler, E. Gaiser, D. Scheidt, and S. Rathbun. 2001. South Florida Ecosystem Assessment: Phase I/II (Technical Report)--Everglades Stressor Interactions: Hydropatterns, Eutrophication, Habitat Alteration and Mercury Contamination. Monitoring for Adaptive Management: Implications for Ecosystem Restoration. EPA 904-R-01-003, USEPA Region 4 Science & Ecosystem Support Division, Water Management Division and Office of Research and Development. Athens, GA. 400 p. plus appendices http://www.epa.gov/region4/sesd/reports/

Thornton, K.W., G.E. Saul, and D.E. Hyatt. 1994. Environmental Monitoring and Assessment Program and Assessment Framework. United States Environmental Agency Report EPA/620/R-94/016. Research Triangle Park, NC. 47 p.

United States Army Corps of Engineers and South Florida Water Management District. July 1999. Rescuing an Endangered Ecosystem: The Plan to Restore America's Everglades. The Central and Southern Florida Project Comprehensive Review Study (The Restudy). 28 p. http://www.evergladesplan.org/

United States Environmental Protection Agency. 1995. Environmental Monitoring and Assessment Program (EMAP) Cumulative Bibliography. United States Environmental Protection Agency, Office of Research and Development. EPA/620/R-95/006. Research Triangle Park, NC. 44 p.

United States Environmental Protection Agency. 1998. Guidelines for Ecological Risk Assessment. Federal Register Notice, Vol. 63, No. 93, May 14, 1998.

United States Environmental Protection Agency. 2001. Water Quality Criterion for the Protection of Human Health: Methylmercury. EPA-823-R-01-001. Office of Science and Technology, Office of Water, US Environmental Protection Agency, Washington, DC.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33: 53-83.

Welch, R. and M. Madden. 1999. Vegetation Map and Digital Database of South Florida National Park Service Lands to Assess Long-Term Effects of Hurricane Andrew. Final Report to the US Dept of Interior, National Park Service, Cooperative Agreement 5280-4-9006, Center for Remote Sensing and Mapping Science, University of Georgia, Athens, GA. 43 pp.

APPENDIX A
Findings and Management Implications

HYDROPERIOD MANAGEMENT–

Findings

- The surface water coverage in the Everglades during the six synoptic surveys ranged from 44 to 100% considering both dry and wet seasons.

- A surface area to volume curve was calculated, which indicated the long hydroperiod marsh covered about 4,200 km^2.

- Inundating the short hydroperiod marsh from 4,200 km^2 to 5,500 km^2 (an increase in area of 1,300 km^2) requires twice the water volume to inundate this area compared to the volume of water covering the long hydroperiod marsh.

- The shortest hydroperiod marsh is located in northwestern WCA3-N and Taylor Slough.

- The area of ponding estimated during the 1999 dry season indicated that if ponding of water north of the Tamiami Trail roadway were eliminated, the wet prairie/slough habitat in the marsh would be reduced by about 400 km^2.

- Total and methylmercury, total phosphorus, total organic carbon, and sulfate concentrations increased during the dry season.

- North to south gradients in this system are apparent in almost every water and soil quality parameter. Their characteristic footprints were identified in this study.

- Drydown of the soil appears to oxidize sulfide to sulfate, which then stimulates mercury methylation by sulfur reducing bacteria when the area re-floods.

Management Implications

- Water management changes to restore sheet flow in this system will require significant volumes of water based on the surface area to volume curve to achieve relatively small surface water coverage of the ecosystem in the dry season.

- Annual drought cycles are a natural occurrence and some will be more severe than others. Large volumes of water continuously supplied will be required to make ecologically significant differences in surface water coverage when system storage capacity is low.

- Ponding in the system increases the wet prairie/slough refugia where aquatic organisms remain during droughts. Careful consideration should be given before any actions to reduce these areas are carried out.

- There may be insufficient volume to reestablish sheet flow in chronically drought prone short hydroperiod areas of the system. This does not mean that additional flow in central and eastern WCA3-N would not begin reversing the soil loss which has occurred there over the last 50 years. However, the build up of peat soil will occur most rapidly if continuous surface water coverage is maintained over long periods of time.

- The water and soil quality gradients identified in this study must be considered before plans are implemented to divert water from contaminated areas farther downstream in this system which could increase the area of impact across the ecosystem.

- There are macrophyte and periphyton community indicators of hydropattern modifications developed in this study that can be used to assess the effectiveness of future restoration efforts prior to and following implementation.

