Chapter 3B: Mercury and Sulfur Monitoring, Research and Environmental Assessment in South Florida

Donald M. Axelrad[1], Ted Lange[2], Mark C. Gabriel and Thomas D. Atkeson[1]

SUMMARY

Elevated concentrations of mercury and sulfur are evident in the Everglades. The highly bioaccumulative form of mercury, methylmercury (MeHg), is a concern due to the neurotoxic threat it poses for Floridians who consume Everglades fish, as well as to resident wildlife. As sulfate, sulfur promotes the methylation of mercury and affects the biogeochemical cycling of other elements including phosphorus. In addition, sulfur may be toxic when in the sulfide form. Because of their ability to cause harm at many levels of the Everglades ecosystem, continued assessment of these elements is critical to restoration efforts.

The very high mercury concentrations evident in fish in the Water Conservation Areas (WCAs) from the late 1980s to the early 1990s have declined substantially. Mercury levels in largemouth bass (*Micropterus salmoides*) (LMB) in the WCAs, however, remain generally above the proposed U.S. Environmental Protection Agency (USEPA) human health criterion for fish consumption [0.3 micrograms per gram (µg/g)].

In contrast to the mercury reductions in LMB in the WCAs, mercury levels in these fish have increased in Everglades National Park (ENP or Park) and the Holey Land Wildlife Management Area (WMA) in recent years. In the ENP, LMB and sunfish (*Lepomis* spp.) mercury levels are both above USEPA wildlife criteria.

Regarding sulfur, approximately 60 percent of Everglades marsh area has sulfate concentrations greater than the Comprehensive Everglades Restoration Plan goal of 1 milligram per liter (mg/L) in surface water. It is probable that broad areas of the Everglades exhibit sulfate concentrations at which increased sulfate levels would enhance and decreased sulfate concentrations would reduce methylmercury bioaccumulation. Sulfur may exhibit detrimental

[1] Florida Department of Environmental Protection, Standards and Assessment Section, Tallahassee, FL
[2] Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, Eustis, FL

effects beyond promoting mercury methylation, including sulfide toxicity to aquatic plants and animals, and phosphate and ammonium release from sediments. Options for reducing Everglades mercury levels include atmospheric mercury source reduction and sulfate loading reduction.

The Florida Department of Environmental Protection (FDEP) and the South Florida Water Management District (SFWMD or District) continue to promote improved understanding of the sources, transformations, and toxicity of mercury in the Everglades, in support of natural resource management decisions. This chapter updates findings reported in earlier consolidated reports, with supporting data on mercury provided in Chapter 3A and Appendix 3B-1 of this volume.[4]

NEW FINDINGS

New findings and issues of continuing concern summarized below are drawn from this chapter and from related appendices.

- In the WCAs, the system-wide median mercury concentration in LMB has declined 70 percent over the past 20 years from a maximum in 1988 of 1.75 µg/g (range; 1.20-3.4 µg/g; n = 12) to a minimum of 0.30 µg/g (range; 0.04-2.0 µg/g; n = 263) in 2007.
- Since 2001 in the WCAs, median mercury concentrations in age-three standardized LMB have varied minimally, reaching a minimum of 0.30 µg/g maximum in 2007 and a maximum of 0.45 µg/g during 2005. In spite of declines in LMB mercury levels in the WCAs, individual LMB continue to show evidence of high rates of mercury bioaccumulation. From 2001 through 2007, 61 percent of all LMB collected from the WCAs exceed the USEPA human-health fish tissue MeHg criterion of 0.3 µg/g; during the same period of time, eight percent of LMB exceeded 1.0 µg/g, suggesting that there are localized areas with high rates of mercury bioaccumulation within the WCAs.
- For the WCAs, from 1990 through 2000, annual mercury medians for LMB from age cohorts one and two exceed the USEPA guidance criterion for protection of fish-eating wildlife of 0.346 µg/g for trophic level (TL) 4 fish. Since 2001, the median concentration has fallen below the wildlife criterion level during a three-year period, and has reached its lowest value of 0.29 µg/g in 2007 (range; 0.05-0.85 µg/g; n = 147). This downward trend is encouraging; still, 39 percent (n = 58) of age cohort one and two LMB exceeded the wildlife guidance criteria during 2007.
- For 2007, 78 percent of all sunfish sampled across the Everglades Protection Area (EPA) exceeded the USEPA TL 3 MeHg criterion for protection of fish-eating wildlife of 0.077 µg/g; 68 percent exceeded the USFWS 0.100 µg/g mercury criterion; and, 10 percent exceeded the USEPA 0.346 µg/g TL 4 MeHg criterion (see Appendix 3B-1).

[4] Chapter 3A and Appendix 3B-1 of this volume provide additional details to meet the Everglades Forever Act (EFA) requirement that the District and the FDEP shall annually issue a peer-reviewed report regarding the mercury research and monitoring program that summarizes all data and findings. Additional detailed scientific information can be found in mercury chapters in the 1999 Everglades Interim Report, 2000–2004 Everglades Consolidated Reports, and 2005–2008 South Florida Environmental Reports.

- For the Shark River Slough in the ENP, annual mercury medians for LMB from age cohorts one and two exceeded the USEPA guidance criterion for protection of fish-eating wildlife of 0.346 µg/g for TL 4 fish for all years sampled. Over 99 percent of age cohort one and two LMB exceeded the USEPA wildlife criterion from 1993 through 2008. These findings continue to suggest that piscivorous avian and mammalian wildlife may experience MeHg exposures above the acceptable dose in broad areas of the EPA, which encompasses WCAs 1, 2, and 3 and the ENP.
- Fish in the Shark River Slough of the ENP – mosquitofish (*Gambusia holbrooki*), sunfish, and LMB – continue to have higher mercury levels than fish elsewhere across the EPA. New data (from 2007 and 2008) for common snook (*Centropomus undecimalis*) from Shark River Slough indicate that these fish have higher mercury levels than snook elsewhere in the ENP, with mean concentrations of 1.6 µg/g and 0.5 µg/g, respectively.

MERCURY IN EVERGLADES FISH AND WILDLIFE

HISTORICAL MONITORING OF MERCURY IN BIOTA

Elevated levels of mercury in biota from Everglades National Park (ENP or Park) were first reported in 1974 (Ogden). In 1988, reports of mercury levels in largemouth bass (*Micropterus salmoides*) (LMB) in the Water Conservation Areas (WCAs) exceeding 1 microgram per liter (µg/L) prompted more widespread sampling of both fish and wildlife (Ware et al., 1990). For the following year (1989) the system-wide median mercury concentration in 89 LMB collected from WCAs 1, 2, and 3 was 1.34 µg/L with a range of 0.25-3.39 µg/L.

These and other findings prompted the state of Florida to issue no-consumption advisories for multiple species of fish in the Everglades Protection Area (EPA). Elevated levels of mercury were not restricted to fish; concurrent monitoring of EPA resident wildlife in the late 1980s by Ware et al. (1990) of alligators (*Alligator mississippiensis*), crayfish (*Procambarus alleni*), Florida softshell turtles (*Apalone ferox*), pig frogs (*Rana grylio*), mottled ducks (*Anas fulvigula*), white-tailed deer (*Odocoileus virginianus*), and the endangered Florida panther (*Felis concolor*), revealed elevated mercury levels in alligators and panthers. The high levels in these two top predators prompted more thorough surveys of piscivorous wildlife that revealed elevated mercury levels in wading birds (Spalding and Forrester, 1991), raccoons (*Procyon lotor*), alligators (Rumbold et al., 2002), Florida panthers (Roelke et al., 1991), and pig frogs (Ugarte et al., 2005) across the Everglades landscape.

MERCURY IN FISH – CURRENT YEAR SAMPLING

Fish Collection, Analysis and Mercury Concentration Normalization

LMB and common snook (*Centropomus undecimalis*) were collected during a current-year period of July 2007 through June 2008 from around South Florida using direct-current electrofishing equipment. To insure a wide distribution of fish sizes, 20 LMB between 200 and 500 millimeters (mm) total length were targeted from most sites, while 12 legally harvestable LMB were collected to meet requirements for human health risk assessments at other sites. Snook were also collected within their legal size limits of 635-838 mm total length.

All fish were weighed, measured, and sexed and the sagittal otoliths of LMB were removed for determination of age as described by Porak et al. (1986). An entire skinless axial muscle fillet was homogenized and an aliquot was submitted to the Florida Department of Environmental Protection (FDEP) Central Laboratory in Tallahassee.

Total mercury (THg) determinations of homogenates were made using U.S. Environmental Protection Agency method 245.6 (USEPA, 1991) with a method detection limit (MDL) of 0.02 mg/L. For SFWMD fish tissue mercury results (from Appendix 3B-1), THg was quantified using USEPA (2007) method 7473 using a Nippon mercury analyzer.

Results are reported on a wet weight basis as micrograms per gram equals parts per million equals milligrams per kilogram (µg/g = ppm = mg/kg). Essentially all of the mercury found in top-level predatory fish such as LMB is in the form of methylmercury (MeHg) (Bloom, 1992); therefore, analyses are conducted for THg and the assumption made that it represents the MeHg concentration in samples.

Largemouth bass are excellent biotic indicators of temporal and spatial trends in mercury bioaccumulation, with tissue concentrations generally reflecting ambient MeHg concentrations; however, LMB mercury concentrations should be considered as being integrated across time and space, and are not necessarily indicative of the exposure at the time or exact location the fish was collected. Likewise, tissue mercury concentrations are dependent upon the duration of exposure, fish age and size, population turnover, and relative trophic level of fish. Sexually dimorphic growth in Florida's LMB (Porak et al., 1988) further complicates interpretation of data since faster growing females typically have lower mercury concentrations than similar sized males (Lange et al., 1993, 1994).

For this study, LMB mercury concentrations were normalized by age to account for size-dependent bioaccumulation of mercury and also to correct for variations in sample size distributions, sex, and collection date. Standardization to fish size or age in order to normalize contaminant concentrations in fish is a common practice (Hakanson, 1980; Wren and MacCrimmon, 1986; Sorenson et al., 1990), and normalization to age has proven effective for spatial and temporal comparison of LMB mercury data for Florida (Lange et al., 1993, 1994). Normalization of monitoring data is necessary to assess the relationships between mercury bioaccumulation and changes in mercury loading to the system, or other environmental factors (e.g., sulfate loading) which would effect mercury bioaccumulation (Wiener et al., 2006).

Therefore during this study, LMB mercury levels were standardized to an expected age-three mercury concentration (EHg3) by regression of mercury level on age for each site and calculating the expected mercury concentration in three-year-old LMB for each sample event. Where no significant relationship between mercury and age was observed ($p > 0.05$), the mean mercury concentration was reported. Snook data are summarized by sample means for each monitoring site to represent the mid-point concentration for a sample of legally harvestable size fish.

Regional annual summaries of LMB mercury levels are reported for the WCAs and Shark River Slough in the ENP. Largemouth bass were collected dating back to 1988 when statewide monitoring identified the Everglades as a mercury hot spot. Also reported are site-specific spatial and temporal trends in LMB from long-term monitoring sites which were established in response to the high levels of mercury found in Everglades biota in the late 1980s and early 1990s. Emphasis is given to temporal analyses of data, but consideration is also given to spatial distributions of mercury bioaccumulation in the EPA as well. A total of 17 long-term monitoring sites were established in Florida, 10 of which are located in the Everglades (**Figure 3B-1**).

