Mercury in the Atmospheric and Coastal Environments of Mexico

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1 Introduction

Though mercury (Hg) occurs naturally in the environment, anthropogenic activities have affected its global cycle in ways that mobilize increasing amounts of this metal; currently, such human-related activities mobilize more Hg than do natural

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processes (Fitzgerald and Lamborg 2005). It has been estimated that the quantity of Hg mobilized into the atmosphere has increased from two to five times (Nriagu and Pacyna 1988) since the beginning of the industrial age. The mercury cycle is complex and involves diverse environmental media that include air, land, and water. For any country that is not landlocked, the estuaries and coastal waters constitute an important link between the terrestrial environment and the open oceanic waters (Mason et al. 1994). However, research thus far performed on Hg as an environmental contaminant has been focused mainly on terrestrial ecosystems (Fitzgerald and Mason 1996). The focus on land contamination by Hg has occurred despite the prominent role played by Hg in the atmosphere (transported by wind and deposited under both dry and wet conditions) and in oceanic processes (horizontal and vertical transportation, accumulation in sediments, and bacterial transformations).

Within the framework of the North America Free Trade Agreement (NAFTA), established among Canada, the United States of America, and Mexico, the Environmental Cooperation Commission (ECC) was created to contribute to solving environmental problems. A relevant issue concerning the environment and human health is the reduction of Hg emissions. Such emissions result from different anthropogenic activities that include industrial and commercial processes, and urban activities. It has been estimated that from 1540 to 1850, about 45,000 t of Hg were sent from Spain to Mexico for use in extraction of gold and silver from mines in Zacatecas and other cities of central Mexico (De-la-Peña-Sobarzo 2003). Although significant uncertainty remains about the occurrence and levels of Hg in the environment, it appears that the global movement of this metal primarily involves inorganic forms (WHO 1990).

The presence of environmental residues of Hg is an issue of concern in many countries; in Mexico, studies that relate to the occurrence of this element are limited. In this review, we address published information on Hg as a pollutant and its presence in diverse environmental compartments. Our aim is to first review the natural and anthropogenic sources of Hg pollution in Mexico. Then, we address the levels of Hg that appear in the atmospheric and aquatic environments of Mexico. Finally, we address how Hg interacts with biota, including invertebrates, vertebrates, and other taxonomic groups.

2 Sources of Mercury

There are four main environmental sources of Hg (PNUMA 2005): (1) natural, (2) anthropogenic releases from mobilizing Hg impurities that exist in raw materials (e.g., fossil fuels and other ores), (3) anthropogenic releases from production processes, and (4) remobilization of Hg from soils, sediments, and water from past anthropogenic releases. Whatever the original source of Hg entry into the environment, the final receptors of such emissions are the atmosphere, aquatic ecosystems, soils, and biota. The biogeochemical cycle of Hg is complex in that several environmental compartments and processes are involved in the cycle. Estimates of Hg emissions to the atmosphere show that natural sources of Hg (median value

2.5×10^9 g year^{-1}) have been surpassed by anthropogenic sources (median value 3.6×10^9 g year^{-1}) as of 1983; among the main natural sources of Hg are wind-borne soil particles, sea salt spray, volcanic activity, forest wildfires, and biogenic emissions (Nriagu 1989).

Estimates have also been made for the amount of Hg that is released from combusting or processing certain raw materials, such as coal and other fuels; in estimates made in 1995, Hg from global coal combustion accounted for 1474.5 t (77%) (Pirrone et al. 1996). Hg released from industrial production processes has been difficult to estimate, because releases of Hg from point sources or those associated with disposal of products and wastes are unavailable. US data for 1994/1995 show that 10–40% of all anthropogenic releases of Hg came from industrial production or processes (Lawrence 2000). Hg is also remobilized from soils, water, and sediments as a result of past anthropogenic releases. Some anthropogenic activities also result in Hg emissions; these include agriculture, deforestation, and dam construction, all of which can increase Hg releases to aquatic ecosystems and can eventually result in Hg being accumulated by biota (PNUMA 2005).

Acosta and Asociados (2001) reported that 31.293 t of Hg were emitted to the atmosphere in Mexico in 1999. The main sources of annual Hg emissions were mining and refining of gold (11.27 t; 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%). Other Hg emission sources (e.g., thermoelectrical plants, lead and zinc smelting, fluorescent lamps, and dental amalgams) accounted for 0.9413 t (3.0%).

3 Mercury in the Atmospheric Compartment

There are large fluctuations of Hg levels in the atmosphere. In addition, there are Hg exchanges between the atmosphere and terrestrial surfaces that are subjected to Hg deposition and subsequent re-emission (Gustin et al. 2008). Moreover, Hg levels are high in some geological belts of the earth, as well as in areas that have high Fe and Zn mineralization (Rytuba 2003). Transportation of pollutants (including Hg) by wind can affect surrounding areas more than source sites (Chopin and Alloway 2007; López et al. 2008). Different forms of Hg exist in the atmosphere. These Hg forms include gaseous elemental Hg (GEM), divalent reactive gaseous Hg (RGM), and particulate Hg (PHg) (Fu et al. 2010). Unlike other trace metals that are mainly found adsorbed or absorbed to the particulate phase in the atmosphere, most Hg (>95%) is in the gaseous phase (Aspmo et al. 2006; Valente et al. 2007). In atmospheric studies, total Hg is usually reported in the form of total gaseous mercury (TGM), which is equivalent to GEM plus RGM. In Mexico, studies related to Hg presence in the atmosphere are scarce, although we summarize those data that are available in Table 1. In this table, we include TGM values that were reported in studies from other sites so as to provide a general view of Hg levels that exist in the atmospheric compartment.

Table 1 Levels (ng m^{-3}) of total gaseous Hg (TGM) in the atmosphere in Mexico and selected other areas worldwide

Site	TGM	Remarks	Reference
Zacatecas (Mexico)	71.82	Mining wastes are used for brick manufacturing	De la Rosa et al. (2004)
Mexico City (Mexico)	9.81	Storing of steel and food processing in the surroundings	De la Rosa et al. (2004)
Hidalgo (Mexico)	1.32	Agricultural activities in the area	De la Rosa et al. (2004)
Oaxaca (Mexico)	1.46	Tropical forests and no industrial activity	De la Rosa et al. (2004)
Mexico City (Mexico)	7.26	Urbanized area	Rutter et al. (2009)
Mexico City (Mexico)	5.0	Rural area	Rutter et al. (2009)
East China Sea (China)	1.52	Cruise between Shanghai and Bering Sea	Kang and Xie (2011)
Mace Head (Ireland)	1.41	Study site located in a clean sector	Ebinghaus et al. (2011)
Guizhou (China)	9.3–40,000	Abandoned Hg mine, artisanal Hg mining	Li et al. (2011)

TGM total gaseous mercury

The TGM values given in Table 1 vary by orders of magnitude; the lowest levels (1.32 ng m^{-3}) corresponded to TGM from Hidalgo state, a rural area primarily engaged in agriculture; such TGM concentrations were comparable to those reported in samples taken during a cruise between Shanghai and the Bering Sea (1.52 ng m^{-3}), and in a pristine site (1.41 ng m^{-3}) in Ireland. The highest TGM value (71.82 ng m^{-3}) in Mexico existed in Zacatecas, where rustic brick manufacturers use mining wastes as a raw material. In another study performed in Yinqiangou (China), TGM levels ranged from 9.3 to 40,000 ng m^{-3}. The latter concentration was found to exist at a smelting site. In China, the maximum occupational standard for atmospheric Hg is set at 10 μg m^{-3}. The reported value for Yinqiangou (9.3–40,000 ng m^{-3}) exceeded this limit; such elevated TGM levels have been reported to exist in artisanal mining workers in China (Li et al. 2008).

4 Mercury in the Aquatic Environment

4.1 Coastal Sediments

Mercury is a dynamic element, and its chemical behavior in waters, sediments, and soils is complex and is influenced by several factors. These factors include redox, pH, salinity, alkalinity, hardness, and organic matter (i.e., composition, reactivity, concentration, etc.). As with other metals, sediments and soils serve as the main reservoirs for Hg; consequently, the levels, distribution, and speciation of Hg in these media must be established to understand its complex behavior. In Table 2, we present selected data on Hg levels that exist in coastal, marine, lagoonal, and estuarine sediments from distinct regions of Mexico. These data show that sediments

Table 2 Mercury concentrations (range in μg g^{-1} on a dry wt basis) in sediments from Mexican coasts

Location	Hg concentrations	Reference
Northwest coast, B.C.	0.030–0.097	Gutiérrez-Galindo et al. (2007)
Todos Santos Bay, B.C.	0.011–0.063	Gutiérrez-Galindo et al. (2008)
Port of Ensenada, B.C.	0.58 ± 0.23[a]	Carreón-Martínez et al. (2002)
Santispac Bight, B.C.	0.006–0.060	Leal-Acosta et al. (2010)
Mangrove lagoon, B.C.	0.015–0.233	Leal-Acosta et al. (2010)
La Paz lagoon, B.C.S.	0.01–0.05	Kot et al. (1999)
Beach sands, SR, B.C.S.	0.01–0.16	Kot et al. (2009)
Coastal sediments, SR, B.C.S.	0.01–0.35	Kot et al. (2009)
Oyster culture areas, Sonora	0.01–0.35	García-Rico et al. (2003)
Kun Kaak Bay, Sonora	0.05–0.15	García-Hernández et al. (2005)
Guaymas Bay, Sonora	0.34–2.25	Green-Ruiz et al. (2005)
Ohuira lagoon	0.03–0.30	Ruiz-Fernández et al. (2009)
Chiricahueto lagoon	<0.002–0.60	Ruiz-Fernández et al. (2009)
Urías lagoon	<0.002–0.28	Ruiz-Fernández et al. (2009)
	0.20–0.46	Jara Marini et al. (2008a)
Navidad lagoon, Colima	0.002–0.032	Willerer et al. (2003)
Tampamachoco lagoon, Ver.	0.011 ± 0.005[a]	Rosas et al. (1983)
Mandinga lagoon, Ver.	0.028 ± 0.012[a]	Rosas et al. (1983)
Alvarado lagoon, Ver.	0.028–0.091	Guentzel et al. (2007)
Coatzacoalcos estuary, Ver.	0.585–1.41	Ochoa et al. (1973)
	0.11–57.94	Báez et al. (1975)
	0.062–0.209	Botello and Páez-Osuna (1986)
	0.070–1.061	Ruelas-Inzunza et al. (2009)
Del Carmen lagoon, Tabasco	0.009 ± 0.003[a]	Rosas et al. (1983)
Atasta lagoon, Campeche	<0.007	Rosas et al. (1983)

B.C. Baja California, *B.C.S.* Baja California Sur, *SR* Santa Rosalía, *Ver.* Veracruz
[a] Mean concentration

reflect the actual or potential impact of being near mining, industrialized areas, municipal wastewater outlets, and tectonic and geothermal areas.

