

Emerging Problems with Mercury in Cambodia

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Abstract

Background: Development of Cambodia is proceeding quickly with deforestation and hydroelectric dams potentially exacerbating mercury contamination from gold mines. Furthermore, mercury in consumer goods also threatens to compromise the health of Cambodians.

Objectives: It is important to provide essential information on sources and pathways of mercury so that Cambodians can avoid exposure to elevated levels of mercury and to support informed decision making about management of consumer goods and the environment.

Methods: We review current data available from our projects and the literature, compare the effects of similar development elsewhere, and discuss relevant methods to mitigate damage.

Discussion: The mercury used by artisanal miners to extract gold contaminates thousands of miners. The extent of the toxic zone from gold mines is not clear due to the compounding effect of deforestation that is likely a larger source of mercury than the gold mines. Downstream from the gold mines, the levels of mercury in human hair in the Srepok River Basin are three to five times higher than that recommended by USEPA ($1 \mu\text{g g}^{-1}$) and the level found associated with attention deficit hyperactivity disorder in the United States. In the same area, mercury in hair is at similar levels as has been correlated with suppressed male fertility in Hong Kong. Fishes in the Srepok River already show levels of mercury that exceed USEPA human consumption guidelines by 4–11 times. This problem could become worse with the completion of new hydroelectric dams, which typically increases levels of mercury in fish by fivefold. Unregulated Chinese traditional medicines sold in pharmacies exceed international guidelines by up to 30,000 times. Children's toys contain up to 2% mercury. Finally, there is widespread use of skin whitening creams with mercury that exceeds ASEAN guidelines by up to 35,000 times.

Conclusion: Further field mercury monitoring of water, fish, and people is needed in Cambodia as the potential for toxicity is significant. Anticipated health problems are subtle and require professional analysis to detect. Those most at risk are women of child-bearing age and children. Assessment of mercury contamination must include several sources of mercury.

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1.1 Introduction

Mercury is one of the most toxic metals. Human activities have increased the fluxes of mercury into the atmosphere and ocean surface water by approximately threefold (Selin, 2009). In the Arctic, global releases of mercury have resulted in a tenfold increase of mercury in top predators such as seals, polar bears, and birds of prey since the preindustrial times (AMAP, 2011). The global concern over mercury has fueled new legislation by many major governments (EU 2013; USA 2013). It is anticipated that the Minamata Convention will soon be ratified by 140 nations to block the trade in mercury and improve its management (UNEP, 2013). Each signing country is to

write a management plan to reduce mercury use. The convention is named after the city of Minamata, Japan, where starting around 1956 >2000 certified victims and approximately 40,000 uncertified victims from mercury-contaminated seafood suffered neurological disorders including numbness of the hands and feet, general muscle weakness, chronic pain, and a narrowing of the field of vision, to the extremes of insanity, paralysis, and death (Harada, 1995; Asahi Shimbun, 2010).

In the developed world over the past 40 years, major sources of mercury have been identified and their emissions have been reduced. Closing of chlor-alkali plants and improvement in pulp and paper manufacturing were major steps suppressing mercury release (Schmeltz et al., 2011). The operators of cement kilns have also decreased mercury release. In addition,

the releases from mining and smelting industries have declined (Parsons and Percival, 2005). In the USA, incineration of mercury containing medical wastes has virtually stopped. The National Vehicle Mercury Switch Recovery Program is expected to reduce mercury air emissions through removal of mercury convenience light switches from scrap vehicles before the vehicles are flattened, shredded, and melted to make new steel (USEPA, 2007). Between 1990 and 2005, total U.S. anthropogenic emissions declined by approximately 59 percent. During the same time period, global anthropogenic emissions increased 17 percent (Pirrone et al., 2010). Asia posted the largest increases in mercury emissions due largely to expanding energy production from coal-fired power plants (Evers et al., 2011). Globally, combustion of fossil fuels is the greatest anthropogenic source of mercury. The consequences of further uncontrolled releases of mercury include loss of a major food supply (i.e. fisheries), impairment of human health and potential loss of species. While hydroelectric power generation should seem to be environmentally benign, the flooded areas become sites for methyl mercury production which leads to increased fish contamination both above and below the power dams (Schetagne et al., 2000).

Cambodia is now entering a new phase of development which should include the management of mercury. In 2011, Cambodia was ranked 139 of 187 countries in the Human Development Index (<http://hdrstats.undp.org/en/countries/profiles/khm.html>). Compared to the large data set and extensive management of mercury reviewed for the Great Lakes of North America (Evers et al., 2011), Cambodia has no such data or plans for management. The limited Cambodian data does illustrate serious problems. The first and only major case of mercury contamination in Cambodia was associated with an illegal shipment of 2,700 metric tons of industrial wastes containing a high concentration of inorganic mercury from Taiwan (Hess and Frumkin, 2000). There was an attempt to dispose of the wastes on land near Sihanoukville initially with no safety equipment and without an engineered disposal facility with a liner. Hess and Frumkin (2000) stated that “at least six deaths and hundreds of injuries have been associated with this incident.” They stressed the importance of prevention and preparedness in containing emergencies in developing countries. Unfortunately in Cambodia the ongoing development plans are not well presented in Environmental Impact Assessments (EIAs.) In spite of limited analysis, less severe cases of mercury toxicity than the Sihanoukville mercury incident have been reported. Agusa et al. (2007) reported the enhancement of female hormones estrone and estradiol in men and women in Phnom Penh by an unknown source of mercury. Cambodia’s artisanal gold miners likely are impaired by their use of mercury (Murphy et al., 2009a). The common presence of mercury in skin whitening creams in Cambodia is also a concern (Murphy et al., 2009b, 2012). As has occurred in Nigeria (Olumide et al., 2008), there have been at least two mortalities associated with skin whitening creams in Cambodia. Other problems with mercury that are well known globally have largely not been evaluated or considered in Cambodian development. This review was written to alert Cambodians of the impending problems which will be important in the development of mitigation options and to facilitate their preparation of a management plan not only for the Minamata Convention but also for the development of safe and reliable practices that are required for the long-term health of the people of Cambodia.

1.2 Methods

Although this is a review paper, we have reevaluated some our own data in order to present a cohesive story about mercury. As such, it is useful to provide a brief summary of our field and laboratory methods as a context for the story, but readers are referred to our various original publications for more detail

on the methods. Our involvement with mercury in Cambodia began in 2004 in response to concerns that mercury from gold mines might be responsible for the declining number of Irrawaddy dolphins (*Orcaella brevirostris*) in the Mekong River (Beasley, 2007). As a control to the gold mine project and because of concerns about urban mercury contamination, we also began to evaluate the mercury content of people and consumer products in Phnom Penh.

1.3 Sites

In December 2004 and 2005 samples were collected from the O Tron gold mine in Mondulkurri Province, eastern Cambodia (45 km N.E. of Kratie (12° 48' N, 106° 16' E, Figure 1). Sampling on this first project also included analysis done near Kratie on the Mekong River and continued up the Mekong River and its tributary the Tonle Srepok in Ratanakirri provinces (Murphy et al., 2005). In 2006 and 2007 additional samples were collected from the Prey Meas gold mine in Ratanakirri, NE Cambodia (13° 31'23" N, 107° 22'46" E) in a dry forest about 48 km SE from Banlung (Murphy et al., 2006, 2008). From 2007 to 2013, consumer goods were sampled in Phnom Penh, the capital of Cambodia.

1.4 Sampling

As an indicator of atmospheric mercury deposition, on June 27, 2005 tree core samples were collected at Lake Yaklom, approximately 3 km east of Banlung, Ratanakirri province (13° 43' 52" N, 107° 01' 01.5" E). September 6, 2005, additional tree core samples were collected near the temple at Phnom Tamao (11° 18' 04" N, 104° 48' 1 8" E), approximately 30 km south of Phnom Penh (Figure 1). The former site was very isolated and undeveloped whereas the latter site reflected the urban influences of Phnom Penh. The tree rings reflecting the changes in growth from wet and dry seasons allow for visual dating of the wood sections.

Channa striata (a snakehead fish) were collected from the Tonle Srepok River by fisherman and bought Feb. 21, 2007 at the market in Banlung. Also in 2007, other fish were collected directly from fishers at Kratie. Samples of muscle, kidney and liver tissues from 7 calf and 3 adult Irrawaddy dolphins (*Orcaella brevirostris*) were sent to Environment Canada, Burlington, Ontario by the Wildlife Conservation Society, Phnom Penh office in 2004. Samples were shipped with dry ice which was replaced at each airport en route to Canada. Once in Canada, samples were stored at minus 60°C.

April 1–3, 2005: hair samples were collected from people living near the Tonle Srepok River near Lumphat, Ratanakirri (13° 28'26" N, 106 59'43" E); on the Tonle Kong River 2 km upstream of Stung Treng (13° 32'34" N, 105° 59'32" E); on the Mekong River 2 km upstream of Stung Treng (13° 34'01" N, 105 58'14" E) and on the Mekong River 2 km upstream of Kratie (12° 36'22" N, 106 01'19" E). Sampling sites were usually remote villages accessed by motorcycle or boat. In 2005 28 hair samples were collected by Mith Samlanh Friends (Phnom Penh) from male methylamphetamine addicts. Some methods of making methylamphetamine use mercury as a catalyst and we had thought it might be a source of mercury in Cambodia. To resolve mercury contamination by skin whitening creams, in 2010 hair samples were collected from young women in Don Bosco Institutes and University of Health Sciences. The data from hair samples that were collected from users of skin whitening creams were not included in data in Figure 1. An experiment was done to determine if hair samples had surface mercury that could be removed by cleaning. These methods included sonication, Triton-X (1%, non-ionic detergent, mixing overnight on a shaker) and rinsing with acetone (Murphy et al., 2008).

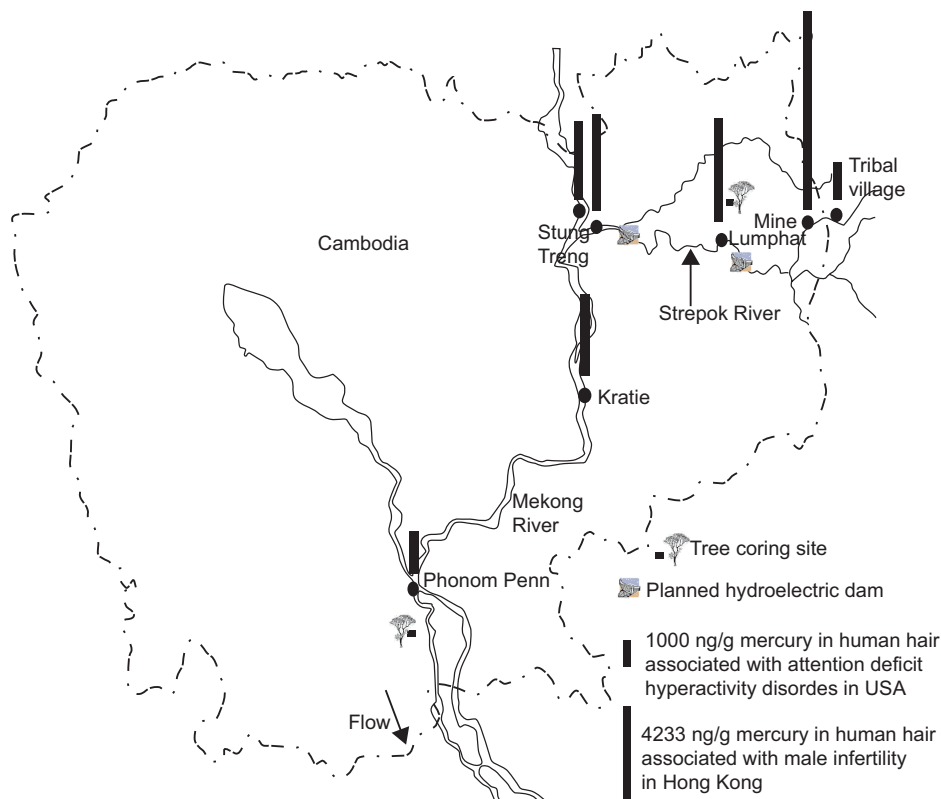


Figure 1. Human Hair Hg Content as an Indicator of Human Health. The mean content of mercury is a good indicator of mercury exposure which can be indicative of health impairment.