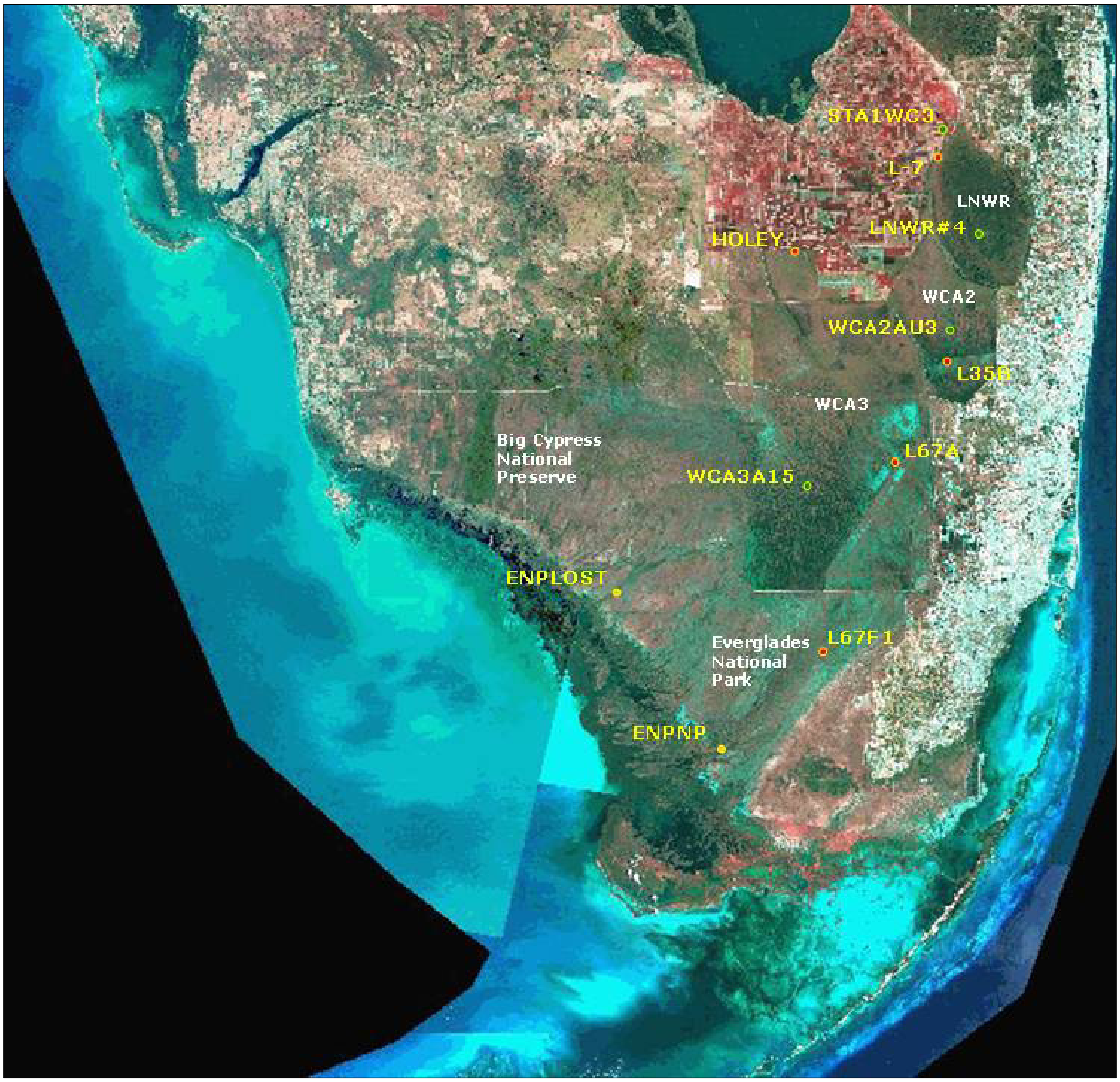


Figure 3B-1. Location of 10 long-term mercury monitoring locations and one additional location in the Everglades Protection Area (EPA) and Stormwater Treatment Area 1 West (STA-1W).

Notes:
Site STA1WC3 is located in Cell 3 of STA-1W
Sites LNWR#4 Marsh and L-7 are located in Water Conservation Area (WCA) 1
Sites L35B and WCA2AU3 are located in WCA-2
Sites L67A and WCA3A15 are located in WCA-3
Sites ENPLOST and ENPNP are located in Everglades National Park (ENP)
Site HOLEY is located in Holey Land Wildlife Management Area
Site L67F1 is not a long-term monitoring site, but is located in the ENP

- Marsh sites
- Canals
- Estuarine creeks

Results: Regional Trends

From July 2007–June 2008, a total of 284 LMB were collected from the WCAs (n = 263) and Shark River Slough in the ENP (n = 21) for assessment of regional trends in these two areas. In addition, 18 snook were collected from three sites in the ENP to assess habitat influences on mercury bioaccumulation. Various other species were collected for health advisory assessments but only LMB and snook are reported in this chapter. Since 1988, a total of 3,242 LMB and 60 snook have been collected.

In the WCAs, the system-wide median mercury concentration has declined 70 percent over the past 20 years from a maximum in 1988 of 1.75 µg/g (range; 1.20-3.4 µg/g; n = 12) to 0.30 µg/g (range; 0.04-2.0 µg/g; n = 263) in 2007 (and 2001) (**Figure 3B-2**). The greatest decline in LMB mercury levels occurred from 1991–2001 when the system-wide median reached a low of 0.3 µg/g. Since 2001, median concentrations have varied minimally reaching a high of only 0.45 µg/g in 2005. In spite of these declines in LMB mercury levels, individual LMB continue to show evidence of high rates of mercury bioaccumulation within the WCAs. From 2001–2007, 922 or 61 percent of all LMB collected from the WCAs exceeded the USEPA human-health fish tissue methylmercury criterion of 0.3 µg/g (USEPA, 2001) and during the same period, 116 LMB (eight percent) exceeded 1.0 µg/g, a result which suggests localized areas with high rates of mercury bioaccumulation exist within the WCAs.

Within the ENP, Shark River Slough appears to have the highest rates of mercury bioaccumulation in LMB and snook. This drainage basin extends from Tamiami Trail (SR41), near site L67F1, south to the southernmost extent of freshwaters at site ENPNP and continues out to Florida Bay and the Gulf of Mexico through various estuarine river and creek channels. Current data indicates elevated levels of mercury in estuarine species in Shark River Slough. A better understanding, however, of the processes effecting transport and bioaccumulation of mercury in estuarine systems is needed, particularly in Shark River Slough, as Everglades restoration efforts change water quality, timing, and quantity.

Mercury concentrations in LMB from Shark River Slough in the ENP have, for the past decade, been much higher than those in the WCAs, with median concentrations exceeding or approaching 1.0 µg/g every year tested since 1989 (**Figure 3B-3**). In 2008, the system-wide median concentration was 1.10 µg/g (range; 0.36-3.50 µg/g; n = 21). From 1989–2008, all but one LMB collected from Shark River Slough in the ENP (sites L67F1 and ENPNP, see **Figure 3B-1**) have exceeded the USEPA human-health MeHg fish tissue criterion of 0.3 µg/g (n = 449). The Florida Department of Health has issued no- and limited-consumption advisories regarding several fish species in the EPA (FDOH, 2007).

Inside the ENP but outside of Shark River Slough, lower rates of mercury bioaccumulation in LMB have been found. To the east, at three sites located in Taylor Slough, Evans (2008) reported a two-year mean mercury concentration in 40 LMB of 0.63 µg/g. Similarly, to the north of Shark River Slough, at site ENPLOST, the median mercury concentration for 40 LMB collected for the present study during 2007 and 2008 was 0.67 µg/g. The ENPLOST site is located outside the direct influence of the Shark River Slough and is situated downstream of Big Cypress National Preserve.

The extent of the elevated mercury bioaccumulation rates within Shark River Slough were further investigated by collecting samples of snook, a migratory marine species, at sites ENPNP and ENPLOST. Two years of data are available for this species. Snook collected from site ENPNP in Shark River Slough during 2007 and 2008 had a median mercury concentration of 1.60 µg/g (range 0.93-2.3 µg/g; n = 12) as compared to those from site ENPLOST which had a median mercury concentration of 0.50 µg/g (range 0.38-0.93; n = 9). Further north along the Gulf Coast in the ENP at Lostmans Five Bay, the median mercury concentration for snook collected during the same period was similar to ENPLOST (mean = 0.48 µg/g, range 0.29-0.94 µg/g; n = 6). These findings suggest that snook collected in Shark River Slough, which likely spend only a portion of their time in its upstream reaches, are exposed to higher ambient levels of MeHg than snook from adjacent estuarine areas.

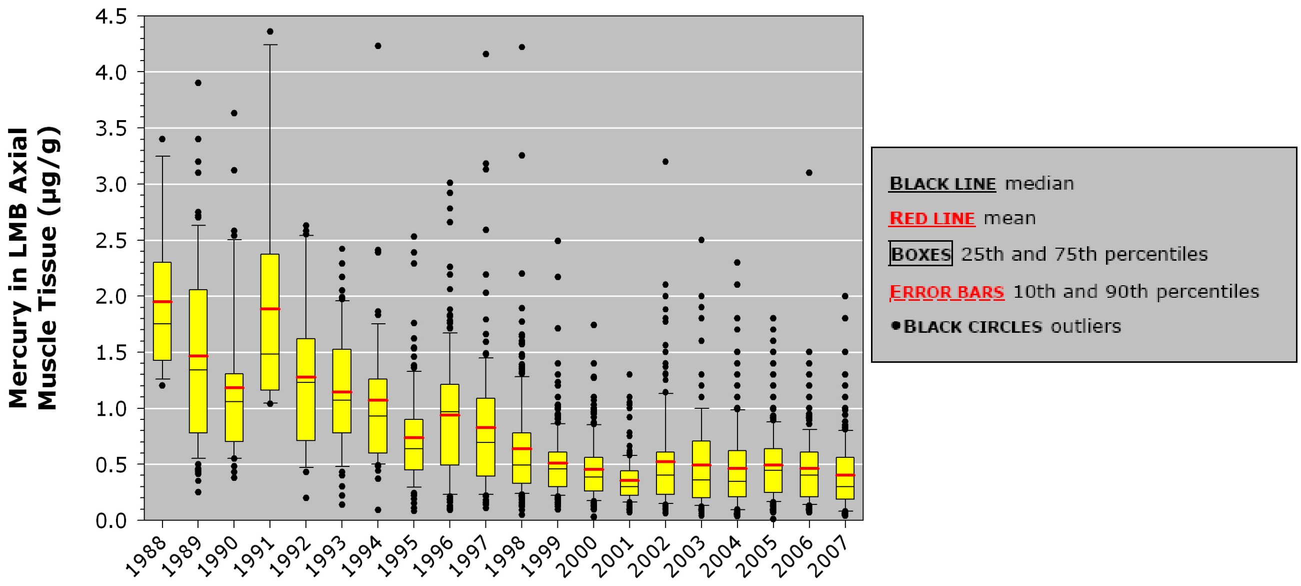


Figure 3B-2. Annual summaries of mercury concentrations in 2,792 largemouth bass (LMB) (all ages) collected from canal and marsh sites in WCAs 1, 2, and 3 between 1988 and 2007.

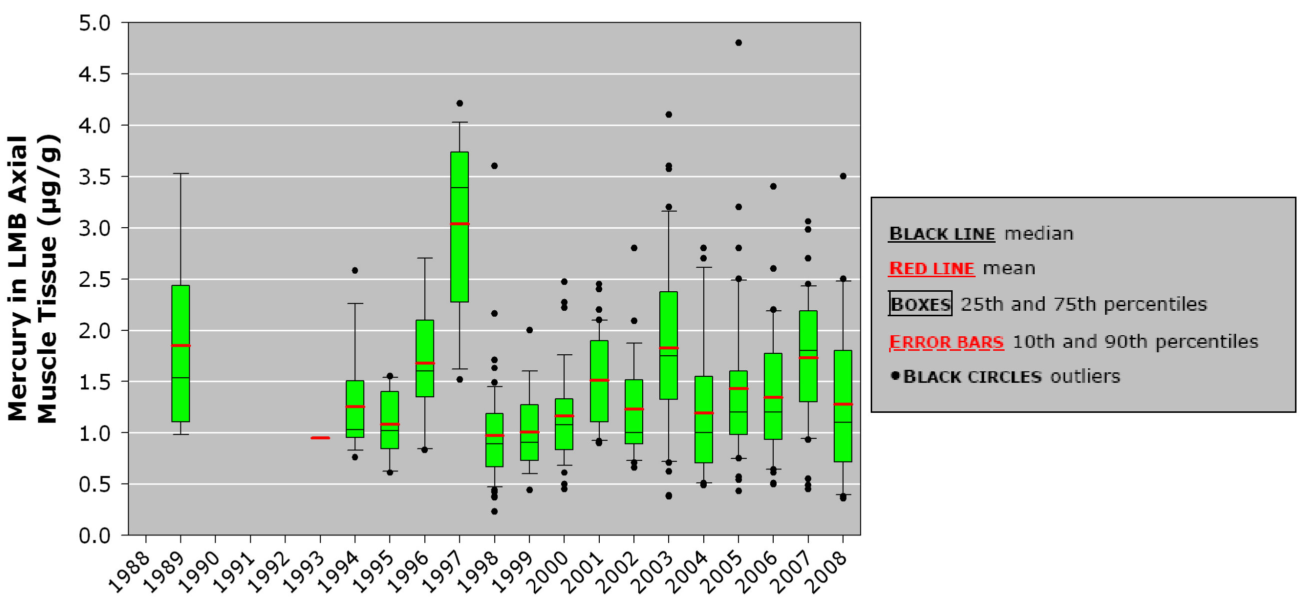


Figure 3B-3. Annual summaries of mercury concentrations in 450 LMB (all ages) collected from two sites in the Shark River Slough of the ENP between 1989 and 2008.

Results: Site-Specific Trends

During October and November 2007, 263 LMB were collected from all three WCAs, 41 from the ENP, 33 from Stormwater Treatment Area 1 West (STA-1W), and 20 from the Holey Land Wildlife Management Area (Holey Land WMA) for analyses of spatial and temporal trends in mercury bioaccumulation. LMB collected from the WCAs and the ENP were also utilized in the regional assessments discussed above.

