Factors associated with the bioaccumulation of mercury in human hair following consumption of fish from the Great Lakes region

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FACTORS ASSOCIATED WITH THE BIOACCUMULATION
OF MERCURY IN HUMAN HAIR FOLLOWING
CONSUMPTION OF FISH FROM THE
GREAT LAKES REGION

by

Anne M. Rothweiler
Bachelor of Science
University of Tulsa
1995

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Environmental Science
Department of Environmental Studies
Greenspun College of Urban Affairs

Graduate College
University of Nevada, Las Vegas
May 2003
Thesis Approval
The Graduate College
University of Nevada, Las Vegas

April 25, 2003

The Thesis prepared by

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Entitled

Factors Associated with the Bioaccumulation of Mercury in Human
Hair Following Consumption of Fish from the Great Lakes Region

is approved in partial fulfillment of the requirements for the degree of

Master of Science - Environmental Science

Examination Committee Chair

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ABSTRACT

Factors Associated with the Bioaccumulation of Mercury in Human Hair Following Consumption of Fish from the Great Lakes Region

by

Anne M. Rothweiler

Dr. Shawn L. Gerstenberger, Examination Committee Chair
Professor of Environmental Science
University of Nevada, Las Vegas

Due to the ubiquitous nature of mercury in the environment, an increase in potential human health risks arises from exposure to different media. The Great Lakes region, for instance, is an area of known mercury pollution. This project examines the relationship between fish consumption of a sensitive human population and the concentration of mercury in humans using information obtained from the Ojibwa Health Study.

Using hair samples and questionnaires, this study focused on the species of fish, the amount of fish, the size of fish, and the geographic source of fish consumed. Also, human factors, such as years of eating Great Lakes fish, gender, height, and weight, were examined. Statistical analysis determined several exposure assessment variables for Ojibwa. Mean hair mercury concentrations was 1.82, with a standard deviation of 7.06. Analysis showed poor correlations between of the variables and their association with hair mercury concentrations.
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ACKNOWLEDGEMENTS

Completion of this project would have been impossible without the guidance, support, and generosity of numerous individuals. First, Dr. Shawn Gerstenberger provided me with expertise and encouragement, and just the right amount of push. His endless pearls of wisdom gave me strength. Dr. Chad Cross gave me more information about statistics and spelling than I ever imagined I could learn. Dr. Dave Hassenzahl helped me to look beyond the numbers to examine what is happening in the big scheme of things. Dr. Dave Kreamer not only taught me hydrology, but he challenged me and kept me motivated.

My family, Robert and Mary Alice Rothweiler, Roger Rothweiler and Bob Coffman, dispensed unwavering support, and they have always believed in my abilities. Steve Twomey offered patience and understanding, and hours of computer assistance. Michelle and Brendan Bogan took me in, and gave me daily encouragement and friendship. Jackie Petrello, Rebecca Pearson, Susan Kennedy, Jenny Hayes gave me technical support. Patti Aaron, Melanie Luna, Rebecca Boulton, Tracy Liang, Lynn Bowdidge, and Rosangela Brazao helped me to maintain sanity, and honored me by sharing their talents and intellects. Finally, I would like to thank the UNLV Department of Environmental Studies for the opportunity to study with energetic and professional instructors.
CHAPTER 1

INTRODUCTION

Mercury has intrigued humans since antiquity. The liquid metal was refined from cinnabar as early as the 15th or 16th century B.C., and it was left in Egyptian tombs as far back as 1500 B.C. (ATSDR, 1999). The mysteries of mercury eluded alchemists, as they spent lifetimes trying to derive gold from liquid silver. More recently, mercury has been used in mining, the manufacture of chloralkali, and in pharmaceuticals, fungicides, and bactericides. In addition to direct sources, the combustion of fossil fuels indirectly releases large amounts of mercury. Human activities have increased the amount of mercury in the atmosphere, leading to deposition in the environment.

Mercury is widespread and persistent in aquatic environments. Although it exists in elemental and various inorganic and organic compounds and complexes, the species of greatest concern is methylmercury (CH₃Hg) due to its high toxicity. Through biotic and abiotic processes, elemental forms (Hg⁰) and inorganic mercury forms (especially Hg⁺) may undergo methylation. Because of a strong potential to bioaccumulate, exposure to methylmercury presents a serious health risk. Accumulation of methylmercury up the food chain leads to high concentrations of methylmercury in predatory fish. Adverse health effects may result through fish consumption and ingestion of methylmercury.

The Great Lakes region is an area of known mercury pollution (Dellinger, 1999; Lathrop, Noonan, Guenther, Brasino, & Rasmussen, 1989). High concentrations of
methylmercury have been detected in fish and sediment samples taken from the area (Lathrop et al., 1989). Mercury contamination has been detected in Great Lakes' walleye and lake trout (Dellinger, Meyers, Gebhardt, & Hansen, 1996; Gerstenberger, Pratt-Shelley, Beattie, & Dellinger, 1993). These species represent a major food source for subsistence fishers, such as the Ojibwa tribes. Whitefish, lake trout, perch, and walleye during spearfishing season, constitute a large portion of the Ojibwa diet (Dellinger, 1999). Consumption of fish represents a major exposure to mercury through dietary intake. Since methylmercury is a lipophilic bioaccumulating environmental contaminant, understanding the factors involved with methylmercury uptake is important in determining the level of risk to people consuming large amounts of fish. Native Americans consume more fish than the general U.S. population (Dellinger, 1999). Fish hold cultural, economic, legal, and political importance to the Ojibwa. They use fish for commercial purposes, as subsistence, and for traditional practices. Because of the potential impact on human health, assessing the risk of mercury exposure through fish consumption emerges as a critical examination.

This study evaluates the fish consumption parameters associated with body burdens of mercury. Through analysis of fish species, geographic source of fish, and patterns of fish consumption, this project integrates the fish and human variables, and provides clues as to the influence of specific factors on the fate of mercury in the environment, biota, and in humans. Hair samples are used to determine the mercury concentrations within an Ojibwa population. Then information on specific fish consumption variables is examined in relation to hair mercury concentrations.
CHAPTER 2

REVIEW OF RELATED LITERATURE

Chemistry

Mercury is a naturally occurring element. This metal with atomic number 80 belongs to Group IIb on the periodic table, has an average atomic mass of 200.59, and a melting point of -38.87 °C (Budavari, 1989). It can be found in three main forms: metallic mercury, also known as elemental mercury, inorganic, and organic. Metallic mercury (Hg°) is a shiny, dense, silver colored liquid, while metallic mercury vapors are odorless and colorless (ATSDR, 1999). It is the only metal that is a liquid in its elemental form at ordinary earth surface temperatures and pressures. Mercury rarely occurs free in nature. Mercury alloys easily with other metals, has a strong tendency to vaporize from any media, has a strong affinity for complexing with anions and sulfhydryl groups, and adsorbs to surfaces easily (Budavari, 1989). Consequently, mercury is uniformly distributed between rocks, soil, air, and water (ATSDR, 1999). Mercury is slightly soluble in organic solvents, such as benzene (Budavari, 1989). Table 1 lists the basic chemical and physical properties of mercury.

Species of inorganic mercury include Hg\(^{1+}\), Hg\(^{2+}\) (mercurous), and Hg\(^{2+}\) (mercuric). Hg\(^{1+}\) is insoluble in water, and is not considered toxic (WHO, 1989). On the other hand, Hg\(^{2+}\) is very soluble in water. In aquatic environments, Hg\(^{2+}\) is converted to methylmercury (ATSDR, 1999). Inorganic mercury forms simple salts, often with
Table 1. Properties of Mercury

<table>
<thead>
<tr>
<th>Property</th>
<th>Elemental Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical Formula</td>
<td>Hg</td>
</tr>
<tr>
<td>Atomic Weight, g/mol</td>
<td>200.59</td>
</tr>
<tr>
<td>Melting Point, °C</td>
<td>-38.87</td>
</tr>
<tr>
<td>Density, g/l</td>
<td>13.534</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>13.456</td>
</tr>
<tr>
<td>Vapor Pressure, Pa</td>
<td>0.16</td>
</tr>
<tr>
<td>Solubility, mg/l or ppm</td>
<td></td>
</tr>
<tr>
<td>In water</td>
<td>0.056</td>
</tr>
<tr>
<td>In benzene</td>
<td>2.387</td>
</tr>
</tbody>
</table>

Recreated from Eisler, 1987

chlorine, sulfur, oxygen and nitrate. These compounds are usually white powders or crystals, except for mercuric sulfide (or cinnabar) which is red (ATSDR, 1999).

Mercury readily forms organic species. Monomethylmercury, phenylmercury, and ethylmercury are white salts, and dimethylmercury is a colorless liquid. In organometallic compounds, mercury attaches to either one or two carbons to form RHgX and RHgR’, where the R and R’ are the organic moiety and X is an anion (WHO, 1989). The mercury-carbon bond is chemically stable, and does not split in water or in weak acids or bases. This stability results from a very low affinity for oxygen (WHO, 1989). The organic moiety is commonly an alkyl, phenyl, or methoxyethyl radical. The short-chain alkyl or methyl, ethyl, and propyl are the most toxicologically important (WHO, 1989). For example, monomethylmercury, or methylmercury, is slightly soluble in water, but is extremely lipid soluble. The methylmercury cation has the structure CH₃Hg⁺, and is associated with either an anion, often chloride, or a large protein molecule (WHO, 1989). Aquatic organisms absorb methylmercury and it bioaccumulates and biomagnifies up the food chain. The chemical structures of the organic species allow...
them to be highly stable, and to cross bilipid membranes, penetrating organic membranes, such as the kidney, liver, and brain (Gerstenberger et al., 1993).

Several forms of mercury can be found in the environment. $\text{Hg}^0$ and $\text{Hg}^{2+}$ are the predominant forms in the atmosphere and in water (Lathrop et al., 1989). For example, cinnabar ore, which contains mercuric sulfide, is found in mineralized soils and sediments (Lathrop et al., 1989). Metallic mercury, mercuric chloride, and methylmercury also exist in a natural state in the environment. Biogeochemical processes readily change the forms of mercury found in the environment. Because methylmercury can accumulate in organic tissue, and transfer to human tissue, it is the species of focus for this project.

Sources and Uses of Mercury

Mercury originates from natural and anthropogenic sources. Natural sources include degassing of the earth's crust, volcanic activity, evaporation from water, specifically oceans, and weathering of rocks and soil (ATSDR, 1999). Several ores contain mercury, such as cinnabar, tetrahedrite, sphalerite, wurtzite, calomel, livingstonite, and corderite (Faust & Aly, 1981). When these ores are weathered, they break down and release mercury at a constant background rate into air and water. Because of mercury's unique properties, it is found widely distributed in the lithosphere, hydrosphere, and atmosphere. Mercury has a strong tendency to vaporize, releasing elemental mercury to the atmosphere (ATSDR, 1999). Also, mercury has a strong ligand affinity and easily sorbs to surfaces (Faust & Aly, 1981). Igneous and many sedimentary rocks have small amounts of mercury, about 200 ppb, while shales, clays, and soils have variable amounts
of mercury, ranging from 30 to 2300 ppb (Faust & Aly, 1981). Runoff from areas near mercury ore deposits may contribute to high local concentrations of mercury in water (ATSDR, 1999).

For over 2,300 years, humans have used mercury for a plethora of purposes (Eisler, 1987). Humans have found over 3,000 uses for mercury, mostly industrial and agricultural applications. The most common commercial use of mercury is in the electrolytic production of chlorine and caustic soda (ATSDR, 1999; Eisler, 1987). Properties such as high fluidity, uniform volume expansion, high surface tension, and non-wettability to glass surfaces make mercury an important component in many measurement and control system instruments, such as thermometers, barometers, manometers, electric switches, thermostats, pressure gauges, and shut-off switches (Moore & Ramamoorthy, 1984). Mercury is also used in manufacturing electric apparatuses, such as batteries, silent switches, high-intensity street lamps, and fluorescent lamps (ATSDR, 1999; Eisler, 1987). Because mercury has low electrical resistivity and high thermal conductivity, it is employed as an electrical conductor and coolant (Moore & Ramamoorthy, 1984).

Until the 1970s, mercury could be found in numerous pharmaceutical products. Laxatives, worming medications, and teething products contained inorganic mercury. Organic mercury was used in antisyphilitic drugs, and phenylmercury was used in contraceptive gels and foams (ATSDR, 1999). Different chemicals have replaced mercury in these products. Yet, some pharmaceuticals still contain mercury, such as antiseptics, diuretics, skin lightening creams, disinfectants, and antibacterials (ATSDR,
Mercury can be used in several other capacities. It is a coloring agent in external and internal paints, and tattoo dyes (ATSDR, 1999). Mercury acts as a catalyst for the formation of polymers such as vinyl chloride and urethane foam. Also, mercury is used in aqueous preparations such as inks, adhesives, and caulking (ATSDR, 1999). Mercury absorbs neutrons, so shields made of mercury protect against atomic radiation (Moore & Ramamoorthy, 1984). Dimethylmercury is used to make mercury nuclear magnetic resonance standards and to make mass spectrometer mercury calibration standards (ATSDR, 1999).

Several industries use mercury compounds as insecticides, bactericides and fungicides. For example, organic mercury compounds are used as antifouling and mildew-proofing agents in paints, and paper industries added mercury compounds to prevent fungal growth in pulp and on the machinery (Eisler, 1987; Faust & Aly, 1981). Banned in 1965 in the United States (U.S.), agricultural seed dressing contained mercury to prevent bacterial and fungal growth (Eisler, 1987). Other uses of mercury have been banned, such as phenylmercury in internal and external paints, mercuric nitrate that hydrolyzes fur for felt hats, and wood preservatives (ATSDR, 1999). Organic mercury was used until the 1970s as an antifungal product in seed grain applications, and as an antifungal agent in paints until 1991 (ATSDR, 1999).

Mercury’s ability to alloy with metals has lead to widespread use of mercury in mining and metallurgy (Eisler, 1987). Mercury amalgams, or alloys, between gold, silver, or tin allow miners to recover the metals from ore bodies (ATSDR, 1999). The
smelting of mercury-containing ores releases mercury to the atmosphere. Lead, zinc, and copper ores contain significant amounts of mercury (Faust & Aly, 1981). Also, mining activities often dumped materials and tailings into streams and lakes, creating long-lasting sources of mercury. The cinnabar ore, which is mostly mercuric sulfide, is mined (ATSDR, 1999). Both open pit and underground mines unearth mercuric sulfide, which can then be processed to $\text{Hg}^0$ (ATSDR, 1999).

Other anthropogenic releases of mercury have been identified. The mercury from consumer goods, laboratories, hospitals, and industries often ends up in wastewater treatment plants. Mercury is a byproduct of cement and phosphate production (ATSDR, 1999). In addition to municipal waste incineration, combustion of fossil fuels releases a large amount of mercury into the atmosphere. According to research, fossil fuel combustion is the largest producer of atmospheric mercury, followed by waste incineration, smelting, and wood combustion (Porcella, 1994). Changes in volume, mercury content in waste and fuels, and analytical techniques make this estimate difficult to calculate. About 25% of all mercury emissions, natural and human, originate from fossil fuel combustion (National Research Council, 2000).

**Biogeochemical Cycle**

**Mercury Cycle**

The biogeochemical cycle of mercury follows a path from emission, to deposition, then to revolatilization and reemission. Natural environmental processes keep emission and deposition in a steady balance (ATSDR, 1999). Mercury moves among air, water, and land through degassing of mineral mercury from the lithosphere and hydrosphere,
long-range transport in the atmosphere, deposition to land and surface water, and sorption to soil and sediment. Some of the mercury deposited on land and surface waters revolatilizes from land and surface water, while particulate bound mercury may undergo conversion to insoluble mercury and be precipitated or biotransformed and bioaccumulated in terrestrial and aquatic food chains (ATSDR, 1999). A simple representation of the mercury cycle can be seen in Figure 1.

Physical weathering of rocks and soils emits mercury to surface water or the atmosphere. Also, volcanic releases and degassing of the earth’s crust emits mercury to the atmosphere, usually as elemental mercury. Once in the atmosphere, mercury may return to land or surface waters through dry or wet deposition. Mercury may revolatilize as elemental mercury from land or surface waters, or it may sorb to soil or sediments. From soil or sediments, mercury may remain sorbed to particulate matter or undergo chemical transformation to produce insoluble mercury sulfide (HgS). HgS may precipitate out of water or be bioconverted to elemental mercury and volatilize to the atmosphere or to a soluble organic species and enter terrestrial and aquatic food chains, or mercury may be methylated (ATSDR, 1999). In summary, the major processes of mercury transport include atmospheric deposition, gas exchange, inflow and outflow of water, burial in sediments or scavenging by particles, chemical and/or biological conversions, and accumulation in biota (Braga, Shaw, & Lester, 2000).

Tracing the mercury pathway becomes difficult, as it “ping-pongs” between emission, deposition, reemission, and makes interconversions between processes. For instance, a mercury atom may be attached to a soil particle traveling in a stream. The mercury atom combines with sulfur, eventually forming insoluble cinnabar. The cinnabar molecule
Figure 1. Major Transformations of Mercury in Air, Water, Sediment, and Biota

Recreated from ATSDR, 1999
may precipitate out of the water, or undergo bioconversion to a volatile form and be released into the atmosphere. Bioconversion can also produce organic forms of mercury, such as methylmercury or dimethylmercury (National Research Council, 2000).

Different human activities release varying amounts of mercury into the environment affecting the natural balance. Approximately one-third to two-thirds of the total annual release of mercury arises from sources such as mining and fossil fuel combustion (ATSDR, 1999; D’Itri, 1993). About 80% of the annual anthropogenic release arises from mining, smelting, burning of fossil fuels, solid waste incineration, both municipal and medical, cement production, and coal-fired power plants, which release elemental mercury to the atmosphere. Almost 15% of the annual release enters the soil through fertilizers, fungicides, and municipal solid waste. The final 5% is released to water through industrial wastewater (ATSDR, 1999).

Transport and Distribution

Air

The major pathway of global transport and deposition of mercury is via the atmosphere. Both natural processes and anthropogenic activities release mercury to the atmosphere (ATSDR, 1999). Natural processes such as volatilization from soils and rocks, volcanic activity, vaporization from aquatic systems, and biological activity release a major proportion of mercury into the atmosphere (Lathrop et al., 1989). Anthropogenic emissions from power plants, mining operations, fossil fuel combustion and manufacturing and industrial activities contribute additional amounts of mercury to the atmosphere (Lathrop et al., 1989). About 25% to 30% of the total mercury burden in the atmosphere arises from anthropogenic emissions (Lathrop et al., 1989). Mercury
compounds may volatilize through three processes; chemical reduction or biological reduction by microbes, plants, and other organisms to Hg$^0$ and biotransformation into volatile organomercurial compounds (D’Itri, 1993). Wind currents mix mercury in the troposphere in a wide and uniform pattern. Concentration and residence time are a function of wind speed and duration, temperature, and barometric pressure (D’Itri, 1993). Mercury eventually falls on surface waters and watersheds in rain, snow, dust, or through gas exchange (D’Itri, 1993).

Most of the mercury in the atmosphere, about 80% to 95%, is in its most reduced form, gaseous Hg$^0$ (ATSDR, 1999; Braga et al., 2000; D’Itri, 1993). Gaseous Hg$^0$ has a residence time in the atmosphere of six days to two years and it is uniformly distributed throughout the atmosphere (ATSDR, 1999; Braga et al., 2000). It is in this form that Hg$^0$ may be transported over long ranges. A small amount of gaseous mercury that falls from the atmosphere revolatilizes after it reaches the ground or water (D’Itri, 1993).

Some of the Hg$^0$ in the atmosphere (about 5%) is oxidized and converted to ionic forms of mercury by oxidizing agents such as ozone and hydrogen peroxide (Braga et al., 2000; D’Itri, 1993). These ionic forms of mercury are nonvolatile and water soluble, and they sorb onto particulate matter (ATSDR, 1999; D’Itri, 1993). Consequently, they are removed from the atmosphere in a short time span, from a few days to a few weeks. The shorter residence time of these forms of mercury result in more localized deposition and distribution patterns, typically accumulating in the environment near the source of emission (ATSDR, 1999; D’Itri, 1993). Also, these ions resulting from oxidation lead to a pool of reactive mercury in precipitation and atmospheric particulate matter that can
enter aqueous systems and participate in methylating processes, reduction to Hg^{0}, uptake by biota, or become isolated with dissolved organic carbon (Braga et al., 2000).

Mercury can travel several thousand kilometers, depending on the emitting source, density and size of particles, physical and chemical changes during transport, sorption processes, and meteorological conditions (D’Itri, 1993). Mercury may remain in the atmosphere for up to 11 days. Because it can be transported over long distances, mercury can enter watersheds far from the original point of emission (Lathrop et al., 1989).

Water

Mercury is found in surface water, groundwater, and leachate (ATSDR, 1999). The natural weathering of mercury-bearing rocks releases mercury directly to surface waters (ATSDR, 1999). Atmospheric deposition of mercury from natural and anthropogenic sources releases mercury indirectly to surface waters (ATSDR, 1999). Surface runoff transports mercury associated with soils into surface waters during storm events (ATSDR, 1999). Also, mercury-containing effluents from industrial operations, such as chloralkali production, as well as sewage effluents, release mercury into surface waters (ATSDR, 1999; Lathrop et al., 1989).

Both dry and wet deposition of mercury removes mercury from the atmosphere, returning it to land and surface waters. For example, sorption of Hg^{0} vapor to soil and water is a method of dry deposition (ATSDR, 1999). Also, precipitation removes mercury, and deposits it on land and water surfaces. Once mercury reaches the earth’s surface, it may be trapped on soil particles or sediments or enter runoff and become a part of the water system. Insoluble forms of mercury may adsorb onto suspended solids in runoff or streams. Mercury is then carried to sediments through particle settling (Braga
et al., 2000). Owing to its high volatility, mercury is released from oceans and surface waters to the atmosphere (Braga et al., 2000).

High concentrations of mercury have been found in lakes remote from point sources of mercury emissions or geological strata containing mercury ores. In these lakes, atmospheric transport and deposition acts as the source of mercury (ATSDR, 1999; Braga et al., 2000; D’Itri, 1993).

Deposition of mercury on surface waters depends on atmospheric deposition, air-water gas exchange, biological interactions, and water movements (D’Itri, 1993). Mercury in water exists in three states: Hg$^0$, mercurous 1+, and mercuric 2+, but mercuric mercury is the predominant form, found as complexes and chelates with ligands (ATSDR, 1999). Speciation depends on pH, redox potential, and the presence of anions that form stable complexes with mercury. For example, mercuric species dominate in aerated water, while Hg$^0$ predominates in reduced conditions (Moore & Ramamoorthy, 1984). Mercury will form stable complexes with several organic ligands. Also, strong covalent complexes develop between mercury and sulfide containing ligands, like cysteine (Moore & Ramamoorthy, 1984). Volatile forms of mercury evaporate, while solid forms associate with soil particulates or enter the water column and move downward to the sediments (ATSDR, 1999).

Mercury strongly sorbs to suspended solids in water (Moore & Ramamoorthy, 1984). The nature of the association depends on water quality parameters, such as pH, salinity, redox potential, and the presence of organic ligands. The chemical form of the dissolved species of mercury controls the association to suspended solids and the residence time in the water column (Moore & Ramamoorthy, 1984).
Acidity from precipitation will cause a change in the mercury dynamics of a lake by redistributing mercury. Acid precipitation may cause a release of natural or deposited mercury trapped in sediments. Research indicates that a negative correlation exists between lake pH and mercury concentrations in fish, possibly arising from increased aqueous concentrations of methylmercury at low pH (Braga et al., 2000).

Mercury stays in water media for only a few weeks, so it is not transported over long distances (ATSDR, 1999). Runoff and percolation effectively distribute mercury in water. Once discharged into water, mercury will separate into a solid or a liquid phase. The ultimate phase of each mercury atom is determined by several factors, including pH, redox potential, and the nature and concentration of mercury-complexing anions in the environment. For example, the presence of chloride and sulfide ions (anions which commonly form complexes with mercury) influences the fate of mercury in aquatic systems (ATSDR, 1999). Suspended sediments and bottom muds readily adsorb mercury. Mercury can be adsorbed onto soil particles and sediments, transformed to organic forms of mercury, revolatilized back into the atmosphere, and deposited as insoluble mercuric sulfide in ocean bottom sediments. Mercury tends to remain on sediments for long periods of time before moving to a different phase. In fact, ocean sediments are considered to act as the ultimate sink for mercury (ATSDR, 1999).

The transport and distribution of methylmercury differs from that of inorganic forms of mercury. Methylmercury will attach to small particles in water or soil media, and remain in the media for a long period of time. This form of mercury tends to stay on the surface of sediments or soil, and it does not usually move through soil to the groundwater. In water, methylmercury will settle to the bottom of the basin (ATSDR,
Methylmercury accumulates in the food chain. It will accumulate at low levels in plants; however, fungi, such as mushrooms, will accumulate large amounts of methylmercury (ATSDR, 1999).

Soil and Sediments

Atmospheric deposition of mercury arising from natural and anthropogenic sources indirectly transports mercury to soil and sediments (ATSDR, 1999). The application of fertilizers, lime, and fungicides containing mercury releases the element to the soil (ATSDR, 1999). The disposal of sewage sludge, industrial and domestic waste products, and municipal incinerator ash release mercury to the soil (ATSDR, 1999).

Because $\text{Hg}^0$ has a low solubility in water and $\text{Hg}^{2+}$ complexes with dissolved particulate matter, inorganic forms of mercury are rapidly deposited into the sediments of aquatic systems (Lathrop et al., 1989). $\text{Hg}^{2+}$ forms mostly insoluble complexes with minerals in sediments. About 90% of mercury in aquatic systems is in sediments (Faust & Aly, 1981). Microorganisms convert inorganic mercury in the surficial sediment layers to methylmercury. Although some methylation occurs in the water column, the primary source of methylmercury is sediment microbes (Lathrop et al., 1989).

Mercury may vaporize from soils, depending on temperature (ATSDR, 1999). In warmer weather, microbial reduction of $\text{Hg}^{2+}$ to volatile mercury is greater than in cooler weather (ATSDR, 1999). The sorption of nonvolatile forms of mercury to soil and sediments is a controlling process in the distribution of mercury, with little resuspension back into the water column (ATSDR, 1999). Also, mercury sorbed to soil does not leach down to groundwater (ATSDR, 1999).
Mercury in Aquatic Systems

Speciation

Mercury in aquatic environments can be found in three oxidation states; Hg\(^0\), Hg\(^{2+}\), and Hg\(^{2+}\) (Braga et al., 2000). This results in the presence of dissolved Hg as Hg\(^0\), organic species, and complexes of Hg\(^{2+}\) with inorganic and organic ligands (Ulrich, Tanton, & Abdrashitova, 2001). Each compound has a different solubility. Hg\(^0\) is the least soluble compound, followed by mercurous chloride, methylmercury chloride and mercuric chloride (Braga et al., 2000). Elemental mercury arises from the reduction of Hg\(^{2+}\) by aquatic microorganisms, decomposition of organic mercury, abiotic reduction by humic substances, and anthropogenic sources (Ulrich et al., 2001). Under mildly oxidizing or reducing conditions, Hg\(^0\) is unreactive and stable, although in the presence of chloride ions it may be oxidized to Hg\(^{2+}\). Surface waters will be supersaturated with Hg\(^0\) in relation to the atmosphere, especially in the summer. Hg\(^0\) is lost from the aquatic environment through volatilization at normal temperatures (Ulrich et al., 2001).

Inorganic Hg\(^{1+}\) is found as a dimer (Hg\(_2^{2+}\)), in aqueous solution, and disproportionates to Hg\(^0\) and Hg\(^{2+}\) (Ulrich et al., 2001).

Mercury compounds in aquatic systems may be in gaseous or aqueous phases, or associated with particulates (Braga et al., 2000). Volatile forms of mercury include Hg\(^0\) and (CH\(_3\)\(_2\)Hg. Water soluble forms of mercury include HgCl\(_2\), Hg(OH)\(_2\), and CH\(_3\)HgCl. Several water soluble or particle-borne species of mercury are reactive, such as Hg\(^{2+}\), HgX\(_2\), HgX\(_3\), HgX\(_4\)^\(^-\) (X=OH\(^-\), Cl\(^-\), Br\(^-\)), Hg\(^0\) on aerosol particles, and Hg\(^{2+}\) complexes with organic acids. Some nonreactive mercury species include CH\(_3\)Hg\(^{+}\), CH\(_3\)HgCl.
CH$_3$HgOH, other organomercuric compounds, Hg(CN)$_2$, HgS, and Hg$^{2+}$ bind to sulfur in humic matter (Braga et al., 2000). Figure 2 displays the division of mercury speciation.

The fate of mercury in aquatic environments depends on how it changes and what species arise, reactions such as reduction and oxidation, methylation and demethylation, the rate of deposition, gas exchange, and scavenging by particles. Although many of the
mechanisms influencing mercury movement and distribution are not completely understood, an examination of the current research provides information on the fate of mercury in aquatic systems.

**Movement and Distribution**

Several physical, chemical, and biological factors influence the chemical form and distribution of mercury in aquatic systems. Redox potential, pH, temperature, availability of nutrients, the concentration of anions, and inorganic and organic complexing agents affect the species of mercury (Braga et al., 2000; Ulrich et al., 2001). The amount of binding between mercury species and sediments depends on sediment properties, pH, and dissolved organic content (DOC) (Ulrich et al., 2001). In general, aerobic conditions favor sediment uptake of mercury and methylmercury, while anoxic conditions favor mercury release and thus lead to an increase in the concentration of mercury and methylmercury (Ulrich et al., 2001). Yet anoxic conditions may also lead to a decrease in the proportion of dissolved mercury as these conditions favor the reduction of Hg to HgS. The formation of soluble sulfide complexes in anoxic conditions increases the solubility of mercury and methylmercury (Ulrich et al., 2001). This may be due to the effects of precipitation and dissolution of iron (Fe) and manganese (Mn) oxides and oxyhydroxides (Ulrich et al., 2001).

