

A Comparison of Mercury in Estuarine Fish Between Florida Bay and the Indian River Lagoon, Florida, USA

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ABSTRACT: Concentrations of mercury (Hg) in fish were compared between two Florida estuaries, the Indian River Lagoon and Florida Bay. The objective was to determine if differences in Hg concentration exist and to attempt to relate those differences to sources of Hg. Five hundred and thirteen estuarine fish were collected and analyzed for Hg concentration. Fish species collected were black drum, bluefish, bonnethead shark, common snook, crevalle jack, gafftopsail catfish, gray snapper, Mayan cichlid, pompano, red drum, sheepshead, southern flounder, spadefish, and spotted seatrout. Analysis of variance of species-specific Hg data among the three defined regions of eastern and western Florida Bay and the Indian River Lagoon substantiated regional differences. Proximity to known anthropogenic sources of Hg appeared to be a significant factor in the distribution of Hg concentration among the fish collected. Sufficient numbers of crevalle jack, gray snapper, and spotted seatrout were collected to permit statistical analysis among regions. Hg concentrations in all three of these species from eastern Florida Bay were higher than those collected in the other two areas. A major fraction of the estuarine fish collected in eastern Florida Bay exceeded one or more State of Florida or U.S. Food and Drug Administration fish consumption health advisory criteria. In general, fish from western Florida Bay contained less Hg than those from the Indian River Lagoon, and fish from the Indian River contained less Hg than those from eastern Florida Bay. Crevalle jack from all areas and spotted seatrout from Florida Bay were placed on a consumption advisory in Florida. Detailed study of Florida Bay food web dynamics and Hg biogeochemical cycling is recommended to better understand the processes underlying the elevated Hg levels in fish from eastern Florida Bay. This information may be vital in the formulation of appropriate strategies in the ongoing South Florida restoration process.

Introduction

Health advisories have been issued due to elevated mercury (Hg) levels in certain freshwater fish species for many Florida waterbodies, including those of Everglades National Park (Hand and Freidmann 1990; Facemire et al. 1995; Florida Department of Health 1999). Concentrations of Hg in fish from Everglades National Park were believed to be among the highest in the southeastern U.S. (Facemire et al. 1995). Of interest was the possibility of Hg contamination in fish from Florida Bay which lies adjacent to and downstream of the Everglades freshwater marshes where Hg contaminated fish are prevalent. An interim report on the current study (Strom and Graves 1995) resulted in fish consumption advisories for the Florida Keys and Florida Bay.

The worldwide concentration of Hg in the atmosphere has increased rapidly in the last few hundred years due to increased industrial activity (Slemr and Langer 1992; Fitzgerald 1995; Martinez-Cortizas et al. 1999). Deposition of Hg from atmospheric sources is believed to have increased to three to five times the pre-industrial era level

(Swain et al. 1992). Sources of atmospheric deposition include emission from distant natural and anthropogenic sources (Boening 2000; Ferrara et al. 2000; Gustin et al. 2000) and local point and nonpoint sources (Fitzgerald 1995; U.S. Environmental Protection Agency 1997; Boening 2000; Kang et al. 2000; Mason et al. 2000). The latter have been shown (Stober 1995; Dvonch et al. 1999) to significantly add to the near-field Hg budget through meteorological processes, principally rainfall (Sorensen et al. 1994; Hoyer et al. 1995; Rudd 1995; Dvonch et al. 1999).

Point sources of Hg in southeast Florida include municipal and medical incinerators, and electrical power plants (U.S. Environmental Protection Agency 1997). Nonpoint sources of Hg include combustion of fossil fuels (especially coal), Hg escaping from manufacture use and disposal of paints, electrical, and laboratory equipment, agricultural burning, and municipal landfills (Jasinski 1994; Stober 1995; U.S. Environmental Protection Agency 1997; Bullock 2000).

Local Hg sources such as municipal incinerators can contribute significantly to regional atmospheric loading (Expert Panel on Mercury Atmospheric Processes 1994; U.S. Environmental Protection Agency 1997; Dvonch et al. 1999). The Miami and

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Tampa areas of South Florida have some of the highest concentrations of Hg emission sources in the U.S. (U.S. Environmental Protection Agency 1997). According to Dvonch et al. (1999), Hg from these sources is predominantly in the water-soluble divalent form Hg (II). Hg from these sources is easily washed from the atmosphere to the Earth's surface by rainfall (Carpi 1997; U.S. Environmental Protection Agency 1997). Recent studies have documented deposition of Hg from rainstorms in the windward plume of Hg emission sources (e.g., Sorensen et al. 1994). The use of specific elemental signatures obtained by sampling smokestacks of Hg emitters was used to attribute deposition measured at a number of sites in Broward and Miami-Dade counties as well as in the Everglades to specific emission sources (Dvonch et al. 1999). Dvonch et al. (1999, p. 4522) stated that "emissions from local urban sources have played the dominant role in the wet deposition of Hg to South Florida and the Everglades." They also showed that for Broward and Miami-Dade counties, "enough Hg was emitted in these two counties alone . . . in a soluble Hg (II) form that is easily incorporated into cloud droplets, to account for the Hg wet deposited to the entire Florida Everglades" (Dvonch et al. 1999, p. 4526). Direct emission measurements made at waste incineration point sources in South Florida found that 75% to 95% of the Hg released was in the Hg (II) form (Dvonch et al. 1999). There exists a plausible link between nearby Hg sources and Hg contamination in the Everglades and Florida Bay.