In July 2007–2008, ~66 skin whitening creams were purchased from Boeng Keng Kong, Central, O’Russej, and Russian markets in Phnom Penh. In 2011–2012 >700 skin whitening creams were analyzed from students at the University of Health Sciences and Don Bosco Institutes. In 2011 more than 100 toys were analyzed at Don Bosco Institutes in Phnom Penh. More than 50 toys were also bought at markets in Phnom Penh and Bangkok. In 2012 nine traditional Cambodian medicines were collected by the Ministry of Health in Phnom Penh. In 2012, 11 traditional Chinese medicines were purchased from Chinese pharmacies in Phnom Penh.

Analyses for our first study of skin whitening creams were done at the University of California, Davis Campus using CVAAS and CRM. Our second study of skin whitening creams mainly used a handheld X-ray fluorescence analyzer (XRF) supplied by Thermo Fisher Scientific using CRM with the analyzer calibrated in their American headquarters (Billerica, Massachusetts, USA). Another XRF analyzer was loaned by the Singapore office of Thermo Fisher Scientific and calibrated in their Hong Kong office. It was used to evaluate mercury in Chinese traditional medicines, toys and other consumer products.

1.5 Analysis

Our studies reviewed in this paper used several professional laboratories. More details can be found in the publications (Murphy et al., 2005, 2006, 2008, 2009a, b, 2012). Analysis of mercury in dolphin tissues (7 calves and 10 adults) used Canada’s National Laboratory for Environmental Testing (NLET), a certified laboratory and Environment Canada’s main analytical laboratory. Technology mainly used inductively coupled plasma mass spectrometry (ICP-MS). Analyses of fish, trees and hair were also done in the same Environment Canada institute using a Milestone DMA80 Direct Mercury Analyzer and certified reference materials (CRM) for hair, fish and sediments (Murphy et al., 2005, 2006, 2008). Analyses of mine tailings for gold and mercury used cold vapor atomic absorption spectrometry (CVAAS) in Environment Canada and included CRM. Throughout this project results were always within the standard deviation of the CRM. Analyses of methyl mercury were also done using CVAAS by Flett Research, a certified laboratory in Winnipeg, MB, Canada using USEPA and ISO/IEC 17025 protocols (<http://www.flettresearch.ca>).

1.6 Results

Cambodia has at least six potential sources of mercury;

1. Artisanal gold mines
2. Deforestation
3. Hydroelectric dams
4. Extraction and combustion of fossil fuels
5. Fisheries
6. Consumer products

1 Artisanal Gold Mines

Artisanal gold mining is the main activity that most Cambodians associate with mercury contamination (Sotham, 2004; Murphy et al., 2005, 2006, 2008, 2009a). Although many reports focus on mercury amalgamation in mine processing as the major source of mercury, Telmer et al. (2006) reported that the land disturbance directly associated with mining was

a greater source of mercury. The effect of soil erosion will be discussed more under deforestation. The Ministry of Environment suggested there are 6,000 artisanal gold miners in Cambodia (MOE 2011). As well as the potential toxic exposure to themselves, the miners leave abandoned mine shafts, trenches and tailings which would continue to release mercury into the atmosphere.

At the Prey Meas, Ratanakirri, NE Cambodia, three of the miners that used open torches to remove mercury from gold-ore amalgams had more than 40,000 ng·g⁻¹ of mercury in their hair. These are extreme levels well beyond the 10,000 ng·g⁻¹ associated with Minamata disease. The mean mercury content of 22 miner's hair was 9,701 ng·g⁻¹ (Figure 1, Table 1). The USEPA alert level for mercury in human hair is 1,000 µg·g⁻¹ (NRC 2000) while the WHO alert level for mercury in hair is 2,500 ng·g⁻¹ (WHO UNEP, 2008). In two samples with a mean total mercury content of 7675 ng·g⁻¹, 19% was present as methylmercury. When the 176 hair samples summarized in Figure 1 were collected (prior to 2007) there was not a laboratory in Cambodia that could measure mercury in blood or urine. These are difficult to ship overseas and hair analysis was chosen as an alternative health indicator (McDowell et al., 2004; Sagiv et al., 2012; Bellanger et al., 2013). We found that extensive washing with Triton X with sonication and an acetone rinse had no effect on the mercury content of hair (Murphy et al., 2008). Any notion of saying that the mercury in hair at the mine reflected surface contamination would have to invoke an unknown reaction whereby mercury in air bonded quickly and tightly with hair. For our purposes it is enough to say that the mercury in the miners' hair reflects exposure to high levels of mercury. The concentration of mercury in human hair downstream of the gold mines was still quite high, cannot represent surface contamination but it not possible to say that it reflected only gold mines (Figure 1).

1.2 Treatment-Artisanal Mine Initiatives

Ultimately in the future mercury would not be used at all in gold extraction. However, as with miners in many countries, gold miners in Cambodia say that mercury amalgamation is simpler and easier than other methods. There are many variables that can influence the efficiency of extraction (Veiga et al., 2006). Spiegel and Veiga (2005) review that many gold extraction techniques are inefficient and use more mercury than necessary. Jønsson et al. (2009) cite two studies where simple mercury amalgamation was efficient. Our analysis at Prey Meas, Ratanakirri suggested a good efficiency of extraction but it also indicated concerns. The efficiency of extraction at two mines was 73% and 97% (Table 2). The more efficient extraction is highly suspicious in that the tailing was supposedly one that was being reprocessed a second time but yet the mercury content (275,000 ± 43,400 ng·g⁻¹) was 300 fold more concentrated than the tailings exiting from another identical flume. Moreover the high gold content suggests it was a concentrate from a hidden process and not a reprocessed ore. There has not been similar analysis done in other mining areas of Cambodia and evaluation of mercury extractions is a consideration for future work. If in other sites the miners could be shown a more profitable extraction method they would likely cooperate more for that reason than for any concern, even their health. Every miner we talked to thought that mercury was the cause of their diarrhea and understood that mercury was toxic. There are other issues with analysis of tailings. This tailing containing 275,000 ± 43,400 ng·g⁻¹ of mercury cannot be processed on laboratory equipment without large dilutions or major contamination. Either all samples from such mines need multiple dilutions or screening with a XRF analyzer. XRF analyzers are quick and resistant to contamination (Palmer et al., 2009) and thus could be used for rapid screening. However, XRF is not sensitive for mapping of tailing contamination. Ten

Table 1. Hair in Cambodia and international sites with Mercury Toxicity.

Site	Mean Hg	SD	N	Comment
Tribal Village	1,580	340	9	^a “Upstream” of mine and deforestation
Prey Meas Mine Workers	9,701	1,2537	22	^a ^c Ratanakirri gold mine
Srepok River Lumphat	4,540	810	25	^a Downstream from mine/deforestation
Sekong R. Stung Treng	4,220	390	17	^a Downstream from mine/deforestation
Mekong R. Stung Treng	3,360	280	16	^b Downstream from mine/deforestation
Mekong R. Kratie	3,470	400	20	^b Downstream from mine/deforestation
Goldsmiths Phnom Penh	3,930	1597	9	^b
Phnom Penh men 2005	1,930	190	28	^a Young men
O Tron Mine workers	2,930	1,100	3	^a In Mondulkirri Province
American women	470	NA	1726	^d
Hong Kong subfertile men	4,233	NA	117	^e Male infertility from Hg in fish
Hong Kong fertile men	3,333	NA	49	^e
Amazon – Cuiba River	4,200	2,400	29	^f Neurotoxicity from Hg in fish
American fish eaters	1,000	NA	421	^g ADHD enhanced from Hg in fish
American fish eaters	1,200		135	^h Reduced cognition from Hg in fish

Mercury in ng·g⁻¹, NA is not available, SD is standard deviation.

^aMurphy et al., 2005. ^bMurphy et al., 2006. ^cMurphy et al., 2008. ^dMcDowell et al., 2004.

^eDickman and Leung 1998. ^fYokoo et al., 2003. ^gSagiv et al., 2012. ^hOken et al., 2005.

Table 2. Efficiency of Gold Extraction.

Gold and Mercury on Prey Ba and Prey Thmei Flumes		
Sample	Gold (ng·g ⁻¹)#	Mercury (ng·g ⁻¹)#
PM In Mean (n = 5)	35,880 (9,464)	275,000 (43,400)
PM Out Mean (n = 5)	980 (790)	4,614 (7,900)
PT In Mean (n = 3)	1,210 (460)	907 (150)
PT Out Mean (n = 3)	330 (179)	992 (168)

PM is Prey Meas mine. PT is Prey Thmei mine.

Each mercury value is a mean of triplicates.

These numbers in brackets are standard deviations.

samples of spent and weathered tailings had mean, standard deviation and maximum mercury as follows: 46, 40, 1,400 ng·g⁻¹ Hg. Since handheld XRF analysis has a typical detection limit for mercury of about 20 µg·g⁻¹, most tailings have too little mercury to be measured by XRF.

1.2.1 Cyanide leaching of gold

Cyanide leaching of gold is the most commonly used alternative to mercury extraction. Once cyanide is oxidized with sodium hypochlorite (or equivalent) it is not toxic. Many Cambodian artisanal miners are experienced with cyanide leaching and the conversion to it is easier than other non-mercury extraction methods. Velásquez-López et al. (2010) stress that one barrier in using cyanide is that it can take one to two weeks for the extraction; miners often cannot afford to wait this long. As well as training, bank loans as a bridging mechanism might be important.

1.2.2 Improved use of mercury

The use of retorts is often a major focus of mitigation efforts. A retort can prevent the release of mercury during the torching of amalgams (Figure 2). They can be quite simple such as a frying pan retort (Figure 3) and yet still recover much of the mercury for reuse. Although attempts to introduce retorts often fail because of lack of preconsultation and follow-up, the work done in Tanzania by Jønsson et al. (2009) is an exception and had very active participation in the use of retorts to recycle mercury. The retorts they used cost about \$10. Similarly Crispin (2003) was able to get good participation in the use simple fish can retorts in Papua New Guinea. Murphy et al. (2005, 2006) introduced frying pan retorts in Ratanakirri but they were not used later. The miners said that the required 20 minutes to process the amalgam was too slow. The failure may not lie with the retorts. We had excellent support from a local NGO (Resource Development International) but it was beyond the budget to travel frequently to the gold mines. It would have been wise to consult with miners on how much they are prepared to pay for a retort and how long they wanted the gold recovery process to take. Follow up and preferably a continuous presence, with advice, and encouragement are needed.