NUTRIENT LOADING–

FINDINGS

- The median concentrations of total phosphorus in water decreased from 1995-96 to 1999, however, the change was not statistically significant across the ecosystem. The greatest change among the subareas was found in WCA2 and WCA3-N.

- Maximum water total phosphorus concentrations occurred in WCA3-N where the median TP concentrations declined from 16 to 11.4 ppb over the intervening three year period.

- Nutrient loading appeared to increase across the northwestern portions of WCA3-N and WCA3-SW in 1999, even though it decreased in other subareas.

- The increased water TP concentrations in WCA3-SE and WCA3-SW during the 1999 dry season probably resulted from phosphorus transport from WCA3-N because a wildfire that occurred in WCA-3N two weeks prior to sampling transformed plants and peat into phosphorus-rich ash.

- The extent of marsh area with TP in water <10 ppb has continued to increase over time, from 41% in 1995 to 78% in 1996 and 87% in 1999.

- The extent of marsh area with TP in water <15 ppb has likewise continued to improve from 65% in 1995 to 87% and 93% in 1996, and 1999, respectively.

- The extent of marsh area with TP in water >50 ppb remained at 2%.

- Median TP concentrations in soil decreased from 350 mg/kg in 1995-96 to 250 mg/kg in 1999.

- Median wet season soil TP concentrations were lower in Loxahatchee, WCA3-N, WCA3-SE, WCA3-SW and Shark Slough in 1999 versus 1995-96 while no change was evident in WCA2.

- The lowest median wet season soil TP concentrations consistently occurred in Taylor Slough.

- Median wet season soil TP concentrations in WCA2 and WCA3-N were 350 and 400 mg/kg, respectively. The invasion of cattails is most prevalent in these subareas.

- Soil TP concentrations greater than 400 mg/kg occur along the EAA border of WCA2 and WCA3-N.

- Future changes in TP concentrations in water and soil require further monitoring to verify trends.

MANAGEMENT IMPLICATIONS

- The phosphorus control program, principally the Best Management Practices which have been in place since 1995, may be reducing the loading to the ecosystem.

- The decline in soil phosphorus concentrations in the less saturated downstream subareas is the area where an initial response to decreased loading is expected. The upstream heavily impacted subareas would be the last subareas expected to respond to decreased phosphorus loading.

- The invasion of the cattail community correlates with the high soil phosphorus in WCA2 and WCA3-N.

- Monitoring using the same methodology needs to continue in order to establish trends used to evaluate the effectiveness of the phosphorus control program.

HABITAT MANAGEMENT–

FINDINGS

Remote Vegetation Assessment

- Remote sensing and GIS techniques were successfully used to assess vegetation patterns over the entire Everglades ecosystem.

- Areal summary statistics indicated spatial trends such as decreasing cattail coverage ranging from 12-17% in the north to 0.4% in the south.

- Plant communities identified in 1 km^2 plots, overlaid on the randomly selected sampling sites, adequately represented the vegetation cover in the Everglades. Comparison of remotely sensed estimates with existing database for ENP-Shark Slough and WCA3-N found the average difference in vegetation type percent cover estimates was 1.5% in ENP-SRS and 0.4% in WCA3-N. This demonstrated the data compatibility among USNPS and SFWMD vegetation mapping efforts.

- This effort establishes a baseline of conditions existing in 1994/1995 and a quantitative methodology for efficiently monitoring future vegetation patterns and assessing changes in the Everglades ecosystem over space and time.

Macrophyte Distributions and Morphology

- Because this study provides a quantitative evaluation of marsh macrophyte community types and their distributions across the Everglades ecosystem, it provides a background for evaluating community change during and after restoration.

- There are four major communities that are found across the entire ecosystem: sawgrass, waterlily-purple bladderwort, spikerush, and cattail. These communities differ in their hydroperiod/water depth, soil type, and nutrient requirements. The dominant species within each community have different tolerances for soil TP.

- Sawgrass is the only community that occurs across the entire ecosystem; the other communities are more localized in their distributions.

- Although sawgrass was present throughout the Everglades, sawgrass morphology and density was correlated with changes in soil type. Controls on variations in density and morphology, as well as patchiness, represent areas for future research.

- Some communities that have been noted to be prominent historically did not appear as distinct communities in our analysis. For example, the *Rhynchospora tracyi* (beakrush) community did not form a distinct community in our clustering. These differences could represent a historical change in community composition in the ecosystem and/or could be a result of the quantitative nature of our analysis.

- *Sagittaria lancifolia* is found across a broad range of soil TP and soil organic content in the Everglades. We have shown in a parallel study that *S. lancifolia* leaf morphology provides an indication of soil nutrient level and water depth. Plants with broader laminae and shorter petioles are found in sites with higher nutrients, while plants with longer petioles are found in deeper sites with lower nutrients.