Hg originating from atmospheric sources may be transported to estuaries via tributaries (Kang et al. 2000). Hg sources to estuaries are dominated by delivery of particulate bound Hg via freshwater inflows and to a lesser extent by direct atmospheric deposition (Mason et al. 1999; Kang et al. 2000). Deposition of Hg in agricultural areas may result in increased flux of total Hg that is associated with particles (Hurley et al. 1995). Hg deposited in wetlands may be associated with dissolved organic carbon (Hurley et al. 1995; Rudd 1995; Mason et al. 1999). Either of these forms of Hg (associated with either suspended particles or colloidal material) may subsequently be transported to estuaries via runoff or wetland baseflow (Hurley et al. 1995; Rudd 1995; Mason et al. 1999). Urban areas are also known to be a source of Hg runoff to estuaries (Mason et al. 1999). The presence of Hg in runoff water to Florida Bay has been demonstrated for its major tributaries (Kannan et al. 1998; Kang et al. 2000). Kang et al. (2000) found that runoff fluxes to Florida Bay ranged from about 4–160 $\mu\text{g Hg m}^{-2} \text{ yr}^{-1}$.

Hg contamination is considered to be the most

serious environmental threat to the well being of fish and wildlife resources in the southeastern U.S. (Facemire et al. 1995). Methylmercury (referring to monomethylmercury, CH_3H^+ , abbreviated as MeHg) is bioconcentrated in the food chain, resulting in levels in predatory fish that may be several orders of magnitude higher than levels in contemporaneous water (Wiener 1995; Lawson and Mason 1998). Chronic MeHg effects on fish include emaciation, brain lesions, cataracts, and various behavioral disorders (Eisler 1987). Fish are important in the diets of many animals, making MeHg a threat to a wide range of wildlife, including alligators, wading birds, otters, and panthers (Eisler 1987; Scheuhammer 1987; Halbbrook et al. 1994; Facemire et al. 1995; Wiener 1995; Yanochko et al. 1997; Cleckner et al. 1998; Duvall and Barron 2000). Effects of MeHg on wildlife include reduced reproductive success (Francis and Bennett 1994); progressive central nervous system deterioration (Halbrook et al. 1994); kidney necrosis and lesions, and delayed sexual maturation (Scheuhammer 1987). A recent risk assessment of Hg in Everglades food webs indicated that piscivorous wildlife of the south-central region of the Everglades are at high risk from consumption of Hg contaminated prey (Duvall and Barron 2000).

MeHg is also threat to human health (D'Itri 1991; Renzoni 1995; U.S. Department of Health and Human Services 1995; National Research Council 2000). Exposure to high levels of MeHg can cause irreversible brain damage (D'Itri 1991). MeHg is a mutagen, teratogen, and carcinogen (Eisler 1987). Eating fish high in MeHg has been shown to cause elevated levels of MeHg in humans (Fleming et al. 1995; Knobloch et al. 1995; Renzoni 1995; Valentino et al. 1995; National Research Council 2000). Fish in the diet has been shown to be the dominant means for human MeHg accumulation (Watras and Huckerbee 1994; U.S. Environmental Protection Agency 1997).

The primary form of Hg in fish tissues is MeHg (Bloom 1991; Lasorsa and Allen-Gil 1995; Southworth et al. 1995). Protein-bound sulphhydryl groups provide a pathway that allows MeHg to bind specifically to fish muscle tissue (Spry and Wiener 1991). Fish muscle MeHg concentrations have been shown to correlate directly to other measures of MeHg contamination such as the Hg concentration in the liver or homogenized whole bodies (Becker and Bigham 1995; Goldstein et al. 1996). Most importantly, muscle is by far the most consumed fish portion by humans, so MeHg in fish muscle concentrations have important implications for human health risk assessment, and are the basis for governmental fish consumption advisories. Concentrations of Hg in muscle tissue are

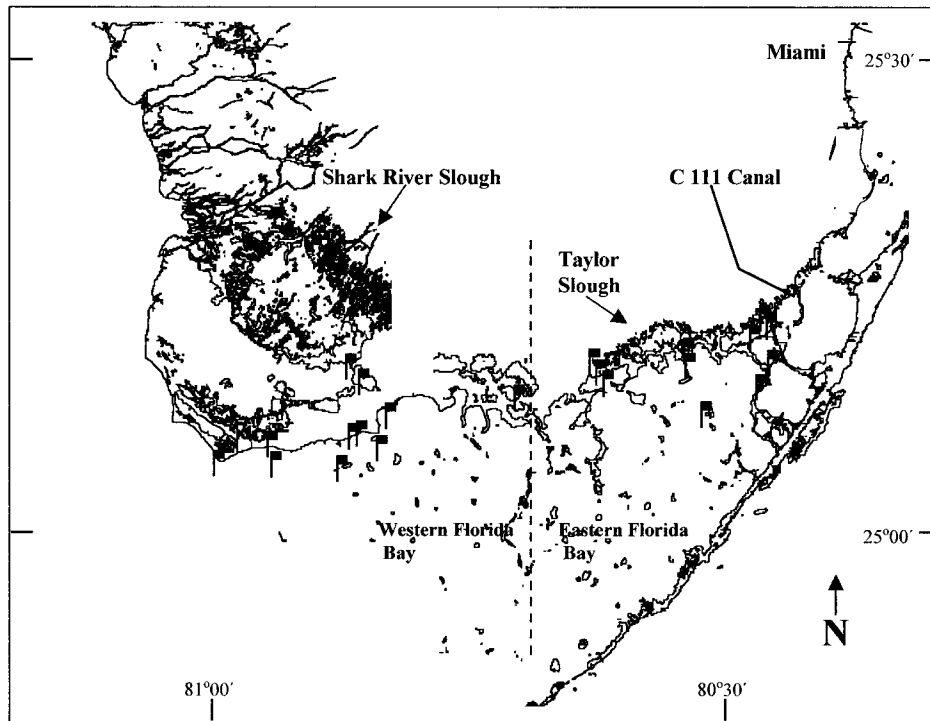


Fig. 1. Fish collection locations in Florida Bay.

the most widely applicable analysis for assessing fish MeHg impacts (Goldstein et al. 1996). The purpose of this study was to evaluate concentrations of Hg in fish with respect to existing health advisory criteria and to test the null hypotheses that no difference exists between Hg levels in fish collected from the Indian River Lagoon and Florida Bay, and between areas near and far from major cities.