A better financial incentive to recycle mercury is required. The ongoing international regulation that is being implemented to reduce the availability of mercury should increase the price of mercury. Veiga (2004) argued that a kilo price for mercury of around \$80 US would be sufficient to persuade miners to recycle mercury.

There are many other simple steps that could be taken to minimize the exposure to mercury (Spiegel and Veiga, 2010). However, any changes that disrupt the miner's normal activities are going to take some time to initiate. Miners are hesitant to leave the immediate environment of their possessions to process their amalgams. Theft in rural Cambodia is an ongoing con-



Figure 2. Mercury Removed from Gold (photo T. Murphy).



Figure 3. Frying Pan Retort (photo T. Murphy). The retort enables separation and recovery of mercury from gold amalgams without exposing the miner to mercury fumes.

cern and security must be considered in their operations. The miners make significant contributions to the local economy and warrant support, albeit hopefully in exchange for better management of their mines.

1.2.3 Cooperation from miners

As noted in the previous section, improved mine processing with regulation, education and promotion of appropriate technologies has worked well in Tanzania (Jønsson et al., 2009) and Zimbabwe (Maponga and Ngorima, 2003). Unfortunately, this is not the common response. So many reports have been produced on required changes to mercury use in mines that at least one author has attacked the work as repetitive and “over the past 15–20 years, the research that has since been undertaken has failed to identify appropriate mitigation measures, and has done little to advance understanding of why contamination persists” (Hilson, 2006).

Regulation with enforcement in Cambodia is only an option for the larger mines with private security. A significant military presence to force the removal of artisanal miners from mining would not only be expensive but current corruption would probably make enforcement ineffective. In 2012, Cambodia was ranked 157 of 172 countries for corruption by Transparency International (<http://cpi.transparency.org/cpi2012/results/>). Sotham (2004) and Titthara and Seiff (2013) reported that at two different gold mines the army or police took money from each miner for an illegal "taxation". The hope that international mine firms will replace artisanal miners is delayed in part by similar concerns over corruption. Soshoeuth and Green (2009) reviewed a report by Global Witness of a "total lack" of transparency in the mining industry and cited a government minister calling a "\$2.5 million BHP Billiton-Mitsubishi social development fund as tea money". The required environmental, health, security and educational management at mines would be difficult to implement without business management being transparent to at least managers of other Cambodian government departments.

With respect to the absence of health care, education and security, we agree with Hinton et al. (2003) that "any program directed at reducing the comparatively invisible health impacts from mercury will be received with minimal success if the program does not comprehensively address these community issues also". The importance of community issues has greater implication than just the immediate health of the miners. The children at the gold mines are part of the future of Cambodia. Their mental development and ability to contribute to Cambodia may not only be compromised, they could become a liability.

Furthermore, some health based actions are relatively inexpensive. Ceramic water filters are very effective at treating diarrhea. When we introduced these filters at one mine, all miners using the filtered water ($n=12$) said it immediately cured their diarrhea (Murphy et al., 2006). We did not do a formal evaluation of diarrhea but likely the effectiveness was similar to that found by Brown et al. (2008). They found that in a randomized, controlled evaluation of a ceramic water filter near Phnom Penh the incidence of diarrhea decreased from 15% to 7.4%. In our analysis at the gold mine, we used the same brand of water filter as Brown et al. (2008) and found that bacteria in the well water were virtually completely removed ($>99\%$) (Murphy et al. 2006). We believe that the results of Brown et al. (2008) with half the diarrhea being treated is likely a fair representation of the filter's effectiveness on diarrhea at the mines. The complete lack of toilets, absence of cleaning stations, crude food preparation and lack of control over animal wastes (pigs, dogs and people) at the gold mines must contribute to diarrhea too. Still the availability of such water filters at the mines should be enhanced. Sanitation should be improved. There has been considerable effort throughout Cambodia to provide simple latrines. The same service is needed at the mines. The same could be said for mosquito netting to suppress malaria and dengue fever. At the same time when these services were supplied new mining practices (including improved extraction and tailings management) also could be introduced with training workshops, as part of a community development package.

2 Deforestation

The clearing of forests to establish agribusiness has the potential to be the largest source of mercury in Cambodia. Veiga et al. (1994) were among the first to point out that deforestation in the Amazon was a greater source of mercury than artisanal gold mining. Roulet et al. (2000) provided more detail on enhanced mercury export from deforestation. Mainville et al. (2006) observed up to a 60% increase of release of mercury from soils after deforestation in the Amazon. Sampaio da Silva et al. (2009) found that mercury in fish was directly correlated to the amount of deforestation upstream. Canuel

et al. (2009) also confirmed that deforestation releases more mercury than gold mining in the Amazon. This effect of deforestation is global and was documented in Canada (Garcia and Carignan, 2000) and Finland (Porvari et al., 2003). Although there is very little quantification of enhanced mercury export in the tropics there are basic reasons to believe it could be larger in the tropics than in temperate climates. Tropical soils have a much longer history, unaltered by glaciation to accumulate mercury. Also tropical soils often have little cation exchange capacity, i.e. they cannot readily adsorb cations like calcium or mercury. The burning of the trash wood left after deforestation not only releases mercury from combusted wood but it also results in a large increase of cations that displaces mercury from the limited number of adsorption sites in soils. The displaced mercury ions are then readily flushed into streams (Farella et al., 2006). This observation certainly applies to Cambodian soils that also have a low cation exchange capacity (Blair and Blair, 2010).

Tree cores can provide an historical record of atmospheric mercury deposition from local emissions and subsequent bioaccumulation (Butkus and Balthazart, 2007). The choice of sampling sites is the determining factor influencing the results. Lake Yaklom, Ratanakirri is part of a sacred park. Until very recently the land around Lake Yaklom was used only for swidden agriculture, i.e. slash and burn of small plots of land by Natives (Maxwell 2001). The trees that were sampled at Phnom Tamao were also within a park but the history here is quite different. Phnom Tamao is 30 km from Phnom Penh. Most records were destroyed but anecdotal reports say the Khmer Rouge logged Phnom Tamao before it fell to the invading Vietnamese in 1979. Direct observation confirms this idea. The only large trees we could find were on temple property. The proximity to Phnom Penh with both domestic and export needs makes it highly likely to have been logged more commercially, intensively and frequently than Lake Yaklom which is very isolated (Figure 1). There were peaks of mercury in the tree rings associated with the recent deforestation in Ratanakirri but similar peaks were not found in association with the logging in 1979 at Phnom Tamao (Figure 4). Peaks of mercury in much older wood at Phnom Tamao and growth rates from visible tree rings probably indicate extensive logging about 1905 and 1840. The most recent 60 years of wood at Phnom Tamao only has background levels of mercury whereas wood 2-8 years old at Ratanakirri has significantly more mercury. Presumably at Phnom Tamao, the mercury that would have accumulated in the forest biome was lost during repeated deforestations. This idea is supported by much smaller growth rings in Phnom Tamao (<1 mm) compared to Ratanakirri (5 mm). Large-scale deforestation would remove nutrients from the ecosystem and impair subsequent growth. In the famous Hubbard Brook calibrated watershed project Hobbie and Likens (1973) observed a 12 fold increase of phosphorus discharge from deforestation. There is much less quantification in the tropics but after deforestation, Davidson et al. (2003) did observe enhanced phosphorus release from Amazon soils that were highly weathered. The important aspect of this comparison of Lake Yaklom and Phnom Tamao is the difference in the pattern of mercury in tree rings as a reflection of mercury deposition apparently reflecting logging not necessarily the differences in growth rate. The tree species cored at the two sites were all different which makes the interpretation of the difference in growth rate less certain (Figure 4).

The significance of deforestation release of mercury is that the new reservoirs in Cambodia downstream of deforestation may become contaminated with mercury regardless of what is done with artisanal gold mines. Moreover this erosion must interfere with fish habitat and will fill in new hydroelectric reservoirs more quickly. Anecdotal reports suggest that infilling of deep holes in rivers and subsequent loss of refuges in dry periods is partly responsible for declining fisheries in rivers such as the Srepok. A general review of the Mekong River found that sediment load has increased at some stations but decreased at others (Walling, 2008). Kumm and Varis (2007) used MRC data to show a significant decrease in TSS concentration occurred at the Chiang Saen (Thailand) sampling station after the 1993 completion of the Manawan

Dam on the upper Mekong River in China. Hydroelectric reservoirs are considered the most obvious reason for sediment load decreasing (Walling, 2008) but during and shortly after construction of dams in the watershed north of the Sesan River sediment load increased (STRIVER, 2009). There has been little documentation of erosion in the Srepok River and no comparison can be made of the relative significance of agriculture, construction or mining on erosion and river sediment load. At times, the sediment load makes the Srepok River look very turbid (Figure 16 in Murphy et al., 2006). Recently English newspapers in Phnom Penh reported huge parcels of land leased to agribusiness (Titthara, 2011). Apparently since 2008 more than 7 million hectares of land concessions has been granted to private firms. It is not possible to determine how of much of this is forested land that will be converted to plantations or other commercial uses but regardless the potential release of mercury from land clearing is very large. Not only is land development occurring more quickly but also it will be done in synchrony with development of new hydroelectric reservoirs which is reviewed later.

2.1 Treatment – Deforestation

There are a number of forestry practices that could be augmented to reduce erosion and subsequent release of mercury (Northcote and Hartman, 2004). Specifically reducing the extent of clear cutting to smaller areas

reduces erosion and release of nutrients and mercury (Prepas, 2013). In western Canada this idea has gone as far as to use a helicopter to selectively remove trees of high value. In Switzerland to prevent severe erosion, trees on steep slopes are not harvested. In Cambodia logging has often been done on steep slopes to develop cashew plantations. These cashew orchards are plowed and managed without a cover crop; the erosion is potentially severe. The establishment of large plantations of rubber trees or palm oil which permit an understory of plants to grow appears less damaging than cashews to erosion but still the wildlife and ecosystem values are gone. Other options include maintaining forest for carbon credits (REDD) (Wertz-Kanounnikoff et al., 2011). This approach has been very successful in Latin America especially where there are concerns associated with the potential effects of deforestation on water reservoir quality and capacity (Locatelli et al., 2011). This option also allows for ecotourism and traditional gathering of mushrooms and resins (Thy, 2009).