The Eh/pH conditions affect mercury chemistry. For example, in aqueous systems, the pH is likely to fall between 5 and 9 and Eh values rarely rise above 0.5 V, favoring the dominance of Hg⁰ and HgS species. At low redox potentials in reducing conditions, sulfide ions immobilize inorganic mercury in sediments (Braga et al., 2000). If the redox potential of the upper layer sediment is not low enough, sulfur will not remain in the
sulfide state. In such a case, mercury may be released into solution through the partial
dissolution of Fe and Mn oxides in sediments (Braga et al., 2000).

At low redox potentials, sulfide ions immobilize mercury (Braga et al., 2000). If the
pH increases above 9, solubility increases as HgS$_2^{2-}$ forms (Braga et al., 2000). The
nonreactive portion in deposited mercury solubilizes under anoxic conditions or in the
presence of sulfite, yielding Hg(SH)$_2$, which can be methylated (Braga et al., 2000).

As seasons affect biotic particulate matter, the seasons also affect the partitioning of
mercury and methylmercury on these particulates (Ulrich et al., 2001). Seasonal
variations in environmental conditions affect organisms and metabolism, thereby
affecting mercury movement and distribution. As temperatures increase, pH decreases,
nutrients are added to a system, and methylmercury release from sediments increases
(Ulrich et al., 2001).

The presence of organic and inorganic complexing agents influences mercury
partitioning. The Hg$^{2+}$ ion and methylmercuric cation (CH$_3$Hg$^+$) have a strong propensity
to form complexes, especially with soft ligands such as sulfur (Ulrich et al., 2001). If
sulfide is absent in a freshwater system, the dominant inorganic species will be Hg (OH)$_2$,
HgOHCl, and HgCl. In the presence of chloride ions, Hg$^{2+}$ forms HgCl$_2^+$, HgCl$_2$, HgCl$_3^-$,
and HgCl$_4^{2-}$ (Ulrich et al., 2001). The amount of mercury associated with suspended
particulates and organic colloids decreases in areas of high chloride concentration,
probably due to competition of Cl$^-$ for binding sites (Ulrich et al., 2001). In oxic water,
organic matter greatly affects mercury speciation. Mercury atoms form strong
associations with humic material, usually bound to the thiol groups (Ulrich et al., 2001).
In freshwater, estuarine, and marine environments, organic colloids make up a large
proportion of the dissolved mercury fraction. For example, more than 90% of mercury is complexed with organic matter in freshwaters, and most of the methylmercury is associated with dissolved organic carbon (Ulrich et al., 2001). If soluble humic complexes form, then the solubility and mobility of mercury in aquatic systems increases, especially above a pH of 5 (Ulrich et al., 2001).

In anoxic conditions, sulfide controls mercury speciation. Mercuric sulfide is the dominant insoluble inorganic mercury compound in aquatic systems (ATSDR, 1999). Mercuric oxide (HgO) is also common. Low pH and low sulfide concentrations favor formation of HgS. In low Eh and high pH conditions, or in the presence of excess sulfide ions, HgS can be transformed to soluble HgS complexes, such as $\text{HgS}_2^{2-}$. Also, organic matter increases HgS solubility, increasing the release of mercury into solution (ATSDR, 1999).

Methylmercury is highly stable in aquatic systems. It is kinetically inert to decomposition, but methylmercury is affected by microbial degradation and photochemical decomposition (Lathrop et al., 1989). Other organomercury compounds break down rapidly, usually to ethane and inorganic Hg ($\text{Hg}^0$ and $\text{Hg}^{2+}$). Dimethylmercury is volatile, nonpolar, and has low solubility. Therefore it escapes aquatic systems quickly through evaporation, and does not bioaccumulate (Lathrop et al., 1989).

Because mercury has a strong tendency to sorb to surfaces, most of the mercury in waters is bound to sediments and most of the dissolved mercury is attached to suspended particles (ATSDR, 1999). Methylmercury sorbs as well, although not to the same extent as inorganic mercury. Consequently, suspended matter is important to transport.
Sediments constitute the main reservoir of mercury in freshwaters (Ulrich et al., 2001). About 1% to 1.5% of the total mercury content in sediments is methylmercury. Sediments may be a secondary source and a sink of mercury (Ulrich et al., 2001). As temperatures and nutrient concentrations increase and pH decreases, sediments release more methylmercury (Ulrich et al., 2001).

The sorption of mercury to humus in sediments increases with increasing acidity. Mercury sorbs to mineral particles, such as Fe oxides and clay minerals, in the neutral to alkaline pH range (Lathrop et al., 1989). Mercury binds to inorganic particles and organic matter, as well as biogenic particles such as bacteria, algae, and phytoplankton (Lathrop et al., 1989). Inorganic mercury associates more with mineral particles and detrital organic matter, while methylmercury binds strongly to biogenic particles. Particulate scavenging and particulate dissolution control mercury and methylmercury distribution in freshwater lakes at the redox boundary (Ulrich et al., 2001). The major route of transport of mercury to the sediment-water interface, the main site of methylation, is through settling of particulate matter. Diffusion upward from sediment porewater is less important to mercury distribution (Ulrich et al., 2001).

Since mercury and humic substances form very stable complexes, organic matter controls the movement of mercury in aquatic systems. A major portion of the mercury in water is in organically complexed forms and found associated with dissolved organic matter. Even the amount of mercury bound to sediments or suspended particles is related to organic content (Braga et al., 2000). If soluble humic complexes form, then the solubility and mobility of mercury increases (Braga et al., 2000).
Fe and Mn oxides also influence the movement of mercury in aquatic systems. Both elements possess large surface areas and an ability to adsorb, precipitate, and rerelease mercury after their dissolution (Ulrich et al., 2001). Redox conditions and oxygen concentrations of water and sediments affect the formation and dissolution of Fe and Mn oxides. For example, anoxic conditions favor the dissolution of oxyhydroxides and the release of any associated mercury. The dissolution of Fe and Mn oxides plays a part in releasing mercury from sediments to the porewater (Braga et al., 2000). Seasonal and diurnal patterns in methylmercury concentrations in sediment porewaters may be affected by temporary anoxic conditions due to these oxyhydroxide changes (Ulrich et al., 2001). The formation and dissolution of oxyhydroxides and organic complexes influences methylation by controlling the availability of inorganic mercury (Ulrich et al., 2001). Oxyhydroxides form complexes with organic matter and clay minerals, which increases the mercury scavenging ability (Ulrich et al., 2001). Once an oxyhydroxide picks up mercury, it is no longer available for methylation.

**Background Concentrations**

Due to several factors, such as geology and human activities, the mercury concentrations vary from region to region. Table 2 presents estimated concentrations of mercury in different media. Mercury is naturally eroded from source rock material; thus some amount of mercury is likely to occur in most surface waters. Even in areas devoid of any known anthropogenic sources, aerobic surface waters contain around 5 ng/l (ppt) of mercury (ATSDR, 1999). Background concentrations of mercury in precipitation are estimated to lie between 0.0032 and 0.0152 ug/m³ (ATSDR, 1999). In general, mercury concentrations in rainwater and freshwater are less than 200 ng/l (ATSDR, 1999).
<table>
<thead>
<tr>
<th>Media</th>
<th>Concentration</th>
<th>Source of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Over the Pacific Ocean</td>
<td>1 ng/m$^3$</td>
<td>D’Itri, 1993</td>
</tr>
<tr>
<td>Air Over Urban Centers</td>
<td>2 to 50 ng/m$^3$</td>
<td>D’Itri, 1993</td>
</tr>
<tr>
<td>Uncontaminated Rainwater</td>
<td>1 to 2 ng/m$^3$</td>
<td>D’Itri, 1993</td>
</tr>
<tr>
<td>Uncontaminated Freshwater</td>
<td>1 to 5 ng/l</td>
<td>D’Itri, 1993</td>
</tr>
<tr>
<td>Uncontaminated Seawater</td>
<td>0.2 to 2 ng/l</td>
<td>D’Itri, 1993</td>
</tr>
<tr>
<td>Uncontaminated Surface Water</td>
<td>&lt; 5 ng/L</td>
<td>Ulrich et al, 2001</td>
</tr>
<tr>
<td>Uncontaminated Sediments</td>
<td>0.2 to 0.4 ug/g</td>
<td>Ulrich et al, 2001</td>
</tr>
<tr>
<td>Sediments in Urban, Industrial, or Mineralized Areas</td>
<td>100 ug/g</td>
<td>Ulrich et al, 2001</td>
</tr>
<tr>
<td>Surface Water</td>
<td>1 to 3 ng/L</td>
<td>Braga et al, 2000</td>
</tr>
<tr>
<td>Ambient Air</td>
<td>10 - 20 ng/m$^3$</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Atmospheric Hg Concentrations Over Wisconsin lakes</td>
<td>2.0 ng/m$^3$</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Particulate Phase Hg in Rural Great Lakes and Vermont Areas</td>
<td>1 - 86 pg/m3</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Particulate Phase Hg in Urban and Industrial Great Lakes and Vermont Areas</td>
<td>15 - 1200 pg/m3</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Uncontaminated Freshwater (Aerobic Surface Water)</td>
<td>5 ng/L</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Unpolluted Marine Waters</td>
<td>&lt; 2 ng/L</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Near-Surface Groundwater, Remote Wisconsin</td>
<td>2 - 4 ng/L</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Top 15 cm of Sediments in Wisconsin Lakes</td>
<td>0.09 - 0.24 ug/g</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Lower Sediment Layers in Wisconsin Lakes</td>
<td>0.04 - 0.07 ug/g</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>Uncontaminated Fish</td>
<td>0.1 mg/kg</td>
<td>Birke et al, 1972</td>
</tr>
</tbody>
</table>

Natural levels of mercury in the air range from 10 to 20 ng/m$^3$, although areas near mercury ore deposits may be as high as 20,000 ng/m$^3$ (ATSDR, 1999; Faust & Aly, 1981). Meteorological factors such as wind speed, wind direction, and seasonal and
diurnal temperature variations influence the amount of atmospheric mercury at different locations (Faust & Aly, 1981).

Average concentrations of mercury in surface soils range from 20 to 625 ng/g (ATSDR, 1999). The highest concentrations are usually found in soils from urban locations and in organic soils (ATSDR, 1999). Mercury concentration varies with depth. Higher concentrations are found near the surface layers (ATSDR, 1999). It is from the surface layers that most mercury is readily eroded and moved into water or air.

Methylation

Mercury can reach aquatic systems through runoff, precipitation, groundwater movement, or from settling sediments. Mercury can enter water systems through direct or indirect discharges (Eisler, 1987). Once mercury enters an aquatic environment through natural or anthropogenic routes, natural processes can convert mercury species into methylmercury. Ionic and divalent mercury compounds, as well as organic mercury compounds and metallic mercury may be methylated to methylmercury. Dimethylmercury can be formed from methylmercury and ionic mercury (ATSDR, 1999; Ulrich et al., 2001).

Methylation represents a major step in the cycling of mercury and the movement of mercury into aquatic organisms (ATSDR, 1999; Ulrich et al., 2001; WHO, 1990). This conversion requires free Hg^{2+} atoms. A bound mercury atom, such as to particulate matter, is unavailable for chemical or biological reactions. For example, mercuric ions (Hg^{2+}) under certain conditions form strong covalent bonds with chloride ions, or with many sulfur-containing organic compounds, removing the ions from circulation (Moore
& Ramamoorthy, 1984). When the Hg\textsuperscript{2+} form is available for conversion in aquatic environments, this mercury species may become methylated.

The processes of methylation and demethylation occur simultaneously, producing a state of equilibrium of the methylmercury concentration in sediments (Zhang & Planas, 1994). Since production and degradation do not take place within organisms at the same rate, the concentration of methylmercury in organisms may be very high (Ulrich et al., 2001).

Methylation occurs in three main areas in an aquatic environment: the subsurface sediment, the sediment-water interface, and the water column (Gerstenberger et al., 1993; Zhang & Planas, 1994). Most methylation occurs in sediments and some in the water column, and it will take place in fish intestinal contents and the outer slime of fish (Ulrich et al., 2001; WHO, 1989). Bacteria in the environment account for a major proportion of methylation, while microorganisms in bronchial mucus, the fish gut, and fish liver produce insignificant amounts of methylmercury (WHO, 1989). Because of the volume of water, methylation in the water column may be significant. Maximum methylation takes place at the redox boundary. The boundary may vary with seasons, and may coincide with the sediment-water interface, with methylation rates decreasing with increasing sediment depth (Ulrich et al., 2001).

In order for methylation to occur, a methyl donor molecule must be present. Numerous molecules in aquatic environments may be suitable, many of which are biologically synthesized (Ulrich et al., 2001). Methylation is conducted through abiotic or biotic pathways, although the abiotic route has only minor importance (ATSDR, 1999; Ulrich et al., 2001). If the right methyl donors are present, abiotic methylation may
occur. Chemical and photochemical processes as well as transmethylation reactions between mercury and lead and tin alkyls may take place (Ulrich et al., 2001). Abiotic methylation occurs mostly in areas high in soluble humic substances, areas of low pH, high light level, and decreased amounts of chloride ions (ATSDR, 1999). Yet, biological methylation is believed to be the predominant process.

Biological methylation may be enzymatic or nonenzymatic (WHO, 1990). The enzymatic pathway needs actively metabolizing organisms, while the nonenzymatic pathway needs the products of metabolism. Methylation involves the transfer of the methyl group of methylcobalamin, a vitamin B12 derivative produced by many organisms, to mercuric ions. While there are many methyl donor molecules in the aquatic environment, methylcobalamin is prevalent in anaerobic ecosystems and organisms, making it a likely methyl source (Ulrich et al., 2001).

Several organisms conduct methylation, predominantly bacteria and fungi (Faust & Aly, 1981; Ulrich et al., 2001). Biotic methylation can be conducted by anaerobes, facultative anaerobes, and aerobes. Methylation rates are thought to be higher in anaerobic conditions. For instance, sulfate-reducing bacteria, identified as the principal methylators in anaerobic sediments, methylate Hg$^{2+}$ (Lathrop et al., 1989). This takes place in the anaerobic bottom sediments, or the anoxic hypolimnion of some large lakes (Carroll, Warwick, Heim, Bonzongo, Miller, & Lyons, 2000). Also yeasts, such as Candida albicans and Saccharomyces cerevisiae, methylate mercury and reduce Hg$^{2+}$ to elemental mercury in low pH conditions (ATSDR, 1999).

Two ideas address the location of biological methylation. The dominant theory maintains that methylation occurs inside bacteria, with the transfer of a methyl group
from a donor molecule, such as methylcobalamin. It is an enzyme-catalyzed process, not a spontaneous chemical reaction. The second theory maintains that methylation is an extracellular process aided by bacterial exoenzymes that also catalyze decomposition of organic matter (Ulrich et al., 2001).

The process of demethylation regulates the concentration of organic mercury in sediments and waters. It is thought to be a microbial-mediated activity, conducted by numerous bacterial strains, mostly aerobic organisms but also anaerobic organisms (Ulrich et al., 2001). Demethylation is a reductive process. The accepted mechanism involves the cleavage of the C-Hg bond by the organomercurial lyase enzyme, producing methane and Hg$^{2+}$. The reduction of Hg$^{2+}$ to Hg$^{0}$ by the mercuric reductase enzyme follows (Ulrich et al., 2001). A photolytic method of demethylation is the only significant abiotic decomposition process (Ulrich et al., 2001).

Different environmental conditions and numerous factors affect the rate of methylation, such as microbial activity and the concentration of bioavailable mercury. The amount of mercury depends on temperature, pH, redox potential, the amount of dissolved organic carbon, salinity, and the presence of inorganic and organic complexing agents (Lathrop et al., 1989; WHO, 1990). The complex interactions of these factors promote or discourage methylation. In general, higher rates of methylation arise in aquatic systems with the following characteristics: low pH, low salinity, low alkalinity, low calcium ions, low productivity, and the presence of decomposable and dissolved organic matter (Lathrop et al., 1989; WHO, 1990). Increased acidification in sediments decreases the methylation rate in anoxic subsurface conditions, and the rate increases in aerobic surficial conditions (Lathrop et al., 1989).
Microbiology

Microbial activity influences mercury cycling. Microorganisms catalyze some of the conversions from one form of mercury to another. Mercury volatilization ($\text{Hg}^{2+}$ to $\text{Hg}^0$) is thought to be a detoxification process for some organisms, and mercury methylation ($\text{Hg}^{2+}$ to methyl and dimethylmercury) is thought to be a natural part of the detoxification process (Ulrich et al., 2001). Although mercury compounds can be toxic to aquatic organisms, many bacteria have developed methods of resistance.

Anaerobic sulfate-reducing bacteria are the major methylators of inorganic mercury. Methanogenic bacteria have a minor role in methylation, but they act mostly as demethylators along with sulfate-reducing bacteria in estuarine and freshwater sediments (ATSDR, 1999). Although methylation in sediments often correlates with sulfate-reduction rates and/or sulfate-reducing bacteria population distribution, not all sulfate-reducing bacteria methylate mercury (ATSDR, 1999).

Several factors affect the efficiency of microbial methylation. The activity and structure of the microbial community, the availability of mercury and nutrients, and the concentration of electron acceptors, such as sulfate, influence methylmercury production (Ulrich et al., 2001). In conditions of limited sulfate, other organic substances may be used in place of sulfate. Such conditions increase the methylating potential of sulfate-reducing bacteria, perhaps due to the inhibitory effect of sulfide on methylation (Ulrich et al., 2001). In conditions of high sulfate concentration, sulfate respiration produces sulfide, which interferes with methylation. Sulfide inhibition may arise from $\text{HgS}$ precipitation, or the formation of charged $\text{Hg-S}$ complexes (Ulrich et al., 2001).
Methylation rates correlate with microbial activity and availability of nutrients. Methylation and sulfate reduction rates are highest in areas where the microbial activity and nutrient supply are greatest, such as in the upper layers of sediment and on suspended organic matter (Choi & Bartha, 1994). The availability and chemical form of mercury affects methylation. Microbial uptake of mercury involves diffusive transport across bacterial membranes, which have a higher permeability for uncharged molecules than ionic species. Uncharged HgCl₂ may diffuse through, while charged complexes, such as HgOHCl and Hg(OH)₂ and Hg²⁺ ions, do not cross readily (Ulrich et al., 2001). Therefore, the availability of mercury is determined by the concentration of neutral dissolved mercury complexes. In oxic waters, HgCl₂ is the key chemical species affecting bacterial uptake, while HgS, bisulfide Hg(SH)₂, and polysulfide complexes are key in anoxic waters (Ulrich et al., 2001).

Environmental conditions influence net methylmercury production by affecting the dominance of either methylation or demethylation (Ulrich et al., 2001). High concentrations of inorganic mercury in sediments may inhibit methylation or favor demethylation. Studies have reported a tendency in sediments with high concentrations of mercury to show increased demethylation rates (ATSDR, 1999). In water, though, an increase in Hg²⁺ leads to an increase in methylation rates, perhaps due to increased availability of Hg²⁺ which can be methylated (WHO, 1989).

**Temperature**

Temperature affects methylation as a result of influencing microbial activity. Methylation rates are highest in summer months, peaking during mid to late summer. Rates decrease in winter as rates of growth and activity also decrease. Thus, the effects
of temperature on methylation are related to seasonal changes in productivity, nutrient supply, and redox conditions (Ulrich et al., 2001; Watras, Morrison, Host, & Bloom, 1995). Increased methylmercury production may be a result of decreased demethylation rather than an actual increase in methylation. Studies have shown that higher temperatures increase methylation, while lower temperatures favor demethylation (Ulrich et al., 2001).

**pH**

In general, low pH values tend to favor methylation (Lathrop et al., 1989). Several studies have shown elevated mercury levels in fish from acidified lakes (Ulrich et al., 2001). The pH of water affects the solubility and mobility of mercury and methylmercury. Low pH conditions aid the release of heavy metals from sediments and particulate matter (Lathrop et al., 1989).

Studies have shown a positive correlation between water pH and Hg$^0$ volatilization. As pH increases, larger volumes of Hg$^0$ volatilize and methylation decreases due to a decrease in Hg$^{2+}$ substrate (Watras et al., 1995). High pH values favor dimethylmercury production. Dimethylmercury then volatilizes. Consequently, neutral and alkaline conditions may lead to reduced methylmercury concentrations while acidic waters may have a higher methylmercury concentration (Ulrich et al., 2001).

Decreasing pH values in water tend to favor an increase in methylmercury concentration. Decreasing pH values at the aerobic sediment-water interface favors an increase in methylmercury concentration. Conversely, a decrease in pH in anaerobic sediments leads to a decrease in methylmercury production. This decrease may be linked to a decrease in available inorganic mercury in sediment porewater, which results from
increased sorption to particles at low pH (Lathrop et al., 1989). The pH also affects demethylation rates, although less so than for methylation. Anaerobic demethylation in surface sediments decreases with decreasing water pH (Ulrich et al., 2001). Although the exact factors that influence methylmercury production are uncertain, acidic conditions tend to favor methylation in lake water and at the sediment-water interface, but acidic conditions decrease methylation rates in anoxic sediments. Lake water acidification may lead to an increase in methylation in water, but not in sediments (Ulrich et al., 2001).

**Organic Material**

Studies have observed increased methylation rates in water, sediments, and fish tissue with increased levels of organic carbon. This may be due to a stimulatory effect of organic nutrients on microbial methylation. Organic particulate matter may act as a substrate for methylating microbes (Lathrop et al., 1989). Some studies propose that DOC may mitigate methylmercury production and/or bioaccumulation in natural waters. One study shows that natural levels of DOC have no effect on methylation in sediments, and high DOC concentrations reduce methylation, perhaps due to complexing of inorganic mercury with organic matter (Miskimmin, Rudd, & Kelly, 1992). Another study shows that DOC decreases the availability of Hg$^{2+}$ to act as a substrate to methylating bacteria. This reduction is greater in neutral conditions than in acidic conditions (Ulrich et al., 2001).

The presence of organic matter in aquatic environments affects several conditions, which in turn affect methylation. The degradation of organic matter produces low molecular weight sulfur compounds, which can form complexes with Hg$^{2+}$, rendering it unavailable for methylation. Yet, degradation of organic matter consumes oxygen,
producing more anoxic conditions at the sediment-water interface. This may increase mobilization and methylation of inorganic mercury (Lathrop et al., 1989). DOC may increase the solubility of HgS and may inhibit HgS precipitation and aggregation (Lathrop et al., 1989). Increased DOC in lakes favors methylation at low pH or evasion at high pH, but low DOC and low pH favor sedimentation (Ulrich et al., 2001). Also, humic substances can reduce Hg$^{2+}$ to Hg$^{0}$ in aquatic environments. This can lead to decreased availability of Hg$^{2+}$ (Ulrich et al., 2001).

In summary, the role of organic material in the methylation process is not completely understood. Organic carbon can increase methylation by stimulating microbial activity, or through abiotic methylation by humic or fulvic substances. But, high DOC may inhibit methylation due to increased complexation of mercury with organic ligands, which decrease mercury bioavailability to bacteria, especially at neutral pH values (Ulrich et al., 2001). Anaerobic methylation increases in areas of high concentration of organic matter, perhaps due to stimulated microbial growth. Aerobic methylation is inhibited by high organic matter or particulate concentration (Ulrich et al., 2001).

**Redox Potential**

Although methylation can occur in both aerobic and anaerobic conditions, methylation rates, and the stability of the methylmercury compound, are highest in anoxic sediments and waters. Mercury methylation takes place mainly in anaerobic environments (Olson & Cooper, 1976; WHO, 1989). Low methylation rates in aerobic conditions may be due to reduced activity of anaerobic sulfate-reducing bacteria. Aerobic conditions favor demethylation (WHO, 1989).
The upper few millimeters of aquatic sediments are aerobic, and the rest of the sediments layers are anaerobic. In moderately anaerobic surface sediments, methylmercury concentrations are highest. Concentrations decrease rapidly with increasing sediment depth (ATSDR, 1999; Ulrich et al., 2001). In sediment porewaters, the concentration of methylmercury is greatest in anoxic layers, and lowest in oxic layers (Ulrich et al., 2001). It has been suggested that the high rate of methylmercury production just below the sediment-water interface results from increased methylation under moderately anaerobic conditions. Bacterial demethylation dominates in both the oxic surface zone and the deeper sediment layers where reduced conditions limit the availability of mercury (Ulrich et al., 2001).

The redox cycling of Fe and Mn oxides influences dissolved mercury concentrations in sediment porewaters. In oxidized surface layers, mercury associates with particulate organic matter and Fe and Mn oxyhydroxides, which limits dissolved mercury concentrations. At the redox boundary, oxyhydroxides accumulate and dissolve, releasing mercury, resulting in high mercury concentrations (Ulrich et al., 2001). Oxygen concentration also affects methylation in the water column. While methylation occurs mostly in anoxic regions, the concentration and distribution of methylmercury is partly controlled by Fe and Mn cycling at the redox boundary (Ulrich et al., 2001). Also, in sulfide-rich sediments, the methylation rate increases, perhaps due to high Fe concentration in the sediment. Fe complexes with sulfide, so the sulfide is unavailable to bind with Hg\(^{2+}\) (Lathrop et al., 1989).

Redox changes and seasonal variations affect methylmercury concentrations. In the hypolimnetic waters of seasonally stratified waters, methylmercury concentrations
increase during summer stratification and decrease after the fall turnover (Ulrich et al., 2001). A similar pattern occurs in surface sediments. Demethylation activities dominate in reaerated waters (Ulrich et al., 2001). As organic matter decomposes during summer months, sediments and waters become more anoxic. Combined with increased temperatures, conditions favor bacterial methylation. Also, redox cycling influences the release of mercury from bottom sediments, enriching the potential for methylation in anoxic waters (Ulrich et al., 2001).

**Sulfide**

Bacterial sulfate reduction produces hydrogen sulfide, which then affects the chemistry of anaerobic sediments. Anoxic conditions, with organic-rich sediments high in sulfate lead to high sulfide levels. High sulfide concentrations inhibit methylation in soils, sediments, and sediment porewaters (ATSDR, 1999). Because mercury forms insoluble HgS in the presence of sulfide, sulfide decreases the availability of Hg$^{2+}$ for methylation in anaerobic environments. In aerobic environments, sulfide may be oxidized to sulfate, which increases the solubility and availability of Hg$^{2+}$ (ATSDR, 1999). The presence of sulfide partly controls mercury speciation, thereby influencing methylation by affecting the bioavailability of mercury (ATSDR, 1999).

**Salinity**

Methylation rates are low in high salinity sediments, and the effect is enhanced in reducing conditions. Also, high salinity conditions favor demethylation. The presence of bicarbonate decreases methylation in aerobic and anaerobic conditions, perhaps due to HgCO$_3$ formation (Ulrich et al., 2001).
In summary, methylation is mainly microbial, and methylcobalamin is the most probable environmental methyl donor (Ulrich et al., 2001). Abiotic methylation plays a minor role in total methylmercury production, although abiotic methylation rates increase in organic-rich waters with the increase in humic and fulvic acids (Ulrich et al., 2001). The precise mechanism of methylmercury formation is unclear. It is influenced by the speciation and biochemical availability of mercury and interrelated environmental factors, such as biological activity, nutrient availability, pH, temperature, redox potential, and presence of inorganic and organic complexing agents. Anaerobic conditions favor methylation, while aerobic conditions favor demethylation (Ulrich et al., 2001). If a body of water is stratified, then methylation occurs mostly at the oxic/anoxic interface (bottom waters or surface sediments). Seasonal variations affect methylation as temperatures, redox potentials, and productivity, which in turn affect nutrient availability, vary with the seasons. Moderately high temperatures increase methylation, while lower temperatures increase demethylation (Ulrich et al., 2001). Acidification of lake water can result in increased methylation in the water column, and decreased methylation in sediments, which could be from the decreased activity of sulfate-reducing bacteria or from increased demethylation. Low pH values in sediments increase desorption of methylmercury. Sulfate-reducing bacteria are important methylators in anaerobic sediments. Sulfate stimulates microbial methylation at low concentrations. High levels of sulfate, found in reducing conditions, inhibit methylation due to the formation of sulfide, HgS precipitation, and decreased availability of mercury by the formation of Hg-S complexes. The precise influence of organic matter on methylation is not understood. Humic matter helps control solubility and mobility of mercury. Organic nutrients increase microbial
activity and methylation, and they may also affect demethylation. In neutral pH areas, an increase in DOC mitigates the production and bioaccumulation of methylmercury due to the formation of mercury complexes. Also, pH values affect the formation and dissolution of Hg-organic matter combinations. Low pH values decrease the complexing of mercury and organic matter. The complexity of the variables involved in the different methylation processes makes it difficult to predict how environmental changes will affect methylation.

**Uptake by Fish**

**Bioaccumulation**

The methylation of inorganic mercury in aquatic systems acts as a major factor in the transport of mercury in aquatic food chains, ultimately affecting human exposure through consumption of fish and shellfish. Factors affecting methylation in turn affect bioaccumulation by influencing the concentration of methylmercury available to aquatic organisms.