Study Areas

Conditions in the Indian River and Florida Bay estuaries differ with respect to direct connection to freshwater areas known to contain MeHg contaminated fish. They also differ in respect to proximity to known sources of Hg, especially incinerators and power plants in large cities (U.S. Environmental Protection Agency 1997). The Indian River in Martin and St. Lucie counties receives minimal direct runoff and is well flushed through two major inlets (Woodward-Clyde 1994a). Eastern Florida Bay is contiguous to and receives runoff from areas of the Everglades known to contain fish with high levels of MeHg (Hand and Friedemann 1990; Lodge 1994). Eastern Florida Bay also receives surface runoff from western areas of Miami-Dade county (U.S. Army Corps of Engineers 1999), and is adjacent to areas known to experience wet deposition of Hg from airborne sources, primarily

municipal incinerators (KBN Engineering 1992; U.S. Environmental Protection Agency 1997; Dvonch et al. 1999). The watershed of western Florida Bay is almost entirely within the undeveloped Everglades National Park, with runoff from the relatively pristine Shark River Slough and tidal exchange with the Gulf of Mexico dominating inflows (Boyer et al. 1999; Nuttle et al. 2000).

FLORIDA BAY

Florida Bay is a large, mostly shallow estuarine basin at the southern tip of the Florida peninsula (Fig. 1). Before massive drainage projects began around 1900, Florida Bay received copious seasonal flows from the Everglades region (Cantillo et al. 1995). Regional water management systems have altered the timing and reduced the quantity of water flowing to Florida Bay (Light and Dineen 1994). Completion of the Hillsboro, Miami, North New River, and the West Palm Beach canals during the period 1915–1920 had the greatest impact on water levels, with water table levels permanently lowered as much as 9 feet (Sklar et al. 1999, 2000). Capacity to divert water to the Atlantic Ocean was increased further by the opening of the St. Lucie and Caloosahatchee canals in 1925–1926 (Sklar et al. 1999). In 1947, the creation of the Central and Southern Florida Flood Control Project gave the U.S. Army Corps of Engineers responsibility for

construction and oversight of water management projects throughout the Kissimmee-Okeechobee-Everglades Basin (Cantillo et al. 1995; Sklar et al. 2000). The initial focus of this project was on flood protection, drainage, and water supply for agricultural and urban development (Patino and Hittle 2000).

Canals draining the Everglades Agricultural Area were completed during 1954–1959 (Light and Dineen 1994). Dikes, levees, and water control structures surrounding the Water Conservation Areas that separated them from the rest of the Everglades were completed by 1963, resulting in a highly compartmentalized system (Light and Dineen 1994; Sklar et al. 2000). Other important structural changes in the Florida Bay watershed included the construction of the Tamiami canal and associated dikes, and the South Dade conveyance system (Light and Dineen 1994). These widespread modifications of hydrology facilitated a burgeoning population in southeastern Florida that presently exceeds four million (Cantillo et al. 1995).

Recent alterations (including installing plugs in canals, increasing the number of culverts through the Tamiami highway dike, and changes in the operation schedules of water control structures) have been made to increase the amount of water released and to synchronize the timing of water flows to Everglades National Park and Florida Bay to more naturally simulate the pre-drainage hydrology (Light and Dineen 1994). Massive restoration plans are beginning to be implemented that will overhaul the South Florida water management system over the next 40 years and will greatly increase flows to the Everglades and Florida Bay (U.S. Army Corps of Engineers 1999).

Under current conditions, salinity in Florida Bay varies considerably both spatially and temporally. Florida Bay is a seasonally hypersaline estuary, where salinity may exceed 40‰ during periods of low freshwater inflows (Nuttle et al. 2000). When inflows are heavy, bay waters near tributaries can become almost entirely fresh (Patino and Hittle 2000). Tidal fluctuations are minimal, and tidal ranges and currents are strongly influenced by the direction and intensity of wind (Nuttle et al. 2000).

Severe degradation of the Florida Bay ecosystem has been attributed to disruption of the natural water cycle (Light and Dineen 1994; Lodge 1994; Cantillo et al. 1995). The amount of freshwater flowing from the Everglades region to Florida Bay is reduced significantly compared to the flows that occurred prior to the implementation of regional water management systems (Light and Dineen 1994; U.S. Army Corps of Engineers 1999). Florida Bay continues to receive drainage from the Everglades and South Florida, albeit in reduced

amounts. Much of this water is affected by runoff from residential and agricultural areas. For example, the C-111 canal and Taylor Slough discharge urban and agricultural stormwater runoff directly into eastern Florida Bay (U.S. Army Corps of Engineers 1999). Seagrass die-offs, algal blooms, increased turbidity, and altered fish and macroinvertebrate communities have been documented in Florida Bay recently (Fourqurean and Robblee 1999; Matheson et al. 1999).

Southwestern peninsular Florida is by comparison largely undeveloped. Much of the land lies within Everglades National Park and is protected from development. In contrast to eastern Florida Bay, the quality of water in western Florida Bay is dominated by the relatively pristine flows from Shark River Slough, and by tidal exchange from the Gulf of Mexico (Boyer et al. 1999; Nuttle et al. 2000). Based on the different sources of water, division of Florida Bay into eastern and western regions (Fig. 2) along the zones of similar influence as proposed by Boyer et al. (1999) is followed in this paper. The western zone used in this study includes parts of the central and western zones delineated by Boyer et al. (1999) and Nuttle et al. (2000).

