

**MERCURY AND METHYLMERCURY IN THE SOUTH CENTRAL
KENTUCKY KARST: ITS TRANSPORTATION, ACCUMULATION AND
POTENTIAL EFFECTS ON VULNERABLE BIOTA**

Kurt Lewis Helf, Ecologist
Division of Science and Resources Management
Mammoth Cave National Park
Mammoth Cave, KY 42259
Kurt_Helf@nps.gov

Introduction

The proposed Thoroughbred Generating Station (TGS) is a potentially large source of mercury (Hg) deposition on South Central Kentucky Karst (SCKK) ecosystems. Indeed, according to Peabody's own estimates TGS will be the fourth largest Hg emitter in the state of Kentucky (Table 1). Because prevailing winds tend to blow northeast, TGS would likely have the second largest impact in the state, in terms of Hg deposition, on SCKK ecosystems. Currently little data are available that would enable researchers to predict the effects of such a large increase in Hg deposition on SCKK ecosystems.

Plant Name	City	Utility Owner	Estimated Hg Emissions (Pounds)
Paradise Fossil Plant	Muhlenberg	Tennessee Valley Authority	519
Big Sandy	Lawrence	Kentucky Power Co.	485
Ghent	Carroll	Kentucky Utilities Co.	480
Thoroughbred Generating Station	Muhlenberg	Peabody Energy	420

Table 1. Rank estimated output of four top mercury emitting facilities in Kentucky. Note Paradise and Thoroughbred are in close proximity. Data for top three emitters were compiled from Environmental Protections Agency and Department of Energy data by the Environmental Working Group (Coequyt et al. 1999). Estimated emissions by Thoroughbred Generating Station are from Thoroughbred PSD/Title V/Phase II Application, 10/25/2001.

While research into the toxic effects of Hg bioaccumulation on organisms has increased recently, largely on commercial species, the toxic effects on ecosystems are not well understood. Further, knowledge of the toxic effects of Hg and bioaccumulation on susceptible SCKK ecosystems ranges from poor (i.e., surface ecosystems) to nonexistent (i.e., subsurface ecosystems). Due to the threat of increased Hg deposition and the absence of baseline knowledge of environmental concentrations of Hg's most toxic molecular form (i.e., methylmercury) in SCKK ecosystems, the author recommends a vigorous research program be initiated.

Transportation of Mercury and Methylmercury to Ecosystems

The abundance and distribution of pollutants in the environment, their bioavailability, and their toxicity to aquatic and terrestrial organisms are best understood in terms of molecular form (Witters 1998). Methylation is the important step that influences the ecological fate and effects of Hg. This is because all forms of Hg (e.g., Hg(II), Hg⁰, (CH₃)₂Hg) can be converted to methylmercury (MeHg) by natural processes in the environment [(Figure 1) (Keating et al. 1997)]. MeHg is the most toxic form of mercury, has a remarkable ability to pass through biological membranes, high chemical stability, and is excreted from most organisms very slowly (Micallef 1984, Eisler 1987, Keating et al. 1997, Downs et al. 1998, French 1999, Boening 2000, Mason et al. 2000).

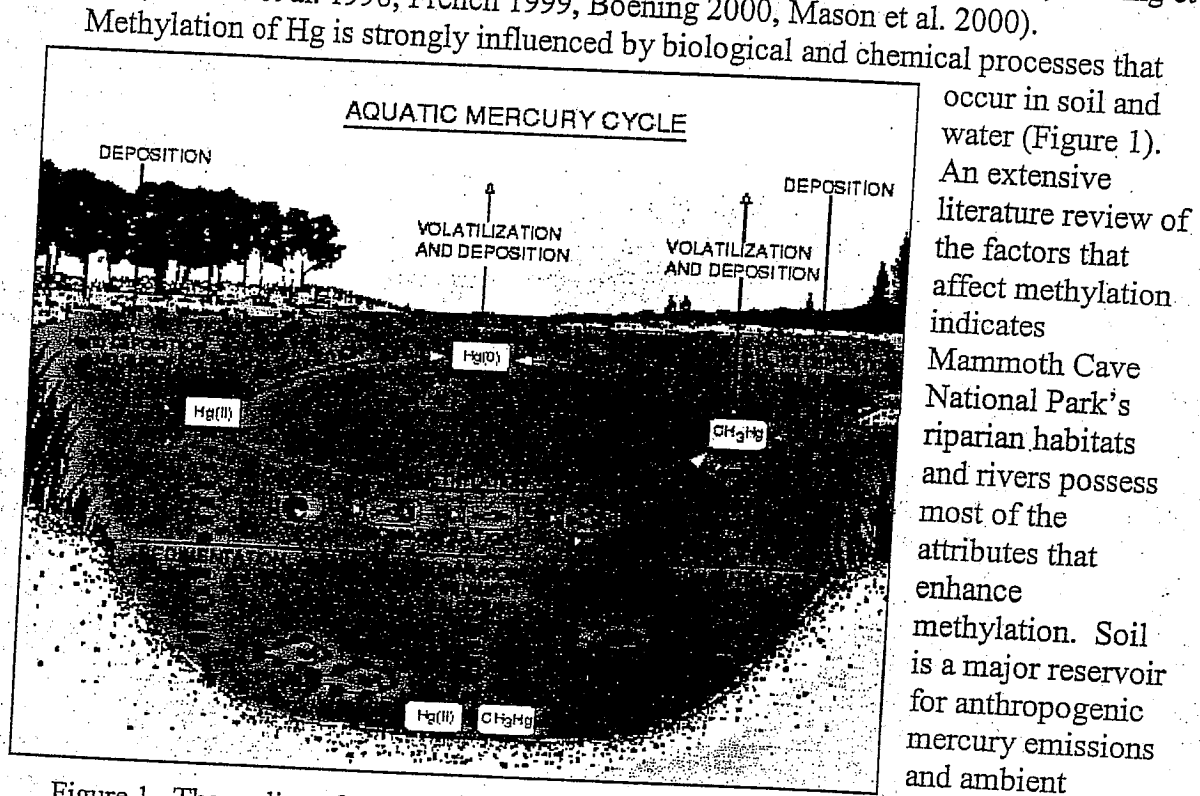


Figure 1. The cycling of various molecular forms of Hg through an aquatic ecosystem. Deposition occurs in several ways: rainwater that passes through a vegetation canopy (throughfall, left), direct deposition (wet, right), and dry deposition. Hg also readily adsorbs onto surfaces and so aquatic organisms may also take in MeHg adsorbed to the surface of contaminated prey.

