Mercury in Fish, Crustaceans and Mollusks from Estuarine Areas in the Pacific Ocean and Gulf of Mexico Under Varying Human Impact

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Abstract

Mercury (Hg) is the most dangerous trace element present in the edible parts of fishes and invertebrates. With the aim of having a general view on Hg occurrence in commercially exploited biota (fish and invertebrates) from selected estuarine systems of Mexico, we compiled information related to Hg levels in fish (elasmobranchs and teleosts), shrimps, clams, mussels and oysters from impacted estuarine areas and other coastal ecosystems in the Pacific Ocean and the Gulf of Mexico. Levels of Hg in the Asiatic clam *Corbicula fluminea* (a freshwater species) were relatively low (<0.32 μg g^{-1}) in comparison to individuals collected in moderate or severely impacted sites. In the case of marine mollusks (*Crassostrea corteziensis* and *Mytella strigata*) Hg concentrations were comparable to those from low or moderately contaminated sites. In shrimps, Hg values were low (<0.72 μg g^{-1}) and consistently higher in hepatopancreas tissue than in muscle. Rays had lower Hg levels (<0.4 μg g^{-1} wet weight) than sharks (<2.0 μg g^{-1} wet weight). Teleost fish have been studied more thoroughly than other groups; Hg levels in muscle tissue varied by two orders of magnitude (from 0.02 to 1.58 μg g^{-1} dry weight). Among studied organisms, fish are known as the main pathway of Hg entrance to humans. It is necessary to generate information of the rates of consumption of fish, especially of predator species. Considering legal limits of Hg and methyl Hg (1.0 and 0.5 μg g^{-1} wet weight, respectively) in edible portion of fish in Mexico, at present there is risk to the human population for the consumption of the scalloped hammerhead shark *Sphyrna lewini*.

Keywords
Mercury · Fish · Mollusks · Crustaceans · Health risk

3.1 Introduction

Mercury (Hg) is an element with an atomic weight of 200.59 g/mole and a boiling point of 356.6 °C; it is a dense, silvery-white liquid at room temperature (Hunter 1975). Hg is distributed worldwide and it is mobilized naturally through the earth's crust, atmosphere, oceans, and life forms. Although Hg occurs naturally in the environment, it is concentrated in geographical belts. In fact, significant Hg deposits belong to one of the two Tertiary or Quarternary orogenic and volcanic belts: the Circum-Pacific and the Mediterranean-Himalayan belt (WGMF 1980). For example, it can be found in

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natural deposits, such as the Hg bed under the Mediterranean Sea, which holds some of the richest reserves of mercury in the world (Bacci 1989). The main ore of mercury is the red sulphide cinnabar (HgS), which has been mined throughout the world in places such as: Spain, Italy, Yugoslavia, Russia, China, Japan, Mexico, California, and British Columbia (Hunter 1975). Mercury is naturally emitted into the air as a result of off-gassing from the earth's surface and from volcanoes. Mercuric vapor can remain in the atmosphere for significant amounts of time and travel long distances before it cycles back to the earth in rainwater. After Hg is released into the environment in inorganic form, it is methylated by bacteria in water and converted to an organic form, usually methylmercury (Rasmussen et al. 2005). Anaerobic microorganisms like sulfate-reducing bacteria are the main producers of methylmercury (Parks et al. 2013). Such transformation enhances the entrance of Hg to the food chain, eventually resulting in biomagnification. Although Hg intake in humans occurs through contaminated food, drink, or air, exposure to organic mercury is almost exclusively a result of consumption of fish and shellfish (Gunderson 1995; NRC 2000). In this sense, Storelli et al. (2002) estimated that fish consumption accounts for 80–90 % of the total exposure to mercury.

An estuary is defined as a semi-enclosed coastal body of water that is either permanently or periodically open to the sea and within which seawater is diluted with water derived from land drainage (Kennish 2001). Estuaries have elevated levels of biological productivity and play important ecological roles (Clark 1996). On the other hand, areas surrounding estuaries have become more densely populated in the last few decades and this has resulted in a wide range of environmental threats: damming of rivers, pollution, urbanization, industrial development, construction of flood-protection devices, mariculture, and recreation (Lindeboom 2002). Estuarine environments are highly dynamic and very sensitive to anthropogenic discharges since they function as sinks for fine-grain sediments that are usually associated with contaminants such as trace metals (Rosales-Hoz et al. 2003). In this chapter, we report Hg levels in biota from estuarine systems of selected areas in Mexico with different degrees of human impact. Data were compiled from published documents related to Hg levels in invertebrates (shrimps, clams and oysters) and vertebrates (elasmobranchs and teleosts) in estuarine systems and other coastal ecosystems of the Pacific Ocean and the Gulf of Mexico.