INDIAN RIVER LAGOON

The Indian River Lagoon is an elongated estuarine waterbody separated from the Atlantic Ocean by barrier islands (Fig. 2). Its estuarine character is maintained by connection to the ocean through widely spaced inlets. Before the late 1800s, these inlets were often closed by shifting sand, and the lagoon was predominately freshwater. When inlets re-opened the Indian River became brackish again. Since European-descended settlers began maintaining permanent inlets, the lagoon has remained estuarine (Woodward-Clyde 1994a). Originally, the watershed of the lagoon was narrow and well defined. Since the 1900s, the size of the basin has been drastically increased by the construction of drainage systems. Canals lowered ground water, created arable lands, and reduced flooding. The present-day watershed of the Indian River in the Martin and St. Lucie counties area consists of 29,000 hectares (Woodward-Clyde 1994a). The majority of the basin remains in agriculture, most of which is either pasture or citrus; the rate of urbanization, and especially the rate of expansion of single-family residential development, has been accelerating over the last 10 years.

Although development has altered the historic patterns of landuse and hydrology, much of the watershed drainage bypasses the Martin-St. Lucie county section of the Indian River by flowing directly out inlets to the ocean. Drainage from the

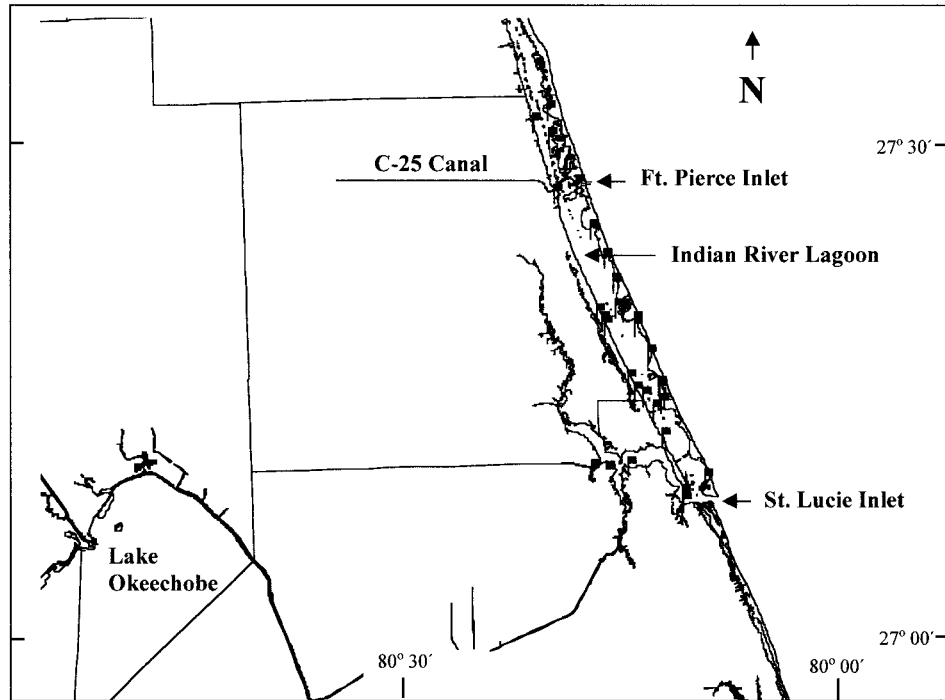


Fig. 2. Fish collection locations within the Indian River Lagoon.

southern section of the Indian River Lagoon study area basin (i.e., from the St. Lucie River watershed) enters the Indian River immediately adjacent to the St. Lucie Inlet. Based on salinity measurements, much of that water appears to exit the inlet to the ocean rather than entering the Indian River (Woodward-Clyde 1994a). Drainage from the northern section of the study area (i.e., from the Canal C-25 basin) enters the lagoon directly opposite the Ft. Pierce Inlet. Woodward-Clyde (1994a) similarly noted that freshwater from C-25 canal appeared to pass through the inlet with little apparent mixing with adjacent lagoon waters on ebb tides.

Flushing of the Indian River by saline waters entering its inlets requires a very long response time on the order of 100 tidal cycles, but this is reduced to 10 to 20 cycles by the effect of prevailing southeast winds (Sheng et al. 1990). Salinities generally are high, except in the immediate vicinities of the inlets when freshwater is being discharged from the St. Lucie River and the C-25 canal (Woodward-Clyde 1994a). There are no major point-source discharges to this part of the lagoon. Direct point and nonpoint releases of pollution to the Indian River Lagoon are minimal. The Indian River Lagoon is among the most diverse estuaries in the world (Swain et al. 1995). The quality of water and sea-grass communities is generally good (Woodward-Clyde 1994b,c). Sampling sites were restricted to

that part of the lagoon in Martin and St. Lucie counties.

Materials and Methods

Fish were collected over an 11-yr period from 1989–1999, primarily by gill net in the Indian River Lagoon and by hook and line in Florida Bay; gill net and hook and line methods were used to some extent in both regions. Some large common snook and crevalle jack from the Indian River Lagoon were obtained by spearfishing and beach seine. Sample collection sites are presented in Figs. 1 and 2.