Because of its highly soluble and mobile nature, methylmercury quickly enters aquatic food chains and accumulates in biological tissue (ATSDR, 1999; Eisler, 1987; WHO, 1989). Evidence for biomagnification can be found in the elevated levels of methylmercury in piscivorous or carnivorous fish compared with non-carnivorous species or fish at lower levels of the food chain (ATSDR, 1999; Bowles, Apte, Maher, Kawei, & Smith, 2001; Burger, Gaines, Boring, Stephens, Snodgrass, & Gochfeld, 2001; Castilhos, Bidone, & Lacerda, 1998; Dellinger, Knieck, Gerstenberger, & Ngu, 1995; Lindestrom, 2001). Virtually all mercury (95% - 99%) found in freshwater fish is methylmercury
Methylmercury is less volatile than other species of mercury, and it diffuses rapidly into organic tissue (Lathrop et al., 1989). Methylmercury has high lipid solubility and is absorbed efficiently through biological membranes, and it is slowly degraded to inorganic mercury and excreted (Lange, Royals, & Connor, 1994; Lathrop et al., 1989; WHO, 1989). Methylmercury possesses a high affinity for sulfhydryl groups. These groups are mainly found in association with proteins. Unlike many other environmental contaminants, mercury accumulates in muscle tissue, as opposed to the skin and fat tissue (Dellinger et al., 1995; Foster et al., 2000). Over 90% of the mercury in fish is methylmercury bound to protein (Bloom 1992; Morgan, Berry, & Graves, 1997). Therefore, the amount of methylmercury in raw fish will remain in fish muscle even after cooking and processing.

Methylmercury enters an organism via passive diffusion, and some is converted to a non-diffusible, protein-bound form (Lange et al., 1994; Lathrop et al., 1989; Mauk & Brown, 2001; WHO, 1989). The protein-bound form equilibrates with the diffusible form, so methylmercury retains some of its mobility within tissues (WHO, 1989). Also, the bound portion of methylmercury maintains a concentration gradient favorable for continual diffusion into organisms (Lathrop et al., 1989). Tissue concentrations vary between fish species, but some species, such as walleye (Stizostedion vitreum vitreum), and largemouth bass (Micropterus salmoides), have higher mercury concentrations in muscle (Foster et al., 2000; Mauk & Brown, 2001). Mercury also accumulates in the liver, gills, brain, and gonads of fish (Foster et al., 2000; Lange et al., 1994).
Methylmercury accumulates in aquatic organisms and concentrates up the trophic levels, resulting in higher mercury concentrations in large carnivorous fish (Lathrop et al., 1989; WHO, 1989). Methylmercury forms in the upper sediment layers or in the suspended sediments in the water column (WHO, 1989). Methylmercury desorbs from sedimentary particles in the water. Also, methylmercury is released into the water column by microbes (Lathrop et al., 1989). It is quickly accumulated from surface waters by aquatic organisms. First bottom fauna, including plankton and zooplankton, accumulate methylmercury, as these organisms are closest to the active sediment layer (WHO, 1989). Phytoplankton is particularly efficient in accumulating methylmercury from the water column, resulting in low concentrations of methylmercury in the water column (Bowles et al., 2001). Methylmercury binds to cell walls and membranes, so bioaccumulation is influenced by cell density and concentration (WHO, 1990).

The length of food webs and the biomagnification factors between trophic levels also influences the bioaccumulation and biomagnification of mercury (Bowles et al., 2001). At the beginning of the food web, zooplankton and phytoplankton absorb methylmercury. When they are eaten by primary consumers, like minnows and darters, the methylmercury is transferred from plankton to the fish, in concentrations relative to the amount of plankton and/or zooplankton consumed (WHO, 1990). Secondary consumers, such as perch, bluegill, and crappies, eat the primary consumers. At the top of the chain consumers like northern pike, largemouth bass, and walleye, and marine organisms like sharks, tuna, swordfish, and whales, concentrate the most methylmercury, which then may be passed on to human consumers via fish consumption (WHO, 1990). Many food webs can be broken down to four trophic levels, including phytoplankton, zooplankton,
planktivore, and piscivore. The length of this chain is sufficient to biomagnify methylmercury 30 fold or more between plankton and piscivorous fish (Bowles et al., 2001). Longer and/or more connected food webs would result in higher concentrations of methylmercury in piscivorous fish. Also, the efficient bioaccumulation of methylmercury at the base of the food web results in higher concentrations in piscivorous fish (Bowles et al., 2001). Table 3 provides an example of methylmercury accumulation at different trophic levels, and the corresponding methylmercury increases associated with each step up the food chain.

Table 3. Biomagnification of Methylmercury in a Freshwater Food Chain

<table>
<thead>
<tr>
<th>Trophic Level</th>
<th>Methylmercury</th>
<th>% Methylmercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>$10^3$</td>
<td>15</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>$10^{5.5}$</td>
<td>30</td>
</tr>
<tr>
<td>Fish</td>
<td>$10^{6.5}$</td>
<td>95</td>
</tr>
</tbody>
</table>

Recreated from ATSDR, 1999

Fish take in methylmercury from food sources and directly from water passing through gill membranes (ATSDR, 1999; Burger et al., 2001; Gerstenberger et al., 1993; Lathrop et al., 1989; WHO, 1989). The importance of the uptake path depends on the trophic level of the organism. Food seems to be the dominant source for organisms in higher trophic levels, such as walleye and northern pike (ATSDR, 1999; Bowles et al., 2001; Foster et al., 2000; Lange et al., 1994; WHO, 1989). Feeding location also affects
bioaccumulation. Bottom-dwelling fish may have higher levels of mercury, especially if they ingest sediments (Burger et al., 2001).

A trend exists between fish age and size characteristics and mercury concentrations in fish. A positive correlation exists between methylmercury concentrations in fish tissue and the age and/or length of the fish (Bowles et al., 2001; Burger et al., 2001; Castilhos et al., 1998; Gutenmann et al., 1992; Lange et al., 1994; Lindestrom, 2001; Mauk & Brown, 2001; WHO, 1989). Older, larger fish are at the top of the food chain, and have had longer exposure time and have consumed more contaminated smaller fish, thus accumulating more methylmercury (WHO, 1989). Methylmercury leaves the fish body extremely slowly. For example, the half-life of methylmercury is approximately 700 days for northern pike (Esox lucius) (Lathrop et al., 1989). Consequently, continual uptake and slow elimination of methylmercury leads to higher concentrations of methylmercury in older, larger fish (Lathrop et al., 1989).

Some forms of mercury can cross respiratory, gastrointestinal, placental, brain, and mucus membranes, so mercury moves between tissues (WHO, 1990). Fish do show signs of mercury poisoning at high concentrations (36 to 68 ppm fresh weight in liver, 16 to 20 ppm fresh weight in brain, and 5 to 7 ppm fresh weight in whole body) (Eisler, 1987). All forms of mercury interfere with the proteins involved with mitosis. Consequently, mercury interrupts cell division, causing immediate and long-term problems (WHO, 1990). Flared gill covers, increased respiratory movements, loss of equilibrium, and sluggishness characterize acute mercury poisoning. A fish with chronic mercury poisoning may have brain lesions, cataracts, decreased response to light changes, abnormal and erratic motor coordination, and emaciation (Eisler, 1987).
Several microorganisms demethylate in aquatic systems. The balance between methylation and demethylation affects the amount of methylmercury available for bioaccumulation (Grieb et al., 1990). Speciation of mercury, the amount of mercury input and the mobilization and cycling of existing mercury, and the water conditions affecting these factors, influence methylation and demethylation processes and the potential for bioaccumulation of methylmercury (Grieb et al., 1990; Lathrop et al., 1989). Table 4 describes mercury concentrations found in selected fish species.

Table 4. Mercury Concentrations Found in Selected Fish Species

<table>
<thead>
<tr>
<th>Species</th>
<th>EPA average ug Hg/g</th>
<th>FDA average ug Hg/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater Bass</td>
<td>1985 Calculation - 0.157 1994 Calculation - 0.38</td>
<td>0.752</td>
</tr>
<tr>
<td>Striped Bass</td>
<td>0.110</td>
<td>0.29</td>
</tr>
<tr>
<td>Freshwater Perch</td>
<td>0.035</td>
<td>0.04</td>
</tr>
<tr>
<td>Salmon</td>
<td>0.013</td>
<td>0.023</td>
</tr>
<tr>
<td>Herring</td>
<td>0.31</td>
<td>0.81</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>0.1</td>
<td>0.016</td>
</tr>
<tr>
<td>Smelt</td>
<td>0.149</td>
<td>0.417</td>
</tr>
<tr>
<td>Freshwater Trout</td>
<td>Not Reported</td>
<td>0.054</td>
</tr>
<tr>
<td>Whitefish</td>
<td>1985 Calculation -0.1 1994 Calculation -0.52</td>
<td>0.149</td>
</tr>
<tr>
<td>Walleye</td>
<td>1985 Calculation -0.1 1994 Calculation -0.52</td>
<td>0.149</td>
</tr>
<tr>
<td>Rainbow and Lake Trout</td>
<td>1985 Calculation -0.149 1994 Calculation for Brown Trout - 0.14</td>
<td>0.149</td>
</tr>
</tbody>
</table>

Recreated from U.S. EPA, 1997

Water Chemistry Factors Influencing Bioaccumulation

A negative correlation seems to exist between water pH and methylmercury concentrations in fish (ATSDR, 1999; Cope, Wiener, & Rada, 1990; Lathrop et al., 1989;
Wren & MacCrimmon, 1983). A low pH in the anoxic sediments below the surface layers may decrease methylation, but in the aerobic sediments of the sediment-water interface, as well as in the water column, methylation increases (Cope et al., 1990; Lathrop et al., 1989). Also, pH affects partitioning of methylmercury. At lower pH values, less mercury sorbs to particulate matter, resulting in more mercury available for methylation (Lathrop et al., 1989). The release of methylmercury from sediments increases at lower pH values (Cope et al., 1990). The effect of low pH on mucus production in fish may also lead to increased methylmercury concentrations in fish (Lathrop et al., 1989).

Water bodies with low alkalinity show increased methylmercury concentrations in fish (ATSDR, 1999; Cope et al., 1990; Lathrop et al., 1989; Wren & MacCrimmon, 1983). Areas with low alkalinity have less particulate matter. Therefore, mercury cannot form as many complexes, increasing the amount of unbound mercury available for methylation (Lathrop et al., 1989).

A negative correlation exists between calcium (Ca$^{2+}$) concentrations and methylmercury concentrations in fish (Cope et al., 1990; Lathrop et al., 1989; Wren & MacCrimmon, 1983). Gill permeability may be affected by calcium-mediated processes (Lathrop et al., 1989). Uptake of waterborne methylmercury by fish occurs mostly across the gills. Low calcium concentration in water increases gill permeability and increases methylmercury concentrations in fish (Wiener et al., 1990).

The organic content of a water body affects bioaccumulation. Mercury, both organic and inorganic species, complexes easily with dissolved and particulate matter (Lathrop et al., 1989). Thus, the amount of organic particulates affects methylation and
bioaccumulation. This is complicated by the amount of productivity and ionic content of an aquatic system. For example, areas of high productivity have low methylmercury concentrations (Lathrop et al., 1989). In areas of high productivity, an internal source is responsible for the organic content. The anoxic conditions of eutrophic water facilitate HgS formation. The Hg in HgS can only be released through aerobic microbiotic processes. So, in areas with large amounts of organic material, mercury complexes with the particulate matter, settles into sediments, and forms HgS (Lathrop et al., 1989). In areas of high organic content, such as an area with high humic input, and low productivity, the methylmercury concentration is lower (Lathrop et al., 1989).

Interactions between these factors make it difficult to isolate the effects of a single factor. For example, pH may affect the complexing of mercury to dissolved organic particulates, making it more or less bioavailable (Lathrop et al., 1989). Also, low Ca\(^{2+}\) concentrations are associated with low alkalinity waters. Such conditions increase the efficiency of methylmercury uptake across the gill membranes (Cope et al., 1990). The relationship between pH, organic content, the amount of mercury in the system, and the amount of dissolved and particulate organic matter influences bioaccumulation of methylmercury (Lathrop et al., 1989). In general, the combination of low pH, low alkalinity, low Ca\(^{2+}\), low productivity, and high dissolved organic content leads to high concentrations of methylmercury in fish (ATSDR, 1999; Lathrop et al., 1989).

Characteristics of a body of water, such as depth, volume, and area affect mercury chemistry and bioaccumulation (Wren & MacCrimmon, 1983). The mercury concentration in water and the speciation affects bioavailability of mercury (Wren & MacCrimmon, 1983). Also, the diet, growth rate and metabolic rate of organisms, and
body size affect bioaccumulation (Wren & MacCrimmon, 1983). Selenium may have a protective effect on mercury toxicity at high concentrations in some fish species (Burger et al., 2001). Therefore, the presence of selenium in tissue may affect bioaccumulation through uptake and metabolism of methylmercury (Burger et al., 2001). Finally, the microbe population present affects methylation rates, and the amounts of Fe and sulfur (S), which both complex with mercury, affect the availability of mercury (Lathrop et al., 1989).

Seasonal and geographic variations in mercury concentrations in fish may arise from different events. For example, factors such as sediment temperature, anoxic conditions, and seasonal flooding affect methylation processes, and may result in higher concentrations of methylmercury in summer months (Foster et al., 2000). Warmer sediments and/or anoxic hypolimnion conditions favor methylation, while flooding of soils releases mercury bound to soil particles, increasing methylation (Foster et al., 2000). Seasonal factors specific to fish influence bioaccumulation. As the temperature increases, metabolism increases and methylmercury uptake may increase (Lathrop et al., 1989; Mauk & Brown, 2001; Wren & MacCrimmon, 1983). Seasonal changes in diet affect bioaccumulation (Foster et al., 2000; Gerstenberger et al., 1993). In one study, mercury concentrations were higher in the liver and gonads in the summer and lower in the spring (Foster et al., 2000). Fish accumulate adipose tissue during the summer months (Dellinger et al., 1995; Gerstenberger et al., 1993). As a result, fish samples analyzed after the fall months may show lower concentrations (or less dilution) of mercury. In addition to the effects of season on mercury bioaccumulation in fish, reproductive status may have an effect on mercury levels in fish tissue (Foster et al.,
Indeed complex interactions between the numerous factors affecting methylation and demethylation, and bioaccumulation and biomagnification of mercury in fish, govern mercury concentrations in fish. Studying the interrelationships between these factors requires site-specific and fish-specific analyses. Table 5 describes several studies examining different variables affecting mercury concentrations in fish.

Due to bioaccumulation, high mercury concentrations in fish in several regions may pose a significant health threat to humans through fish consumption. For example, methylmercury is a persistent environmental contaminant in the Great Lakes and related tributaries (Beattie, Gerstenberger, Hoffman, & Dellinger, 1996; Henry, Kannon, Nagy, Kevern, Zabik, & Giesy, 1998). In fact, numerous fish and wildlife consumption advisories have been issued for the Great Lakes region (Figure 2).

Studies have found high concentrations of mercury in piscivorous fish in low alkalinity lakes in the north central and northeastern United States (Cope et al., 1990). For example, high mercury concentrations have been found in walleyes from rural, low alkalinity lakes in north central Wisconsin (Cope et al., 1990). Walleye is an important sport fish in the U.S. and Canada, and an important fish integral to the culture and religion of several Native American populations (Wiener et al., 1990). Walleye accumulates mercury in the edible muscle tissue (Cope et al., 1990; Wiener et al., 1990). The high metabolic rate, high rate of food consumption, and their trophic status results in a rapid uptake of mercury by adult walleye (Wiener et al., 1990). Yellow perch (Perca flavescens) is the predominant prey of adult and juvenile walleye (Cope et al., 1990; Wiener et al., 1990). A pathway for the bioaccumulation of methylmercury in walleye...
<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Fish Species</th>
<th>Fish Characteristics</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiener et al., 1990</td>
<td>Wisconsin</td>
<td>Walleye</td>
<td>pH, Ca, Hg concentrations</td>
<td>High Hg in fish in areas of low pH. The net rate of methylation was greater in low pH lakes, (but not as a result of acidification)</td>
</tr>
<tr>
<td>Bache, Gutenmann, &amp; Lisk, 1971</td>
<td>New York</td>
<td>Lake Trout</td>
<td>Age and Hg concentration</td>
<td>High Hg in older fish due to longer exposure</td>
</tr>
<tr>
<td>Grieb et al., 1990</td>
<td>Upper Michigan Peninsula</td>
<td>Yellow Perch, Northern Pike, Largemouth Bass, White Sucker</td>
<td>pH, fish species, DOC</td>
<td>MeHg concentration increases with age. Northern Pike and Bass had highest Hg accumulation. Correlation between areas of low DOC and high Hg, (Hg binds to organics)</td>
</tr>
<tr>
<td>Cope et al., 1990</td>
<td>North central Wisconsin</td>
<td>Yellow Perch, Walleye</td>
<td>pH, alkalinity</td>
<td>Correlation between Hg concentration in Perch and Walleye. High Hg in low alkalinity lakes, high Hg in low pH lakes</td>
</tr>
<tr>
<td>Wren &amp; MacCrimmon, 1983</td>
<td>Ontario</td>
<td>Sunfish</td>
<td>Environmental conditions</td>
<td>High Hg in low pH water, high Hg with low Ca levels. Lake volume and depth affects water quality and subsequently Hg bioavailability</td>
</tr>
<tr>
<td>Bowles et al., 2001</td>
<td>Papua New Guinea</td>
<td>Food webs</td>
<td>Trophic levels</td>
<td>Older, piscivorous had higher Hg concentrations</td>
</tr>
<tr>
<td>Study</td>
<td>Location</td>
<td>Species</td>
<td>Variable</td>
<td>Description</td>
</tr>
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<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Amrhein &amp; Geis, 2001</td>
<td>Wisconsin</td>
<td>Yellow Perch</td>
<td>Hg concentration over time</td>
<td>Hg concentrations higher now than in 1920s</td>
</tr>
<tr>
<td>Henry et al., 1998</td>
<td>Michigan</td>
<td>Smallmouth Bass</td>
<td>Weight</td>
<td>No correlation between Hg concentration and weight. Perhaps a dilution factor working. (fish grows faster than Hg accumulates)</td>
</tr>
<tr>
<td>Lange et al., 1994</td>
<td>Florida</td>
<td>Largemouth Bass</td>
<td>Age, size, Hg concentration</td>
<td>Hg concentration increases with age and size</td>
</tr>
<tr>
<td>Gutenmann et al., 1992</td>
<td>New York</td>
<td>Lake Trout</td>
<td>Age and Hg Concentration</td>
<td>Hg concentration increases with age</td>
</tr>
</tbody>
</table>

may begin with yellow perch and their consumption of contaminated zooplankton (Cope et al., 1990). Studies show a correlation between mercury concentrations in walleye and mercury concentrations in yellow perch (Cope et al., 1990).

Many lakes in northern Wisconsin have lakes with characteristics conducive to bioaccumulation of methylmercury. These bodies of soft water receive mercury from natural sources, as well as atmospheric-borne mercury (Lathrop et al., 1989; Wiener et al., 1990). With low pH and low alkalinity, and low buffering capacities, acid deposition increases the availability of methylmercury to fish (Grieb et al., 1990; Lathrop et al., 1989). Studies in the area show a positive correlation between walleye fish length and methylmercury concentration (Dellinger et al., 1995; Gerstenberger et al., 1993; Lathrop et al., 1989). The study areas have soft water, low pH, poor buffering capacity, and high
Recreated from ATSDR, 1999

Figure 2. Listing of Fish and Wildlife Consumption Advisories Issued for Mercury
levels of mercury (Lathrop et al., 1989). Also, studies indicate that atmospheric inputs of mercury into northern Wisconsin lakes may be increasing (Wiener et al., 1990).

Walleye has long been an important fish to the diet and culture of the Ojibwa tribes of Wisconsin (Dellinger et al., 1995; Gerstenberger et al., 1993). Fish analysis has shown that walleye regularly exceed the fish consumption advisory of 0.5 ppm set by the Wisconsin Department of Natural Resources (Dellinger et al., 1995). Traditionally, the Ojibwa harvest spawning walleye with spears during a three to four week period in the spring (Dellinger et al., 1995). Also, Ojibwa harvest lake whitefish and lake trout from Lake Superior. Studies show that lake trout, a piscivorous species, may have high concentrations of mercury (Dellinger et al., 1996). Consequently, the bioaccumulation and biomagnification of mercury poses a significant threat to human health through fish consumption.

Uptake by Humans

Toxicology of Mercury

Absorption

Methylmercury absorption takes place primarily through oral routes, and organic mercury compounds are more readily absorbed through ingestion than inorganic mercury compounds (ATSDR, 1999). Once ingested, methylmercury is readily absorbed from the gastrointestinal tract (Airey, 1983; ATSDR, 1999; Satoh, 2000). The gastrointestinal tract will efficiently absorb most of the methylmercury, approximately 95% (ATSDR, 1999; Magos, 1997; Sweet & Zelikoff, 2001; WHO, 1989). The small intestine is the
site of most absorption in the gastrointestinal tract (Kershaw & Dhahir, 1980). Metallic mercury is poorly absorbed from the gastrointestinal tract. Organic mercury compounds may also exist in particulate form, and be absorbed through inhalation (WHO, 1989). Indirect evidence suggests that absorption through the alveolar tissue is high, around 80% (WHO, 1989). There is limited evidence of dermal absorption of methylmercury. Absorption may depend on age, with greater absorption occurring in younger children (Sweet & Zelikoff, 2001).

**Distribution**

From the gastrointestinal tract, methylmercury moves to the blood, where it attaches to the red blood cells, and eventually distributes to all tissues (Bartell, Ponce, Sanga, & Faustman, 2000; Clarkson, 1991; Magos, 1997). The fraction of the absorbed dose in blood varies, but 5% to 10% of the dose immediately after ingestion is in the blood, and drops to 1% to 5% of the dose over 100 days (U.S. EPA, 2001). More than 90% of the ingested methylmercury binds to hemoglobin, while smaller amounts bind to plasma proteins (ATSDR, 1999; National Research Council, 2000). Methylmercury reaches tissues within four days, and maximum level will be reached after five to six days (WHO, 1990).

Methylmercury can cross diffusion barriers and cross all membranes with ease (ATSDR, 1999). Tissue concentrations stay constant in relation to blood levels (ATSDR, 1999). Due to its high lipophilicity, methylmercury can cross tissue and cell membranes. The target organs are the kidneys, liver, and brain, and methylmercury readily crosses the blood-brain barrier and the placental barrier (Clarkson, 1972). The highest level of mercury deposition occurs in the kidneys (ATSDR, 1999). Methylmercury is

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demethylated to inorganic mercury, with the rate of demethylation depending on species, tissue, dose, and time (ATSDR, 1999). Inorganic mercury then accumulates in tissues, especially the kidneys and liver (ATSDR, 1999).

Methylmercury crosses the placental barrier, and the fetal brain preferentially absorbs methylmercury (Clarkson, 1991). This results in an accumulation of methylmercury in the developing fetus. Methylmercury may complex with the amino acid cysteine in plasma. The structure of this complex is similar to methionine, an amino acid (Clarkson, 1991). The complex crosses the blood-brain barrier, and is transported into the developing brain (Clarkson, 1991).

Oxidation of methylmercury to inorganic mercuric ion results in the retention of mercury in the brain and fetus (ATSDR, 1999). An amino acid carrier transports methylmercury across the blood brain barrier as a methylmercury-cysteine complex. Methylmercury and elemental mercury are oxidized to the mercuric form, which binds to metallothionein and cannot cross the barrier. Mercury then accumulates in the calcarine cortices, parietal cortices, and the cerebellum (National Research Council, 2000).

Demethylation occurs in all organs, except the skeletal muscle, but the rate of demethylation is slower in the brain (ATSDR, 1999).

Organ distribution depends on the type of mercury absorbed. Methylmercury will be converted to mercuric ion, therefore the amount of mercuric ion in the body increases with increasing time after exposure to methylmercury (WHO, 1989). The proportion of inorganic mercury to methylmercury depends on the rate of uptake, elimination of inorganic mercury and methylmercury, and the specific biotransformation rate in a tissue (WHO, 1990). Distribution of methylmercury in humans varies by age. Neonates and
young children concentrate methylmercury in the target tissues more than adults (WHO, 1990).

Methylmercury travels through the body by binding to cystinyl residues in the hemoglobin molecule. The position of the residue in an amino acid chain differs among species. In humans, methylmercury complexes with glutathione in erythrocytes. These complexes may be involved with blood transport and tissue distribution, biliary secretion, and membrane transport (WHO, 1990).

Metabolism

In the body, methylmercury is stable, and is slowly demethylated to inorganic mercury, specifically mercuric ion, $\text{Hg}^{2+}$ (ATSDR, 1999). Methylmercury breaks down at a rate of 1% per day (Airey, 1983). Biotransformation, or demethylation, occurs in the liver, intestinal microflora, and tissue macrophages. This process takes a long period of time, from several months to years. In chronic cases, the latent period lasts about one month (National Research Council, 2000). During this latent period, a person exposed to methylmercury will feel no effects. The half-life of mercury in the brain is longer than the half-life in the blood; therefore the brain accumulates large concentrations of mercury. In acute cases of methylmercury poisoning, the dominant mercury species in the brain is organic. In chronic cases, the predominant form is inorganic (U.S. EPA, 2001). Demethylation of organic mercury compounds may lead to a concentration of inorganic compounds, such as $\text{HgCl}_2$, $\text{HgCl}_3$, $\text{HgCl}^{2-}$, $\text{Hg(OH)}_2$, and $\text{Hg}^{2+}$, in an organism (Sweet & Zelikoff, 2001).

A possible mechanism for the metabolic pathway, and the long latent period, begins with the carbon-mercury bond. Homolytic cleavage releases the methyl free radical (U.S.
EPA, 2001). The radical then activates a chain of events, including the peroxidation of lipid components of the neuronal cells. Symptoms of this peroxidation are delayed while the body prevents or repairs the cells. Eventually, body defenses are overwhelmed, and rapid and progressive tissue degeneration takes place (U.S. EPA, 2001).

Since the intestinal wall does not absorb inorganic mercury, most of it is excreted. Accumulation of mercury occurs when uptake exceeds elimination. Eventually a steady state may be reached, when uptake equals elimination. Factors such as the duration of exposure and the interval after cessation, control the total mercury concentration in tissues, and ultimately determine the amount of time until a steady state is reached (WHO, 1990).

Excretion

In humans roughly 1% of the body burden of methylmercury is excreted per day, primarily through the feces as mercuric ion (National Research Council, 2000). In fact, approximately 90% of the mercury excreted from humans is through the feces (Magos, 1997; U.S. EPA, 2001; WHO, 1990). Smaller amounts of methylmercury may be excreted through bile and urine. Mercury will also be excreted through sweat, lungs, hair and breast milk (National Research Council, 2000). Urinary mercury probably results from the deposition of demethylated mercury in kidneys (U.S. EPA, 2001). Biliary methylmercury can be reabsorbed. First, methylmercury forms a complex with glutathione in the hepatocytes. The complex is then secreted via a glutathione protein into bile, then through the gallbladder and intestines. The complex moves into blood, where the methylmercury is reabsorbed. Blood travels to the intestines, where microflora demethylate the methylmercury to mercuric ion, and the ion leaves the body in feces
(U.S. EPA, 2001). The rate of excretion may be age dependent as well. In rats and monkeys, neonates are unable to excrete mercury until they are weaned, potentially due to the inability of intestinal flora to demethylate (National Research Council, 2000).

Several studies have estimated the amount of time methylmercury remains in the human body. The whole body half-life in the human body is 70 to 80 days (U.S. EPA, 2001; WHO, 1990). The half-life of methylmercury in blood is 48 to 53 days (National Research Council, 2000). In cases of chronic exposure, a steady state, in which methylmercury intake equals mercury excretion, can take approximately one year to reach (National Research Council, 2000).

**Mechanisms of Action**

Methylmercury has a high affinity for sulfhydryl groups, which are found in elevated amounts in some proteins such as cysteine (Airey, 1983). Therefore, methylmercury affects proteins. It can inhibit many enzymes, precipitate proteins, and kill every kind of living cell (Airey, 1983).

The critical organ for methylmercury toxicity is the brain (ATSDR, 1999; WHO, 1990). Methylmercury can cross the blood brain barrier, undergo oxidation to mercuric ion, which is then trapped inside the brain bound to macromolecules. Mercury possesses a high affinity for sulfhydryls. These compounds are widely dispersed throughout the body, as they are found in proteins. Consequently, mercury may combine with the active centers of numerous important enzymes and structural proteins (National Research Council, 2000). Also, mercury binds to thiol found in proteins, cysteine, and glutathione. The formation of mercury-thiol bonds increases the mobility and toxicity of methylmercury (National Research Council, 2000).
Several ideas concerning the biochemical mechanisms of toxicity exist. The presence of methylmercury may cause changes in mitochondria, affecting cellular energy production, or disrupt protein synthesis or the mitotic process. By binding to thiols in tubulin, methylmercury may disrupt the normal functioning of microtubules in cell division. Methylmercury may produce membrane peroxidation in nerve cells, or produce oxidative stress by binding up the antioxidant glutathione (WHO, 1989). Methylmercury reacts with important receptors in the nervous system, and may affect acetylcholine receptors in the peripheral nerves (WHO, 1990).

The main mechanisms of toxicity may begin with the inhibition of protein synthesis in target nerve cells (WHO, 1990). The first stage involving transfer RNA may be the most sensitive step. Ribosomes have many sulfhydryl groups, half of which are exposed and reactive during peptide formation. This leads to the potential vulnerability of protein formation to methylmercury (WHO, 1990). Studies have shown that methylmercury also interferes with lipids, myelin, mitochondrial DNA, and glutathione peroxidase (WHO, 1990).