Localized trends in LMB mercury levels were monitored at 10 locations within the EPA using age-standardized mercury concentrations in LMB (EHg3). Location names and descriptions along with the period of record (POR) are given for each long-term site in **Table 3B-1**. Sampling sites were located along a transect starting in STA-1W and moving south through WCAs 1, 2, and 3 and into the ENP. A site is also located in Holey Land WMA, which is situated on the northern boundary of WCA-3 (**Figure 3B-1**). Spatial and temporal trends for these long-term monitoring stations are reported in **Table 3B-2** and **Figures 3B-4** through **3B-9**. The periods of record (POR) and number of sampling events vary among sites due to differences in initial sampling dates and inability to collect LMB samples during some years.

Throughout the LMB mercury monitoring project, the spatial distribution of mercury has remained consistent with increasing mercury bioaccumulation moving from north to south in the EPA (**Table 3B-2**). The current year data (July 2007–June 2008) show increasing EHg3 moving south along the site transect from site LNWR#4 south to site ENPNP with the exception of site HOLEY. Although the declines from the very high levels of mercury in LMB in the mid-1990s are encouraging, temporal trends at individual sites indicate recent increases.

Site-specific trends in EHg3 at sites located in WCAs 1, 2, and 3 (**Figures 3B-4** through **3B-6,** respectively) show similar trends as observed in system-wide median concentrations observed in **Figure 3B-2**. The site-specific targeted sampling for the long-term monitoring does not go back as far as the system-wide monitoring; however, maximal concentrations of EHg3 at the six sites in the WCAs occurred from 1992–1996 with a range of values between 0.61 and 2.39 µg/g (**Table 3B-2**).

These maximal concentrations typically occurred near the initiation of sampling (early or mid 1990s) while the minimal concentrations at these sites were observed from 2001 through 2004 with the exception of site L35B which reached its minimum earlier, in 1998. Minimal values during this time period averaged 0.34 µg/g (range; 0.09 - 0.79 µg/g) and represent an overall decline from maximal concentration in the mid-1990s to minimal concentrations early 2000s of 75 percent (range; 61-85 percent decline) (**Table 3B-2** and **Figures 3B-4** through **3B-6**). These declines were somewhat consistent within the WCAs and also within STA-1W at site STA1WC3, which declined from maximal to minimal EHg3 from 1996–2004; a 57 percent decline (**Table 3B-2** and **Figure 3B-7**).

In contrast to these downward trends are recent increases in EHg3 within the WCAs. Since reaching minimal concentrations, EHg3 at the six sites in the WCAs increased to an average of 0.57 µg/g (range 0.29-0.78 µg/g), representing increases ranging from 37 to 334 percent (102 percent average) at the six sites (**Table 3B-2** and **Figures 3B-4, 3B-5,** and **3B-6**). The greatest increase was observed in WCA-1 where sites L-7 and LNWR#4 experienced increases of 334 and 71 percent, respectively, during this period ending in 2007. Similarly, at site STA1WC3, EHg3 increased from 2004–2007 by 59 percent (**Table 3B-2**). Recent increases in mercury bioaccumulation do not approach the levels measured in LMB during the early-1990s, but they do represent a troublesome trend of increased MeHg exposure for piscivorous wildlife and humans.

Of greater concern are the temporal trends experienced at sites located in the ENP and Holey Land WMA. Although the magnitude of change over the POR is similar at these sites to those in the WCAs and STA-1W, the timing of maximal and minimal concentrations differs, with the ENP and Holey Land WMA sites trending upwards in recent times. Moreover, among all sites sampled during the POR, EHg3 was the highest at HOLEY, ENPNP, and ENPLOST.

Site HOLEY (**Figure 3B-8**) reached its maximal EHg3 of 0.86 µg/g in 2006 after a minimal EHg3 in 1999 of 0.27 µg/g (**Table 3B-2**), a trend that is exactly opposite of what occurred in the WCAs during the same period of time. For the POR, EHg3 at HOLEY was 0.80 µg/g, nearly three times higher than the EHg3 in 1999 (**Table 3B-2**).

Mercury concentrations in Shark River Slough in the ENP were discussed in the *Results: Regional Trends* section of this chapter; however, trends at site ENPNP, which represent half of the LMB used in the Shark River Slough regional analyses, should be noted. At ENPNP, EHg3 declined from a high of 2.36 µg/g in 1994 to 1.11 µg/g in 2008, representing a 53 percent decrease over the POR for the site (**Table 3B-2**). However, levels of mercury continue to pose a significant risk to piscivorous wildlife and humans even after declines in EHg3 from 2003–2008 (**Figure 3B-9**).

EHg3 concentrations at site ENPLOST remain lower than those at site ENPNP (**Figure 3B-9**) but also pose a risk to consumers of these fish. Trends in EHg3 are not strongly evident, particularly in light of the fact that no samples were collected from 2001–2006; nevertheless, EHg3 increased 41 percent from 1995–2008 (**Table 3B-2**).

Mercury concentrations in age one and two cohort LMB are summarized in (**Figure 3B-10**) for the WCAs and Shark River Slough in ENP and were evaluated as an approximation of a TL 4 fish that is of an age/size class that is more appropriate as prey for avian wildlife than older LMB.

Annual mercury medians for LMB from age cohorts one and two exceed the USEPA guidance criteria for protection of fish-eating wildlife of 0.346 µg/g for TL 4 fish during all years sampled in Shark River Slough, and from 1990–2000 in the WCAs (**Figure 3B-10**). Since 2001 in the WCAs, the median age cohorts one and two LMB mercury concentration has fallen below this criteria level during three years, and has reached its lowest value of 0.29 µg/g in 2007 (range; 0.05-0.85 µg/g; n = 147). This downward trend is encouraging; still, 39 percent (n = 58) of age cohort one and two LMB exceeded the guidance wildlife criterion in the WCAs during 2007, while in Shark River Slough over 99 percent of age cohort one and two exceeded the USEPA wildlife criterion for 1993–2008.

Risks to fish-eating avian and mammalian wildlife continue to be of concern in the EPA. Adverse effects from mercury exposure can be evaluated within the context of the U.S. Fish and Wildlife Service (USFWS) proposed predator protection criterion of 0.1 µg/g (Eisler, 1987) and the USEPA piscivorous wildlife protection criteria of 0.077 µg/g and 0.346 µg/g for trophic level (TL) 3 and 4 fish, respectively (USEPA, 1997) (**Figure 3B-11**).

As reported in Appendix 3B-1, in 2007 across the EPA, 20 percent of all mosquitofish collected (considered to be at TL 2 and 3, depending on age; Loftus et al., 1998) exceeded the USEPA criterion of 77 nanograms per gram (ng/g; 1 ng/g = 0.001 µg/g) and 13 percent exceeded the USFWS criterion of 100 ng/g (**Figure 3B-12**). These exceedances were all from the L67F1, ROTENF1, and WCA2U3 stations (Appendix 3B-1; Table 6). This is an increase from 2006 where there were no exceedances of the 77 ng/g criterion for mosquitofish.[4]

Sunfish also showed an increase from 2006 (Appendix 3B-1). For 2007, 78 percent of all sunfish [which are generally TL 3 (*L. gulosus* at TL 4; Loftus et al., 1998)] exceeded the USEPA 77 ng/g criterion; 68 percent exceeded the USFWS 100 ng/g criterion and 10 percent exceeded the EPA 346 ng/g TL 4 criterion (Appendix 3B-1, Table 7) (**Figure 3B-13**). In 2006, 73 percent of all sunfish exceeded TL 3 criteria and 56 percent exceeded USFWS criteria of 100 ng/g. As discussed previously by Rumbold (2005), these findings are significant because sunfish and mosquitofish represent the preferred prey item of many fish-eating species in the Everglades.

All LMB collected at stations WCA2U3, L67F1, and HOLYBC, accounting for 41 percent of all LMB collected, exceeded the guidance value for TL 4 fish (Appendix 3B-1, based on the calculation where whole body THg concentration = 0.695 x fillet THg; Lange et al., 1998). Four percent of all bass exceeded the FDOH's human no-consumption advisory criterion of 1,500 ng/g for the general population (**Figure 3B-14**). These samples were all collected from site L67F1 in Shark River Slough. Based on 2007 findings, some Everglades populations of fish-eating birds and mammals may be at risk for adverse effects from mercury exposure.

Mercury levels in Everglades great egret (*Ardea alba*) feathers are not reported this year due to low nesting rates in 2008 (see Chapter 6 of this volume for details on wading bird nesting patterns in the EPA). Feathers from only two birds from a single colony were collected (Appendix 3B-1).

Additionally, trends in atmospheric wet deposition of mercury are not reported, as in 2007 there were numerous missing samples at all three mercury deposition network (MDN) stations in the EPA due to mechanical failure and other issues, making estimation of mercury deposition and interpretation of among-year differences in volume-weighted mean concentration problematic (Appendix 3B-1). However, the National Atmospheric Deposition Program's 2007 estimate demonstrates that South Florida continues to receive elevated mercury deposition relative to the rest of the continental U.S., which is a result of South Florida's relatively high annual precipitation and high volume-weighted mean wet deposition mercury concentration (**Figure 3B-15**).

[4] These observed increases should, however, be viewed with caution as they may be related to the change in analytical laboratory. In October 2007, all fish mercury analysis responsibilities were transferred from the FDEP to the District. The agencies use different instrumentation for mercury detection (see the *Laboratory Quality Control* section of Appendix 3B-1). An investigation is currently under way to determine if there are analytical differences in mercury quantification between instruments.

Table 3B-1. Location and description of sites for long-term monitoring of mercury bioaccumulation in LMB from the Everglades Protection Area (EPA) and Stormwater Treatment Area 1W (STA-1W). Each site's period of record (POR) and number of annual samples collected over the POR are shown. For site locations, see **Figure 3B-1**.

Location/Site	Description	Site POR	Sample Events
Stormwater Treatment Area 1 West			
STA1WC3	Interior marsh, two sites in Cell 3	1995-2007	14
Holey Land Wildlife Management Area			
HOLEY	North Borrow Canal, connected to marsh	1996-2007	12
Arthur R. Marshall Loxahatchee National Wildlife Refuge			
LNWR#4	Marsh	1995-2007	13
L-7	L-7 conveyance canal	1995-2007	13
Water Conservation Area 2A			
WCA2AU3	Marsh	1993-2007	16
L35B	L-35B conveyance canal	1994-2007	17
Water Conservation Area 3A			
WCA3A15	Marsh	1993-2007	14
L67A	L-67A conyance canal	1990-2007	21
Everglades National Park			
ENPLOST	Lostmans Creek (estaurine), Big Cypress NP	1995-2008	10
ENPNP	North Prong Creek (estuarine), Shark River Slough	1994-2008	16

Table 3B-2. Trends in age-standardized mercury levels (EHg3) in LMB for various PORs at 10 long-term monitoring sites in the EPA. The POR, percent change during the POR (first to current year), historic maximal and minimal EHg3 concentrations and current EHg3 are shown. Sites are aligned from north to south and EHg3 is reported as µg/g = mg/kg = ppm.

