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POLYCHLORINATED BIPHENYL COMPOUND AND METAL CONTAMINATION
AND REMEDIATION IN TORCH LAKE, HOUGHTON COUNTY, MI

By

Ankita Juhi Mandelia

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

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This thesis has been approved in partial fulfillment of the requirements for the Degree of
MASTER OF SCIENCE in Environmental Engineering

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PREFACE

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ABSTRACT

Torch Lake was subject to approximately 100 years of industrial pollution due to the dumping of waste associated with copper mining in the Keweenaw Peninsula, which lasted from approximately the 1860s through the 1960s. It is well-known that this waste included copper-containing mine tailings. What was less understood are the impacts of polychlorinated biphenyls (PCBs) and heavy metals besides copper on the lake system.

The objectives of this thesis are to summarize the status of contamination and remediation activities in Torch Lake and to estimate the magnitude of potential sources of PCBs to Torch Lake. First, a brief overview of the history and problems at Torch Lake is provided. Next, the activities that generated the metals contamination and the impact of the dumping of mine tailings into the lake are described. Then, the history of remediation activities at Torch Lake is summarized. These two historical summaries provide context for the analysis of heavy metals and PCBs in Torch Lake. Following that is an analysis of the spatial and temporal distribution of heavy metal observations and occurrence of criteria concentration exceedances. Finally, an analysis of the contamination of Torch Lake by polychlorinated biphenyl compounds (PCBs) is performed, in which evidence for possible local and ongoing sources of PCBs to Torch Lake is presented.

Analysis of metals in Torch Lake revealed two major findings: 1) that the western shoreline is not safe for development, and 2) that a more effective remediation method for the shoreline soils and lake sediment should be considered. The western shoreline is not safe for residential development because arsenic, and lead are present in the soil at concentrations that are considered harmful to humans. Many of the concentrations of the metals in sediment are above the Threshold Effect Concentrations, which implies that the vegetated soil caps along the shoreline are failing to achieve one of the goals of their

creation. . The possible failure of vegetated soil caps and natural sedimentation suggest that a more effective remediation method is necessary.

Evidence points to the existence of a local and possibly ongoing source of PCBs in Torch Lake. This is inferred from several facts. Concentrations of PCBs in water and fish from Torch Lake are higher than concentrations found in water and fish from other area lakes. The location of concentrations of PCBs above detection limits in sediment, soil and groundwater, compared to the locations of historical industrial buildings, indicate that a source of PCBs to Torch Lake besides atmospheric (re)deposition does exist. A possible ongoing source of PCBs to Torch Lake was inferred from comparison of mass balance modeled concentrations to SPMD-estimated concentrations of dissolved PCBs. The mass-balance-modeled concentrations of PCBs in Torch Lake were lower than the SPMD-estimated concentrations, which implies that an input of PCBs to the lake exists which has not yet been identified. In addition, over time, the concentrations of PCBs in fish caught in Torch Lake remain higher than fish caught in Huron Bay (a waterbody assumed to be subject only to PCB contamination from atmospheric (re)deposition).

This thesis demonstrates the advantage gained from examining the transport and transformations of chemicals in an environmental system when determining remedial action on that system. It is demonstrated that it is important to understand how a chemical can be transported before choosing a method of remediation for that chemical. It is shown that one cannot simply infer that because concentrations of a chemical in one medium are low, that it cannot cause high concentrations of that same chemical in another medium. This thesis also demonstrates how examining the historical activities of a site can be used to help predict the type, location and extent of contamination, especially when combined with examining the behavior of the chemicals involved. This thesis is a case study of how remediation policy should be re-examined to become more effective.

1 INTRODUCTION

1.1 Description of Torch Lake

Torch Lake is located in Houghton County, within the Keweenaw Peninsula, within the Upper Peninsula, of Michigan (Figure 1.1 and Figure 1.2). The Keweenaw Peninsula was rich in native copper (copper not combined with other elements); and because of this, the region was home to a major copper mining industry which lasted from the 1840s to the mid-1990s. (Lankton, 2010) Torch Lake currently has an area of 9,820 m² and a volume of 0.15 km³; but as will be discussed later, these were not the original dimensions of the lake. The western shore of Torch Lake was the site of activities involved with separating the copper from ore including milling, smelting, reclamation, leaching and flotation - all discussed in Chapter 2. These activities resulted in the disposal of mine tailings and other industrial waste into Torch Lake, also discussed in Chapter 2.

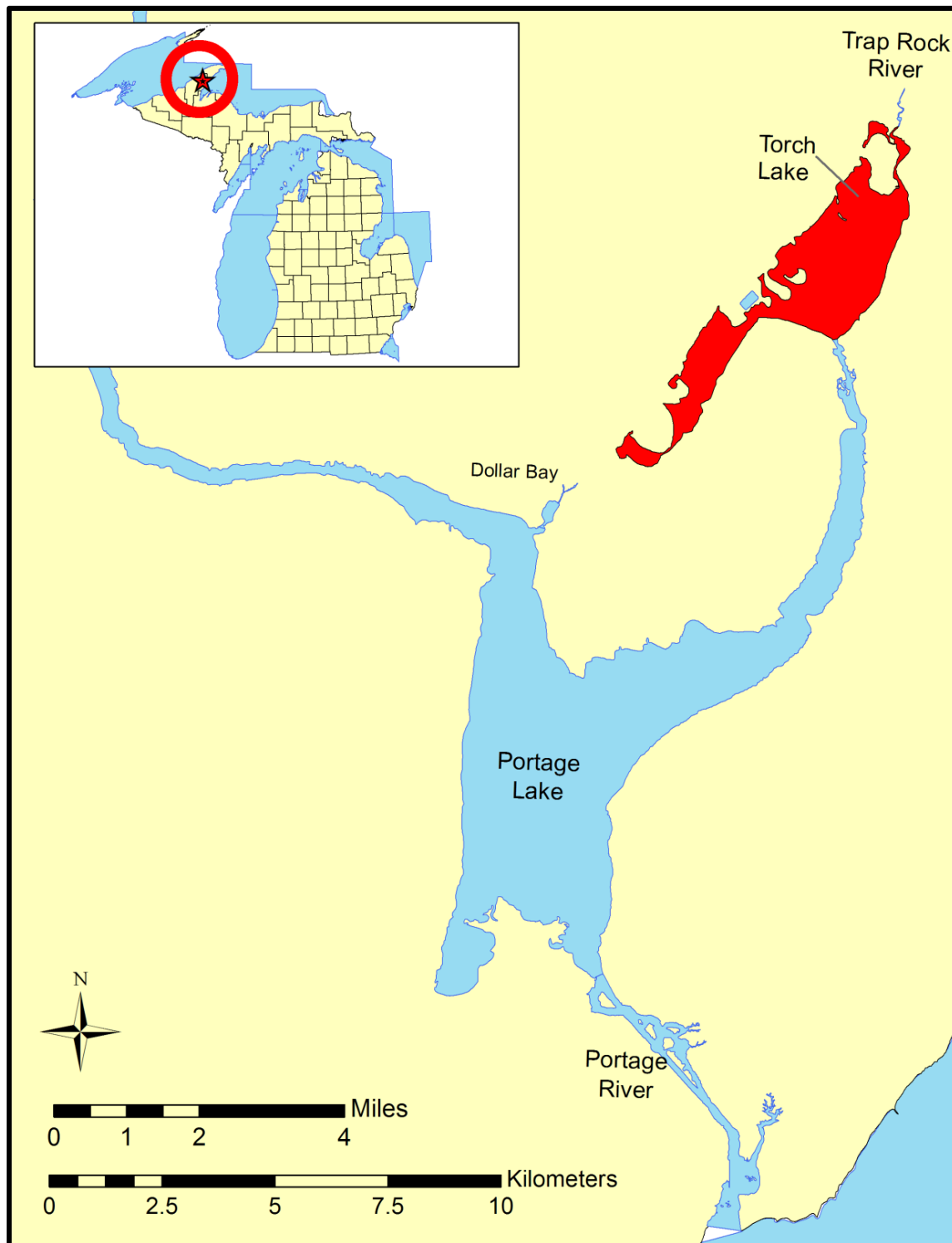


Figure 1.1: Location of Torch Lake

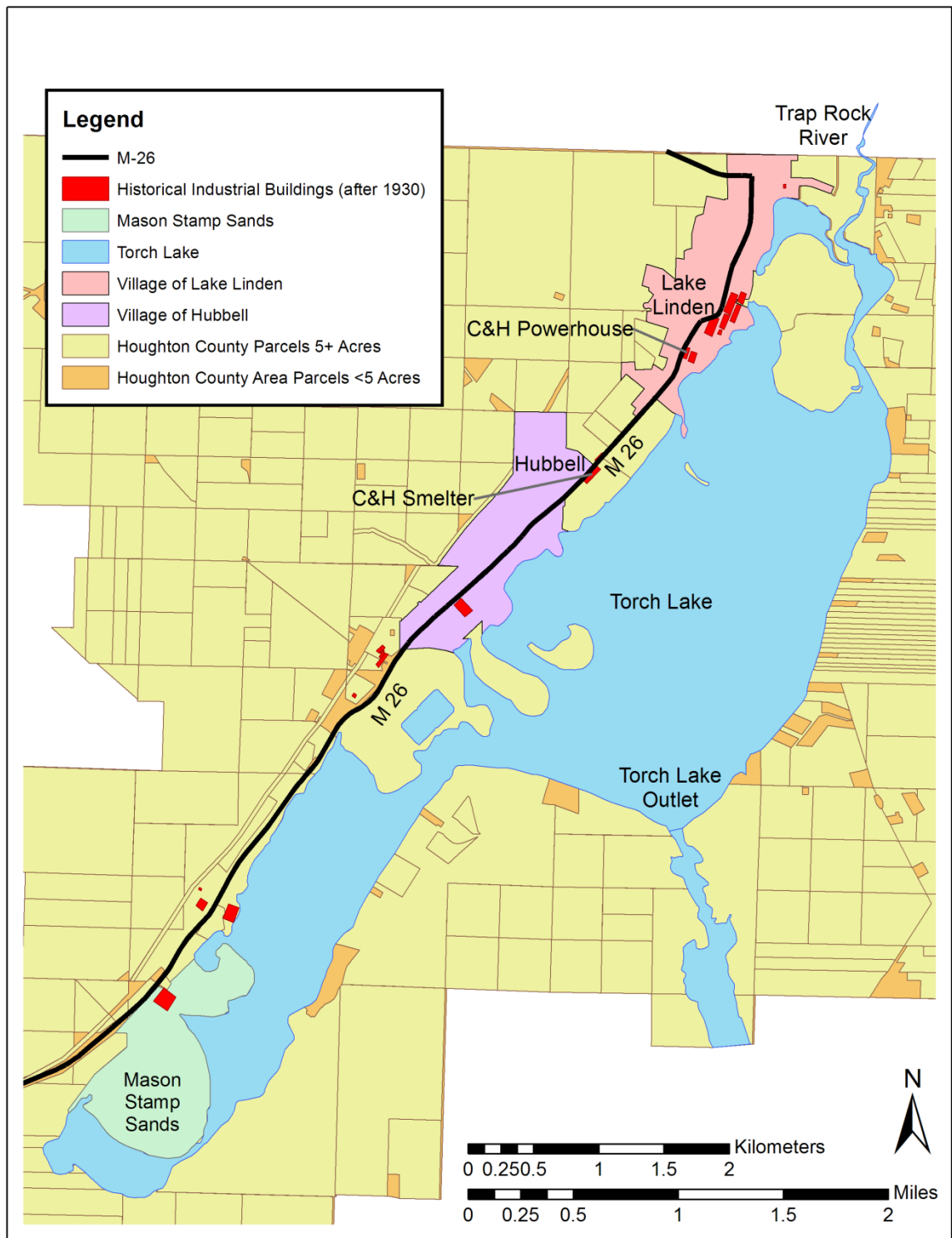


Figure 1.2: Torch Lake Details

The contamination of Torch Lake has been extreme; its extents are discussed throughout this thesis. Several studies about the contamination conducted on the lake during the 1970s and the early 1980s led to its listing on the National Priorities List (as a Superfund site) and as a Great Lakes Area of Concern (AOC). The studies leading to Torch Lake's inclusion in these programs, along with the remediation activities that have occurred under these programs, are discussed in Chapter 3. The description of the Superfund and AOC sites are discussed later in this chapter.

1.2 Brief History of Contamination and Remediation Activities

Copper mining itself did not take place on Torch Lake. Mining-related activities (e.g. copper processing), in particular stamping, smelting, reclamation, leaching and flotation, did take place along the industrialized western shore of Torch Lake. These activities began in the 1860s and continued through the 1960s (Schwaiger Zawisza, 2016 (Expected)). Dumping of waste from copper processing caused the copper contamination found in Torch Lake. In addition to causing copper contamination, the dumping of the tailings also impacted the lake by filling about half the original volume of the lake. PCBs found in the lake likely came from the electrical equipment, in particular transformers and capacitors, used in electrical substations that provided power to the processing operations along the western shore.

As the copper mining industry declined, the concern about the environmental and public health impacts of Torch Lake grew. These concerns became particularly prominent when leachate spilled from the flotation plant in Lake Linden into the lake water in 1971-1972. Throughout the 1970's and into the 1980s, Torch Lake was the subject of many studies that examined the contamination of fish and sediment and the water quality of Torch Lake; which are discussed in more detail in Chapter 3. Between the leachate spill and growing concern about raw residential and industrial sewage being dumped into the lake (Goffin, 1983; Swift, 1984), the presence of fish tumors, and the copper contamination of the sediment, Torch Lake was listed on the National Priorities List and as a Great Lakes AOC.

Under the Superfund program, a remedial investigation and feasibility study (RI/FS) were conducted (actually, one for each operable unit was conducted, which is explained later in this chapter as well as in Chapter 3). The remedial investigation tested for concentrations of copper, heavy metals, and organic chemicals primarily on the protruding mine tailings piles. Based on the results of the RI/FS, the exposed mine tailing piles were capped with a six-inch soil cover and vegetation, and the lake sediment was left to recover by natural attenuation (EPA, 2003). Under the Superfund program, PCBs were identified as present during the remedial investigation of operable unit I, but they were not regarded as a major problem and were not treated under the Superfund program.

Under the AOC program, fish caught in Torch Lake were monitored for tumors. By 2007, once at least five years had passed without a report of fish tumors, the fish tumor BUI was delisted (MDEQ, 2007). The Degradation of Benthos BUI is considered addressed by the decision to let the Torch Lake sediment naturally attenuate (MDEQ, 2007). The fish consumption advisory was established in 1983 due to the presence of fish tumors. The consumption advisories due to mercury and PCBs contamination were established in 1992 and 1998, respectively, and they still exist.

1.3 AOC Listing

Torch Lake was recommended for the list of Great Lakes Area of Concern (AOC) in 1985 (IJC-GLWQB, 1985). Torch Lake was officially designated an AOC in 1987 with the establishment of the AOC program under the Revised Great Lakes Water Quality Agreement (The United States and Canada, 1987). The boundaries of the Torch Lake AOC, as described in the 1987 RAP, are Torch Lake and its immediate environs (MDNR, 1987), shown in Figure 1.3 below.