Methylmercury selectively affects cells in the central nervous system. This may depend on the selective ability of individual cells to repair damage (WHO, 1990). Those cells that cannot repair the damage wrought by methylmercury will not survive. For example, the small granule cells in the cerebellum lack the capacity to repair damage. Thus, they are destroyed first (WHO, 1990). Inter-neuronal axonal transport may also affect methylmercury toxicity. Sensory centers may be affected because axonal transport in the afferent direction leads to local accumulation. Motor systems are relatively unaffected because axonal transport in the efferent direction leads to removal (WHO, 1990).
Methylmercury interferes with cell division and cell migration (Clarkson, 1990). It destroys microtubules, and disrupts the cytoarchitecture of the brain, inhibiting division and migration (Clarkson, 1990; Clarkson, 1991).

**Human Health Effects of Toxicity**

The mercury-carbon bond in methylmercury is more stable than the bond in other organic mercury compounds (Satoh, 2000). This strong bond gives methylmercury its toxic properties. Both metallic and organic mercury can be partitioned in the brain, be converted to inorganic mercury, and remain trapped inside the brain as inorganic mercury, since inorganic mercury cannot pass the blood-brain barrier (ATSDR, 1999). Methylmercury deposited in the brain can irreversibly destroy brain and nerve cells, and lower concentrations may actually affect intelligence (Airey, 1983). Sensory, visual, auditory, and coordination problems (all cerebellum functions) relate to damage done in the brain and central nervous system (Gaggi, Zino, Duccini, & Renzoni, 1996). Effects depend on the age and stage of development, and are very different for prenatal life, the more sensitive stage, than for adults (ATSDR, 1999). The effects of methylmercury stem from the inhibition of protein synthesis (WHO, 1990).

Initial problems may include personality changes, such as irritability, shyness, and nervousness (ATSDR, 1999). The early effects include non-specific symptoms such as paraesthesia, malaise, tremors, and blurred vision. The problems intensify to constriction of the visual field, deafness, muscle incoordination, loss of sensation, memory problems, and ataxia (ATSDR, 1999; Clarkson, 1998; Satoh, 2000). The worst cases lead to coma and death. In less severe cases, some degree of recovery from all symptoms can occur, depending on the compensatory function of the brain (ATSDR, 1999; WHO, 1990). Due
to the long latent period of methylmercury biotransformation, acute poisoning can take place several months after exposure. Such poisoning leads to damage mostly in the central nervous system. Areas of damage to the brain are localized, particularly in the visual cortex and the granular layer of the cerebellum (WHO, 1990).

Prenatal exposure can result in several serious health effects, even if the mother shows no signs of poisoning (Clarkson, 1991). In developing tissue, the central nervous system is more sensitive than in the adult (ATSDR, 1999; WHO, 1990). The overall effect is dose dependent, as measured in the maternal blood. The main pattern involves cerebral palsy, microcephaly, hyperreflexia, gross motor and mental impairment, and some blindness and deafness (Clarkson, 1991). In mild cases, the effects, such as psychomotor impairment and the persistence of pathological reflexes, cannot be determined until later in the infant’s life (WHO, 1990). Also, children may show delayed achievement of developmental milestones, or other neurological problems (Clarkson, 1991). Methylmercury may affect normal neuronal development by affecting cell division during formation of the central nervous system. This inhibition of the microtubular system leads to altered brain cytoarchitecture (due to the incomplete and abnormal migration of neuronal cells to the cerebellar and cerebral cortices), heterotopic cells, and decreased brain size (WHO, 1989).

**Estimated Human Levels**

Numerous studies have been conducted to determine the extent of human exposure to mercury, and determine the concentrations of mercury in humans through consumption of fish. Table 6 summarizes some of the estimates of mercury intake levels and...
Table 6. Concentrations of Mercury in Humans

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Media</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49 ug/day</td>
<td>Average daily intake for infants</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>1.3 ug/day</td>
<td>Average daily intake for two-year-olds</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>2.9 ug/day</td>
<td>Average daily intake for females, ages 25 - 30</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>3.9 ug/day</td>
<td>Average daily intake for males, ages 25 - 30</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>2.4 ug methylmercury/day from all sources</td>
<td>Average daily intake</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>2.61 ug/day</td>
<td>Average daily intake from background sources, without dental amalgams</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>3.5 ug/day</td>
<td>Average daily intake of an adult (assuming 50 ng/kg body weight)</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>40 – 50 ng total Hg/kg</td>
<td>Average daily intake in the U.S.</td>
<td>Clarkson, 1990</td>
</tr>
<tr>
<td>0.1 ug/kg/day</td>
<td>RfD (reference dose) for methylmercury</td>
<td>EPA, 1997</td>
</tr>
<tr>
<td>0.3 ug/kg/day</td>
<td>MRL (minimum risk level)</td>
<td>ATSDR, 1999</td>
</tr>
<tr>
<td>1 – 8 ug/l</td>
<td>Mean total Hg in whole blood – general population</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>20 – 50 ug.100 ml Blood</td>
<td>Effects of Hg poisoning detectable in adults</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>50 – 120 mg/kg Hair</td>
<td>Effects of Hg poisoning detectable in adults</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>0.5 – 0.8 mg/kg Body Weight</td>
<td>Effects of Hg poisoning detectable in adults</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>3 – 7 ug/kg/day</td>
<td>Effects of Hg poisoning seen in adults with long-term daily intake at this level</td>
<td>WHO, 1990</td>
</tr>
<tr>
<td>0.002 – 0.006 mg/l Blood</td>
<td>Normal Value</td>
<td>Katz &amp; Katz, 1992</td>
</tr>
<tr>
<td>0.5 – 10 mg/kg Hair</td>
<td>Normal Value</td>
<td>Katz &amp; Katz, 1992</td>
</tr>
</tbody>
</table>

concentrations associated with adverse health effects. Table 7 compares mercury concentrations among human populations experiencing different exposures to mercury.

Table 8 summarizes mercury intake levels, specifically in the U.S.
Table 7. Comparisons of Mercury Exposure

<table>
<thead>
<tr>
<th>Population</th>
<th>Intake (ug Hg/day)</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minamata, Iraq</td>
<td>3000</td>
<td>Severe cases</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>Adult LOEL</td>
</tr>
<tr>
<td>Subsistence fish eaters</td>
<td>Between 30 and 300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>WHO tolerable limit</td>
</tr>
<tr>
<td>General Population</td>
<td>Below 3</td>
<td></td>
</tr>
</tbody>
</table>

Recreated from Clarkson, 1998

Table 8. Comparison of Mercury Intake in the U.S.

<table>
<thead>
<tr>
<th>Population</th>
<th>Intake (ng/kg/day)</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme Fish Eaters</td>
<td>10000</td>
<td>Effect Level (adults)</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>Effect Level (prenatal)</td>
</tr>
<tr>
<td>US Upper 0.1 – 0.2%</td>
<td></td>
<td>WHO Safe Limit</td>
</tr>
<tr>
<td>US Upper 1%</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>US Mean</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Recreated from Clarkson, 1990

The limit of consumption set by WHO is 300 ug/week of total mercury (Gaggi et al., 1996). Of this tolerable weekly limit of 300 ug Hg, or 0.3 mg Hg, no more than 200 ug, or 0.2 mg, may be methylmercury (Lopez-Artiguez, Grilo, Martinez, Soria, Nunez, Ruano, Moreno, Garcia Fuente, & Repetto, 1994). The acceptable daily intake of mercury is 40 ug according to the Agency for Toxic Substances and Disease Registry (ATSDR, 1999). Long-term daily ingestion of 200 to 500 ug of methylmercury leads to a blood concentration of 200 to 500 ug/l and a hair concentration of 50 to 125 ug/g (Gaggi et al., 1996). A 60 kg person has to eat 0.3 mg of methylmercury/day to reach a hair
concentration of 50 ug/g (Kyle & Ghani, 1982). Studies show that the intake of methylmercury occurs mostly through fish consumption (Table 9).

Table 9. Estimated Average Daily Intake and Retention of Total Mercury and Mercury Compounds in the Adult General Population

<table>
<thead>
<tr>
<th>Source of Exposure</th>
<th>Elemental Mercury Vapor Intake (ug/day)</th>
<th>Retention of Elemental Mercury Vapor</th>
<th>Inorganic Mercury Intake (ug/day)</th>
<th>Retention of Inorganic Mercury Compounds</th>
<th>Methylmercury Intake (ug/day)</th>
<th>Retention of Methylmercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.030</td>
<td>0.024</td>
<td>0.002</td>
<td>0.001</td>
<td>0.008</td>
<td>0.0064</td>
</tr>
<tr>
<td>Food:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td>0</td>
<td>0</td>
<td>0.600</td>
<td>0.042</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Non-fish</td>
<td>0</td>
<td>0</td>
<td>3.6</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>0</td>
<td>0</td>
<td>0.050</td>
<td>0.0035</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dental Amalgams</td>
<td>3.8 - 21</td>
<td>3 - 17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>3.9 - 21</td>
<td>3 - 17</td>
<td>4.3</td>
<td>0.3</td>
<td>2.41</td>
<td>2.31</td>
</tr>
</tbody>
</table>

Recreated from ATSDR, 1999

A normal acceptable range for hair is less than 6 ppm Hg (Gerstenberger, Tavris, Hansen, Pratt-Shelley, & Dellinger, 1997). Heavy consumption of contaminated fish may lead to levels of 20 to 50 ug/kg of hair (Adimado & Baah, 2002). Hair levels over 50 ug/g methylmercury are considered to be indicative of an increased risk of adverse health effects. In other words, symptoms of mercury poisoning may occur (Gaggi et al., 1996; Kyle & Ghani, 1982). A hair residue greater than 1.4 ppm may indicate exposure to mercury, this is the minimal risk level (MRL) for hair established by the U.S. Public Health Service (Dellinger et al., 1996). The threshold for adverse neurological effects in a fetus is 10 to 20 ug Hg/g maternal hair (Dolbec, Mergler, Larribe, Roulet, Lebel, &
Lucotte, 2001; Lopez-Artiguez et al., 1994). Also, a 5% risk of the fetus having mercury-related disorders is associated with a hair mercury concentration in the mother of 10 to 20 ug Hg/g of hair (Lopez-Artiguez et al., 1994). The Canadian Department of National Health and Welfare, Medical Services Branch, established categories for mercury risks using blood levels based on World Health Organization and Swedish Expert Group: a normal acceptable range is less than 20 ppb, concentrations between 20 ppb and 100 ppb represent an increasing risk of health problems, and concentrations greater than 100 ppb indicate an at risk category (Gerstenberger et al., 1997).

**Biomarkers of Mercury Exposure**

**Blood**

Since methylmercury distributes throughout the human body easily, blood analysis can be a good measurement of immediate exposures to methylmercury (Bartell et al., 2000). Methylmercury readily crosses diffusion barriers and penetrates all membranes easily. Therefore, tissue concentrations remain constant to blood levels (ATSDR, 1999). Mercury concentrations in blood will fluctuate with changing physiological and environmental conditions, so blood analysis provides an instant snapshot of mercury exposure (Katz & Katz, 1992).

Blood concentrations are good indicators of body burden and of brain doses (Kershaw & Dhahir, 1980). The potential exists for overestimating concentrations of mercury in blood, especially during the two to three days after consumption of contaminated fish. A peak concentration during this time may exceed blood concentrations after tissue distribution, especially after a single large dose rather than after chronic exposure (Kershaw & Dhahir, 1980). Peak blood concentrations may not occur until 14 hours after
ingestion (Kershaw & Dhahir, 1980). Methylmercury is mobile within the body, and quickly establishes constant ratios of concentrations between red blood cells and plasma, and between plasma and other tissues (Kershaw & Dhahir, 1980).

The biological half-life of mercury in humans is 44 to 76 days (Bartell et al., 2000; Clarkson, 1990). It takes approximately one year, or five biological half-lives, for human adults to attain steady-state body burden of mercury (Clarkson, 1990). The average 70 kg adult attains a steady state of mercury when the adult contains 1% of the total body burden of mercury in one liter of whole blood (Clarkson, 1990).

Hair

Hair samples can give a relatively more permanent record of mercury exposure (ATSDR, 1999; Katz & Katz, 1992). Mercury will deposit and remain in hair strands. About 40 to 50 days after initial ingestion of methylmercury, mercury can be detected in hair. The distribution between hair and blood follows a constant ratio, therefore the concentration of mercury in hair is proportional to the concentration in whole blood (WHO, 1989). Mercury is absorbed into the scalp at the hair follicle in proportion to the content in the blood. Also, hair is largely proteinaceous, consisting of sulfur-sulfur bonds, and the amino acid composition is high in cysteine (U.S. EPA, 1997). This results in mercury deposition in hair strands due to the high affinity of mercury for sulfur compounds. Mercury deposition in hair is irreversible, making hair analysis a useful tool for determining the historical record and the extent of mercury exposure over time.

Hair integrates mercury as it grows. During growth, the metabolic activity takes place in the matrix cells at the papilla of the follicle, and they produce hair at the rate of 0.4 mm/day, or about one cm per month (Airey, 1983; Dolbec et al., 2001; Katz & Katz,
Mercury from blood capillaries penetrates hair follicles as hair forms (Dolbec et al., 2001). When growing hair reaches the skin surface, it is keratinized, or hardened, and any mercury accumulated during its formation “are sealed into the protein structure of the hair,” (Katz & Katz, 1992). Mercury in new hair growth indicates blood mercury concentrations or the body burden of mercury during the time of hair growth (Airey, 1983).

A constant ratio between mercury distribution in hair and blood develops in humans. Several studies have calculated the ratio of hair to blood in the range of 250 to 300 µg Hg/g hair to 1 mg Hg/1 blood (Clarkson, 1990; U.S. EPA, 2001; WHO 1990). Because hair accumulates approximately 300 times more mercury than blood, analysis using hair is easier than using blood samples (Airey, 1983). An average delay of two to four weeks separates the time of blood sampling and the emergence of the appropriate hair sample above the scalp (WHO, 1989). Table 10 describes several studies examining the relationship between hair and blood mercury concentrations.

Table 10. Relationship Between Mercury Concentrations in Blood and Hair Samples in People Having Long-term Exposure to Methylmercury in Fish

<table>
<thead>
<tr>
<th>Number of Subjects</th>
<th>Whole Blood (mg/kg) (x)</th>
<th>Hair (mg/kg) (y)</th>
<th>Linear Regression</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.004 – 0.65</td>
<td>1 – 180</td>
<td>y = 280x - 1.3</td>
<td>Birke et al, 1972</td>
</tr>
<tr>
<td>51</td>
<td>0.004 – 0.11</td>
<td>1 – 30</td>
<td>y = 230x + 0.6</td>
<td>Swedish Expert Group, 1971</td>
</tr>
<tr>
<td>50</td>
<td>0.005 – 0.27</td>
<td>1 – 56</td>
<td>y = 140x + 1.5</td>
<td>Swedish Expert Group, 1971</td>
</tr>
<tr>
<td>45</td>
<td>0.002 – 0.8</td>
<td>20 – 325</td>
<td>y = 260x + 0</td>
<td>Tsubaki, 1971</td>
</tr>
<tr>
<td>60</td>
<td>0.044 – 5.5</td>
<td>1 – 142</td>
<td>y = 230x – 3.6</td>
<td>Skerfving, 1974</td>
</tr>
</tbody>
</table>

Recreated from WHO, 1989

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The concentration of mercury in hair is in a constant ratio with the concentration of mercury in target tissues and is proportional to the daily intake of chronically exposed humans (Phelps, Clarkson, & Kershaw, 1980). Because hair mercury concentrations reflect the mercury concentration in the body at the time of formation, and can be used to indicate blood concentrations and exposure levels at the time of formation, hair acts as a useful tool in compiling a historical record of chronic methylmercury exposure (Lee & Lee, 1999; Phelps et al., 1980). Hair more accurately recreates the total body pool of mercury than blood or urine (Lee & Lee, 1999). Also, the ratio between methylmercury and inorganic mercury is constant in each individual. Thus, measuring total mercury in hair provides an accurate depiction of the body burden of mercury (Airey, 1983).

Confounding Variables for Hair

Hair can accumulate mercury from external sources, such as scalp sweat, sweat and dirt from hands, from dust and air, and dyes, shampoos and bleaches (Airey, 1983). Hair samples may be washed before analysis to reduce mercury on the surface of the hair samples. Other confounding variables for measuring mercury in hair include the concentration of mercury vapor, hair treatments, natural hair color, and growth rate (U.S. EPA, 2001).

Also, place of residence and nutritional status of the hair donor may affect mercury concentrations (Katz & Katz, 1992). According to Airey (1983), external uptake of air mercury concentrations, even up to 100 times natural levels, contributes insignificant concentrations of mercury to hair levels (Airey, 1983). Geographical place of residence may have an affect on hair mercury levels. Mean hair mercury concentrations peak in midlatitude northern hemisphere countries (Airey, 1983). Mercury levels may be higher
in people living in areas known to be contaminated with mercury than in people living in unpolluted areas (Airey, 1983). Several occupations may lead to heightened concentrations of mercury in hair, such as molybdenum refinery workers, fishermen, mercury miners and processors, chemical industrialists, pesticide preparers, dentists, hospital employees, thermometer workers, chlorine manufacturers, and polarography students (Airey, 1983). Also, hairstyle can affect measurements. Care must be taken to start sampling from the scalp end of a hair sample, especially when some samples are long and others are short.

**Review of Human Studies Involving Mercury and Fish Consumption**

Since the epidemic methylmercury poisoning event in Minamata, Japan in the 1950s, studies have been performed to better understand the effects of mercury and mercury species, especially methylmercury, on human health. Several studies also attempted to determine a threshold concentration of mercury in biomarkers, beyond which the risk of toxicity significantly increases. Table 11 outlines historical highlights in mercury research on humans.

Numerous studies have investigated the possible relationship between consumption of mercury contaminated fish and body burdens. Increased fish consumption may lead to increased blood mercury concentrations (Mahaffey & Mergler, 1998). Also, consumption of contaminated fish leads to an accumulation of mercury in human hair (Birke, Johnels, Plantin, Sjostrand, Skerfving, & Westermark, 1972; CDC, 2001). Although many of the studies record elevated levels of mercury in blood and hair samples, none of the studies record a single case of adult or prenatal poisoning due to
Table 11. Timeline of Events Involving Human Exposure to Mercury

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>First chemical synthesis by Professor Franklin in London - laboratory spill of synthesized dimethylmercury heightened awareness of Hg hazards</td>
<td>1852-65</td>
<td>Two Deaths</td>
</tr>
<tr>
<td>Poisoning outbreak in a factory manufacturing methylmercury compounds for fungicides</td>
<td>1938-1954</td>
<td>Clinical syndrome described brain pathology in adults</td>
</tr>
<tr>
<td>Minamata acetaldehyde manufacturing plant released Hg into the bay, leading to an epidemic of neurological disease. This incident pointed out the potential for Hg bioaccumulation, the increased severity of prenatal poisoning</td>
<td>1956</td>
<td>Prenatal effects</td>
</tr>
<tr>
<td>Niigata acetaldehyde plant released Hg into the river, leading to a poisoning outbreak. Observations from Minamata and Niigata lead to the establishment of a LOEL in blood (200 ug Hg/L whole blood) and scalp hair (50 ug Hg/g of hair)</td>
<td>1964</td>
<td>Hg in blood and hair</td>
</tr>
<tr>
<td>Swedish Group Report Based on Swedish fish consumers, this report examined the relationship between the long-term daily intake of methylmercury in fish and blood levels. An</td>
<td>1971</td>
<td>LOEL in adults</td>
</tr>
<tr>
<td>WHO Report</td>
<td>1972</td>
<td>Tolerable intakes</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>This report used the Swedish group data to get a tolerable weekly intake of methylmercury. An intake of 30 ug Hg/day corresponds with a blood level of 20 ug Hg/l and a hair level of 5 ug Hg/g. A second WHO report set the provisional tolerable weekly intake at 300 ug Hg, no more than 200 ug should be in the methylmercury form (Kershaw &amp; Dhahir, 1980).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iraq</td>
<td>1971 - 1972</td>
<td>Adult dose response</td>
</tr>
<tr>
<td>The application and ingestion of a methylmercury fungicide on seed grains lead to mass poisoning. It has been described as the “worst mass health disaster in the history of human chemical poisoning.” Studies arising from this incident confirmed the LOEL and provided more information on the prenatal effects (inhibition of neuronal migration and disruption of cytoarchitecture)</td>
<td></td>
<td>Prenatal dose response</td>
</tr>
<tr>
<td>Studies on Subsistence Fish Eaters</td>
<td>1980 - present</td>
<td>No cases of poisoning</td>
</tr>
<tr>
<td>WHO has reviewed numerous studies on over 100 fish eaters with blood</td>
<td></td>
<td>No clear cut epidemiologic outcome</td>
</tr>
</tbody>
</table>
levels of Hg exceeding the LOEL of 200 \( \mu \text{g Hg/l} \), none suffering from methylmercury poisoning. An ongoing study in the Faroe Islands in the North Atlantic is observing the relationship between the consumption of marine fish and whales and the effects on children exposed before birth and during development. An ongoing study in the Seychelles Islands in the Indian Ocean if observing the effects of ocean fish consumption in infant-mother pairs.

Recreated from Clarkson, 1998

methylmercury consumption through ocean or freshwater fish (Clarkson, 1998). These studies do not provide convincing evidence of a significant human health risk from mercury or methylmercury in fish. Table 12 displays the average hair mercury concentrations for several countries, as researched by Airey (1983). Table 13 presents a summary of several studies conducted on human exposure to mercury through fish consumption. Table 14 summarizes the average total mercury concentration in hair determined in several studies on human consumption of fish. Table 15 presents an additional summary of average hair mercury concentration from a study examining individuals from several countries, separated by fish consumption levels.

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Table 12 Weighted Mean Hair Mercury Concentrations for 35 Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Average Weighted Mean Hair Hg Concentrations, ppm*</th>
</tr>
</thead>
<tbody>
<tr>
<td>America South</td>
<td>1.3</td>
</tr>
<tr>
<td>Australia</td>
<td>1.7</td>
</tr>
<tr>
<td>Bolivia</td>
<td>1.3</td>
</tr>
<tr>
<td>Brazil</td>
<td>5.7</td>
</tr>
<tr>
<td>Burma</td>
<td>3.5</td>
</tr>
<tr>
<td>Canada</td>
<td>1.8</td>
</tr>
<tr>
<td>China</td>
<td>2.8</td>
</tr>
<tr>
<td>Finland</td>
<td>1.4</td>
</tr>
<tr>
<td>France</td>
<td>1.3</td>
</tr>
<tr>
<td>W. Germany</td>
<td>0.5</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>3.0</td>
</tr>
<tr>
<td>India</td>
<td>1.6</td>
</tr>
<tr>
<td>Iraq</td>
<td>1.0</td>
</tr>
<tr>
<td>Italy</td>
<td>1.6</td>
</tr>
<tr>
<td>Japan</td>
<td>5.0</td>
</tr>
<tr>
<td>Kenya</td>
<td>7.9</td>
</tr>
<tr>
<td>S. Korea</td>
<td>2.3</td>
</tr>
<tr>
<td>Mexico</td>
<td>1.5</td>
</tr>
<tr>
<td>Monaco</td>
<td>1.7</td>
</tr>
<tr>
<td>Nepal</td>
<td>0.3</td>
</tr>
<tr>
<td>New Zealand</td>
<td>1.8</td>
</tr>
<tr>
<td>Norway</td>
<td>2.7</td>
</tr>
<tr>
<td>Pakistan</td>
<td>3.5</td>
</tr>
<tr>
<td>Papua, New Guinea</td>
<td>2.8</td>
</tr>
<tr>
<td>Poland</td>
<td>0.3</td>
</tr>
<tr>
<td>Pribilof Is.</td>
<td>4.6</td>
</tr>
<tr>
<td>South Africa</td>
<td>1.9</td>
</tr>
<tr>
<td>Spain</td>
<td>2.7</td>
</tr>
<tr>
<td>Sweden</td>
<td>7.9</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0.8</td>
</tr>
<tr>
<td>Thailand</td>
<td>2.1</td>
</tr>
<tr>
<td>U.K.</td>
<td>5.0</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>2.9</td>
</tr>
<tr>
<td>Venezuela</td>
<td>1.0</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Results from people who ate fish every day, who ate contaminated fish, or who were occupationally exposed were omitted

Recreated from Airey, 1983
<table>
<thead>
<tr>
<th>Study Location</th>
<th>Variables</th>
<th>Methods</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest Quebec, St. Lawrence River (Mahaffey &amp; Mergler, 1998)</td>
<td>Fish consumption; Reference Dose</td>
<td>Blood; Survey on dietary habits</td>
<td>Blood Hg is a good biomarker for short-term exposure. One individual with 70 ppb total Hg, most likely a subsistence fisher. Increases in blood Hg correlate with increases in fish consumption. Limiting consumption leads to a decrease in blood Hg. Blood Hg reflects the frequency and quantity of fish consumed, and the Hg concentration in fish. Males often eat more fish than women, therefore they may have greater exposure to mercury through greater consumption per day and greater body weight than women.</td>
</tr>
<tr>
<td>Great Lakes region – Ojibwa reservations (Dellinger et al., 1996)</td>
<td>Fish consumption</td>
<td>Survey of dietary history, demographics, lifestyle, medical history, exposure, and environmental health risk perception; Hair and blood samples; Fish samples</td>
<td>Hg high in walleye composite samples</td>
</tr>
<tr>
<td>Ojibwa around Great Lakes (Gerstenberger et al., 1997)</td>
<td>Fish consumption</td>
<td>Survey of dietary habits; Dental amalgams; Hair and blood samples</td>
<td>Highest consumption of Lake Trout, Walleye and Whitefish. Most subjects ate fish once a week. Higher consumption in spring and summer months (March, Apr, May, June); Hair concentrations less</td>
</tr>
<tr>
<td>Region/Country</td>
<td>Study Details</td>
<td>Measured Parameters</td>
<td>Mercury Concentrations</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>---------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Sweden (Skerfving, 1974)</td>
<td>Fish consumption</td>
<td>Blood and hair samples; Dietary habits; Occupation</td>
<td>Blood Hg between 3 – 390 ng/l, no evidence of full poisoning</td>
</tr>
<tr>
<td>Indians Reservations in Northwestern Ontario (Phelps et al., 1980)</td>
<td>Fish consumption</td>
<td>Blood and hair samples</td>
<td>Hg concentration was highest in hair corresponding to late summer and early fall months. Concentration and form of Hg do not change once deposited in hair. The relationship between organic Hg and total Hg is linear, so a measure of total Hg is adequate for assessment</td>
</tr>
<tr>
<td>Sweden (Birke et al., 1972)</td>
<td>Mercury exposure through fish consumption and occupation</td>
<td>Blood and hair samples; General health conditions</td>
<td>Linear relationship exists between the total Hg in hair and blood samples</td>
</tr>
<tr>
<td>St. Lawrence River, Montreal (Kosatsky, Przybysz, &amp; Armstrong, 2000)</td>
<td>Fish consumption</td>
<td>Dietary habits; Blood and hair samples</td>
<td>Those who eat fish more have higher Hg concentrations in blood and hair, (2.3 times higher). Open-water fishers have higher blood Hg than ice fishers. Higher blood Hg correlates with increasing age. Consumers of Pike have higher blood Hg levels.</td>
</tr>
<tr>
<td>Madeira Island, Mediterranean (Renzoni, Zino, &amp; Franchi, 1998)</td>
<td>Seafood consumption; Pregnant women tested</td>
<td>Blood and hair samples</td>
<td>Noted a need more research on Hg cycling and Hg limits in seafood, especially for individuals consuming seafood frequently.</td>
</tr>
<tr>
<td>Location</td>
<td>Activity</td>
<td>Methodology</td>
<td>Findings</td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Philippines, Mt. Diwata (Drasch, Bose-O’Reilly, Beinhoff, Roider, &amp; Maydl, 2001)</td>
<td>Gold mining; Hg in water and the atmosphere</td>
<td>Health survey; Blood, hair, and urine samples</td>
<td>Alcohol is a confounding variable. Ethanol inhibits catalase, leading to a decreased oxidation of Hg vapor into ionic Hg in the blood. More Hg crosses the blood-brain barrier after inhalation.</td>
</tr>
<tr>
<td>French Guiana (Frery, Maury-Brachet, &amp; Maillot, 2001)</td>
<td>Gold mining</td>
<td>Hair samples; Dietary survey; Fish samples</td>
<td>Hair Hg levels from study subjects higher than the Guyanese average. Age, hair length, body fat and location of residence affects hair Hg, (children under 1 yr had higher concentrations). Sex did not affect hair Hg concentration. Population in Wayana has Hg levels higher than WHO recommendations, denoting an area of concern. Higher hair Hg concentrations in November than March.</td>
</tr>
<tr>
<td>Population around Balbina Reservoir, Brazil (Kehrig, Malm, Akagi, Guimaraes, &amp; Torres, 1998)</td>
<td>Atmospheric deposition to reservoir; Fish consumption</td>
<td>Fish survey; Hair samples</td>
<td>Daily intake is close to WHO recommended tolerable daily intake</td>
</tr>
<tr>
<td>Korea (Lee &amp; Lee, 1999)</td>
<td>Fish consumption</td>
<td>Hair samples</td>
<td>City subjects from Seoul vs. fishing village – villagers had significantly higher Hg levels.</td>
</tr>
<tr>
<td>Southwest Ghana (Adimado &amp; Baah, 2002)</td>
<td>Gold mining</td>
<td>Fish samples; Blood, hair, urine, and nail samples</td>
<td>Consuming large quantities of fish, (800 g/day or more), could lead to large body burden of Hg</td>
</tr>
<tr>
<td>Papua New Guinea (Saeki, Fujimoto, Kolinjim, &amp; Tatsukawa, 1996)</td>
<td>Gold mining</td>
<td>Hair samples</td>
<td>Population eating fish had a higher hair Hg concentration than the background concentration. Hg co</td>
</tr>
<tr>
<td>Location</td>
<td>Activity</td>
<td>Method</td>
<td>Findings</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------------</td>
<td>----------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>13 Countries (Airey, 1983)</td>
<td>Fish consumption; Geography</td>
<td>Hair samples</td>
<td>As more fish is consumed, the body burden of Hg increases. Hg levels differ among countries. People in latitudes above or below 40° in the northern and southern hemispheres have lower hair Hg concentrations. Geometric mean is a useful way to report hair Hg concentrations. Background levels of gaseous Hg not absorbed onto hair during storage. Hg concentrations increase with increasing age. Males have higher hair Hg concentrations than females.</td>
</tr>
<tr>
<td>Amazon, Brazil (Barbosa, Jardim, Dorea, Fosberg, &amp; Souza, 2001)</td>
<td>Gold mining</td>
<td>Hair samples</td>
<td>No influence on hair Hg concentrations from age, pregnancy, or gender.</td>
</tr>
<tr>
<td>Tapajos River (Dolbec et al., 2001)</td>
<td>Gold mining</td>
<td>Hair; Dietary survey</td>
<td>Seasonal variations in hair Hg exist, (dry and rainy season). Herbivorous fish are eaten at the end of the rainy season, and piscivorous fish are eaten at the end of the dry season. A higher hair Hg in was detected from the dry season.</td>
</tr>
<tr>
<td>Madeira, Portugal (Gaggi et al., 1996)</td>
<td>Seafood and fish consumption</td>
<td>Hair samples</td>
<td>Higher Hg concentration in males.</td>
</tr>
<tr>
<td>Papua New Guinea (Kyle &amp; Ghani, 1982)</td>
<td>Fish consumption</td>
<td>Hair samples; Dietary survey</td>
<td>Hair Hg concentration increases with increasing fish consumption. No</td>
</tr>
</tbody>
</table>

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differences in hair Hg concentrations from different genders or ages. If children ingest fish daily, they quickly accumulate a high body burden due to their smaller weight. They maintain this level throughout their lives. Only a few subjects had hair Hg concentrations greater than 50 ppm. No signs of intoxication in subjects.

| Southern Spain (Lopez-Artiguez et al., 1994) | Seafood consumption from area of known metal pollution | Hair samples | Females had a lower hair Hg concentration than males. |

Confounding Variables

Selenium.