Location/Site	Site POR	POR %Change	Historic Levels Max EHg3(Yr)	Historic Levels Min EHg3(Yr)	Current Levels EHg3(Yr)
Stormwater Treatment Area 1 West					
STA1WC3	1995-2007	-7	0.12 (1996)	0.05 (2004)	0.09 (2007)
Holey Land Wildlife Management Area					
HOLEY	1996-2007	55	0.86 (2006)	0.27 (1999)	0.80 (2007)
Arthur R. Marshall Loxahatchee National Wildlife Refuge					
LNWR#4	1995-2007	-63	0.88 (1996)	0.17* (2003)	0.29* (2007)
L-7	1995-2007	3	0.61 (1996)	0.09 (2004)	0.40 (2007)
Water Conservation Area 2A					
WCA2AU3	1993-2007	-45	1.27 (1993)	0.48 (2001)	0.70 (2007)
L35B	1994-2007	-47	1.32 (1994)	0.51 (1998)	0.70 (2007)
Water Conservation Area 3A					
WCA3A15	1993-2007	-67	2.39 (1993)	0.49 (2003)	0.78 (2007)
L67A	1990-2007	-65	1.83* (1992)	0.32 (2001)	0.54 (2007)
Everglades National Park					
ENPLOST	1995-2008	41	1.14 (1997)	0.62 (1996)	0.80 (2008)
ENPNP	1994-2008	-53	2.36 (1994)	0.79 (1998)	1.11 (2008)
Average		**-25**	**1.28**	**0.38**	**0.62**

**Mean value of THg reported for these sites due to insignificant (p > .05) relationship between fish mercury and age.*

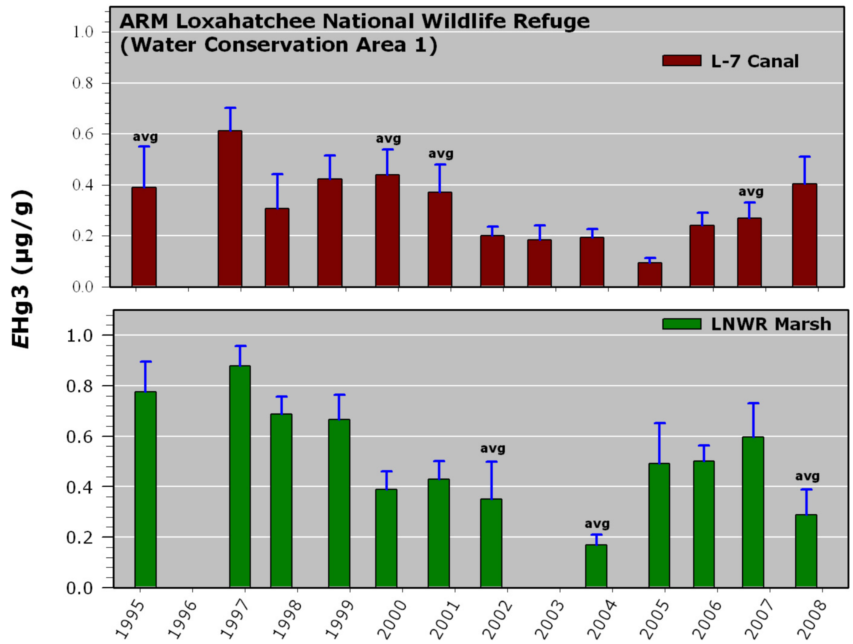


Figure 3B-4. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in LMB at long-term monitoring sites located within WCA-1. The average THg concentration (avg) is reported where calculation of the EHg3 was not appropriate.

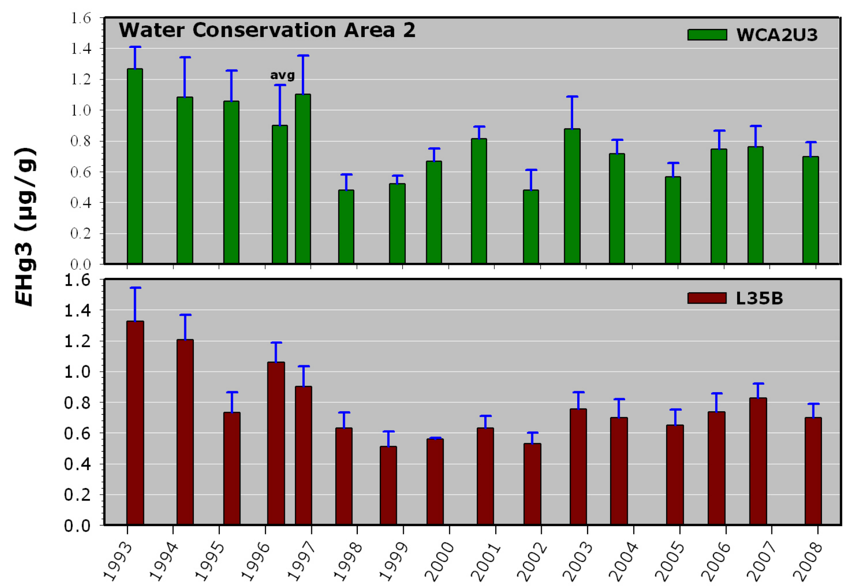


Figure 3B-5. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in largemouth bass at long-term monitoring sites located within WCA-2A. The average THg concentration (avg) is reported where calculation of the EHg3 was not appropriate.

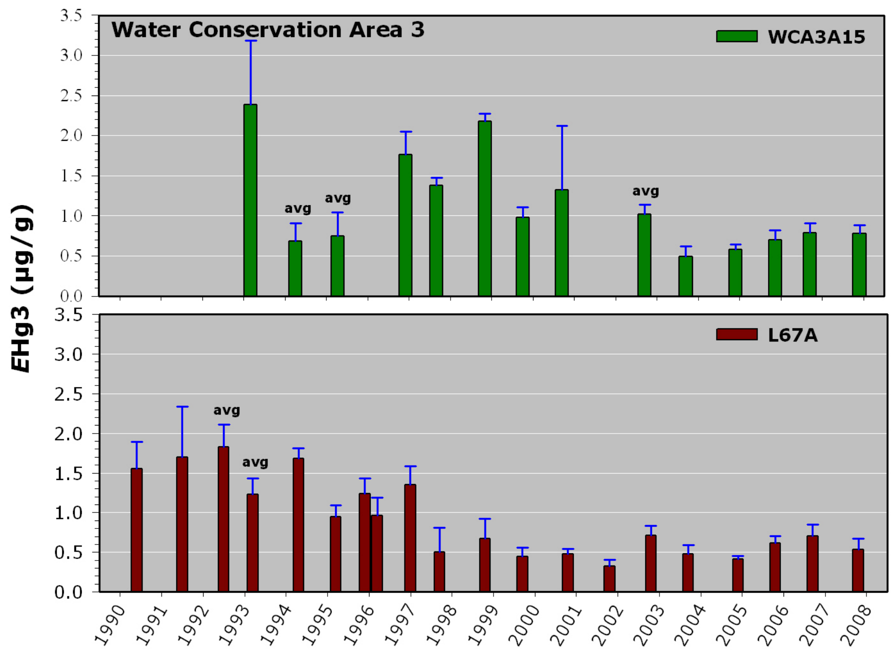


Figure 3B-6. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in LMB at long-term monitoring sites located within WCA-3A. The average THg concentration (avg) is reported where calculation of the EHg3 was not appropriate.

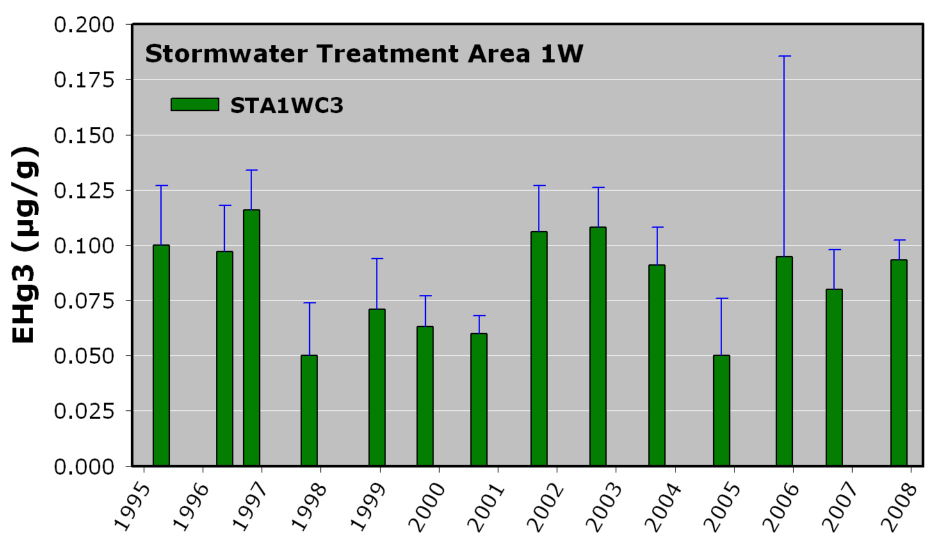


Figure 3B-7. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in LMB at long-term monitoring sites located within STA-1W.

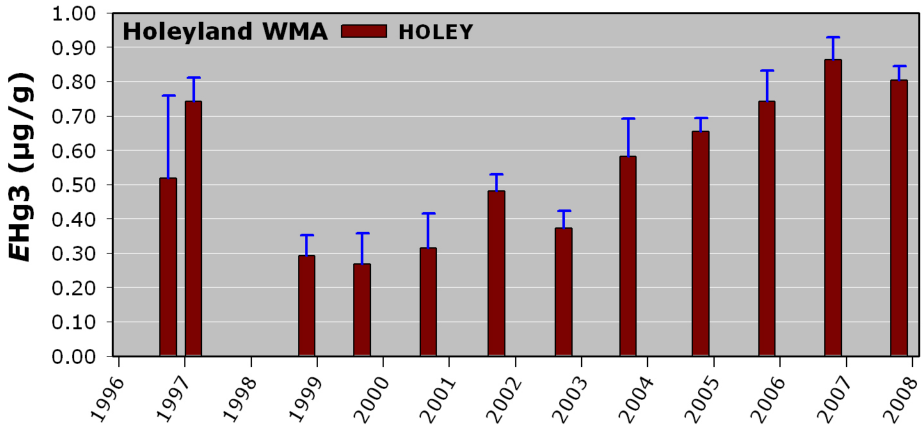


Figure 3B-8. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in LMB at long-term monitoring sites located within Holey Land Wildlife Management Area.

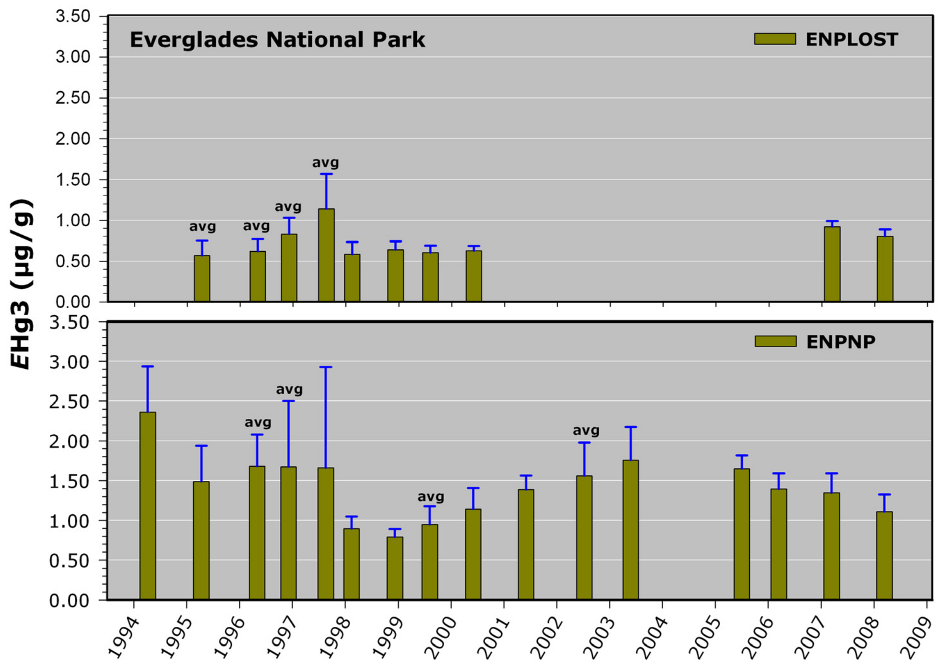
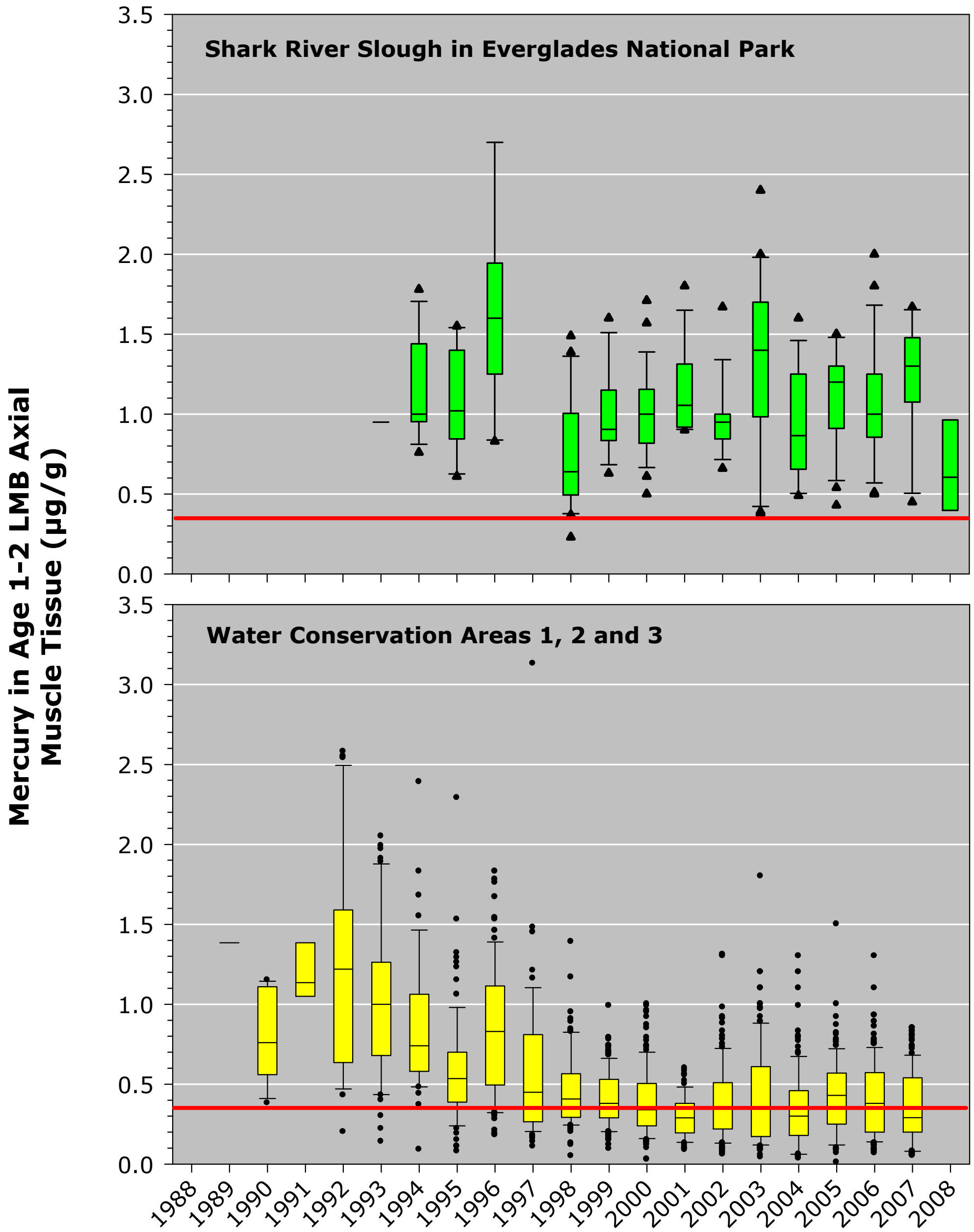