Immediately after capture, fish were placed in labeled plastic bags and kept on ice in coolers; fish were processed within 12 h of collection. Weight, standard length, sex, and gonad ripeness stage were recorded as per Nielsen and Johnson (1983). Unusual conditions and stomach contents were also noted. Specimens were filleted and skinned with a stainless steel knife on a polyethylene cutting board. The cutting board and knife were cleaned with laboratory-grade deionized water between each fish. For fish less than 1 kg the sample consisted of an entire fillet; for larger fish an approximately 200-g portion was removed from the front top part of the fillet. The sample was rinsed with deionized water before being sealed in a 0.5-l Whirlpac plastic bag. Deionized water rinsed from

the knife, cutting board, measuring board, samples of the deionized rinse water, and water stored in Whirlpac plastic bags were analyzed repeatedly to ensure freedom from detectable concentrations of Hg. Duplicate blind fish samples were submitted to the laboratory to ensure quality control and sample identification tracking. To minimize the possibility of contamination, labeled sample bags were sealed inside a Ziploc bag. This bag was sealed inside a plastic garbage bag that was shipped on ice to the laboratory for analysis.

The samples were maintained unfrozen at 1°C to 4°C until delivered to the laboratory, where they were frozen until analyzed. Total Hg was determined for portions from the interior of the skinless fillets, and was reported as wet weight concentration. All samples were analyzed by cold-vapor atomic absorption spectrophotometry using U.S. Environmental Protection Agency (1991) method 245.6. Laboratory quality control included duplicate and spiked analysis of laboratory fortified blank water and tissue aliquots for 5% of the fish samples. Standardized certified reference Hg in fish tissue (DORM-1, dogfish muscle tissue, for samples prior to 1999; DORM-2, dogfish muscle tissue, and DOLT-2, dogfish liver tissue, for samples collected and analyzed during 1999) from the National Research Council of Canada was also analyzed. Samples collected from the Indian River in 1989 were analyzed at the Florida Department of Environmental Protection Southeast District Laboratory in Port St. Lucie. Samples collected during 1993–1999 were analyzed at the Florida Department of Environmental Protection Central Laboratory in Tallahassee. All fish collected were analyzed. No analytical data were discarded.

STATISTICAL ANALYSES

Analysis of data was facilitated by Minitab statistical software (Minitab 1999). The Box-Cox procedure was used to select the optimum data transformation to improve normality and homogeneity of variances (Box and Cox 1964). Tests for significance were predicated on a $p \leq 0.05$ criterion. Analysis of variance (ANOVA; Zar 1984) was employed to test the null hypothesis that there were no regional differences in Hg concentration. ANOVA was also used to explore differences in Hg concentration, fish size (represented by weight), and other factors among location-based groups. Tukey's pairwise comparison test was used to identify differences among individual groups (Zar 1984). Regression analysis of transformed data was used to examine relationships between Hg burden and fish size (Zar 1984). The difference in Hg content of similar-sized spotted seatrout from eastern and western Florida Bay was examined by remov-

ing all data representing eastern Florida Bay seatrout heavier than the heaviest western Florida Bay seatrout, and then removing data representing small seatrout in 50 g stepwise increments. Comparable weight was considered to be achieved when a *t*-test of the transformed weight data between eastern and western Florida Bay showed no difference. The Hg concentration was then transformed to optimize normality (Box and Cox 1964), and the *t*-test (Zar 1984) was employed to evaluate whether there was a significant difference between the Hg concentrations from these two areas.

Results and Discussion

Hg in fish data is summarized in Table 1. Raw Hg in fish and laboratory quality assurance data is available on request from the authors. Analysis of deionized water rinsed from the knife, cutting board, and measuring board used to process fish tissue samples revealed no measurable Hg concentrations. Deionized rinse water and water stored in Whirlpac plastic bags was found to be free from Hg. Results of analyses of duplicate blind fish samples were well within acceptable limits of precision. Spiked analysis of deionized blank water and tissue aliquots resulted in recovery rates within acceptable precision limits. Results of analysis of standardized certified reference Hg in fish tissue were well within specified error limits for this material.

The majority of red drum, sheepshead, snook, and southern flounder were collected from the Indian River (Table 1). Mean Hg content for red drum from all three areas were below health advisory criteria, although the mean red drum Hg content from eastern Florida Bay was higher. Mean Hg content for snook from eastern Florida Bay was also higher than the other two regions, and was slightly above (0.52 mg kg^{-1}) the Florida limited consumption advisory level (Table 2). No sheepshead or southern flounder were collected from eastern Florida Bay, and average Hg levels were low for both species. Mayan cichlids, an exotic species that has invaded the estuarine areas of Everglades National Park (Faunce and Lorenz 2000), were only collected from Taylor River (the estuarine outlet of Taylor Slough) in the eastern Florida Bay region. Despite their small average size, the Hg level of these exotic fish averaged just below the Florida limited consumption advisory level.

Only one bluefish was collected from Florida Bay with the remainder collected from the Indian River. Bluefish from the Indian River had average Hg concentrations well over the Florida limited consumption advisory level. Average Hg in gafftopsail catfish collected from the Indian River (only two fish were collected from western Florida Bay) ex-

TABLE 1. Summary of mercury (Hg) in fish from the Indian River Lagoon (IRL) and eastern (EFB) and western (WFB) Florida Bay 1989–1999. — denotes no data available.