In Table 2, we present data on the Hg levels that have been reported in sediments along Mexico's Pacific coastal areas or in the Gulf of Mexico. These levels ranged from 0.0002 to 57.94 μg g^{-1}. This range clearly reveals pristine or nearly pristine concentrations in locations along the northwest coasts of Baja California (B.C.), Todos Santos Bay, B.C., Santispac Bight, La Paz lagoon, the Navidad lagoon, and the Alvarado lagoon. In contrast, Guaymas Bay and Coatzacoalcos estuary registered levels that were relatively high. These higher levels reflect the influence of both anthropogenic and natural Hg pollutant sources. However, high levels were also found at locations where no data exist to show that Hg enrichment has occurred; such cases include sites in Sonora where oysters are cultured. Sadiq (1992) reviewed Hg in sediments from different regions of the world and established a value of 0.05 μg g^{-1} as the background Hg concentration that normally exists in uncontaminated sediments. In this context, surficial sediments from Coatzacoalcos estuary have both low (0.062 μg g^{-1}) and extremely high (57.94 μg g^{-1}) Hg concentrations (Table 2).

Another approach frequently used to evaluate the contamination of marine sediments is to contrast levels found at a selected location with general background levels; such background concentrations may be established by using the concentration of the metal in different media (e.g., soil; Fergusson 1990) that occurs in a particular region, or in sedimentary rocks (Turekian and Wedepohl 1961). In addition, Hg levels found may be contrasted with established threshold effect levels.

The NOAA (National Oceanic and Atmospheric Administration) SQR (Screening Quick Reference) provides tables that present preliminary screening concentrations for Hg and numerous other contaminants; the values in these tables are used to identify coastal-resource areas that may potentially be affected by contaminants (Buchman 2008). Long et al. (1995), in a classical study, proposed two guideline values, the effects range-low (ERL) and the effects range-median (ERM) for Hg, the values of which were 0.15 μg g^{-1} and 0.71 μg g^{-1}, respectively. The maximum Hg levels in coastal sediments at various sites in Mexico exceeded ERL and ERM limits. The ERL was exceeded at the Port of Ensenada, in mangrove lagoons, beach sands and coastal sediments of Santa Rosalia, and in oyster culture areas of Sonora. The ERM was exceeded at Guaymas Bay and at Coatzacoalcos, among others. However, caution should be exercised in using such comparisons. O'Connor et al. (1998) concluded that guidelines that are based on bulk chemistry can provide useful triggers for further analysis, but should not be used alone as indicators of toxicity. In this context, Adams et al. (1992) indicated that the toxicity of different sediments may differ by a factor of 10 or more for the same metal concentration. In addition, the toxicity of metals in sediments is highly influenced by chemical speciation of the metal of interest, the sediment type, and organic matter content. Below, we describe the general characteristics of several studies in which Hg contamination was evaluated in coastal sediments at different locations in Mexico.

Only fairly recently have studies been performed on mercury residues in coastal sediments of Mexico. Kot et al. (1999) was the first to evaluate Hg levels along the Pacific coast; his studies were performed in La Paz lagoon, Baja California. This lagoonal system is located in the south-eastern portion of the Baja California peninsula (110.30 and 110.42°W; 24.10 and 24.19°N). The drainage area of the lagoon has a unique geological setting, in which a zone of tectonic crustal deformation is cut by active faults (Henry 1989). Eighty surface sediment samples were collected in the lagoon by Kot et al. (1999); stream sediments and soils associated with the margins of the lagoon were also collected. These authors indicated that, in general, the Hg levels found (Table 2) were relatively low, with variations depending on the region; the highest concentrations were found at sites associated with discharges from the wastewater treatment facility at La Paz city. The authors reported that the Hg concentrations found in the La Paz area were lower than typical background values for uncontaminated marine deposits; the results were also lower than the average abundance of this metal in sedimentary rocks (i.e., shales, 0.4 μg g^{-1}; Turekian and Wedepohl 1961) and soils (0.01–0.50 μg g^{-1}; Fergusson 1990).

In other studies, mercury concentrations were evaluated in surface sediments off the northwest coast of Baja California (116.8 and 117.3°W; 31.9 and 32.6°N) (Table 2), and results indicated a relatively homogenous spatial distribution of the metal. Hg enrichment occurred at four stations located in the northern and central

zones. In general, Hg levels were relatively low and posed no environmental concerns, because the levels found were lower than the North American marine sediment quality guidelines of the NOAA's National Status and Trends Program for low and medium toxic effects of Hg in marine sediment (Long et al. 1995; Gutiérrez-Galindo et al. 2007).

Another study was performed in Northwest Mexico, where Hg levels in sediment samples from Todos Santos Bay (located 100 km south of the US–Mexico border) on the Pacific coast of the Baja California peninsula (116.6 and 116.85°W; 31.7 and 31.9°N) were analyzed (Table 2). This bay is exposed to potential pollution from domestic and industrial effluents, shipping and fishing traffic, and agricultural run-off (Gutiérrez-Galindo et al. 2008). With the exception of the port zone and marina, the bay was considered by these authors to be a region that has relatively low levels of trace metals. The average concentration of Hg found (0.023 μg g^{-1}) in Todos Santos Bay is similar to those in La Paz lagoon, Baja California Sur (0.020 μg g^{-1}).

Romero-Vargas (1995) studied sediments from the port of Ensenada (inside Todos Santos Bay) and discovered that they had relatively low metal concentrations, except for the zone encompassed by the port zone and marina (covering an area of 1.15 km^2), where metals tend to increase in fine-grain sediments from the effects of low wave energy. In addition to discharges from urban runoff and the contributions released from marine vessels, dry docks liberate antifouling paints and mine tailings from sand blasting operations (Carreón-Martínez et al. 2002). Each time that the port zone of Ensenada is dredged, from 150,000 to 300,000 m^3 of anoxic sediments are extracted and transported to other sites within and outside the Bay. Considering the concentration of Hg in such sediments (Table 2), one can estimate that approximately 45–96 kg of Hg is present in the sediment dredged during each operation. Carreón-Martínez et al. (2001, 2002) examined a core from the port zone to evaluate the importance of pyrite and other geochemical fractions as Hg reservoirs. They found that Hg in sediments was associated mainly with the Hg-HCl fraction (<0.03–0.17 μg g^{-1}) that includes the Hg linked to carbonates, Fe and Mn oxyhydroxides, iron monosulfides, and to the Hg-pyrite (<0.0.03–0.20 μg g^{-1}) linked to pyrite and other iron monosulfides.

Leal-Acosta et al. (2010) examined the composition of sediments of the intertidal geothermal hot spring zone and the adjacent area of Playa Santispac in Bahia Concepción (pristine area), Baja California (111.88 and 111.89°W; 26.75 and 26.77°N) (Table 2). High concentrations of Hg (and As) were found in the sediments of the geothermal sources. Hg levels decreased rapidly in the adjacent small mangrove lagoon sediments and finally reached background concentrations of 0.006–0.060 μg g^{-1}. The authors concluded that the geothermal hot springs located in Playa Santispac are important sources for imparting Hg (and As) to the sediments of the mangrove lagoon, and to the adjacent part of Concepción Bay. However, due to decreased temperature and oxygenated sea water, Hg is rapidly incorporated in the solid phase near the hot springs, and probably also into the freshly forming Mn-oxides and silicates.

Kot et al. (2009) traced the halo of Hg's dissipation in copper mines under arid conditions, at El Boleo mining district near Santa Rosalía in east-central Baja California, Mexico (27°24′–27°40′N and 112°22′–112°24′W). In this region, copper mining and smelting operations were abundant during the period 1885–1985. They found that marine sediments near Santa Rosalía are affected by material

discharged through creeks and represent an indicator of metal dissipation from the mines. The alluvium in downstream waters included waste products from the smelter. Kot et al. 2009 found evidence that Hg was dispersed from the abandoned mines via stream sediments. The halo of Hg contamination was of a local character. Except for the two sites found near the San Luciano mine and in the Providencia stream, Hg concentrations far from the San Luciano stream approached the regional average. Nevertheless, this background level (0.14 μg g^{-1}) was an order of magnitude greater than that of La Paz lagoon and their associated stream sediments (0.016–0.020 μg g^{-1}; Kot et al. 1999). Coastal sediments adjacent to the affected area were found to be Hg enriched by an order of magnitude, compared to the smaller values found in the carbonate-diluted sediments from the south of Santa Rosalía. The highest Hg concentrations were registered in the harbor, probably from slag material originating from the smelter. The authors concluded that, in such an area, Hg is dispersed in the environment by diverse mechanisms: (a) the migration of Hg, in and with weathered material washed down from the immediate area of the abandoned mines; (b) oxidation of Hg sulfides typically resulting in the formation of soluble species (organic and chloride complexes). Such Hg compounds are easily trapped and immobilized by co-precipitation with iron oxides and amorphous aluminum oxides. Considering the arid climate, transport of particulate forms of Hg appears to be more significant, since the solubility of Hg sulfides is extremely low.

A peculiar study was performed in 2003 at Kun Kaak Bay, Sonora (112°0.4′W and 28°52′N) by García-Hernández et al. (2005). They reported levels of Hg and other trace metals in sediments and organisms during a harmful algal bloom. This event was associated with a massive die-off of fish and mollusks. An analysis of phytoplankton showed the presence of *Chatonella marina*, *Gymnodinium catenatum*, and *Gymnodinium sanguineum*. The levels of Hg in sediments (Table 2) were higher than background levels for this area.