Figure 3B-9. Age-standardized mercury concentration (EHg3) and the 95 percent confidence interval in LMB at long-term monitoring sites located within the ENP. The average THg concentration (avg) is reported where calculation of the EHg3 was not appropriate.



BLACK LINE median

RED LINE USEPA Trophic Level 4 criteria for the protection of piscivorous wildlife (0.346 µg/g)

BOXES 25th and 75th percentiles

ERROR BARS 10th and 90th percentiles

●**BLACK CIRCLES** outliers

Figure 3B-10. Annual summaries of mercury concentrations in age cohort one and two LMB collected from two sites in the Shark River Slough of the ENP between 1993 and 2008 (top panel) and numerous canal and marsh sites in WCAs 1, 2, and 3 between 1989 and 2007 (bottom panel).

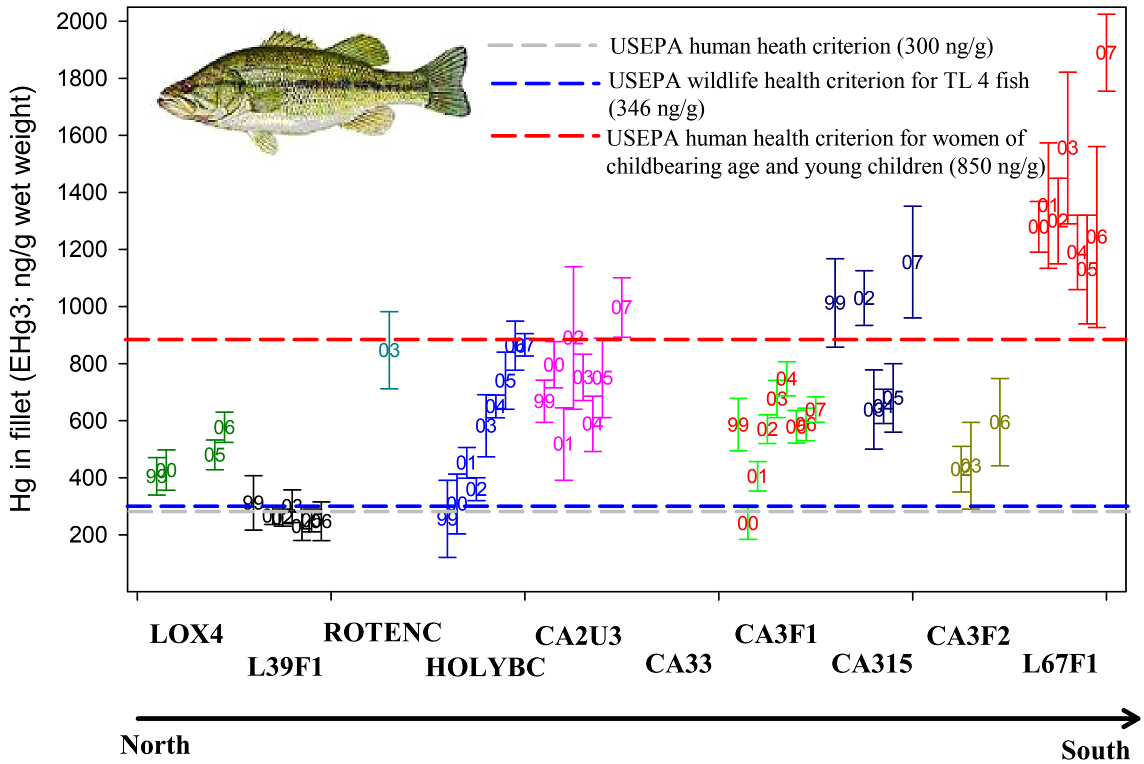


Figure 3B-11. Age standardized expected Hg concentration (EHg3) in LMB collected throughout the EPA from 1999–2007. EHg3 was not calculated if regressions were not significant or if age distributions were narrow. Error bars show the 95% confidence interval.

Notes: The two-digit numbers on the graph represent the year of sampling; for example, "99" means the sample was taken in 1999 (and so on). For sampling locations, see Appendix 3B-1, Figure 3.

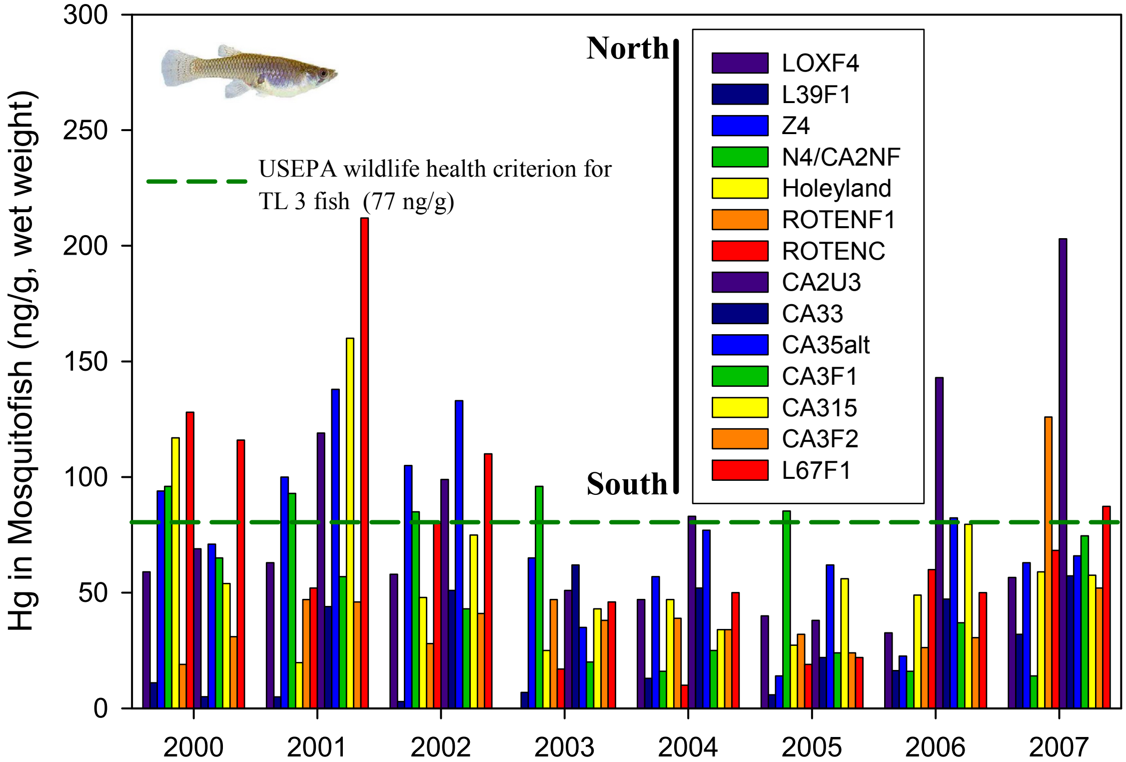


Figure 3B-12. Average mercury concentrations in mosquitofish collected throughout the EPA for the POR from 1998–2007.

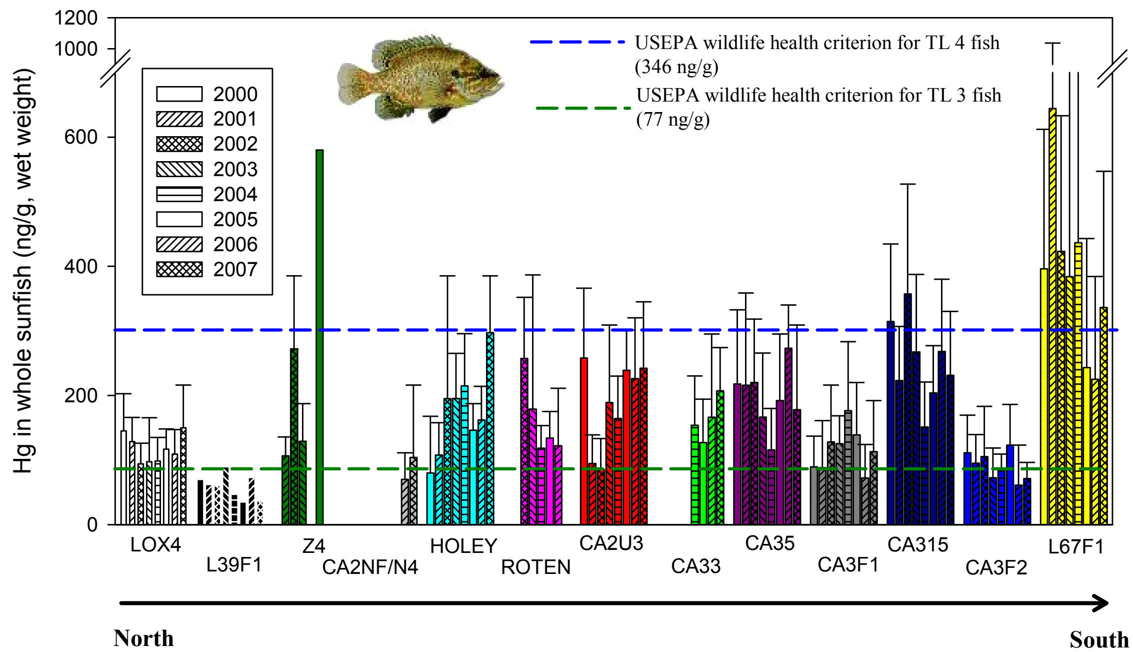


Figure 3B-13. THg concentration of whole sunfish (*Lepomis* spp.) collected throughout the EPA from 2000–2007. Data points display the mean and standard deviation.