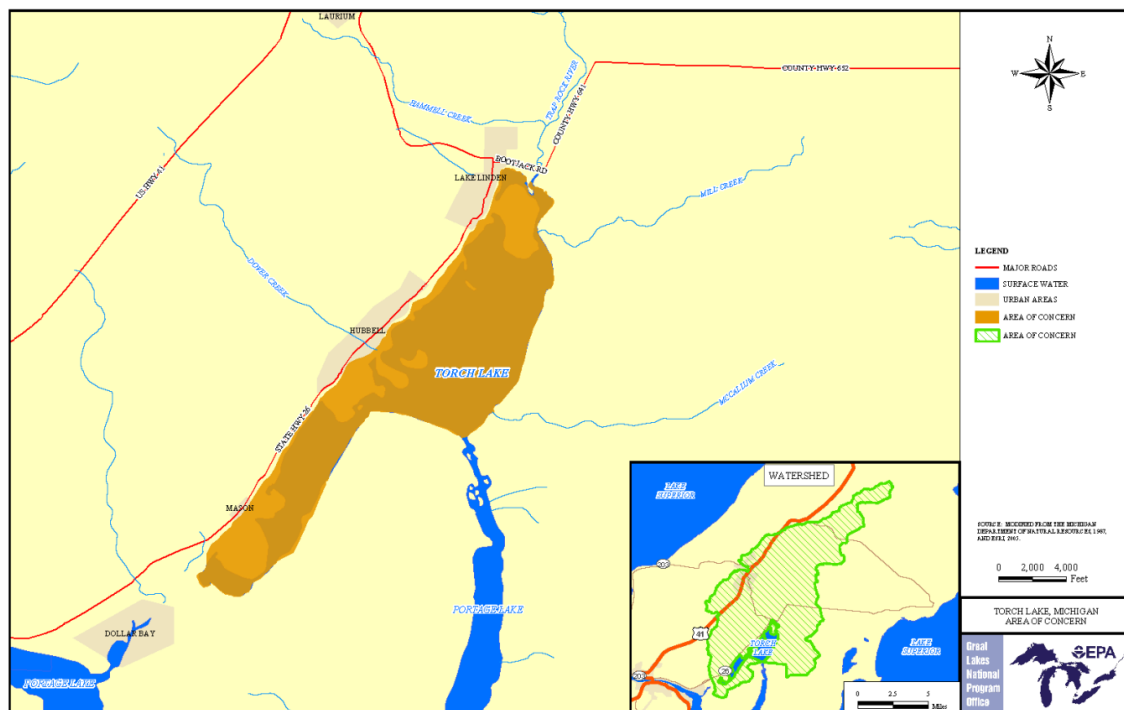


Figure 1.3: Torch Lake Area of Concern (U.S. EPA, 2006)

In addition to the presence of fish tumors, in the 1987 Remedial Action Plan, degradation of benthos and restrictions on fish consumption were also listed as beneficial use impairments (BUIs). (MDNR, 1987) The fish tumor BUI was delisted in 2007, once five years without a report of fish tumors had passed (MDEQ, 2007). Degradation of the

benthic community BUI exists because of the copper present in the sediment at the lake bottom, and copper is toxic to benthic organisms. The effects of copper and other heavy metals on the Torch Lake system are discussed in detail in this chapter.

The original advisory on fish consumption was established in 1983 due to the presence of fish tumors on sauger and walleye (MDEQ, 2007). This advisory was removed in 1993. A consumption advisory due to mercury contamination was instated in 1992, and one based on PCB contamination was instated in 1998 (MDEQ, 2007). The current fish consumption advisory is due to elevated concentrations of both mercury and PCBs found in the fish. The effects of PCBs on fish and the Torch Lake system are discussed in detail later in this chapter.

1.4 Superfund Listing

Torch Lake was listed on the National Priorities List (NPL) in 1986 due to the volume of contaminated sediments in the lake, the presence of fish tumors, the 1971-1972 Lake Linden flotation plant leachate spill, and because the State of Michigan did not have an approved program under the Surface Mining Control and Reclamation Act of 1977 (EPA (inferred), 1986 (inferred)). The listing of Torch Lake on the NPL made the site eligible for certain funding for remediation that would not otherwise have been available.

It should be noted that the boundaries of the Torch Lake Superfund site are different from the boundaries of the Torch Lake AOC. The Torch Lake AOC consists of Torch Lake and its immediate environs. The Torch Lake Superfund site consists of three operable units (OUs). OUI is made up of the upland area immediately adjacent to Torch Lake and the mine tailings piles that protrude from the lake surface near the western shore. OUII is made up of the surface water, groundwater and sediments in Torch Lake and the Keweenaw Waterway. OUIII consists of other selected deposits of mine tailings on the

Keweenaw Peninsula (Donohue and Associates, 1989). Figure 1.4 displays a map of the Torch Lake Superfund site. OUs I and II are contained within the red oval.

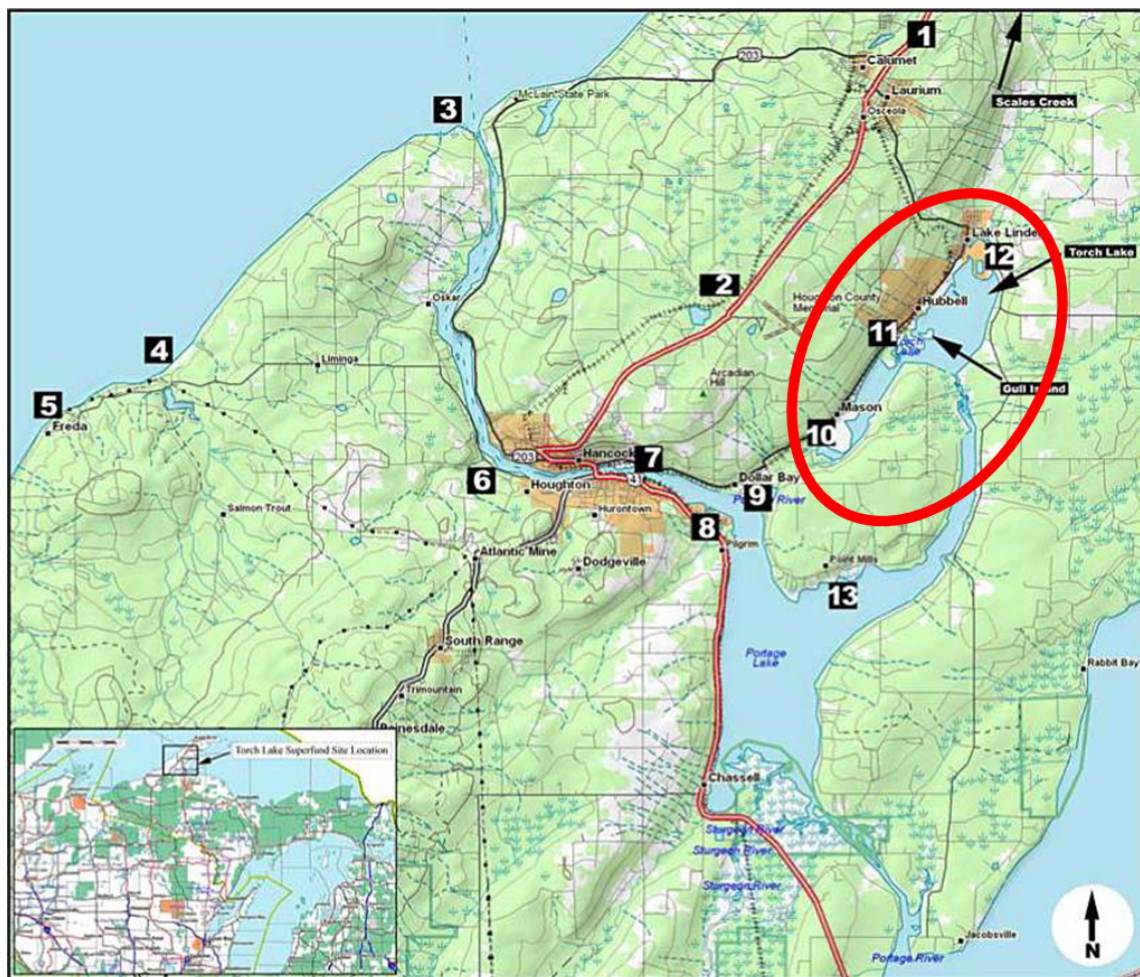


Figure 1.4: Torch Lake Superfund Site with OUs I and II location (MDEQ, 2007)

1.5 Superfund Delisting

In general, once a site is listed on the NPL, the goal of the community becomes to remediate the site until it is delisted from the NPL (the same concept applies to the AOC program). Prior to delisting, the Torch Lake Superfund site passed through three main stages: the study of the site, the decision of remedy for each operable unit, and the execution of the remedial actions. From 1989-1990, the EPA and its contractors

conducted a number of investigations on different media throughout the Torch Lake Superfund site as part of the required Superfund process of remediation investigation and feasibility study (RI/FS) (Donohue and Associates, 1990a; Donohue and Associates, 1992). In 1992, the Record of Decision (ROD, the document stating the final decision on remediation methods to be applied at the site) for OUs I and III was published (U.S. EPA, 1992), and in 1994 the ROD for OU II was published (U.S. EPA, 1994a).

Due to its size and complexity, the Torch Lake Superfund site was delisted in parts from 2002-2014. The exposed mine tailings and piles of mine tailings along the western industrial shore were covered with soil and vegetated (OU I). The lake sediment was left to recover by natural attenuation (OU II) (U.S. EPA, 1994b). Though the site was delisted, it was not fully remediated. The benthic community is still degraded. Though it was sampled, PCB pollution was never identified as a problem nor remediated under the Superfund Program; the problem is only addressed by the AOC program. Five-Year Reviews are completed by U.S. EPA “to determine whether the remedy implemented at the site is protective of human health and the environment.” (U.S. EPA, 2008) The first Five-Year Report was published in 2003, and the most recent Five-Year Report was published in 2013. The state manages the operation and maintenance for the Superfund site.

1.6 Contamination in Torch Lake

Torch Lake has received contamination from approximately 100 years of mining-related activities including milling, smelting and reclamation. The lake is most known for its copper contamination. Mine tailings and stamp sands have about halved the original volume of the lake; the widely-cited value of 20% reduction in volume (MDNR, 1987; MDEQ, 2007; Donohue and Associates, 1990b; Donohue and Associates, 1990a) refers only to volume reductions occurring from 1946 to 1970 (Wright et al., 1973). In addition to copper contamination, the sediment, soil and groundwater are contaminated with a

variety of other metals and polychlorinated biphenyl compounds (PCB compounds). Metals that contaminate the sediment, soil and groundwater include, but are not limited to, arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg) and Zinc (Zn) (Donohue and Associates, 1990a; Life Systems, 1991; Donohue and Associates, 1991).

1.6.1 Copper and Other Metal Contamination

Aside from copper and mercury, the metals analyzed in this thesis were not addressed in the original Superfund remediation actions. Copper is of concern in Torch Lake because its presence in high concentrations in the sediment kills organisms that would ordinarily reside there. This decreases the diversity of the food web, and consequently, the ecosystem. The other heavy metals analyzed have various environmental and human health effects based on type of exposure. Arsenic can cause a reduction in the number of species present in a natural environment and is a carcinogen (GreenFacts, 2001-2015). Cadmium exposure causes health problems; acute exposure causes stomach problems and chronic exposure can cause kidney damage (ATSDR (inferred)). Exposure to chromium(VI) compounds can cause respiratory problems (EPA, 2013). Chromium can contaminate surface water and soil (SERC, 2013). Lead can contaminate soil and groundwater. In humans, lead exposure can lead to developmental, cardiovascular, kidney and reproductive problems (EPA). Mercury is ubiquitous, bioaccumulates in fish and has negative impacts on human neurological systems (EPA).

As a part of the integrated assessment of Torch Lake and this thesis research, because they were not investigated as part of the Superfund and AOC programs, the suite of metals described above were analyzed for temporal and spatial patterns in concentrations. These patterns were compared to the locations of historical industrial buildings and known areas of waste disposal. The sampled concentrations were compared to the Michigan Part 201 Residential Soil Direct Contact Criteria (DCC), the Threshold Effect

Concentration (TEC) and Probable Effect Concentration (PEC). The comparison to the DCC was chosen due to the fact that the mine tailings are in close proximity to residential areas and are used for residential purposes. The comparison to TEC and PEC levels was chosen because these levels can be used to help characterize the sediment (MDEQ, 2012). The comparison can be found in more detail in Chapter 4.

1.6.2 PCB Contamination

Polychlorinated biphenyls (PCBs) are a group of synthetic chemicals. There are 209 congeners which are composed of two phenyl rings and 1-10 chlorine atoms attached to these rings on the various carbon atoms in the rings (Thomas, 2008), as shown in Figure 1.5.

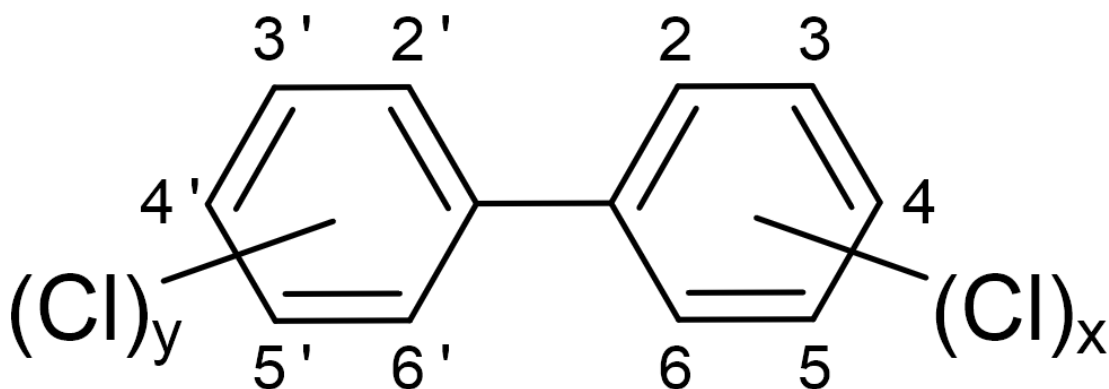


Figure 1.5: Polychlorinated biphenyl molecule (Dschanz, 2007)

The number and position of the chlorine atoms in the congener's molecule determine the environmental transport, bioaccumulation and toxicity of the particular congener. More chlorinated congeners tend to have lower aqueous solubility and vapor pressure than those of less chlorinated congeners, which means that less chlorinated congeners are more mobile in the environment than more chlorinated congeners (Thomas, 2008). This

means that in the Torch Lake system, we are likely to see more chlorinated congeners in the lake sediment and upland soil because the less chlorinated congeners are more likely to have volatilized.

PCBs are neutral compounds and undergo air-water exchange, they do not undergo acid-base reaction in the environment, are not easily oxidized or reduced, are soluble in a wide range of organic solvents, and have low electrical conductivity (Thomas, 2008).

According to the Canadian Council of Resource and Environment Ministers, “Commercial production of PCBs began in the United States in 1929 in response to the electrical industry’s need for a safer cooling and insulating fluid for industrial transformers and capacitors.” (CCME, 1986) In the United States, the primary manufacturer of PCBs was Monsanto Industrial Chemicals Co., which produced mixtures of PCB congeners called Aroclors. Each Aroclor mixture was distinguished by its percent weight of chlorine (de Voogt & Brinkman, 1989). Aroclors composed of heavy congeners tended to be used in the electrical industry as well as for lubricants. Aroclors composed of light congeners tended to be used in heat transfer liquids, sealants, lubricants, paints, adhesives and as plasticizers (Thomas, 2008). Production and use of PCBs were banned in the late 1970s (de Voogt & Brinkman, 1989).

In general, PCBs are of concern because of their impact on human and environmental health. Impacts of PCBs on human health include disruption of reproductive function, neurobehavioral and developmental deficits in newborns and children, immunological disorders and increased cancer risks. The United States Environmental Protection Agency U.S. EPA considers PCBs to be probable human carcinogens (EPA).

The primary environmental problem with PCBs is that because they were manufactured to be very stable chemicals, they are persistent in the environment. They are ubiquitous throughout all environmental media (such as air, soil, groundwater, surface water and sediments). PCBs sorb to organic matter, which makes their persistence in the

environment harmful to biota, fish and wildlife. Because PCBs volatilize, they can be transported through the atmosphere. This means that an area that does not have a local source of PCBs can still be contaminated with the chemicals due to atmospheric deposition.

Of particular concern in the Torch Lake system is the bioaccumulation of PCBs that occurs as they travel up the food chain. Because PCBs are hydrophobic, they are readily absorbed through many tissue membranes, including by microorganisms, the gills of fish, the skin of many animals, and the gastrointestinal tract” (Thomas, 2008). PCBs accumulate in fatty tissue. As larger fish eat smaller fish, the larger fish absorb PCBs through the gills from the lake water and absorb the PCBs that are present in the organisms they consume. The result is that the concentration of PCBs in fatty tissue increases as PCBs travel up the food chain, and is significant at the top of the food chain, which is where humans are found (CCME, 1986).