3 Hydroelectric Dams

There is a new risk to the area of Ratanakirri. A 305 km² hydroelectric reservoir is being built downstream of these gold mines on the Sesan River (Baird, 2009). Several hydroelectric reservoirs are being built in Cambodia (Middleton, 2008; Ritouch, 2011). The 193 megawatt (MW) Kamchay hydroelectric dam in Kampot province was officially opened Dec. 8, 2011. There are currently six hydroelectric dams under construction. Two hydroelectric

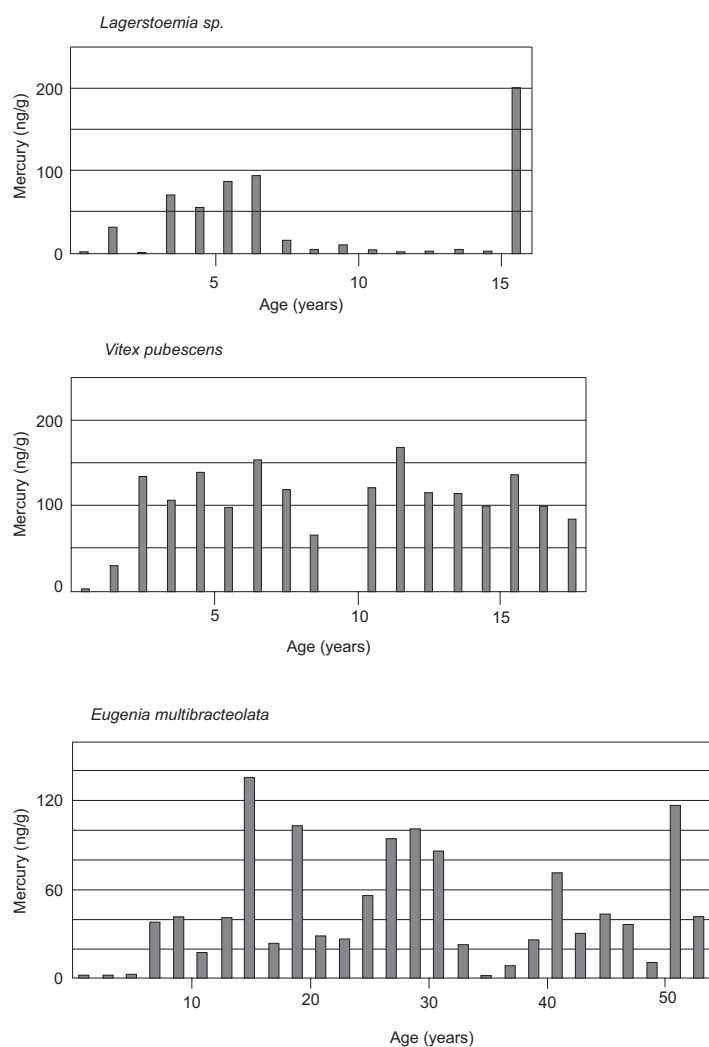


Figure 4. (a) Mercury in Trees – Effect of Atmospheric Loading – A – Ratanakirri.

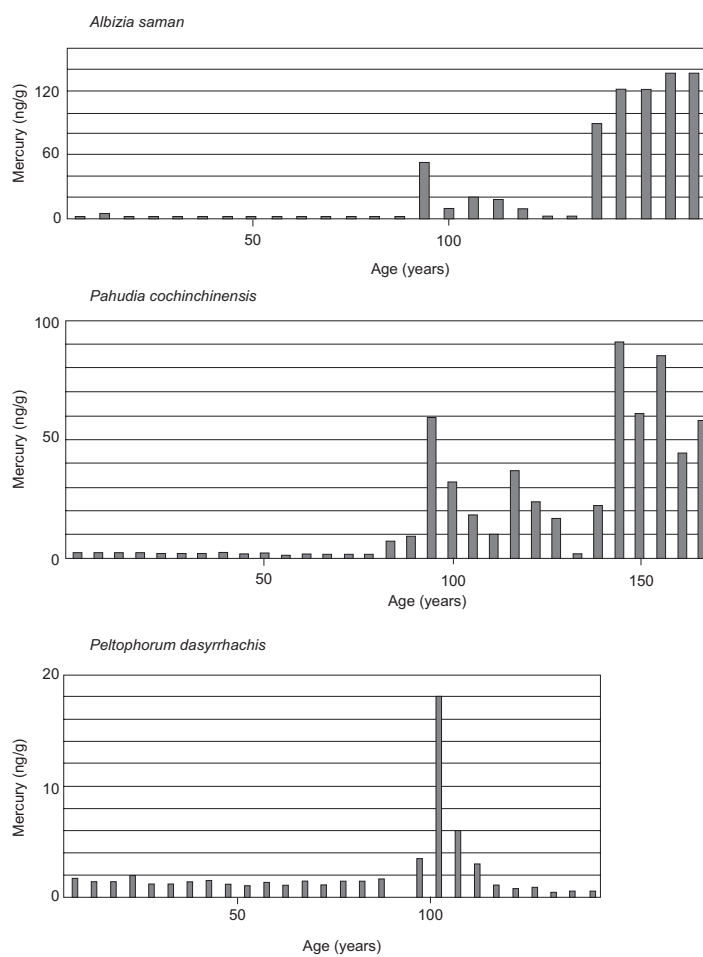


Figure 4. (b) Mercury in Trees – Effect of Atmospheric Loading – B Phnom Tamao.

dams in Pursat Province are planned to go on line in 2013 and 2014, respectively; Stung Atay, 120 megawatts and Stung Tatay 247 megawatts. There is also the 338 megawatt Russei Chrum dam in Koh Kong Province that will open in 2015 (Reaksmey and Chen, 2011). The construction and erosion mobilizes mercury. The roads that are built to access the dams also enhance logging which increases mercury export. More importantly the bottom of the reservoirs becomes anoxic which provides required conditions for bacterial mediated methylation of mercury. Methylmercury is up to 1,000 times more toxic than inorganic mercury (Vezer et al., 2005; Chuu et al., 2007). In such reservoirs it is very common for mercury to become methylated (Canuel et al., 2009; Bodaly et al., 1984; Verdon et al., 1991; Schetagne and Verdon, 1999; Mailman et al., 2006; Tuomola et al., 2008), for fish to bioaccumulate high levels of mercury and become unsafe to eat. Furthermore this methylated mercury in reservoirs can be exported downstream (Schetagne et al., 2000). In Canada, at least four models have been developed to predict the bioaccumulation of mercury in fish (Azimuth, 2010). In Canada the development of a new reservoir includes assessments and communication to the public of how long a reservoir will have high mercury concentrations (Harris et al., 2009). In the lower Mekong River (Cambodia, Laos and Vietnam) there does not appear to have been any analysis or discussion of mercury in the many Environmental Impact Assessments done for hydroelectric dams (Grimsditch, 2012). In Canada, Brazil, United States and many other countries, Native communities and other potential users of a reservoir are often instructed to restrict consumption of fish from such reservoirs (Dumont et al., 1998; WHO, 2008).

Although many studies report enhanced mercury in reservoirs, there are relatively few studies that monitored fish in hydroelectric reservoirs over several years (Table 3). Mercury in fish tends to increase about five fold from predevelopment. There is considerable variability in both species and sites in how long it takes for the maximum amount to mercury to occur in fish (3 to 13 years) and how long it takes for the concentration of mercury in fish to return to background (up to 30 years). There appears to be only one tropical hydroelectric reservoir with five studies (Ahlin and Larsson, 2011) over an extended period, Lake Manso in Brazil. Three years after the Manso hydroelectric dam was built in Brazil, the mercury content of predator fish initially increased three to four fold (Hylander et al., 2006). Three years later the mercury content of four species of fish in Lake Manso had increased another three to four fold (Tuomola et al., 2008). Eleven years after completion of the dam the mercury content of four fish species had increased 10 fold from preconstruction (Ahlin and Larsson, 2011). The mean mercury of non-predatory and predatory fish exceeded 500 and 1,000 ng·g⁻¹, respectively (Ahlin and Larsson, 2011). One predator, *Salminus brasiliensis* had a mean mercury content of more than 6,000 ng·g⁻¹. These mercury levels are more

extreme than the Canadian hydroelectric reservoirs where fisheries were closed (Verdon et al., 1991; Schetagne et al., 2003; Bodaly et al., 2007; Anderson, 2011). Ahlin and Larsson (2011) report “fish from Lago Manso should not be consumed and appropriate recommendations should be announced until future studies eventually demonstrate the return of fish Hg to acceptable levels”. Lago Manso may be an extreme case but there are reasons to consider a serious mercury situation for the Sesan River, Cambodia. Boudou et al. (2005) reported a synergy between gold mines above a hydroelectric dam in French Guiana such that the mercury content of fish increased up to eight fold. The Sesan River watershed has gold mines too. Deforestation has been proceeding quickly in the Sesan River Basin.

Hydrocarbon deposits in SE Asia are more enriched with mercury than in many other regions (Carnell et al., 2005; Gallup and Strong, 2008) and presumably this reflects a generally higher than normal level of mercury in soils and bedrock. Another aspect that will enhance methylation is the morphometry of the planned Cambodian reservoirs. They will often be shallow with large littoral zones which is where most mercury methylation occurs (Hall et al., 2008). The basic concepts of mercury methylation are the same everywhere. It is only the variables and rates that change. Accurate predictions of eventual mercury levels of fish in new Cambodian reservoirs are not possible: fish monitoring is essential.

3.1 Treatment – Hydroelectric Dams

Treatment of mercury in reservoirs has often been discussed but only rarely implemented. In-lake treatment of mercury has mainly used traditional engineering such as dredging or capping of sediments. Dredging is expensive and only warranted for the most contaminated sediments. Capping is also expensive but unlike dredging does not consume land for permanent storage of toxic wastes. Capping usually involves use of sand which can be enriched with iron sulphides to enhance immobilization of mercury (Liu et al., 2008a). Additions of reactive clay to complex mercury were also considered in Canada to reduce mercury bioavailability (Parks and Hamilton, 1987) but this option was rejected. For one, clay is readily resuspended. The massive amounts of clay required would have negative effects too. The potential to use selenium in geotextiles to enhance complexation of mercury is possible, would be expensive, but has the added benefit of not requiring the addition of selenium to the whole lake (discussed more in fisheries section).

Lake aeration, nitrate and iron addition have been suggested as treatments to oxidize sediments and in turn suppress sulphate bacteria that methylate mercury. Lake aeration has often been proposed to suppress methylation of mercury and thus greatly reduce mercury toxicity (Parsons, 2007) but uncertainty over its effectiveness remains. A very elegant experiment in Washington State, USA recently indicated it might not work. A twin lake experiment was conducted aerating one basin while the other basin acted as control. The aerated basin had higher amounts of total and methylmercury bioaccumulation. The author proposed that the aeration was inadequate to oxidize the surface sediments (Reed, 2011).

Nitrate addition has also been proposed in part because nitrate is much more soluble than oxygen and the same inability of aeration to oxidize sediments would be less of a problem. Parsons (2009) has advocated use of nitrification in Onondaga Lake to reduce the onset of methylation of mercury. Via similar biogeochemical oxidation, iron addition in mesocosms was able to block up to 90% of methylation of mercury (Sedlak and Ulrich, 2009).

4 Extraction and Combustion of Fossil Fuels

Globally the biggest single source of mercury contamination is the burning of fossil fuels. National plans call for seven thermal power plants to be built in Cambodia including Sihanoukville and Koh Kong (Ritouch, 2011).

Table 3. Hydroelectric reservoirs with long historical analysis of Mercury Bioaccumulation.

Site	Mercury Increase	Comments	Author
La Grande Canada	4 to 8 fold (2 species)	20 years later not fully recovered, peaked in 3 to 13 years	Verdon et al, 1991 Schetagne et al., 2003
Smallwood, Canada	~5 fold (8 species)	~30 years later recovered	Anderson 2011
N. Manitoba, Canada	3 to 5 fold (3 species)	~10 to 20 years to recover	Bodaly et al., 2007
Manso Brazil	~10 fold (4 species)	~still increasing 11 years after being built	Ahlin and Larson 2011

A 270-megawatt coal plant will be online in Sihanoukville in 2014 (Weinland and Seangly, 2011). These thermal power plants apparently are required to supply electricity during the dry season when hydroelectric production declines. The plans for thermal generation of electricity in Sihanoukville should consider their effluents in their planning process. Atmospheric discharges of mercury could impact the new reservoirs being built in the neighboring Cardamom Mountains such as the Kamchay dam in Kampot Province. Evers et al. (2011) review how common this problem is globally. Locally it is also significant to note that the natural gas deposits in this region and the associated oil are more enriched with mercury than in other regions (Carnell et al., 2005; Gallup and Strong, 2008). Natural gas and oil deposits are being found in Cambodia both off-shore and on-shore, including in the Tonle Sap Basin.