Monthly measurements of Hg and other trace metals were made by García-Rico et al. (2003, 2006) in intertidal surface sediments from four areas, in which oysters were cultured. The four areas were near Puerto Peñasco (site 1, 113°23.1′W and 31°11.2′N), Caborca (site 2, 113°27.6′W and 31°10.3′N), Hermosillo (site 3, 1,110°55.5′W and 28°49.5′N), and Guaymas (site 4, 110°58.0′W and 27°54.5′N), which lie along the Sonoran coast (Table 2). The mean Hg concentration registered at the four sites was 0.07 μg g^{-1}, with the highest level found at site 3 (0.35 μg g^{-1}). The lowest mean levels were detected in February and the highest in August. The authors concluded that Hg levels were within typical background concentrations for uncontaminated marine deposits. Considering the examined geochemical fractions in surficial sediments, the authors found that Hg was detected only in the exchangeable and residual fractions, with the highest levels in the residual fraction. The first fraction was attributed to past mining activities and to residues from the atmospheric route. The residual fraction is probably linked to the structure of crystalline minerals and to unavailable unreactive forms of the sediments.

Mercury concentrations in surface sediments from Guaymas Bay (Sonora) (110°48′ and 110°55′W; 27°50′ and 28°00′W) were investigated by Green-Ruiz et al. (2005). The authors found an average Hg level of 1.0 ± 0.5 μg g^{-1}, which is

higher than the values reported for the coastal zone of Baja California (Table 2). In this study, the highest concentrations were found in Guaymas city, near the shipyards, and areas where the canning industry and the fishing fleet are located. According to the authors, Guaymas Bay has higher levels than those reported in other coastal ecosystems that are considered to be unpolluted or moderately polluted, such as La Paz lagoon (Kot et al. 1999), Todos Santos Bay (Gutiérrez-Galindo et al. 2008), and the Northwest coast in Baja California (Gutiérrez-Galindo et al. 2007).

Ruiz-Fernández et al. (2009) determined Hg and other metals in four selected sediment cores collected in three lagoons: Ohuira (108.8°W; 25.6°N), Chiricahueto (107.5°W; 24.6°), and Urías (106.3°W; 23.1°N). These ecosystems are located in the coastal plain of the southeastern Gulf of California; they have been included among the Priority Zones of the National Commission for the Knowledge and Use of Biodiversity of Mexico (CONABIO 2004) because of their importance as threatened natural areas. Ohuira is a shallow and brackish coastal lagoon that supports local fishing, shrimp farming, and intensive agriculture in the surrounding areas. Chiricahueto lagoon is a wetland marsh that has a limited water exchange with the sea and a freshwater swamp area produced by wastewaters from Culiacán valley. Critical pollution by agrochemicals, municipal and industrial loads, and urban wastes have been reported for this ecosystem (Páez-Osuna et al. 2007). Urías lagoon is a shallow water body that has a free and permanent exchange with the sea. The section that lies close to the sea functions as a navigation channel for the Mazatlán harbor shipping terminal. This area is surrounded by human settlements; in the area far from the mouth of the water body there is a thermoelectric plant and two shrimp farms (400 ha in pool size). The levels of Hg found in the sediment cores of the three lagoons were of the same order of magnitude, although the highest concentrations were found in Chiricahueto (Table 2). Ages and sedimentation rates were calculated by using ^{210}Pb activities in the three cores. From such values Hg fluxes were estimated; although fluxes varied with the time, there was a clear tendency for increased Hg levels in recent years. In Ohuira, the increase was more evident. For example, in the years 1905–1945, the Hg accumulation fluctuated between 1 and 15 ng cm^{-2} year^{-1}, while in years 1985–2005 the Hg fluxes were between 15 and 31 ng cm^{-2} year^{-1}. The authors concluded that Chiricahueto and Urías showed consistent signs of Hg pollution, with enrichment factors from 10 to 80, respectively. They explained that the historical increase of Hg obtained from the sediment records was related to the release of agricultural wastes in Ohuira and Chiricahueto, and to atmospheric release of the exhausts generated by the thermoelectric plant of Mazatlán, located in Urías lagoon.

Jara Marini et al. (2008a) analyzed surface sediments, water samples, and biota in Urías lagoon to evaluate the concentrations of Hg. Measurements in surface sediments (0–2.5 cm) revealed moderate Hg levels that were relatively homogenous. These concentrations were comparable to those reported by Ruiz-Fernández et al. (2009) in a sediment core (Table 2). According to McDonald et al. (1996), the total metal concentrations determined by these authors were higher than the Threshold Effects Level (TEL), and Hg concentrations were slightly higher than the Probable Effects Level (PEL). In addition, Jara Marini et al. (2008a) determined the bioavailable fraction of Hg (operationally defined: reactive + pyrite; Huerta-Díaz and Morse

1990). They found levels between 0.11 and 0.15 μg g^{-1}, and these levels fell between the TEL and PEL criteria values for sediment quality, indicating a level that is occasionally expected to produce adverse biological effects.

Willerer et al. (2003) studied Hg levels in surface sediments of the Marabasco River, the estuary, and the lagoon (Navidad lagoon). The watershed of the Marabasco River has a tectonically active province, which is rich in mineral deposits, Hg-ore deposits, an abandoned Hg-ore mine (Mina Martínez), and the Peña-Colorado iron-ore mine in Sierra "El Mamey." The river originates in the Sierra Manantlán and supplies freshwater for irrigating a large agricultural area, and finally flows into Navidad lagoon. For Navidad lagoon (104.65° and 104.68°W; 19.18° and 19.20°N), the Hg content in surface sediments varied from 0.002 to 0.032 μg g^{-1} (Table 2), with a mean concentration of 0.015 ± 0.009 μg g^{-1}. These relatively low levels were regarded to be natural background levels in sedimentary material. The source of variation is attributed to the grain size of sediments and their organic matter content; finer particles were richer in organic matter and Hg content. The authors concluded that existing Hg deposits and the ancient Hg mines situated in the drainage basin of the Marabasco River were the sources of the excess Hg in the sediments of the Navidad lagoon.

Rosas et al. (1983) conducted a pioneering study in Mexico on the relative heavy metal pollution that exists in the following four coastal lagoons in the Gulf of Mexico: Tampamachoco (97.6°W; 20.8°N), Mandinga (96.1°W; 19.0°N), Del Carmen (93.9°W; 18.3°N), and Atasta (92.1°W; 18.6°N). The four lagoons are characterized by fishing activities, oil extraction (PEMEX) activities, and having rural residential communities in the watershed. Mandinga is an urbanized area, which is close to the port and the city of Veracruz. The authors established the levels of Hg and other metals that existed in water, oysters, and sediment samples from these lagoons. The highest Hg values in surface sediments were reported from Mandinga lagoon, and the lowest concentrations were reported from Atasta lagoon (Table 2). They concluded that the variations of Hg content in the sediments of the four lagoons may result from their different edaphic composition.

The Alvarado lagoon system located (95°45′ and 96°00′W; 18°40′ and 18°53′N) within the Papaloapan River in southern Veracruz is a shallow system that is connected to the Gulf of Mexico through a narrow channel. This lagoon is a large mangrove-dominated coastal wetland that is formed by the confluence of four rivers, the Papaloapan, Blanco, Acula, and Limón, which descend from the central Mexican cordillera. The main economic activities of the watershed associated with this lagoon system are agriculture, including sugarcane cultivation and cattle ranching, and fishing. The nearest urban areas are the cities of Veracruz (50 km distant), Oaxaca (250 km distant), and Puebla (300 km distant). The potential sources of Hg in the area comprise wastes from fisheries and aquaculture, agriculture, and urban wastewater (population ~50,000 inhabitants). Guentzel et al. (2007) collected water, fish, sediment, and hair samples during the wet and dry seasons of 2005 and analyzed the samples for Hg content. The authors described the surface sediments of the Alvarado lagoon as being comprised of a mixture of sand, mud, and shells. The levels of Hg found were not significantly different between the wet and dry seasons of 2005 (Table 2). The authors concluded that the values found in the samples they collected were within the US EPA background sediment criteria level of <0.30 μg g^{-1} (US EPA 1997) and were below the threshold effects level for marine sediments (Buchman 1999).

Within the coastal zones of Mexico, Coatzacoalcos estuary (94°25′and 94°31′W; 17°46′and 18°10′N) is the location where more research on mercury, and perhaps also organic contaminants, has been carried out. The major petrochemical center of the Gulf of Mexico region is located in this estuary. From data included in Table 2, it is evident that Hg values found in the estuary were variable. Hg levels were more elevated during the decade of the 1970s, that is, Ochoa et al. (1973) and Báez et al. (1975) found mean values for Hg of 1.10 μg g^{-1} and 8.31 ± 14.64 μg g^{-1}, respectively. During the decade of the 1980s, Botello and Páez-Osuna (1986) reported a mean value of 0.13 ± 0.07 μg g^{-1}. Finally, during 2005 and 2006 Ruelas-Inzunza et al. (2009) found Hg levels in the range of 0.070–1.061 μg g^{-1}. From such studies, it is clear that the high levels of Hg in Coatzacoalcos appear to be limited to critical zones of the estuary that are more heavily polluted. Residue level variability also depended on several factors related to industrial discharges: magnitude, time, concentration, chemical forms, tendency of Hg to accumulate, and characteristics of sediments (grain size, organic matter, and mineralogy).

Recently, Ruelas-Inzunza et al. (2009) studied Hg concentrations in surface sediments of the Coatzacoalcos River. Results showed that Hg levels ranged from 0.07 μg g^{-1} at upstream sites that were far from industrialized areas to 1.06 μg g^{-1} in the river area located near the highly industrialized port of Coatzacoalcos (Table 2). Báez et al. (1975) earlier found Hg levels of 0.11–57.94 μg g^{-1} in surficial sediments from the same area. It can be seen that the highest Hg levels were detected at sites located near a refinery drainage (San Francisco stream) point, and along the most industrialized zone of Coatzacoalcos. When the Hg levels found at these sites are compared with levels found along other Mexican coastal areas, it is observed that the Coatzacoalcos estuary had higher Hg values than those at La Paz lagoon (Table 2), which was an unpolluted to moderately polluted site (Kot et al. 1999). However, the samples taken at the Coatzacoalcos River had Hg levels lower than those (14.2–31.4 μg g^{-1}) taken at Kastela Bay, Croatia, a site considered to be highly polluted (Kwokal et al. 2002). Considering the average Hg residue at Coatzacoalcos estuary, this ecosystem is (until 2008) regarded to be moderately contaminated at most sites tested.