In Torch Lake, PCBs are a concern because they contribute to the Fish Consumption Beneficial Use Impairment (BUI). The average concentration of PCBs present in fish caught in Torch Lake is higher than that of fish caught from other area lakes (MDEQ, 2008), as demonstrated in Chapter 5. The fish consumption advisory exists specifically because if a person consumes too much fish, he/she could experience the health impacts described above. From the research documented in this thesis, it is inferred that PCBs were introduced into the Torch Lake system by spilled fluid from electrical transformers and capacitors used in the substations along the western shore of Torch Lake, as well as by the burning of copper wire coated in a PCB-laden cover in the Hubbell smelter yard. The analysis of PCB content in fish is discussed in detail later in Chapter 5.

Prior to the research reported here, sampling for and analysis of PCBs had been conducted in fish caught in Torch Lake and nearby waterbodies (Portage Lake and Huron Bay), in Torch Lake sediment, and in soil and groundwater along the western shore of Torch Lake. Based on the results it was concluded that a local source of PCBs to Torch Lake likely exists (MDEQ, 2008; GLEC, 2006).

A 2009 EPA Sediment Aroclor Investigation report states that “the surficial sediment PCB concentrations detected in 2007 and 2008 in the Hubbell/Tamarck area... are generally at or below the ranges of concentrations expected to impact aquatic species” (EPA, 2009). This conclusion did not address the source of PCBs required to maintain high concentration in fish that, in turn, led to imposition of fish consumption advisories for the past 15 years. Chapter 5 discusses a mass balance calculated on PCBs in Torch Lake to determine if an ongoing source of PCBs to the lake exists, and to determine if the already sampled inputs can account for the aqueous concentrations measured in the 2005 MDEQ SPMD study. The inputs to the model are the concentrations found in the sediment and groundwater. These steady-state aqueous concentrations predicted by the model were compared to the aqueous concentrations measured in 2005 (which were assumed to be steady-state based on the residence times of each of the congeners in Torch Lake). If the concentrations equal each other, the known inputs can explain the concentrations found in the water, and ultimately, in the fish. If the modeled concentrations were less than the measured concentrations, as was the case in this research, then the known inputs cannot account for the measured concentrations, and an additional source to the lake is inferred to exist.

1.7 Thesis Objectives, Research Question, and Roadmap

This research is part of a larger project funded by Michigan Sea Grant to conduct an integrated assessment of Torch Lake. The goals of the overall integrated assessment are to: 1) collect and summarize data about the history and current status of the Torch Lake

Area of Concern (AOC), 2) inform stakeholders of the current status of the site, 3) discuss remediation strategies with stakeholders, 4) assemble existing data to consider different remediation solutions, and 5) clarify what further information is needed in order to fully evaluate remediation options (Urban et al., 2011). The research presented in this thesis contributes directly to reaching all of the integrated assessment goals. In addition to this research, work on the history of the electrical distribution system and industrial processes and how these contributed to the pollution of Torch Lake is presented in E. Schwaiger Zawisza's thesis, *Powering an Industry: The Calumet and Hecla Story* (Schwaiger Zawisza, 2016 (Expected)).

The objectives of this thesis are to summarize the status of contamination and remediation activities in Torch Lake and to estimate the magnitude of potential sources of PCBs to Torch Lake. The overall question guiding this research is the following: what is the status of remediation efforts in Torch Lake with regards to metals and PCBs? Specifically, there are two parts to this question: 1) are the implemented methods of remediation for copper, other metals, and PCBs effective; and 2) can the identified sources of PCBs explain the aqueous concentrations estimated to be in the water?

Nothing about improving Torch Lake's environmental condition is short work. Contamination occurred over a period of approximately 100 years, and remediation has been occurring over the past approximately 35 years. The extent of contamination in Torch Lake is wide, deep and diverse. The contaminants are all chemicals, and the transport and transformation of chemicals can cause the characteristics of the contamination to change over time from when it was first disposed into the lake. Examining the historical activities that caused the contamination, along with the behavior of the contaminating chemicals, gives valuable context to its location, quantity and content. This context should be used to help investigators focus their sampling and remediation efforts.

Because the amount of time over which contamination and remediation has occurred at Torch Lake, and how connected individual events are to other events, the best way to tell this story is chronologically. The overall organization of this thesis is to 1) present what is the contamination; 2) explain what caused the contamination to occur; 3) present remediation efforts to date; and 4) to present current conditions at Torch Lake, comment on the effectiveness of remediation efforts and suggest further direction. Chapter 1 provides a brief overview of the history of and problems at Torch Lake, and orients the reader on how to think about the discussion throughout this thesis. Chapter 2 gives more detail on the Torch Lake industrial history, a description of the activities that generated metal contamination and the impact of dumping mine tailings and other industrial waste into the lake. Chapter 3 summarizes the history of remediation at Torch Lake. Chapter 4 summarizes the measurements of heavy metals in the sediment and soil of Torch Lake, and what we learn from the spatial and temporal distribution of these concentrations and occurrence of criteria concentration exceedances. Contamination with PCBs is the focus of Chapter 5; this chapter includes a summary comparing PCB concentrations among fish in Torch Lake and reference lakes, a summary of the mapping of PCB concentrations found in the sediment, soil and groundwater, a discussion of the SPMD sampling analysis – from which aqueous PCB concentrations were estimated – and the results of the mass balance of PCBs in Torch Lake and inferred local sources.

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NOTE: Figure 1.4 is in the public domain - appropriate documentation can be found in Appendix A.

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NOTE: Figure 1.3 is in the public domain - documentation is provided in Appendix A

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2 HISTORY OF CONTAMINATION WITH POLYCHLORINATED BIPHENYL COMPOUNDS, COPPER AND OTHER METALS

2.1 Torch Lake Mining History: Overview of the General History of the Area and Significance of Mining

Up until 1840, the Keweenaw region was rather sparsely populated; however, it was known that copper existed in the region. Ancient people of the region dug for copper and worked it by hand into a variety of objects. Between 1660 and 1840, French, British and American explorers all came to the Keweenaw seeking the copper about which they had heard; however, the resources of these groups generally led to unsuccessful expeditions; or at least expeditions that resulted in a lack of copper mining. In 1820, the United States and the Michigan Territory became serious about exploring the Keweenaw region – in this year the governor of the Michigan Territory, Lewis Cass, himself led the expedition to the region to discover its resources. During the 1830s, Henry Schoolcraft and Douglass Houghton (Michigan's first state geologist) led further efforts to explore and survey the mineral resources. (Lankton, 2010)

In 1840, Douglass Houghton published a report on the geology of the Upper Peninsula of Michigan, which included a description of the Keweenaw Peninsula's copper deposits (NPS). The copper in the Keweenaw was pure and required little processing before use (Quirk, 1999), making it extremely valuable. Shortly after this report was published, a land rush began in the region (NPS). The mining era lasted from the 1840s to the late 1960s and produced about 11 billion pounds of copper. (Lankton, 2010) During this time, copper was employed for many different purposes, including kitchen utensils, housewares, plumbing, shipbuilding, munitions, and electrical wires (Quirk, 1999). It could also be combined with tin and zinc to produce bronze and brass, respectively (Quirk, 1999). In short, copper was an extremely useful metal and the demand for it was great. (Lankton, 2010)

Torch Lake was not the site of any mines, but it was the site of supporting industrial activities such as stamping, smelting, and (once technology had advanced) reclamation, all of which produced wastes that were discarded into and near Torch Lake. The majority of the wastes were stamp sands or mine tailings, which are the remains of copper ore after the copper has been removed. Other wastes from these processes are mentioned and discussed further later in this chapter and in Chapter 4. The first stamp mill on Torch Lake opened in 1868. For the next nearly 100 years, about 200,000,000 tons of mine tailings and slag were discarded into the lake. (Leddy et al., 1986) It is widely cited that approximately 20 percent of Torch Lake's original volume is now occupied by stamp sands (MDNR, 1987; Baker, 2007; Donohue and Associates, 1990b; Donohue and Associates, 1990a). However, the Operable Unit II Record of Decision, along with recent efforts to profile the lake suggest that this quantity is closer to 50 percent (Yousef, 2012) The percent occupation given by the OUII ROD and by Yousef are more accurate estimates because both studies compared bathymetry maps from the 1860s to modern bathymetry to determine the percent difference in lake water volume. In addition to copper, the lake contains heavy metals and other chemicals associated with the mining industry such as PCBs and PAHs.

2.1.1 Early Mining Companies and Practices

Due to its physical characteristics, Torch Lake was used for mine tailing disposal. To dispose of the massive amount of tailings produced, the copper mills “moved the crushed rock with thousands of gallons of water and were built to take advantage of gravity, letting the tailings wash down hillsides into lakes.....The local lakes which provided water to the mills had steep banks and impressive depths.” (Quirk, 1999) Torch Lake fit this description of having impressive depths. At present, the maximum depth in the lake is about 38 meters; in 1865, the maximum depth in the lake was about 47 meters (Yousef, 2012).

The practices that are responsible for the contamination in Torch Lake are milling, separation, leaching, flotation and smelting. All of these processes were involved in extracting the copper from its ore. The early (pre-1900) milling and separation processes were purely physical means of separating copper from ore. The first separation processes did not involve mills; they were simply the manual separation of ore from the copper by drilling, blasting and chipping away barren rock from copper (Quirk, 1999; Lankton, 2010). Between 1845 and 1855, stamp mills were developed. Early stamps consisted of four or five rise-and-fall stamps attached to a rotating main shaft. The stamps relied on gravity to fall. Jigging, a process that used gravity to separate copper from ore, was done by hand. Buddles were obstacles in rapid water flow that assisted in settling out the copper from the ore, which was flushed with the water. In the 1850s, milling technology evolved, partially due to knowledge brought by Cornishmen who had come to work in the mines. The Cornishmen introduced technologies such as mechanical jigs and buddles. At the same time, stamps evolved from using gravity to being powered by steam, increasing the yield of copper from this process. (Lankton, 2010)

In 1855, once the Soo Locks had opened, larger and more sophisticated milling and separation equipment could be brought to the Keweenaw. The equipment brought in included ball mills, steam stamps and jigging tables. Ball mills consisted of a large revolving drum containing a load of hard granite pebbles or steel balls in various sizes. They were used after stamping to further crush the ore into a fine powder to facilitate separation of copper from its ore. By this time, processes to separate the copper from the crushed ore had evolved, though the use of chemicals had not yet been employed. After the ore had been stamped, the ore and the copper were transported by water to another part of the mill where separation occurred. Separation occurred by gravity: the operations relied on the fact that the specific gravity of metallic copper is greater than the specific gravity of the associated ore. The heavier copper settled out of the mixture first, and the stamp sands were allowed to flow through launders into nearby lakes (Quirk, 1999), which included Torch Lake.

From the 1860s to 1969, a total of eight mills operated on the shore of Torch Lake. The following description lists the mills by location from north to south along the western shoreline of the lake. Two mills were located in Lake Linden: Calumet (which operated from the 1860s to 1944) and Hecla (which operated from the 1870s to 1921). Tamarack City was home to four mills: Ahmeek (1909-1969), Tamarack (1887-1919), Lake Mill / Tamarack #2 (1898-1930), and Osceola (1899-1921). Quincy #1 (1889-1945) and Quincy #2 (1900-1921) were located in Mason. (Urban et al., 2016 (Expected))

Environmental impacts of early stamping and milling activities consisted of dumping stamp sand into Torch Lake. Early methods of extracting copper from ore were not efficient. As a result the stamp sands the methods produced consisted of about 3% copper (Urban, 2012). Copper is toxic to benthic organisms, therefore it is likely that the dumping of stamp sands into Torch Lake led to the degradation of the benthic community. The impacts of the mine tailings and other wastes produced from these mills are discussed in further detail in Chapters 4 and 5, when the contamination by heavy metals and polychlorinated biphenyls are discussed.

2.1.2 Advancement of Technology and Mining/Industrial Practices

The need for flotation and leaching developed from the implementation of second-stage crushers by Calumet & Hecla in 1909 (Quirk, 1999). The material produced from the second-stage crushers had the consistency of slime and released considerably more of the metallic copper from its ore. With the resulting material being so fine, gravimetric methods of sorting the copper from the crushed rock were no longer considered the most effective, and leaching and flotation were introduced. (Quirk, 1999)

Leaching was best applied to fine granular materials, or sands (Quirk, 1999). Once the sands reached the leaching tanks, copper and copper oxides were dissolved in ammonium carbonate to form cupric ammonium carbonate. The cupric ammonium carbonate then reacted with metallic copper and was reduced to cuprous ammonium carbonate according to the following equation:



The cuprous ammonium carbonate then oxidized rapidly to the cupric state and dissolved more copper. When both forms of copper carbonate were boiled or distilled, the products were ammonia and carbon dioxide, copper (I)- and copper (II)-oxide solids, and copper (Benedict, 1955). The gaseous solvents were reclaimed and reused, the copper products sold or further refined, and the leached solids were discarded into local lakes (Quirk, 1999), including Torch Lake. The most prominent contaminant in the discarded mine tailings included solid phases of copper. Copper is toxic to benthic organisms in Torch Lake's sediments and immediately above them. The zooplankton, phytoplankton and fish do not appear to be affected by the presence of dissolved copper.

Flotation was applied to the slime products of secondary crushing. The slime was mixed with water and a frothing agent. The frothing agent used in the Keweenaw was a mixture of coal-tar, coal-tar creosote, residual coal-tar oil, and wood creosote, with the addition of some pine oil as required for frothing (Quirk, 1999). Coal-tar creosote, a mixture rich in polycyclic aromatic hydrocarbons (PAHs), was not used after 1929 (EPA Final Ecological Assessment 1992). The slime mix was pumped into the center of a V-shaped trough, where the copper floated up in the center and the rock slime flowed to the ends of the trough. The flotation of copper was instigated by aeration or agitation of the slime mix. The copper particles adsorbed to the resulting bubbles and were skimmed off and collected. The oils were returned to the system and the ore was sent to the smelter (Quirk, 1999).

Around 1901, Alexander Agassiz, President of Calumet & Hecla, realized that due to the inefficiencies of previous crushing methods, the tailings that were discarded into Torch Lake were likely profitable. He took samples of the tailings and determined that 34,470,000 tons of conglomerate tailings were available for retreatment, and that these tailings contained, on average, 0.9% copper (Quirk, 1999). As a result, Calumet & Hecla's and Quincy's mills were upgraded with more efficient crushing equipment, and, once the technology was developed, leaching and flotation devices (Quirk, 1999). In

addition, two dredges were constructed and used to obtain the mine tailings from Torch Lake for reprocessing by more efficient crushing methods, leaching and flotation. Contaminants from the flotation process include dissolved copper ions, xanthates, creosote, and fine, still metal-rich particles.