conditions determine the rate of MeHg produced in soils. For example, soil fertilization increases the availability of Hg for methylation and so waterways with high levels of anthropogenic nitrogen deposition also show increased production of MeHg (Keating et al. 1997, Guimarães et al. 2000, Cooper and Gillespie 2001, Matilainen et al. 2001). These conditions already exist in the SCKK due to its receipt of nitrogen loads through long-range transport and subsequent deposition (DAQ 2000). In aquatic ecosystems, anaerobic sulfur-reducing bacteria in sediments are a major source of MeHg (Zillioux et al. 1993). Indeed, sediments contaminated with Hg can also serve as important reservoirs, with sediment-bound Hg recycling back into the aquatic ecosystem for

decades or longer (Keating et al. 1997, French et al. 1999, Mason et al. 2000). Mammoth Cave National Park's Green and Nolin Rivers sediment deposits increase in the impoundment zones created by Lock and Dam #6 increased, relative to non-impounded zones, due to reduced flow (Olson and Leibfreid 1999). If these deposits are already contaminated with Hg, they are likely a significant source of MeHg production in the Green and Nolin Rivers.

Hg and MeHg input from groundwater can be relatively constant temporally and spatially (Zelewski 1999), but increased Hg concentrations and production of MeHg in streams and rivers is highly seasonal. Indeed, most Hg and MeHg input to waterways is associated with snowmelt, storm-generated runoff (bound to suspended soil/humus or dissolved organic carbon), and throughfall or rainwater that passes through a vegetation canopy (Keating et al. 1997, Allan and Heyes 1998, Balogh and Johnson 1998, Mikac et al. 1999, Mason et al. 2000). In summer, high levels of MeHg in aquatic sediments are a result of elevated temperatures and increased activity of methylating microbes (Weber 1993, Hintelmann and Wilken 1995, Watras et al. 1998, Cooper and Gillespie 2001) and so production of MeHg coincides with the most productive periods in aquatic ecosystems. Mammoth Cave National Park is heavily forested and possesses extensive riparian habitat and so likely MeHg production in aquatic habitats is also highly seasonal.

Bioaccumulation of Hg and MeHg

Hg and MeHg are bioaccumulated rapidly because organisms are exposed through multiple pathways. Bioaccumulation refers to an organism's net uptake through all possible pathways including bioconcentration and biomagnification. Bioconcentration refers to the accumulation of Hg and MeHg that occurs when an organism is in direct contact with its surrounding medium (e.g., uptake from water through a fish's gills) and only accounts for a small percentage of an organism's total accumulated Hg and MeHg. However, Hg and MeHg are highly toxic and so even exposure to low levels can lead to toxic effects and death. Biomagnification is the largest contributor to the accumulation of MeHg in living tissue (Eisler 1987, Keating et al. 1997, Watras et al. 1998, Boening 2000, Mason et al. 2000). Biomagnification refers to increased concentration in organisms at successively higher trophic levels through ingestion of contaminated organisms at lower trophic levels.

Exposure Pathways of Hg and MeHg in Mammoth Cave National Park's Ecosystems

A. Surface aquatic ecosystems

In aquatic ecosystems MeHg concentration generally increases with trophic level (Figure 2). Primary producers accumulate MeHg within their cytoplasm at levels several orders of magnitude higher than water (Bloom 1992, Keating et al. 1997, Boening 2000, Mason et al. 2000, Simon et al. 2000). Phytoplankton are ingested by zooplankton which biomagnify MeHg approximately 3-10 times that amount (Downs et al. 2000, Mason et al. 2000). Organisms at higher trophic levels generally biomagnify MeHg at a similar rate and, once it is stored in their muscle tissue, excrete it very slowly (Downs et al. 2000). Hg also has a high affinity of surface adsorption and so organisms that feed on seston (i.e., suspended particulate matter such as plankton) or detritus (i.e., dead organic matter) can also ingest it in this manner (Keating et al. 1997, Ledin et al. 1997). Uptake of Hg can also occur through skin or gills and is heavily influenced by a consumer's size (i.e., surface area/volume ratio) and functional group (Boening 2000, Downs et al. 2000, Canivet et al. 2001).