4.1 Treatment – Extraction and Combustion of Fossil Fuels

The management of the oil and gas industry must be designed to minimize releases of mercury. The processing of natural gas must first remove mercury because it reacts with aluminum in the gas processing facilities. The aluminum pipes then become brittle and could fail with serious damage and loss of lives. This extracted mercury must then either be stored permanently, injected back down an old gas or oil well or injected into the finished gas product. Mercury is often stored in landfills with activated carbon which we worry may eventually be released into the atmosphere. The last option of relying upon dilution via the end user to resolve the problem may no longer be appropriate as the levels of mercury are increasing everywhere (Selin, 2009; Sunderland et al. 2009). Also the drilling of oil generates processed water that can be rich in mercury. At times this processed water is boiled off releasing the mercury to the atmosphere and assuming dilution resolves any mercury problem. Alternative treatments of processed water such as filtration result in a concentrate and a hazardous waste. The oil and gas industry produces a variety of wastes including those rich in mercury that must be stored permanently in a managed hazardous waste disposal facility. The health of the associated workers should be monitored to protect them and indirectly the communities where they work and live.

5 Fisheries

Fish are the major source of protein in Cambodia and are also essential sources of fatty acids, iron and other micronutrients (Hortle et al., 2004; Baran et al., 2007). Unfortunately because methylmercury is lipid soluble it is readily bioaccumulated into fish. In the future, predator fish in some areas of Cambodia may not be a safe food.

The mercury content of fish at Kratie was on average $103 \text{ ng}\cdot\text{g}^{-1}$ ($n=153$) but in the top predator species it was up to six fold higher (Murphy et al., 2005). The relative standard deviation of fish analyses was 4%. The current risks presented by the mercury concentrations in fish at Kratie are modest but not insignificant. Surveys by FAO (2011) indicate that people in fishing villages in Cambodia eat 219 g of fish a day. Using the mean mercury of $103 \text{ ng}\cdot\text{g}^{-1}$ gives a daily mercury intake of $501 \text{ ng}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ for a 45 kg woman. To be conservative this should be converted to methylmercury. In 2012 the European Food Safety Authority published two summaries of fish samplings of different populations showing a typical proportion of methylmercury of ~76.3% (Table 8, page 36) and 87.5% (Table 6, page 34) (EFSA, 2012). If we use the more conservative 76% then the above consumption of fish at Kratie would exceed by 3.9 times, the USEPA Reference Dose (RfD) exposure recommendations. Similarly the WHO guidelines of $1.6 \text{ ug}\cdot\text{kg}^{-1}\cdot\text{wk}^{-1}$ would be exceeded by more than two fold which is of concern especially for childbearing women (EFSA, 2012; WHO, UNEP, 2008). Since people prefer to eat predator fish, parts of the population would likely exceed USEPA and WHO guidelines 8 and 4 fold respectively.

The fish that were collected from the Sesan River contained about 50% more mercury than was found at Kratie but the differences in species and fish size weaken such a comparison (Table 4). Although more data are needed, it is still useful to use the existing data from the Srepok River for risk analysis. Using the same calculation as the above at Kratie, the fish in the Sesan River at Lumphat exceeded USEPA guidelines by 5.6 to 11 times and the WHO guidelines 3 to 6 times. In order to redo these calculations more rigorously the following are needed: more mercury data of fish, an assessment of the proportion of methylmercury in a composite sample and a survey of how much of each fish species are eaten with an associated estimate of fish size. If the above calculations were confirmed, WHO management protocols recommend considering public education and regulatory measures (WHO, UNEP, 2008). It should be noted that these fish were collected in 2007 and since then deforestation has expanded and presumably the usual associated release of mercury has continued or increased. In the near future when new hydroelectric dams are completed methylation of mercury has the potential to increase levels of mercury in fish by five-fold.

Although with respect to fish biodiversity, the direct physical effect of dams on fish migration is likely more important, the potential toxic effects of mercury on biodiversity should not be forgotten. There is “sufficient evidence from laboratory studies to link exposure to mercury with reproductive impairment in many fish species” in the wild (Crump and Trudeau, 2009). Piscivorous fish in many freshwaters and geographic regions bioaccumulate methylmercury to concentrations exceeding those associated with sublethal and reproductive effects in toxicological studies (Sandheinrich et al. 2011).

5a Dolphin Mercury Bioaccumulation

The mean content of mercury in two samples of dolphin muscle from Kratie was $419 \text{ ng}\cdot\text{g}^{-1}$ (Murphy et al., 2005). This is about a four-fold increase over the mercury of the fish. The small data set of dolphin muscle tissue makes the comparison weak but some bioaccumulation is expected. There is a larger dataset of dolphin liver ($n=11$) and kidney tissue ($n=8$) which indicated that the Mekong dolphins have one of the lowest reported concentrations of mercury (Table 5). Table 5 is only a short list of recent papers. Lahaye et al. (2006) reviews 17 publications on mercury in dolphins that like Table 5 shows the Mekong dolphins have less mercury than is usually found. The same can be said for several publications on mercury in dolphins reviewed by Wagemann and Muir (1984) who stated that “the limit of Hg tolerance for the mammal’s liver to be in the range of $100\text{--}400 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ wet weight”, (page 1). The Mekong dolphins had <10% of the mercury in this inferred range of tolerance. Once mercury is inactivated by selenium it is mostly stored in the liver and not excreted (LaHaye et al., 2006; Wagemann et al., 2000). This inactivation results in much more mercury in the livers of dolphins than flesh of dolphins or of fish. But when the Mekong dolphins are compared to dolphins elsewhere their mercury concentration is low. Although there are widespread concerns about declining numbers of Mekong River dolphins (Beasley, 2007), it is not possible to prove that mercury resulted in the sampled Mekong dolphin mortality.

5b Selenium

The selenium content in dolphin kidney tissues was found to be closely correlated to the mercury content ($r^2 = .98$, $n=8$). The molar ratio of selenium to mercury in the kidneys was 1.78 which is not much different than in liver tissue (1.80, without the one extreme liver sample with high Se and Hg concentrations). The selenium and mercury contents of the livers were not so closely correlated ($r^2 = 0.58$, $n=8$, again without the outlier). However when

Table 4. Mercury in Fish from Srepok River.

Fish Species	FAO name	Mass g	Hg ng·g ⁻¹	SD	Habitat
<i>Channa melasoma</i>	black snakehead	1,700	414	16	Fish predator
<i>Channa melasoma</i>	black snakehead	400	28	4	Fish predator
<i>Channa melasoma</i>	black snakehead	350	156	3	Fish predator
<i>Channa melasoma</i>	black snakehead	350	60	0	Fish predator
<i>Channa marulius</i>		1,400	297	15	Fish predator
<i>Channa orientalis</i>	walking snakehead	50	25	0	Fish predator
<i>Ompok bimaculatus</i>	butter catfish	800	371	29	Crustacean fish predator
<i>Clarias meladerma</i>	blackskin catfish	250	84	4	predator
<i>Microneam micronema</i>		100	228	25	Crustacean fish predator
<i>Hemasilurus mekongensis</i>		300	206	26	Fish predator
<i>Mystus nemurus</i>		200	141	1	Insect, fish crustacean predator
<i>Mystus wykioikes</i>		400	13	2	Crustacean fish predator
<i>Mystus wykioikes</i>		100	249	16	Crustacean fish predator
<i>Datnoides quadrifasciatus</i>	barbed tigerfish	150	124	5	Crustacean fish predator
<i>Notopterus notopterus</i>	bronze leatherback	100	53	2	Insect fish predator
<i>Pangasius larnaudiei</i>		8,000	112	4	Omnivore
<i>Mactrognathus taeniagaster</i>		100	53	2	Insects worms
<i>Osphroenmus exodon</i>	elephant ear gourami	400	13	2	Herbivore
<i>Laides sinensis</i>		100	52	4	Unknown
mean			149		

Table 5. Dolphin Mercury Content.

Location	Lead author	Liver mean	Liver Max	Kidney mean	Number
Japan [#]	Endo et al, 2002	370 ± 525	1,980	43 ± 44	22L, 15K
Guinea ^{##}	Lailson-Brito et al, 2012	20 ± 31	132	ND	19 L
Adriatic ^{###}	Pompe-Gotal et al, 2009	336 ± 498	916	28 ± 40	16 both L, K
Texas ^{###}	Meador et al, 1999	212 ± 313	1,404	33 ± 65	30L, 29K
Mekong ^{###}	Murphy et al. 2005	8.1 ± 20	67	2.2 ± 3.3	11L 8K

[#] These dolphins were captured alive. ^{##} Accidentally captured in gill nets.
^{###} Stranded on shores
 L is liver, K is kidney, all concentrations as wet weight µg·g⁻¹, ND no data.

all the data are plotted it becomes obvious that with the exception of the one outlier with high mercury, the mercury to selenium ratio is fairly constant (Figure 5).

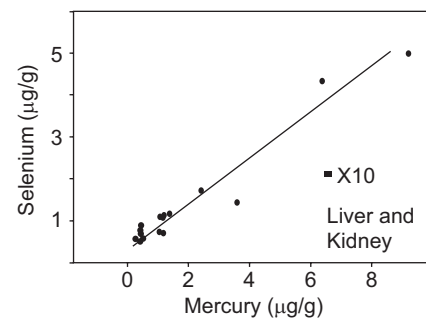


Figure 5. Mercury/Selenium Ratio in Mekong River Dolphins.

Marine mammals are known for their low susceptibility to mercury toxicity, and selenium may play a role in this protection against mercury (Koeman et al., 1973; Wang et al., 2001). It has been reported that Brazil has high concentrations of selenium that may provide some natural protection against mercury contamination there (Soares de Campos et al., 2002). The consistency in the ratio with the Mekong dolphins might suggest successful detoxification of mercury. The Environmental Department of South Australia also assumes that a constant ratio of selenium to mercury indicates successful detoxification of mercury (SAEPA, 2005).

5.1 Treatment - Fisheries

The only common approach to mitigate the problem of mercury in fish is a combination of monitoring, education and selective consumption of fish. Eventually the reservoirs will recover from a slug of mercury loading but it can take 10 to 20 years (Munthe et al., 2007). Not all fish will respond the same. Predator fish will become more toxic than omnivores or herbivores. Roulet et al. (2000) showed that predator fish in the Amazon have up to nine times the mercury content as herbaceous fish. In some locations, fish that eat algae (i.e. *Ospbroenmus* in Table 4) will likely remain safe to eat. Only in extreme situations like Lake Manso (Ahlin and Larsson, 2011) would all fish species be too contaminated to eat. Public education and direction of which fish are safe can only be done with an extensive monitoring program. Now that the Cambodian government (Camcontrol, within Ministry of Commerce) has purchased the required analytical equipment for such analysis, these monitoring activities should be achievable.

The large biodiversity of fish in Cambodia requires either very large data sets or use of indicator species to provide advice to the public. Decisions can be made better with more data but likely indicator species and general concepts related to predators vs. plankton eaters, size and location of fish will be the basis of fish advisories. An example of the complexities can be seen in Table 4.