3.2 Environmental Impact in Studied Areas

The estuarine areas where biota was collected are located in states of the Pacific coast and in the Gulf of Mexico (Table 3.1). Human impacts vary from extreme in Veracruz (specifically in Coatzacoalcos estuary; Ortíz-Lozano et al. 2005) to severe in some parts of Sinaloa state (Baluarte estuary; Table 3.1).

Table 3.1 Degrees of human impact in coastal states of Mexico

State	Human impact
Sonora	Severe (fisheries and aquaculture, industrial, harbors, urban development, wastewater discharges, mining)
Sinaloa	Severe (aquaculture, fisheries, agriculture, industrial, tourism and recreation, harbors, mining and wastewater discharges)
Baja California	Severe (urban development, industrial, garbage presence, wastewater discharges)
Veracruz	Extreme (industrial, harbors, urban development, garbage presence, habitat destruction, wastewater discharges)

Scale for impacts: 0 = not present; 1 = light; 2 = moderate; 3 = intense; 4 = severe; 5 = extreme (Ortiz-Lozano et al. 2005)

Wastewater discharges are the agents of human impact that exist in all of the study areas. Other relevant activities that affect estuarine environments considered in this study were industrial, agriculture, mining, and aquaculture (Ortíz-Lozano et al. 2005). Several of the activities mentioned in Table 3.1 emit Hg to the environment; however, estimations of the relative contributions for every source are not complete.

3.3 Mercury Sources of Mexico

In 1999, it was reported that the main sources of annual Hg emissions to the atmosphere were: mining and refining of gold (11.27 t; equivalent to 36.0 % of the total), mining and refining of Hg (9.666 t; 30.8 %), chloralkali plant processes (4.902 t; 15.7 %), copper smelting (1.543 t; 4.9 %), residential combustion of wood (1.168 t; 3.7 %), carboelectric plants (0.7855 t; 2.5 %), and oil refining (0.680 t; 2.2 %; Acosta y Asociados 2001). Other Hg emission sources (e.g., thermoelectrical plants, lead and zinc smelting, fluorescent lamps and dental amalgams) accounted for 0.9413 t (3.0 %; Acosta y Asociados 2001). Considering other environmental compartments as well as Hg contained in wastes and products, total releases are considered in Table 3.2.

Four of the six states included in Table 3.2 correspond to the locations of the studied estuarine areas; for the purpose of contrasting results, the states with the highest (Durango) and lowest (Baja California Sur) Hg releases were also listed. The decreasing order of total releases of Hg in the studied areas was Sonora > Veracruz > Sinaloa > Baja California. It is worth mentioning that Hg levels in certain areas do not correspond to local releases; in this sense, in some sites it has been found that mine wastes can more greatly affect the surrounding areas of the mines than the mining operation itself (Fernández-Caliani et al. 2009); this is because of the allocation of Hg through mine drainage and its transportation in the atmosphere (Chopin and Alloway 2007).

Table 3.2 Total releases of mercury (Hg, tons) in selected states of Mexico during 2004

	Air	Water	Soil	Waste	Product	Total	National rank
Durango	0.68	0.13	53.34	2.53	0.09	56.77	1st
Sonora	1.90	0.17	38.95	5.71	2.03	48.73	2nd
Veracruz	4.21	0.48	5.53	14.11	1.30	25.63	5th
Sinaloa	0.88	0.21	4.24	4.35	0.15	9.84	18th
Baja California	1.02	0.22	0.97	4.65	0.19	7.05	21st
Baja California Sur	0.16	0.05	0.17	0.85	0.03	1.26	32nd (last)

The issue of Hg supply to the Mexican environment through anthropogenic activities is not recent. Between 1540 and 1850, about 45,000 t of Hg were sent from Spain for the extraction of gold and silver (de la Peña-Sobarzo 2003); as a consequence, there still exist many places considered "hot spots" (i.e. soils with Hg concentrations above 10 ppb).