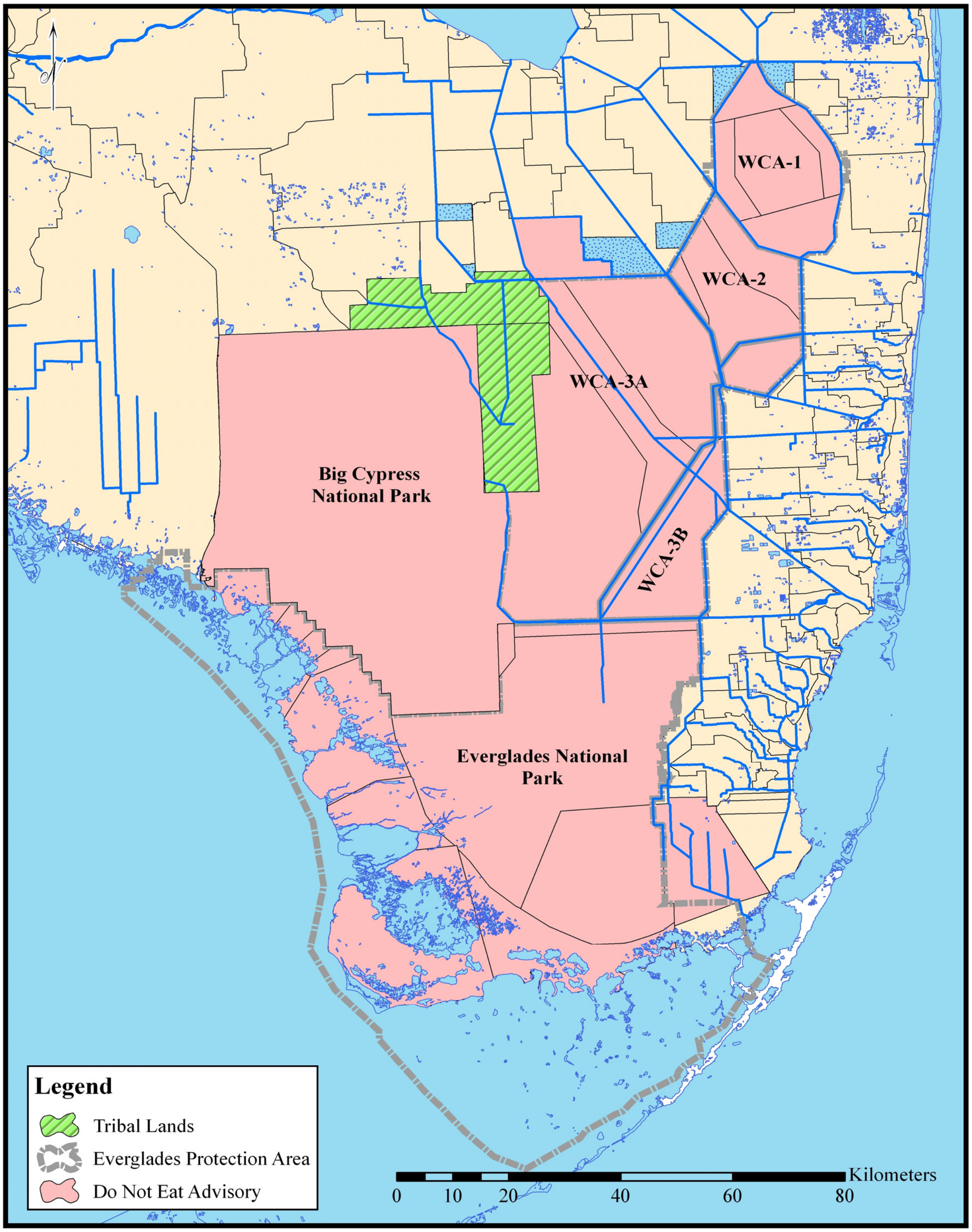


Figure 3B-14. Areas of the Everglades Protection Area where the Florida Department of Health issues public "do not eat" advisories for LMB.

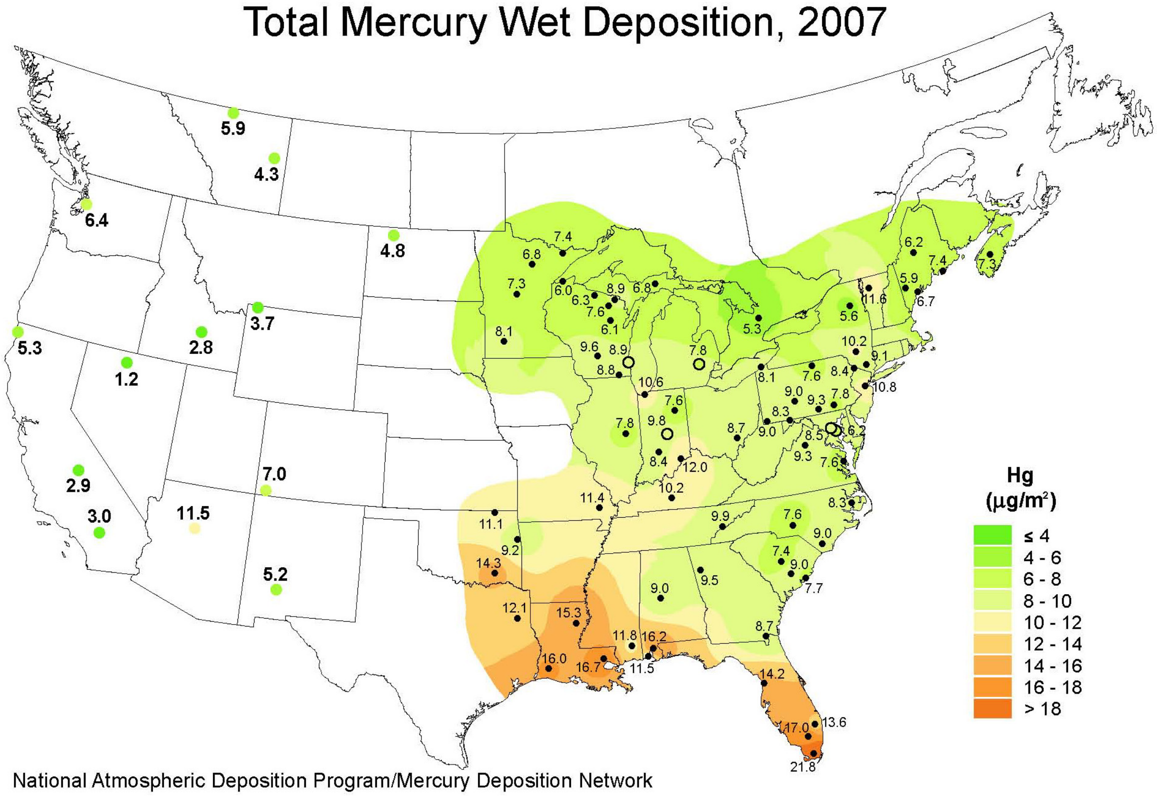


Figure 3B-15. Wet deposition of total mercury (µg/m^2) in 2007. Data from National Atmospheric Deposition Program's Mercury Deposition Network (NADP, 2008).

SULFUR IN THE EVERGLADES

Sulfate-reducing bacteria (SRB) are the predominant producers of MeHg in aquatic ecosystems, and methylation of inorganic mercury by SRB is dependant on sulfate availability (Ekstrom et al., 2003; Gilmour et al., 2004). The effect of sulfur on mercury methylation in the Everglades is determined by the balance between sulfate (SO_4^{2-}) and sulfide (S^{2-}); (Benoit et al., 2003; Gilmour et al., 1998; Gilmour et al., 2007a).

Sulfate inputs are an important factor in supporting high mercury methylation rates in the Everglades (Bates et al., 2002; Benoit et al., 1999, 2001, 2003; Gilmour et al., 2007a). At present, it is likely that broad areas of the Everglades exhibit sulfate concentrations at which increased sulfate levels would enhance, and decreased sulfate concentrations would reduce net MeHg accumulation in soils and therefore MeHg accumulation in fish, birds and mammals (Gilmour et al., 2007a).

The USEPA has not issued any guidance regarding a water quality criterion for sulfate, and thus the state of Florida has no sulfate water quality criterion. The Comprehensive Everglades Restoration Plan (CERP) goal for sulfate in surface water is 1 mg/L. By comparison, background sulfate in the Everglades may be ≤ 0.1 mg/L (Scheidt and Kalla, 2007; Weaver et al., 2007).

At the CERP goal of 1 mg/L sulfate in Everglades surface water, data indicate that microbial sulfate reduction and MeHg production rates would be low due to sulfate limitation, and sediment porewater sulfide levels would only be in the tens of µg/l, minimizing both sulfide toxicity to aquatic plants and animals and internal eutrophication – phosphate and ammonium release from sediments (Gilmour et al., 2007a, b). Surface water sulfate concentrations above 1 mg/L are evident in about 60 percent of the total area of freshwater Everglades marshes (Scheidt and Kalla, 2007).

Managing sulfate inputs to the Everglades is a potential option for reducing MeHg bioaccumulation, and to accomplish this, determination of the major sources of sulfate to the Everglades is critical. Based on sulfate concentration data, it may be concluded that much of the sulfate entering the Everglades originates from Everglades Agricultural Area (EAA) canals (Bates et al., 2001; 2002; Orem, 2004; Gilmour et al., 2007b; Scheidt et al., 2000; and Scheidt and Kalla, 2007), and as a first step towards managing sulfate inputs, the SFWMD plans a sulfur mass balance study to quantify the specific sources of this sulfate to these canals, and the surface water loading exchange between South Florida's major land uses.

For Water Year 2008 (WY2008) (May 1, 2007–April 30, 2008), sulfate concentrations across the EPA continued to exhibit a general north-to-south gradient (see **Figure 3A-9** and Chapter 3A of this volume), as has been the pattern for previous years (Axelrad et al., 2007, 2008; Bates et al., 2002; Gilmour et al., 2007b; Weaver et al., 2007).

Highest sulfate concentrations within the EPA for WY2008 were observed in the WCA-1 rim canal and in WCA-2. The interior of WCA-2 is the marsh area most effected by EAA runoff and consequently exhibits the highest sulfate concentrations. For WY2008, the interior sites in WCA-2 exhibited a median sulfate concentration of 15.9 mg/L compared to a minimum median concentration of 0.7 mg/L observed in the ENP (Chapter 3A).

During WY2008, the sulfate concentrations at both the inflow and interior sites measured in WCA-1 and WCA-2, which are more directly influenced by runoff from the EAA and Lake Okeechobee discharges, were lower than for monitoring periods WY1979–WY1993, WY1994–WY2004, and WY2005–WY2008. This is likely the result of reduced runoff from the EAA and reduced discharges from Lake Okeechobee during the dry conditions experienced during the 2006–2008 drought (Chapter 3A).

Data are available for sulfate from northwest WCA-2A, pre- and post-hydropattern restoration (Garrett and Ivanoff, 2008). Historically, the northwest section of WCA-2A received water via the S-10E structure, but the structure was closed in 1997, causing rainfall to be the primary source of water to the northwest section of WCA-2A. Beginning in July 2001, treated water from STA-2 was released into the northwest section of WCA-2A. Monitoring data were collected during the pre-discharge period (March 1998–June 2001) and the post-discharge period (July 2001–September 2006).

There were significant increases over the post-discharge period in surface water sulfate concentrations. Monitoring-station sulfate means ranged from 4-12 mg/L pre-discharge to 52-78 mg/L post-discharge (**Figure 3B-16**). The post-discharge sulfate average concentration of 60.8 ± 1.0 mg/L in northwest WCA-2A is consistent with sulfate levels found in the WCA-2A interior and in STA-2 discharge surface water (Garrett and Ivanoff, 2008).

Concerning sediment porewater chemistry, nearly all monitoring stations exhibited an increase in sulfate and sulfide concentrations after hydroperiod restoration occurred (Garrett and Ivanoff, 2008).

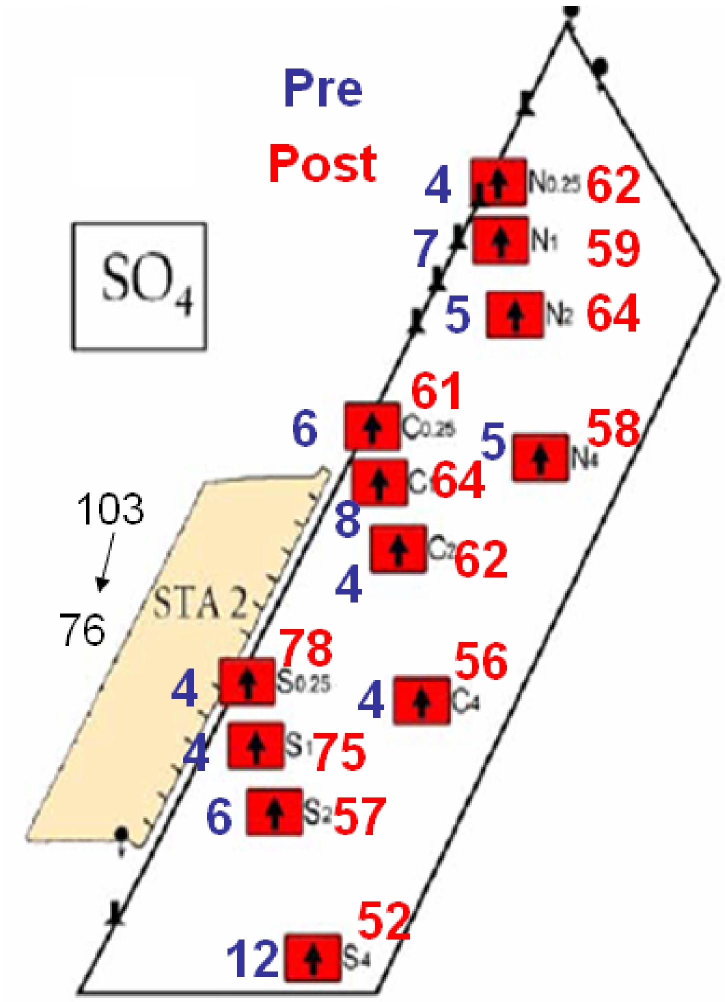


Figure 3B-16. Sulfate (SO_4^{2-}) concentrations (mg/L) in the northwest section of WCA-2A, with pre-hydropattern restoration values in blue and post-hydropattern restoration values in red. (Figure adapted from Garrett and Ivanoff, 2008, by Dan Scheidt, USEPA).