- The distribution of the major macrophyte communities can be used to monitor the effects of restoration actions.

Periphyton Distributions

This study demonstrated that diatom community metrics are associated with specific environmental changes and can be a useful tool in environmental monitoring. Diatom community metrics should be integrated into Everglades assessment protocols for the following reasons:

- Diatoms are ubiquitous in the Everglades yet species have non-random distributions. Baseline distribution data is now available for use in detecting environmental change.

- Diatoms are sensitive to environmental variation. Assemblage and species responses to spatial variation in ion content, nutrient availability and hydroperiod have been identified. Temporal models can be built from these spatially explicit data to predict community change under different management scenarios with a measurable degree of accuracy.

- Diatoms respond quickly to environmental change. Unlike many other biotic indicators, changes in diatom assemblage composition can happen over very short time scales (days to weeks) and, therefore, can provide sensitive early warning signals of impending ecosystem change.

- The taxonomic reference base generated from this survey will increase efficiency of future diatom inventories. Many surveys exclude diatom analyses because of perceived technical difficulties in collection and assessment. Currently available taxonomic databases should substantially reduce allocation of time and resources to identification. There are fewer species of diatoms in the Everglades than vascular plants. Given currently available reference materials, lack of technical expertise in this field is no longer a viable argument against diatom assessments, especially given their potential in environmental monitoring.

Management Implications

- A baseline of vegetative conditions using remote sensing, ground transect macrophyte community sampling, macrophyte morphology and periphyton communities has been established for monitoring and assessing future changes of the Everglades marsh habitat.

- The mosaic of plant communities across the ecosystem integrates the natural and the anthropogenic impacts imposed on this ecosystem.

- Changes in plant community response are of critical importance in evaluating the effectiveness of restoration practices.

- Indicator macrophyte and periphyton species have been identified which respond to multiple key interacting variables that can be used in assessing change.

- Each habitat methodology applied in this study has developed a unique and cost effective data set needed to track future habitat responses across the entire ecosystem.

MERCURY CONTAMINATION

HOW BIG IS THE PROBLEM (MAGNITUDE)?

Findings

- Over 60% of the marsh mosquitofish exceeded the USFWS proposed predator protection criteria for mercury.

- Less than 20% of the canal mosquitofish exceeded the USFWS proposed predator protection criteria for mercury.

- About 98% of the sampling sites had total mercury concentrations less than the mercury water quality criteria of 12 ppt (parts per trillion).

- Methylmercury concentrations in the water rarely exceeded 1 ppt, yet mercury concentrations in mosquitofish and largemouth bass exceeded 500 ppb and 1 ppm, respectively. This is a biomagnification factor of 500,000 to 1,000,000 times the methylmercury concentration in the water.

Management Implications

- The methylmercury criteria based on mercury concentrations in fish tissue (300 ppb) is appropriate because it considers bioaccumulation and biomagnification through the food chain.

WHAT IS THE EXTENT OF THE PROBLEM (EXTENT)?

Findings

- There is a hot spot in Water Conservation Area 3A, just below Alligator Alley, where methylmercury concentrations are highest in water, algae, fish, and wading birds. This hot spot has an area of over 200 square miles.

- There is an area that extends from this hot spot below Alligator Alley down through Shark River Slough in Everglades National Park in which fish and wading birds also have elevated mercury concentrations.

Management Implications

- By both magnitude and extent, fish, alligators, wading birds, the Florida panther, and other organisms in the marsh have greater mercury contamination than organisms in the canals. Focus management actions on the marsh.

- The mercury hot spot corresponds with an area in which wading birds breed and feed.

IS IT GETTING BETTER OR WORSE OVER TIME (TRENDS)?

Findings

- A solid baseline (1993–1996) has been established to evaluate future trends. The comparative comprehensive monitoring in 1999 has provided the opportunity to begin trend assessment which can be compared to other more frequent trend monitoring in top predators to determine the status of mercury contamination in the Everglades ecosystem through time.

- During the past 10 years there has been an estimated 95% decrease in local atmospheric emissions in South Florida. There also has been a corresponding reduction in total mercury concentrations in surface water and declines in prey fish, largemouth bass and great egret chick feathers.

- Total mercury concentrations in Everglades prey fish greater than 200 ppb declined from a 40% exceedance in 1995-96 to a 20% exceedance in 1999. This indicates an approximate reduction of 50% in mercury in fish with the highest concentrations.