3.4 Benthic Invertebrates

The dietary importance of benthic invertebrates to numerous species of fish, birds and mammals underscores their importance in the trophic transfer of mercury and their potential significance as biological indicators (Wiener et al. 2007). Benthic invertebrates such as oysters, mussels, clams and shrimps are also currently consumed by humans, providing a direct pathway for human exposure to mercury. Of all the benthic invertebrate groups, mollusks have been the group mostly employed in coastal biomonitoring (Rainbow and Phillips 1993; Zhou et al. 2008). In the last 15 years (1997–2012), 364 documents related to the topic of biomonitoring have been published regarding the Mexican coasts; fishes and mollusks have been the most studied.

There are difficulties associated with comparing metal levels in mollusks of different species and from different geographical regions (NAS 1980; Rainbow 2002; Osuna-Martínez et al. 2010). Mercury levels among species of mollusks from distinct regions of the world vary depending on metabolism (regulation and accumulation rates), feeding habits, and ecological conditions. Additionally, mercury levels may vary depending on sampling season, size (age), and gonadal maturation. Consequently, comparison of mercury levels among mollusks must be made with caution and data should only be used in preliminary analyses. In this context, Osuna-Martínez et al. (2010) found that Hg concentration in the soft tissue of *Crassostrea corteziensis* (Y) and *C. gigas* (X) was positively correlated (linear equation: $Y=0.616X+0.084$) when both species of oysters were exposed in the field to the same Hg concentration. Therefore, this equation may be used when comparing Hg levels between different sites involving these two species.

Mercury content of aquatic mollusks varies throughout the world and can be classified based on mollusk habitats including freshwater, mangrove, and lagoon/estuarine environments (Table 3.3). The only bivalve species collected in freshwater environments of Mexico for Hg studies is the Asiatic clam *Corbicula fluminea*. Mercury levels were relatively low ($<0.32\ \mu g\ g^{-1}$) in comparison to specimens from moderate or severely impacted regions. South Virginia (USA) and the Ebro River (Spain) contained clams with mean Hg concentrations of 1.89 and 2.30 $\mu g\ g^{-1}$, respectively (Neufeld 2010; Faria et al. 2010). These results suggest that the upper region (Hidalgotitlán) of Coatzacoalcos estuary, Mexico, and Cerro Prieto geothermal field in Baja California, Mexico are relatively un-impacted by Hg.

Mollusk species collected from mangroves in northwestern Mexico are *C. corteziensis* and the tropical mussel *Mytella strigata*. Mercury concentrations of these species varied from 0.30 to 0.56 µg Hg/g in Tobari lagoon (Sonora) and from 0.032 to 0.145 $\mu g\ g^{-1}$ in Mazatlán harbor (Urías lagoon, Sinaloa). Mercury levels of bivalves from northwest Mexico corresponded to low or moderately contaminated sites as compared to mangrove oyster *C. rhizophorae* from other regions (Table 3.3; Vaisman et al. 2005; Olivares-Rieumont et al. 2012).

Two oyster species, *C. gigas* and *C. corteziensis*, were collected in estuarine or lagoon environments (oyster farms) of the study area (Table 3.3). Additionally, various wild clam species were examined from these lagoon systems. The levels of Hg were similar among the sites in northwest Mexico and varied from 0.08 to 0.93 $\mu g\ g^{-1}$ for *C. gigas*, and 0.18–0.56 $\mu g\ g^{-1}$ for *C. corteziensis*. These ranges are comparable to levels measured in *C. virginica* in estuarine systems of the Gulf of Mexico (Reimer and Reimer 1975; Aguilar et al. 2012; Apeti et al. 2012); *C.gigas* in a Moroccan coastal lagoon (Maanan, 2008); and *Perna perna* in Ghana, west Africa (Joiris et al. 2000; Otchere et al. 2003). The higher Hg levels found in the aforementioned regions are considered to have moderate or clearly impacted sites, similar to northwest Mexico.