Between 1909 and 1967, three reclamation facilities existed on Torch Lake. Calumet & Hecla owned facilities in Lake Linden and Tamarack. The Lake Linden facility operated from 1914 to 1967. Both leaching and flotation occurred at this facility. All buildings at the Lake Linden facility operated until 1953, except for the flotation plant which operated until 1967. This facility reclaimed copper from conglomerate sands that had been previously discarded in Torch Lake near Lake Linden, and after 1953 the leaching facility continued to be used to process copper scrap. The Tamarack facility operated from 1926 to 1968, and processed mine tailings (from Ahmeek, Tamarack, Lake #2 and Osceola mills), slag (from the C&H Hubbell smelter) and copper scrap. In addition to reclamation, Lake Chemical Co. used the Tamarack plant to produce copper-based chemicals for fertilizers and fungicide from 1945 to 1965. (Urban et al., 2016 (Expected)) The Quincy Mining Company owned the third reclamation facility, which was located in Mason. The Quincy Reclamation Plant operated from 1943 to 1967 (Lankton, 2010) and processed the mine tailings from Quincy Mills #1 and #2. (Urban et al., 2016 (Expected))

2.1.3 Introduction of Electrical Distribution Systems

In 1901, Calumet & Hecla contracted General Electric to develop an electricity distribution system to power the new part of the Hecla Mill in Lake Linden. Construction on the electric power house was completed in 1903 (Schwaiger Zawisza, 2016 (Expected); McIntosh & Burgan, 1931). The Lake Linden Power Plant was operational until 1930; it remained non-operational until 1949, when it was updated with new generation equipment. In 1930, a new boiler and power plant consisting of two turbines were constructed in Ahmeek (Schwaiger Zawisza, 2016 (Expected)). Ultimately,

Calumet & Hecla constructed an electrical distribution system that ran from Lake Linden to Hubbell and served various mills, smelters, and the coal dock. A schematic of the electrical distribution system is shown Figure 2.1 below:

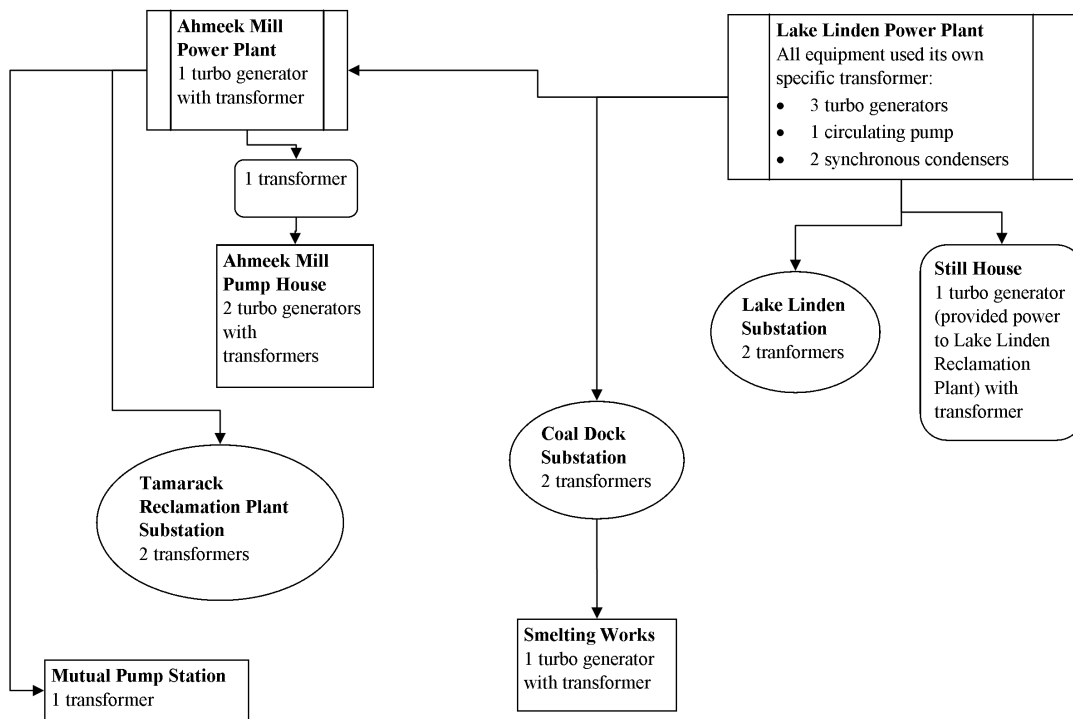


Figure 2.1: Schematic of the electrical distribution system along western shore of Torch Lake in the early 1930s identifying buildings in which electrical transformers are known to be located (Adapted from McIntosh & Burgan, 1931; Schwaiger Zawisza, 2016 (Expected)).

The electrical system was driven by coal and included several facilities that handled coal. At the coal docks north of Hubbell, coal was transferred from ships to company trains which shipped the coal to boilers at mills and power plants. C&H had a coal pulverization plant at the coal dock site that received coal and delivered it to the C&H smelter in Hubbell and the C&H power plant in Lake Linden. As stated in the Torch Lake Integrated Assessment report, “Power facilities fueled by coal (Lake Linden,

Ahmeek Mill) distributed PAHs and contained PCBs in their transformers.” (Urban et al., 2016 (Expected))

Equipment used in the electrical distribution system employed polychlorinated biphenyls (PCBs) as cooling liquids in transformers and dielectric liquids in capacitors (de Voogt & Brinkman, 1989). When all of the mining-associated industry operations (all of the mills, smelters and the electrical distribution system) were closed, the facilities and equipment were sold, moved locally for re-use, or abandoned. Transformer oil was spilled and as a result may have contaminated the groundwater, which flows into Torch Lake. PCB contamination causes human and wildlife health impacts, which are discussed in further detail below.

2.1.4 End of Mining and Industrial Activity

Decommissioning of some electrical and industrial buildings and equipment started in the 1920s mostly as a result of business decisions related to the diminishing supply of copper from the mine and the diminishing demand of copper due to the Great Depression. (Lankton, 2010) Many of the mills on Torch Lake stopped running in the early 1930s as a result of primary copper sources running low. As a result of the evolution of reclamation technology, mills and reclamation plants on Torch Lake returned to operation. In the early 1940s, due to World War II, the Navy had great need for copper, so copper reclamation flourished during this time. After the war ended, the Navy’s demand for copper also ended. By this time, resources for reclamation were diminished, and in the 1950s, reclamation and leaching plants and smelters were shutting down. In the 1960s, what little copper was left in the mine tailings was reclaimed, and by the end of the decade, all reclamation activities were over (Schwaiger Zawsiza, 2016 (Expected)).

The end of the industrial activity in the Keweenaw Peninsula and on Torch Lake was slow and somewhat indirect. In the late 1910s, due to the demand for copper during

World War I, the price of copper significantly increased from 17.3 cents per pound in 1915 to 29.2 cents per pound in 1917. This increase in price caused a significant increase in copper production which led the companies in the region to overproduce and stockpile copper. Before the war ended, the price of copper fell to approximately 18 cents per pound, and by 1921, the price fell even further to 12.5 cents per pound. The fall of demand for copper caused the region to significantly reduce production. The Great Depression of the 1930s only further lowered the production of copper. World War II briefly increased demand for copper. The federal government stabilized the price of copper and provided a market for its reclamation from mine tailings in Torch Lake and scrap metal. Once the war was over, however, the region's copper industry managed permanent decline through the 1960s. (Lankton, 2010) These historical events drove the opening and closing of industrial buildings along Torch Lake, which are chronologically listed in Table 2.1 below:

Table 2.1: Opening and closing of industrial buildings along Torch Lake

Year	Event	Source
1921	Quincy Mill #2	(Schwaiger Zawisza, 2016 (Expected))
1928	Improvements made to Quincy Mill #2, including the installation of a boiler and flotation equipment.	(Schwaiger Zawisza, 2016 (Expected))
1945	Quincy Mill #1 closes	(Schwaiger Zawisza, 2016 (Expected))
1943	Quincy reclamation plant constructed	(Lankton, 2010)
1967	Quincy reclamation plant closed	(Lankton, 2010)
1960	Quincy finished extracting copper from the Quincy #1 mine tailings	(Schwaiger Zawisza, 2016 (Expected))
1916	C&H leaching plant begins operation	(Schwaiger Zawisza, 2016 (Expected))
1918	C&H flotation plant begins operation	(Schwaiger Zawisza, 2016 (Expected))
1919	Tamarack mill abandoned	(Schwaiger Zawisza, 2016 (Expected))
1920	Tamarack mill dismantled	(Schwaiger Zawisza, 2016 (Expected))
1921	Hecla and Osceola mills closed	(Schwaiger Zawisza, 2016 (Expected))
1924	Hecla flotation plant dismantled	(Schwaiger Zawisza, 2016 (Expected))
1926	Tamarack reclamation plant begins operation	(Urban et al., 2016 (Expected))
1956	Tamarack reclamation plant closes operation	(Urban et al., 2016 (Expected))
1930	Lake Mill / Tamarack #2 closed	(Schwaiger Zawisza, 2016 (Expected))
1949	Lake Linden Power Plant begins operation	(Schwaiger Zawisza, 2016 (Expected))
1953	Lake Linden reclamation plant closes	(Schwaiger Zawisza, 2016 (Expected))
1960	All C&H Calumet Division operations closed	(Schwaiger Zawisza, 2016 (Expected))

All mining and related activities stopped by the mid-1990s, including those on Torch Lake (Lankton, 2010). By this time, 200,000,000 tons of mine tailings had been discarded into the lake. The industrial infrastructure was dismantled (Baker, 2007) and many buildings were razed or abandoned.

Examining the historical industrial activities on the Torch Lake shore helps to understand the origin of the contamination found in the Torch Lake system. The processing of copper ore was a significant source of mine tailings, slag and other waste in which heavy metals and polychlorinated biphenyls could be found. Knowledge of the full extent of contamination when it originally occurred serves as a base for understanding the contamination that is seen today, and can give clues as to whether there is more to be examined besides what can be found by sampling.

2.2 Impacts of Contaminants on the Torch Lake System

2.2.1 Impacts of Local Metals Contamination

The ecological impact of the stamp sands at the bottom of Torch Lake is the degradation of the benthos or bottom-dwelling organisms. Copper is poisonous to benthic organisms, which form a link in the lacustrine food chain. If the benthic organisms are low in number and diversity, then organisms that rely upon them for survival are also low in number and diversity. Fish reproduction is also impaired due to toxicity to eggs and hatching fry.

Human health impacts of contaminants present in groundwater, surface water, sediments, and surface tailings are described in the Baseline Risk Assessments for Operable Units I (1991) and II (1992). In the groundwater, arsenic and beryllium are of concern due to carcinogenic effects. Chemicals posing non-carcinogenic health risks due to ingestion of

groundwater include antimony, arsenic, barium, copper, manganese and vanadium. In the surface water, skin exposure to beryllium can cause cancer. In the sediment, arsenic is of concern due to carcinogenic effects. In the surface mine tailings, arsenic and beryllium are of carcinogenic risk to lagoon workers by ingestion of tailings, and copper poses a non-chronic hazard to children by ingestion or inhalation (Life Systems, 1992).

2.2.2 Impact of Local PCB Contamination

The presence of PCBs and mercury in the Torch Lake system resulted in the fish consumption advisory that currently exists for Torch Lake. PCBs are neutral substances that can become widely distributed in an ecosystem and the environment, including in water, sediments and air. They are hydrophobic (i.e., log of octanol-water partition coefficients of the congeners studied in this research range from 5.50 to 7.36 (Paasivirta & Sinkkonen, 2009)), meaning that they are more likely to sorb to fatty tissue rather than to water. Because of their lack of charge and hydrophobicity, fish tend to take them up from the water through their gills in addition to ingesting them. PCBs are bioaccumulative, so the concentration of PCBs present in the fish increases in higher organisms in a food chain. For this reason, humans have to be particularly careful when consuming fish from Torch Lake, and this is one reason that a fish consumption advisory exists for the lake.

PCBs are hydrophobic chemicals (Thomas, 2008), which means that they tend to sorb to fatty tissue and bioaccumulate (CCME, 1986). The high concentrations they can reach in organisms through these processes cause them to be a major health concern (CCME, 1986). PCBs cause neurological disorders and are considered a probable carcinogen, and they can cause lesions on the skin and liver problems (EPA). In humans, they can also be transferred from mother to child (EPA). For Torch Lake, the primary exposure pathway is through the consumption of fish.

2.3 Conclusion

The 100-year copper mining industry left a significant impact on Torch Lake. Milling, smelting, leaching, flotation and reclamation activities led to copper-containing mine tailings occupying about 50% of the original lake volume. These copper-contaminated tailings and related waste caused the degradation of the benthic community. Imprudent decommissioning of PCB-containing electrical equipment, and burning of the coating off of copper wire, may have led to the contamination of fish in Torch Lake.

In this chapter the causes of contamination of the Torch Lake system were described. The history of the contamination spanned a period of approximately 100 years, which makes understanding its effects a rather complex task. With a site that has undergone such extreme contamination, it is not enough to simply sample the surface and expect that remediation based off of this sampling will be enough to restore the site. Understanding what processes occurred where and when gives a much clearer picture of what contaminants should be expected to be found in certain locations, and to what depth and width. Knowing the full extent of the contamination is useful to adequately sample the site for contaminants and then remediate it. This chapter is meant to give the reader some context for the remainder of this thesis, which overviews attempts at remediation of the site and describes the contamination of the lake system by heavy metals and polychlorinated biphenyls. More details about the industrial history of Torch Lake can be found in E.Schwaiger Zawisza's thesis (Schwaiger Zawisza, 2016 (Expected)).

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3 HISTORY OF THE REMEDIATION OF TORCH LAKE

3.1 Introduction

This chapter summarizes environmental and public health studies and remediation activities in Torch Lake from the 1970s to the present. As stated in the introduction of this thesis, the objectives of this thesis are to determine the status of contamination and remediation activities in Torch Lake and to estimate the magnitude of potential sources of PCBs to Torch Lake. Specifically, the questions this thesis aims to answer are 1) Are the implemented methods of remediation for copper and other metals effective; and 2) Can the identified sources of PCBs explain the aqueous concentrations estimated to be in the water? This chapter describes the major remediation actions taken and the reasons for taking them; doing so is necessary because action or inaction over the approximately 45-year period since major industrial activity ceased on Torch Lake may have shaped the current state of contamination. The content in this chapter serves to link the industrial activities described in the previous chapter to some of the remedial actions described in the following chapters. First, the major programs and parties involved in the remediation of Torch Lake are described. Next, the early studies and actions leading to the listing of Torch Lake as a Great Lakes Area of Concern (AOC) and on the National Priorities List (NPL) are discussed. The sections that follow that discussion describe what has been done in Torch Lake under each program. At the end of this chapter, a timeline puts these activities in chronological order.

3.2 Major Programs and Parties Involved in Remediation

The major programs under which studies and remedial actions are completed in Torch Lake are the Great Lakes Area of Concern, Superfund, and Part 201 of Michigan's Natural Resources and Environmental Protection Act. The major parties involved in studying and remediating the lake are the United States Environmental Protection

Agency (U.S. EPA), the Michigan Department of Environmental Quality (MDEQ), Michigan Technological University (Michigan Tech), the Michigan Department of Natural Resources (MDNR), the Michigan Department of Community Health (MDCH, formerly the Michigan Department of Public Health - MDPH), and the Natural Resources Conservation Service (NRCS, contracted to do remediation). This section describes the programs and the roles of these entities in those programs.

The International Joint Commission Water Quality Board suggested that Torch Lake be designated as a Great Lakes Areas of Concern in 1985 ¹; it was designated an AOC under the 1987 revision of the Great Lakes Water Quality Agreement (GLWQA) between Canada and the United States, which established the AOC program ². According to the 2012 revision of the GLWQA, AOCs are defined as geographic areas “designated by the Parties where significant impairment of beneficial uses has occurred as a result of human activities at the local level.” ³ Torch Lake was listed as an Area of Concern because of the presence of tumors on Sauger and Walleye ¹. In addition to the presence of fish tumors, two other beneficial use impairments (BUIs) for Torch Lake were identified in the 1987 Remedial Action Plan (RAP): the advisory on fish consumption and the degradation of the benthic community ⁴. As will be explained in further detail later in this chapter, the fish tumor BUI has been delisted, but the other two still remain. Under the AOC program, the Torch Lake site consists of “Torch Lake and its immediate environs” ⁴, where ‘immediate environs’ consist of “...those areas along the shore of Torch Lake proper where wastes from the production of copper contributed directly to the contaminant loadings of Torch Lake” ⁵.

Torch Lake was listed on the National Priorities List in 1986 ⁶. According to the EPA, “The *National Priorities List* (NPL) is the list of national priorities among the known releases or threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories. The NPL is intended primarily to guide the EPA in determining which sites warrant further investigation.” ⁷ The reasons cited

for listing included the occupation of 20 percent of the original lake volume by stamp sands (which was actually an incorrect estimate – the percentage of the original lake volume occupied by the stamp sands is closer to 50 percent, as suggested by depth profiling we performed in summers 2013 and 2014), the contamination of the sediments by copper, the spill of cupric ammonium carbonate that occurred in 1972, and the presence of tumors on Walleye and Sauger. It is also noted in the listing that the site was listed on the NPL because the State of Michigan did not have an approved program under the Surface Mining Control and Reclamation Act of 1977 ⁶. Being listed on the NPL made Torch Lake eligible for remediation efforts and funding that would not have been available to it without the Superfund status. According to the Superfund program, the Torch Lake Site consists of three operable units (OUs): OU I is composed of the surface stamp sand piles along the western shore of Torch Lake; OU III is composed of selected surface stamp sands piles within the Keweenaw Peninsula but outside of the Torch Lake vicinity; and OU II consists of the surface water, sediments, stamp sands and biota within Torch Lake, the soil and groundwater in its immediate vicinity, and Keweenaw Waterway, Boston Pond, Calumet Lake, Portage Lake, Portage Channel and [parts of] Lake Superior ^{8,9}. Within this thesis OU III is not discussed, as none of its locations are within the watershed of Torch Lake (except for one instance in which the Hubbell slag pile and beach are included in OUIII).