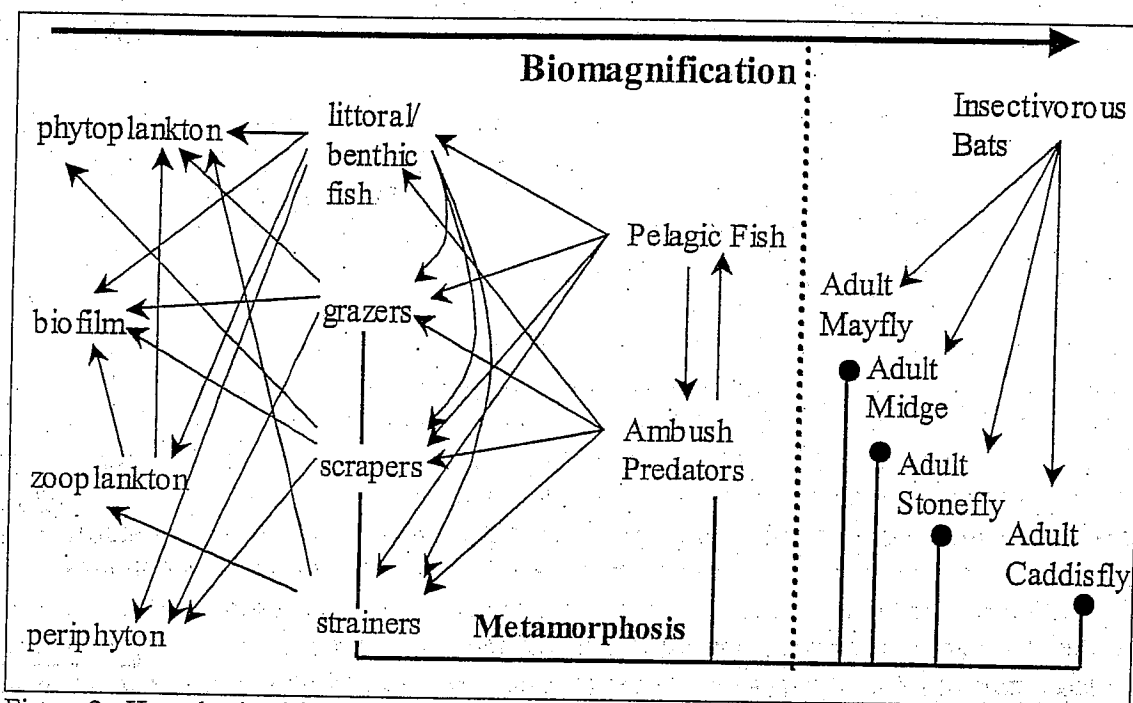


Figure 2. Hypothesized food web for biomagnification of Hg and MeHg within aquatic community and between aquatic and terrestrial communities. Note insectivorous bats accumulate Hg and MeHg from terrestrial (i.e., adult) forms of contaminated aquatic insects.

B. Subsurface aquatic ecosystems

Mammoth Cave's subsurface aquatic ecosystems are subsidized by the storm-generated influx of runoff and detritus from the surface, so transport of contaminants is most likely episodic (Meiman and Hall 1995). Storm-generated subsidies that enter through sinkholes or vertical shafts mostly acquire Hg from throughfall and detritus (Watras et al. 1998, Mason et al. 2000). These periodic subsidies likely form the basis for methylating conditions in accumulated sediments between storm events (Barr 1985). Further, during upstream floods on the Green River, backflowing through spring orifices brings the direct influx of river water into the cave (Hess et al. 1989) which also contributes MeHg contaminated water and sediment.

Subsurface aquatic organisms may accumulate MeHg in much the same manner as their epigeal congeners. However, it is not known which exposure pathway determines the toxic effects of contaminants. Laboratory experiments indicated long-term exposure (i.e., 10 days) to low concentrations of toxic metals (i.e., <0.5 mg/L) were lethal to subsurface amphipods (*Niphargus rhenorhodanensis*) and that surface and subsurface amphipods (*Gammarus fossarum* and *N. rhenorhodanensis*, respectively) bioaccumulated pollutants at the same rate (Canivet 2001). However, cave biota undoubtedly biomagnify Hg and MeHg through absorption and feeding on detritus and/or prey (Figure 3). In addition, the life history of subsurface organisms may make them particularly vulnerable to Hg and MeHg contaminated water and detritus. Indeed, due to their slow metabolism and long life span subsurface invertebrates likely bioaccumulate high levels of Hg and MeHg. Finally, invertebrate larval stages are particularly sensitive to Hg and MeHg (Boening 2000). Some subsurface invertebrates (e.g. Cave crayfish, *Orconectes pellucidus*) may take years to reach maturity which increases the length of time they are most vulnerable to contaminants.

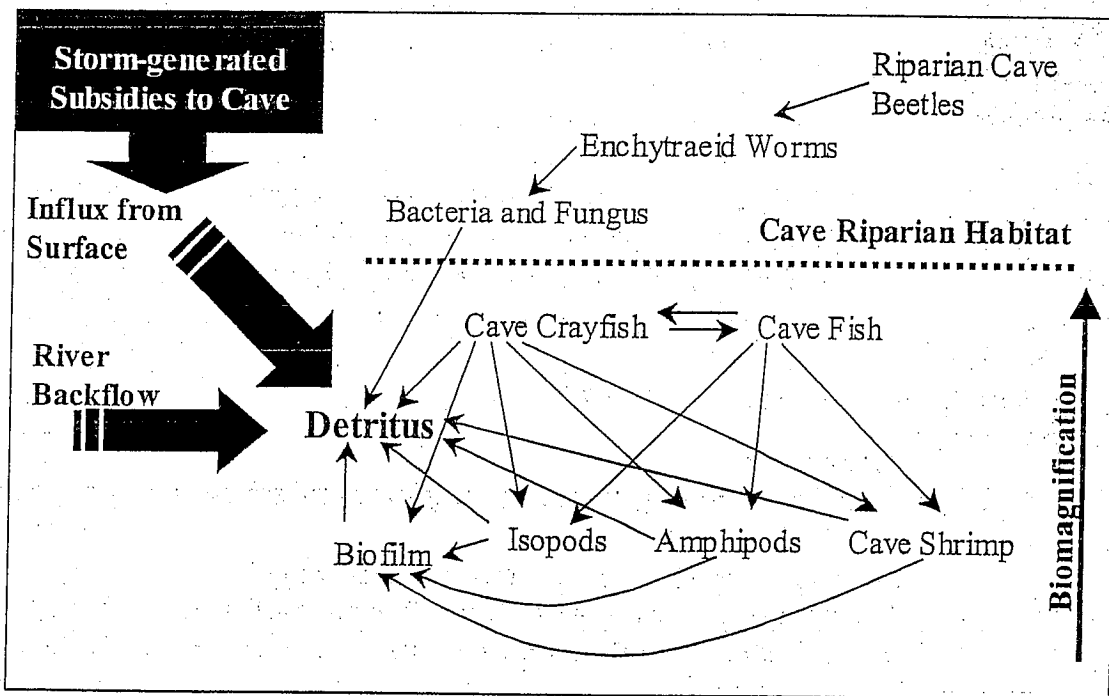


Figure 3. Hypothesized exposure pathways for biomagnification of Hg and MeHg within cave aquatic community and between cave aquatic and cave terrestrial communities.