The Hg content of marine crustaceans is variable throughout Mexico and other parts of the world (Table 3.4). Reimer and Reimer (1975), the first study to document Hg content of shrimp collected from local markets in Mexico, found comparable Hg levels in the muscle of three species: *Penaeus setiferus* from Veracruz, *Farfantepenaeus californiensis* from Mazatlán, and *Litopenaeus stylirostris* from Topolobampo and Guaymas. Ruelas-Inzunza et al. (2004) found similar or

Table 3.3 Mercury concentrations (μg g^{-1} dry weight) in mollusks from different coastal areas throughout the world

Species	Common name	Area	Hg	Reference
		Freshwater environments		
Corbicula fluminea	Asian clam	Cerro Prieto Geothermal field, (Mexico)	0.11 (0.01–0.32)	Gutierrez-Galindo et al. (1988)
Corbicula fluminea	Asian clam	Coatzacoalcos River, (Mexico)	0.09±0.008	Ruelas-Inzunza et al. (2009)
Corbicula fluminea	Asian clam	North River, Virginia (USA)[a]	0.12±0.01	Neufeld (2010)
Corbicula fluminea	Asian clam	South River, Virginia (USA)[c]	1.89±0.11	Neufeld (2010)
Corbicula fluminea	Asian clam	Ebro River (Spain)[c]	2.30±0.49 (1.8–3.0)	Faria et al. (2010)
		Mangrove environments		
Crassostrea corteziensis	Cortez oyster	Tobari lagoon, (Mexico)	0.43±0.07 (0.30–0.56)	Jara-Marini et al. (2013)
Crassostrea corteziensis	Cortez oyster	Urías lagoon, (Mexico)	0.056±0.017 (0.032–0.078)	Jara-Marini et al. (2008)
Mytella sirigata	Mussel	Urías lagoon, (Mexico)	0.067±0.035 (0.034–0.145)	Jara-Marini et al. (2008)
Crassostrea gasar	Mangrove oyster	Sine-Saloum estuary, (Senegal)[a]	0.063±0.003 (0.060–0.103)	Bodin et al. (2013)
Crassostrea gasar	Mangrove oyster	(Ghana)[b]	0.155±0.060 (0.09–0.34)	Otchere et al. (2003)
Crassostrea rhizophorae	Mangrove oyster	Sepetiva Bay (Brazil)[b]	(0.015–0.023)	Kehrig et al. (2006)
Crassostrea rhizophorae	Mangrove oyster	Jaguaribe estuary,, (Brazil)[a]	0.052±0.024 (0.022–0.123)	Vaisman et al. (2005)
Crassostrea rhizophorae	Mangrove oyster	Pacoti estuary, (Brazil)[a]	0.045±0.019 (0.021–0.065)	Vaisman et al. (2005)
Crassostrea rhizophorae	Mangrove oyster	Cocó estuary, (Brazil)[b]	0.084±0.024 (0.039–0.116)	Vaisman et al. (2005)
Crassostrea rhizophorae	Mangrove oyster	Ceará estuary, (Brazil)[c]	0.154±0.060 (0.056–0.300)	Vaisman et al. (2005)
Crassostrea rhizophorae	Mangrove oyster	Santa Cruz River (Brazil)[c]	(0.270–2.210)	Vaisman et al. (2005)
Crassostrea rhizophorae	Mangrove oyster	Sagua la Grande River (Cuba)[c]	0.570 (0.190–0.690)	Olivares-Ricumont et al. (2012)
		Estuarine or lagoon environments		
Crassostrea gigas (cultured)	Giant oyster	Tobari lagoon, (Mexico)	0.40±0.13 (0.24–0.77)	Jara-Marini et al. (2013)
Anadara tuberculosa	Pustulose ark	Tobari lagoon, (Mexico)	0.21±0.07 (0.05–0.31)	Jara-Marini et al. (2013)
Chione fluctifraga	Smooth venus	Tobari lagoon, (Mexico)	0.28±0.10 (0.12–0.38)	Jara-Marini et al. (2013)
Chione gnidia	Gnidia venus	Tobari lagoon, (Mexico)	0.51±0.19 (0.26–0.80)	Jara-Marini et al. (2013)
Crassostrea gigas (cultured)	Giant oyster	Coastal lagoons, SE Gulf of California, (Mexico)	0.427±0.348 (0.08–0.93)	Osuna-Martínez et al. (2010)
Crassostrea corteziensis (cultured)	Cortez oyster	Coastal lagoons, SE Gulf of California, (Mexico)	0.370±0.269 (0.18–0.56)	Osuna-Martínez et al. (2010)
Crassostrea virginica	American oyster	Boca de Atasta, (Mexico)	0.15±0.10[d] (0.05–0.30)	Reimer and Reimer (1975)
Crassostrea virginica	American oyster	Términos lagoon, (Mexico)	0.73 (0.20–2.00)	Aguilar et al. (2012)
Crassostrea virginica	American oyster	Tamiahua lagoon, (Mexico)	0.10±0.05[d] (0.05–0.30)	Reimer and Reimer (1975)
Polymesoda caroliniana	Carolina marshclam	Coatzacoalcos estuary, (Mexico)	0.142±0.045 (0.105–0.225)	Ruelas-Inzunza et al. (2009)
Crassostrea virginica	American oyster	N Gulf of Mexico (USA)	(0.03–0.500)	Apeti et al. (2012)
Crassostrea gigas	Giant oyster	Oualidia lagoon, Morocco[b,c]	0.08–0.84	Maanan (2008)
Perna perna	Brown mussel	Ghana[b]	0.29 (0.01–0.76)	Joiris et al. (2000)
Perna perna	Brown mussel	Ghana[b]	0.334±0.200 (0.19–0.84)	Otchere et al. (2003)
Anadara senilis	Bloody cockle	Ghana[b]	0.254±0.185 (0.10–0.86)	Otchere et al. (2003)