DISCUSSION

The Everglades has a significant mercury problem. Health advisories warning people to limit or avoid consuming fish are widespread and fish-eating wildlife are overexposed to mercury in some areas of the ecosystem. Everglades sulfate levels also appear problematic from the standpoint of stimulating mercury methylation, and potentially with regard to sulfide toxicity in plants and animals, and to sulfate-induced liberation of other elements, such as phosphate and ammonium, from Everglades soils.

The declines in mercury levels in fish from 1990–2000 are heartening, and the mechanism that appears to best account for these declines is a combination of both declining rates of atmospheric mercury deposition and declining concentrations of sulfate. As such, the best options for reducing MeHg production in the Everglades appear to be the reduction of atmospheric deposition of mercury and reducing sulfate loading to the Everglades.

RESEARCH PROGRESS

The following research needs were identified in peer-review comments regarding Everglades Consolidated Reports (ECRs) and South Florida Environmental Reports (SFERs). An update on the progress made with respect to each of the research needs is presented below.

1. **Quantify the no-effect level for Everglades fish-eating bird dietary exposure to methylmercury to support development of a water quality criterion (2000 ECR).** Following FDEP's initial support for research on MeHg effects on white ibis (*Eudocimus albus*) (Axelrad et al., 2008; Frederick et al., 2005; 2007), the USFWS and U.S. Army Corps of Engineers provided additional funding. A final report on this project was expected to be completed the end of 2008. The University of Florida is seeking continued funding to maximize information return on MeHg effects on wading birds using their 13,000-square feet aviary and captive white ibis population.

   In the study conducted by Drs. Jayasena and Frederick of the University of Florida, white ibises were exposed to 0.05, 0.1, and 0.3 mg dietary MeHg/kg. This was the third year of breeding for the captive birds. All males nested in all groups in 2008, with 0 percent, 18 percent, 26 percent, and 22 percent of the control, low-, medium- and high-dose group males nesting homosexually, respectively.

   The apparent dose-related degree of homosexuality was similar in nature to the two previous years. However, the percentage of homosexual males has declined for all the groups each year. Of the total males who nested in 2006, 20, 27, 45, and 52 percent were homosexually paired for the control, low-, medium- and high-dose groups, respectively. The percentages of males that nested homosexually in 2007 were 5, 27, 43, and 44 percent for the same dose groups.

   The percentage of nests producing eggs in 2008 was 100, 94, 95, and 94 percent for the control, low-, medium- and high-dose groups, respectively. Unlike 2007, for 2008 there were no significant differences among treatments in the proportion of nests producing eggs, and there were no significant differences in the numbers of chicks fledged per nest start.

   While there seems to be good evidence for an effect of chronic, low-level exposure to mercury on degree of homosexuality, the effect appears to decline with time, probably as a result of mate switching following unproductive pairing. Switching is a typical response to poor reproduction for heterosexual pairs in most birds, and seems to be occurring in the ibises. The mechanism by which mate choice might be effected by mercury remains unknown. The degree of the affect appears to be large – up to 44 percent of pairs are not productive – enough so as to effect population size through fecundity. The degree to which this has occurred in the field is unknown, though it might be expected that poor reproduction would be exacerbated by the harsher conditions evident in the wild.

2. **Quantify "global versus local" atmospheric mercury sources to South Florida to better define options for reducing mercury levels in Everglades biota (2002 ECR).** Refer to the Statewide Mercury Total Maximum Daily Load Program in the *Future Activities of the Mercury Program* section of this chapter.

3. **Revise the Everglades Mercury Cycling Model (E-MCM) to include relationships between sulfur concentrations and mercury dynamics (2001 ECR).** Significant progress was made last year (Gilmour et al., 2007c) to better define the biogeochemical relationships between the mercury and sulfur cycles, and to link these to the E-MCM. Compilation and summarization of ACME data may serve to allow more improvement to the E-MCM. (See the *Future Activities of the Mercury Program* section of this chapter.)

4. **Research biogeochemical controls on mercury methylation (2001 ECR).** Significant progress has been made in our understanding of biogeochemical controls on mercury methylation through research conducted by the U.S. Geological Survey (USGS) and the Smithsonian Environmental Research Center (SERC), through support by the USGS, the FDEP, and the SFWMD. Findings are noted in the *Previous Findings* section of Axelrad et al. (2008). The USGS plans two more years of mercury biogeochemical research, as detailed in the *Future Activities of the Mercury Program* section of Axelrad et al. (2008). Additionally, the FDEP has contracted with SERC for compilation and synthesis of ACME data – see *Future Activities of the Mercury Program* section of this chapter.

5. **Determine sulfur sources to and effects on the Everglades (2006 SFER).** Refer to the projects, Regional Sulfur Mass Balance Study, and Evaluation of Sulfate Effects in South Florida Wetlands in the *Future Activities of the Mercury Program* section below.

FUTURE ACTIVITIES OF THE MERCURY PROGRAM

Statewide Mercury Total Maximum Daily Load Program

By 2012, the FDEP is required to develop a mercury Total Maximum Daily Load (TMDL) for mercury-impaired waters of the state. The FDEP has initiated plans for a statewide mercury TMDL study that include both atmospheric and aquatic field and modeling components. The mercury TMDL study consists of gathering and assessing a complex suite of data involving mercury atmospheric emissions and deposition (both wet and dry), and aquatic cycling data; it also involves conducting atmospheric and aquatic modeling to quantify the needed mercury reductions to address mercury-related impairment in state surface waters. Aquatic and atmospheric monitoring and for the study began in the third and fourth quarters of 2008, respectively.

The FDEP has developed a collaborative research team to undertake the mercury TMDL study. At this time, the collaborators are the FDEP, the University of Michigan Air Quality Laboratory (UMAQL, as the prime contractor to FDEP for the project), Atmospheric Research & Analysis (as a subcontractor to the FDEP contract with UMAQL), Aqua Lux Lucis, Inc. (as a subcontractor to the FDEP contract with UMAQL), the United States Environmental Protection Agency Office of Research and Development National Exposure Research Laboratory (USEPA ORD-NERL), USEPA Science and Ecosystem Support Division, the Florida Fish and Wildlife Conservation

Commission (through contract with the FDEP), Southern Company Services, Inc., the ENP, Orlando County Environmental Protection Division, and the University of Central Florida.

Elements of the Florida mercury TMDL study include:

- Comprehensive, highly temporally resolved measurements of wet and dry mercury deposition at four locations, along with a suite of tracers that may be used to associate deposition with sources. These sampling areas are referred to as supersites. The four proposed supersite monitoring locations are Tampa, Fort Lauderdale, Pensacola, and Jacksonville. Additional wet deposition-only satellite sites will be located, one each, in Orange County and the ENP Research Station.
- Identification of all significant sources of mercury, whether fixed or mobile, within Florida (emissions inventory).
- Monitoring of 128 lakes and streams throughout Florida for mercury content in fish tissue and for a suite of water chemistry parameters for use in aquatic cycling modeling.
- Development of an empirical probabilistically based aquatic cycling model to link mercury deposition with bio-magnification in fish as a function of waterbody geochemistry.
- Conducting atmospheric modeling (both dispersion and receptor models) for the purpose of quantifying Florida mercury sources versus those sources outside Florida that must be quantified to satisfy the mercury TMDL.

Mercury in Coastal Waters

Excessive concentrations of mercury have been found in fish for all of Florida's coastal waters, effecting numerous species of commercial or sport-fishing interest. Human health advisories regarding consumption of marine fish have been issued for about 60 species and there are no-consumption advisories for several species for all of Florida's coastal waters. Floridians' exposure to MeHg is predominantly from eating marine fish. The FDEP is seeking funding to determine the sources of mercury to the Gulf of Mexico and the most important sites of mercury methylation in the Gulf, through discussions with the USEPA together with representatives of the other four Gulf states (Louisiana, Alabama, Texas and Mississippi), and with the Gulf of Mexico Alliance.

Regional Sulfur Mass Balance Study

The objective of the Regional Sulfur Mass Balance Study being conducted by the SFWMD is to (1) quantify the mass exchange of sulfur between the four major land use areas of South Florida (Lake Okeechobee, EAA, WCAs, and urban areas) and (2) reevaluate each sulfur source using up-to-date urban and agricultural sulfur application information. These objectives will be executed by collecting information on surface water chemistry, atmospheric deposition, surface flow, agricultural/urban applications, and soil subsidence rates. Sulfur mass exchange for each land use will be calculated on annual and semi-annual (seasonal dry-wet cycle) bases. Three separate years will be investigated: a high-precipitation year (2004), a drought year (2007), and an intermediate scenario (to be determined). The project will continue through the end of 2011.

Evaluation of Sulfate Effects in South Florida Wetlands

In order to assess for adverse ecological effects of sulfate in the Everglades regarding phosphorus release from sediments, and sulfide toxicity to wetland plants, three projects are being funded by the SFWMD:

Project #1: Laboratory screening trials to determine effects of elevated water column sulfate levels on microbial respiration and phosphorus release, using soils collected from unimpacted and impacted wetlands (with respect to both phosphorus and sulfur) in South Florida. Objectives include:

1. Define the role of sulfate/sulfide on the release of sediment phosphorus (i.e., internal eutrophication) in South Florida wetlands.
2. Define the importance of sulfate/sulfide on organic matter mineralization in South Florida wetlands.
3. Describe the interactions between sulfur, calcium, and iron in wetland environments.
4. Assist in screening treatments (e.g., appropriate chemical amendments and dosages) to be applied to subsequent mesocosm-scale experiments (see *Project #3* below).
5. Define accrual rates and diagenesis of sulfur, phosphorous, iron, and calcium in impacted and unimpacted sediments.

Project #2: Field monitoring to assess spatial and temporal variations in surface water and sediment porewater phosphorus and sulfur chemistry, and effects on wetland vegetation. The results obtained from the field monitoring and laboratory sediment phosphorus release studies will:

1. Provide necessary background information on the in situ concentrations of key elements and ions influenced by biogeochemical processes responsible for the sequestration/release of phosphorus.
2. Examine the spatial variability of elements and ions along sulfur and phosphorus gradients.
3. Characterize vertical concentration gradients within sediments and overlying water for calculating vertical diffusive fluxes.
4. Describe the role played by sulfate reduction in regulating phosphorus cycling.
5. Provide insight as to potential toxic effects of porewater sulfide on marsh flora.

Project #3: Consists of mesocosm studies to evaluate plant toxicity and phosphorus cycling effects for a number of water, vegetation, and soil types. Objectives include:

1. Quantify the direct effects of sulfide and/or ammonium toxicity to native South Florida wetland flora.
2. Examine the effect of sediment history (e.g., high versus low phosphorus loadings) on internal phosphorus cycling and sulfur interactions.
3. Using flow-through, outdoor platforms, confirm results of laboratory incubations on effects on phosphorus cycling of varying calcium, sulfate, and phosphorus concentrations.
4. Characterize effects of inflow sulfate concentrations on phosphorus removal effectiveness of STAs.

Sulfate, Sulfide, Nutrient and Dissolved Organic Carbon Relationships to Methylmercury Production in the Everglades

Since 1995, the Aquatic Cycling of Mercury in the Everglades (ACME) project team – comprised of USGS and SERC scientists – has studied mercury cycling in the Everglades. Significant progress has been made in our understanding of biogeochemical controls on mercury methylation through ACME, supported by funding from the USGS, the FDEP and the SFWMD. A summary of findings are noted in the Previous Findings section of Axelrad et al., (2008). The ACME project team plans further mercury biogeochemical research, as detailed in the Mercury Program Future Activities section of Axelrad et al. (2008).

The ACME study has included two main components. One is a detailed assessment, through time, of the biogeochemistry of core ACME sites across the full length of the Everglades ecosystem. These core sites include locations in each of the main components of the system, from WCA-1 to the ENP.

The dataset for core ACME sites includes information on mercury and MeHg concentrations in surface water, soil interstitial waters (porewater), soils, and the food web. Food web components include invertebrates and small fish. Detailed biogeochemical data for the sites was also measured, including microbial activity and soils and water chemistry, with a focus on sulfur cycling and organic matter characterization.

The second component of the study is a series of field mesocosm experiments designed to test cause and effects hypotheses. Additions to mesocosms have included mercury, sulfate, dissolved organic carbon, and phosphate. Mesocosm experiments have been run in WCAs 1, 2, and 3, the most detailed sulfate and dissolved organic carbon addition studies were carried out at site 3A-15 in WCA-3. Study data have been published in a variety of papers in the primary literature and in reports to the FDEP, SFWMD, and the USGS. Updates on the study appear regularly in SFERs.