Direct treatment of a reservoir to inactivate mercury has only been done a few times. A Swedish team added selenium directly to a reservoir to inactivate mercury and reduced the mercury content of fish by about 80% (Paulsson and Lundbergh, 1989). This option was considered but rejected in Canada. Selenium has a very high affinity for mercury, selenium is an essential element for human health but in high concentrations it is toxic. Enhanced harvesting of fish has also been proposed to treat a lake with mercury but this option produces a waste and takes time. Anything that reduces eutrophication and carbon input to the reservoir would reduce anoxia of sediments and should decrease methylation of mercury. Alternative protein supplies are required in sites where fish will likely to become too toxic for consumption. Aquaculture is one option but it requires training and ongoing assistance with fish management. There is no inexpensive quick fix for a mercury contaminated lake. It is best to avoid the problem.

6 Consumer Products

The best documented consumer products in Cambodia with substantial mercury are skin whitening creams (Murphy et al., 2009b, 2012) (Table 6). About 16% of whitening creams collected contained more than 20 $\mu\text{g}\cdot\text{g}^{-1}$ of mercury. American and ASEAN guidelines for mercury in these products prohibits more than 1 $\mu\text{g}\cdot\text{g}^{-1}$. The highest concentration of mercury in a skin whitening cream in Phnom Penh was about 35,000 $\mu\text{g}\cdot\text{g}^{-1}$. For users of the creams with the most mercury, the potential for neurological toxicity is high. Weldon et al. (2000) reviewed neurological damage and a presence of high levels of mercury in urine of skin cream users (average of 146.7 $\mu\text{g}\cdot\text{L}^{-1}$) from a skin whitening cream with 6–8% mercury. In our analysis it was not uncommon for ladies to cover their whole body twice a day and with creams that were 2 to 3.5% mercury. A third of the samples that were custom-made or modified by beauty shops contained more than 20 $\mu\text{g}\cdot\text{g}^{-1}$ of mercury. A handheld XRF analyzer proved to be an excellent tool for screening mercury in about 700 skin creams, and could be particularly useful in developing countries because it is relatively inexpensive, requires no sample preparation or extraction, can be used by staff with little technical background, and can facilitate on-site education. We can accurately measure the mean mercury content but risk analysis is compromised by clients being uncertain or evasive about their skin cream use. Also the dermal

Table 6. Mercury in worst brand name skin whitening creams.

Product	Apparent Source	Total Mercury
Eucerin	USA	23,200
Hua Tha Li	China	19,256
Chang Chun	China	18,458
Enjoy	USA	13,800
Rojzy Jiali	Vietnam	12,528
Yimei Yellow	China	12,014
Guoyao	China	11,500
Diamond	Unknown	6,147
Hua Hin	China	5,454
Qian Mei	China	5,110
FC	Cambodia	4,949
Malis	Thailand	3,552
Lulanjena	China	2,990
Oreal2	Unknown	2,852
Maly	Thailand	1,938
Japanese	Japan	1,652
SS-II	Unknown	1,410
Britney	Cambodia	1,223
Mlis	Thailand	996

Note that the real source of these products is unknown. This selection of samples were processed by XRF analysis. Concentrations are in $\mu\text{g}/\text{g}$. American and ASEAN guidelines are 1 $\mu\text{g}\cdot\text{g}^{-1}$ of mercury.

absorption is not well resolved. The best relevant analysis is with guinea pigs where about 3% of mercury was dermally absorbed (Skog and Wahlberg, 1964). A simple comparison of guidelines for various sources of mercury indicates skin whitening creams are one of largest sources of mercury contamination to Cambodians (Table 7). In Table 7 we show the relative exceedances of relevant guidelines for the maximum, arithmetic and geometric mean of major sources of mercury in Cambodia.

We also evaluated the mercury content of hair to help link our results to the studies done by Agusa et al. (2005, 2007) where they found high concentrations of mercury in hair in Phnom Penh. Figure 6 shows that hair from users of skin whitening creams does indeed contain high concentrations of mercury (up to 24,000 $\text{ng}\cdot\text{g}^{-1}$). Furthermore, note that the concentration of mercury on the distal portion of the hair was always higher than the proximal portion. The probability of this happening by chance is 1 in 65,536. It is highly suggestive that the mercury comes from surface contamination associated with sleeping while the face is covered with whitening cream. Especially for isolated sites, hair analysis is much more convenient than urine or blood analysis but for skin whitening creams, urine or blood analysis of mercury would be a better assessment of mercury assimilation than hair analysis or interviews. We also evaluated the mercury content of hair from 28 methylamphetamine addicts and found 1,930 $\text{ng}\cdot\text{g}^{-1}$ of mercury (Murphy et al., 2005). This indicates that

Table 7. Relative guideline exceedances of Major Sources of Mercury*.

Source of Hg	#	Geo mean	Arith mean	Max	Guideline	Comment
Chinese meds ^{&}	11	13	7,000	30,000	RfD	Rare, unclear
Whitening creams	734	4.9	456	35,000	ASEAN	Common serious urban Problem
Artisanal mining	29	3.2	8.5	42	RfD	Localized
Fish sesan river [%]	19	3.7	5.3	11	RfD	Growing major rural Issue
Toys (Hg) ^{&}	152	0.4	5	218	EU	Rare, unclear
Dental amalgams	82	NA	0.22	0.55	RfD	Common, probably occasionally NB

* Geo mean (geometric mean), Arith mean (arithmetic mean) and max (maximum) are the relative times or multiples of the guidelines given. For example, for Chinese traditional medicines, the geometric mean of 11 samples was 13 times the USA EPA Guideline RfD limit of exposure. RfD is USA EPA approach to a guideline. EU is European Union guideline. ASEAN is Association of Southeast Asian Nations guideline.

[&]-absorption is poorly documented. # Number of samples. NB, important.

[%]Max for fish assumes people select for preferred *Channa* (snakehead) predator species.

Dental RfD Mean from Halbach et al. (2007).

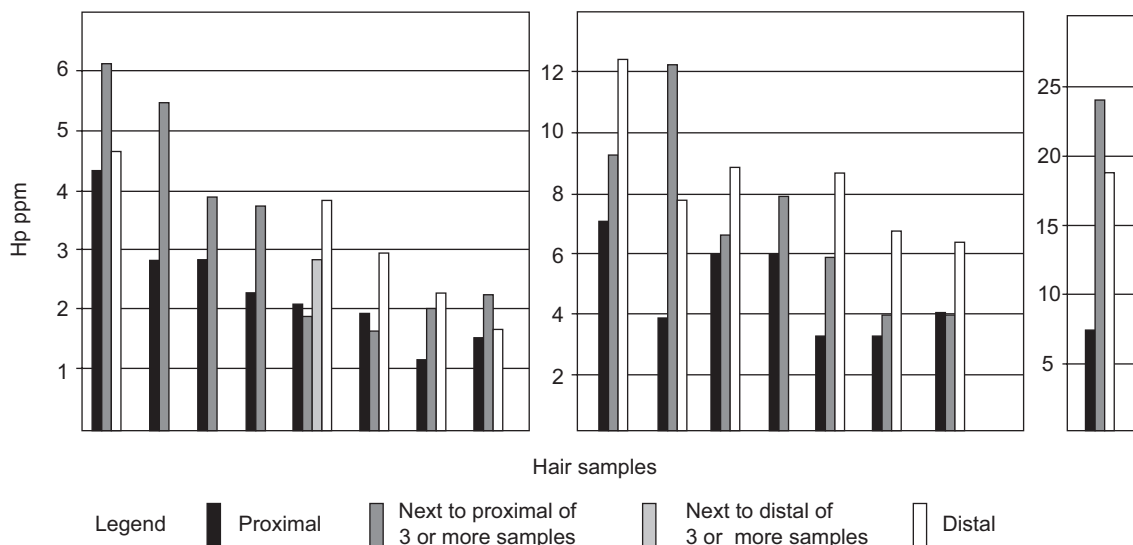


Figure 6. Mercury in Hair of Users of Skin Whitening Creams. Sections of hair were cut to distinguish mercury content next the scalp (proximal) to distal, (farthest from the head).

methylamphetamine in Cambodia is not made with mercury, a common catalyst in its production. We chose not to include the hair data of selected users of skin whiteners known to contain mercury in Figure 1. Since skin whitening creams are now very common in urban areas in Cambodia, likely Agusa's studies of mercury in Phnom Penh (2007, 2005) reflected use of skin whitening creams.

We used an XRF analyzer to measure the metal content of traditional medicines in Phnom Penh that are produced in China and Cambodia. Nine products from Cambodia had no significant content of toxic metals. However four of eleven products from China contained mercury, at times in extreme concentrations. The worst products were two forms of cinnabar (HgS) which were 77% and 82% mercury. Two patent formulations contained 2,784 and 2,693 $\mu\text{g}\cdot\text{g}^{-1}\text{Hg}$. The other traditional Chinese medicines we sampled did not contain measurable mercury ($<20 \mu\text{g}\cdot\text{g}^{-1}$). The oral dose of mercury in one patent product we sampled was 21 mg and the resulting mercury exposure is about 1,600 times the USEPA RfD guidelines.

The oral dose of cinnabar is about 0.65 g (<http://www.nutritionalwellness.com/nutrition/herbs/c/cinnabar.php>) which for our two samples would be 517 mg or 11.5 $\text{mg}\cdot\text{kg}^{-1}\text{d}^{-1}$ for a 45 kg person and the resulting mercury exposure of this traditional medicine is therefore more than 30,000 times the USEPA RfD of 300 $\text{ng}\cdot\text{kg}^{-1}\text{d}^{-1}$. When first advocated for medical use in ancient times these compounds were likely effective in controlling parasites which remain a problem in Cambodia. Apparently cinnabar is still commonly given to children as a sedative (Beers and Mousavi, 2013). Hopefully these products are only used infrequently and perhaps their absorption is low. They are only available in small minority of "pharmacies" and some are beyond the expensive of most Khmers. The Center for Disease Control and Prevention in the USA found mercury, lead and arsenic in traditional medicines from China and India (CDC, 2012). In a review of 40 Chinese traditional medicines in current use, Liu et al. (2008b) stated "Little is known about toxicology profiles or toxicokinetics of cinnabar and cinnabar-containing traditional medicines, and the high mercury content

in these Chinese medicines raises justifiable escalations of public concern". Because of their high mercury content, these products are barred from the USA and EU (CDC, 2012). There are at least two publications showing toxicity of cinnabar to mice at doses used by people (Huang et al., 2008, 2012). A recent publication reviews the debate that the problem may be inappropriate doses of mercury not an unsuitable medicine (Beers and Mousavi, 2013). Clearly aspects of the use of traditional Chinese medicines as intestinal absorption need more analysis. Any one studying mercury in Cambodia should know of their presence.

Another potential source of mercury is children's toys. Some of the bright shiny paints on toys purchased from a well-known international vendor contained as much as 0.5% mercury but the worst product with 2% mercury were spinning tops apparently copying a very popular top with much less mercury from China. These tops contained mercury more than 200 times the EU guideline. Of 152 analyzes of toys, mercury was detected in 23 toys above the EU guideline for scrapeable Hg of $94 \mu\text{g}\cdot\text{g}^{-1}$ (Directive 2009/48/EC). The oral absorption of mercury in toys is unknown; thus, these results are preliminary and only demonstrate a potential concern with mercury poisoning.