C. Surface terrestrial ecosystems

Several possible exposure pathways to Hg and MeHg exist for terrestrial organisms: ingestion of contaminated food or water, direct contact with soil, and inhalation (Keating et al. 1997). The most important exposure pathway for terrestrial organisms is biomagnification because Hg and MeHg can accumulate at increasing concentrations with successively higher trophic levels. Terrestrial carnivores that consume prey from aquatic sources (e.g., insectivorous bats) are particularly vulnerable to biomagnification of Hg and MeHg [(Figure 2) (Hickey et al. 2001)].

Potential Effects of Hg and MeHg on Biota of Special Concern in Mammoth Cave National Park

I. Surface aquatic biota

A. Mussels

Freshwater mussels readily bioaccumulate Hg and MeHg because they ingest contaminated organisms, sediment, and have direct contact with contaminated water and sediment (McMahon 1991, Hickey et al. 1995, Keller 1989). Transplant experiments using *Elliptio complanata* indicated mussel growth was negatively correlated with tissue concentrations of total Hg (Beckvar et al. 2000). Further, exposure to Hg has been shown to disrupt gill function and may interfere with the respiratory system at every level of organization (Spicer and Weber 1991). Finally, experimental evidence suggests heavy metal contaminated water may affect Unionid mussel populations by reducing the ability of obligate parasitic larvae (i.e., glochidia) to close their valves and therefore attach themselves to host fish (Huebner and Pynnönen 1992). These results are particularly alarming because in natural populations only .0004% of released glochidia successfully encyst in fish hosts (McMahon 1991).

Indirectly, Hg may contribute to the decline in mussel species by affecting population viability of the host fish that disperse their glochidia (Havlik and Marking 1987, Hardison and Layzer 2001). Fish are typically at the top trophic levels and so accumulate high levels of Hg and MeHg in their tissue (Downs et al. 1998, Boening 2000, Mason et al. 2000). Indeed, concentration of MeHg in larval walleye (*Stizostedion vitreum*) was positively correlated with MeHg concentration in eggs and so demonstrated maternal transference (Latif et al. 2001). Further, hatching success of walleye eggs was significantly negatively correlated with MeHg concentration in water (Latif et al. 2001). Hg has also been shown to alter the processes that regulate the magnitude and specificity of fish immune response to environmental pathogens, decrease growth rate, and decrease prey capture ability (Nicoletto and Hendricks 1988, MacDougal et al. 1996, Zhou et al. 2001). Three known host fish (i.e., largemouth bass *Micropterus salmoides*, walleye *S. vitreum*, and bluegill *Lepomis macrochirus*) for two species of mussels federally listed as endangered in Mammoth Cave National Park rivers are known to accumulate Hg and MeHg (Pinkney et al. 1997, Olson and Leibfreid 1999, Gilmour et al. 2000, Latif et al. 2001).

B. Potential mitigation/compensation measures for Mussels

1. Research into effect of Hg and MeHg on mussel glochidia

2. Research into effect of Hg and MeHg on mussel growth rate
3. Research bioaccumulation of Hg and MeHg by other known host fish
4. Monitor populations of known host fish
5. Research into effect of Hg and MeHg on host fish hatching success
6. Determine host species of other endangered Unionids in Green and Nolin Rivers
7. Husbandry/propagation of endangered mussel species

II. Subsurface aquatic biota

A. Decapod Crustaceans

Like other subsurface arthropods, the decapod crustaceans in Mammoth Cave (i.e., cave shrimp and cave crayfish) are long-lived and so likely bioaccumulate high concentrations of MeHg in their tissue over their lifetime. The author is aware of only one study that compared tissue concentrations of heavy metals between a troglomorphic and a troglotitic crayfish (*Cambarus tenebrosus* and *Orconectes australis australis*, respectively); the study indicated heavy metal concentration was higher in *O. a. australis*' tissues (Dickson et al. 1979). The authors hypothesized that *O. a. australis* and *C. tenebrosus* were exposed to heavy metals primarily by preying on isopods and amphipods and exposure to water (Dickson et al. 1979). The higher concentration of heavy metals in *O. a. australis*' tissues, relative to *C. tenebrosus*, was attributed to its increased longevity (Dickson et al. 1979).

Many contamination studies conducted on surface crustaceans rely heavily on Cambarid crayfish, a family that contains Mammoth Cave's troglotitic crayfish (*O. pellucidus*). The surface crayfish *Astacus astacus* demonstrated both biomagnification (via food intake) and bioconcentration (via gills and carapace) of Hg(II) and MeHg (Simon et al. 2000, Simon and Boudou 2001). Indeed, MeHg had a higher assimilation efficiency than Hg(II), and was accumulated in both the tail muscle and the green gland [(i.e., ca. 1000 ng/g and 2500 ng/g, respectively) (Simon et al. 2000)]. Hg was also detected in the tail muscle (i.e., 220 ng/g) of crayfish (*O. virilis*) inhabiting a prairie stream in Saskatchewan (Munro and Gummer 1980). Clearly, accumulation of MeHg in the crayfish tail muscle indicates biomagnification of MeHg is possible through predation and scavenging. In addition, accumulation of MeHg in the green gland may affect a crayfishes' ability to maintain fluid and solute balance. Finally, one study compared the ability

of males and females in two species of crayfish (*Procambarus clarkii* and *Faxonella clypeata*) to withstand increasing concentrations of mercuric chloride to cause 50% mortality expressed in days (i.e., LC₅₀ hr). The authors found significant differences between species and sexes exposed to relatively low concentrations of mercuric chloride [(Table 2) (Heit and Fingerman 1977)]. These data indicate

Species	Sex	LC ₅₀ hr (20 μg/L)	LC ₅₀ hr (10 μg/L)	LC ₅₀ hr (.2 μg/L)
<i>P. clarkii</i>	Male	6	24	72
	Female	48	72	--
<i>F. clypeata</i>	Male	48	48	72
	Female	24	72	--

Table 2. Determination of LC₅₀ hr (ability of crayfish to withstand increasing concentrations of mercuric chloride to cause 50% mortality expressed in days) for males and females in *P. clarkii* and *F. clypeata*. Note at .2 μg/L females of both species were apparently healthy for the duration of the 30 day experiment (taken from Heit and Fingerman 1977).

significant variability both within and among species and so without further studies, some uncertainty exists as to the levels of bioaccumulation and toxicity of Hg and MeHg in subsurface species.