[a] Not impacted area

[b] Minor or moderately impacted

[c] Impacted from chloro-alkali plants and/or industrial effluents

[d] Calculated with a humidity of 80% in soft tissue

Table 3.4 Concentrations of mercury ($\mu g\ g^{-1}$ dry weight) in shrimp sampled from coastal areas throughout the world

Species	Common name	Area	Tissue	Hg content	Reference
		Mexico			
Farfantepenaeus brevirostris	Crystal shrimp	AEP lagoon, SE Gulf of California	Hepatopancreas	0.35 ± 0.07	Ruelas-Inzunza et al. (2004)
			Muscle	0.21 ± 0.07	Ruelas-Inzunza et al. (2004)
Farfantepenaeus californiensis	Brown shrimp	AEP lagoon, SE Gulf of California	Hepatopancreas	0.62 ± 0.11	Ruelas-Inzunza et al. (2004)
			Muscle	0.13 ± 0.08	Ruelas-Inzunza et al. (2004)
Litopenaeus stylirostris	Blue shrimp	AEP lagoon, SE Gulf of California	Hepatopancreas	0.57 ± 0.01	Ruelas-Inzunza et al. (2004)
			Muscle	0.30 ± 0.036	Ruelas-Inzunza et al. (2004)
Litopenaeus vannamei	Whiteleg shrimp	AEP lagoon, SE Gulf of California	Hepatopancreas	0.72 ± 0.07	Ruelas-Inzunza et al. (2004)
			Muscle	0.20 ± 0.01	Ruelas-Inzunza et al. (2004)
Xiphopenaeus kroyery	Seabob	AEP lagoon, SE Gulf of California	Hepatopancreas	0.27 ± 0.04	Ruelas-Inzunza et al. (2004)
			Muscle	0.13 ± 0.04	Ruelas-Inzunza et al. (2004)
Litopenaeus vannamei	Whiteleg shrimp	Mazatlán harbor, SE Gulf of California	Whole body	0.04 ± 0.01	Jara-Marini et al. (2012)
Farfantepenaeus californiensis	Brown shrimp	Mazatlán harbor, SE Gulf of California	Whole body	0.039 ± 0.006	Jara-Marini et al. (2012)
Penaeus setiferus	White shrimp	Veracruz, W Gulf of Mexico	Muscle^a	0.16 ± 0.08	Reimer and Reimer (1975)
Farfantepenaeus californiensis	Brown shrimp	Mazatlán, SE Gulf of California	Muscle^a	0.48 ± 0.40	Reimer and Reimer (1975)
Litopenaeus stylirostris	Blue shrimp	Topolobampo, SE Gulf of California	Muscle^a	0.20 ± 0.20	Reimer and Reimer (1975)
Litopenaeus stylirostris	Blue shrimp	Guaymas, E Gulf of California	Muscle^a	0.36 ± 0.28	Reimer and Reimer (1975)
		International			
Crangon crangon	Common shrimp	Limfjord, Denmark	Muscle	0.09 ± 0.03	Riisgard and Famme (1986)
Penaeus sp	Shrimp	Malaysia	Muscle	0.36 ± 0.13	Rahman et al. (1997)
Penaeus semisulcatus	Green tiger prawn	Gulf of Arabia	Whole body	0.013 ± 0.007	Al-Saleh and Al-Doush (2002)
Penaeus semisulcatus	Green tiger prawn	Northern Persian Gulf	Muscle	0.19 ± 0.05	Elahi et al. (2007)
Litopenaeus stylirostris	Blue shrimp	New Caledonia	Muscle	0.20 ± 0.06	Chouvelon et al. (2009)
Penaeus monodon	Giant tiger prawn	Mekong River Delta, S Vietnam	Muscle	0.06 ± 0.04	Tu et al. (2008)
Penaeus monodon	Giant tiger prawn	Mekong River Delta, S Vietnam	Exoskeleton	<0.05	Tu et al. (2008)
Penaeus monodon	Giant tiger prawn	Mekong River Delta, S Vietnam	Hepatopancreas	0.07 ± 0.02	Tu et al. (2008)
Metapenaeus ensis	Middle prawn	Guangdong Province, S China	Whole body	0.012	Li et al. (2013)
Penaeus japonicus	Kuruma prawn	Guangdong Province, S China	Whole body	0.017	Li et al. (2013)
Penaeus monodon	Giant tiger prawn	Guangdong Province, S China	Whole body	0.017	Li et al. (2013)