Common Name ^a <i>Species epithet</i>	Region	N	Hg mg kg ⁻¹ (SD)	Weight g (SD)	Std. Length cm (SD)
Black drum	IRL	—	—	—	—
<i>Pogonias cromis</i>	EFB	—	—	—	—
	WFB	2	0.14 (0.08)	2,055 (2,226)	37.7 (16.6)
Bluefish	IRL	10	0.64 (0.332)	850 (249)	37.1 (3.0)
<i>Pomatomus saltatrix</i>	EFB	—	—	—	—
	WFB	1	0.68	2,268	45
Bonnethead shark	IRL	—	—	—	—
<i>Sphyrna tiburo</i>	EFB	2	0.65 (0)	616 (30)	39.5 (0.7)
	WFB	1	0.23	306	32
Crevalle jack	IRL	38	0.60 (0.50)	1,374 (2,345)	33.1 (13.8)
<i>Caranx hippos</i>	EFB	31	1.00 (0.39)	377 (285)	23.4 (5.1)
	WFB	24	0.37 (0.11)	555 (343)	26.3 (6.8)
Common snook	IRL	38	0.39 (0.16)	4,076 (2,653)	63.4 (12.7)
<i>Centropomus undecimalis</i>	EFB	6	0.52 (0.14)	2,239 (1,143)	52 (9.3)
	WFB	3	0.39 (0.11)	1,653 (563)	49.8 (5.8)
Gafftopsail catfish	IRL	4	0.59 (0.16)	1,295 (288)	39.3 (2.9)
<i>Bagre marinus</i>	EFB	—	—	—	—
	WFB	2	0.57 (0.04)	382 (83)	27.5 (2.1)
Gray snapper	IRL	40	0.20 (0.06)	435 (231)	25.9 (4.4)
<i>Lutjanus griseus</i>	EFB	42	0.35 (0.13)	363 (82)	23.2 (2)
	WFB	24	0.11 (0.04)	297 (57)	21.5 (1.6)
Mayan cichlid	IRL	—	—	—	—
<i>Cichlassoma urophthalmus</i>	EFB	18	0.44 (0.23)	103 (47)	13.3 (2.1)
	WFB	—	—	—	—
Pompano	IRL	2	0.09 (0.02)	719 (518)	28 (7.1)
<i>Trachinotus carolinus</i>	EFB	—	—	—	—
	WFB	—	—	—	—
Red drum	IRL	9	0.21 (0.11)	1,646 (917)	41.6 (5.3)
<i>Sciaenops ocellatus</i>	EFB	4	0.30 (0.06)	1,514 (271)	42.1 (2)
	WFB	2	0.18 (0.04)	1,553 (208)	43.5 (1.4)
Sheepshead	IRL	19	0.20 (0.09)	669 (312)	23.9 (3.2)
<i>Archosargus probatocephalus</i>	EFB	—	—	—	—
	WFB	3	0.20 (0.12)	380 (224)	21.1 (4.7)
Southern flounder	IRL	12	0.23 (0.13)	780 (675)	33.5 (7)
<i>Paralichthys lethostigma</i>	EFB	—	—	—	—
	WFB	1	0.16	265	22.5
Spadefish	IRL	1	0.22	1,150	28.6
<i>Chaetodipterus faber</i>	EFB	—	—	—	—
	WFB	—	—	—	—
Spotted seatrout	IRL	76	0.36 (0.13)	787 (554)	36 (7.2)
<i>Cynoscion nebulosus</i>	EFB	65	0.96 (0.37)	740 (492)	34.2 (7.4)
	WFB	33	0.21 (0.15)	443 (289)	29.2 (6.3)

^a Common names from American Fisheries Society (1991).

ceeded the Florida limited consumption advisory level. Two bonnethead sharks collected from eastern Florida Bay possessed Hg concentrations above the Florida limited consumption advisory, while a single smaller specimen collected from western Florida Bay was low in Hg.

Referring to Table 1, the number of crevalle jack, gray snapper, and spotted seatrout collected

from the Indian River and eastern and western Florida Bay were sufficient to allow statistical comparisons of Hg burdens among regions. As shown in Fig. 3, crevalle jack collected from the Indian River Lagoon (Table 1) were heavier ($p \leq 0.05$) than those from eastern Florida Bay. Weight differences were not significant between Indian River Lagoon and western Florida Bay crevalle jack, or

TABLE 2. Fish consumption advisory levels.

Mercury (mg kg ⁻¹ wet wt)	Consumption Advisory	Agency
0.5	Limited Consumption	Florida Health Department (1999)
1.0	No Consumption	U.S. Food and Drug Administration (U.S. Environmental Protection Agency 1995, 1997)
1.5	No Consumption	Florida Health Department (1999)

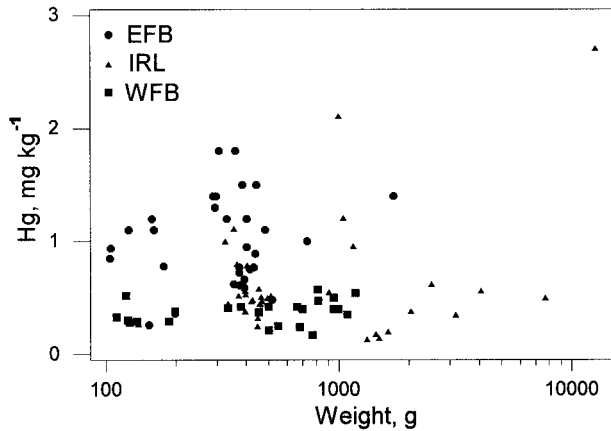


Fig. 3. Distribution of mercury as a function of weight in crevalle jack from eastern Florida Bay (EFB), Indian River Lagoon (IRL), and western Florida Bay (WFB).

between eastern and western Florida Bay jacks. Hg content in jacks from eastern Florida Bay was higher ($p \leq 0.05$) than that in crevalle jacks from either the Indian River or western Florida Bay. The mean concentration of Hg in jacks from eastern Florida Bay was equivalent to the U.S. Food and Drug Administration's no consumption advisory level, while the mean concentration in jacks from the Indian River Lagoon, although lower, was above the Florida limited consumption advisory criteria (Table 2). The difference in Hg concentration between Indian River and western Florida Bay crevalle jack was not statistically significant.