4.2 Coastal Waters

The information on concentrations of Hg in waters from coastal environments in Mexico is limited to a few studies that are briefly summarized in this section. Some characteristics of Mexico's coastal water bodies have been described in the previous section. Historically, the locations at which more research has been conducted are Coatzacoalcos and the coastal lagoons of the Gulf of Mexico. In those coastal regions, such past research was motivated mainly by the existence of oil extraction and processing activities.

For the Urías lagoon, Jara Marini et al. (2008b) found that the concentrations of Hg in the dissolved fraction of waters ranged from 0.64 to 1.05 μg L^{-1}, while residue levels in the suspended fraction ranged from 2.22 to 2.64 μg L^{-1}. According to the authors, these concentrations exceeded the Hg levels commonly reported to exist in open sea and coastal waters as reported (Table 3) by Sadiq (1992), who gave a concentration of

Table 3 Mercury concentrations (μg L^{-1}) in waters sampled along Mexican coasts

Location	Hg concentrations	Reference
Urías lagoon, Sinaloa (dissolved)	0.64–1.05	Jara Marini et al. (2008b)
Urías lagoon, Sinaloa (suspended)	2.22–2.64	Jara Marini et al. (2008b)
Tampamachoco, Ver.	<0.2	Rosas et al. (1983)
Mandinga, Ver.	<0.2	Rosas et al. (1983)
Alvarado, Ver.	0.0009–0.0126[a]	Guentzel et al. (2007)
Coatzacoalcos estuary, Ver.	30.0 ± 10.0[a]	Ochoa et al. (1973)
	0.1–75.0[a]	Báez et al. (1975)
	12.0 ± 3.0[a]	Pérez-Zapata et al. (1984)
Mecoacán lagoon, Tabasco	0.1–0.8[a]	Pérez-Zapata et al. (1984)
Del Carmen lagoon, Tabasco	<0.2	Rosas et al. (1983)
	0.2–0.6[a]	Pérez-Zapata et al. (1984)
Machona lagoon, Tabasco	0.1–1.1[a]	Pérez-Zapata et al. (1984)
Atasta lagoon, Campeche	<0.2	Rosas et al. (1983)
Open sea and coastal waters	0.0002–1.42	Sadiq (1992)
Uncontaminated seawater	0.02	Sadiq (1992)

[a]Unfiltered water samples

0.02 μg L^{-1} for uncontaminated seawater. In general, and in comparison to open seawaters, the Hg levels that exist in estuarine and coastal waters from various regions worldwide are high because these regions are proximate to input sources, both natural and anthropogenic. The values reported by Jara Marini et al. (2008b) in waters of the Urías lagoon are appreciably higher than the concentrations normally expected in uncontaminated seawaters. This may be related to the activities that take place in the area surrounding this lagoon (viz., shipping, fish industry, and food industry), domestic effluents, and particularly to the presence of a thermoelectric plant.

Rosas et al. (1983) reported that Hg concentrations in water were below the limit of detection (<0.2 μg L^{-1}) in the coastal lagoons of the Gulf of Mexico: Tampamachoco, Mandinga, Del Carmen, and Atasta. Guentzel et al. (2007) reported levels of Hg from 0.9 to 12.6 ng L^{-1} in unfiltered water samples taken during 2005 and 2006, in the Alvarado lagoon system. The higher concentrations they reported were associated with river waters that were enriched with organic matter, or with elevated total suspended solids in the brackish mixing zones of the lagoon. Total Hg in the lagoonal waters was significantly ($p < 0.001$) correlated with suspended matter in the water column. The authors concluded that these levels exceeded the US EPA ambient surface water quality criteria (0.77–1.4 ng L^{-1}) (US EPA 2006).

Results on the levels of Hg in water samples from Coatzacoalcos estuary were compiled by Villanueva and Botello (1998); measurements were made by Ochoa et al. (1973), Báez et al. (1975), and Pérez-Zapata et al. (1984), and they reported rather elevated levels of Hg (Table 3). Hg concentrations were higher than those reported in the Alvarado lagoon and in other coastal lagoons of the Gulf of Mexico, such as Tampamachoco, Mandinga, Del Carmen, and Atasta. Rosas et al. (1983) reported levels of <0.2 μg L^{-1}. Pérez-Zapata (1981) also reported lower levels in Machona lagoon (0.42 ± 0.31 μg L^{-1}), Mecoacan lagoon (0.34 ± 0.21 μg L^{-1}), and Del Carmen lagoon (0.36 ± 0.09 μg L^{-1}). When these Hg levels were compared with those in estuarine and coastal waters from other regions (0.0002–1.42 μg L^{-1}; Sadiq 1992),

Coatzacoalcos estuary had extremely elevated Hg levels during the 1970s. A possible explanation for such elevated Hg values may be that water samples in early studies were not filtered. The waters of this system are characterized by having a high suspended particulate load that corresponds with the sediment load in the river, the tidal regime, and the discharge of effluents from a nearby petrochemical complex.

Coatzacoalcos estuary hosts the largest petrochemical facilities in Mexico. It is worth noting that previous analyses (between 1973 and 1984) showed rather high residues (from 0.1 to 30.0 μg L^{-1}) of Hg, when compared with the lower concentrations that were reported from the 1990s (from 0.0009 to 2.64 μg L^{-1}). This difference may have resulted from less sensitive analytical techniques and a greater chance of having had sample contamination in the early studies (Sadiq 1992).

5 Mercury in Aquatic Biota

Hg residues in aquatic biota are of great concern because of their potential implications to human health. In addition, such residues may indicate the general condition of ecosystems. Biomonitoring involves monitoring individual organisms, parts thereof, or even a community of organisms for the presence of pollutants. The purpose of such monitoring is to provide data on the quantitative aspects of environmental quality (Markert et al. 2003). Apart from indicating the concentration of trace metals or other contaminants present, or the effects on the environment and organisms therein, the gathered data may also provide evidence of environmental stresses (e.g., desiccation, acidification, and eutrophication).

Anthropogenic activities such as mining, and municipal and industrial discharges are usually the main sources of metals in the environment; metals can accumulate in aquatic ecosystems to toxic levels and may induce adverse effects that produce ecological concern (Wang et al. 2002). Diverse authors have used a wide range of organisms in biomonitoring studies. Oysters and mussels have been preferred over other species because of their biological characteristics. Despite the growing environmental concern for the presence of Hg in the environment, few monitoring studies on it have been performed in Mexico, a country that hosts a significant array of anthropogenic activities that may produce metal contaminants.

5.1 Invertebrates

Table 4 shows that *Vesicomya gigas* from Guaymas basin (hydrothermal field at 2,000 m depth) has a higher content of Hg than other bivalve species collected along the NW coastal zone of Mexico, or in other areas worldwide. These Hg residues in the Guaymas basin probably resulted from natural input sources of Hg that were concentrated in this organism from bioaccumulation. Comparing Hg content in *Crassostrea corteziensis* (0.02 ± 0.003 μg g^{-1}), collected from the coast of Sonora, and *Crassostrea gigas* (0.16 ± 0.06 μg g^{-1}) from the Gulf of California with levels in those similar bivalve species (from 0.04 to 0.11), we found that values were similar.

Table 4 Concentration of mercury (μg g^{-1} on a dry wt basis) in molluscs from different areas

Species	Area	Hg	Reference
National			
Vesicomya gigas	Guaymas basin, Gulf of California	2.41 ± 2.21	Ruelas-Inzunza et al. (2003b)
Crassostrea corteziensis	Sonoran coast	0.02 ± 0.003	García-Rico et al. (2010)
Crassostrea gigas	SE Gulf of California	0.16 ± 0.06	Osuna-Martínez et al. (2010)
International			
Crassostrea gigas	Deep Bay, Hong Kong	0.084 ± 0.19	Phillips et al. (1982)
Crassostrea sp.	Gulf of Paria, Venezuela	0.04 ± 0.02	Roja de Astudillo et al. (2002)
Perna viridis	Gulf of Paria, Venezuela	0.06 ± 0.05	Roja de Astudillo et al. (2002)
Crassostrea rhizophorae	Northeast Brazil	0.08 ± 0.05	Vaisman et al. (2005)
Mytilus galloprovincialis	NW Mediterranean	0.23 ± 0.15	Zorita et al. (2007)
Dreissena polymorpha	Ebro River, NE Spain	0.11 ± 0.14	Carrasco et al. (2008)

Table 5 Concentrations of mercury (μg g^{-1} on a dry wt basis) in shrimp sampled from different areas

Species	Area	Tissue	Hg	Reference
National				
Farfantepenaeus brevirrostris	AEP lagoon, Sinaloa	Hepatopancreas	0.35 ± 0.07	Ruelas-Inzunza et al. (2004)
		Muscle	0.21 ± 0.07	Ruelas-Inzunza et al. (2004)
Farfantepenaeus californiensis	AEP lagoon, Sinaloa	Hepatopancreas	0.62 ± 0.11	Ruelas-Inzunza et al. (2004)
		Muscle	0.13 ± 0.08	Ruelas-Inzunza et al. (2004)
Litopenaeus stylirostris	AEP lagoon, Sinaloa	Hepatopancreas	0.57 ± 0.01	Ruelas-Inzunza et al. (2004)
		Muscle	0.30 ± 0.036	Ruelas-Inzunza et al. (2004)
Litopenaeus vannamei	AEP lagoon, Sinaloa	Hepatopancreas	0.72 ± 0.07	Ruelas-Inzunza et al. (2004)
		Muscle	0.20 ± 0.01	Ruelas-Inzunza et al. (2004)
Xiphopenaeus kroyery	AEP lagoon, Sinaloa	Hepatopancreas	0.27 ± 0.04	Ruelas-Inzunza et al. (2004)
		Muscle	0.13 ± 0.04	Ruelas-Inzunza et al. (2004)
International				
Crangon crangon	Limfjord, Denmark	Muscle	0.09 ± 0.03	Riisgard and Famme (1986)
Penaeus sp.	Malaysia	Muscle	0.36 ± 0.13	Rahman et al. (1997)
Penaeus semisulcatus	Gulf of Arabia	Whole tissue	0.013 ± 0.007	Al-Saleh and Al-Doush (2002)
Penaeus semisulcatus	Northern Persian Gulf	Muscle	0.19 ± 0.05	Elahi et al. (2007)
Litopenaeus stylirostris	New Caledonia	Muscle	0.20 ± 0.06	Chouvelon et al. (2009)

The exception was the 0.23 ± 0.15 μg g^{-1} value reported by Zorita et al. (2007) in *Mytilus galloprovincialis* collected from the NW Mediterranean, which has been previously reported to be an area that has significant natural sources of mercury, as well as anthropogenic discharges.