Contamination studies conducted on surface crustaceans have also utilized Palaemonid shrimp, a family that contains Mammoth Cave's troglobitic shrimp (*Palaemonias ganteri*). Palaemonid shrimp have been shown to bioaccumulate high concentrations of heavy metals in their tissue (Abdenmour et al. 2000). In addition, of three metal salts tested for toxicity on the shrimp *Palaemon elegans*, LC₅₀ levels (i.e., concentrations needed to kill 50% of shrimp) for mercury were lowest relative to copper and cadmium; mercury toxicity also increased with time [(Table 3) (Lorenzon et al. 2000)].

	24 hr, LC ₅₀ (mg/L)	48 hr, LC ₅₀ (mg/L)	96 hr, LC ₅₀ (mg/L)	n
HgCl ₂	9.54	3.54	0.67	20
CdCl ₂	49.77	8.91	1.46	20
CuCl ₂	249.46	12.79	3.27	20

Table 3. LC₅₀ levels (i.e., concentrations needed to kill 50% of shrimp) in *P. elegans* of both sexes. Hg was the most toxic metal in the 96 hr assay, followed by Cd and Cu. The order of toxicity did not change during the experiments (taken from Lorenzon et al. 2000).

Crustaceans' physiological processes (e.g., molting, limb regeneration, blood glucose levels, and reproduction) are often coordinated by hormones and exposure to heavy metals can induce rapid changes in hormone levels that interfere with these processes (Fingerman et al. 1998). Experimental data show Hg decreased fecundity in Red Swamp Crayfish (*Procambarus clarkii*) through inhibition of maturation in

ovaries (Reddy et al. 1997). Freshwater prawn (*Macrobrachium kistenensis*) exposed to Hg exhibited high variations in blood glucose which indicated a stress response (Lorenzon et al. 2000). Finally, Hg has also been found to inhibit limb regeneration and molting in the horseshoe crab [*Limulus polyphemus*] (Itow et al. 1998)]. Undoubtedly the potential exists for deleterious effects on subsurface crustaceans due to bioaccumulation of Hg and MeHg.

B. Potential mitigation/compensation measures for subsurface decapod crustaceans

- 1. Toxicity studies on subsurface decapod crustaceans**
- 2. Bioaccumulation studies on subsurface decapod crustaceans**
- 3. Research into trophic transfer rates of Hg and MeHg in subsurface ecosystems**
- 4. Collection of baseline data on concentrations of Hg and MeHg in subsurface water and sediment**
- 5. Monitor subsurface levels of Hg and MeHg in storm-generated pulses v. baseflow levels**

III. Terrestrial Biota

A. Indiana and Gray Bats

Bats are vulnerable to Hg and MeHg bioaccumulation because they are small, mobile, long-lived, and generally consume 40-100% of their body mass in prey each night (Hickey and Fenton 1996). In addition, bats are also exposed to contaminants through the placenta, nursing, breathing, and drinking water (Keating et al. 1997, Straube 1998, Clark and Shore 2001). Insectivorous bats that feed heavily on emerging aquatic insects (e.g., Trichoptera), which spend their larval stages in contaminated sediments, are particularly susceptible to biomagnification of Hg and MeHg (Miura 1978, Massa and Grippo 1999, O'Shea et al. 2001). This is particularly worrisome because two insectivorous bats in Mammoth Cave National Park are federally listed endangered species (i.e., *Myotis grisescens* and *M. sodalis*). Non point-source contamination was responsible for Hg levels in bat hair (i.e., *M. lucifugus*, *M. septentrionalis*, *M. leibii*, and *Eptesicus fuscus*) that exceeded the threshold (i.e., 10 mg/kg) at which deleterious effects are detected in humans (Hickey et al. 2001). High levels of Hg have also been found in guano deposits beneath *M. grisescens* colonies (Ryan et al. 1992).

The toxic effects of Hg and MeHg on bats are not well researched. However, bats exposed to other nonessential heavy metals (e.g., cadmium) have been found with damage to their heart, kidneys, and lungs (Clark and Shore 2001). In addition, exposure to heavy metals has been associated with reproductive failure, neurological disorders, and death in bats (Clark and Shore 2001). Heavy metals may also indirectly affect insectivorous bats by affecting their prey's behavior, prey populations, and composition of prey communities (Winner et al. 1980, Cain et al. 1992, Kiffney and Clements 1993, Beltman et al. 1999, Groenendijk et al. 1999). Given the high toxicity of Hg and MeHg relative to well-studied heavy metals, the sensitivity of small carnivorous mammals (e.g., minks) to Hg, and the relative

paucity of toxicological data on Hg and MeHg with respect to bats, a research and monitoring program must be initiated (Keating et al. 1997).