Referring to Fig. 4, gray snapper collected from the Indian River Lagoon (Table 1) were heavier ($p \leq 0.05$) than those from western Florida Bay. Weight differences were not significant between Indian River Lagoon and eastern Florida Bay, and between eastern and western Florida Bay snapper weights. Hg content in snapper from eastern Florida Bay, although below health advisory levels, was significantly higher than the snapper Hg concentration from both the Indian River and from western Florida Bay (Table 1). The Hg concentration in snapper from the Indian River was significantly higher than those from western Florida Bay.

Spotted seatrout collected from the Indian River Lagoon and eastern Florida Bay (Table 1) were heavier ($p \leq 0.05$) than those from western Florida Bay (Fig. 5). Despite the lack of a significant difference in size, the Hg content in seatrout from eastern Florida Bay was greater ($p \leq 0.05$) than Hg in trout from the Indian River Lagoon. Hg in seatrout from western Florida Bay was significantly less than those from both the Indian River and eastern Florida Bay, which could arguably be attributed simply to differences in size. If the set of Florida Bay seatrout data was censored such that

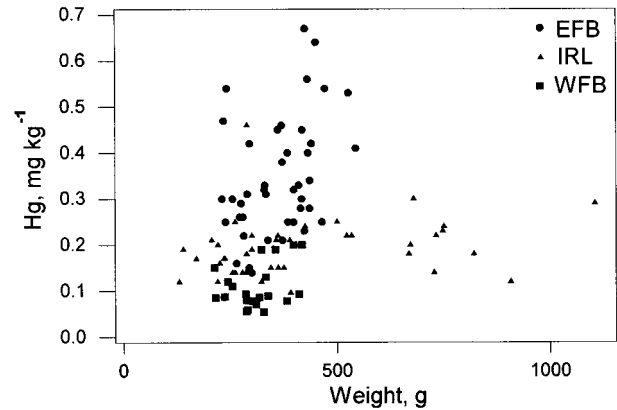


Fig. 4. Distribution of mercury as a function of weight in gray snapper from eastern Florida Bay (EFB), Indian River Lagoon (IRL), and western Florida Bay (WFB).

the difference in weight between western and eastern Florida Bay was not significant, the difference between Hg concentration remained significant. Using the subset of Florida Bay seatrout that weighed greater than 350 g and less than or equal to the heaviest fish caught from western Florida Bay (Fig. 6), the Hg concentration in similarly sized Florida Bay seatrout was significantly higher in those from eastern Florida Bay ($p < 0.001$). Hg in spotted seatrout from eastern Florida Bay (mean 0.96 mg kg^{-1}) was well above the limited consumption advisory level and almost equal to the U.S. Food and Drug Administration's no consumption advisory level (Table 2). Conversely, seatrout from both the Indian River Lagoon and western Florida Bay were below any advisory level.

While the analyses performed for this study were for total Hg, it has been shown that greater than 95% of the Hg in fish tissues is MeHg (Bloom

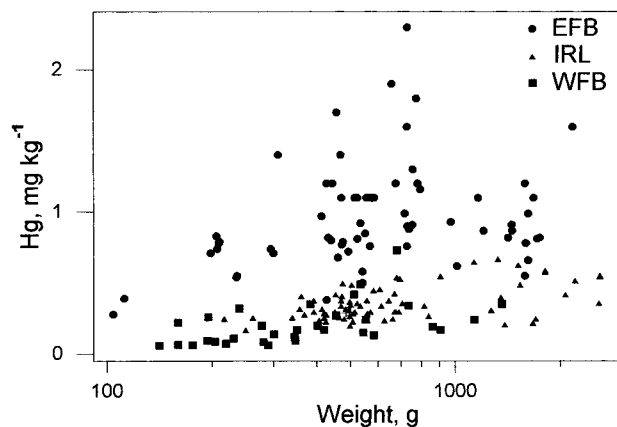


Fig. 5. Distribution of mercury as a function of weight in spotted seatrout from eastern Florida Bay (EFB), Indian River Lagoon (IRL), and western Florida Bay (WFB).

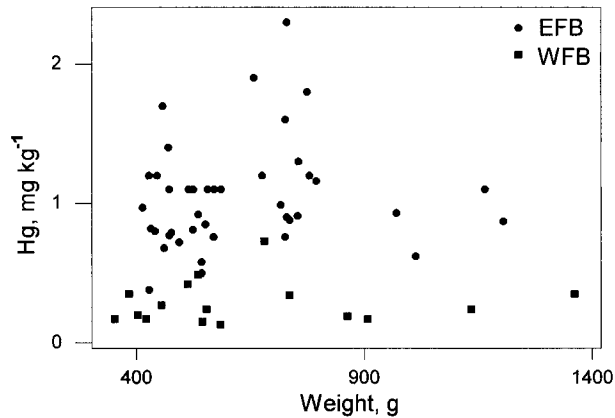


Fig. 6. Distribution of mercury as a function of weight for spotted seatrout weighing between 350–1,400 g from eastern Florida Bay (EFB) and western Florida Bay (WFB).

1992; Becker and Bigham 1995; Lasorsa and Allen-Gil 1995). MeHg concentrations in sediments and fish have been shown to be negatively correlated to the phosphorus gradient in the freshwater Everglades, with higher levels of MeHg measured in the oligotrophic areas (Stober 1995; Gilmour et al. 1998; Hurley et al. 1998). Because phosphorus is quickly assimilated and retained by Everglades wetlands receiving discharges from canals (Davis 1994; Rudnick et al. 1999), oligotrophic conditions are more prevalent in the southern marshes near Florida Bay. The observed higher levels of MeHg in eastern Florida Bay fish may be the result of Hg in runoff (Kannan et al. 1998; King et al. 2000), MeHg in prey fish migrating from the Everglades to Florida Bay, and/or Hg cycling from in situ Hg contaminated Florida Bay sediments (Evans and Crumley 2000).