- Although Everglades largemouth bass monitoring by Florida Fish and Wildlife Conservation Commission (FFWCC) indicates a 75% decline in total mercury through 2001 in fillets, these fish still exceed the Florida fish consumption advisory of 0.5 ppm.

- Monitoring of Everglades great egret chick feathers by University of Florida scientists from 1994-2000 has shown a 75% decline in mercury through 2001.

Management Implications

- Maintain the US EPA Region 4 monitoring program with seasonal sampling, but emphasize the marsh sites compared to the canals. Establish trend sites.
- Continue monitoring the great egret check feathers, largemouth bass, and mosquitofish to assess trends.
- The mercury problem did not occur overnight and it will not be corrected overnight. Long-term management practices will be required to fix the mercury problem.
- Consistent long-term monitoring is the only approach for assessing the effectiveness of management and restoration practices to control eutrophication, restore natural hydropattern changes, and eliminate mercury contamination.

WHAT IS CAUSING THE PROBLEM (CAUSATION)

Findings

- The exact causes of mercury contamination in the South Florida ecosystem are unknown. However, it is likely the interaction of total phosphorus, TOC, and sulfate loading from the EAA, water depth, organic matter sources and production, food chain links and continued input of atmospheric mercury to the ecosystem control mercury contamination.
- The large scale spatial patterns of these environmental conditions have been established through the US EPA Region 4 program, FFWCC fish sampling, and NPS/FDEP wading bird sampling programs.
- Processes responsible for these large-scale patterns are being studied through the USGS ACME program, US EPA and FDEP atmospheric deposition studies.

Management Implications

- There is no “magic bullet” that can be implemented to control one factor and eliminate mercury contamination.
- Factors controlling mercury should be determined in the hot spot and compared with factors in other areas without extensive mercury contamination to develop effective management strategies.
- Controlling EAA loading of phosphorus, sulfate, and TOC concentrations might also reduce the mercury problem by reducing constituents that are influencing mercury contamination.

WHAT ARE THE SOURCES OF THE PROBLEM (SOURCES)?

Findings

- Annual atmospheric mercury loading is from 35 to 70 times greater than mercury loading from the Everglades Agricultural Area.
- An EPA ORD study indicated municipal and medical waste incineration emissions had higher mercury concentrations than emissions from a coal-fired cement kiln.

Management Implications

- Local emissions are a significant source of inorganic mercury.
- Mercury emissions controls would reduce mercury loadings to the Everglades ecosystem.
- However, waste disposal is a multimedia problem. Controlling mercury emissions might create other problems such as disposal of solid waste, including not only the waste, but also the mercury removed from the emissions.

WHAT IS THE RISK TO THE ECOSYSTEM (RISKS)?

Findings

- Mercury methylation is also controlled or influenced by hydropattern, habitat alteration, and food web complexity.
- Over 60% of the marsh area has mosquitofish with mercury concentrations that exceed the proposed predator protection level.
- Mercury concentrations during the early-1990s were high, near toxic levels in wading bird livers and other organs but have been declining in largemouth bass and wading birds over the past 8 years.
- There is a 200 square mile hot spot where mercury contamination in biota is greatest, which corresponds with an area of wading bird rookeries.

Management Implications

- Biological species higher in the aquatic food chain are at increased risk from mercury contamination, even though the effects are subtle. Because mercury bioaccumulates, the risks increase over time. The longer management is delayed, the greater the risks.
- However, the greatest threat to the Everglades ecosystem is to assume the environmental problems are independent.

WHAT CAN WE DO ABOUT THE PROBLEM (MANAGEMENT)?

Findings

- The SFWMD Everglades Nutrient Removal project removes nutrients and total and methylmercury from the inflow to the Project.
- Atmospheric mercury loading to the Everglades is much greater than mercury loading from EAA stormwater.

Management Implications

- Controlling nutrient loading, hydropattern and habitat type should contribute to reducing the mercury contamination problem.
- Controlling local atmospheric mercury emissions has apparently reduced the mercury load to the South Florida Everglades ecosystem and the concentration in biota. However, there has been no apparent change in mercury deposition over the past 8 years, suggesting the greatest change in mercury deposition occurred before monitoring began and there is a time lag in the biological response.
- Emission controls have multimedia impacts and must be assessed as a multimedia issue, not as a single media issue.
- If the nutrients, sulfate and TOC concentration gradients, were decreased further and moved upstream, the zone of impact where fish mercury is high could be reduced and might be outside the areas where wading birds concentrate for breeding, feeding, and with reduced emissions, the overall fish concentrations might be lower.