The Hg content that exists in marine crustaceans collected from Mexico and from other areas is presented in Table 5. Only Ruelas-Inzunza et al. (2004) have performed studies on shrimp; they sampled the Altata-Ensenada del Pabellón (AEP)

coastal lagoon, which is associated with drainage of an agriculturalized basin. In their study, the hepatopancreas of shrimp showed higher Hg values than did muscle (0.27–0.72 μg g^{-1} vs. 0.13–0.30 μg g^{-1}, respectively). The higher residue values present in the hepatopancreas probably relate to the biological functions performed by this organ (viz., metabolize xenobiotics, digest food, store lipids and carbohydrates, and synthesize enzymes and proteins) (Manisseri and Menon 1995). Values reported in muscle of shrimp from AEP lagoon were higher than the mercury content found by Al-Saleh and Al-Doush (2002) in *Penaeus semisulcatus* from the Gulf of Arabia, but lower than the values reported by Rahman et al. (1997) in *Penaeus* sp. from Malaysia. Chouvelon et al. (2009) reported 0.20 μg g^{-1} in muscle of *Litopenaeus stylirostris* from New Caledonia. Ruelas-Inzunza et al. (2004) reported a level of 0.30 μg g^{-1} in the same species from the AEP lagoon (NW Mexico), indicating a similar contamination pattern as existed for mercury.

Clearly, more studies should be conducted along coastal Mexico, focusing on analyzing the Hg content in different marine organisms (viz., oysters, shrimp, and crabs), which are consumed at high rates, both locally and nationally.

5.2 Vertebrates

Vertebrates have been monitored in Mexico for Hg residue content. The monitored taxa included fish, reptiles, birds, and mammals. Data on the Hg concentrations in selected tissues of elasmobranchs is presented in Table 6. Reported levels of Hg were sourced from nine studies published between 1998 and 2012 and included 24 species. Data on elasmobranch species taken from the Pacific Ocean (seven contributions) were more abundant than those taken from the Gulf of Mexico area (two studies).

Tissues and organs of main interest were gills, brain, liver, pancreas, muscle, kidney, and fins. In most studies, Hg was analyzed in muscle tissue. Average Hg concentrations among species and tissues tested were highly variable. The highest Hg level (27.2 μg g^{-1}) reported was in the muscle of the smooth hammerhead shark *Sphyrna zygaena*, which was taken from the Gulf of California (García-Hernández et al. 2007). The lowest concentration was found in fins of the same species taken from offshore of Baja California Sur (Table 6). In a study with *S. zygaena* collected from the Ionian Sea, high total Hg (21.1 μg g^{-1} on a wet wt basis, equivalent to 70.3 μg g^{-1} on a dry wt basis) levels were found in muscle tissue (Storelli et al. 2003). The average Hg concentration detected in muscle of all species included in Table 6 was 2.59 ± 4.59 μg g^{-1}; in the species collected from the Gulf of Mexico the average was 1.98 ± 1.91 μg g^{-1}, and in species from the Pacific Ocean the average was 2.62 ± 4.72 μg g^{-1}. Results were highly variable and may have resulted from the heterogeneity of compared species, their sizes, and particular habit. For example, muscle tissue levels of Hg varied by two orders of magnitude (from 0.20 to 27.2 μg g^{-1}) in *S. zygaena* (three reports), and one order of magnitude (from 0.89 to 4.6 μg g^{-1}) in *Prionace glauca* (three reports) and *Carcharhinus falciformis* (from 0.99 to 3.4 μg g^{-1}; two reports).

The Hg levels in muscle tissue of teleost fish from the Pacific Ocean and the Gulf of Mexico are presented in Table 7. In Mexican waters, teleost fish have been more

Table 6 Mercury levels (μg g^{-1} dry wt) in selected tissues and organs of elasmobranchs from Mexican waters

Species	Common name	Tissue	Site	Hg	Reference
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Gills	Gulf of Mexico (Veracruz state)	0.66	Núñez-Nogueira et al. (1998)
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Brain	Gulf of Mexico (Veracruz state)	0.45	Núñez-Nogueira et al. (1998)
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Liver	Gulf of Mexico (Veracruz state)	0.16	Núñez-Nogueira et al. (1998)
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Pancreas	Gulf of Mexico (Veracruz state)	0.51	Núñez-Nogueira et al. (1998)
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Muscle	Gulf of Mexico (Veracruz state)	0.63	Núñez-Nogueira et al. (1998)
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Kidney	Gulf of Mexico (Veracruz state)	0.42	Núñez-Nogueira et al. (1998)
Carcharhinus leucas	Bull shark	Muscle	Altata-Ensenada del Pabellón (SE Gulf of California)	0.20	Ruelas-Inzunza and Páez-Osuna (2005)
		Liver	Altata-Ensenada del Pabellón (SE Gulf of California)	0.60	Ruelas-Inzunza and Páez-Osuna (2005)
Sphyrna lewini	Scalloped hammerhead	Muscle	Altata-Ensenada del Pabellón (SE Gulf of California)	4.84	Ruelas-Inzunza and Páez-Osuna (2005)
		Liver	Altata-Ensenada del Pabellón (SE Gulf of California)	0.12	Ruelas-Inzunza and Páez-Osuna (2005)
Carcharhinus limbatus	Blacktip shark	Muscle	Gulf of Mexico	3.33	Núñez-Nogueira (2005)
		Liver	Gulf of Mexico	7.78	Núñez-Nogueira (2005)
		Gills	Gulf of Mexico	7.03	Núñez-Nogueira (2005)
		Brain	Gulf of Mexico	1.33	Núñez-Nogueira (2005)
Sphyrna zygaena	Smooth hammerhead shark	Muscle	Off Baja California Sur, Mexico	0.73	Escobar-Sánchez et al. (2010)
		Fin	Off Baja California Sur, Mexico	0.007	Escobar-Sánchez et al. (2010)
Prionace glauca	Blue shark	Muscle	Off Baja California Sur, Mexico	4.6[a]	Escobar-Sánchez et al. (2011)
Sphyrna zygaena	Smooth hammerhead shark	Muscle	Gulf of California	27.2[a]	García-Hernández et al. (2007)
Alopias pelagicus	Pelagic thresher	Muscle	Gulf of California	4.3[a]	García-Hernández et al. (2007)
Rhizoprionodon longurio	Pacific sharpnose shark	Muscle	Gulf of California	4.3[a]	García-Hernández et al. (2007)
Carcharhinus obscurus	Dusky shark	Muscle	Gulf of California	3.82[a]	García-Hernández et al. (2007)
Sphyrna lewini	Scalloped hammerhead	Muscle	Gulf of California	3.56[a]	García-Hernández et al. (2007)
Nasolamia velox	Whitenose shark	Muscle	Gulf of California	3.36[a]	García-Hernández et al. (2007)
Carcharhinus limbatus	Blacktip shark	Muscle	Gulf of California	1.68[a]	García-Hernández et al. (2007)

Carcharhinus falciformis	Silky shark	Muscle	Gulf of California	0.99[a]	García-Hernández et al. (2007)
Prionace glauca	Blue shark	Muscle	Gulf of California	0.89[a]	García-Hernández et al. (2007)
Mustelus henlei	Brown smoothhound shark	Muscle	Gulf of California	0.59[a]	García-Hernández et al. (2007)
Triakis semifasciata	Leopard shark	Muscle	Gulf of California	0.26[a]	García-Hernández et al. (2007)
Prionace glauca	Blue shark	Muscle	Baja California Peninsula	1.96	Maz-Courrau et al. (2012)
Carcharhinus falciformis	Silky shark	Muscle	Baja California Peninsula	3.40	Maz-Courrau et al. (2012)
Isurus oxyrinchus	Mako shark	Muscle	Baja California Peninsula	1.05	Maz-Courrau et al. (2012)
Sphyrna zygaena	Smooth hammerhead shark	Muscle	Baja California Peninsula	0.98	Maz-Courrau et al. (2012)
Sphyrna lewini	Scalloped hammerhead	Muscle	Sinaloa state	2.72[a]	Hurtado-Banda et al. (2012)
Sphyrna lewini	Scalloped hammerhead	Liver	Sinaloa state	0.83[a]	Hurtado-Banda et al. (2012)
Rhizoprionodon longurio	Pacific sharpnose shark	Muscle	Sonora state	3.05[a]	Hurtado-Banda et al. (2012)
Rhizoprionodon longurio	Pacific sharpnose shark	Liver	Sonora state	0.21[a]	Hurtado-Banda et al. (2012)
Mustelus albipinnis	Smoothhound shark	Muscle	Sonora state	1.12[a]	Hurtado-Banda et al. (2012)
Mustelus albipinnis	Smoothhound shark	Liver	Sonora state	0.42[a]	Hurtado-Banda et al. (2012)
Dasyatis longus	Longtail stingray	Muscle	Gulf of California	2.34[a]	García-Hernández et al. (2007)
Dasyatis brevis	Whiptail stingray	Muscle	Gulf of California	1.48[a]	García-Hernández et al. (2007)
Rhinoptera steindachneri	Pacific cownose ray	Muscle	Gulf of California	1.42[a]	García-Hernández et al. (2007)
Rhinoptera steindachneri	Pacific cownose ray	Muscle	Upper Gulf of California	0.31	Gutiérrez-Mejía et al. (2009)
Rhinoptera steindachneri	Pacific cownose ray	Liver	Upper Gulf of California	0.22	Gutiérrez-Mejía et al. (2009)
Rhinobatos productus	Shovelnose guitarfish	Muscle	Gulf of California	1.02[a]	García-Hernández et al. (2007)
Gymnura marmorata	California butterfly ray	Muscle	Gulf of California	0.46[a]	García-Hernández et al. (2007)
Rhinobatos glaucostigma	Speckled guitarfish	Muscle	Gulf of California	0.46[a]	García-Hernández et al. (2007)
Narcine entemedor	Giant electric ray	Muscle	Gulf of California	0.39[a]	García-Hernández et al. (2007)
Zapteryx exasperata	Banded guitarfish	Muscle	Gulf of California	0.36[a]	García-Hernández et al. (2007)
Myliobatis californica	Bat Eagle ray	Muscle	Gulf of California	0.17[a]	García-Hernández et al. (2007)