B. Potential mitigation/compensation measures for Indiana and Gray bats

1. **Research foraging behavior of endangered bats in Mammoth Cave National Park**
2. **Research biomagnification of Hg and MeHg in endangered bat species in Mammoth Cave National Park**
3. **Further research maternal transfer of Hg and MeHg**
4. **Examine toxicity of Hg and MeHg in bats**
5. **Determine and monitor prey of endangered bats in Mammoth Cave National Park**
6. **Research biomagnification of Hg and MeHg in bat prey**
7. **Research into effects of Hg and MeHg on bat prey**
8. **Research and monitor levels of Hg and MeHg in air and water**
9. **Quantify and monitor Hg and MeHg levels in sediments and water**

Conclusion

The data presented in this briefing paper are based on an extensive literature search and represent the best available knowledge on Hg and MeHg bioaccumulation and toxicity in aquatic and terrestrial biota. All studies indicated long-term exposure to Hg and MeHg produces deleterious effects and even death in affected organisms. Most of the SCKK species discussed in this briefing paper are long-lived and so particularly vulnerable to the deleterious effects produced by long-term exposure to Hg and MeHg. However, data on Hg and MeHg bioaccumulation and toxicity for SCKK species of special concern are either sparse (e.g., bats and mussels) or practically nonexistent (e.g., decapod crustaceans). Therefore, baseline data on Hg and MeHg levels in SCKK surface and subsurface ecosystem and long-term monitoring of Hg and MeHg levels in species that may be affected are required. In addition, results were highly variable in those bioaccumulation and toxicity studies that examined species comparable to SCKK species of concern. Therefore, Hg and MeHg bioaccumulation and toxicity studies must be performed on SCKK ecosystems to determine which species are affected. Thus, valuable resources and mitigation efforts will not be "wasted" on SCKK species less or unaffected by Hg and MeHg, if any.

LITERATURE CITED

- Abdennour, C., Smith B.D., Boulakoud, M.S., Samraoui, B., and P.S. Rainbow. 2000. Trace metals in marine, brackish, and freshwater prawns (Crustacea, Decapods) from northeast Algeria. *Hydrobiologia* 432: 217-227.
- Allan, C.J., and A. Heyes. 1998. A preliminary assessment of wet deposition and episodic transport of total and methyl mercury from low order Blue Ridge watersheds, S.E., U.S.A. *Water, Air, and Soil Pollution* 105: 573-592.
- Balogh, S., Meyer, M. and K. Johnson. 1998. Diffuse and point source mercury inputs to the Mississippi, Minnesota, and St. Croix Rivers. *The Science of the Total Environment*. 109-113.
- Barr, Thomas C. Jr. 1985. Cave life of Kentucky. In: *Caves and Karst of Kentucky*. Editor Percy H. Dougherty. Kentucky geological survey special publication 12, series XI. Pp. 146-167.
- Beckvar, Nancy, Salazar, Sandra, Salazar, Michael, and Ken Finkelstein. 2000. An *in situ* assessment of mercury contamination in the Sudbury River, Massachusetts, using transplanted freshwater mussels (*Elliptio complanata*). *Can J Fish Aquat Sci* 57: 1103-1112.
- Beltman, Douglas J., Clements, William H., Lipton, Joshua, and David Cabela. 1999. Benthic invertebrate metals exposure, accumulation, and community-level effects downstream from a hard-rock mine site. *Environmental Toxicology and Chemistry* 18(2): 299-307.
- Bloom, N.S. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Can J Fish Aquat Sci* 46: 1131-1140.
- Boening, Dean W. 2000. Ecological effects, transport, and fate of mercury: a general review. *Chemosphere* 40: 1335-1351.
- Cain, Daniel J., Luoma, Samuel N., Carter, James L., and Steven V. Fend. 1992. Aquatic insects as bioindicators of trace element contamination in cobble-bottom rivers and streams. *Can J Fish Aquat Sci* 49: 2141-2153.
- Canivet, V., Chambon, P., and J. Gibert. 2001. Toxicity and bioaccumulation of arsenic and chromium in epigeal and hypogean freshwater macroinvertebrates. *Archives of Environmental Contamination and Toxicology* 40: 345-354.
- Clark, Donald R. Jr., and Richard F. Shore. 2001. "Chiroptera" In: *Ectotoxicology of Wild Mammals*. Eds. R. F. Shore and B.A. Rattner.

- Coequyt, John, Wiles, Richard, Stadler, Felice, and David Hawkins. 1999. Mercury Falling: an analysis of mercury pollution from coal-burning power plants. Environmental Working Group, Washington, D.C.
- Cooper, C.M. and W.B. Gillespie Jr. 2001. Arsenic and mercury concentrations in major landscape components of an intensively cultivated watershed. Environmental Pollution 111: 67-74.
- Dickson, Gary W., Briese, Linda A., and John P. Giesy, Jr. 1979. Tissue metal concentrations in two crayfish species cohabiting a Tennessee cave stream. Oecologia 44(8): 8-12.
- Division for Air Quality. 2001. Kentucky Ambient Air Quality Annual Report. Natural Resources & Environmental Protection Cabinet, Department for Environmental Protection. 74 pp.
- Downs, S.G., MacLeod, C.L. and J.N. Lester. 1998. Mercury in precipitation and its relation to bioaccumulation in fish: a literature review. Water, Air, and Soil Pollution 108: 149-187.
- Eisler, R. 1987. Mercury hazards to fish, wildlife, and invertebrates: A synoptic review. Publication No. 85 (1.10), U.S. Fish and Wildlife Service, Department of the Interior, Washington, D.C.
- Farag, A.M., Woodward, D.F., Goldstein, J.N., Brumbaugh, W., and J.S. Meyer. 1998. Concentrations of metals associated with mining waste in sediments, biofilm, benthic macroinvertebrates, and fish from the Coeur d'Alene River Basin, Idaho. Archives of Environmental Contamination and Toxicology 34: 199-127.
- Ferguson, Peter Donald. 1997. Mercury and methyl mercury concentrations in *Hyaella azteca*: relationships with environmental factors and potential use of *Hyaella azteca* as a biological monitor of mercury. M.SC. Dissertation. 189 pp.
- Fingerman, M., Jackson, N.C., and R. Nagabhushanam. 1998. Hormonally-regulated functions in crustaceans as biomarkers of environmental pollution. Comparative biochemistry and physiology Part C 120: 343-350.
- French, K.J., Scruton, D.A., Anderson, M.R., and D.C. Schneider. 1999. Influence of physical and chemical characteristics on mercury in aquatic sediments. Water, Air, and Soil Pollution 110: 347-362.
- Gilmour, C.C. and G.S. Riedel. 2000. A survey of size-specific mercury concentrations in game fish from Maryland fresh and estuarine waters. Archives of Environmental Contamination and Toxicology 39: 53-59.