AEP Altata-Ensenada del Pabellón

[a] Obtained from fish market and fishermen; calculated with a humidity of 75 %

lower Hg content in muscle of five shrimp species (*F. brevirostris*, *F. californiensis*, *L. stylirostris*, *L. vannamei*, *Xiphopenaeus kroyery*) collected in Altata-Ensenada del Pabellón (AEP) lagoon. This work demonstrated that hepatopancreas contained higher Hg levels than muscle. In a more recent study in Urías lagoon (Mazatlan harbor), Jara-Marini et al. (2012) found the lowest Hg concentrations measured from whole-body samples of *L. vannamei* and *F. californiensis*.

The elevated Hg levels in hepatopancreas tissue is probably related to the biological functions performed by this organ (e.g., metabolism of xenobiotics, digestion of food, storing of lipids and carbohydrates, and synthesis of enzymes and proteins; Manisseri and Menon 1995; Ruelas-Inzunza et al. 2013). Values reported in muscle of shrimp from AEP lagoon were higher than the Hg content found in *P. semisulcatus* from the Gulf of Arabia (Al-Saleh and Al-Doush 2002); *P. monodon* from the Mekong River Delta in south Vietnam (Tu et al. 2008); and *Metapenaeus ensis*, *P. japonicus* and *P. monodon* from Guangdong Province in southern China (Li et al. 2013). However, Hg levels in muscle of shrimp from AEP lagoon were lower than the values reported by Rahman et al. (1997) in *Penaeus* spp. from Malaysia. Chouvelon et al. (2009) reported 0.20 μg g^{-1} of Hg in muscle of *L. stylirostris* from New Caledonia. Ruelas-Inzunza et al. (2004) found a level of 0.30 μg g^{-1} in the same species from the AEP lagoon (northwest Mexico), indicating a similar level of contamination.

3.5 Elasmobranchs

There are about 970 species of elasmobranchs (sharks and rays) in the world that live in a broad range of marine habitats varying from the deep ocean to shallow coastal waters, including estuaries (Nelson 2006). Even though sharks and rays are considered to be primarily oceanic species, they are commonly found in estuarine waters. As with other fish, the estuary is a nursery site for elasmobranchs (Simpfendorfer et al. 2005) where batoid fishes (rays) occur more frequently than sharks.

Rays and juvenile sharks use the shallow and protected water of estuaries to escape from their potential predators and to feed on an abundance of prey. Elasmobranch fishes are among the top predators in the marine environment and play an important role in the transfer of energy within marine ecosystems; they regulate the size and dynamics of prey populations through predation (Cortés 1999; Wheterbee and Cortés 2004). In the estuaries, elasmobranchs are also considered to be top predators, which makes them susceptible to accumulation of contaminants like mercury.