[a]Original results were given on a wet wt basis; conversions to dry wt were made based on a 70% water content

Table 7 Mercury levels (μg g^{-1} dry wt) in muscle tissue of teleost fish collected from Mexican waters

Species	Common name	Site	Hg	Reference
Istiophorus platypterus	Indo-Pacific sailfish	Gulf of California	1.32[a]	García-Hernández et al. (2007)
Makaira mazara	Indo-Pacific blue marlin	Gulf of California	1.18[a]	García-Hernández et al. (2007)
Acanthocybium solandri	Wahoo	Gulf of California	0.49[a]	García-Hernández et al. (2007)
Tetrapturus audax	Striped marlin	Gulf of California	0.46[a]	García-Hernández et al. (2007)
Seriola lalandi	Yellowtail amberjack	Gulf of California	0.23[a]	García-Hernández et al. (2007)
Coryphaena hippurus	Pompano dolphinfish	Gulf of California	0.16[a]	García-Hernández et al. (2007)
Thunnus albacares	Yellowfin tuna	Gulf of California	0.09[a]	García-Hernández et al. (2007)
Mycteroperca jordani	Gulf grouper	Gulf of California	1.18[a]	García-Hernández et al. (2007)
Mycteroperca rosacea	Leopard grouper	Gulf of California	1.12[a]	García-Hernández et al. (2007)
Epinephelus analogus	Spotted grouper	Gulf of California	0.89[a]	García-Hernández et al. (2007)
Paralabrax auroguttatus	Goldspotted sand bass	Gulf of California	0.56[a]	García-Hernández et al. (2007)
Mugil curema	White mullet	Veracruz, Veracruz	0.04	Reimer and Reimer (1975)
Sphyraena guachancho	Guachanche barracuda	Villa Cardel, Veracruz	0.11	Reimer and Reimer (1975)
Polynemus virginicus	Barbu	Villa Cardel, Veracruz	0.07	Reimer and Reimer (1975)
Centropomus sp.	Snook	Coatzacoalcos, Veracruz	0.27	Reimer and Reimer (1975)
Mugil cephalus	Gray mullet	Tampico, Tamaulipas	0.07	Reimer and Reimer (1975)
Mugil cephalus	Gray mullet	Guaymas, Sonora	0.03	Reimer and Reimer (1975)
Mugil cephalus	Gray mullet	Topolobampo, Sinlaoa	0.03	Reimer and Reimer (1975)
Mugil cephalus	Gray mullet	Mazatlán, Sinaloa	0.06	Reimer and Reimer (1975)
Anisotremus interruptus	Burrito grunt	Mazatlán, Sinaloa	0.12	Reimer and Reimer (1975)
Diapterus sp.	White mojarra	Ciudad del Carmen, Campeche	0.06	Reimer and Reimer (1975)
Thunnus albacares	Yellowfin tuna	Baja California Sur	0.51	Ordiano-Flores et al. (2011)
Not determined	Tuna (canned in oil)	–	4.06[a]	Velasco-González et al. (2001)
Not determined	Sardine (canned in oil)[b]	–	2.44[a]	Velasco-González et al. (2001)
Thunnus albacares	Yellowfin tuna (canned in oil)	Sold in NW Mexico	0.258	Ruelas-Inzunza et al. (2011b)
Thunnus albacares	Yellowfin tuna (canned in water)	Sold in NW Mexico	0.362	Ruelas-Inzunza et al. (2011b)
Istiophorus platypterus	Indo-Pacific sailfish	Southeast Gulf of California	4.88[a]	Soto-Jiménez et al. (2010)
Tetrapturus audax	Striped marlin	Southeast Gulf of California	5.67[a]	Soto-Jiménez et al. (2010)
Tilapia mossambica	Tilapia	Baja California	0.05	Gutiérrez-Galindo et al. (1988)
Ariopsis felis	Catfish	Southern Gulf of Mexico	0.083	Vázquez et al. (2008)

Oreochromis sp.	Tilapia	Coatzacoalcos estuary	0.054	Ruelas-Inzunza et al. (2009)
Gobiomorus polylepis	Finescale sleeper	Coatzacoalcos estuary	0.492	Ruelas-Inzunza et al. (2009)
Gerres cinereus	Yellowfin mojarra	Coatzacoalcos estuary	0.135	Ruelas-Inzunza et al. (2009)
Centropomus viridis	White snook	Coatzacoalcos estuary	0.612	Ruelas-Inzunza et al. (2009)
Lepisosteus osseus	Longnose gar	Coatzacoalcos estuary	0.141	Ruelas-Inzunza et al. (2009)
Elops affinis	Pacific ladyfish	Sinaloa coast	0.97	Ruelas-Inzunza et al. (2008)
Sphoeroides annulatus	Bullseye puffer	Sinaloa coast	0.77	Ruelas-Inzunza et al. (2008)
Lutjanus colorado	Colorado snapper	Sinaloa coast	0.53	Ruelas-Inzunza et al. (2008)
Diapterus peruvianus	Peruvian mojarra	Sinaloa coast	0.58	Ruelas-Inzunza et al. (2008)
Haemulopsis axillaris	Yellowstripe grunt	Sinaloa coast	1.18	Ruelas-Inzunza et al. (2008)
Pomadasys leuciscus	White grunt	Topolobampo	0.95	Ruelas-Inzunza et al. (2008)
Caranx caninus	Pacific crevalle jack	Topolobampo	3.32	Ruelas-Inzunza et al. (2008)
Oligoplites saurus	Leatherjacket	Topolobampo	1.74	Ruelas-Inzunza et al. (2008)
Centropomus armatus	Armed snook	Topolobampo	1.51	Ruelas-Inzunza et al. (2008)
Scomberomorus sierra	Pacific sierra	Topolobampo	0.64	Ruelas-Inzunza et al. (2008)
Roncador stearnsii	Spotfin croaker	Topolobampo	1.39	Ruelas-Inzunza et al. (2008)
Haemulopsis axillaris	Yellowstripe grunt	Topolobampo	1.01	Ruelas-Inzunza et al. (2008)
Nematistius pectoralis	Roosterfish	Topolobampo	1.34	Ruelas-Inzunza et al. (2008)
Paralichthys woolmani	Speckled flounder	Topolobampo	0.68	Ruelas-Inzunza et al. (2008)
Centropomus nigrescens	Black snook	Topolobampo	0.56	Ruelas-Inzunza et al. (2008)
Haemulon sexfasciatum	Graybar grunt	Santa María	1.49	Ruelas-Inzunza et al. (2008)
Trachinotus paitensis	Paloma pompano	Santa María	1.42	Ruelas-Inzunza et al. (2008)
Centropomus medius	Blackfin snook	Santa María	0.82	Ruelas-Inzunza et al. (2008)
Caulolatilus princeps	Ocean whitefish	Altata	0.57	Ruelas-Inzunza et al. (2008)
Pomadasys branickii	Sand grunt	Fishing ground	1.17	Ruelas-Inzunza et al. (2008)
Mugil curema	White mullet	Sinaloa coast	0.47	Ruelas-Inzunza et al. (2008)
Mugil cephalus	Striped mullet	Sinaloa coast	0.07	Ruelas-Inzunza et al. (2008)
Gerres cinereus	Yellow fin mojarra	Sinaloa coast	0.82	Ruelas-Inzunza et al. (2008)
Selar crumenophthalmus	Bigeye scad	Topolobampo	0.65	Ruelas-Inzunza et al. (2008)
Arius platypogon	Cominate sea catfish	Topolobampo	0.98	Ruelas-Inzunza et al. (2008)
Eucinostomus gracilis	Graceful mojarra	Fishing ground	0.68	Ruelas-Inzunza et al. (2008)

[a]Original results were given on a wet wt basis; conversions to dry wt were made based on a 70% water content
[b]Whole fish

studied than any other group. Eleven studies have been published (seven dealt with the Pacific Ocean and four dealt with other sites in Mexico), and these studies represent Hg levels for 47 species (species names were not provided in two studies). The first data on teleost fish Hg residues were published in 1975, and the newest data in 2011. As with elasmobranchs, the Hg levels in these fish varied by two orders of magnitude; the highest value (5.67 μg g^{-1} dry wt) was in the striped marlin (*Tetrapturus audax*) collected from the SE Gulf of California. The lowest Hg concentration (0.03 μg g^{-1} dry wt) was detected in the gray mullet (*Mugil cephalus*) taken from Guaymas, Sonora, and Topolobampo, Sinaloa.

Studies related to the occurrence of Hg in tissues of teleost fish are abundant, and geographic areas where levels of this metal in muscle exceed regulations for human consumers include Italy, Spain, Taiwan, Florida, and Oregon (Eisler 2010). It is notable that elevated concentrations of Hg do exist in top predator fish like marlins. Elevated Hg levels in muscle tissue were reported in the blue marlin (*Makaira nigricans*; 10.5 μg g^{-1} wet wt) collected from the northern Gulf of Mexico (Cai et al. 2007) and in the black marlin (*Makaira indica*) from NE Australia (Mackay et al. 1975).