The State of Michigan manages the remedial activities and monitoring in Torch Lake related to the AOC and Superfund programs. The MDEQ assists with the implementation of remedial actions under the Superfund program and oversees activities related to the AOC. They also set cleanup criteria requirements under the Michigan Part 201 program (the state's program for site investigation and remediation), and work together with the MDCH to monitor contaminant concentrations in fish and set the fish consumption advisory. The MDCH has also been involved with groundwater studies on the Torch Lake Superfund site.

Finally, Michigan Tech is responsible for many studies on Torch Lake since the 1970s. These studies have focused on the fish and sediment contamination in Torch Lake and the historical use of the land. Michigan Tech has also given its opinion on matters including the remediation plan for the site and the concern about surface water and groundwater use in Lake Linden. Michigan Tech recently completed an integrated assessment of Torch Lake, of which this thesis is a part.

3.3 Early Environmental Studies

General awareness of the contamination problem in Torch Lake has existed since the 1970s, and it may have existed before then, but in the scientific literature there are no records of such concern from before the 1970s. Throughout the 1970s and into the 1980s, Torch Lake was the subject of many academic studies, two studies conducted by the Michigan Department of Natural Resources (MDNR), and one commercial study done to evaluate the use of a seepage cell and irrigation at the wastewater lagoons in the Tamarack and Lake Linden stamp sands¹⁰.

Most of these studies focused on the effects of copper contamination on the Torch Lake ecosystem and other water quality issues, such as Tomljanovich's study on fish tumors (which was the first study on fish tumors in Torch Lake)¹¹, Yanko's study on mine pumpage¹², and Sabol's and Sypniewski's studies on sediment toxicity^{13, 14}. The studies are listed in Table 4 at the end of this chapter, and occurred in the years from 1969 – 1986. Several studies conducted by Michigan Tech concluded that the water quality in Torch Lake was degraded as a result of the industrial activities that occurred on the western shoreline. In general, it was found that macroinvertebrates are or have been negatively impacted by the presence of mine tailings in Torch Lake due to the presence of copper^{15, 16}, and nutrients^{17, 18, 19}. During the early 1970s, many physical and chemical changes were observed in Torch Lake^{20, 21}. One study conducted by the MDNR determined what local sources of groundwater were acceptable for use as drinking water²².

In 1986, Michigan Tech published a comprehensive study examining fish tumors, the environmental fate of xanthates, creosotes, and heavy metals in sediments and mine wastes, and a copper budget for Torch Lake. The study that examined the fish tumors concluded that exposure to creosote could result in the liver tumors that were observed in the Torch Lake fish²³. The study that examined the environmental fate of xanthates and creosotes concluded that xanthates would not be expected to persist in the environment for more than one year²³. The study that concerned heavy metals in sediments and mine wastes concluded that the metals are not contaminating the lake water directly²³. Finally, the copper budget showed chemical processes such as chemical precipitation, complex formation, dissolution, physical adsorption, diffusion of pore water from sediments, and infiltration of copper-bearing water from shoreline stamp sand deposits control the concentration of dissolved copper in the surface water²³.

Two studies were conducted concerning the effects of the 1971-1972 copper leachate spills on the water quality of Torch Lake. According to the MDNR, at least 27,000 gallons of cupric ammonium carbonate were spilled from the Calumet Division of Universal Oil Products' Lake Linden leaching plant ²⁴. According to Michigan Tech, "...between 114 and 3000 m³ of solution containing 0.69-36 g/L ammonia and 0.07-7.8 g/L of copper were lost in the spill." ²⁵ To clarify, this spill refers to two spill events in the fall of 1971 and the spring of 1972 ²⁵.

The two studies on the effects of the copper leachate reached different conclusions due to the difference in each study's timing compared to the incident. The study conducted by the MDNR was conducted in the fall of 1973, and concluded that the spill, which occurred several months before the study was conducted, had no deleterious effects on the water, benthos, algae or fish ²⁴. According to the study conducted by scientists at Michigan Tech during the summer of 1972, the cupric ammonium spill caused increased levels of dissolved copper, carbonate alkalinity, pH and ammonia nitrogen, and unusual oxygen depletion in the hypolimnion ²⁵. This study also concluded that "the water in the spill bay was decidedly toxic to aquatic invertebrates." ²⁵ The different conclusions point to the short-term nature of the effects on the lake. Michigan Tech stated in their study that "Firm conclusions are difficult because the lake has not been adequately studied over a complete annual [cycle], except with respect to chloride and specific conductivity." ²⁵ They acknowledged the data gathered by the MDNR and at the time of publishing the article tentatively accepted it as valid ²⁵.

Two studies focusing on the effects of chemical contamination of fish were completed. One was the subject of a Michigan Tech M.S. thesis that looked at trends in growth and abnormality occurrence in sauger. Of particular note from this study was the occurrence of extreme fat accumulation, fat lesions and external tumors on the sauger¹¹. The other study that focused on fish was published by Black et al. in 1982, and described in detail the contamination of Torch Lake sauger and walleye, specifically, the tumors found on these species²⁶.

In addition to the studies concerning the ecosystem, water quality, and fish of Torch Lake, a few studies during this time concerned the practical usefulness of the mine tailings. A study completed by Michigan Tech's Institute of Mineral Research (IMR) in 1970 was performed to determine if more copper could be extracted from the tailings piles. It was determined that some of the piles investigated could have yielded more copper²⁷. A study done for the Houghton County Board of Public Works was completed in 1981 "to determine the propriety of operating the wastewater treatment facilities utilizing one lined cell, one seepage cell and irrigation."¹⁰

In addition to all of these studies, several newspaper articles document the general public concern about contamination in Torch Lake. Local residents, particularly those living in the Village of Lake Linden, had concerns about contaminated lake water entering their drinking water supply. Specifically, they were concerned about the residential raw sewage that was flowing into Torch Lake, then making its way to the groundwater wells that supplied drinking water²⁸. In addition to the concern about the raw sewage, there was also concern about the overfilling of the sewage lagoons on the Tamarack Stamp Sands with contaminated waste from the industrial park²⁹, the presence of fish tumors, and the contaminated lake sediment. All of these concerns were in addition to the one which already existed about the contaminated sediments in Torch Lake.

3.4 AOC and Superfund Designations

Due to the growing environmental concerns about Torch Lake, in 1982, the EPA conducted an assessment to determine if Torch Lake should be listed as a Hazardous Waste Site. The results of this assessment indicated that copper concentrations in the lake water were 30-45 ppb, while average background concentrations were 3.4 ppb ³⁰. In 1984 the EPA proposed to list Torch Lake on the NPL ⁶; and in 1986, Torch Lake was listed on the NPL. The reasons cited for listing included the occupation of 20 percent of the original lake volume by stamp sands, the contamination of the sediments by copper, the spill of cupric ammonium carbonate that occurred in 1972, and the presence of tumors on walleye and sauger. It is also noted in the listing that the site was listed on the NPL because the State of Michigan did not have an approved program under the Surface Mining Control and Reclamation Act of 1977 ⁶. Once listed on the NPL, action to remediate Torch Lake gained momentum.

Due to the occurrence of tumors on sauger and walleye, the IJC recommended Torch Lake as an Area of Concern in 1985 ¹. The original BUI cited was the presence of fish tumors ²³. A fish consumption advisory was issued shortly after the occurrence of tumors was noticed even though the cause of the tumors was not identified ⁴. In 1987, the Stage 1 Remedial Action Plan (RAP) for the Torch Lake AOC was finalized. In the RAP, two more BUIs were identified: the restriction on fish consumption and the degradation of the benthic community ⁴. Progress towards delisting the remaining two BUIs will be slow because a viable solution for degradation of benthos has yet to be discovered, and the local source of PCB contamination in the fish has yet to be found. According to the 2007 RAP update, the State of Michigan's guidance to remove the fish consumption advisory on account of mercury has been met because the concentrations found in Torch Lake fish are not statistically significantly different from those found in Lake Superior ⁵.

3.5 Superfund Actions

Once Torch Lake was listed on the NPL, the EPA became more active in its remediation. In 1988, a contractor of the EPA, Donohue and Associates, Inc. (Donohue), published a compository summary on Torch Lake. This document was an overview of various aspects of the site up to that year, including environmental problems and studies, regulatory actions, response actions, hazardous materials and affected media and regional and local site characteristics ³¹. The compository summary described what the conditions of Torch Lake were and the historical activities that led to those conditions.

Between 1989 and 1990, the EPA/Donohue conducted various sampling campaigns in different media that informed the Torch Lake Remedial Investigation (RI). As a part of the RI, among the three operable units, the following media were sampled: drums, tailings, soil, air, sediment, floc, surface water, groundwater, and biota ⁹. In addition to the RI, Baseline Risk Assessments were conducted on each operable unit to determine what chemical hazards to human health existed at each unit, a wetland investigation was performed, and a leachability evaluation was performed on the tailings.

The 1989-90 RIs of OUs I and II revealed a variety of findings concerning the surface tailings, sediment, groundwater and surface water and air. In the RI for OUI several findings were revealed about the surface tailings and air. Bis(2-ethylhexyl)phthalate, polycyclic aromatic hydrocarbons and inorganic compounds (specifically, aluminum, antimony, arsenic, barium, beryllium, boron, chromium, cobalt, copper, lead and magnesium) were detected in surface and subsurface tailings, though the concentration and distribution of these compounds were similar in surface and subsurface tailings and slime materials ³². Concentrations of arsenic, chromium, copper and lead were higher in the slag piles than in other material ³². Organic compound concentrations were orders of magnitude higher in soil samples than in tailings samples, while metals concentrations were similar between the two types of materials. Hot spots of contamination could not be reliably located or predicted ³².

The 1989-90 RI of OUII revealed a variety of findings concerning the surface tailings, sediment, groundwater and surface water. It was found that human exposure to the surface tailings did not present a health hazard, and that the material was generally homogeneous. Slag materials did exhibit elevated levels of inorganic contaminant compounds that presented risk to human populations for combined inhalation and ingestion of the slag material ³³. Drums were not found buried in the surface tailings. It was determined that “More than 179,000 cubic yards of tailings were deposited into Torch Lake, reducing the surface area by approximately 600 acres and reducing the water volume by 111,000 acre feet.” ³³ A thin layer of organic materials covering the submerged tailings was observed. Contaminated groundwater was detected in monitoring wells in the Lake Linden tailings pile. The groundwater was found to be contaminated by inorganic compounds, specifically, aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel and vanadium. In the Lake Linden well nest, arsenic, barium and manganese were detected. Surface waters showed a relatively uniform distribution of organic compounds of interest ³³.

The wetland investigation revealed several findings. It was found that “wetlands were developing over tailings around Torch Lake, usually near stream inlets”, that “natural wetland area near the southern and southeastern portion of the lake do not seem to be affected by tailings deposits”, and that “some possible natural wetlands near Lake Linden may be affected by tailings deposits”³⁴. The leachability study indicated that “very little metal [was] being released from Torch Lake”³⁵.

In addition to the studies described above, in 1989 and 1990, the EPA investigated drums located on the shore and underwater in Lake Linden. The sampling showed that the drums may have contained hazardous substances. As a result, an Administrative Order by Consent was issued to Universal Oil Products and five other companies to sample and remove drums from the area³⁶. Ultimately, 83 drums from the shore and 20 drums from underwater were removed, along with drum carcasses and stained soils found on the shore⁵.

Based on the above findings, in 1992 the EPA decided upon and published remedial actions for OUs I and III and in 1994 for OU II. The major components of the 1992 Record of Decision (ROD) pertaining to OUI include the following: 1. Deed restriction to control the use of tailing piles, 2. Removal of debris from the tailing piles, 3. Soil cover with vegetation on tailing piles in OUs I and III³⁷. The design for the Superfund remedial action began in 1994 and was complete in 1998³⁶. For OUII, largely due to the assumption made by the EPA of the supposed similarity between the Portage Lake and Torch Lake systems, it was decided that natural sedimentation would provide a cap for the contaminated lake bottom stamp sands; although they did acknowledge that natural sedimentation would occur more slowly in Torch Lake than it occurred in Portage Lake^{38, 37}. For the groundwater, it was determined that existing institutional controls were sufficient to protect human health³⁹.

In 1998, the EPA reserved \$15.2 million for the Torch Lake remedial action ³⁶. In 1999, construction/execution of these designs began ^{5, 36}. In OUI, the tailings piles were covered with soil and vegetated. In the summer of 1999, the Lake Linden stamp sands were covered with soil and vegetated. The same was done to the stamp sands in Hubbell/Tamarack and Mason in the summers of 2000 and 2001/2002, respectively. In OUIII, the slag piles and the beach in Hubbell were also covered with soil and vegetated^{38, 37}.

With the execution of these remediation actions, along with those recommended for the non-Torch Lake parts of OUIII, the Torch Lake Superfund site was delisted in parts from 2002-2014. Parts of OUIII have yet to be delisted. The first five-year review inspections occurred in 2002, and OUII and the Lake Linden stamp sands were deleted from the NPL in 2002. The Hubbell/Tamarack City stamp sands were deleted from the NPL in 2004. The Mason stamp sands were deleted in 2012 along with the Michigan Smelter site and the Isle Royale stamp sands (neither of the latter two are a part of the actual Torch Lake or its shoreline; they both reside in OUIII).

The third five-year review report indicated that the remedies for OUs I and III were protective of human health and the environment in the short term, but that a review of institutional controls should be performed in the long term with follow up with affected property owners and local governments ³⁶. For OUII it was reported that institutional controls continue to protect human health and the environment from exposure to site-affected groundwater, but that in the long term, residential wells should be monitored and controls improved as necessary. Groundwater monitoring wells at the site indicate concentrations of arsenic and lead are above maximum contaminant levels ³⁶. According to the five year reports, the Superfund program dismissed the lake sediments as addressed by natural attenuation.

In reality, the remedial actions are not truly solving the problems. The soil and vegetation cap on the surface stamp sands is eroding at a rate of approximately 0.1"/year⁵. The multiple Emergency Removal Actions (see below) conducted after the Superfund cleanup was completed attest to the inadequacy of the remediation. The remedial action on the lake sediments is also ineffective. According to McDonald et al. (2009), the rate of diffusion of copper out of the zone of contamination (cm/yr) is at least equal to the rate of fresh sediment accumulation at the lake bottom⁴⁰. The amount of time that it would take for fresh sediments to provide a thick enough cap over the contaminated sediments to allow benthic communities to survive was estimated to be 800 years.

Table 3.1: Superfund milestones.