Estuaries like Florida Bay may act as Hg traps, where significant internal recycling and methylation can occur (Mason et al. 1999). Sediments are the most important storage component for Hg in estuaries (Mason and Lawrence 1999), and are the dominant location for Hg methylation in estuaries (Gilmour and Henry 1991; Benoit et al. 1998). In the northern Everglades, the distribution of MeHg production rates is correlated with sediment MeHg concentrations and MeHg concentrations in biota, but methylation was not observed in overlying waters (Gilmour et al. 1998). Similar results were found for the estuarine Taylor River adjoining northern Florida Bay where aqueous MeHg levels were low, but total Hg was high in sediments and periphyton (Lewis et al. 2000). Gilmour et al. (1998) suggest that in situ MeHg production in sediments controls MeHg concentrations and availability to resident organisms at the base of the food web.

Estuarine sediments are often rich in sulfur compounds due to the abundance of sulfur in seawater (Garrels et al. 1975; Marvin-DiPasquale and Capone 1998). Sulfate-reducing bacteria (SRB) predominate Hg methylation pathways in estuarine sediments (Gilmour et al. 1992; Gilmour 1995; King et al. 2000). As rates of sulfate reduction increase in more anoxic conditions, increasing sulfide concentrations (which are a product of sulfate reduction) limit MeHg formation (Gilmour et al. 1998; Benoit et al. 1999; Braga et al. 2000). Under anaerobic conditions, sulfide is believed to react with MeHg to cause precipitation of HgS (cinnabar) and/or volatilization of elemental Hg (Benoit et al. 1999; Braga et al. 2000).

Analysis of stable isotope ratios in the tissues of organisms can be used to elucidate food web details (Cabana and Rasmussen 1994), and may also indicate whether oxidizing or reducing conditions are prevalent in the environment of the organism whose tissue is analyzed (e.g., higher δ^{15} ratios indicate reducing conditions; Kendall et al. 1997). Recent stable isotope research has shown higher δ^{15} nitrogen ratios in gray snapper, red drum, and spotted seatrout from eastern Florida Bay that had elevated Hg concentrations (Evans and Crumley 2000). These higher δ^{15} N ratios are attributed to enhanced denitrification rates in eastern Florida Bay (Kendall et al. 1977; Evans and Crumley 2000). Evans and Crumley (2000, p. 4) state that “these high δ^{15} N ratios, if they are due to denitrification of known nitrogen nutrient inputs, is suggestive of a collocated source of Hg methylation within eastern Florida Bay which could operate in addition to any external Everglades source.” Denitrification occurs under anaerobic conditions, which also favor sulfate reduction by SRB (Kadlec and Knight 1996). Assuming anoxia is not severe, pervasive, or continuous, sulfide accumulation (and accompanying MeHg production inhibition) may be limited. Such circumstances (suboxic rather than anaerobic conditions) may favor MeHg accumulation (Braga et al. 2000), and explain the higher Hg levels measured in tissues of fish from eastern Florida Bay.

Conclusions

This study found that gray snapper, crevalle jack, and spotted seatrout collected from eastern Florida Bay contained a higher concentration of Hg than the same species collected from either the Indian River Lagoon or western Florida Bay. Gray snapper accumulated less Hg than crevalle jack or spotted seatrout irrespective of location. A number of other species collected from eastern Florida Bay appeared to contain more Hg than these same species collected from western Florida Bay or the In-

dian River, although the number and distribution of individual fish collected prevents making any statistically supportable inference. The data presented herein suggest the presence of an enhanced rate of Hg bioaccumulation in eastern Florida Bay. Although heavier crevalle jack were collected from western versus eastern Florida Bay, Hg content was lower, which supports the hypothesis that the potential for MeHg bioaccumulation in western Florida Bay is lower than for the other areas examined. Of the species studied, crevalle jack seems to hold the most potential as a Hg bioconcentration estuarine health indicator species. It is common, easily obtained, and readily accumulates Hg. Spotted seatrout is another likely candidate and is a popular sport and food fish, although the population of spotted seatrout is believed to be declining in some areas and is the subject of increasingly strict harvest regulations.

These results support the hypothesis that fish may exhibit higher concentrations of Hg in estuaries near dense areas of urbanization. Where point and nonpoint sources of Hg are spatially concentrated, i.e., in typical high-density urban areas, the adjoining waters possess increased potential for receiving Hg from near-field atmospheric fallout and stormwater runoff. According to this hypothesis, fish from estuarine waters adjoining other urban areas in Florida (as well as fish from other urban-affected estuaries elsewhere in the world) should carry a measurably higher Hg concentration in comparison to fish from estuaries far from developed areas. This would indicate that more stringent Hg emission and control strategies are most needed to protect estuaries near heavily developed areas.

Although levels of Hg reported herein were not as high as those recorded for the Everglades, Hg concentrations in fish from eastern Florida Bay are clearly elevated. Implementation of more rigorous emission standards is expected to reduce anthropogenic atmospheric Hg releases (U.S. Environmental Protection Agency 1997). Hg in fish monitoring in Florida Bay (in conjunction with isotopic food web studies) should be continued to track temporal trends in Hg contamination that may be affected by these emission reductions. Isotopic and tagging studies should be performed to determine whether fish migrations are involved in the processes that cause elevated Hg in fish in eastern Florida Bay.

With regional restoration initiatives underway to increase flows to Florida Bay, it is important to fully understand the ecosystem processes that may be affected by these changes. Increased flows could conceivably exacerbate or expand the existing area in Florida Bay where Hg bioaccumulation is al-

ready a problem. A better understanding of the transport, fate, and cycling of Hg and its compounds in the sediments of the bay is necessary to predict the effects that restoration initiatives will have on MeHg levels in fish, so that effective measures can be implemented to minimize them.

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