- Groenendijk, D., van Opzeeland, B., Dionisio Pires, L.M., and Postma, J.F. 1999. Fluctuating life-history parameters indicating temporal variability in metal adaptation in riverine Chironomids. *Archives of Environmental Contamination and Toxicology* 37: 175-181.
- Guimarães, J.R.D., Ikingura, J., and H. Akagi. 2000. Methyl Mercury production and distribution in rivers water-sediment systems investigated through radiochemical techniques. *Water, Air, and Soil Pollution* 124: 113-124.
- Hardison, Bart S., and James B. Layzer. 2001. Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers. *Regulated Rivers: Research & Management* 17: 77-84.
- Havlik, M.E., and L.L. Marking. 1987. Effects of contaminants on naiad mollusks (Unionidae): a review. U.S. Department of the Interior, Fish and Wildlife Service Resources Publication (164). 28pp.
- Heit, Merrill, and Milton Fingerman. 1977. The influences of size, sex, and temperature on the toxicity of mercury to two species of crayfishes. *Bulletin of environmental contamination and toxicology* 18(5): 572-580.
- Hess, John W., Wells, Stephen G., Quinlan, James F., and William B. White. 1977. Hydrogeology of the south-central Kentucky karst. In: *Karst Hydrology: Concepts from the Mammoth Cave area*, eds. William B. White and Elizabeth L. White. Pp. 15-63.
- Hickey, C.W., Roper, D.S., and S.J. Buckland. 1995. Metal concentrations of resident and transplanted freshwater mussels *Hyridella menziesi* (Unionacea: Hyriidae) and sediments in the Waikato River, New Zealand. *The Science of the Total Environment* 175: 163-177.
- Hickey, C.W., and M.B. Fenton. 1996. Behavioural and thermoregulatory responses of female hoary bats, *Lasiurus cinereus* (Chiroptera: vespertilionidae), to variations in prey availability. *Ecoscience* 3: 414-422.
- Hintelmann, Holger and Rolf-Dieter Wilken. 1995. Levels of total mercury and methylmercury compounds in sediments of the polluted Elbe River: influence of seasonally and spatially varying environmental factors. *The Science of the Total Environment* 166: 1-10.
- Huebner, J.D., and K.S. Pynnönen. 1992. Viability of glochidia of two species of *Anodonta* exposed to low pH and selected metals. *Canadian Journal of Zoology* 70: 2348-2355.

- Hickey, M.B.C., Fenton, M.B., MacDonald, K.C., and C. Soulliere. 2001. Trace elements in the fur of bats (Chiroptera: Vespertilionidae) from Ontario and Quebec, Canada. *Bulletin of environmental contamination and toxicology* 66: 699-706.
- Itow, T., Igarashi, T., Botton, M.L., and R.E. Loveland. 1998. Heavy metals inhibit limb regeneration in Horseshoe Crab larvae. *Archives of Environmental Contamination and Toxicology* 35: 457-463.
- Keating, Martha H., Mahaffey, Kathryn R., Schoeny, Rita, Rice, Glenn, Glenn E., Bullock, O. Russell, Ambrose, Robert B., Swartout, Jeff, and John W. Nichols. 1997. USEPA Mercury study report to Congress, EPA 452-R-97-004.
- Keller, Anne E. 1989. Toxicity testing with fish, zooplankton and mussels-a comparison of sensitivities. Ph.D. Dissertation. University of Florida. 223 Pp.
- Kiffney, Peter M. and William H. Clements. 1993. Bioaccumulation of heavy metals by benthic invertebrates at the Arkansas River, Colorado. *Environmental Toxicology and Chemistry* 12: 1507-1517.
- Latif, M.A., Bodaly, R.A., Johnston, T.A., and R.J.P. Fudge. 2001. Effects of environmental and maternally derived methylmercury on the embryonic and larval stages of walleye (*Stizostedion vitreum*). *Environmental pollution* 111: 139-148.
- Ledin, M., Pedersen, K., and B. Allard. 1997. Effects of pH and ionic strength on the adsorption of Cs, Sr, Eu, Zn, Cd, and Hg by *Pseudomonas putida*. *Water, Air, and Soil Pollution* 93: 367-382.
- Lorenzon, S., Francese, M., and E.A. Ferrero. 2000. Heavy metal toxicity and differential effects on the hyperglycemic stress response in the shrimp *Palaemon elegans*. *Archives of Environmental Contamination and Toxicology* 39: 167-176.
- MacDougal, K.C., Johnson, M.D., and K.G. Burnett. 1996. Exposure to mercury alters early activation events in fish leukocytes. *Environmental health perspectives* 104(10): 1102-1106.
- Mason, R.P., Laporte, J.-M., and S. Andres. 2000. Factors controlling the bioaccumulation of mercury, methylmercury, arsenic, selenium, and cadmium by freshwater invertebrates and fish. *Archives of Environmental Contamination and Toxicology* 38: 283-297.
- Massa, Steve A. and Richard S. Grippo. 1999. Mercury levels in Arkansas bats from areas under fish consumption advisories. Comments, The 29th annual N. American symposium on bat research. Oct 27-30, Madison, Wisc.