Year	Event/Activity	Party	Program	Ref(s)
1982	EPA conducts preliminary assessment site investigation to determine if Torch Lake should be listed as a Hazardous Waste Site	U.S. EPA	Superfund	30
1986	Torch Lake is listed on NPL	U.S. EPA	Superfund	6
1988	Donohue and Associates publish Compository Summary	U.S. EPA/Donohue	Superfund	31
1989-1990	Donohue and Associates conduct Remedial Investigations in all three Operable Units.	U.S. EPA/Donohue	Superfund	32, 33
1989-1990	Drums on shore and underwater in Lake Linden are sampled	U.S. EPA	Superfund	
1990	Wetlands investigation is conducted	Weston	Superfund	34
1990	Mine Tailings are evaluated for leachability	U.S. Bureau of Mines	Superfund	35
1991	Drums removed	U.S. EPA	Superfund	
1992	Record of Decision for OUs I and III published	U.S. EPA	Superfund	37
1994	Record of Decision for OU II published	U.S. EPA	Superfund	8
1998	Lake Linden stamp sands capped with soil and vegetated	U.S. EPA	Superfund	
2000/2001	Hubbell/Tamarack stamp sands capped with soil and vegetated	U.S. EPA	Superfund	
2002	Mason stamp sands capped with soil and vegetated	U.S. EPA	Superfund	
2002	Lake Linden stamp sands deleted from NPL	U.S. EPA	Superfund	
2002	OU II deleted from NPL	U.S. EPA	Superfund	

Year	Event/Activity	Party	Program	Ref(s)
2003	First Five-Year Review published	U.S. EPA	Superfund	
2004	Hubbell/Tamarack stamp sands deleted from NPL	U.S. EPA	Superfund	
2007-2008	Survey of lake sediments for PCBs	MDEQ and U.S. EPA		
2008	Second Five-Year Review published	U.S. EPA	Superfund	41
2012	Mason stamp sands deleted from NPL	U.S. EPA	Superfund	
2013	Third Five-Year Review published	U.S. EPA	Superfund	36

3.6 Emergency Removal Actions

Several remediation activities occurred in Torch Lake after the Superfund remedial actions were executed. By 2007, it was found that mine tailings that had previously been underwater were exposed due to the lake level dropping approximately 2 feet. Specifically, a sludge material was exposed near the Lake Linden Public Beach ⁴¹. As a result, the MDEQ sampled the sludge. “Laboratory analysis of the sludge revealed the presence of antimony, arsenic, barium, copper, and lead at concentrations exceeding MDEQ Part 201 Residential Direct Contact Criteria (RDCC)... and exceeded, by a factor of 20, the extract of Toxicity Characteristic Leaching Procedure (TCLP) limits.” ⁴² Upon the discovery of these contaminants, an emergency removal of the contaminated materials was performed until the concentrations were below direct contact levels ⁴¹.

Also as a result of discovery of the contaminants, the Torch Lake Area Assessment was conducted by Weston, Inc. in 2007 ⁴¹. The goal of this study was “to evaluate imminent threats to human health, welfare and the environment, along with identification of areas for additional investigation.” ⁴² The Torch Lake Area Assessment revealed the presence of elevated concentrations of arsenic, lead and copper in the Mason stamp sands ⁴² and an emergency removal was conducted at this location in 2008 ³⁶.

In 2013, the Tamarack Stamp Mill site was sampled by the MDEQ as a part of ongoing environmental assessments at the site ⁴³. Asbestos was found in three samples of the historic remnants piles. The asbestos-containing material was removed in July and August of 2014 ⁴⁴.

At the C&H Lake Linden Power Plant, another contaminant removal occurred. As part of the landowner’s site evaluation for residential development, a variety of contaminants were found at this site. Asbestos-containing material was widespread throughout the site and inside the power plant, and detected in surface soil and air samples. Soil was also contaminated by arsenic, antimony, copper, iron and lead. These metals were present in concentrations above the Michigan Part 201 Residential Direct Contact Criteria. PCBs were detected in water in the basement of the power plant ⁴⁵. Perhaps because a Responsible Party was available to pay for the cleanup, remediation was conducted to enable the site to be used for commercial purposes. Emergency removal actions on the site included: soil investigations for metals and asbestos in 2012-2014, activity-based asbestos sampling, removal of berms and debris piles, abatement and decontamination of asbestos inside the power plant, demolition of the power plant, cleaning asbestos from onsite foundations, removing or covering remaining contaminated soils, treating and discharging PCB-contaminated basement water, removing the building floor and assessing the contamination present in the basement of the building, air monitoring, and restoring the site ⁴⁶.

Table 3.2: Emergency Removal actions.

Year	Location	Action Taken	Contaminants	Precipitating Event
2004-2005, 2008	Quincy Smelter	Removal of drums, tanks, vats, small containers of hazardous substances, and asbestos-containing material; stack height removal; air monitoring ⁴⁷	Asbestos, mercury	An asbestos abatement assessment was conducted on the site; the removal was conducted as a result. ⁴⁷
2007	Lake Linden	Sludge material removed	Antimony, arsenic, barium, copper, lead, PCBs	Previously submerged mine tailings were exposed due to lake level dropping approx. 2 feet.
2008	Mason	Contaminated material removed	Arsenic, lead, copper	Contaminated material was found in Mason during sampling conducted for the Torch Lake Area Assessment.
2011	C&H Lake Linden Power Plant	Preliminary sampling conducted	Asbestos	From ongoing environmental assessments it was found that asbestos contamination is widespread throughout the site.

Year	Location	Action Taken	Contaminants	Precipitating Event
2012-2014	C&H Lake Linden Power Plant	Activities consist of soil sampling, activity-based asbestos sampling, removal of berms and debris piles, abatement and decontamination of asbestos from inside the power plant and demolition of the power plant	Asbestos, arsenic, antimony, copper, iron, lead, PCBs	
2013	Tamarack Stamp Mill	Asbestos-containing material removed	Asbestos	From ongoing environmental assessments, it was found that asbestos contamination is widespread throughout the site.
2013	Michigan Smelter	Removal of accessible waste piles, posting of contamination warning signs around the boundaries of the smelter ruins, installing a 6-inch cover over approximately 1.5 acres of the site. ⁴⁸	Arsenic, lead, copper, metal-contaminated smelter waste, asbestos-containing materials, a battery pile. ⁴⁸	

3.7 AOC Actions

Under the AOC program, three Beneficial Use Impairments (BUIs) were identified for Torch Lake: 1) Fish Tumors and Other Deformities, 2) Restrictions on Fish and Wildlife Consumption, and 3) Degraded Benthos. External and internal fish tumors were found on Sauger and Walleye caught from Torch Lake starting in the late 1960s⁵. The cause for these tumors was not confirmed. It could have been the presence of creosotes in the water discharged for years from the flotation plants; a study conducted by Michigan Tech in 1986 stated that it was possible that exposure to creosote could result in liver tumors²³, but this was never confirmed as the cause of the tumors found in the Sauger and Walleye. The Fish Tumor and Other Deformities BUI was delisted in 2007 – it met the state criteria for delisting because no reports of fish tumors or deformities due to chemical contaminants were verified through observation or analysis by the MDNR or MDEQ for a period of five years prior to 2007⁵.

The Degraded Benthos BUI is considered addressed (but not delisted) by the Superfund program's remedial actions for OUs I and II. The degradation of benthos is caused by the presence of copper in the sediment and water, as copper is toxic to benthic organisms. According to the 2007 RAP Update, the capping of the exposed stamp sand piles and the natural attenuation of the lake sediments meet Michigan's delisting criteria guidance for the degradation of benthos, though it is mentioned that this is dependent upon monitoring of the natural attenuation process⁵. Once the capping was complete, the degradation of benthos could be delisted⁵.

The Restriction on Fish and Wildlife Consumption BUI has been listed since 1987, but fish consumption advisories have been placed, removed and replaced since 1983. In 1983, a restriction on fish consumption was put in place by the Michigan Department of Public Health due to the presence of fish tumors⁵. This was a precautionary action because it was not clear what caused the fish tumors⁴. The original fish consumption

BUI was listed in 1987 in the original RAP for the Torch Lake AOC ⁴. In the 1990 MDNR report on Fish Growth Anomalies in Torch and Portage Lakes, it was stated that the frequency of tumors decreased and that the data no longer supported the original fish consumption advisory ⁴⁹. The original fish consumption advisory was removed in 1993 ⁵.

The present restriction on fish consumption BUI is caused by the elevated concentrations of PCBs and mercury found in the fish (mainly Walleye, Northern Pike and Smallmouth Bass) caught in Torch Lake. The advisory due to mercury has been in place since 1992 and applies to all inland lakes in Michigan, while the advisory due to PCBs was established in 1998 based on revised state trigger levels for PCBs ⁵. The present BUI exists because the Torch Lake fish consumption advisories based on PCBs and mercury in fish are more restrictive than those of their associated Great Lake, Lake Superior ⁵.

According to the 2007 RAP Update, the next step to delisting the Fish Consumption BUI is identifying and remediating the source of PCBs driving the Fish Consumption Advisories ⁵, a goal towards which part of this research works. “If it is determined that sediments are the source, then the next decision will be whether sediment remediation will be necessary or if the U.S. EPA’s natural attenuation/natural sedimentation for Torch Lake with monitoring is adequate to address this issue over time.” ⁵ In an effort to determine if a source of PCBs that could lead to the fish consumption advisory exists within Torch Lake itself, three sampling campaigns were performed: one using semi-permeable membrane devices to derive PCB concentrations in water (done in 2005) and two in 2007 and 2008 sampling sediment. The results of these studies were used in this research and will be further discussed in Chapter 5.

A fish consumption advisory due to mercury still exists at Torch Lake, because a fish consumption advisory due to mercury exists for all inland lakes in Michigan ⁵. The fish consumption BUI does not still exist in Torch Lake on account of mercury. In 2007 it

was determined that the fish consumption advisory BUI in Torch Lake due to mercury was no longer necessary because the criteria to delist the BUI in terms of mercury had been met ⁵. This criteria was that the fish consumption advisory in an AOC must be as or less restrictive than the fish consumption advisory in its associated Great Lake ⁵.

In summary, the remedial actions or lack thereof that took place in the decades succeeding the last mining-related activities on Torch Lake have had a significant impact on the current contamination state of the Torch Lake site. By reading this overview of the remedial actions and environmental studies, one understands the environmental impact the processing of copper ore had on the Torch Lake system and the disparities between the environmental evaluations made and the remedial actions taken. Despite the findings of studies conducted in the 1970s and 1980s, remedial actions were not taken until the early 1990s, by when the findings of the first studies may not have been entirely valid. That several post-delisting emergency removal actions were required in OUI indicates that the remedial actions taken under the Superfund program were not fully effective. Two BUIs under the AOC program (the restriction on fish consumption and the degradation of benthos) have existed since 1987 and continue to exist today, which suggests that the approach to delisting these BUIs needs to be examined. The next two chapters solidify the suggestions that the remedial actions that have been executed to date have not effectively treated, let alone solved the contamination issues on the Torch Lake site. In Chapter 4, the existing metals contamination is examined, and in Chapter 5, the existing PCB contamination is examined.

Table 3.3: AOC and AOC-related remediation milestones.

Year	Event/Activity	Party	Program	Reference(s)
1970	Report published - Biological Evaluation of Torch Lake, Houghton Michigan	Michigan Water Resources Commission Bureau	N/A	15
1973	Report published - An Evaluation of a Cupric Ammonium Carbonate Spill into Torch Lake, Houghton County, Michigan	Michigan Water Resources Commission Bureau	N/A	24
1973	Conference Proceedings - Water Quality Alternation of Torch Lake, Michigan by Copper Leach Liquor	Michigan Tech / Wright et al.	N/A	25
1974	Thesis published - Growth Phenomena and Abnormalities of the Sauger, <i>Stizostedion Canadense</i> (Smith), of the Keweenaw Waterway	Michigan Tech/Tomljanovich	N/A	11
1977	Thesis published - Benthos, particle size composition, and sediment copper comparisons between the North and South Keweenaw Waterway Entries	Michigan Tech / Sypniewski	N/A	50
1979	Article published - Pontoporeia distribution along the Keweenaw shore of Lake Superior affected by copper tailings	Kraft, K.J.		51
1981	Article published – Effect of Sediment Copper on the Distribution of Benthic Macroinvertebrates in the Keweenaw Waterway	Kraft, K.J. and Sypniewski, R.H.		19

Year	Event/Activity	Party	Program	Reference(s)
1982	Article published - Epizootic neoplasms in fishes from a lake polluted by copper mining wastes	Black, J.J et al.	N/A	26
1983	Original fish consumption advisory established as a result of the presence of fish tumors.	MDP[C]H		
1985	IJC Water Quality Board identifies Torch Lake as a Great Lakes Area of Concern	IJC	AOC	1
1986	Michigan Tech publishes report on Torch Lake examining fish tumors, the environmental fate of xanthates, creosotes, and heavy metals in sediments and mine wastes, and a copper budget in Torch Lake	Michigan Tech		23
1987	Torch Lake is designated as an AOC with the establishment of the program under the Revised Great Lakes Water Quality Agreement	U.S. EPA	AOC	2
1987	AOC Remedial Action Plan published	MDNR	AOC	4
1990	Fish study report	MDNR		
1992	Statewide advisory for Hg in inland lakes	MDCH		
1993	Fish consumption advisory due to fish tumors is removed	MDCH		

Year	Event/Activity	Party	Program	Reference(s)
1998	Fish consumption advisory due to elevated PCB and Hg concentrations in TL fish established	MDCH		
2005	MDEQ conducts SPMD study	MDEQ	AOC	
2007	AOC Remedial Action Plan Update published	MDEQ	AOC	5
2007	Fish Tumor BUI removed	MDCH	AOC	
2007	MDEQ conducts sediment chemistry site investigation	MDEQ	AOC	
2008	EPA samples sediment throughout Torch Lake	U.S. EPA	AOC	

Table 3.4: All Torch Lake remediation milestones.

Year	Event/Activity	Party Program	Notes	Ref(s)
1969	Thesis published - The Biological and Chemical Effects of Saline Mine Water on the Receiving Water System (Torch Lake)	Michigan Tech/Yanko N/A		
1970	Report published - Ground Water and Geology of Keweenaw Peninsula	MDNR N/A		22
1970	Report published - Recovery of Copper from Michigan Stamp Sand	Michigan Tech / Institute of Mineral Research N/A		27
1970	Report published - Biological Evaluation of Torch Lake, Houghton Michigan	Michigan Water Resources Commission Bureau N/A		15
1972	Thesis published - The Effects of Fertilization on Interstitial Water Quality in Copper Mine Tailings	Michigan Tech/Wilson N/A		17
1973	Thesis published - Factors Controlling Soluble Copper(II) Levels in the Keweenaw Waterway	Michigan Tech/Brandt N/A		20
1973	Report published - An Evaluation of a Cupric Ammonium Carbonate Spill into Torch Lake, Houghton County, Michigan	Michigan Water Resources Commission Bureau N/A		24
1973	Report published - Factors Controlling Copper(II) Concentrations in the Keweenaw Waterway: A Project Completion Report	Michigan Tech/Leddy N/A		21

Year	Event/Activity	Party Program	Notes	Ref(s)
1973	Thesis published - Aqueous environmental chemistry of copper and other heavy metals in Torch Lake and selected waters of the Keweenaw Peninsula of Lake Superior	University of Wisconsin / Lopez Diaz N/A		16
1973	Thesis published - Vegetative stabilization of reclaimed copper stamp-sands	Michigan Tech/Prather N/A		
1973	Conference Proceedings - Water Quality Alternation of Torch Lake, Michigan by Copper Leach Liquor	Michigan Tech / Wright et al. N/A		25
1974	Thesis published - Growth Phenomena and Abnormalities of the Sauger, <i>Stizostedion Canadense</i> (Smith), of the Keweenaw Waterway	Michigan Tech/Tomljanovich N/A		11
1974	Thesis published - Long-Term Water Quality Analysis of Torch Lake, Michigan	Michigan Tech/Virnig N/A		18
1977	Article published - Environmental chemistry of copper in Torch Lake, Michigan	Lopez, J.M. N/A		
1977	Report published - Establishing Vegetation on Alkaline Iron and Copper Tailings	MDNR N/A		
1981	Report published - Hydrogeological Evaluation for Houghton County Wastewater Disposal	L.M. Miller and Associates Consulting Engineers and Geologists N/A		18

Year	Event/Activity	Party Program	Notes	Ref(s)
1981	Article published - Effect of Sediment Copper on the Distribution of Benthic Macroinvertebrates in the Keweenaw Waterway	Kraft, K.J. and Sypniewski, R.H. N/A		19
1982	Article published - Epizootic neoplasms in fishes from a lake polluted by copper mining wastes	Black, J.J et al. N/A		26
1982	EPA conducts preliminary assessment site investigation to determine if Torch Lake should be listed as a Hazardous Waste Site	U.S. EPA Superfund		30
1983	Original fish consumption advisory established as a result of the presence of fish tumors.	MDP[C]H		
1985	IJC designates Torch Lake as a Great Lakes Area of Concern	IJC N/A		1
1986	Torch Lake is listed on NPL	U.S. EPA Superfund		6
1986	Michigan Tech publishes report on Torch Lake examining fish tumors, the environmental fate of xanthates and creosotes, heavy metals in sediments and mine wastes, and a copper budget in Torch Lake	Michigan Tech		23
1987	Torch Lake is designated as an AOC with the establishment of the program under the Revised Great Lakes Water Quality Agreement	U.S. EPA	AOC	2