More importantly, Hg can be assimilated by marine organisms and consequently transferred to the upper trophic levels, which can eventually lead to adverse effects on humans due to the consumption of contaminated food (Wang 2002). Contaminants have increased pressure on coastal and estuarine ecosystems over the past decades because of enhanced human activities in these areas. The input of toxic chemicals into estuarine areas from various sources can result in deleterious effects on wildlife habitats, degradation of the ecosystem, and possible poisoning of humans (Moreno et al. 1984; Morton and Blackmore 2001; Ip et al. 2004; Pan and Wang 2012). The human population is often the ultimate receptacle of anthropogenic pollutants that may magnify the concentration of Hg in the food chain.

Within the elasmobranchs, the bull shark (*Carcharhinus leucas*) is perhaps the most notorious species for migrating into estuarine ecosystems (Ortega et al. 2009). Mercury concentrations reported for this shark in Mexican estuaries (Altata-Ensenada del Pabellón, Sinaloa) ranged from 0.06 μg g^{-1} wet weight in muscle to 0.18 μg g^{-1} wet weight in liver (Ruelas-Inzunza and Páez-Osuna 2005). In the same area, the scalloped hammerhead shark (*Sphyrna lewini*) showed more contrasting Hg values of 0.03 μg g^{-1} wet weight in liver and 1.45 μg g^{-1} in muscle (Table 3.5). The estuarine area of Altata-Ensenada del Pabellon is considered to be severely impacted by humans; habitat degradation has resulted from agriculture, aquaculture, and industrial activities (Ortiz-Lozano et al. 2005; Ruelas-Inzunza and Páez-Osuna 2005). However, the variation of Hg levels in sharks collected in this estuary could be due to differences in shark diet (Monteiro et al. 1996). In Florida estuaries, the highest Hg level in muscle tissue of bull shark (0.97 μg g^{-1} wet weight) was higher than in specimens from Altata-Ensenada del Pabellón (0.06 μg g^{-1} wet weight). *S. lewini* from Florida (Adams et al. 2003) had Hg concentrations (1.25 μg g^{-1} wet weight) that were comparable to values reported in Altata-Ensenada del Pabellón (1.45 μg g^{-1} wet weight; Table 3.5). Contrastingly, elevated concentrations were found in Cape Canaveral estuary (Florida) relative to other estuarine areas (i.e. Mexican estuaries and other estuarine areas in Florida), where Hueter et al. (1995) found Hg concentrations in muscle tissue of 1.27 μg g^{-1} wet weight for *C. leucas* and 1.99 μg g^{-1} wet weight in *C. limbatus*.

Total Hg concentrations in muscle of batoids were consistently low (<0.4 μg g^{-1} wet weight) and less than sharks. This difference is likely due to the higher trophic status of sharks. The trophic dynamics of estuaries tend to be complex and the concentration of Hg is magnified in upper trophic levels of the food web (Day et al. 1989). Sharks are primarily carnivores and their diet consists mostly of fish (i.e., proportion by biomass and number; Wetherbee and Cortés 2004), crabs, shrimp, and other elasmobranchs. Contrastingly, batoids feed on organisms from lower trophic levels including crustaceans and mollusks; they rarely prey on fishes.

Table 3.5 Mercury concentrations (µg g^{-1} wet weight) in muscle of elasmosbranchs (sharks and rays) from estuaries worldwide