Hg residue data on reptiles, birds, and mammals are presented in Table 8. Only four studies on reptiles in Mexico have been published, and all of these were on marine turtles. The levels found in these turtles ranged from 0.795 μg g^{-1} dry wt in liver of *Lepidochelys olivacea* to 0.0006 μg g^{-1} dry wt in blood of the same species. When Hg was measured in liver and kidney, these organs displayed the highest concentrations. It has been observed that in marine reptiles Hg seldom exceeds 0.5 μg g^{-1} dry wt (Eisler 2010); such is the case also with reptiles sampled from Mexico's ecosystems (with the exception of liver samples of *L. olivacea*).

Hg levels in birds have been studied more often than levels in reptiles and mammals. The only published study that deals with the Hg distribution in tissues of birds from Mexico compared levels between migratory and resident avifauna. For resident birds, the sequence of Hg concentrations detected in different tissues was as follows: liver > feathers > heart > muscle > viscera. For migratory birds, the descending order of Hg levels was feathers > liver > muscle > heart > viscera. The highest values for Hg in the liver (5.08 μg g^{-1} dry wt) were recorded in the olivaceous cormorant (*Phalacrocorax olivaceus*); the highest Hg concentration in feathers (3.57 μg g^{-1} dry wt) was detected in the American avocet (*Recurvirostra americana*). It has been established that Hg levels of 5.0 μg g^{-1} dry wt in feathers may cause adverse reproductive effects (Eisler 1987). Liver levels above 3.0 μg g^{-1} dry wt may cause sublethal effects to these birds (Hui et al. 2001).

In Mexico, marine mammals have been scarcely studied for their Hg content, although species that were stranded in the southern portion of the Gulf of California were examined for Hg residues (Ruelas-Inzunza et al. 2003a). The Hg concentrations detected in these species were highly variable, ranging from 70.35 μg g^{-1} dry wt in liver of the spinner dolphin (*Stenella longirostris*) to 0.145 μg g^{-1} dry wt in muscle of the gray whale (*Eschrichtius robustus*). It appeared that Hg levels did not play a key role in the stranding of these organisms. In a study with *S. longirostris* from the Lesser Antilles (Gaskin et al. 1974), Hg concentrations in liver were of the same magnitude as reported in the study of Ruelas-Inzunza et al. (2003a). To our

Table 8 Mercury levels (μg g^{-1} dry wt) in selected tissues of reptiles, birds, and marine mammals from Mexico

Species	Common name	Tissue	Site	Hg	Reference
Reptiles					
Lepidochelys olivacea	Olive ridley turtle	Yolk	Oaxaca	0.028	Páez-Osuna et al. (2011)
		Albumen	Oaxaca	0.0010	Páez-Osuna et al. (2011)
		Eggshell	Oaxaca	0.0087	Páez-Osuna et al. (2011)
		Blood	Oaxaca	0.0006	Páez-Osuna et al. (2011)
Caretta caretta	Loggerhead turtle	Blood	Baja California Sur	<0.01	Ley-Quiñónez et al. (2011)
Chelonya midas	Green turtle	Fat	Baja California Sur	0.011	Kampalath et al. (2006)
		Liver	Baja California Sur	0.168	Kampalath et al. (2006)
		Muscle	Baja California Sur	0.059	Kampalath et al. (2006)
		Kidney	Baja California Sur	0.310	Kampalath et al. (2006)
Chelonia midas agassizii	Black sea turtle	Scutes	Gulf of California	0.17[a]	Presti et al. (1999)
Caretta caretta	Loggerhead turtle	Fat	Baja California Sur	0.028	Kampalath et al. (2006)
		Liver	Baja California Sur	0.183	Kampalath et al. (2006)
		Muscle	Baja California Sur	0.041	Kampalath et al. (2006)
		Kidney	Baja California Sur	0.135	Kampalath et al. (2006)
Lepidochelys olivacea	Olive ridley turtle	Fat	Baja California Sur	0.156	Kampalath et al. (2006)
		Liver	Baja California Sur	0.795	Kampalath et al. (2006)
		Muscle	Baja California Sur	0.144	Kampalath et al. (2006)
		Kidney	Baja California Sur	0.372	Kampalath et al. (2006)
Birds					
Pelecanus occidentalis	Brown pelican	Muscle	Altata-Ensenada del Pabellón Lagoon	2.11	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	1.92	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	3.70	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	2.05	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.85	Ruelas-Inzunza et al. (2007)

(continued)

Table 8 (continued)

Species	Common name	Tissue	Site	Hg	Reference
Phalacrocorax olivaceus	Olivaceous cormorant	Muscle	Altata-Ensenada del Pabellón Lagoon	1.13	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	1.62	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	5.08	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	3.19	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	1.02	Ruelas-Inzunza et al. (2007)
Casmerodius albus	Great egret	Muscle	Altata-Ensenada del Pabellón Lagoon	1.58	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	1.67	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	3.18	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	0.73	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.66	Ruelas-Inzunza et al. (2007)
Bubulcus ibis	Cattle egret	Muscle	Altata-Ensenada del Pabellón Lagoon	0.36	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.32	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.87	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	0.07	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.58	Ruelas-Inzunza et al. (2007)
Plegadis chihi	White-faced ibis	Muscle	Altata-Ensenada del Pabellón Lagoon	0.30	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.42	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.42	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	2.23	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.09	Ruelas-Inzunza et al. (2007)
Recurvirostra americana	American avocet	Muscle	Altata-Ensenada del Pabellón Lagoon	0.66	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.40	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.87	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	3.57	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.25	Ruelas-Inzunza et al. (2007)

Dendrocygna autumnalis	Black-bellied duck	Muscle	Altata-Ensenada del Pabellón Lagoon	0.023	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.005	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.20	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	0.38	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.10	Ruelas-Inzunza et al. (2007)
Anas cyanoptera	Cinnamon teal	Muscle	Altata-Ensenada del Pabellón Lagoon	0.264	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.15	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.15	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	0.49	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.07	Ruelas-Inzunza et al. (2007)
Fulica americana	American coot	Muscle	Altata-Ensenada del Pabellón Lagoon	0.163	Ruelas-Inzunza et al. (2007)
		Heart	Altata-Ensenada del Pabellón Lagoon	0.309	Ruelas-Inzunza et al. (2007)
		Liver	Altata-Ensenada del Pabellón Lagoon	0.77	Ruelas-Inzunza et al. (2007)
		Feathers	Altata-Ensenada del Pabellón Lagoon	1.18	Ruelas-Inzunza et al. (2007)
		Viscera	Altata-Ensenada del Pabellón Lagoon	0.23	Ruelas-Inzunza et al. (2007)
Marine mammals					
Eschrichtius robustus	Gray whale	Muscle	Gulf of California, Mexico	0.145	Ruelas-Inzunza et al. (2003a)
		Kidney	Gulf of California, Mexico	0.277	Ruelas-Inzunza et al. (2003a)
		Liver	Gulf of California, Mexico	0.185	Ruelas-Inzunza et al. (2003a)
Stenella longirostris	Spinner Dolphin	Muscle	Gulf of California, Mexico	1.66	Ruelas-Inzunza et al. (2000)
		Kidney	Gulf of California, Mexico	6.975	Ruelas-Inzunza et al. (2000)
		Liver	Gulf of California, Mexico	70.35	Ruelas-Inzunza et al. (2000)

[a]Original results were given on a wet wt basis; conversions to dry wt were made based on a 70% water content

Table 9 Mercury levels (μg g^{-1} dry wt) in macrophytes and vestimentiferan tube worms from Mexico

Species	Tissue	Site	Hg	Reference
Macrophytes				
Codium amplivesciculatum	Fronds	Guaymas Bay, NW Mexico	0.099	Green-Ruiz et al. (2005)
Enteromorpha clathrata	Fronds	Guaymas Bay, NW Mexico	0.134	Green-Ruiz et al. (2005)
Gracilaria subsecundata	Fronds	Guaymas Bay, NW Mexico	0.095	Green-Ruiz et al. (2005)
Ulva lactuca	Fronds	Guaymas Bay, NW Mexico	0.058	Green-Ruiz et al. (2005)
Vestimentiferans				
Riftia pachyptila	Trophosome	Guaymas basin, NW Mexico	22.2	Ruelas-Inzunza et al. (2005)
	Vestimentum	Guaymas basin, NW Mexico	22.5	Ruelas-Inzunza et al. (2005)

knowledge, no other data in Mexico has been published on Hg residues in the whale (*E. robustus*); however, Varanasi et al. (1994) reported results on this whale species that had become stranded along the coasts of Washington, Alaska, and California. The average residues of Hg found in liver (0.27 μg g^{-1} dry wt) and kidney (0.13 μg g^{-1} dry weight) samples from the analyzed specimens (Varanasi et al. 1994) were comparable to those measured in specimens taken from Mexican waters.

5.3 Other Groups

Because of the dearth of Hg for biota, other than vertebrates and invertebrates, the few data available on other species are grouped for presentation in Table 9. Levels of Hg in macrophytes have been recorded only in specimens collected from NW Mexico; the concentrations detected in fronds of *Enteromorpha clathrata* were rather high (0.134 μg g^{-1} dry wt). The Hg levels in *E. clathrata* were much higher than those found in the rest of the macroalgae species (Green-Ruiz et al. 2005). In a study with fronds of *Enteromorpha* spp., performed in NW Portugal, Leal et al. (1997) reported a high value of 0.160 μg g^{-1} dry wt, which was comparable to values in the Green-Ruiz et al. (2005) study.