Year	Event/Activity	Party Program	Notes	Ref(s)
1987	AOC Remedial Action Plan published	MDNR AOC		4
1988	Donohue and Associates publishes Compository Summary	U.S. EPA/Donohue Superfund		31
1989-1990	Donohue and Associates conducts Remedial Investigations in all three Operable Units	U.S. EPA/Donohue Superfund		32, 33
1989-1990	Drums on shore and underwater in Lake Linden are sampled	U.S. EPA Superfund		
1990	Wetlands investigation is conducted	Weston Superfund		34
1990	Mine tailings are evaluated for leachability	U.S. Bureau of Mines Superfund		35
1991	Drums removed	U.S. EPA Superfund		
1992	Record of Decision for OUs I and III published	U.S. EPA Superfund		37
1993	Fish consumption advisory due to fish tumors is removed.	MDCH		
1994	Record of Decision for OU II published	U.S. EPA Superfund		8
1998	Fish consumption advisory due to elevated PCB and Hg concentrations in TL fish established	MDCH		
1998	Lake Linden stamp sands capped with soil and vegetated	U.S. EPA Superfund		

Year	Event/Activity	Party Program	Notes	Ref(s)
2000/ 2001	Hubbell/Tamarack stamp sands capped with soil and vegetated	U.S. EPA Superfund		
2002	Mason stamp sands capped with soil and vegetated	U.S. EPA Superfund		
2002	Lake Linden stamp sands deleted from NPL	U.S. EPA Superfund		
2002	OU II deleted from NPL	U.S. EPA Superfund		
2003	First Five-Year Review published	U.S. EPA Superfund		
2004	Hubbell/Tamarack stamp sands deleted from NPL	U.S. EPA Superfund		
2005	MDEQ conducts SPMD study	MDEQ AOC		
2007	Extensive sampling conducted on newly-exposed Lake Linden stamp sands	MDEQ Emergency Removal		
2007	Emergency removal occurs at Lake Linden mine tailings	U.S. EPA Emergency Removal	Sludge material containing antimony, arsenic, barium, copper and lead was removed.	
2007	AOC Remedial Action Plan Update published	MDEQ		5
2007	Fish Tumor BUI removed	MDCH AOC		
2007	As a result of finding contaminants in the Lake Linden coastal sediments, MDEQ and EPA sample sediment along western shore and down to Quincy Smelter	Weston Emergency Removal		42

Year	Event/Activity	Party Program	Notes	Ref(s)
2007	MDEQ conducts sediment chemistry site investigation	MDEQ AOC		
2008	Emergency removal occurs at Mason stamp sands	U.S. EPA Emergency Removal	Material containing arsenic, lead and copper removed	42
2008	Second Five-Year Review published	U.S. EPA Superfund		41
2008	U.S. EPA samples sediment throughout Torch Lake	U.S. EPA AOC		
2011	Emergency removal activity begins at C&H Power Plant in Lake Linden	U.S. EPA Emergency Removal	Preliminary sampling is conducted	45
2012	Mason stamp sands deleted from NPL	U.S. EPA Superfund		
2012-2014	Emergency removal activity continues at the C&H Power Plant site in Lake Linden	U.S. EPA Emergency Removal	Activities consist of soil sampling, activity-based asbestos sampling, removal of berms and debris piles, abatement and decontamination of asbestos from inside the power plant and demolition of the power plant	45
2013	Emergency removal occurs at the Tamarack Stamp Mill site	U.S. EPA Emergency Removal	Asbestos-containing material removed	45
2013	Third Five-Year Review published	U.S. EPA Superfund		36

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49. MDNR Staff Report: Fish Growth Anomalies in Torch and Portage Lakes 1974-1988 Houghton County, Michigan; MDEQ: March 1990.
50. Sypniewski, R. H., Benthos, particle size composition, and sediment copper comparisons between the North and South Keweenaw Waterway Entries. 1977.
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4 METALS ANALYSIS

4.1 Introduction

To those who are already familiar with Torch Lake, the pollution of the lake by mine tailings, stamp sands and copper is well-known. These are the obvious products of stamping and reclamation/reprocessing. What is less obvious is the presence of other metals that were involved in or are byproducts of milling and reprocessing. The metals that were selected for this analysis are Arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), and zinc (Zn). All of these metals were byproducts of the stamping or gravimetric separation of copper from ore (Donohue and Associates, 1991a; GreenFacts, 2015). The selection of metals sampled in each study depended on what is of most concern to human health and what is listed on the U.S. EPA's Target Contaminant List (Donohue and Associates, 1991a; Life Systems, 1991). The purpose of this metals analysis is to determine where elevated concentrations of selected metals of concern are located in Torch Lake sediments and the soil along the western shore. The locations and magnitudes of these elevated concentrations are useful for evaluating potential human and environmental health impacts; such risk analysis, in turn, should inform remedial actions.

The goals of this chapter include the following:

1. compile all available metals concentration data into maps;
2. determine spatial and temporal trends of the metals concentrations in sediment and upland material; and
3. compare recorded concentrations to environmental and human health standards.
4. recommend where/how remediation should be conducted.

Compiling the data enables us to view trends in the concentrations. By determining the spatial and temporal trends of the concentrations, along with comparing these trends to the locations of historical industrial buildings, we may be able to determine what the main causes of pollution were and where future remediation should be concentrated. The comparison of recorded concentrations to environmental and human health standards helps to prioritize future remediation actions that could be more effective than the ones that have been implemented so far.

The data compilation also helps us to understand if there are patterns in the metals concentrations based on the materials in which they were sampled. In many of the data sources, sample media were identified as either soil or sediment. The lake sediment is actually mostly mine tailings underneath a few centimeters of natural sediment cover (McDonald & Urban, 2007). The edge of the western shore is currently comprised of mine tailings covered by a vegetated six-inch soil cap. A key difference between the samples taken on the tailings piles in the late 1980s-early 1990s and the later samples collected from 2007 to 2011 is that the earlier samples did not include a vegetated soil cap, as they were sampled before the caps were put in place in 1998 (Lake Linden), 2000-2001 (Hubbell-Tamarack) and 2002 (Mason).

The historical analysis of buildings along the western shoreline of Torch Lake can be used to determine if there are other metals or chemicals that should be considered in environmental sampling based on what industrial processes took place at different locations. For example, points of interest include the Calumet and Hecla Stamp Mills sites in Lake Linden and the C&H Smelter in Hubbell. Metals that could be found at the stamp mill sites include copper, arsenic, chromium, lead and zinc (Donohue and Associates, 1991a). As shown in the results section, all of these metals are found at these sites. Besides the stamp mills, other points of interest include the flotation plants, the electrolytic plant and the smelter. Many of the chemicals that were involved in or are by-products of flotation are non-metals, though slimes (very fine grained sands) from

modernized mills and flotation plants at reclamation facilities may have contained heavy metals.(Urban et al., 2016 (Expected)) Leaching may have produced heavy metals besides copper. Heavy metals associated with flotation and leaching are likely to be found near the Lake Linden and Tamarack mine tailings piles. Wastes produced by smelting include slag, which consisted of oxides of silicon, aluminum, calcium and magnesium, as well as copper and nickel metals. Smelter waste also included fly ash produced by burning coal to run the smelter furnaces, and scrap copper. Wastes associated with smelting are likely to be found near the C&H Smelter in Hubbell. Waste heavy metals from coal combustion can be found near the C&H Power Plant in Lake Linden. (Urban et al., 2016 (Expected))

The elements of this chapter include this introduction, methods (sampling and mapping analysis), and results and discussion. The methods section is divided into two parts: a summary of the field methods and a description of the analysis methods. The results section discusses what trends were found in the reported metals concentrations and how the reported concentrations compare to Michigan Part 201 Residential Soil Direct Contact Criteria (SDCC), Threshold Effect Concentrations, and Probable Effect Concentrations (explained in further detail in the Results section). The ensuing discussion explains what is learned from the results.

4.2 Methods

All available documents on Torch Lake were reviewed for any metals sampling data.

The sources for the metals data mapped consist of the following documents:

Table 4.1: Sources of Data.

Source Title	Source Year	Source Author	Sample Medium	Sample Type (and Depth if available)
Emergency Removal Investigation	2011	MDEQ	Soil	Surface (Ranges from 0"-10")
Emergency Removal Investigation	2011	MDEQ	Soil	Boring (Most cores were taken to 8', one was taken to 10' and two were taken to 12')
Emergency Removal Investigation	2011	MDEQ	Sediment	Surface (Depth of samples averaged 3")
Weston Area Assessment	2007	Weston	Tailings	Mostly XRF, occasional laboratory backups (though
Sediment survey	2007	MDEQ	Sediments	Surface (6")
Baseline Study	2001	EPA	Sediment	Grab
Baseline Study	2001	EPA	Sediment	Core
RI/FS OUII Vol.2 Appendices A,B,C	1991	Donohue	Sediment	Mostly surface, some core
Final Baseline Risk Assessment Report OUI	1991	Life Systems	Tailings	Surface (0"-6")
Final Baseline Risk Assessment Report OUI	1991	Life Systems	Tailings	Core (0'-3')
Final Remedial Investigation Report OUI Vol.1	1990	Donohue	Tailings	Surface (0"-6")
Final Remedial Investigation Report OUI Vol.1	1990	Donohue	Tailings	Subsurface (0'-3')

4.2.1 Sampling Methods

This section gives an overview of the sampling methods used for the studies listed in Table 4.1 above.

MDEQ Emergency Removal 2011

Three types of samples were included in the data received from the 2011 Emergency Removal: surface soil, soil boring and sediment samples. Based on the data available (MDEQ 2011c), it is assumed that the soil borings were done using a split-spoon sampler. Most of the borings were done in 4-foot intervals down to 8 feet. Three samples were bored down to 12 feet, and one sample was bored down to 10 feet. Though the material sampled is listed as soil, based on the locations of the samples, it is more likely that the material sampled consisted of tailings or slag. For both the surface soil and sediment samples, based on the depths of the samples (MDEQ 2011c; MDEQ 2011a) and the locations of the samples, it is assumed that the samples were taken using either a trowel or a petite ponar. Again, though the sampled material is listed as soil and sediment, this material is likely tailings or slag. The lab analysis procedures for the different samples are described in several documents (EPA, 2011b; EPA, 2011a; EPA, 2011c).

Weston Torch Lake Area Assessment 2007

The Weston Torch Lake Area Assessment (“Assessment”) spanned various locations in all three operable units. The locations that pertain to our integrated assessment are those that exist in Operable Unit I, the stamp sands along the western shore of Torch Lake. Concentrations of metals were obtained using XRF Screening (Weston Solutions, 2007). Further details about the sampling were not provided in the report.

U.S. EPA Baseline Study 2001

In the Baseline Study, sediment, surface water and groundwater samples were taken. Only the sediment samples were analyzed. Sediment samples were taken in 1999 and 2000. Thirty-two of these samples were grab samples (including 2 duplicates), 8 were vibrocore samples and 4 were multicore samples. The grab samples were taken using either a full ponar (1999) or a petite ponar (2000) and all grab samples were taken at an interval of 0"-6". It is inferred by the author that the organic layer was analyzed, but it is not specified in the report if the ponar samples were mixed. The vibrocore samples were taken in 1999 and approximately 100 inches of material was recovered in 26 segments (EPA, 2001). For this analysis, only concentration for the surficial layer of the core (which ranged in depth from 12" to 36") was used. The entire concentrations of the multicore samples were used and the depths of these concentrations ranged from 6" to 100".

Remedial Investigation / Feasibility Study OUII Vol.2 Appendices A, B, C

Sediment samples were taken at 25 locations throughout the lake. Both grab and core samples were taken. Grab samples were taken using an Ekman dredge and reached a depth of 4". Core samples reached a depth of 2'. The first two layers (ranging from 0.1"-0.8" and 0.4"-2.4") of sediment consisted of organic material, which in most instances was removed from the samples before they were prepared for laboratory analysis. The material underneath the organic layers consisted of mine tailings (Donohue and Associates, 1991b).

Final Baseline Risk Assessment Report OUI

Mine tailings samples were taken at locations in Lake Linden, Tamarack/Hubbell and Mason. Both surficial ponar and core samples were taken at each location. Surficial samples ranged in depth from 0"-6" and core samples ranged in depth from 0'-3' (Life Systems, 1991).

Final Remedial Investigation Report OUI Vol.1

Mine tailings samples were taken at locations in Lake Linden, Tamarack/Hubbell and Mason. Both surficial and core samples were taken at each location. Surficial samples ranged in depth from 0"-6" and core samples ranged in depth from 0'-3' (Life Systems, 1991).

4.2.2 Analysis Methods

The metals that were selected for analysis here are Arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg) and zinc (Zn). There are a variety of reasons that these metals were chosen for analysis. The reason to analyze copper is obvious, as the material that was processed on Torch Lake was copper ore. Arsenic was analyzed because it is a natural enrichment of copper ore. The other metals were analyzed due to their presence as trace metals in copper ore, their enrichment in the metal concentrate sent from the flotation plant to the smelter (particularly zinc, chromium and lead), their enrichment in the slimes that reached the lake, and their presence in the scrap metal that was leached to recover copper (especially lead). (Urban et al., 2016 (Expected)) Mercury was selected because there is currently a fish advisory consumption on Torch Lake, due in part to the presence of Mercury. Point data layers for these and

other sampled metals (but not included in this analysis) were created using data from the documents/data listed in Table 1 above. In addition to the point data layers, polygon layers for Torch Lake and Houghton County were taken from the Michigan Geographic Data Library (MiGDL); and the polygon layer for the Houghton County Parcels (which was also used to derive village / surface stamp sand layers) was obtained from the Western Upper Peninsula Planning and Development Region (WUPPDR).

Three types of maps were created for each metal of concern. The first is an overview map showing the range of concentrations of the metal in both sediment and soil. The second type of map compares concentrations of a selected metal sampled to the Michigan Part 201 Residential Soil Direct Contact Criteria (DCC). The final type of map created for each metal compares concentrations of the selected metal found in the sediment to the Threshold Effect Concentration (TEC) and the Probable Effect Concentration (PEC). The TEC is the concentrations below which harmful effects are unlikely to be observed; the PEC is the concentration above which harmful effects are likely to be observed (MacDonald et al., 2000).

4.2.2.1 Overview Analysis

The first type of map is an overview map showing the range of concentrations of the metal in both sediment and soil. The classification method chosen is a log scale, to accommodate the full range of concentrations detected for each metal. In an effort to keep the colors of the classes consistent among layers, the same scale was chosen for all layers. The layers are distinguished by source and type of information, as explained above. On each map, only the classes that are used in that map appear in the legend.

4.2.2.2 Soil Metal Concentration Analysis

The second type of map compares concentrations of a selected metal sampled to the Michigan Part 201 Residential Soil Direct Contact Criteria (SDCC). The Michigan Part 201 Residential Soil Direct Contact Criteria was used because the surface stamp sand piles are in close proximity to residential areas and are themselves used for residential purposes. In the 2007 Weston Torch Lake Area Assessment, reported metals concentrations were also compared to the Michigan Part 201 Statewide Default Background Levels (SDBL) and the MDCH Screening Values, but these values are greater in magnitude and therefore less conservative than the SDCC. The most updated criteria are from 2012 and are shown in Table 4.2:

Table 4.2: Residential Soil Direct Contact Criteria for Analyzed Metals (MDEQ, 2012).

Metal	Residential Soil Direct Contact Criteria (ppm)
Arsenic (As)	7.6
Cadmium (Cd)	550
Chromium (Cr)	790000
Copper (Cu)	20000
Lead (Pb)	400
Mercury (Hg)	160
Zinc (Zn)	170000

For each metal, locations where the concentration is equal to or exceeds the DCC are shown in red, locations where the concentration is below the DCC are shown in green, and locations where the metal was sampled but not detected are distinguished with the symbol “X”. Because two sources of soils data were provided approximately 20 years before the other two sources of soils data, it was decided to distinguish this time difference. The solution was to represent the older data using faded versions of the colors used to represent the more recent data; using light red to represent concentrations that meet or exceed the DCC, and light green to represent concentrations that are below the DCC. Locations where the metal was not detected are still represented with the symbol “X”.