Estuarine Site	Species	Common name	Hg	Reference
		Sharks		
Altata-Ensenada del Pabellón México	*Carcharhinus leucas*	Bull shark	0.06	Ruelas-Inzunza and Páez-Osuna (2005)
Altata-Ensenada del Pabellón México	*Carcharhinus leucas*	Bull shark	0.18[a]	Ruelas-Inzunza and Páez-Osuna (2005)
Altata-Ensenada del Pabellón México	*Sphyrna lewini*	Scalloped hammerhead shark	1.45	Ruelas-Inzunza and Páez-Osuna (2005)
Altata-Ensenada del Pabellón Mexico	*Sphyrna lewini*	Scalloped hammerhead shark	0.03[a]	Ruelas-Inzunza and Páez-Osuna (2005)
Cape Canaveral, Florida	*Carcharhinus leucas*	Bull shark	1.27	Hueter et al. (1995)
Cape Canaveral, Florida	*Carcharhinus limbatus*	Blacktip shark	1.99	Hueter et al. (1995)
Cape Canaveral, Florida	*Carcharhinus plumbeus*	Sandbar shark	0.86	Hueter et al. (1995)
Indian River Lagoon, Florida	*Carcharhinus leucas*	Bull shark	0.77	Adams and McMichael (1999)
Charlotte Harbor, Florida	*Carcharhinus leucas*	Bull shark	0.97	Adams et al. (2003)
Indian River Lagoon, Florida	*Carcharhinus leucas*	Bull shark	0.78	Adams et al. (2003)
Tampa Bay	*Carcharhinus leucas*	Bull shark	0.66	Adams et al. (2003)
Charlotte Harbor, Florida	*Negaprion brevirostris*	Lemon shark	0.70	Adams et al. (2003)
Charlotte Harbor, Florida	*Carcharhinus limbatus*	Blacktip shark	0.79	Adams et al. (2003)
Tampa Bay	*Carcharhinus limbatus*	Blacktip shark	0.54	Adams et al. (2003)
Volusia County, Florida	*Rhizoprionodon terraenovae*	Atlantic sharpnose shark	0.57	Adams et al. (2003)
Indian River Lagoon, Florida	*Sphyrna lewini*	Scalloped hammerhead shark	0.44	Adams et al. (2003)
Tampa Bay	*Sphyrna lewini*	Scalloped hammerhead shark	1.25	Adams et al. (2003)
Charlotte Harbor, Florida	*Sphyrna tiburo*	Bonnethead shark	0.34	Adams et al. (2003)
Choctawhatchee Bay	*Sphyrna tiburo*	Bonnethead shark	0.58	Adams et al. (2003)
Indian River Lagoon, Florida	*Sphyrna tiburo*	Bonnethead shark	0.39	Adams et al. (2003)
Tampa Bay	*Sphyrna tiburo*	Bonnethead shark	0.59	Adams et al. (2003)
Cape Canaveral, Florida	*Negaprion brevirostris*	Lemon shark	0.34	Nam et al. (2011)
Tampa Bay	*Negaprion brevirostris*	Lemon shark	0.18	Adams et al. (2003)
Bahía Blanca Bay, Argentina	*Mustelus schmitti*	Gatuzo shark	0.85	Marcovecchio et al. (1986)
		Rays		
Tampa Bay	*Dasyatis americana*	Southern stingray	0.17	Adams et al. (2003)
Charlotte Harbor, Florida	*Dasyatis sabina*	Atlantic stingray	0.25	Adams et al. (2003)
Choctawhatchee Bay	*Dasyatis sabina*	Atlantic stingray	0.25	Adams et al. (2003)
Indian River Lagoon, Florida	*Dasyatis sabina*	Atlantic stingray	0.16	Adams et al. (2003)
Tampa Bay	*Dasyatis sabina*	Atlantic stingray	0.33	Adams et al. (2003)
Tampa Bay	*Dasyatis say*	Bluntnose stingray	0.2	Adams et al. (2003)
Charlotte Harbor, Florida	*Dasyatis say*	Bluntnose stingray	0.02	Adams et al. (2003)
Indian River Lagoon, Florida	*Dasyatis say*	Bluntnose stingray	0.07	Adams et al. (2003)
Indian River Lagoon, Florida	*Gymnura micrura*	Smooth butterfly ray	0.15	Adams et al. (2003)
Volusia County, Florida	*Gymnura micrura*	Smooth butterfly ray	0.07	Adams et al. (2003)
Indian River Lagoon, Florida	*Myliobatis freminvillei*	Bullnose ray	0.12	Adams et al. (2003)

[a] Liver

Use of sediments as a food source by benthic organisms is common (Hoffman et al. 1995). Consequently, mercury in sediments can be transferred up the trophic web of the ecosystem (Díaz-Jaramillo et al. 2013). Even in pristine areas, Hg can be magnified within food webs. This magnification is more severe in estuaries that contain high levels of Hg (due to anthropogenic activities) in low trophic levels; trophic transfer then elevates concentrations in top predators.

Estuaries have the greatest food availability of any ecoregion in the world (Haedrich and Hall 1976) and provide important habitat for elasmobranchs. Some shark and ray species have the osmoregulatory ability to tolerate abrupt estuarine changes in salinity and oxygen concentrations over seasonal cycles (Ortega et al. 2009). Due to this use of variable habitats, high levels of Hg in estuarine areas may contribute to increased physiological stress in these species (Saiz-Salinas and González-Oreja 2000).