Selenium may protect organisms against the toxic effects of methylmercury (WHO, 1990). The methylmercury cation has a strong affinity for selenides and diselenides (WHO, 1990). Therefore, selenium may complex with methylmercury, therefore it influences deposition in tissues by reducing the bioavailability of methylmercury (ATSDR, 1999; National Research Council, 2000). This phenomenon may explain an observed negative correlation between hair selenium and brain mercury (ATSDR, 1999). Selenium may have a hormetic affect on organisms (National Research Council, 2000). The exact nature of selenium’s affect on the amount of mercury and the location of mercury deposition depends on the dose, form, and route of exposure (National Research Council, 2000).
Table 14. Summary of Studies Comparing Mean, Median, or Range of Total Mercury in Hair

<table>
<thead>
<tr>
<th>Reference</th>
<th>Country</th>
<th>n</th>
<th>Total Hg in Hair (µg/g)</th>
<th>Sampling Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adimado &amp; Baah (2002)</td>
<td>Southwestern Ghana</td>
<td>7</td>
<td>1.61</td>
<td>Different locations in the Ankobra river basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>4.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Akagi, Malm, &amp; Branches (1995)</td>
<td>Brazil</td>
<td>12</td>
<td>3.1 - 36</td>
<td>Tapajos River</td>
</tr>
<tr>
<td>Barbosa et al. (2001)</td>
<td>Brazil</td>
<td>163</td>
<td>20</td>
<td>Negro River</td>
</tr>
<tr>
<td>Barbosa, Silva, &amp; Dorea (1998)</td>
<td>Brazil</td>
<td>55</td>
<td>34.2</td>
<td>Apiacás Reservation</td>
</tr>
<tr>
<td>Barbosa, Garcia, &amp; Souza (1997)</td>
<td>Brazil</td>
<td>142</td>
<td>17.2</td>
<td>Madeira River</td>
</tr>
<tr>
<td>Birke et al. (1972)</td>
<td>Sweden</td>
<td>6</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Brhun, Rodriguez, Barrios, Jaramillo, Becerra, Gras, Nunez, &amp; Reyes (1997)</td>
<td>Chile</td>
<td>33</td>
<td>0.3 – 2.5</td>
<td></td>
</tr>
<tr>
<td>Chen (1990)</td>
<td>Japan</td>
<td>49</td>
<td>0.8</td>
<td>Initial values in China</td>
</tr>
<tr>
<td>Study</td>
<td>Location</td>
<td>Hair Hg Concentration</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------</td>
<td>-----------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Dermelj, Horvat, Byrne, &amp; Stegnar (1987)</td>
<td>Yugoslavia</td>
<td>26</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Dolbec et al. (2001)</td>
<td>Brazil, Tapajos River</td>
<td>10</td>
<td>14 - 23</td>
<td></td>
</tr>
<tr>
<td>Drasch et al. (2001)</td>
<td>Philippines</td>
<td>Not Given</td>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>Egeland, Ponce, Knecht, Bloom, Fair, &amp; Middaugh (1999)</td>
<td>Alaska</td>
<td>16</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Feng, Suzuki, &amp; Hisashige (1998)</td>
<td>China</td>
<td>64</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indonesia</td>
<td>55</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Japan</td>
<td>243</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Foo, Ngim, Phoon, &amp; Lee (1988)</td>
<td>Malaysia</td>
<td>150</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Frery et al. (2001)</td>
<td>French Guiana</td>
<td>Not Given</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>Gaggi et al. (1996)</td>
<td>Madeira, Portugal</td>
<td>58</td>
<td>39.76</td>
<td></td>
</tr>
</tbody>
</table>

After 1 year, values taken from 17 subjects in Japan.

Hair Hg concentrations of daily fish consumers peak in late summer and early fall.

Hair Hg concentrations of weekly fish consumers peak in summer.

Chinese

Malay

Indian

Males

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<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Sample Size</th>
<th>Detection Limit</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerstenberger et al. (1997)</td>
<td>Great Lakes, Ojibwa population</td>
<td>79</td>
<td>Detection limit - 2.57</td>
<td>Females</td>
</tr>
<tr>
<td>Ikingura &amp; Akagi (1996)</td>
<td>Tanzania</td>
<td>29</td>
<td>Not detected – 5.4</td>
<td>Gold Miners</td>
</tr>
<tr>
<td>Ishihara &amp; Urushiyama (1994)</td>
<td>Japan</td>
<td>Not Given</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Kehrig et al. (1998)</td>
<td>Brazil</td>
<td>20</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Kosatsky et al. (2000)</td>
<td>Montreal, St. Lawrence River</td>
<td>60</td>
<td>Below detection - 6.59; median = 0.87</td>
<td>Frequent consumer defined as &gt;1 meal/week</td>
</tr>
<tr>
<td>Kyle &amp; Ghani (1982)</td>
<td>Papua</td>
<td>114</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Lee &amp; Lee (1999)</td>
<td>Korea</td>
<td>315</td>
<td>1.7</td>
<td>Males and Females</td>
</tr>
<tr>
<td>Lebel, Mergler, Lucotte, Amorim, Dolbec, Miranda, Arantes, Rheault, &amp; Pichet (1996)</td>
<td>Brazil</td>
<td>29</td>
<td>14.0</td>
<td>Tapajos River</td>
</tr>
</tbody>
</table>

Frequent consumer defined as >1 meal/week
Infrequent Consumer defined as <1 meal/week

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<table>
<thead>
<tr>
<th>Study/Location</th>
<th>Country</th>
<th>Sample Size</th>
<th>TBP Value</th>
<th>Diet/Activity Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lebel et al.</td>
<td>Brazil</td>
<td>91</td>
<td>12.5</td>
<td>Tapajos River</td>
</tr>
<tr>
<td>Lopez-Artiguez et al.</td>
<td>Southern Spain</td>
<td>92</td>
<td>0.99 – 5.94</td>
<td>Pregnant Women</td>
</tr>
<tr>
<td>Malm et al.</td>
<td>Brazil</td>
<td>121</td>
<td>18 – 34</td>
<td>Tapajos River</td>
</tr>
<tr>
<td>Renzoni et al.</td>
<td>Madeira Island</td>
<td>66</td>
<td>38.9</td>
<td>Males</td>
</tr>
<tr>
<td>Sarmani et al.</td>
<td>Malaysia</td>
<td>10</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Saeki et al.</td>
<td>Papua New Guinea</td>
<td>1.8</td>
<td>Different locations in the Wau-Bulolo area</td>
<td></td>
</tr>
<tr>
<td>Soria et al.</td>
<td>Spain</td>
<td>50</td>
<td>2.8</td>
<td>Winter</td>
</tr>
</tbody>
</table>
Blood mercury may be related to dental amalgams (Gerstenberger et al., 1997). A single amalgam has average surface area of 0.4 cm², which releases up to 15 ug Hg/day, through mechanical wear, evaporation and dissolution into saliva (ATSDR, 1999). Assuming that the average person has eight amalgams, that equates to 120 ug of mercury released daily. A portion of that mercury is swallowed or inhaled. The actual amount absorbed may range from 3 to 17 ug (ATSDR, 1999). Figuring that the average fish absorbance is 2.31 ug/day and average absorbance from other foods, air, and water is 0.3 ug/day, dental amalgams may contribute greatly to the body burden of mercury. A study by Lopez-Artiguez et al. (1994) calculates the average daily dose of mercury from amalgams to be 1.7 ug/g (Lopez-Artiguez et al., 1994). In this case, dental amalgams do not add a significant amount of mercury to the body burden compared to fish (Lopez-Artiguez et al., 1994).
Table 15 Hair Mercury Concentrations from 13 Countries Separated by Fish Consumption Levels

<table>
<thead>
<tr>
<th>Country</th>
<th>Arithmetic Mean Hair Hg (ppm)</th>
<th>n</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A = once a month or less</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B = once every two weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C = once a week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = every day</td>
</tr>
<tr>
<td>Australia</td>
<td>2.2</td>
<td>21</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>22</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>28</td>
<td>C</td>
</tr>
<tr>
<td>Canada</td>
<td>0.7</td>
<td>9</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>15</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>6</td>
<td>C</td>
</tr>
<tr>
<td>China</td>
<td>0.9</td>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>10</td>
<td>D</td>
</tr>
<tr>
<td>W. Germany</td>
<td>0.4</td>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>9</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>9</td>
<td>C</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>2.0</td>
<td>9</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>9</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>9</td>
<td>C</td>
</tr>
<tr>
<td>Italy</td>
<td>1.4</td>
<td>13</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>6</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>7</td>
<td>C</td>
</tr>
<tr>
<td>Japan</td>
<td>3.7</td>
<td>6</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>15</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td>Monaco</td>
<td>0.6</td>
<td>11</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>11</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>11</td>
<td>C</td>
</tr>
<tr>
<td>New Zealand</td>
<td>0.8</td>
<td>15</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>6</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>13</td>
<td>C</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>1.2</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>21</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>13</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>16.7</td>
<td>11</td>
<td>D</td>
</tr>
<tr>
<td>South Africa</td>
<td>1.5</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>3</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td>U.K.</td>
<td>1.0</td>
<td>34</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>33</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>33</td>
<td>C</td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>----</td>
</tr>
<tr>
<td>U.S.A</td>
<td>2.1</td>
<td>24</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>31</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>24</td>
<td>C</td>
</tr>
</tbody>
</table>

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CHAPTER 3

QUESTIONS, OBJECTIVES, AND HYPOTHESES

Questions

• What are the concentrations of mercury in the hair of a Native American population that practices subsistence fishing?

• Is there a relationship between fish consumption and hair mercury concentrations?

Objectives

• This study will attempt to determine the hair mercury concentrations in a Native American population.

• The study will evaluate important fish consumption parameters, such as species of fish, fish size and age, and location and season of fishing and possible associations between fish consumption and hair mercury concentration.
Hypotheses

Fish

The concentration of mercury in the human body depends on the species, age, and size of fish consumed, as well as the geographical origin of the fish consumed.

Species

- Consumers of piscivorous fish, such as Walleye or Northern Pike, will have higher concentrations of mercury, since these fish have bioaccumulated more mercury.

The following fish species will be examined: Bass, Herring, Northern Pike, Panfish, Perch, Lake Trout, Rainbow Trout, Salmon, Smelt, Walleye, Whitefish, Other species. A frequency distribution will be used to analyze total meals consumed for each fish species. A Chi-Square test will then be used to analyze the frequency of fish meals per fish species. Correlation and linear regression will test for an association between each species and hair mercury concentration.

Amount

- People who consume a greater total amount of fish will have higher concentrations of mercury, as increased consumption increases exposure to methylmercury.

Correlation and linear regression will test for an association between total fish meals consumed and hair mercury concentration. The total fish meals will then be converted to servings per year and grams consumed per year and compared to hair mercury concentrations.

Size

- People who consume longer/larger fish will have higher concentrations of mercury, due to increased bioaccumulation in larger, older fish.
Correlation and linear regression will test for an association between length of fish and hair mercury concentrations. Then length will be used as a covariate in analyzing total fish consumed and hair mercury concentration.

**Geographic Source**

- People who consume fish from inland lakes and streams will have higher concentrations of mercury than people who consume fish from the Great Lakes fisheries, because of the chemical and hydrological properties that lead to increased rates of methylation in inland lakes.

The following geographic sources will be examined: Lake Superior, Lake Michigan, Store Bought, Restaurant, Inland Lake or Stream. An ANOVA will test for significance between sources, or areas, of fish procurement. Correlation and linear regression test for an association between source location and hair mercury concentration.

**Human**

Individual human characteristics, such as age, gender, and size, affect hair mercury concentrations.

**Age**

- Older members of the study population will have higher concentrations of mercury in the hair, as these people have eaten more fish over time.

First, a correlation and linear regression will analyze for any potential association between age in years and the total number of years consuming fish. Second, an ANOVA will examine any significant difference between the total number of years consuming fish and hair mercury concentrations.
Gender

- Males will have higher hair mercury concentrations than females, because males consume a greater total amount of fish than females.

A Student’s t-test will test for significance between males and females hair mercury concentrations.

Human Size

- Native Americans of a larger size (greater height and weight) will have higher hair mercury concentrations than those of a smaller size due to increased bioaccumulation through greater fish consumption (they eat more).

Both height and weight will be converted to metric units. Then correlation and linear regression will test for an association between height, weight, and hair mercury concentration.
CHAPTER 4

METHODOLOGY

Volunteers from ten tribes were asked to participate in the Ojibwa Health Study. Ojibwa reservations were divided into three geographical groups; Lake Superior fishery (LS), Lake Michigan and Superior fisheries (MS), and Wisconsin inland fisheries (IN). Participants also came from two groups; Non-Ojibwa Rivers and Green Bay (Non), and Other Participants, or non-Native Americans (OT). For the remainder of the study, results and discussion will be reported for these geographical groupings. Participants included adult American Indian heads-of-household and their spouses residing within the geographical boundaries of the reservation. These participants completed a questionnaire detailing their past and present fish consumption habits and preferences, as well as other personal data (Dellinger et al., 1996; Gerstenberger et al., 1997). Questionnaires were completed in June, July, and August. Dental amalgams were counted and recorded. After completion of the questionnaire, subjects were asked to give a blood and/or hair sample for chemical analysis. All human subject experimentation was done in accordance with the ethical standards of the institutional committee on human experimentation at the University of Wisconsin-Superior and at the University of Nevada, Las Vegas (Dellinger et al., 1996; Gerstenberger et al., 1997).

Hair samples were taken from the scalp at the center and back of the head (Dellinger et al., 1996; Gerstenberger et al., 1997). An attempt was made to collect a pencil-width
section of hair, but hair length, hair thickness, and personal concerns may have limited the quantity of hair obtained from each person. Hair samples were placed into a freezer bag, stapled and labeled with a sample code. No cleaning or pretreatment of hair samples was done. The questionnaire contains inquiries regarding the use of medicated shampoo (Dellinger et al., 1996; Gerstenberger et al., 1997).

Total mercury was analyzed using the AMA 254 Atomic Absorption Mercury Analyzer manufactured by the Leco Corporation. The instrument analyzes total mercury. Hair samples were analyzed in nickel sample boats with drying, decomposition (550°C), and waiting times of 60:240:45 seconds for all tissues and certified reference materials. Ultra pure oxygen was used as the carrier gas with an inlet pressure of 250 kPa and a flow rate of 200 ml/min (Gerstenberger & Pearson, 2002). The detector is a silicon UV diode. The analyzer has a detection limit of 0.01 ng Hg and a linear range from 0.05 to 40 ng (Gerstenberger & Pearson, 2002).

QA/QC was performed with certified reference material from Health Canada Hair Mercury Quality Control Program, blank samples (empty boat), and a prepared mercury solution of known concentration. A run using the certified reference material or standard solution was made after every ten hair samples. Blank runs were made before and after each set of ten hair samples. Approximately 5 mg of hair of a concentration around 15 ppm or lower was loaded into the sample boat. Laboratory results consistently met the QA/QC performance limits in the Health Canada Hair Mercury Quality Control Program (Gill, Schwartz, & Bigras, 2002).

Hair was collected from about 480 people. Each hair sample was cut into segments representing a month of growth (roughly one cm). An attempt was made to analyze all...
segments representing hair grown during April, May, June, July, and August. Owing to hair length and quantity, some samples represented a single month of hair growth or growth during the fall or winter months. If only one hair segment was available, that was the only segment run. On average two segments per person were analyzed. Hair segments were run separately and an average concentration for each person was calculated. Only one five mg sample was run for each segment, except for hair samples that exceeded 15 ppm, in which case a smaller mass was analyzed.

Confounding variables, such as dental amalgams, medicated shampoo use, pregnancy, and occupation, also affect mercury concentrations in the body. Therefore, statistical analyses were conducted to determine the influence of these confounding variables on hair mercury concentrations. The hypotheses and statistical procedures for each variable are defined below.

- The presence of dental amalgams will increase mercury concentration readings, as it increases the total amount of mercury in the system.

Correlation and linear regression will test for an association between number of dental amalgams and hair mercury concentration.

- The use of cosmetics containing mercury will increase the concentration of mercury, as exposure to mercury through these products increases the total amount of mercury in the system.

A Student’s t-test will analyze a difference in the mean hair mercury concentration between people who use medicated shampoo and those who do not use medicated shampoo.
- People with occupations that involve exposure to mercury will have higher concentrations of mercury.

A frequency table will be used to analyze the distribution of occupations. A Chi-Square test will analyze the distribution of differences in fish meal consumption between occupations. An ANOVA will test for a difference in the mean hair mercury concentration between occupations.

- During pregnancy, women will have lower concentrations of mercury, since the developing fetus will accumulate a large proportion of the total mercury in the mother’s body.

A Student’s t-test will test for a difference in mean hair mercury concentration between pregnant women and women who are not pregnant.

SPSS, Minitab, and Excel software programs were used to perform statistical tests. Appropriate tests were performed for statistical assumptions. The following tests were performed (Zar, 1999): (1) the Kolmogorov-Smirnov test was used to test for normality (owing to large sample size); (2) Levene’s test was used to test for equal variances; (3) the Kruskal-Wallis test was used instead of ANOVA tests; and (4) Mann-Whitney tests were used instead of Student’s t-tests.

The Kruskal-Wallis test assumes that samples are random and independent, that there are more than five measurements in each sample, and that samples come from a continuous distribution (McClave & Sincich, 2000; Zar, 1999). The Nemenyi test was used for post-hoc comparisons. This technique parallels the Tukey post-hoc test, but uses rank sums (Zar, 1999). Therefore, the Nemenyi test can be used to analyze pair-wise differences when significant differences are found from the Kruskal-Wallis tests. The
Mann-Whitney test is a powerful statistical method for analyzing nonparametric distributions, and was chosen because the data did not meet the normality and equal-variance assumptions of the Student’s t-test (Zar, 1999).

Four main assumptions were made for the regression analyses: (1) the data have a common variance structure, (2) all samples are statistically independent of each other, (3) samples are drawn from normally distributed populations, and (4) the data will have correct functional form (i.e., a linear relationship will exist between dependent and independent variable) (Bowerman & O’Connell, 1990). Levene’s test of equal variance and the Kolgomorov-Smirnov normality test were used to test assumptions (1) and (3). Inasmuch as individuals were a random selection of available research participants, and that their questionnaire responses were not likely influenced by other respondents, assumption (2) was satisfied. Assumption (4) is derived from a review of the literature (Bache et al., 1971; Bowles et al., 2001; Gerstenberger et al., 1997; Grieb et al., 1990; Gutenmann et al., 1992; Lange et al., 1994). Analyses will be run with and without outliers to determine the presence of a potential influential effect of the data. Correlation coefficients (and the subsequent coefficients of determination) were calculated using both the Pearson Product-Moment and the Spearman Rank methods where appropriate (Zar, 1999).
CHAPTER 5

RESULTS AND DISCUSSION

Several observations guide the statistical analyses. In order to convert fish meals to fish servings and then to fish grams, the following formulas were used:

- Fish Meals * Fish Servings = Total Fish Servings
- Total Fish Servings * 85 Grams = Total Grams of Fish

These formulas, described in the Ojibwa Health Study, assume that individuals consume the same number of servings at every meal, and that a fish servings is equal to 85 grams. Results after running a few cases with both the Kolgomorov-Smirnov and Shapiro-Wilk tests for normality resulted in similar results. Thus, the Kolgomorov-Smirnov test for normality was used for all analyses. Both the Pearson Product-Moment and Spearman Rank methods produced similar coefficients of correlation. Therefore, parametric regression analyses were performed to reduce error inherent in transforming data. Also, inclusion of outliers produced similar results to tests run without outliers. Therefore, outliers were included in statistical analyses.

Hair Analysis

In order to determine the hair mercury concentrations in the Ojibwa population, a total of 873 hair samples from 343 different individuals were analyzed. The mean hair mercury concentration for the data set was 1.82 ppm, with standard deviation of 7.06 ppm. Figure 4 illustrates the distribution of hair mercury concentrations.
Figure 4 Frequency Histogram of Mean Hair Mercury Concentrations

Figure 5 Frequency Histogram of Mean Hair Mercury Concentrations Less Than 1 ppm

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Nineteen individuals in this study had mean hair mercury concentration values greater than 3.0 ppm (Table 16).

<table>
<thead>
<tr>
<th>Region</th>
<th>Hair Mercury Concentration, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>12.01</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>3.19 3.38 5.63 6.53 7.82 9.25 9.39 13.86 15.74 18.54 23.26 25.82 35.33 54.29 60.82</td>
</tr>
<tr>
<td>Other</td>
<td>6.31 8.98 40.14</td>
</tr>
</tbody>
</table>

The Control group had the highest mean hair mercury concentration, followed by Michigan and Superior group, Other group, Inland Lakes group, Lake Superior group, and then Non-Ojibwa (Table 17).

Kolgomorov-Smirnov normality tests indicated a non-normal distribution of average hair mercury concentrations; therefore a Kruskal-Wallis test was performed to compare the medians between the five regions. The Kruskal-Wallis test showed a significant difference between at least two of the regions ($X^2(4) = 14.320; p = 0.006$), with the
median hair mercury concentration significantly higher for Other individuals than Inland Lakes ($q = 3.460, q_{critical, p = 0.05, k = 5} = 2.807$). Figure 6 shows the distribution of median hair mercury concentrations for each region, with extreme and outlier values. Outliers lay 1.5 to 3 interquartile ranges from the upper and lower edges of the box, and extreme values lay more than 3 interquartile ranges from the upper and lower box edges. Figure 7 focuses on the median hair mercury concentrations between the upper and lower quartiles, allowing for a better view of the distribution within that range. The solid line represents the median value. A great deal of overlap exists between the boxplots, suggesting that hair mercury concentration distributions from each region are similar.

A detailed examination of the strictly Ojibwa groups was completed. Figure 8 shows the overlap in the distribution of hair mercury concentrations. A Kruskal-Wallis test was performed to focus on the median hair mercury concentrations between the three Ojibwa regions. Again, the results indicated a significant difference between at least two of the

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Mean Hair Mercury Concentration (ppm)</th>
<th>Standard Deviation (ppm)</th>
<th>Standard Error (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>119</td>
<td>0.4626</td>
<td>1.13</td>
<td>.10</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>86</td>
<td>3.7061</td>
<td>10.32</td>
<td>1.11</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>39</td>
<td>0.5014</td>
<td>0.34</td>
<td>.05</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>51</td>
<td>0.4550</td>
<td>0.54</td>
<td>.07</td>
</tr>
<tr>
<td>Other</td>
<td>36</td>
<td>1.7392</td>
<td>6.81</td>
<td>1.14</td>
</tr>
<tr>
<td>Control</td>
<td>12</td>
<td>14.9866</td>
<td>17.60</td>
<td>5.08</td>
</tr>
</tbody>
</table>
regions, \( (X^2_{(2)} = 7.750; \ p = 0.021) \). Individuals from Inland Lakes had a significantly higher median hair mercury concentration than individuals from Lake Superior \( (q = 2.680, q_{critical, p = 0.05, k = 3} = 2.394) \).

Several individuals within each region indicated that they did not eat fish. A Mann-Whitney test was used to examine the difference in hair mercury concentration between fish eaters and non-fish eaters \( (z = -1.304; \ p = 0.192) \). Mann-Whitney tests
were used to examine the median hair mercury concentrations between fish eaters and non-fish eaters within each region, except for the Inland Lakes region, which showed a normal distribution of median hair mercury concentrations, in which case a Student’s t-test was used (Table 18). Based on these analyses, the median hair mercury concentration of non-fish eaters does not differ significantly from the hair mercury
Figure 8  Boxplot Showing the Median Hair Mercury Concentrations for the Three Ojibwa Regions

REGION

* Indicates extreme value
O Indicates outlier

In order to determine the influence of fish species consumed on hair mercury concentrations, an analysis of the reported species of fish consumed was made.
Table 18. Statistical Results for Comparison of Mean Hair Mercury Concentrations between Fish Eaters and Non-Fish Eaters Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Test</th>
<th>Test Statistic</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>119</td>
<td>Mann-Whitney</td>
<td>( z = -1.661 )</td>
<td>0.097</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>87</td>
<td>Mann-Whitney</td>
<td>( z = -0.275 )</td>
<td>0.783</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>39</td>
<td>Student t-test</td>
<td>( t = 1.37 )</td>
<td>0.178</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>51</td>
<td>Mann-Whitney</td>
<td>( z = -0.292 )</td>
<td>0.770</td>
</tr>
<tr>
<td>Other</td>
<td>36</td>
<td>Mann-Whitney</td>
<td>( z = -0.315 )</td>
<td>0.753</td>
</tr>
</tbody>
</table>

According to analyses of the average number of meals per year, average servings per year, and average grams of fish per year, Whitefish, Perch, Walleye, and Lake Trout were the most frequently consumed species (Table 19).

In order to determine the difference between species, a Chi-square test was conducted to analyze the frequency of consumption of fish meals. Expected values were assumed to be equal among the 12 fish species. The distribution of fish meals was significantly different than the model of equal distribution \( (X^2_{11}) = 7856.503 \). The Chi-Square test for each region also showed a significant deviation from the expected distribution (Table 20).

Another method of determining the distribution of fish species consumed involved an analysis of the servings and grams of fish consumed per species. Due to the non-normal distribution, the Kruskal-Wallis test was performed. The servings per year of each species was significantly different between species \( (X^2_{11}) = 200.683; p < 0.001 \), as well as the grams per year of each species \( (X^2_{11}) = 200.683; p < 0.001 \). The subjects...
Table 19. Summary of Descriptive Statistics for Analysis of Fish Species Consumed

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Mean Meals per Year</th>
<th>Meals SD</th>
<th>Mean Servings per Year</th>
<th>Servings SD</th>
<th>Mean Grams per Year</th>
<th>Grams SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>284</td>
<td>3.57</td>
<td>14.77</td>
<td>9.55</td>
<td>38.68</td>
<td>811.33</td>
<td>3287.53</td>
</tr>
<tr>
<td>Herring</td>
<td>284</td>
<td>3.14</td>
<td>12.83</td>
<td>7.79</td>
<td>30.54</td>
<td>662.10</td>
<td>2595.59</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>284</td>
<td>2.75</td>
<td>10.38</td>
<td>7.37</td>
<td>27.30</td>
<td>626.55</td>
<td>2320.39</td>
</tr>
<tr>
<td>Panfish</td>
<td>284</td>
<td>5.30</td>
<td>18.69</td>
<td>17.55</td>
<td>73.22</td>
<td>1491.51</td>
<td>6223.79</td>
</tr>
<tr>
<td>Perch</td>
<td>284</td>
<td>12.58</td>
<td>28.57</td>
<td>36.39</td>
<td>96.58</td>
<td>3093.34</td>
<td>8209.19</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>284</td>
<td>10.52</td>
<td>24.25</td>
<td>25.14</td>
<td>59.57</td>
<td>2136.91</td>
<td>5063.58</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>284</td>
<td>4.69</td>
<td>15.78</td>
<td>10.01</td>
<td>33.07</td>
<td>851.02</td>
<td>2810.50</td>
</tr>
<tr>
<td>Salmon</td>
<td>284</td>
<td>4.45</td>
<td>16.80</td>
<td>10.75</td>
<td>41.10</td>
<td>913.33</td>
<td>3493.58</td>
</tr>
<tr>
<td>Smelt</td>
<td>284</td>
<td>6.49</td>
<td>18.89</td>
<td>17.55</td>
<td>67.22</td>
<td>1491.99</td>
<td>5713.63</td>
</tr>
<tr>
<td>Walleye</td>
<td>284</td>
<td>11.71</td>
<td>28.88</td>
<td>33.69</td>
<td>94.63</td>
<td>2863.78</td>
<td>8043.75</td>
</tr>
<tr>
<td>Whitefish</td>
<td>284</td>
<td>14.00</td>
<td>33.57</td>
<td>35.74</td>
<td>96.59</td>
<td>3037.85</td>
<td>8209.85</td>
</tr>
<tr>
<td>Other</td>
<td>284</td>
<td>3.08</td>
<td>12.49</td>
<td>8.84</td>
<td>44.93</td>
<td>751.41</td>
<td>3819.00</td>
</tr>
</tbody>
</table>

Table 20. Chi-Square Test Results for Fish Meals per Species within Each Region, Critical Value $\chi^2_{0.05} = 19.675$

<table>
<thead>
<tr>
<th>Region</th>
<th>df</th>
<th>$\chi^2$ calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>11</td>
<td>3855.30</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>11</td>
<td>9826.08</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>11</td>
<td>4139.60</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>11</td>
<td>873.82</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>967.46</td>
</tr>
</tbody>
</table>

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consumed significantly more servings of Perch, Whitefish, Walleye, and Lake Trout than Herring, Northern Pike, Bass, Salmon, Panfish, Rainbow Trout, and Other species (Table 21).