To our knowledge, only one study on Hg levels in vestimentiferan tube worms (*Rifita pachyptila*) has been published in Mexico. This study involved specimens collected from the hydrothermal field of the Guaymas basin at a 2,000 m depth. The Hg concentration in trophosome (the organ that hosts bacteria responsible for part of their metabolism) was 22.2 μg g^{-1} dry wt. In *R. pachyptila* from other hydrothermal areas in the east Pacific Rise (13ºN), Hg levels (from 11.3 to 23 μg g^{-1} dry wt) in trophosome were comparable to values reported in specimens from the Guaymas basin. The vestimentum is a distinctive part of the body of *R. pachyptila*,

made of muscle that forms a chitinous tube, where the animal lives. The average Hg concentration in the vestimentum of organisms from Guaymas basin was higher than those in *R. pachyptila* (from 1.5 to 4.0 μg g^{-1} dry wt) from the East Pacific Rise (13ºN) (Cosson 1996). The elemental concentrations in organisms from vent sites were quite variable and resulted from variations in chemistry, intensity, frequency, and duration of vent fluids.

6 Effects in Humans

In the 1950s, mercury attracted attention as a potent environmental threat to human health because of the Minamata disease incident in Japan. In this event, residents of a small fishing village, where a plastic production plant was located, suffered many effects from organic mercury intake, including central nervous system (CNS) impairment in children, adults, and in utero exposed newborns. Studies in humans have demonstrated that the brain retains mercury for approximately 21 days, and this metal causes neurotoxicity when accumulated in the CNS (Echeverria et al. 2005). According to Landis and Yu (1999), the main effect of Hg is the inhibition of a large variety of enzymes, due to the affinity of this metal for SH groups. Methylmercury (CH_3Hg) is considered to be more toxic than inorganic mercury, since the methyl group increases its absorption into the bloodstream, enhances its bioavailability, and facilitates its distribution throughout the body (Friberg and Monet 1989).

Although fish contain omega-3 fatty acids and provide many benefits to humans who consume them, fish and other marine organisms are also potential dietary sources of metals and other pollutants such as mercury and methylmercury (Cohen et al. 2005). Xue et al. (2007) reported a positive relationship between consuming fish and the resulting mercury levels in human hair. Wang et al. (2002) pointed out that consuming fish and vegetables in Tianjin, China, posed a potential health risk to humans because both contained mercury.

In a Hg exposure study of a subsistence fishing community in western Mexico (Lake Chapala), it was found that consuming carp and other fish purchased or captured in Lake Chapala was associated with elevated Hg levels in hair (Trasande et al. 2010). The authors highlighted the fact that consuming these contaminated fish contributed significantly to hair Hg concentration in women of childbearing age, a sector of the population of high concern because of the potential for methylmercury-induced developmental neurotoxicity.

Ruelas-Inzunza et al. (2011a) evaluated the hazard quotient (HQ) for the NW Mexico population, based on the Hg content that existed in fish and shrimp they consumed. Though fish and shrimp consumption (9.01 kg $person^{-1}$ $year^{-1}$ and 1.49 kg $person^{-1}$ $year^{-1}$, respectively) are lower than the world average, these authors found that organisms like *Caranx caninus* and the top predator *Sphyrna lewini* represented a potential health risk for consumers, mainly to fishermen and their families who consume two or three times more seafood than an average person. Levy et al. (2004) states that children are more vulnerable to the effects of mercury, and

prolonged exposure may cause impairment of the developing of CNS, and motor function and behavioral disorders. In this context, White et al. (1992) pointed out that the symptoms of mercurialism are loss of mental capacities (i.e., memory, logical reasoning, or intelligence) and motor effects (i.e., imbalance, coordination, and tremor in muscles).

In humans, the kidney is a common target for metals, since it serves as a major excretory pathway for metals and has important metabolic functions. Nephrotoxic effects of Hg species are characterized by damage to cellular membrane and loss of mitochondrial functionality (Fowler 1996). People occupationally exposed to Hg have high urinary Hg levels (>50 μg L^{-1}) with the prospect of concomitant deleterious effects. Gonzalez-Ramírez et al. (1995) carried out a study in dental and non-dental personnel in Monterrey, Mexico, and found that urinary mercury levels were higher in personnel who formulated amalgams. Later, Woods et al. (2007) found a strong and positive correlation between urinary mercury levels and the number of amalgams emplaced and the elapsed time since their emplacement.

People living in proximity to mining areas are often as vulnerable to Hg exposures as are those occupationally exposed to Hg. Therefore, Acosta-Saavedra et al. (2011) concluded that women and children in Mexico face Hg exposure risks for both geographical and socioeconomical conditions. For example, in a monitoring study of Hg and other toxic metals in children living in areas close to mine tailings in southern Mexico, it was found that urinary Hg was elevated (Moreno et al. 2010). The individuals of interest were 50 children whose age ranged from 6 to 11 years; the results indicated that 30% of children had Hg levels above the reference value (0.7 μg L^{-1}) for urine.

In research intended to explore other routes of Hg exposure, Peregrino et al. (2011) analyzed the Hg content in skin-lightening creams manufactured in Mexico. It was noticed that none of the labels of the analyzed products gave Hg as being among the ingredients. In six of the creams, Hg concentrations were extremely elevated (from 878 to 36,000 ppm). Such Hg values imply a serious health risk, and indeed more research is needed on this topic.

The main functions of the human liver are to metabolize, transform, and store a wide variety of substances (Nieminen and Lemasters 1996). Moreover, considering its structure, function, and biochemistry, the liver is vulnerable to damage from excessive amounts of many toxic compounds (Timbrell 2009). Regarding effects on humoral immune responses, some investigations reported increased blastogenesis in human and animal lymphocytes when exposed in vitro to mercury (Exon et al. 1996; Rice 2001).

In Mexico, as in other developing countries, there is a need to study the toxicological effect of mercury and others pollutants (Yáñez et al. 2002). The main research areas that need attention as regards the effects of Hg on humans include (a) patterns of human consumption of predator fish species and Hg levels in the edible portion of these fish; (b) levels of Hg in people occupationally exposed to this element (personnel who formulate dental amalgams, miners, workers in chloralkali plants, etc.); and (c) concentration of Hg in skin-lightening creams manufactured in Mexico.

7 Summary

In Mexico, published studies relating to the occurrence of Hg in the environment are limited. Among the main sources of Hg in Mexico are mining and refining of Au and Hg, chloralkali plants, Cu smelting, residential combustion of wood, carboelectric plants, and oil refineries. Hg levels are highly variable in the atmospheric compartment because of the atmospheric dynamics and ongoing metal exchange with the terrestrial surface. In atmospheric studies, Hg levels are usually reported as total gaseous Hg (TGM). In Mexico, TGM values ranged from 1.32 ng m^{-3} in Hidalgo state (a rural agricultural area) to 71.82 ng m^{-3} in Zacatecas state (an area where brick manufacturers use mining wastes as a raw material).

Published information on mercury levels in the coastal environment comprise 21 studies, representing 21 areas, in which sediments constituted the substrate that was analyzed for Hg. In addition, water samples were analyzed for Hg in nine studies. Few studies exist on Hg levels in the Caribbean and in the southwest of the country where tourism is rapidly increasing. Hence, there is a need for establishing baseline levels of mercury in these increasingly visited areas. In regions where studies have been undertaken, Hg levels in sediments were highly variable. Variations in Hg sediment levels mainly result from geological factors and the varying degree of anthropogenic impacts in the studied areas. In areas that still have pristine or nearly pristine environments (e.g., coast, Baja California, Todos Santos Bay, and La Paz lagoon), sediment Hg levels ranged from <0.006 to 0.35 μg g^{-1} on a dry wt basis.

When higher levels exist (0.34–57.94 μg g^{-1} on a dry wt basis), the environment generally shows the influence of inputs from mining, oil processing, agriculture, geothermal events, or harmful algal bloom events (e.g., Guaymas Bay and Coatzacoalcos estuary). From chronological studies performed in selected coastal lagoons in NW Mexico, it is clear that Hg fluxes to sediments have increased from 2- to 15-fold in recent years. Since the 1940s, historical increases of Hg fluxes have resulted from higher agricultural waste releases and exhaust from the thermoelectric plants.

The levels of Hg in water reveal a moderate to elevated contamination of some Mexican coastal sites. In Urías lagoon (NW Mexico), moderate to high levels were found in the dissolved and suspended fraction, and these are related to shipping, the fishing industry, domestic effluents, and the presence of a thermoelectric plant. In Coatzacoalcos (SE Mexico), extremely elevated Hg levels were found during the decade of the 1970s. Low to moderate levels of Hg were measured in waters from the Alvarado lagoon (SE Mexico); those concentrations appear to be associated with river waters that became enriched with organic matter and suspended solids in the brackish mixing zone.

Regarding the Hg content in invertebrates, the use of bivalves (oysters and mussels) as biomonitors must be established along the coastal zones of Mexico, because some coastal lagoons have not been previously monitored. In addition, more research is needed to investigate shrimp farms that are associated with agricultural basins and receive effluents from several anthropogenic sources (e.g., mining activity and urban discharges).

Hg residues in several vertebrate groups collected in Mexico have been studied. These include mammals, birds, reptiles, and fish. In elasmobranch species, the highest Hg concentration (27.2 μg g^{-1} dry wt) was found in the muscle of the smooth hammerhead shark (*Sphyrna zygaena*). Teleost fish are the vertebrate group that has been most studied, with regard to Hg residue content; the highest value (5.67 μg g^{-1} dry wt) was detected in the striped marlin (*T. audax*). Among reptiles, only marine turtles were studied; Hg levels found ranged from 0.795 in the liver to 0.0006 μg g^{-1} dry wt in the blood of *L. olivacea*. In birds, the highest Hg concentration (5.08 μg g^{-1} dry wt) detected was in the liver of the olivaceous cormorant (*P. olivaceous*). Specimens from stranded marine mammals were also analyzed; levels of Hg ranged from 70.35 μg g^{-1} dry wt in the liver of stranded spinner dolphin (*S. longirostris*), to 0.145 μg g^{-1} dry wt in the muscle of gray whale (*E. robustus*). The presence of Hg in these marine animals is not thought to have caused the stranding of the animals.

Other organisms like macroalgae and vestimentiferan tube worms were used to monitor the occurrence of Hg in the aquatic environment; levels were comparable to data reported on similar organisms from other areas of the world. Few investigations have been carried out concerning the mercury content in human organs/tissues in Mexico. Considering the potential deleterious effects of Hg on kidney, lung, and the central nervous system, more information about human exposure to organic and inorganic forms of mercury and their effects is needed, both in Mexico and elsewhere.

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