This project will compile data from all ACME researchers in one central database where it can be queried and studied as controls on sulfur inputs to the Everglades are debated. Metadata will be included and the dataset will be made openly accessible to the public (as well as submitted to USGS for consideration for publication as an open file report). The project will also include a text report on the synthesized dataset.

As part of that report, a synthesis of the literature on MeHg production with a detailed focus on studies of the relationship between sulfate, sulfide and MeHg will be produced. The literature summary will help to put the ACME datasets into a larger context, and provide information to decision makers.

ACKNOWLEDGMENTS

The authors wish to thank Reed Harris (Reed Harris Environmental Ltd.), Curtis D. Pollman (Aqua Lux Lucis, Inc.), Grover Payne (FDEP), Denise Miller (FDEP), William H. Orem (USGS), Daniel J. Scheidt (USEPA), Cynthia C. Gilmour (SERC), Peter I. Kalla (USEPA), Peter C. Frederick (University of Florida), and Darren G. Rumbold (Florida Gulf Coast University) for helpful discussions regarding Everglades mercury and sulfur science.

LITERATURE CITED

Axelrad, D.M., T.D. Atkeson, T. Lange, C.D. Pollman, C.C. Gilmour, W.H. Orem, I.A. Mendelssohn, P.C. Frederick, D.P. Krabbenhoft, G.R. Aiken, D.G. Rumbold, D.J. Scheidt and P.I. Kalla. 2007. Chapter 3B: Mercury Monitoring, Research and Environmental Assessment. In: *2007 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Axelrad, D.M., T. Lange, M. Gabriel T.D. Atkeson, C.D. Pollman, W.H. Orem, D.J. Scheidt, P.I. Kalla, P.C. Frederick and C.C. Gilmour. 2008. Chapter 3B: Mercury and Sulfur Monitoring, Research and Environmental Assessment. In: *2008 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Bates, A.L., W.H. Orem, J.W. Harvey and E.C. Spiker. 2001. Geochemistry of Sulfur in the Florida Everglades; 1994 through 1999. U.S. Geological Survey Open-File Report 01–0007.

Bates, A.L., W.H. Orem, J.W. Harvey and E.C. Spiker. 2002. Tracing Sources of Sulfur in the Florida Everglades. *J. of Environ. Qual.,* 31: 287-299.

Benoit, J.M., C.C. Gilmour, A. Heyes, R.P. Mason and C. Miller. 2003. Geochemical and Biological Controls Over Methylmercury Production and Degradation in Aquatic Ecosystems. Y. Chai and O.C. Braids, eds. In: *Biogeochemistry of Environmentally Important Trace Elements*, pp. 262–297, ACS Symposium Series #835, American Chemical Society, Washington, D.C.

Benoit, J.M., C.C. Gilmour, R.P. Mason and A. Heyes. 1999. Sulfide Controls on Mercury Speciation and Bioavailability in Sediment Porewaters. *Environ. Sci. Technol.,* 33: 951-957.

Benoit, J.M., R.P. Mason, C.C. Gilmour and G.R. Aiken. 2001. Constants for Mercury Binding by Dissolved Organic Carbon Isolates from the Florida Everglades. *Geochim. Cosmochim. Acta,* 65: 4445-4451.

Bloom, N.S. 1992. On the Chemical Form of Mercury in Edible Fish and Marine Invertebrate Tissue. *Can. J. Fish. Aquat. Sci.,* 49: 1010-1017.

Eisler, R. 1987. Mercury Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. *U.S. Fish and Wildlife Service Biological Report*, 85(1.10).

Ekstrom, E.B., F.M.M. Morel and J.M. Benoit. 2003. Mercury Methylation Independent of the Acetyl-Coenzyme A Pathway in Sulfate-Reducing Bacteria. *Applied and Environmental Microbiology*, 69(9): 5414-5422.

Evans, D.W. 2008. Assessment of Mercury Bioaccumulation in Sentinel Fish in South Florida. Annual Report for the Period October 1, 2006 to June 30, 2008, submitted to the U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL.

FDOH. 2007. Your Guide to Eating Fish Caught in Florida. Florida Department of Health. Tallahassee, FL.

Frederick, P.C., E. Adams and N. Jayasena. 2007. Effects of Environmental Mercury Exposure on Development and Reproduction in White Ibises (*Eudocimus albus*). Annual Progress Report for the U.S. Fish and Wildlife Service, Vero Beach Field Office, FL.

Frederick, P., D. Axelrad, T. Atkeson and C. Pollman. 2005. Contaminants Research and Policy: The Everglades Mercury Story. National Wetlands Newsletter January–February 2005, 27(1):3–6. Environmental Law Institute. Washington, D.C.

Garrett B. and D. Ivanoff. 2008. Hydropattern Restoration in Water Conservation Area 2A. Prepared for the Florida Department of Environmental Protection in Fulfillment of Permit # 0126704-001-GL (STA-2), by the STA Management Division, South Florida Water Management District. 113 pp.

Gilmour, C.C., D. Krabbenhoft, W. Orem and G. Aiken. 2004. Appendix 2B-1: Influence of Drying and Rewetting on Mercury and Sulfur Cycling in Everglades and STA Soils In: *2004 Everglades Consolidated Report*. South Florida Water Management District, West Palm Beach, FL.

Gilmour, C.C., D. Krabbenhoft, W. Orem, G. Aiken and E. Roden. 2007a. Appendix 3B-2. Status Report on ACME Studies on the Control of Mercury Methylation and Bioaccumulation in the Everglades. In: *2007 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Gilmour, C.C., W. Orem, D. Krabbenhoft and I.A. Mendelssohn. 2007b. Appendix 3B-3. Preliminary Assessment of Sulfur Sources, Trends and Effects in the Everglades. In: *2007 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Gilmour, C.C., E. Roden and Reed Harris. 2007c. Appendix 3B-3: Approaches to Modeling Sulfate Reduction and Methylmercury Production in the Everglades. In: *2008 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Gilmour, C.C., G.S. Riedel, M.C. Ederington, J.T. Bell, J.M. Benoit, G.A. Gill and M.C. Stordal. 1998. Methymercury Concentrations and Production Rates Across a Trophic Gradient in the Northern Everglades. *Biogeochemistry*, 40(2-3): 327-345.

Hakanson, L. 1980. The Quantitative Impact of pH, Bioproduction, and Hg-contamination on the Hg-content of Fish (Pike). *Environmental Pollution Series B*, 1: 285-304.

Lange, T.R., D.A. Richard and H.E. Royals, 1998. Trophic relationships of mercury bioaccumulation in fish from the Florida Everglades. FINAL Annual Report. Florida Game and Fresh Water Fish Commission, Fisheries Research Laboratory, Eustis, FL. Prepared for the Florida Department of Environmental Protection, Tallahassee, FL. April.

Lange, T.R., H.E. Royals and L.L. Connor. 1993. Influence of Water Chemistry on Mercury Concentration in Largemouth Bass from Florida Lakes. *Trans Am Fish Soc*, 122: 74-84.

Lange, T.R., H.E. Royals and L.L. Connor. 1994. Mercury Accumulation in Largemouth Bass (*Micropterus salmoides*) in a Florida Lake. *Arch Environ Contam and Toxicol*, 27: 466-471.

Loftus, W.F., J.C. Trexler and R.D. Jones. 1998. Mercury Transfer through the Everglades Aquatic Food Web. Final Report submitted to the Florida Department of Environmental Protection, Tallahassee, FL.

Ogden, J.C., W.B. Robertson, G.E. Davis and T.W. Schmidt. 1974. Pesticides, Polychlorinated Biphenyls and Heavy Metals in Upper Food Chain Levels, Everglades National Park and Vicinity. PB-231 359, 27 p. National Park Service, Washington, D.C.

Orem, W.H. 2004. Impacts of Sulfate Contamination on the Florida Everglades Ecosystem. U.S. Geological Survey Fact Sheet, No. FS 109–03. January 2004. 4 pp. Available online at http://pubs.usgs.gov/fs/fs109-03/fs109-03.pdf (as of December 22, 2006).

Porak, W., W.S. Coleman and S. Crawford. 1986. Age, Growth, and Mortality in Florida Largemouth Bass Utilizing Otoliths. *Proc Southeast Assoc Fish and Wildlife Agencies*, 40:206-215.

Porak, W., W.S. Coleman and S. Crawford. 1988. Age, Growth, and Mortality of Florida Largemouth Bass Utilizing Otoliths. *Proc Southeast Assoc Fish Wildlife Agencies*, 40:202-215.

Roelke, M.E., D.P. Schultz, C.F. Facemire, S.F. Sundlof and H.E. Royals. 1991. Mercury Contamination in Florida Panthers. Report of the Florida Panther Technical Subcommittee to the Florida Panther Interagency Committee.

Rumbold, D.G. 2005. A Probabilistic Risk Assessment of the Effects of Methylmercury on Great Egrets and Bald Eagles Foraging at a Constructed Wetland in South Florida Relative to the Everglades. *Hum. Ecol. Risk Assess.,* 11:365–388.

Rumbold, D.G., L.E. Fink, K.A. Laine, S.L. Niemczyka, T. Chandrasekhar, S.D. Wankel, and C. Kendall. 2002. Levels of Mercury in Alligators (*Alligator mississippiensis*) Collected Along a Transect Through the Florida Everglades. *The Science of the Total Environment*, 297: 239-252.

Scheidt, D., J. Stober, R. Jones and K. Thornton. 2000. South Florida Ecosystem Assessment: Everglades Water Management, Soil Loss, Eutrophication and Habitat. Monitoring for Adaptive Management: Implications for Ecosystem Restoration. EPA 904-R-00-003. U.S. Environmental Protection Agency, Region 4, Athens, GA.

Scheidt, D. and P. Kalla. 2007. Everglades Ecosystem Assessment: Water Management and Quality, Eutrophication, Mercury Contamination, Soils and Habitat. Monitoring for Adaptive Management: A REMAP Status Report. U.S. Environmental Protection Agency Report 904-R-07-001.

Sorenson J.A., G.E. Glass, K.W. Schmidt, J.K. Huber, G.R. Rapp. 1990. *Airborne Mercury Deposition and Watershed Characteristics in Relation to Mercury Concentrations in Water, Sediments, Plankton, and Fish of Eighty Northern Minnesota Lakes.* Environ. Sci. Technol. 24: 1716-1727.

Spalding, M.G. and D.J. Forrester. 1991. Effects of Parasitism and Disease on the Nesting Success of Colonial Wading Birds (*Ciconiiformes*) in Southern Florida. Report to the Florida Game and Fresh Water Fish Commission. Report No. NG88-008. Tallahassee, FL.

Ugarte, C.A., K.G. Rice and M.A. Donnelly. 2005. Variation of Total Mercury Concentrations in Pig Frogs (*Rana grylio*) Across the Florida Everglades. *Sci Total Environ*, 345: 51–59.

USEPA. 1991. Determination of Mercury in Tissues by Cold Vapor Atomic Absorption Spectrometry (Method 245.6). In: *Methods for the Determination of Metals in Environmental Samples*. EPA-600/4-91-010. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

USEPA. 1997. Mercury Study Report to Congress. Volume 1: Executive Summary Report. Office of Air Quality Planning and Standards and Office of Research and Development, EPA-42/R-97-003. U.S. Environmental Protection Agency, Washington, D.C.

USEPA. 2001. Water Quality Criteria: Notice of Availability of Water Quality Criterion for the Protection of Human Health: Methylmercury. FR Doc. 01-217. U.S. Environmental Protection Agency, Washington, D.C.

USEPA. 2007. Mercury in Solids and Solutions by Thermal Decomposition, Amalgamation, and Atomic Absorption Spectrophotometry (SW-846 Method 7473). U.S. Environmental Protection Agency, Washington, D.C.

Ware, F.J., H.R. Royals and T.R. Lange. 1990. Mercury Contamination in Florida Largemouth Bass. *Proceedings of the Southeast Assoc Fish Wildlife Agencies*, 44:5-12.

Wiener, J.G., R.A. Bodaly, S.S. Brown, M. Lucotte, M.C. Newman, D.B. Porcella, R.J. Reash, and E.B. Swain. 2006. Monitoring and Evaluating Trends in Methylmercury Accumulation in Aquatic Biota. Pages 87 – 121 *in* R. Harris, D.P. Krabbenhoft, R. Mason, M.W. Murray, R. Reash, and T. Saltman, editors. Ecosystem Responses to Mercury Contamination, Indicators of Change. Society of Environmental Toxicology and Chemistry, Workshop on Mercury Monitoring and Assessment.

Weaver, K., G. Payne and S. Xue. 2007. Chapter 3A: Status of Water Quality in the Everglades Protection Area. G. Redfield, ed. In: *2007 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Wren, C.C. and H.R. MacCrimmon. 1986. Comparative Bioaccumulation of Mercury in Two Adjacent Freshwater Ecosystems. *Water Research*, 20: 763-769.