Because the servings per year and the grams per year represent the same value, the analysis of fish species consumed within each region focused on the servings per year of each species. Using Kruskal-Wallis tests, the analysis of servings eaten per species separated by region showed a significant difference between species for each region (Table 22).

Lake Superior subjects consumed more Lake Trout, Walleye, Whitefish, Smelt, and Rainbow Trout than other fish species, particularly Panfish and Bass (Table 23). Michigan and Superior subjects ate more Whitefish and Perch than other fish species (Table 24). Inland Lakes subjects consumed Walleye significantly more than other fish species (Table 25). Non-Ojibwa subjects ate significantly more Perch than other fish species (Table 26). Other subjects consumed significantly more Whitefish than Herring (q = 4.964, q critical, p = 0.05, k = 12 = 4.622).

Regression analyses were conducted to test for correlation between consumption of individual fish species and mean hair mercury concentrations. The first set of analyses focused on the association between fish meals per species and mean hair mercury concentration. Poor associations were detected with all R^2 values less than 0.02 (Table 27).

Regression analyses on fish meals and mean hair mercury concentration were performed for each region. Again, poor associations were found between fish meals per each species and mean hair mercury concentrations. The R^2 values for Lake Superior and
Table 21. Results of Nemenyi Tests on Servings per Year of Each Species, Critical $q, p = 0.05, k = 12 = 4.622$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$q$</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perch v Herring</td>
<td>7.743</td>
<td>Perch consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Perch v Northern Pike</td>
<td>7.361</td>
<td>Perch consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Perch v Bass</td>
<td>7.225</td>
<td>Perch consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Perch v Other</td>
<td>7.045</td>
<td>Perch consumption greater than Other consumption</td>
</tr>
<tr>
<td>Perch v Salmon</td>
<td>6.616</td>
<td>Perch consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Perch v Panfish</td>
<td>6.323</td>
<td>Perch consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Perch v Rainbow Trout</td>
<td>5.563</td>
<td>Perch consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Whitefish v Herring</td>
<td>7.669</td>
<td>Whitefish consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Whitefish v Northern Pike</td>
<td>7.287</td>
<td>Whitefish consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Whitefish v Bass</td>
<td>7.151</td>
<td>Whitefish consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Whitefish v Other</td>
<td>6.971</td>
<td>Whitefish consumption greater than Other consumption</td>
</tr>
<tr>
<td>Whitefish v Salmon</td>
<td>6.542</td>
<td>Whitefish consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Whitefish v Panfish</td>
<td>6.249</td>
<td>Whitefish consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Whitefish v Rainbow Trout</td>
<td>5.489</td>
<td>Whitefish consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Comparison</td>
<td>p-value</td>
<td>Conclusion</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>Lake Trout v Herring</td>
<td>7.505</td>
<td>Lake Trout consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Lake Trout v Northern Pike</td>
<td>7.124</td>
<td>Lake Trout consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Lake Trout v Bass</td>
<td>6.987</td>
<td>Lake Trout consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Lake Trout v Other</td>
<td>6.808</td>
<td>Lake Trout consumption greater than Other consumption</td>
</tr>
<tr>
<td>Lake Trout v Salmon</td>
<td>6.378</td>
<td>Lake Trout consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Lake Trout v Panfish</td>
<td>6.085</td>
<td>Lake Trout consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Lake Trout v Rainbow Trout</td>
<td>5.325</td>
<td>Lake Trout consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Walleye v Herring</td>
<td>7.400</td>
<td>Walleye consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Walleye v Northern Pike</td>
<td>7.018</td>
<td>Walleye consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Walleye v Bass</td>
<td>6.882</td>
<td>Walleye consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Walleye v Other</td>
<td>6.703</td>
<td>Walleye consumption greater than Other consumption</td>
</tr>
<tr>
<td>Walleye v Salmon</td>
<td>6.273</td>
<td>Walleye consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Walleye v Panfish</td>
<td>5.980</td>
<td>Walleye consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Walleye v Rainbow Trout</td>
<td>5.220</td>
<td>Walleye consumption greater than Rainbow Trout consumption</td>
</tr>
</tbody>
</table>
Table 22. Results of the Kruskal-Wallis Test Comparing the Mean Servings per Year of Each Species Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>df</th>
<th>Test Statistic</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>11</td>
<td>132.761</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>11</td>
<td>209.348</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>11</td>
<td>91.478</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>11</td>
<td>58.552</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>37.505</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Lake Michigan and Superior were less than 0.02 (Tables 28 and 29). A stronger association between hair mercury concentration and Whitefish consumption existed in the Inland Lakes region (Table 30). Stronger association between hair mercury concentration and Herring, Panfish, Perch, Lake Trout, Rainbow Trout, Salmon, Walleye, Whitefish, and Other species was found for Non-Ojibwa individuals (Table 31). A stronger association between hair mercury concentration and Perch consumption was found for the Other group (Table 32).

Eleven fish species, excluding Other species, were divided by trophic levels, either high: (Bass, Northern Pike, Lake Trout, Rainbow Trout, Salmon, and Walleye), or low, (Herring, Panfish, Perch, Smelt, and Whitefish), to examine any difference in the number of meals consumed from each level and the potential impact on hair mercury concentration. This analysis addresses the possible influence of trophic level on mercury intake. A Mann-Whitney test was performed ($z = -2.291; p = 0.022$) and indicated that subjects consumed significantly more fish meals from low trophic level than from the
Table 23. Summary of Nemenyi Tests on Servings per Year of Each Fish Species in the Lake Superior Region, $Q$ critical, $p = 0.05, k = 12 = 4.622$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$q$</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Trout v Panfish</td>
<td>8.300</td>
<td>Lake Trout consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Lake Trout v Bass</td>
<td>8.191</td>
<td>Lake Trout consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Lake Trout v Other</td>
<td>15.225</td>
<td>Lake Trout consumption greater than Other consumption</td>
</tr>
<tr>
<td>Lake Trout v Northern Pike</td>
<td>7.311</td>
<td>Lake Trout consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Lake Trout v Perch</td>
<td>6.567</td>
<td>Lake Trout consumption greater than Perch consumption</td>
</tr>
<tr>
<td>Lake Trout v Salmon</td>
<td>5.980</td>
<td>Lake Trout consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Lake Trout v Herring</td>
<td>5.310</td>
<td>Lake Trout consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Walleye v Panfish</td>
<td>6.574</td>
<td>Walleye consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Walleye v Bass</td>
<td>6.465</td>
<td>Walleye consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Walleye v Other</td>
<td>5.908</td>
<td>Walleye consumption greater than Other consumption</td>
</tr>
<tr>
<td>Walleye v Northern Pike</td>
<td>5.585</td>
<td>Walleye consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Walleye v Perch</td>
<td>4.841</td>
<td>Walleye consumption greater than Perch consumption</td>
</tr>
<tr>
<td>Whitefish v Panfish</td>
<td>5.423</td>
<td>Whitefish consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Whitefish v Bass</td>
<td>5.314</td>
<td>Whitefish consumption greater than Bass consumption</td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Whitefish v Other</td>
<td>4.757</td>
<td>Whitefish consumption greater than Other consumption</td>
</tr>
<tr>
<td>Smelt v Panfish</td>
<td>5.276</td>
<td>Smelt consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Smelt v Bass</td>
<td>5.166</td>
<td>Smelt consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Rainbow Trout v Panfish</td>
<td>4.980</td>
<td>Rainbow Trout consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Rainbow Trout v Bass</td>
<td>4.870</td>
<td>Rainbow Trout consumption greater than Bass consumption</td>
</tr>
</tbody>
</table>

high trophic level.

**Amount**

To determine the level of association between total quantity of fish consumed and hair mercury concentrations, a regression analysis was performed. No association between fish meals and hair mercury concentration was detected for all subjects ($R^2 < 0.001$, $F = 0.057$, $p = 0.812$). An analysis focusing on total servings of fish per year and hair mercury concentration for all subjects showed a poor association ($R^2 < 0.001$, $F = 0.022$, $p = 0.883$). A weak association between fish meals and hair mercury concentrations was found in each region, with all $R^2$ values below 0.10, except for the Non-Ojibwa individuals with an $R^2$ of 0.527 (Table 33).

A separate regression analysis focusing on servings of fish per year and hair mercury concentrations in each of the five regions also showed weak associations with $R^2$ values less than 0.20 (Table 34).
Table 24. Summary of Nemenyi Tests on Servings per Year of Each Fish Species in Michigan and Superior Region, $Q$ critical, $p = 0.05, k = 12 = 4.622$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whitefish v Northern Pike</td>
<td>8.507</td>
<td>Whitefish consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Whitefish v Rainbow Trout</td>
<td>8.334</td>
<td>Whitefish consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Whitefish v Bass</td>
<td>8.140</td>
<td>Whitefish consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Whitefish v Herring</td>
<td>8.099</td>
<td>Whitefish consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Whitefish v Salmon</td>
<td>7.750</td>
<td>Whitefish consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Whitefish v Panfish</td>
<td>7.604</td>
<td>Whitefish consumption greater than Panfish consumption</td>
</tr>
<tr>
<td>Whitefish v Other</td>
<td>7.476</td>
<td>Whitefish consumption greater than Other consumption</td>
</tr>
<tr>
<td>Whitefish v Walleye</td>
<td>7.437</td>
<td>Whitefish consumption greater than Walleye consumption</td>
</tr>
<tr>
<td>Whitefish v Smelt</td>
<td>5.128</td>
<td>Whitefish consumption greater than Smelt consumption</td>
</tr>
<tr>
<td>Perch v Northern Pike</td>
<td>8.449</td>
<td>Perch consumption greater than Northern Pike consumption</td>
</tr>
<tr>
<td>Perch v Rainbow Trout</td>
<td>8.276</td>
<td>Perch consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Perch v Bass</td>
<td>8.082</td>
<td>Perch consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Perch v Herring</td>
<td>8.041</td>
<td>Perch consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Perch v Salmon</td>
<td>7.692</td>
<td>Perch consumption greater than Salmon consumption</td>
</tr>
</tbody>
</table>
A regression analysis was done to determine the association between the number of servings of fish per each meal and hair mercury concentration. A poor association was detected for all subjects ($R^2 < 0.001$, $F = 0.017$, $p = 0.897$). Also, the analyses for each of the five regions indicated poor associations with $R^2$ values less than 0.02, except for Other individuals with a $R^2$ value of 0.407 (Table 35).

**Size**

A regression analysis was performed to test for an association between size, or length in inches, of fish consumed and hair mercury concentrations. A weak association was found for all subjects ($R^2 = 0.007$, $F = 0.389$, $p = 0.535$). Similarly, weak associations were found in each of the five regions (Table 36). Non-Ojibwa individuals did not provide this information on their questionnaires.

A Kruskal-Wallis test was conducted to compare the median fish length in inches between the four reporting regions. The test showed no significant difference between the mean length of fish consumed in Lake Superior, Michigan and Superior, Inland Lakes, and Other regions ($X^2_{(3)} = 3.204; p = 0.361$).

<table>
<thead>
<tr>
<th>Perch v Panfish</th>
<th>7.546</th>
<th>Perch consumption greater than Panfish consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perch v Other</td>
<td>7.418</td>
<td>Perch consumption greater than Other consumption</td>
</tr>
<tr>
<td>Perch v Walleye</td>
<td>7.379</td>
<td>Perch consumption greater than Walleye consumption</td>
</tr>
<tr>
<td>Perch v Smelt</td>
<td>5.070</td>
<td>Perch consumption greater than Smelt consumption</td>
</tr>
</tbody>
</table>
Table 25. Summary of Nemenyi Tests on Servings per Year of Each Fish Species in Inland Lakes Region, $Q$ critical, $p = 0.05, k = 12 = 4.622$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walleye v Whitefish</td>
<td>7.530</td>
<td>Walleye consumption greater than Whitefish consumption</td>
</tr>
<tr>
<td>Walleye v Herring</td>
<td>7.444</td>
<td>Walleye consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Walleye v Rainbow Trout</td>
<td>7.216</td>
<td>Walleye consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Walleye v Lake Trout</td>
<td>6.751</td>
<td>Walleye consumption greater than Lake Trout consumption</td>
</tr>
<tr>
<td>Walleye v Smelt</td>
<td>6.734</td>
<td>Walleye consumption greater than Smelt consumption</td>
</tr>
<tr>
<td>Walleye v Salmon</td>
<td>6.687</td>
<td>Walleye consumption greater than Salmon consumption</td>
</tr>
<tr>
<td>Walleye v Other</td>
<td>6.348</td>
<td>Walleye consumption greater than Other consumption</td>
</tr>
<tr>
<td>Walleye v Bass</td>
<td>5.776</td>
<td>Walleye consumption greater than Bass consumption</td>
</tr>
<tr>
<td>Walleye v Northern Pike</td>
<td>5.322</td>
<td>Walleye consumption greater than Northern Pike consumption</td>
</tr>
</tbody>
</table>

**Geographic Source**

An analysis determined the presence of any significant difference in the fish harvests from the five different geographical sources of fish described in the questionnaire. Most fish meals were obtained from Inland Lakes, followed by Lake Superior, Restaurant, Lake Michigan, and finally Store (Table 37). The pattern of fish procurement was identical for the servings of fish per year.
Table 26. Summary of Nemenyi Tests on Servings per Year of Each Fish Species in Non-Ojibwa Region, $Q$ critical, $p = 0.05, k = 12 = 4.622$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perch v Herring</td>
<td>5.955</td>
<td>Perch consumption greater than Herring consumption</td>
</tr>
<tr>
<td>Perch v Smelt</td>
<td>5.217</td>
<td>Perch consumption greater than Smelt consumption</td>
</tr>
<tr>
<td>Perch v Whitefish</td>
<td>4.993</td>
<td>Perch consumption greater than Whitefish consumption</td>
</tr>
<tr>
<td>Perch v Rainbow Trout</td>
<td>4.838</td>
<td>Perch consumption greater than Rainbow Trout consumption</td>
</tr>
<tr>
<td>Perch v Salmon</td>
<td>4.799</td>
<td>Perch consumption greater than Salmon consumption</td>
</tr>
</tbody>
</table>

Table 27. Fish Meals v. Mean Hair Mercury Concentration

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>284</td>
<td>0.001</td>
<td>0.409</td>
<td>0.523</td>
</tr>
<tr>
<td>Herring</td>
<td>284</td>
<td>0.001</td>
<td>0.388</td>
<td>0.534</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>284</td>
<td>0.002</td>
<td>0.436</td>
<td>0.509</td>
</tr>
<tr>
<td>Panfish</td>
<td>284</td>
<td>0.002</td>
<td>0.480</td>
<td>0.489</td>
</tr>
<tr>
<td>Perch</td>
<td>284</td>
<td>0.010</td>
<td>2.852</td>
<td>0.092</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>284</td>
<td>0.000</td>
<td>0.036</td>
<td>0.850</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>284</td>
<td>0.001</td>
<td>0.406</td>
<td>0.525</td>
</tr>
<tr>
<td>Salmon</td>
<td>284</td>
<td>0.002</td>
<td>0.426</td>
<td>0.514</td>
</tr>
<tr>
<td>Smelt</td>
<td>284</td>
<td>0.005</td>
<td>1.344</td>
<td>0.247</td>
</tr>
<tr>
<td>Walleye</td>
<td>284</td>
<td>0.000</td>
<td>1.039</td>
<td>0.309</td>
</tr>
<tr>
<td>Whitefish</td>
<td>284</td>
<td>0.002</td>
<td>0.488</td>
<td>0.486</td>
</tr>
<tr>
<td>Other</td>
<td>284</td>
<td>0.005</td>
<td>1.453</td>
<td>0.229</td>
</tr>
</tbody>
</table>

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Table 28. Fish Meals v. Mean Hair Mercury Concentration for Lake Superior

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>106</td>
<td>0.002</td>
<td>0.221</td>
<td>0.639</td>
</tr>
<tr>
<td>Herring</td>
<td>106</td>
<td>0.003</td>
<td>0.277</td>
<td>0.600</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>106</td>
<td>0.002</td>
<td>0.246</td>
<td>0.621</td>
</tr>
<tr>
<td>Panfish</td>
<td>106</td>
<td>0.011</td>
<td>1.114</td>
<td>0.294</td>
</tr>
<tr>
<td>Perch</td>
<td>106</td>
<td>0.001</td>
<td>0.109</td>
<td>0.742</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>106</td>
<td>0.002</td>
<td>0.189</td>
<td>0.665</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>106</td>
<td>0.000</td>
<td>0.005</td>
<td>0.945</td>
</tr>
<tr>
<td>Salmon</td>
<td>106</td>
<td>0.001</td>
<td>0.064</td>
<td>0.801</td>
</tr>
<tr>
<td>Smelt</td>
<td>106</td>
<td>0.006</td>
<td>0.604</td>
<td>0.439</td>
</tr>
<tr>
<td>Walleye</td>
<td>106</td>
<td>0.003</td>
<td>0.264</td>
<td>0.608</td>
</tr>
<tr>
<td>Whitefish</td>
<td>106</td>
<td>0.005</td>
<td>0.518</td>
<td>0.473</td>
</tr>
<tr>
<td>Other</td>
<td>106</td>
<td>0.000</td>
<td>0.008</td>
<td>0.928</td>
</tr>
</tbody>
</table>

Table 29. Fish Meals v. Mean Hair Mercury Concentration for Lakes Michigan and Superior

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>79</td>
<td>0.004</td>
<td>0.271</td>
<td>0.604</td>
</tr>
<tr>
<td>Herring</td>
<td>79</td>
<td>0.007</td>
<td>0.534</td>
<td>0.467</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>79</td>
<td>0.005</td>
<td>0.372</td>
<td>0.544</td>
</tr>
<tr>
<td>Panfish</td>
<td>79</td>
<td>0.005</td>
<td>0.418</td>
<td>0.520</td>
</tr>
<tr>
<td>Perch</td>
<td>79</td>
<td>0.005</td>
<td>0.358</td>
<td>0.551</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>79</td>
<td>0.000</td>
<td>0.035</td>
<td>0.832</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>79</td>
<td>0.000</td>
<td>0.000</td>
<td>0.987</td>
</tr>
<tr>
<td>Salmon</td>
<td>79</td>
<td>0.004</td>
<td>0.293</td>
<td>0.590</td>
</tr>
<tr>
<td>Smelt</td>
<td>79</td>
<td>0.016</td>
<td>1.248</td>
<td>0.267</td>
</tr>
<tr>
<td>Walleye</td>
<td>79</td>
<td>0.007</td>
<td>0.526</td>
<td>0.471</td>
</tr>
<tr>
<td>Whitefish</td>
<td>79</td>
<td>0.001</td>
<td>0.101</td>
<td>0.751</td>
</tr>
<tr>
<td>Other</td>
<td>79</td>
<td>0.079</td>
<td>6.648</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Table 30. Fish Meals v. Mean Hair Mercury Concentration for Inland Lakes

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>37</td>
<td>0.013</td>
<td>0.446</td>
<td>0.509</td>
</tr>
<tr>
<td>Herring</td>
<td>37</td>
<td>0.001</td>
<td>0.025</td>
<td>0.876</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>37</td>
<td>0.049</td>
<td>1.801</td>
<td>0.188</td>
</tr>
<tr>
<td>Panfish</td>
<td>37</td>
<td>0.052</td>
<td>1.918</td>
<td>0.175</td>
</tr>
<tr>
<td>Perch</td>
<td>37</td>
<td>0.058</td>
<td>2.152</td>
<td>0.151</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>37</td>
<td>0.072</td>
<td>2.729</td>
<td>0.107</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>37</td>
<td>0.082</td>
<td>3.145</td>
<td>0.085</td>
</tr>
<tr>
<td>Salmon</td>
<td>37</td>
<td>0.007</td>
<td>0.239</td>
<td>0.628</td>
</tr>
<tr>
<td>Smelt</td>
<td>37</td>
<td>0.003</td>
<td>0.119</td>
<td>0.732</td>
</tr>
<tr>
<td>Walleye</td>
<td>37</td>
<td>0.057</td>
<td>2.135</td>
<td>0.153</td>
</tr>
<tr>
<td>Whitefish</td>
<td>37</td>
<td>0.369</td>
<td>20.493</td>
<td>0.000</td>
</tr>
<tr>
<td>Other</td>
<td>37</td>
<td>0.004</td>
<td>0.137</td>
<td>0.713</td>
</tr>
</tbody>
</table>

Table 31. Fish Meals v. Mean Hair Mercury Concentration for Non-Ojibwa

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>36</td>
<td>0.078</td>
<td>2.874</td>
<td>0.099</td>
</tr>
<tr>
<td>Herring</td>
<td>36</td>
<td>0.494</td>
<td>33.183</td>
<td>0.000</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>36</td>
<td>0.072</td>
<td>2.657</td>
<td>0.112</td>
</tr>
<tr>
<td>Panfish</td>
<td>36</td>
<td>0.131</td>
<td>5.111</td>
<td>0.030</td>
</tr>
<tr>
<td>Perch</td>
<td>36</td>
<td>0.107</td>
<td>4.094</td>
<td>0.051</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>36</td>
<td>0.285</td>
<td>13.526</td>
<td>0.001</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>36</td>
<td>0.312</td>
<td>15.445</td>
<td>0.000</td>
</tr>
<tr>
<td>Salmon</td>
<td>36</td>
<td>0.448</td>
<td>27.611</td>
<td>0.000</td>
</tr>
<tr>
<td>Smelt</td>
<td>36</td>
<td>0.000</td>
<td>0.013</td>
<td>0.910</td>
</tr>
<tr>
<td>Walleye</td>
<td>36</td>
<td>0.545</td>
<td>40.704</td>
<td>0.000</td>
</tr>
<tr>
<td>Whitefish</td>
<td>36</td>
<td>0.450</td>
<td>27.848</td>
<td>0.000</td>
</tr>
<tr>
<td>Other</td>
<td>36</td>
<td>0.386</td>
<td>21.375</td>
<td>0.001</td>
</tr>
</tbody>
</table>

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Table 32. Fish Meals v. Mean Hair Mercury Concentration for Others

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>26</td>
<td>0.007</td>
<td>0.177</td>
<td>0.677</td>
</tr>
<tr>
<td>Herring</td>
<td>26</td>
<td>0.003</td>
<td>0.071</td>
<td>0.792</td>
</tr>
<tr>
<td>Northern Pike</td>
<td>26</td>
<td>0.005</td>
<td>0.118</td>
<td>0.734</td>
</tr>
<tr>
<td>Panfish</td>
<td>26</td>
<td>0.010</td>
<td>0.239</td>
<td>0.630</td>
</tr>
<tr>
<td>Perch</td>
<td>26</td>
<td>0.360</td>
<td>13.524</td>
<td>0.001</td>
</tr>
<tr>
<td>Lake Trout</td>
<td>26</td>
<td>0.003</td>
<td>0.064</td>
<td>0.802</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>26</td>
<td>0.020</td>
<td>0.481</td>
<td>0.495</td>
</tr>
<tr>
<td>Salmon</td>
<td>26</td>
<td>0.016</td>
<td>0.398</td>
<td>0.534</td>
</tr>
<tr>
<td>Smelt</td>
<td>26</td>
<td>0.017</td>
<td>0.417</td>
<td>0.524</td>
</tr>
<tr>
<td>Walleye</td>
<td>26</td>
<td>0.019</td>
<td>0.457</td>
<td>0.505</td>
</tr>
<tr>
<td>Whitefish</td>
<td>26</td>
<td>0.015</td>
<td>0.357</td>
<td>0.556</td>
</tr>
<tr>
<td>Other</td>
<td>26</td>
<td>0.004</td>
<td>0.084</td>
<td>0.774</td>
</tr>
</tbody>
</table>

Table 33. Fish Meals v. Hair Mercury Concentration in the Five Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>106</td>
<td>0.002</td>
<td>0.240</td>
<td>0.625</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>79</td>
<td>0.007</td>
<td>0.538</td>
<td>0.465</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>37</td>
<td>0.091</td>
<td>3.506</td>
<td>0.070</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>36</td>
<td>0.527</td>
<td>37.939</td>
<td>0.000</td>
</tr>
<tr>
<td>Other</td>
<td>26</td>
<td>0.010</td>
<td>0.249</td>
<td>0.622</td>
</tr>
</tbody>
</table>

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Table 34. Fish Servings per Year v. Hair Mercury Concentrations in the Five Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>106</td>
<td>0.001</td>
<td>0.122</td>
<td>0.727</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>79</td>
<td>0.004</td>
<td>0.312</td>
<td>0.578</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>37</td>
<td>0.073</td>
<td>2.747</td>
<td>0.106</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>36</td>
<td>0.131</td>
<td>5.121</td>
<td>0.030</td>
</tr>
<tr>
<td>Other</td>
<td>26</td>
<td>0.166</td>
<td>4.772</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Table 35. Number of Servings per Each Meal v. Hair Mercury Concentration in the Five Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>106</td>
<td>0.000</td>
<td>0.008</td>
<td>0.927</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>79</td>
<td>0.005</td>
<td>0.405</td>
<td>0.526</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>37</td>
<td>0.018</td>
<td>0.657</td>
<td>0.423</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>36</td>
<td>0.003</td>
<td>0.087</td>
<td>0.769</td>
</tr>
<tr>
<td>Other</td>
<td>26</td>
<td>0.407</td>
<td>16.503</td>
<td>0.000</td>
</tr>
</tbody>
</table>

A Kruskal-Wallis test showed a significant difference in the median fish meals obtained by all subjects from the five sources ($X^2_{(4)} = 37.633; p = 0.000$). Significantly more meals came from Inland Lakes than Lake Michigan and Store. More meals came from Lake Superior than Lake Michigan and the Store. Also, more meals came from the Restaurant than Lake Michigan (Table 38).

A Kruskal-Wallis test showed a significant difference in fish servings per year consumed by all subjects from the five sources ($X^2_{(4)} = 39.507; p = 0.000$). The significant comparisons were identical to the fish meals results. Significantly more
### Table 36. Fish Length in Inches v. Hair Mercury Concentration in the Five Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>14</td>
<td>0.120</td>
<td>1.637</td>
<td>0.225</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>15</td>
<td>0.006</td>
<td>0.082</td>
<td>0.779</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>17</td>
<td>0.000</td>
<td>0.002</td>
<td>0.968</td>
</tr>
<tr>
<td>Other</td>
<td>15</td>
<td>0.003</td>
<td>0.039</td>
<td>0.846</td>
</tr>
</tbody>
</table>

### Table 37. Mean Fish Meals and Mean Servings per year Obtained from the Five Geographical Sources of Fish

<table>
<thead>
<tr>
<th>Fish Source</th>
<th>N</th>
<th>Mean Fish Meals per Year</th>
<th>Mean Meals Standard Deviation</th>
<th>Mean Fish Servings per Year</th>
<th>Mean Servings per Year Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>285</td>
<td>19.17</td>
<td>46.95</td>
<td>52.00</td>
<td>139.21</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>285</td>
<td>10.65</td>
<td>40.55</td>
<td>27.51</td>
<td>119.86</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>285</td>
<td>15.13</td>
<td>31.67</td>
<td>39.70</td>
<td>95.54</td>
</tr>
<tr>
<td>Restaurant</td>
<td>285</td>
<td>12.41</td>
<td>24.75</td>
<td>33.00</td>
<td>84.03</td>
</tr>
<tr>
<td>Store Bought</td>
<td>285</td>
<td>9.76</td>
<td>24.17</td>
<td>24.44</td>
<td>81.48</td>
</tr>
</tbody>
</table>

servings of fish per year were consumed from fish obtained from Inland Lakes than Lake Michigan or the Store, more servings from Lake Superior than Lake Michigan or the Store, and more servings from the Restaurant than Lake Michigan (Table 39).