Another common source of mercury in Cambodia is dental amalgams. The risks of dental amalgams are still debated. Mutter (2009) disputed a publication by the European Union (EU) that dental amalgams were safe (SCENIHR, 2008). Mutter states that the EU ignored autopsy data showing a "2–12 fold increase in several body tissues was observed in deceased individuals with dental amalgam". Mutter further stated that there is a "2–5-fold increase of mercury levels in blood and urine in living individuals with dental amalgam". Since 2009 WHO (WHO 2009) has called for the phasing down of dental amalgams. Furthermore it will be part of the 2012 Mercury Convention but interpretations include the viewpoint that the phasing down will be voluntary (ADA, 2013). In another European study, Halbach et al. (2008) stated that "The integrated daily Hg dose absorbed from amalgam was estimated up to $3 \mu\text{g}$ for an average number of fillings and at 7.4 for a high amalgam load which are within the limits proposed by WHO, ATSDR and EPA". Under the USEPA guidelines, a 45 kg woman with a high amalgam load would represent about 0.55% of the RfD. Halbach's report is the only report we found with specific data for risk assessment and facilitates comparison of mercury exposure in Cambodia (Table 7). Using Halbach's data it appears that dental amalgams are one of the least dangerous sources of mercury in Cambodia. Dental amalgams are much less a problem than skin whitening creams, Chinese traditional medicines or fish. There are of course uncertainties such as the amount of absorption with each of these mercury sources. It is interesting that USEPA concedes that "existing data indicate that certain individuals with a pre-existing hypersensitivity or allergy to mercury may be at risk for adverse health effects from mercury vapor released from dental amalgam" (CDRH, 2010). The same must apply to some of the extreme exposures to mercury in skin whitening creams and Chinese traditional medicines.

There are a variety of minor sources of mercury that should be considered in any evaluation of a client with mercury poisoning. In 2010, Khy Sovuthy reported in a major newspaper that 9,003 kg of quail meat in three shipments from Vietnam to Phnom Penh were confiscated and incinerated because they were preserved with mercury. An anecdotal story of relevance is that some fruits from Vietnam are treated with mercury to prevent fungal spoiling of fruit. Traditionally some fungicides did contain mercury. This latter idea is speculative for Cambodia but the story is associated with a fruit very susceptible to fungus and similar cases are documented elsewhere. In 1972 about 10,000 Iraqis died and another 100,000 were severely compromised by organic mercury that had been applied to wheat seeds to prevent spoilage (Bakir et al., 1973). In 2004, Ghosh et al. reported that mercury was still used to suppress fungus in India to protect seeds intended for planting and on fruit for human consumption.

1.7 Discussion

1.7.1 Effect of Mercury on Cambodian Human Health

The extremes of Minamata disease (Harada, 1995) are unlikely in Cambodia but without good management, disasters like the Sihanoukville mercury spill could reoccur. Expected toxicity from mercury in Cambodia includes neurocognitive disorders, suppressed immune systems, impaired fertility and perhaps kidney damage. Perhaps the greatest concern to the Cambodian gold mines are demonstrations by German medical teams of mental impairment in children both working with mercury and living nearby gold mines in Indonesia and Zimbabwe (Bose-O'Reilly et al., 2008). American medical doctors also documented that children living in gold mines using mercury in Ecuador had neurocognitive deficits in visual-spatial reasoning (Counter et al., 2006). It is important to note that the mean concentration of mercury in hair of these children was $8.5 \mu\text{g}\cdot\text{g}^{-1}$, which is not different than the mean concentration of mercury that we found at Prey Meas gold mine in Cambodia (Figure 1). In the Bose-O'Reilly et al. (2000) study the chronic mercury intoxication was strongest in ball-mill workers (approximately 65%) and amalgam smelters (85%) but was identified in 38% of the non-occupationally exposed population downstream. They recommended treatment of the worst miners with a chelating agent "indisputably". Cambodia does not have the capacity for chelation therapy of mercury poisoning.

The only data that exists to evaluate the potential effect of mercury on human health in NE Cambodia is hair analysis. The levels of mercury in human hair at Prey Meas gold mine are twice that of Lumphat, Ratanakirri which is 80 km downstream of the gold mines (Figure 1). To be conservative and more representative of the watershed, it might be best to compare Lumphat to four studies of mercury assimilated from eating fish. 1) The mean levels of mercury in human hair in Lumphat ($4,540 \pm 810 \text{ ng}\cdot\text{g}^{-1}$, $n=25$), is virtually the same as the level the mercury in hair associated with impaired male fertility in Hong Kong ($4,233 \text{ ng}\cdot\text{g}^{-1}$, $n=117$) (Dickman and Leung, 1998). These Hong Kong men consumed high amounts of mercury in marine fish. 2) It is also almost the same as the mean concentration of mercury in the hair of the fish-eating population of the Cuiaba River, Amazon ($4,200 \pm 2,400 \text{ ng}\cdot\text{g}^{-1}$, $n=29$) which was associated with reductions of fine motor speed, dexterity, concentration, verbal learning and memory (Yokoo et al., 2003). 3) The hair in Lumphat has more than four times the level associated with attention deficit hyperactivity disorder in the USA (ADHD, $1,000 \text{ ng}\cdot\text{g}^{-1}$) (Sagiv et al., 2012). 4) Furthermore, Oken et al. (2005) found that in the USA mothers who ate some fish did better on cognition evaluations but when mercury in maternal hair exceeded $1,200 \text{ ng}\cdot\text{g}^{-1}$ the infant's cognition was impaired. This level is less than a third that found in people along the Sesan River. This pattern of children being stimulated by eating some fish but higher doses of mercury in fish impairing them was also observed by Sagiv et al. (2012). Further downstream, from Lumphat the mercury in hair decreased slightly (Figure 1, Table 1). We also sampled one remote village upstream of the mine and deforestation that had much lower levels of mercury in hair: mean = $1,576 \pm 1,000 \text{ ng}\cdot\text{g}^{-1}$, $n=9$. This upstream site could represent the baseline for this region before mining and deforestation. In the data sets from Ratanakirri most of these women had never left their villages and none had left the area. Their isolation, poverty and skin color makes the probability of any of them using skin whitening creams highly unlikely. The rural development is proceeding quickly and whitening creams may soon reach remote areas. In Phnom Penh such creams appear to contaminate hair with mercury. The only obvious source of mercury for these isolated villages is fish. The fish data in Table 4 supports this concern but more data on mercury in fish is required.

By comparison in a large study of 1,726 Americans, the average content of mercury in hair was $470 \text{ ng}\cdot\text{g}^{-1}$ (McDowell et al., 2004). The National Research Council (2000) published that USEPA's Reference dose (RfD) of $0.1 \mu\text{g}\cdot\text{kg}^{-1}/\text{body weight}/\text{day}$ corresponds to a concentration of mercury in hair of about $1,000 \text{ ng}\cdot\text{g}^{-1}$. More recently Bellanger et al. (2013) proposed that a level of $580 \text{ ng}\cdot\text{g}^{-1}$ of mercury in human hair reflected safe levels of exposure to avoid mercury mediated neurotoxicity. The idea that mercury can impair the nervous system of children is not new (WHO, 2003; Poulin and Gibb, 2008). But as with the agreement to phase out dental amalgams (Mutter, 2009; SCENIHR, 2009) this analysis by Bellanger et al. reflects increasing concerns with low levels of mercury. It has huge relevance to the Native communities who rely upon fish as their main source of protein. Even with older guidelines, the intervention to Native community diets in Canada at hydroelectric dams contaminated with mercury three decades ago was controversial (Dumont et al., 1998). At one such site impacted by hydroelectric dams, the proportion of Cree Native people with mercury levels in hair in excess of $15,000 \text{ ng}\cdot\text{g}^{-1}$ declined after intervention from 14.2% in 1988 to 2.7% in 1993/94 (Dumont et al., 1998).

There will always be concerns about how results from other countries will apply to Cambodia. It should not be forgotten that "methylmercury is a potent toxin, bioaccumulated and concentrated through the aquatic food chain, placing at risk people throughout the globe and across socioeconomic spectrum who consume predatory fish as a dietary mainstay" (Mergler et al., 2007). Mergler et al. (2007) also reviewed how diet and choice of biomarkers can influence the apparent toxicity of mercury but it only modifies not removes the risks. Both Mergler et al. (2007) and the EFSA Panel on Contaminants in the Food Chain (2012) reviewed many such studies including the long-term analysis on the effect of methylmercury in fish on people in the Faroe Islands and the Seyshelles. The differences are significant but again the details substantiate that the risks are strong and the prediction of toxicity is not exact. As with the ADHD work of Sagiv et al. (2012) in the USA, the studies on fertility by Dickman et al. (1998) in Hong Kong or Oken et al. (2005) in the USA, analysis pertaining directly to Cambodia is uncertain but the risks are real. Furthermore the very complete review by Mergler et al. (2007) did report occasionally the rare lack of an anticipated toxic response which may reflect unknown variables or analytical methods. It should not be forgotten that Cambodia is still in the initial stages of development, especially with hydroelectric dams and the simple review of existing data is mainly for demonstration. The risks of mercury contamination are increasing and analysis of suitable biomarkers and health analysis should be implemented.

Agusa et al. (2005) found mercury problems in Phnom Penh that were not associated with fish. If the source of mercury in their study was skin whitening creams and if the pattern of mercury in sampled hair was representative of surface contamination as is suggested in Figure 6, then Agusa's mercury in hair data should be interpreted carefully. However Agusa et al. (2007) also had data on mercury in blood which is more appropriate as an estimate of mercury exposure, especially for urban Cambodia. They found serum estrone and estradiol levels were positively correlated with blood mercury level for both males and females, indicating possible induction of female hormones by mercury exposure in Cambodians (Agusa et al., 2007). These observations are consistent with studies indicating mercury is an endocrine disruptor in mercury exposure experiments with birds, fish, and human cell cultures. Since an increase in these female hormones can induce impotence (Harrington, 1982), it is also consistent with observations by Dickman et al. (1998) of men in Hong Kong who ate a lot of top predator fish with mercury and were subfertile. It would be informative to assess the relationship with use of skin whitening creams and endocrine disruption. Ideally some of the medical assessment techniques used to measure

neuropsychological impairment in miners (Bose-O'Reilly et al., 2008; Counter et al., 2006) and the fishing population (Lebel et al., 1996) would also be applied to users of skin whitening creams.

The only enforcement on mercury in consumer goods in Cambodia has been on skin whitening creams. However, a lot more work is required to improve the management of skin whitening creams. There has been strong media coverage of events such as the criminal trial of a Cambodian vendor who sold a skin whitening cream that apparently killed a young lady. Our observation has been that the worst creams are now often hidden at markets but these creams remain available. The assessment for non compliance and a decision rule for enforcement were very conservative. The Ministry of Health banned all skin whitening products that had in excess of $1,000 \mu\text{g}\cdot\text{g}^{-1}$ of mercury. This decision is mostly a reflection of the need to suppress the availability of the worst products and the limitations of Cambodian enforcement. This decision rule is 1,000 times the ASEAN guideline and 50 times the detection limit of handheld XRF analysis. Analysis typically had relative standard deviations of 4% (Murphy et al. 2012) so analytical measurement is not a factor in enforcement. Adoption of the EU guideline of $70 \mu\text{g}\cdot\text{g}^{-1}$ Hg (Global Mercury Assessment 2002) for a decision rule would still allow for use of XRF analysis without any concern of analysis variation compromising decisions. However, there is a lack of analytical capacity to quickly measure such creams in SE Asia. Handheld XRF analysis is an appropriate tool to facilitate management of mercury in skin whitening creams. Similarly handheld XRF analysis would also be a useful tool to suppress the presence of mercury in traditional medicines, toys and jewelry.