- Matilainen, T., Verta, M. Korhonen, H. Uusi-Rauva, A., M. Niemi. 2001. Behavior of mercury in soil profiles: impact of increased precipitation, acidity, and fertilization on mercury methylation. *Water, Air, and Soil Pollution* 125: 105-119.
- McMahon, Robert F. 1991. Mollusca: Bivalvia. In: *Ecology and Classification of North American Freshwater Invertebrates*. Eds. James H. Thorp and Alan P. Covich. Academic Press, Inc. San Deigo. Pp. 315-400.
- Meiman, J. and C.L. Hall. 1995. Water quality variations and contaminant mass flux signatures relative to flood pulse activity within the Mammoth Cave Karst Aquifer: a preliminary report. *Proceeding of Mammoth Cave National Park's Fourth Science Conference*. Pp. 145-154.
- Micallef, Stefan R. 1984. The effects of mercury pollution on freshwater systems. M.Sc. Dissertation. York University (Canada). 180pp.
- Mikac, N., Niessen, S., Ouddane, B., and M. Wartel. 1999. Speciation of mercury in sediments of the Seine Estuary (France). *Applied Organometallic Chemistry* 13: 715-725.
- Miura, t., Koyama, T. and I. Nakamura. 1978. Mercury content in museum and recent specimens of chiroptera in Japan. *Bulletin of environmental contamination and toxicology* 20(5): 696-701.
- Munro, D.J. and W.D. Gummer. 1980. Mercury accumulation in biota of Thunder Creek, Saskatchewan. *Bulletin of environmental contamination and toxicology* 25: 884-890.
- Nicoletto, P.F., and A.C. Hendricks. 1988. Sexual differences in accumulation of mercury in four species of centrarchid fishes. *Canadian Journal of Zoology* 66: 944-949.
- Odin, M., Ribeyre, F., and A. Boudou. 1996. Temperature and pH effects on cadmium and methylmercury bioaccumulation by nymphs of the burrowing mayfly *Hexagenia rigida*, from water column or sediment source. *Archives of environmental contamination and toxicology* 31: 339-349.
- Olson, Rick and Teresa Leibfreid. 1999. The importance of inventory and monitoring data sets in resolving ecosystem management problems at Mammoth Cave National Park. *Proceedings of the 10th conference on research and resource management in parks and on public lands*. Pp. 149-155.
- O'Shea, T.J., Everette, A.L., and L.E. Ellison. 2001. Cyclodiene insecticide, DDE, DDT, Arsenic, and Mercury contamination of big brown bats (*Eptesicus fuscus*) foraging at a Colorado Superfund site. *Archives of environmental contamination and toxicology* 40: 112-120.

- Parkman, Anna Helena. 1993. Mercury accumulation in zoobenthos: an important mechanism for the transport of mercury from sediment to fish. Ph.D. Dissertation. Uppsala Universitet (Sweden). 42 pp.
- Pinkney, A.E., Logan, D.T., and H.T. Wilson. 1997. Mercury concentrations in pond fish in relation to a coal-fired power plant. *Archives of Environmental Contamination and Toxicology* 33(2): 222-229.
- Reddy, Palla S., Tuberty, Shea R., and Milton Fingerman. 1997. Effect of cadmium and mercury on ovarian maturation in the red swamp crayfish, *Procambarus clarkii*. *Ecotoxicology and environmental safety* 27: 62-65.
- Simon, O., Ribeyre, F., and A. Boudou. 2000. Comparative experimental study of cadmium and methylmercury trophic transfers between the asiatic clam *Corbicula fluminea* and the crayfish *Astacus astacus*. *Archives of Environmental Contamination and Toxicology* 38: 317-326.
- Simon, O., and A. Boudou. 2001. Simultaneous experimental study of direct and indirect plus trophic contamination of the crayfish *Astacus astacus* by inorganic mercury and methylmercury. *Environ Toxicol Chem* 20(6): 1206-1215.
- Snyder, Craig David. 1992. Physiological, population, and genetic responses of an aquatic insect (*Isonychia bicolor*) to chronic mercury pollution (physiological responses, population responses). Ph.D. Dissertation. Virginia polytechnic institute and state university. 157 pp.
- Spicer, J.I., and R.E. Weber. 1991. Respiratory impairment in crustaceans and molluscs due to exposure to heavy metals. *Comparative biochemistry and physiology. C, Comparative pharmacology and toxicology* 100(3): 339-342.
- Straube, M. 1998. The present significance of environmental poisons to bats. *Eurobat Chat* (9): 10-13
- Watras, Carl J. and Nicolas S. Bloom. 1992. Mercury and methylmercury in individual zooplankton: Implication for bioaccumulation. *Limnol. Oceanogr.* 37(6): 1313-1318.
- Watras, C.J., Back, R.C., Halvorsen, S., Hudson, R.J.M., Morrison, K.A., and S.P. Wente. 1998. Bioaccumulation of mercury in pelagic freshwater food webs. *The Science of the Total Environment* 219: 183-208.
- Weber, J.H. 1993. Review of possible paths for abiotic methylation of mercury (II) in the aquatic environment. *Chemosphere* 26: 2063.

- Winner, R.W., Boesel, M.W., and M.P. Farrell. 1980. Insect community structure as an index of heavy-metal pollution in lotic ecosystems. *Can. Jour. Fish. Aquat. Sci.* (37): 647-655.
- Witters, H.E. 1998. Chemical speciation dynamics and toxicity assessment in aquatic systems. *Ecotoxicology and Environmental Safety* 41: 90-95.
- Zelewski, Linda Marie. 1999. Trace metal dynamics in rivers: factors influencing concentration and transport (mercury, wetlands). Ph.D. Dissertation, The University of Wisconsin-Madison. 132 p.
- Zhou, T., Scali, R., and J.S. Weis. 2001. Effects of methylmercury on ontogeny of prey capture ability and growth three populations of larval *Fundulus heteroclitus*. *Archives of Environmental Contamination and Toxicology* 41: 47-54.
- Zillioux, E.J., Porcella, D.B., and J.M. Benoit. 1993. Mercury cycling and effects in freshwater wetland ecosystems. *Environmental Toxicology and Chemistry* 12: 2245-2264.