When separated by the five subject regions, Kruskal-Wallis tests comparing the median number of fish meals from each geographical source was significant for each region (Table 38). Lake Superior subjects obtained their fish meals mostly from Lake Superior, Michigan and Superior subjects caught their fish mostly from Lake Michigan,
Table 38. Results of Nemenyi Tests for Fish Meals Obtained from Each Geographical Source, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>6.046</td>
<td>More fish meals consumed from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>5.255</td>
<td>More fish meals consumed from Inland Lakes than Store Bought</td>
</tr>
<tr>
<td>Lake Superior v. Lake Michigan</td>
<td>4.770</td>
<td>More fish meals consumed from Lake Superior than Lake Michigan</td>
</tr>
<tr>
<td>Lake Superior v. Store Bought</td>
<td>3.979</td>
<td>More fish meals consumed from Lake Superior than Store Bought</td>
</tr>
<tr>
<td>Restaurant v. Lake Michigan</td>
<td>3.952</td>
<td>More fish meals consumed from Restaurant than Lake Michigan</td>
</tr>
</tbody>
</table>

Table 39. Results of Nemenyi Tests for Fish Servings per Year Obtained from Each Geographical Source, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>6.086</td>
<td>More fish servings consumed from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>5.481</td>
<td>More fish servings consumed from Inland Lakes than Store Bought</td>
</tr>
<tr>
<td>Lake Superior v. Lake Michigan</td>
<td>4.856</td>
<td>More fish servings consumed from Lake Superior than Lake Michigan</td>
</tr>
<tr>
<td>Lake Superior v. Store Bought</td>
<td>4.252</td>
<td>More fish servings consumed from Lake Superior than Store Bought</td>
</tr>
<tr>
<td>Restaurant v. Lake Michigan</td>
<td>3.983</td>
<td>More fish servings consumed from Restaurant than Lake Michigan</td>
</tr>
</tbody>
</table>

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Inland Lakes individuals obtained their fish from inland lakes, and Non-Ojibwa subjects caught their fish meals mostly from inland lakes (Tables 40 – 44). Other individuals obtained their fish meals significantly more from Lake Michigan than Lake Superior, \( (q = 3.970, q_{\text{critical}}, p = 0.05, k = 5 = 3.858) \).

Table 40. Results of the Kruskal-Wallis Test Comparing Mean Fish Meals Obtained from the Five Geographical Sources Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>df</th>
<th>Test Statistic</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>4</td>
<td>115.137</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>4</td>
<td>22.829</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>4</td>
<td>66.645</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>4</td>
<td>43.134</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>13.410</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Kruskal-Wallis tests were performed to compare the median number of fish servings per year from each geographical source within each subject region. The results mirrored the results for the fish meal analyses. Subjects obtained fish servings significantly more from at least one geographical source (Table 45). Again, Lake Superior subjects consumed more fish from Lake Superior, Michigan and Superior subjects consumed more fish from Lake Michigan, Inland Lakes individuals consumed more fish from Inland Lakes, and Non-Ojibwa subjects consumed more fish from Inland Lakes (Tables 46 - 49). Although the Kruskal-Wallis test indicated a difference between the median fish servings for the Other group, the Nemenyi tests did not result in a significant difference between any median fish serving from geographic source.
Regression analyses were conducted to examine the association between geographical source of fish harvest and hair mercury concentrations. The first analysis focused on the fish meals from geographical sources and hair mercury concentrations for all subjects. Results showed poor associations for all geographical sources, with $R^2$ values less than 0.02 (Table 50).
Table 42. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Michigan and Superior, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Michigan v. Inland Lakes</td>
<td>4.745</td>
<td>Significantly more fish meals obtained from Lake Michigan than Inland Lakes</td>
</tr>
<tr>
<td>Lake Michigan v. Store Bought</td>
<td>4.191</td>
<td>Significantly more fish meals obtained from Lake Michigan than Store Bought</td>
</tr>
<tr>
<td>Lake Michigan v. Lake Superior</td>
<td>4.082</td>
<td>Significantly more fish meals obtained from Lake Michigan than Lake Superior</td>
</tr>
</tbody>
</table>

Table 43. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Inland Lakes, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>7.747</td>
<td>Significantly more fish meals obtained from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Lake Superior</td>
<td>7.139</td>
<td>Significantly more fish meals obtained from Inland Lakes than Lake Superior</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>5.961</td>
<td>Significantly more fish meals obtained from Inland Lakes than Store Bought</td>
</tr>
<tr>
<td>Inland Lakes v. Restaurant</td>
<td>5.222</td>
<td>Significantly more fish meals obtained from Inland Lakes than Restaurant</td>
</tr>
</tbody>
</table>
Table 44. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Non-Ojibwa, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Superior</td>
<td>6.751</td>
<td>Significantly more fish meals obtained from Inland Lakes than Lake Superior</td>
</tr>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>6.021</td>
<td>Significantly more fish meals obtained from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>4.568</td>
<td>Significantly more fish meals obtained from Inland Lakes than Store Bought</td>
</tr>
</tbody>
</table>

Table 45. Results of Kruskal-Wallis Test Comparing Median Fish Servings per Year Obtained from the Five Geographical Sources Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>df</th>
<th>Test Statistic</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>4</td>
<td>121.356</td>
<td>0.000</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>4</td>
<td>22.809</td>
<td>0.000</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>4</td>
<td>66.665</td>
<td>0.000</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>4</td>
<td>44.039</td>
<td>0.000</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>13.009</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Regression analyses were conducted to examine the associations between geographical source of fish meals and hair mercury concentrations within each region. Results indicated weak associations for all sources for Lake Superior individuals, with $R^2$ values less than 0.02 (Table 51). Weak associations were found for Michigan and Superior subjects, with $R^2$ values less than 0.03 (Table 52). Poor associations were found for Inland Lakes individuals (Table 53). Inland Lakes subjects did not report
Table 46. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Lake Superior, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior v. Lake</td>
<td>13.278</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>Lake Superior than Lake Michigan</td>
</tr>
<tr>
<td>Lake Superior v. Store</td>
<td>8.717</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Bought</td>
<td></td>
<td>Lake Superior than Store Bought</td>
</tr>
<tr>
<td>Lake Superior v. Restaurant</td>
<td>7.669</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lake Superior than Restaurant</td>
</tr>
<tr>
<td>Lake Superior v. Inland</td>
<td>5.780</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Lakes</td>
<td></td>
<td>Lake Superior than Inland Lakes</td>
</tr>
<tr>
<td>Inland Lakes v. Lake</td>
<td>7.499</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Restaurant v. Lake</td>
<td>5.609</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>Restaurant than Lake Michigan</td>
</tr>
<tr>
<td>Store Bought v. Lake</td>
<td>4.561</td>
<td>Significantly more fish servings consumed form fish obtained from</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>Store Bought than Lake Michigan</td>
</tr>
</tbody>
</table>

consumption of any fish meals from Lake Michigan. A small association between Inland Lakes subjects' hair mercury concentration and fish bought from a store was found ($R^2 = 0.203$). Minimal associations were found for Non-Ojibwa subjects (Table 54). The highest association was between fish meals obtained from Lake Michigan and hair mercury concentration, followed by fish meals obtained from Restaurant, Store Bought,
Table 47. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Michigan and Superior, Q Critical, $p = 0.05$, $k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Michigan v. Inland Lakes</td>
<td>4.724</td>
<td>Significantly more fish servings consumed from fish obtained from Lake Michigan than Inland Lakes</td>
</tr>
<tr>
<td>Lake Michigan v. Store Bought</td>
<td>4.282</td>
<td>Significantly more fish servings consumed from fish obtained from Lake Michigan than Store Bought</td>
</tr>
<tr>
<td>Lake Michigan v. Lake Superior</td>
<td>3.985</td>
<td>Significantly more fish servings consumed from fish obtained from Lake Michigan than Lake Superior</td>
</tr>
</tbody>
</table>

Table 48. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Inland Lakes, Q Critical, $p = 0.05$, $k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>7.742</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Lake Superior</td>
<td>7.163</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Lake Superior</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>5.938</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Store Bought</td>
</tr>
<tr>
<td>Inland Lakes v. Restaurant</td>
<td>5.201</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Restaurant</td>
</tr>
</tbody>
</table>
Table 49. Results of Nemenyi Post Hoc Tests on Fish Meals per Geographical Source for Non-Ojibwa, Q Critical, $p = 0.05, k = 5 = 3.858$; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes v. Lake Superior</td>
<td>6.842</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Lake Superior</td>
</tr>
<tr>
<td>Inland Lakes v. Lake Michigan</td>
<td>6.095</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Lake Michigan</td>
</tr>
<tr>
<td>Inland Lakes v. Store Bought</td>
<td>4.633</td>
<td>Significantly more fish servings consumed from fish obtained from Inland Lakes than Store Bought</td>
</tr>
</tbody>
</table>

Table 50. Regression Analysis Results for Geographical Source of Fish Meals v. Hair Mercury Concentrations for All Subjects

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>285</td>
<td>0.005</td>
<td>1.317</td>
<td>0.252</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>285</td>
<td>0.015</td>
<td>4.317</td>
<td>0.039</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>285</td>
<td>0.005</td>
<td>1.489</td>
<td>0.223</td>
</tr>
<tr>
<td>Restaurant</td>
<td>285</td>
<td>0.004</td>
<td>1.065</td>
<td>0.303</td>
</tr>
<tr>
<td>Store Bought</td>
<td>285</td>
<td>0.002</td>
<td>0.431</td>
<td>0.512</td>
</tr>
</tbody>
</table>

and Inland Lakes. Weak associations were found between source of fish meals and hair mercury concentration for Other subjects, with $R^2$ values less than 0.03 (Table 55).
Table 51. Regression Analysis of Geographical Source of Fish Meals v. Hair Mercury Concentration, Lake Superior Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>106</td>
<td>0.000</td>
<td>0.018</td>
<td>0.893</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>106</td>
<td>0.001</td>
<td>0.055</td>
<td>0.815</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>106</td>
<td>0.015</td>
<td>1.589</td>
<td>0.210</td>
</tr>
<tr>
<td>Restaurant</td>
<td>106</td>
<td>0.003</td>
<td>0.271</td>
<td>0.604</td>
</tr>
<tr>
<td>Store Bought</td>
<td>106</td>
<td>0.001</td>
<td>0.099</td>
<td>0.754</td>
</tr>
</tbody>
</table>

Table 52. Regression Analysis of Geographical Source of Fish Meals v. Hair Mercury Concentration, Michigan and Superior Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>79</td>
<td>0.014</td>
<td>1.061</td>
<td>0.306</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>79</td>
<td>0.005</td>
<td>0.350</td>
<td>0.556</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>79</td>
<td>0.021</td>
<td>1.644</td>
<td>0.204</td>
</tr>
<tr>
<td>Restaurant</td>
<td>79</td>
<td>0.019</td>
<td>1.493</td>
<td>0.225</td>
</tr>
<tr>
<td>Store Bought</td>
<td>79</td>
<td>0.010</td>
<td>0.791</td>
<td>0.377</td>
</tr>
</tbody>
</table>

Table 53. Regression Analysis of Geographical Source of Fish Meals v. Hair Mercury Concentration, Inland Lakes Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>36</td>
<td>0.019</td>
<td>0.641</td>
<td>0.429</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>No Meals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Superior</td>
<td>36</td>
<td>0.004</td>
<td>0.138</td>
<td>0.712</td>
</tr>
<tr>
<td>Restaurant</td>
<td>36</td>
<td>0.010</td>
<td>0.349</td>
<td>0.559</td>
</tr>
<tr>
<td>Store Bought</td>
<td>36</td>
<td>0.203</td>
<td>8.652</td>
<td>0.006</td>
</tr>
</tbody>
</table>

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### Table 54. Regression Analysis of Geographical Source of Fish Meals v. Hair Mercury Concentration, Non-Ojibwa Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>36</td>
<td>0.197</td>
<td>8.322</td>
<td>0.007</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>36</td>
<td>0.439</td>
<td>26.599</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>36</td>
<td>0.000</td>
<td>0.007</td>
<td>0.933</td>
</tr>
<tr>
<td>Restaurant</td>
<td>36</td>
<td>0.349</td>
<td>18.246</td>
<td>0.000</td>
</tr>
<tr>
<td>Store Bought</td>
<td>36</td>
<td>0.287</td>
<td>13.655</td>
<td>0.001</td>
</tr>
</tbody>
</table>

### Table 55. Regression Analysis of Geographical Source of Fish Meals v. Hair Mercury Concentration, Other Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>28</td>
<td>0.011</td>
<td>0.300</td>
<td>0.588</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>28</td>
<td>0.000</td>
<td>0.001</td>
<td>0.972</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>28</td>
<td>0.006</td>
<td>0.165</td>
<td>0.688</td>
</tr>
<tr>
<td>Restaurant</td>
<td>28</td>
<td>0.026</td>
<td>0.691</td>
<td>0.413</td>
</tr>
<tr>
<td>Store Bought</td>
<td>28</td>
<td>0.010</td>
<td>0.264</td>
<td>0.612</td>
</tr>
</tbody>
</table>

### Table 56. Regression Analysis Results for Geographical Source of Fish Servings per Year v. Hair Mercury Concentrations for All Subjects

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>285</td>
<td>0.004</td>
<td>1.100</td>
<td>0.295</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>285</td>
<td>0.017</td>
<td>5.013</td>
<td>0.026</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>285</td>
<td>0.004</td>
<td>1.177</td>
<td>0.279</td>
</tr>
<tr>
<td>Restaurant</td>
<td>285</td>
<td>0.004</td>
<td>1.086</td>
<td>0.298</td>
</tr>
<tr>
<td>Store Bought</td>
<td>285</td>
<td>0.003</td>
<td>0.937</td>
<td>0.334</td>
</tr>
</tbody>
</table>
A second regression analysis focused on the geographical source of fish (in servings per year) and hair mercury concentration. The result showed a poor association between source of fish and hair mercury concentration for all subjects, with all $R^2$ values less than 0.02 (Table 56).

Regression analyses were conducted to examine the association between geographical source of fish servings per year and hair mercury concentrations for each of the five regions. The results were similar to the regression analyses on geographical source of fish meals. Poor associations existed for all sources of fish servings for Lake Superior subjects, with $R^2$ values less than 0.01 (Table 57). Weak correlations between fish servings source and hair mercury concentrations existed for Michigan and Superior subjects, with $R^2$ values less than 0.02 (Table 58). Results showed weak associations for Inland Lakes individuals, except for a slightly higher correlation between fish servings bought from the store and hair mercury concentration (Table 59). Weak associations existed for Non-Ojibwa subjects, except for a slight correlation between fish servings from Lake Michigan and hair mercury concentration (Table 60). Weak associations were found for Other individuals, with $R^2$ values less than 0.03 (Table 61).

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>106</td>
<td>&lt; 0.001</td>
<td>0.019</td>
<td>0.890</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>106</td>
<td>0.001</td>
<td>0.079</td>
<td>0.780</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>106</td>
<td>0.008</td>
<td>0.079</td>
<td>0.349</td>
</tr>
<tr>
<td>Restaurant</td>
<td>106</td>
<td>0.000</td>
<td>0.006</td>
<td>0.938</td>
</tr>
<tr>
<td>Store Bought</td>
<td>106</td>
<td>0.001</td>
<td>0.110</td>
<td>0.741</td>
</tr>
</tbody>
</table>

Table 57. Regression Analysis of Geographical Source of Fish Servings per Year v. Hair Mercury Concentration, Lake Superior Region

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Table 58. Regression Analysis of Geographical Source of Fish Servings per Year v. Hair Mercury Concentration, Michigan and Superior Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>79</td>
<td>0.009</td>
<td>0.710</td>
<td>0.402</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>79</td>
<td>0.005</td>
<td>0.417</td>
<td>0.520</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>79</td>
<td>0.015</td>
<td>1.151</td>
<td>0.287</td>
</tr>
<tr>
<td>Restaurant</td>
<td>79</td>
<td>0.016</td>
<td>1.253</td>
<td>0.266</td>
</tr>
<tr>
<td>Store Bought</td>
<td>79</td>
<td>0.010</td>
<td>0.758</td>
<td>0.387</td>
</tr>
</tbody>
</table>

Table 59. Regression Analysis of Geographical Source of Fish Servings per Year v. Hair Mercury Concentration, Inland Lakes Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>36</td>
<td>0.006</td>
<td>0.218</td>
<td>0.643</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>No Servings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Superior</td>
<td>36</td>
<td>0.004</td>
<td>0.138</td>
<td>0.712</td>
</tr>
<tr>
<td>Restaurant</td>
<td>36</td>
<td>0.023</td>
<td>0.800</td>
<td>0.377</td>
</tr>
<tr>
<td>Store Bought</td>
<td>36</td>
<td>0.166</td>
<td>6.753</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 60. Regression Analysis of Geographical Source of Fish Servings per Year v. Hair Mercury Concentration, Non-Ojibwa Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>36</td>
<td>0.076</td>
<td>2.786</td>
<td>0.104</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>36</td>
<td>0.190</td>
<td>7.960</td>
<td>0.008</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>36</td>
<td>0.000</td>
<td>0.016</td>
<td>0.899</td>
</tr>
<tr>
<td>Restaurant</td>
<td>36</td>
<td>0.097</td>
<td>3.645</td>
<td>0.065</td>
</tr>
<tr>
<td>Store Bought</td>
<td>36</td>
<td>0.020</td>
<td>0.679</td>
<td>0.416</td>
</tr>
</tbody>
</table>
Table 61. Regression Analysis of Geographical Source of Fish Servings per Year v. Hair Mercury Concentration, Other Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland Lakes</td>
<td>28</td>
<td>0.011</td>
<td>0.294</td>
<td>0.592</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>28</td>
<td>0.020</td>
<td>0.544</td>
<td>0.467</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>28</td>
<td>0.008</td>
<td>0.201</td>
<td>0.658</td>
</tr>
<tr>
<td>Restaurant</td>
<td>28</td>
<td>0.025</td>
<td>0.656</td>
<td>0.426</td>
</tr>
<tr>
<td>Store Bought</td>
<td>28</td>
<td>0.010</td>
<td>0.264</td>
<td>0.612</td>
</tr>
</tbody>
</table>

Age

Several analyses were performed to examine the relationship between age, years eating Great Lakes fish, and hair mercury concentrations. First, a regression analysis was performed to study the association between age and years consuming Great Lakes fish. The test indicated a weak association for all subjects ($R^2 = 0.249$, $F = 68.468$, $p < 0.001$).

Regression analyses showed minimal associations between age and years of eating Great Lakes fish within each of the regions (Table 62). A stronger correlation existed in the Michigan and Superior region than in Lake Superior, Inland Lakes, and Other regions.

Table 62. Regression Analysis of Age v. Years Eating Great Lakes Fish

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>86</td>
<td>0.197</td>
<td>20.301</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>61</td>
<td>0.462</td>
<td>50.643</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>34</td>
<td>0.111</td>
<td>3.986</td>
<td>0.054</td>
</tr>
<tr>
<td>Other</td>
<td>27</td>
<td>0.251</td>
<td>8.385</td>
<td>0.008</td>
</tr>
</tbody>
</table>
A Chi-Square test was performed to examine the distribution of individual ages. Age groupings were based on the U.S. Census age groupings. The results indicated that the number of subjects was not evenly distributed between the age groups ($X^2(9), \alpha = 0.05 = 225.731$). In order to check any significant difference in hair mercury concentration between the age groups, a Kruskal-Wallis test was performed. The results showed no significant difference in hair mercury concentration between the age groups ($X^2(8) = 7.525; p = 0.481$).

Next, regression analyses were performed to study the association between hair mercury concentration and the number of years eating Great Lakes fish. The test showed little association for all subjects ($R^2 = 0.03, F = 6.347, p = 0.013$). Weak associations were found within the five regions (Table 63). All $R^2$ values were less than 0.30.

Table 63. Regression Analysis of Years eating Great Lakes Fish v. Hair Mercury Concentration for Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>86</td>
<td>0.000</td>
<td>0.032</td>
<td>0.860</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>61</td>
<td>0.010</td>
<td>0.591</td>
<td>0.445</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>34</td>
<td>0.037</td>
<td>1.233</td>
<td>0.275</td>
</tr>
<tr>
<td>Other</td>
<td>27</td>
<td>0.229</td>
<td>7.417</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Focusing on the Ojibwa regions, a Kruskal-Wallis test was conducted to compare the median number of years eating Great Lakes fish in the Lake Superior, Michigan and Superior, and Inland Lakes regions. The test indicated a significant difference in the number of years of eating Great Lakes fish between the three regions ($X^2(2) = 26.590; p <$
0.001). The Michigan and Superior and Lake Superior groups had significantly higher median years eating Great Lakes fish than the Inland Lakes group (Table 64).

Table 64. Results from the Nemenyi Post Hoc Tests on the Median Number of Years Eating Great Lakes Fish in the Strictly Ojibwa Regions, Q Critical, \( p = 0.05, k = 3 = 2.394 \); significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan and Superior v. Inland Lakes</td>
<td>5.030</td>
<td>Michigan and Superior region had a significantly higher mean number of years of eating Great Lakes fish than Inland Lakes</td>
</tr>
<tr>
<td>Michigan and Superior v. Lake Superior</td>
<td>1.30</td>
<td>Michigan and Superior region had a significantly higher mean number of years of eating Great Lakes fish than Lake Superior</td>
</tr>
<tr>
<td>Lake Superior v. Inland Lakes</td>
<td>4.240</td>
<td>Lake Superior region had a significantly higher mean number of years of eating Great Lakes fish than Inland Lakes</td>
</tr>
</tbody>
</table>

Finally, subjects were divided into groups based on the number of years of eating Great Lakes fish. A Kruskal-Wallis test was then run to examine any significant difference in the hair mercury concentrations between years of eating Great Lakes fish groups (Group 1 = 0 – 9 years eating Great Lakes fish, Group 2 = 10 – 19, Group 3 = 20 – 29, Group 4 = 30 – 39, Group 5 = 40 – 49, Group 6 = 50 – 59, Group 7 = 60 – 69, and Group 8 = 70 – 79). The test showed a significant difference in the median hair mercury concentrations between years eating Great Lakes fish groupings \( (X^2)_{(7)} = 15.265; p = \)
Group 6, or 50 to 59 years of eating Great Lakes fish, had a significantly higher hair mercury concentration than the 10 to 19 years group ($q = 3.350$, $q_{\text{critical}}$, $p = 0.05$, $k = 3 = 3.124$), and the 30 to 39 years group ($q = 3.200$, $q_{\text{critical}}$, $p = 0.05$, $k = 3 = 3.124$).

Kruskal-Wallis tests were run to compare the hair mercury concentrations of each years of eating Great Lakes fish group within each of the five regions. The results were insignificant, except for the Other region (Table 65). In general, subjects who ate fish longer had higher median hair mercury concentrations than subjects with fewer years of eating Great Lakes fish (Table 66).

Table 65. Kruskal-Wallis Test Results for the Comparison of Mean Hair Mercury Concentrations for Years Eating Great Lakes Fish Groups Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>df</th>
<th>Test Statistic</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>6</td>
<td>8.675</td>
<td>0.193</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>7</td>
<td>13.573</td>
<td>0.059</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>5</td>
<td>6.956</td>
<td>0.224</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>13.650</td>
<td>0.034</td>
</tr>
</tbody>
</table>

**Gender**

Mann-Whitney tests were conducted to examine a significant difference in hair mercury concentration between males and females. The test showed no difference in the hair mercury concentration between all male and female subjects ($z = -0.181$, $p = 0.857$). Similarly, no significant difference existed between males and females within each
Table 66. Results of Nemenyi Post Hoc Tests Comparing Mean Hair Mercury Concentrations of Years Eating Great Lakes Fish Groups, Other Region, Q Critical, \( p = 0.05 \), \( k = 3 \) = 3.038; significant results shown

<table>
<thead>
<tr>
<th>Comparison</th>
<th>q value</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 - 69 years v. 0 - 9 years</td>
<td>6.930</td>
<td>60 - 69 years significantly higher hair mercury concentration than 0 - 9 years</td>
</tr>
<tr>
<td>60 - 69 years v. 10 - 19 years</td>
<td>8.290</td>
<td>60 - 69 years significantly higher hair mercury concentration than 10 - 19 years</td>
</tr>
<tr>
<td>60 - 69 years v. 20 - 29 years</td>
<td>5.130</td>
<td>60 - 69 years significantly higher hair mercury concentration than 20 - 29 years</td>
</tr>
<tr>
<td>60 - 69 years v. 30 - 39 years</td>
<td>3.970</td>
<td>60 - 69 years significantly higher hair mercury concentration than 30 - 39 years</td>
</tr>
<tr>
<td>50 - 59 years v. 0 - 9 years</td>
<td>7.810</td>
<td>50 - 59 years significantly higher hair mercury concentration than 0 - 9 years</td>
</tr>
<tr>
<td>50 - 59 v. 10 - 19 years</td>
<td>9.440</td>
<td>50 - 59 years significantly higher hair mercury concentration than 10 - 19 years</td>
</tr>
<tr>
<td>50 - 59 v. 20 - 29 years</td>
<td>5.220</td>
<td>50 - 59 years significantly higher hair mercury concentration than 20 - 29 years</td>
</tr>
<tr>
<td>50 - 59 v. 30 - 39 years</td>
<td>3.810</td>
<td>50 - 59 years significantly higher hair mercury concentration than 30 - 39 years</td>
</tr>
<tr>
<td>40 - 49 years v. 0 - 9 years</td>
<td>6.660</td>
<td>40 - 49 years significantly higher hair mercury concentration than 0 - 9 years</td>
</tr>
<tr>
<td>40 - 49 years v. 10 - 19 years</td>
<td>8.590</td>
<td>40 - 49 years significantly higher hair mercury concentration than 10 - 19 years</td>
</tr>
</tbody>
</table>

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### Table 67. Mann-Whitney Test Results for Comparison of Median Hair Mercury Concentrations Between Males and Females Within Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Z value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>119</td>
<td>-0.989</td>
<td>0.322</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>86</td>
<td>-1.251</td>
<td>0.211</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>39</td>
<td>-0.161</td>
<td>0.872</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>51</td>
<td>-2.201</td>
<td>0.028</td>
</tr>
<tr>
<td>Other</td>
<td>36</td>
<td>-1.283</td>
<td>0.199</td>
</tr>
</tbody>
</table>

region, except for the Non-Ojibwa region (Table 67). Non-Ojibwa males had a higher hair mercury concentration (0.66 ppm) than Non-Ojibwa females (0.33 ppm).

In order to determine any significant difference between the hair mercury concentrations between males and females in the three strictly Ojibwa regions, a Kruskal-Wallis test was performed. The results indicated a significant difference in hair mercury concentrations in females between the three regions ($X^2_{12} = 7.842; p = 0.02$). Females from the Inland Lakes region had a significantly higher hair mercury concentration than
females from the Lake Superior region ($q = 2.430$, $q_{\text{critical}} = 0.05$, $k = 3 = 2.394$). No significant difference was found in male hair mercury concentration between the three regions ($X^2_{(2)} = 2.628; p = 0.269$).

**Human Size**

An analysis of the effect of human size on hair mercury concentration was made. Regression tests between human size (weight and height) and hair mercury concentrations showed a weak association between weight of all subjects and hair mercury concentration ($R^2 = 0.001$, $F = 0.317$, $p = 0.574$), and a weak association between height of all subjects and hair mercury concentration ($R^2 = 0.002$, $F = 0.455$, $p = 0.501$). The regression tests for each of the five regions also indicated poor associations for both weight, with $R^2$ values less than 0.03, and height, with $R^2$ values less than 0.20 (Tables 68 and 69).

Table 68. Results of Regression Analyses of Human Weight v. Hair Mercury Concentrations for Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>101</td>
<td>0.000</td>
<td>0.003</td>
<td>0.956</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>75</td>
<td>0.001</td>
<td>0.056</td>
<td>0.813</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>37</td>
<td>0.012</td>
<td>0.423</td>
<td>0.520</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>38</td>
<td>0.028</td>
<td>1.033</td>
<td>0.316</td>
</tr>
<tr>
<td>Other</td>
<td>27</td>
<td>0.019</td>
<td>0.494</td>
<td>0.489</td>
</tr>
</tbody>
</table>
Table 69. Results of Regression Analyses of Human Height v. Hair Mercury Concentrations for Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>101</td>
<td>0.035</td>
<td>3.578</td>
<td>0.061</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>75</td>
<td>0.002</td>
<td>0.118</td>
<td>0.732</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>37</td>
<td>0.000</td>
<td>0.007</td>
<td>0.934</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>38</td>
<td>0.110</td>
<td>4.461</td>
<td>0.042</td>
</tr>
<tr>
<td>Other</td>
<td>27</td>
<td>0.051</td>
<td>1.338</td>
<td>0.258</td>
</tr>
</tbody>
</table>

In order to determine the presence of any significant difference in weight and height within the three strictly Ojibwa regions, Kruskal-Wallis tests were preformed. No significant difference in weight between the three regions was detected ($X^2(2) = 4.440; p = 0.109$). The test indicated a significant difference in height between the three regions ($X^2(2) = 6.706; p = 0.035$). The Lake Superior group was significantly taller than the Inland Lakes group ($q = 2.540$, $q_{critical, p = 0.05, k = 3} = 2.394$).

**Dental Amalgams**

A regression analysis was conducted to examine the association between the number of dental amalgams and hair mercury concentration. The test showed a poor correlation between the number of amalgams and mean hair mercury concentration ($R^2 = 0.004$, $F = 0.944$, $p = 0.332$). Also, regression analyses test showed weak associations within each of the five regions, with $R^2$ values less than 0.04 (Table 70).
Table 70. Results of Regression Analyses of Dental Amalgams v. Hair Mercury Concentration in the Five Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>Coefficient of Determination, $R^2$</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>76</td>
<td>0.032</td>
<td>2.425</td>
<td>0.124</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>61</td>
<td>0.015</td>
<td>0.885</td>
<td>0.351</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>31</td>
<td>0.002</td>
<td>0.050</td>
<td>0.825</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>36</td>
<td>0.030</td>
<td>1.051</td>
<td>0.313</td>
</tr>
<tr>
<td>Other</td>
<td>26</td>
<td>0.008</td>
<td>0.201</td>
<td>0.658</td>
</tr>
</tbody>
</table>

A Kruskal-Wallis test was run to assess any significant difference in the number of dental amalgams between the five regions. The test showed no significant difference in dental amalgams between the regions ($X^2_{(4)} = 6.215; p = 0.184$).