Especially in remote locations any assessment of a link between mercury, immune system and human health is compromised by their lifestyle. The miners suffer in a few obvious ways such as poor nutrition, diarrhea, malaria and exposure to high levels of mercury. Although there has been no analysis at the mines, as with most of rural Cambodia they must also suffer from parasites, and a variety of other diseases such as thalassemia and tuberculosis (TB) (NIPH, 2011). The miners often asked for medical attention. Headaches were common which could represent many things including mercury poisoning. Analysis of malaria and TB should be considered. Suppression of the immune system by mercury is well known (Clarkson and Magos, 2006; Gardner et al., 2009) but seems less commonly studied than the neurological aspects. TB strikes those with weakened immune systems. Vitamin A deficiency which is common in NE Cambodia where the gold mines mostly occur (Hellen Keller Int., 2001) is believed to weaken the immune system (Russell, 2001). It has been estimated that gold workers in Brazil are four times more likely to have a malaria infection (Crompton et al., 2002). This was validated by Silbergeld et al. (2005). However, work by Alves et al. (2006) indicates that for exposure to methylmercury from fish, malaria is not enhanced. Comparison of projects and extrapolation to Cambodia should be done cautiously. Factors like selenium in Brazil are believed to naturally reduce mercury toxicity (Soares de Campos et al., 2002) and its concentration likely varies. Synergies of mercury toxicity with poor nutrition such as vitamin A deficiency must also vary.

Lastly there is always the potential for a hypersensitive response to mercury. The senior author of this paper has seen four hypersensitive responses to environmental toxins, two of which without prompt medical attention would have resulted in death. As per the conclusion by the USEPA that some Americans suffer from hypersensitive responses to dental amalgams (CDRH, 2010), we do not doubt that some Cambodians exposed to mercury for gold extraction, in the oil and gas industry, skin whitening creams or other consumer products could suffer from mercury hypersensitivity.

1.8 Monitoring

A variety of monitoring techniques are required to evaluate management of mercury and to alert agencies to take action to protect the workers and public. Monitoring of workers in industries using mercury should include air monitoring such as with Draeger-tubes. In the UK urine analysis for occupational exposure is recommended every one to three months with blood analysis for more acute exposure (Mason et al., 2001). Ideally regional assessments of people relying upon fish for most of their protein would include both blood and urine monitoring. As well as monitoring of mercury in urine, kidney damage can be monitored by analysis of N-acetyl-beta-D-glucosaminidase and beta2-microglobulin in urine (Schaller et al., 1980; Zhao et al., 2008). For workers known to be exposed to mercury, monitoring could use neurological assessment techniques (Lebel et al., 1996; Counter et al., 2006; Bose-O'Reilly et al., 2008). A medical review in a factory has to consider the occasional contamination that workers can expose themselves to outside of work.

Environmental monitoring should include a variety of representative targets. With the exception of factory outfalls, water is the least appropriate substrate to be monitored. Its composition changes too quickly with seasonality and storm events. Plus most mercury is attached to particles and many simple methods of water collection poorly represent particulate matter. It would take a very large data set of water analysis to show any significant changes associated with increased mercury loading. Because they are very susceptible to bioaccumulation, top predator birds are often used for biomonitoring. Monitoring in Finland by Häkkinen and Häsänen (2005) documented mortalities of ospreys from mercury. In Canada and NE USA, monitoring of common loons, a fish eating bird observed behavior changes and reduced nesting success (Burgess et al., 2005). Monitoring programs in Canada and the USA were set up to resolve the effect of mercury on reductions in populations of otters and mink (Yates et al., 2005). There are always concerns with sampling of endangered species. In Canada for many years, eggs of a common bird with opportunistic feeding habits, Herring Gulls were collected for biomonitoring of the ecosystem (Weseloh et al., 2006).

Because of the importance of fish in human diets and the desire to export fish, this is one of the most obvious targets for biomonitoring in Cambodia. There are several hundred fish species in Cambodia and predators should be selected as indicator species for initial if not most sampling. There are very extensive monitoring programs in Canada for fish with Ontario's program available in other languages including Khmer (http://www.ene.gov.on.ca/environment/en/resources/collection/guide_to_eating_ontario_sport_fish/STDPROD_075994.html). Figure 7 shows that for *Channa striata* collected at Lumphat, on the Srepok River in 2007 there is linear relationship between the size of the fish and the mercury content. The data points in Figure 7 were means of triplicate analyses with the standard deviations being smaller than the data point. This linear relationship is the anticipated classic response derived in studies usually done in temperate latitudes. However, in the Amazon more complicated relationships between size and mercury content exist and some predators do not have a higher mercury content when larger (Sampaio da Silva 2005). Roulet et al. (2000) have shown that predator fish in the Amazon have up to nine times the mercury content as herbaceous fish. To manage the risks associated with mercury in fish in Cambodia, more analysis is required.

For the long term, monitoring of atmospheric mercury deposition would be interesting. The tree data in Figure 4 indicates that over the last 100 years local net deposition of mercury in Cambodia has varied up to 100 fold. Atmospheric movements of mercury are global processes (Sunderland

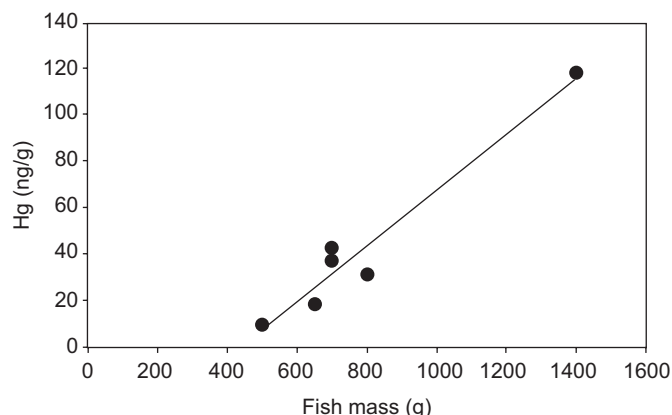


Figure 7. Mercury in *Channa striata*.

et al., 2009). Significant local atmospheric mercury deposition from point sources such as the Alberta oil sands (Kelly et al. 2010) and non-point sources (O'Driscoll et al. 2005) have been documented in Canada. Air pollution is a major concern in SE Asia. Emissions from forest fires in Indonesia have resulted in severe smog in Singapore (The Telegraph 2013) and impaired air quality at least as far as northern Thailand (Tiyapairat 2012). Logging and associated burning of these mature tropical forests in Indonesia is the typical process in SE Asia to develop plantations. These fires must release mercury and it will be bioconcentrated into fish in new hydroelectric dams. However, there does not appear to be any public data on mercury releases from these large fires or other suspect mercury sources such as large oil refinery complexes in SE Asia. Cambodia has the same land clearing underway as in Indonesia but is not able to set up atmospheric monitoring of mercury now. Biomonitoring likely is the quickest strategy to assess the anticipated changes of atmospheric mercury deposition. Wherever such sources are suspect and where there is an opportunity for biomagnification of mercury into people, monitoring of people's urine, hair and blood is warranted.

Perhaps it is appropriate to end with a comment on monitoring of umbilical cord tissue or umbilical cord blood which could be considered biomonitoring to detect future neurological toxicity. This technique has been used in the USA (TEACH, 2007), Canada (Muckle et al., 2001), Sweden (Ask et al., 2002), Japan (Sakamoto et al., 2007), Foroe Islands (Grandjean et al. 2005) and elsewhere (Mergler et al., 2007) as a biomonitor of newborn mercury exposure in the womb. Babies not only receive mercury from their mothers, they concentrate it. The concentration of mercury in the placenta blood can be 1.7 (Mergler et al., 2007) to 2 (Ask et al., 2002; Sakamoto et al., 2007) times higher than maternal blood. Some of the most extensive studies on mercury bioaccumulation have documented neurological damage to infants via this exposure route (Grandjean et al., 2005). The nervous system in the growing fetus is five to ten times more sensitive to methylmercury than the nervous system of adults (WHO, 1990). The Cambodians who eat a diet richest in fish are in isolated locations with minimal medical services so collection of umbilical cord tissue or umbilical cord blood would be difficult where it might be most important. Most studies on mercury exposures in the womb have measured total mercury or methylmercury (TEACH, 2007). However studies by Brender et al. (2006) and a Swedish team (Ask et al., 2002) did observe inorganic mercury passage into the womb. Moreover Brender et al. (2006) found that mothers with high inorganic mercury blood concentrations were nine time more likely to have a child with a neural tube defect. We are not aware of any study on inorganic mercury in umbilical cord tissue or umbilical cord blood for users of skin whitening creams.

1.9 Conclusions

1. Mercury contamination from skin whitening creams and artisanal gold mining in Cambodia is a concern requiring improved management.
2. Increased bioaccumulation of mercury from hydroelectric dams and deforestation in other countries and current data in Cambodia suggest that mercury contamination may become a problem in hydroelectric reservoirs in Cambodia.
3. There are some poorly documented sources of mercury in Cambodia especially traditional Chinese medicines and perhaps toys that potentially could harm individuals.
4. Levels of mercury in dolphins at Kratie were not at toxic levels.

1.10 Recommendations for Cambodia

1.10.1 Short-term

1. To assess the bioaccumulation and toxicity of mercury from fish in people, the following details should be evaluated at critical sites: proportion of mercury in a composite fish sample present as methylmercury and inorganic mercury, human ingestion rates of specific fish species, and relationships between fish size and mercury content.
2. To assess the toxicity of mercury in subsistent people dependent upon fish for protein, users of skin whitening creams and traditional Chinese medicines, mercury analysis of urine and blood should be used as bioindicators.
3. To assess sediment and mercury loading rates in watershed where hydroelectric dams are planned, monitoring should be conducted prior to, during and after construction in at least in a model study. Ideally the duration of post monitoring would be for a few years.

1.10.2 Long-term

1. Monitor the mercury content of indicator fish species in reservoirs every three to four years.
2. Monitor the processing of oil, natural gas and coal to ensure best available technology to reduce emissions.
3. Monitor storage of toxic wastes to protect workers and people living near sites with significant mercury.
4. Develop the partnerships and resources to assess neurological impairment by mercury in new situations such as skin whitening creams.
5. Improve the analytical capacity to measure mercury, including total mercury in natural gas, methylmercury and XRF equipment for rapid screening of consumer products and hazardous wastes.

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ASEAN	Association of Southeast Asian Nations
ATSDR	Agency for Toxic Substances and Disease Registry
CRM	Certified reference material
CVAAS	Cold vapor atomic absorption spectrometry
EIAS	Environmental Impact Assessments
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
Hg	Mercury
Km	Kilometer
MOE	Ministry of Environment
ng·g ⁻¹	Nanograms per gram
RfD	A reference dose is the estimated daily dose of a substance that can be consumed safely over a lifetime.
TB	Tuberculosis
UNDP	United Nations Development Programme
WHO	World Health Organization
XRF	X-ray fluorescence
µg·g ⁻¹	Microgram per gram

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