**Shampoo**

In order to test for a significant difference in hair mercury concentration between people using a medicated shampoo containing mercury, and those not using the shampoo, a Mann-Whitney test was performed. The test indicated no significant difference in hair mercury concentrations between people who use the shampoo and those who do not use the shampoo ($z = -1.103, p = 0.270$).

**Occupation**

A Kruskal-Wallis test was conducted to study the difference in hair mercury concentrations between people of different occupations. The test indicated no significant difference in hair mercury concentration between occupations for all subjects ($X^2_{(5)} = 6.394; p = 0.270$) and no significant difference within each of the five regions (Table 71).
Table 71. Results of Kruskal-Wallis Tests Comparing Hair Mercury Concentrations Between Different Occupations for Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>df</th>
<th>Test Statistic</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>10</td>
<td>2</td>
<td>2.577</td>
<td>0.276</td>
</tr>
<tr>
<td>Michigan and Superior</td>
<td>10</td>
<td>3</td>
<td>1.691</td>
<td>0.639</td>
</tr>
<tr>
<td>Inland Lakes</td>
<td>18</td>
<td>3</td>
<td>0.581</td>
<td>0.901</td>
</tr>
<tr>
<td>Non-Ojibwa</td>
<td>27</td>
<td>4</td>
<td>8.023</td>
<td>0.091</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
<td>3</td>
<td>2.109</td>
<td>0.550</td>
</tr>
</tbody>
</table>

Pregnancy

In order to determine if hair mercury concentration was significantly different in pregnant females compared to nonpregnant females, a Mann-Whitney test was performed. Only one individual reported being pregnant during the study. The test showed no significant difference in hair mercury concentration between the pregnant woman and the other respondents (z = -0.073, p = 0.941).
CHAPTER 6

CONCLUSIONS

Introduction

Research suggests that subsistence fishing populations may be susceptible to the effects of mercury toxicity. This project developed out of a desire to examine a specific group of subsistence fishers, the Ojibwa in the Great Lakes area, and the relationships between fish, fish consumption, and body burdens of mercury. Fish consumption habits held limited explanatory power for hair mercury concentrations. Problems with the questionnaire contributed to the limited findings. Nonetheless, this project did determine the hair mercury concentrations of this Ojibwa population. With a few exceptions, the Ojibwa population contained low hair mercury concentrations. This project also detected differences in fish consumption habits between different regions of Ojibwa groups and delineated important exposure assessment variables.

Hair Mercury Concentrations

The Ojibwa consume large amounts of fish, yet their hair mercury concentrations, on average, do not reflect the bioaccumulation of mercury. Based on this study, restrictions on the consumption of Great Lakes fish are not warranted. The health benefits derived from eating fish outweigh the possible adverse effects of high concentrations of mercury in the body – with a few exceptions, the Ojibwa simply do not have high concentrations
of mercury in their bodies. Future studies may discover a relationship between fish consumption and body burden of mercury. Nevertheless, the body burdens of mercury among the Ojibwa, in general, do not raise fears of chronic mercury poisoning.

The range of hair mercury concentrations found in this study mirrored findings in other studies (Table 11). The mean hair mercury concentration in this study of 1.82 ppm was actually lower than many human studies examining fish consumption as a source of mercury, Egeland et al., 1999; Gerstenberger et al., 1997; Kosatsky et al., 2000). Since the U.S. Public Health Service proposed minimal risk level for hair mercury is 1.4 ppm, this population may have concerns about the risks of mercury exposure. Research indicates that symptoms of mercury poisoning may be seen in adults with mercury concentration of 50 to 120 ppm in hair (Gaggi et al., 1996; Kyle & Ghani, 1982; WHO, 1990), and, although a few subjects from this study fall within this range, the average hair mercury concentration does not reach the concentration that may lead to adverse health effects. Overall, the mean hair mercury concentrations from this study did not deviate significantly from other findings, and did not indicate a need for alarm over mercury concentrations in hair.

Fish Consumption and Hair Mercury Concentrations

Although this project described important exposure parameters, it did not identify a significant relationship between fish consumption variables and hair mercury concentration. The following variables had very poor associations to hair mercury concentrations in this study:

• Fish Species Consumed
• Amount of Fish Consumption
• Size of Fish Consumed
• Geographic Source of Fish Consumed

While previous studies indicated a difference in mercury concentrations between fish eaters and non-fish eaters (Tables 13 – 15), no difference in mean hair mercury concentrations existed between fish eaters and non-fish eaters in this study. This suggests that fish consumption habits in this study had minimal, or no, influence on hair mercury concentrations.

Fish consumption was analyzed in several different ways. An examination of fish species consumed, the amount and servings of fish, the size of fish, and the geographical source of fish revealed differences in species and sources between Ojibwa groups, but these differences did not affect hair mercury concentrations. Also, fish consumption variables were analyzed using fish meals per year, fish servings per year, and grams of fish per year. All three metrics produced the same results for analysis of fish consumption variables, indicating that extremely poor associations exist between the variables and hair mercury. This differs from other studies that found an increase in body burdens of mercury with increased consumption of fish (Adimado & Baah, 2002; Airey, 1983; Kosatsky et al., 2000).

Analyses of these data indicate that no strong association between fish species consumed and hair mercury concentrations exist. This finding differs from other studies (Table 13); however, a few cases did stand out from the sea of insignificance. Whitefish accounted for 36.9% of the variability in mercury concentrations in the hair of Inland Lakes individuals. For Non-Ojibwa individuals, walleye accounted for 54.5% of the
variability in hair mercury concentrations, while herring accounted for 49.4% and salmon 44.8% of the variability. In Other individuals, perch consumption influenced 36.0% of the variability in mercury concentrations.

The size of fish consumed also did not influence hair mercury concentrations. The size of the fish was assumed to represent its age, larger fish being older fish. Several studies note a correlation between age, or size, and mercury concentration (Amrhein & Geis, 2001; Gutenmann et al., 1992; Lange et al., 1994); older fish have more mercury than younger fish (Bowles et al., 2001; Lange et al., 1994; WHO, 1989). Consequently, consumption of more, larger fish was expected to lead to a significantly higher hair mercury concentration; however, this study did not support this finding.

This project did not detect an influence of geography on hair mercury concentrations. The expectation that different bodies of water would affect bioaccumulation, and consequently affect hair mercury concentrations, was not met. Although Inland Lakes individuals possessed a higher hair mercury concentration than Lake Superior individuals, the different hydrological characteristics of the fisheries did not contribute to the hair mercury levels in this study.

Human Variables and Hair Mercury Concentrations

According to other studies, several human variables affect hair mercury concentrations (Table 13 - 15). Analyses indicate that the human variables had little affect on hair mercury concentrations. The number of years eating Great Lakes fish did not affect mean hair mercury concentrations, nor did human size, as represented by
height and weight (Tables 63 – 69). No difference in mean hair mercury concentrations existed between males and females.

Hair mercury concentrations may be confounded by numerous factors. This study controlled for dental amalgams, medicated shampoos, pregnancy, or occupation (Tables 70 and 71). The number of dental amalgams did not appear to be a confounding factor in this study. Too few individuals used the medicated shampoo (n = 5), or were pregnant (n = 1), to evaluate the influence of the shampoo or pregnancy on hair mercury concentrations. Reported occupation did not affect hair mercury concentrations.

Questionnaire Concerns

One explanation of the results of this study involves the questionnaire itself. Elements of the questionnaire prevented a more detailed analysis of the fish consumption variables and related hair mercury concentrations. A major source of weakness surrounded the method of recording the amount of fish consumed. Two different questionnaires were used during the project. The first questionnaire asked subjects to rate the amount of fish consumption (once per week, once a week when in season, less than once per week but at least once per month, less than once per week but at least once per month, but only in season, or rarely), rather than asking subjects to give a total amount of fish meals consumed per region. The ratings were then converted to the number of fish meals per year. The second questionnaire asked respondents to give the total number of meals of fish consumed, and provide the number of servings eaten during a typical meal. The numbers of meals were then converted to total servings and then total grams of fish
consumed. This confusion and manipulation of information created error in the analysis, which may have resulted in poor statistical associations.

Even more confusion was created in the questionnaire as subjects were asked to provide the number of meals of a species consumed per a geographical source. This required subjects to recall and quantify multiple variables at once. Research shows that a large source of error in studies evaluating surveys involves the uncertainty of subjects to accurately recall the foods consumed on the recall day (U.S. EPA, 1997; Youland & Engle, 1976). A study by Karvetti and Knuts (1985) notes that fish consumption is more precisely remembered than most other food groups within a 24-hour period (Karvetti & Knuts, 1985).

Subjects were asked to record the number of fish meals of twelve different fish species over a period of one year. Recall bias was likely a major factor in this study. The questionnaire did not allow for daily variations in consumption, nor did it effectively address seasonal variations. As the study relied on the amount of fish consumed from different species, this bias may have introduced a large amount of error into the analytical models. Also, the questionnaire was lengthy and involved, which may have discouraged respondents from answering all questions.

Another concern arises from the lack of focus on the occupations of subjects. The questionnaire contained a simplified section on occupation, asking respondents to choose from a list of nine options. The options represented broad categories representing all possible occupations. Perhaps a closer examination of occupations, particularly those in industrial or medical areas, will show a relationship with hair mercury concentration.
Other Possible Factors Contributing to Hair Mercury Concentrations

The effects of diet, selenium, and alcohol consumption may be influencing hair mercury concentrations (as reported in other studies, e.g. Drasch et al., 2001; National Research Council, 2000). Other toxicants and food components, such as polychlorinated biphenyls (PCBs) or dichlorodiphenyltrichloroethane (DDT), may affect mercury metabolism, or have an additive effect on mercury toxicity. The co-consumption of alcohol and mercury can increase the toxicity of mercury especially in the kidneys (National Research Council, 2000). Animal studies show a protective effect of selenium against mercury toxicity (National Research Council, 2000). Since some fish species contain high levels of selenium, fish consumption may actually decrease hair mercury concentrations. Wild rice, another stable component of the Ojibwa diet, also contains selenium and may work antagonistically with mercury. The diet combining fish and wild rice may limit mercury deposition in the human body.

Health conditions may influence hair mercury concentrations. Diabetes, heart and liver diseases, and general health considerations affect metabolism and vulnerability to toxicity (Gerstenberger et al., 1997). Also, the presence of other contaminants, such as cadmium or PCBs, may influence mercury body burdens (National Research Council, 2000). Individual genetic variability may affect sensitivity to methylmercury and mercury deposition.

Land use variables could explain hair mercury concentrations. Proximity to mining, wastewater treatment plants, municipal incinerators, tanning facilities, or industrial facilities may increase mercury concentrations in humans, and surpass the influence of the bioaccumulation in fish and fish consumption. Also, these land uses may alter the
hydrological characteristics of the Great Lakes and inland lakes, promoting an increase in methylation and bioaccumulation rates.

Finally, since many of the hair samples were held for five to seven years, the hold time of may confound the results. A few studies have been done on ancient hair samples (400 to 800 years old) buried in the soil (Egeland et al., 1999). Analytical results showed that methylmercury constituted a small percentage of total mercury in hair, and could arise from the degradation of methylmercury (Egeland et al., 1999). Degradation, metabolism, and loss of mercury to the atmosphere may be a factor in the poor associations between fish consumption and hair mercury concentrations.

Exposure Assessment Parameters

This project confirmed several hypotheses about the Ojibwa and the potential routes of mercury exposure affecting the Ojibwa. First, Inland Lakes individuals had higher hair mercury concentrations than Lake Superior individuals. The difference may arise from the fact that Inland Lakes people ate walleye from inland lakes, whereas Lake Superior people ate a variety of species, such as lake and rainbow trout, whitefish, Smelt, and some walleye from Lake Superior. Previous research found that fish from inland lakes had a higher mercury concentration than fish from the Great Lakes, partly due to the hydrological properties of inland bodies of waters (Gerstenberger et al., 1993). Differences in hydrological qualities between Lake Superior and inland lakes may influence mercury bioaccumulation, and consequently affect hair mercury concentrations in humans. Factors such as microbiology, pH, temperature, organic material, redox potential, sulfide concentrations, and salinity affect the movement, speciation, and
methylation in a body of water (Lathrop et al., 1989). Differences in hydrology between Lake Superior, a much larger body of water, and smaller inland lakes lead to differences in the factors affecting mercury speciation and methylation. Consequently, one would expect mercury concentrations in fish to differ between the two aquatic systems.

Also, elevated concentrations of mercury were found in walleye from ceded territories (Dellinger et al., 1995; Gerstenberger et al., 1993). Since walleye represent a higher trophic level organism, they may be eating fish with greater bioaccumulation of mercury, which would explain the higher hair mercury concentrations in Inland Lakes subjects. The differences in the fish species they are consuming and the geographic source of their fish may contribute to the differences in hair mercury concentrations.

Second, the Ojibwa consume lake trout, walleye, whitefish, and perch. Separated by the five regions, fish consumption corresponded with the source of fish. For instance, Inland Lakes individuals predominantly ate walleye, while Ojibwa around Lake Michigan and Lake Superior ate more whitefish and perch, and Ojibwa from Lake Superior ate more lake and rainbow trout, walleye, whitefish, and smelt (Tables 23 – 26). This pattern of fish consumption was expected and was seen in previous studies (ATSDR, 1999).

Third, this study determined the geographic source of fish for Ojibwa members. Respondents procured fish from Inland Lakes, Lake Superior, and Restaurants significantly more than from Lake Michigan or the store. The pattern of fish source for each region met expectations. Lake Superior subjects acquired fish from Lake Superior, and Inland Lakes subjects get their fish from inland lakes (see Tables 41 – 44).
The mercury exposure information in this thesis provides a useful resource for future studies on Ojibwa populations. This study catalogued the fish species and geographic source of fish. Also, it provides the average size and amount of fish consumed by region, as well as data on human variables such as age, height and weight, and dental amalgams. Present and future exposure assessments need to consider these variables to study the risks associated with fish consumption from the Great Lakes region.

Summary

The impetus for this project was human health concerns involving consumption of fish containing mercury. Hair analysis determined the concentration of mercury in hair. The average hair mercury concentrations are not higher than the U.S. average of 10 ppm. Questionnaire analysis ascertained the fish consumption variables that most influenced hair mercury concentrations. The results found no consumption variables significantly affected mercury concentrations. This study suggests that the risk of mercury exposure through fish consumption is minimal.

This study provides insights into the relationship between fish consumption and mercury concentrations in hair. It also provides information on the use of a questionnaire as a method of acquiring data for hair mercury studies. Individuals from Inland Lakes areas have a higher hair mercury concentration than Lake Superior individuals. While the study supports the differences in choice of fish species consumption and geographical sources of fish between different Ojibwa regions, the study does not support the hypothesis that such differences lead to differences in hair mercury concentrations. Despite the lack of evidence supporting a relationship between fish consumption and hair...
mercury concentration, this project represents an important initial step in studying humans, quantifying their consumption of fish, and understanding the connection between fish consumption and exposure to mercury.

A major component affecting this analysis of fish consumption and mercury is the inadequacy of the questionnaire to quantify fish consumption variables. Future research can improve upon the techniques used here to better measure human consumption of fish, capturing differences in species consumed, geographic source, and temporal variations. A plethora of environmental, physiological, or toxicological influences may be involved. Determining the fate and transport of mercury in the environment, the bioaccumulation of mercury in biota, and the amount of intake of mercury through fish consumption enables a better understanding of the risks associated with mercury exposure and toxicity through fish consumption.

Recommendations for Future Research

Continued research would ensure greater enlightenment of the interrelationships between the environment, mercury, and humans. Some changes to the questionnaire format and the question content and details may increase the reliability for future research projects. First, the method of recording and calculating the amount of fish consumed must be determined before the study begins. Second, the time span of recall of fish consumption should not be so great as to reduce accuracy. For instance, subjects could be asked several times during a year, either weekly or monthly, to recall the number of fish meals consumed.
One technique that could be employed is a prospective study. Such a study would more accurately measure fish consumption variables. For every meal, subjects could record the exact amount of fish consumed, as well as the species and source of fish. Future studies may include any seasonal variations in fish consumption and hair mercury concentration by taking hair samples each month for at least one year. This method would capture seasonal variations, minimize recall bias, and increase accuracy and precision of fish intake. Figure 9 displays a sample log sheet that could be used in such a study.

In addition to a prospective study, future research could focus on the individuals with high hair mercury concentrations. The characteristics of each person, their fish consumption habits, as well as general health conditions, occupation, family medical history, and lifestyle choices, could be analyzed with hair sampling. Information as to the set of variables most influencing the individual’s hair mercury concentration will provide information for other individuals. Such an analysis would require the permission of each individual and the Ojibwa tribe.

Finally, a potentially more realistic model of fish consumption and human intake of mercury would include the complex interactions of numerous factors. Additional statistical analyses of this data could employ a multiple regression model. For instance, a model may include fish species, geographical source of fish, size, and amount of fish consumed. Since amount and size of fish are continuous variables, and fish species and geographic source are discrete, the variables would have to be transformed. The total servings or grams consumed per fish species and per geographic source can be calculated.
Fish Consumption and Hair Mercury Concentration Study
Log Book Meal Sheet

Please fill out one sheet per family member, per meal consumed.

Date: ___________________ Time: ________________

1. Did you catch this fish? (Please circle one)
   - Yes
   - No

2. Did someone in your family catch this fish? (Please circle one)
   - Yes
   - No

3. Did someone outside of your family give you this fish to eat? (Please circle one)
   - Yes
   - No

4. Type of fish? (Please circle one)
   - Bass
   - Herring
   - Northern Pike
   - Panfish
   - Perch
   - Lake Trout
   - Rainbow Trout
   - Salmon
   - Smelt
   - Walleye
   - Whitefish
   - Other ________________________

5. Where did you get this fish? Please be as specific as possible:
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________

6. Serving Size: ___________________________ grams

7. What is the length of the whole fish?
   - 0 – 4 inches
   - 5 – 8 inches
   - 9 – 12 inches
   - 13 – 16 inches
   - 17 – 20 inches
   - 21 – 24 inches
   - 25 – 28 inches
   - 29 – 32 inches
   - Larger? ________________________

(Please Turn Over)
Figure 9 Sample Log Sheet for a Prospective Study on the Relationship between Fish Consumption and Hair Mercury Concentration

Another method of handling the variables involves placing amount of fish consumed and fish size into categories, and developing a suitable categorical model (e.g., using logistic regression; Zar, 1999).
APPENDIX I

OJIBWA HEALTH STUDY QUESTIONNAIRE
Personal Characteristics

1. Birth Date .............................................. ____/____/____

2. Sex ...................................................... Male ____ Female ____

3. Are You Pregnant? ................................. Yes ____ No _____

4. How Many Years of Education Have you Completed? ........................................
   (For example, 8=8th grade; 12=high school, etc.)

5. What is Your Height? ............................... ____ Feet _____ Inches

6. What is Your Weight? ............................... _____ Pounds

7. How Long Have You Lived at Your Current Address? ..................................... ________ years

8. (a) What is the nearest town or city from your home? ........................................
   (b) How far is that town or city from your house? ........................................... ________ Miles

Please refer to the model below to answer the questions on the pages that follow.

FISH PORTION MODEL
1 Piece or Serving

(This size fillet comes from an approximately 14" walleye)
Please estimate the number of fish meals you have eaten in the last 12 months for each of the sources and species listed (for example, if you eat fish once every day, you eat 365 meals, so you would enter 365; if you eat fish once per week, it is 52 meals, etc.)

**PLEASE USE NUMBERS.**

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>Taken from Lake Superior</th>
<th>Taken from Lake Michigan</th>
<th>Taken from Wisconsin Inland Lakes &amp; Streams</th>
<th>Bought From a Store</th>
<th>Bought At a Restaurant</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herring</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Northern Pike</td>
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<td></td>
<td></td>
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<tr>
<td>Panfish</td>
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<tr>
<td>Perch</td>
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<tr>
<td>Lake Trout</td>
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<td></td>
</tr>
<tr>
<td>Rainbow Tr.</td>
<td></td>
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<td></td>
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<tr>
<td>Salmon</td>
<td></td>
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<td></td>
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<tr>
<td>Smelt</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Walleye</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Whitefish</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Other</td>
<td></td>
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<td></td>
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<tr>
<td>Total</td>
<td></td>
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</tr>
</tbody>
</table>

10. Using the Models Available, Please Indicate How Many Servings of Fish You Would Usually Consume at One Meal? (Note, consider each piece of fish to be one serving.)

_______ Servings At One Meal

**IF YOU EAT LOCALLY CAUGHT FISH (either fresh or frozen):**

11. In What Months Do You Eat The Most Fish? (please circle all that apply)

   JAN   FEB   MAR   APR   MAY   JUN
   JUL   AUG   SEP   OCT   NOV   DEC

12. (a). From head to tail, what is the length of the fish you usually eat? _______ (in inches)

   (b). From head to tail, what is the longest fish you ate this past year? _______ (in inches)
13. Please rank how often you eat the following parts of the fish, using the following scale:

1 - Most Commonly Eaten Part
2 - Sometime Eat
3 - Seldom Eat
4 - Never Eat

a. Fillet (skin on) ________
b. Fillet (skin off) ________
c. Steak cut ________
d. Whole Fish Deheaded (gutted) ________
e. Liver ________
f. Head ________
g. Eggs ________
h. Other ________

14. Please rank the methods you use to prepare fish, using the following scale:

1 - Most Commonly Used
2 - Sometimes Used
3 - Seldom Used
4 - Never Used

a. Pan Fry ________
b. Deep Fry ________
c. Poach ________
d. Bake ________
e. Soup ________
f. Boil (not soup) ________
g. Broil ________
h. Smoke ________
i. Roast/BBQ (open fire) ________
j. Can ________
k. Dry ________
l. Powder ________
m. Raw ________
15. What Do You Do With the Fat Drippings When You Fry Fish? *(please check all that apply)*
   - Use to fry other foods
   - Use for baking
   - Use for making gravy
   - Discard drippings/don’t use
   - Other ____________________________

16. Do You Ever Trim Fat From Your Fish Prior To Cooking/Eating? *(please check one)*
   - Always
   - Sometimes
   - Seldom
   - Never

17. Do You Eat The Skin Of Any Of The Fish You Eat? *(please check one)*
   - Always
   - Sometimes
   - Seldom
   - Never

18. (a). Do You Ever Freeze Your Catch and Eat it Later? YES _____ NO _____
   (b). If Yes, What Is the Longest Time You Would Freeze it Before Eating it?

19. How Many Years Have You Been Eating Great Lakes Fish? _______________________

20. Are you aware of a fish consumption health advisory published by your state? *(please check the ONE best answer)*
   - I am aware of an advisory in my state *(please go to #22)*
   - I read my state’s advisory *(please go to #21)*
   - I am not aware of an advisory in my state *(please go to #22)*
21. If you have read the advisory, please check the advice you follow (check any or all that apply).

- which lakes to fish
- which species to fish for
- whether to keep or to throw back a caught fish
- how to clean and cook your catch
- how often you should eat fish
- I do not follow the advice

22. What other wild game or fowl have you eaten in the last year? For each species of wild game or fowl you've eaten, please indicate how many times you've eaten them in the last 12 months.

<table>
<thead>
<tr>
<th></th>
<th>Number of Times in Last 12 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dear</td>
<td>Y      N</td>
</tr>
<tr>
<td>Bear</td>
<td>Y      N</td>
</tr>
<tr>
<td>Duck</td>
<td>Y      N</td>
</tr>
<tr>
<td>Beaver</td>
<td>Y      N</td>
</tr>
<tr>
<td>Pheasant/Partridge/Grouse</td>
<td>Y      N</td>
</tr>
<tr>
<td>Moose</td>
<td>Y      N</td>
</tr>
<tr>
<td>Turtle</td>
<td>Y      N</td>
</tr>
<tr>
<td>Other (specify)</td>
<td>Y      N</td>
</tr>
</tbody>
</table>

23. How many servings of wild rice do you eat in an average week? ________________

24. How often do you eat each of the following foods? (place one check mark per row).

<table>
<thead>
<tr>
<th>Food</th>
<th>3x/Day or More</th>
<th>2x/Day</th>
<th>1x/Day</th>
<th>Less Than Once A Day But More Than Once Per Week</th>
<th>Less than Once Per Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat</td>
<td></td>
<td></td>
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<tr>
<td>Poultry</td>
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<tr>
<td>Eggs</td>
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<td>Milk</td>
<td></td>
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<tr>
<td>Fruits &amp; Vegetables</td>
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<tr>
<td>Bread &amp; Cereal</td>
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</tbody>
</table>
Medical

25. Have you ever been told by a doctor that you had any of the following *(check all that apply)*

- High Blood Pressure or Hypertension
- Kidney Disease
- Heart Disease
- Liver Disease
- Diabetes
- Asthma
- Migraine Headaches
- Stomach Ulcer
- Bowel Disease
- Infertility
- Hay Fever or Other Allergies
- Miscarriage
- Goiter or Thyroid Problems
- Arthritis or Rheumatism
- Skin Allergies or Other Skin Diseases
- Emphysema, Chronic Bronchitis, or Persistent Cough
- Epilepsy or Seizures
- Neurologic Disorders (Other Than Epilepsy)
- Cancer [What Type? __________________________]
- Persistent Ear Infections
- Birth Defects of Any Type [What Type? __________________________]
- None of the Above

26. Have you experienced any of the following health conditions *(check all that apply)*

- Stiff or Painful Muscles or Joints
- Numbness or Tingling in Arms or Legs
- Shaking or Unsteadiness, Especially of the Hands and Arms
- Difficulty with Coordination
- General and Persistent Fatigue
- Dizziness, Lightheaded, Fainting
- Loss of Memory (For Names or Numbers)
- Persistent Headaches (More Than Once a Week)
- Blurred Vision
- Pain or Itching In or Around the Eyes
- Discharge From the Eyes, or Swelling of the Eyelids
- Burning or Itching Skin
- Persistent Skin Rashes or Eruptions
- Frequent Head Colds (For Two or More Months in a Row)
- Wheezing or Gasping for Breath
- Coughing Spells
- Coughing Up A Lot of Phlegm
- Coughing Up Blood
- Chest Colds (More Than Once a Month)
- None of the above
**Women of Child-Bearing Age and Greater Please Complete This Page:**

27. For each of your children, please record the following information:

<table>
<thead>
<tr>
<th>SEX (M/F)</th>
<th>DATE OF BIRTH (mo/day/yr)</th>
<th>MONTHS CARRIED (1-10 months)</th>
<th>BIRTH WEIGHT</th>
<th>LENGTH AT BIRTH</th>
<th>ANY LABOR COMPL.</th>
<th>ANY BIRTH DEFECTS</th>
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<tbody>
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</table>

28. If you have had a stillbirth or miscarriage, please complete as much of the following as you can:

<table>
<thead>
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<th>DUE DATE (mo/yr)</th>
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29. What was the date of the first day of your last period? __/__/
Exposures

30. What is your occupation?

_____ Manual Labor
_____ Clerical/Secretarial
_____ Administration
_____ Teaching
_____ Fishing
_____ Science
_____ Student
_____ Home Maker
_____ Other

31. Have you been exposed to any of the following?

_____ Dust from wood, grain, hay, or straw
_____ Dust from stone cuttings
_____ Asbestos or glass fiber dust
_____ Paint fumes
_____ Pesticides

32. Are you using a birth control method? 
   YES   NO

   a. If it is a pill or implant, what is its name?

33. Do you use medicated shampoos? 
   YES   NO

34. Smoking History:
   a. Do you currently use tobacco? 
      YES   NO
   b. Have You Ever Used Tobacco? 
      YES   NO
   c. If yes to a. or b., do/did you use tobacco for spiritual purposes ONLY? 
      YES   NO
   d. If yes to a. or b., in an average day, how much tobacco do/did you use?
      _____ Pack(s) of Cigarettes
      _____ Pipe Bowls
      _____ Cigars
      _____ Snuff
   e. What age did you start? 
   f. At what age did you stop? 

35. In an average week, how much of the following do you drink?

_____ Wine (glasses)
_____ Beer (cans)
_____ Liquor (shots)
_____ None
36. What Is The Source of Your Drinking Water?

________ Private Well

________ Piped (community/city water lines); From Where? ______________

________ Bottled

________ Other (Specify) ______________

________ Don’t know

37. Do You Have A Personal Water Filter Installed On Your Tap?

YES ____ NO ____

38. Does Your Drinking Water Undergo Chemical (e.g. chlorine, fluoride) treatment?

YES ____ NO ____

39. Which of the following do you or your family use for recreation? (check any or all that apply)

________ local inland lakes

________ local rivers and streams

________ Lake Superior

________ Lake Michigan

________ None (go to #40)

40. What activities do you do?

________ swimming

________ recreational fishing

________ kayaking/canoeing/boating

________ other (please specify) ______________

41. What Do You Use To Heat Your Home?

________ Oil

________ Gas

________ Electric

________ Wood Stove

________ Solar

________ Other (Specify) ______________

42. How Close Is The Nearest Dump/Landfill Site To Your Community? (Check one)

________ Less Than 2 miles

________ 2 - 5 miles

________ 5 - 10 miles

________ more than 10 miles

________ don’t know
APPENDIX II

RESULTS OF HAIR MERCURY ANALYSIS

Sample codes were removed to preserve anonymity.

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Member of Mortar Board National Honor Society

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Following Consumption of Fish from the Great Lakes Region

Thesis Examination Committee:
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Committee Member, Dr. Chad Cross, Ph.D.
Committee Member, Dr. David Hassenzahl, Ph.D.
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