4.2.2.3 Sediment Metal Concentration Analysis

The final type of map created for each metal is a map comparing concentrations of the selected metal found in the sediment to the Threshold Effect Concentration (TEC) and the Probable Effect Concentration (PEC). According to the MDEQ, remediation criteria for a site are determined on an individual basis based on a list of factors mentioned in the Remediation and Redevelopment Division (RRD) Operational Memorandum No.4. However, when the MDEQ is in the initial phase of characterizing the sediment, the TEC and PEC levels can be used to help characterize the sediment (MDEQ, 2012). The development of the TEC and PEC values used by the MDEQ is described in MacDonald et al., 2000. The TEC and PEC levels are the geometric means of values compiled from other sources (MacDonald et al., 2000). For this reason, they are the values to which the metal concentrations in sediments are compared. The TEC and PEC values are summarized in Table 4.3 below:

Table 4.3: Threshold and Probable Effect Concentrations for Analyzed Metals.

Metal	Threshold Effect Concentration (ppm)	Probable Effect Concentration (ppm)
Arsenic (As)	9.79	33.0
Cadmium (Cd)	0.99	4.98
Chromium (Cr)	43.4	111
Copper (Cu)	31.6	149
Lead (Pb)	35.8	128
Mercury (Hg)	0.18	1.06
Zinc (Zn)	121	459

For these maps, the two sources of sediment contaminant concentrations mentioned above are used. Locations where the concentration of the metal of concern is at or above the PEC are represented by red stars. Locations where the concentration is at or above the TEC but below the PEC are represented by gray stars, and locations where the concentration is detected below the TEC are represented by green circles. As with the soil concentration maps, due to the approximately 20 year difference between the two sources of data, the color scheme used for the older data is a faded version of that used for the more recent data, consisting of light red, white, and light green in place of bright red, gray and bright green.

4.3 Results and Discussion

To assist in understanding the results of the mapping analyses, the statistics of the sediment and soil sample concentrations are provided in Table 4.4 and Table 4.5, respectively. The sediment and soil datasets include all samples taken, regardless of depth of sample. Maximum likelihood estimation (MLE) was used to calculate statistics for both sediment and soil samples; this method provides the most robust estimates of sample statistics in highly censored data (i.e., data in which many samples are reported as below the detection limit). In Table 4.4, values in red exceed the PEC, values in orange

are less than the PEC but greater than the TEC. In Table 4.5, values in red exceed the DCC. In both sets of statistics, the median values tend to be more representative of the concentrations than the mean value.

Table 4.4: Statistics of Sediment Concentrations.

Metal	As	Cd	Cr	Cu	Pb	Hg	Zn
Mean (ppm)	61.9	1.5	58.2	2189.7	180.2	0.2	230.2
Variance (ppm)	415.8	5.4	69.2	3036.2	741.8	0.2	258.4
Median (ppm)	14.0	1.7	51.6	1600.0	45.9	0.2	170.0
Maximum (ppm)	4560.0	57.2	690.0	28000.0	7800.0	1.2	2170.0
Minimum (ppm)	0.7	0.1	1.9	5.0	1.3	0.0	7.0
Number of samples below detection limit	3	72	2	1	5	49	0
Number of samples above detection limit	116	47	117	118	114	70	119
Total Number of Samples	119	119	119	119	119	119	119

Table 4.5: Statistics on Upland Concentrations.

MLE	As	Cd	Cr	Cu	Pb	Hg	Zn
Mean	135.8	30.8	137.8	25590.0	317.5	0.5	2606.0
Variance	672.4	36.2	743.3	196410.0	1673.2	2.6	22496.0
Median	2.6	1.2	23.4	794.0	6.7	0.1	63.5
Maximum	5600.0	96.3	7850.0	2735217.0	16100.0	20.8	261353.0
Minimum	0.4	0.2	3.4	8.8	0.9	0.0	11.4
Number of Samples NOT Identified as NDs or Below Detection Limit	103	27	164	245	202	112	178
Total Number of Samples	255	255	255	255	255	255	255

As with the sediments, for values that were below their detection limits, half the detection limit was used in the analysis, except for the Weston dataset, for which these values were not available. More variation was observed in the upland data because concentrations of metals tend to be higher near certain locations such as the C&H Smelter in Hubbell, the Quincy Reclamation Plant in Mason, the Calumet and Hecla Stamp Mills, and the C&H Power Plant in Lake Linden.

4.3.1 Overview Analysis

The overview analysis maps (Figure 4.1-Figure 4.7) of each metal show the distribution of concentrations in the sediment and adjacent soil. Point layers are distinguished by source so that temporal changes can be seen in addition to spatial variation. Observations for each metal are summarized in Table 4.6 (following Figure 4.7):

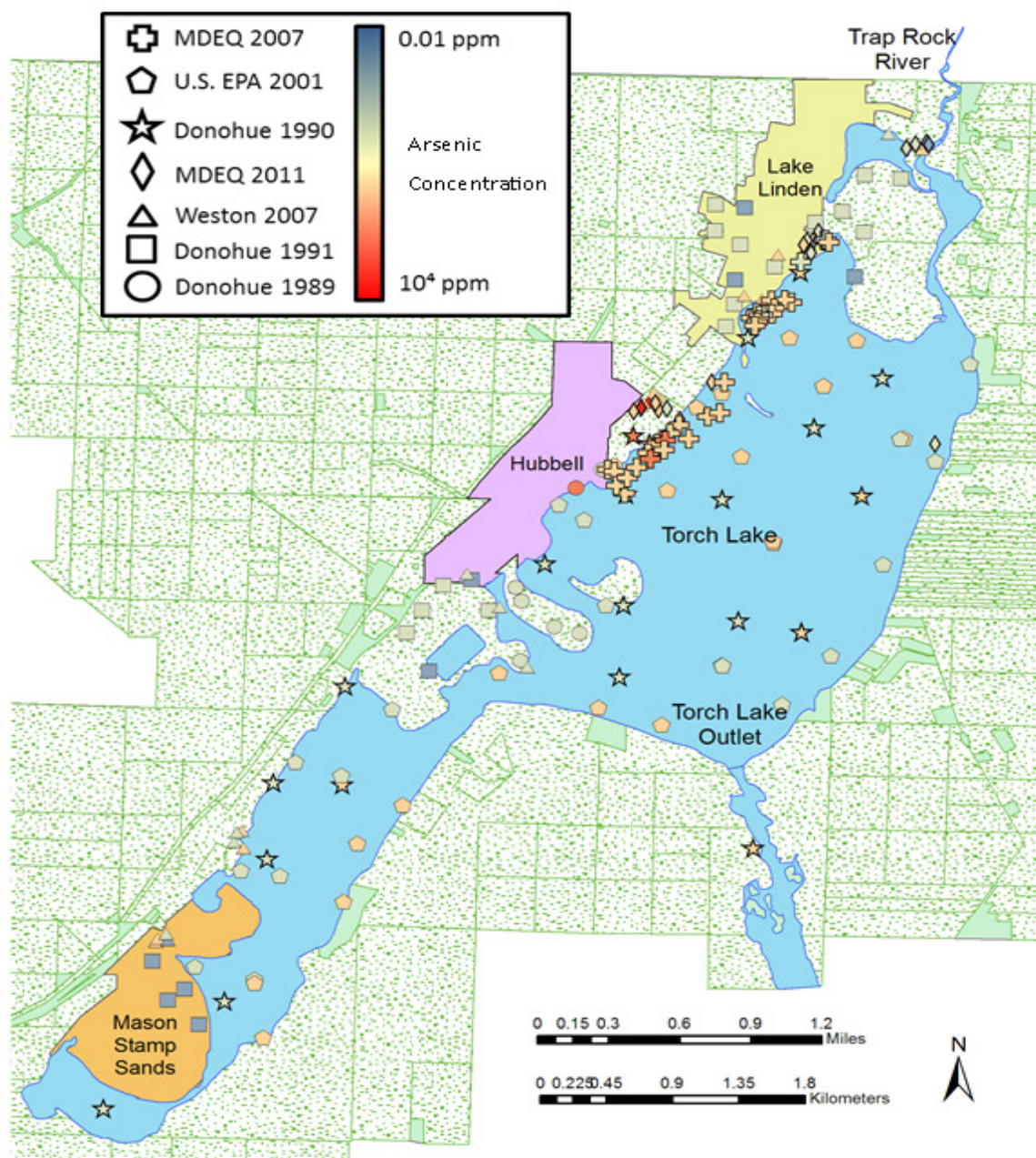


Figure 4.1: Arsenic concentrations in soil and sediment 1989-2011 (ppm).

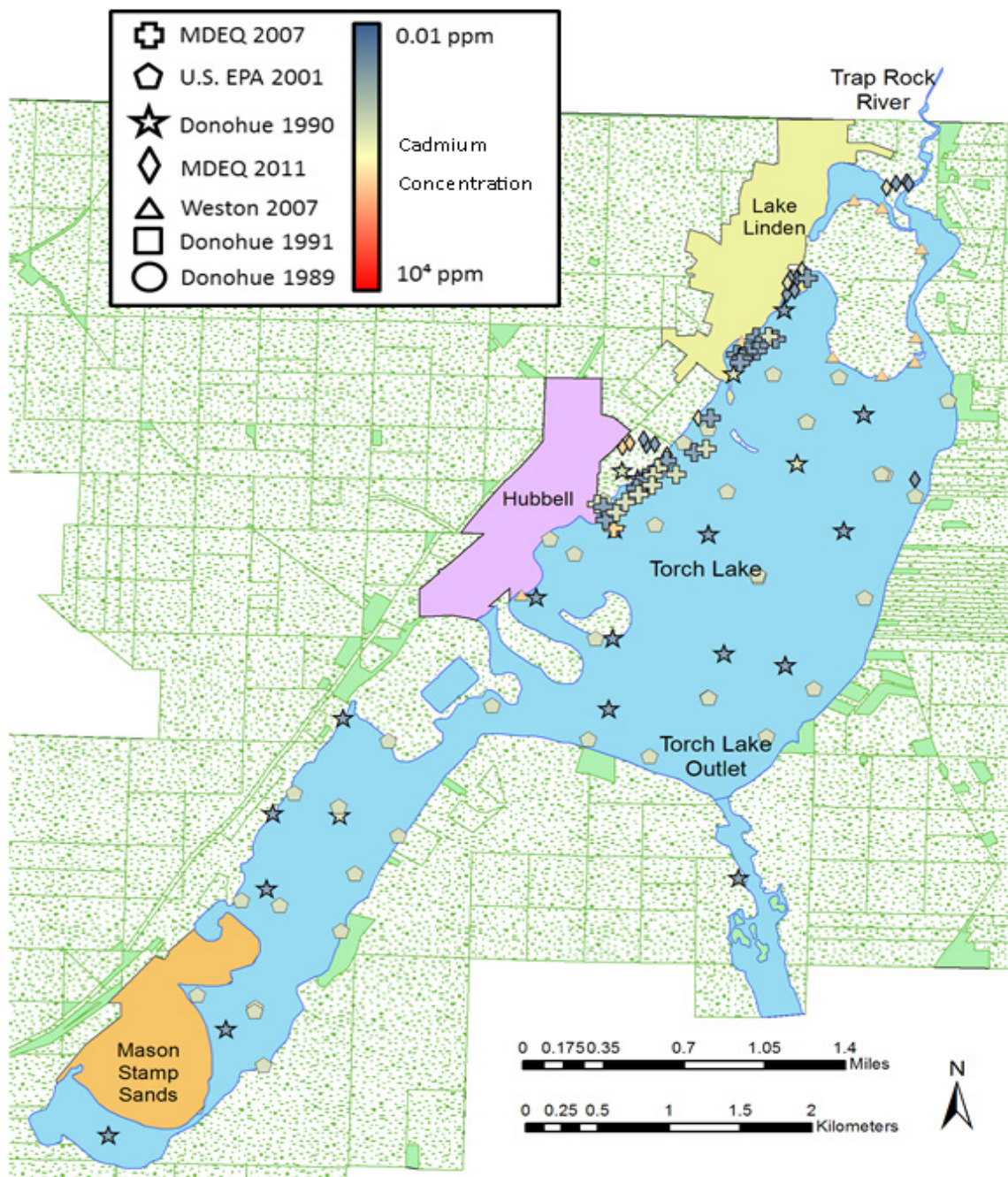


Figure 4.2: Cadmium concentrations in soil and sediment 1989-2011 (ppm).

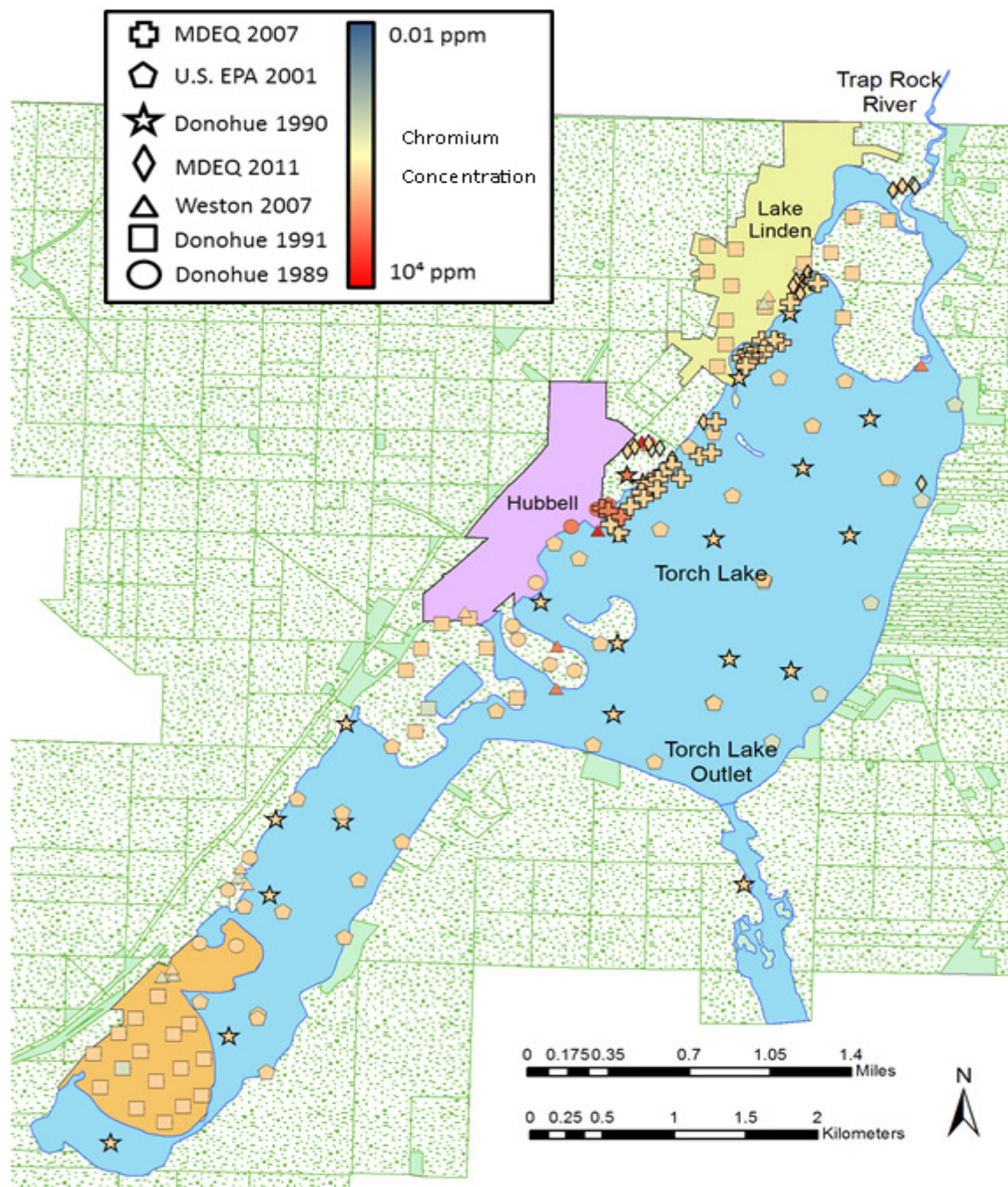


Figure 4.3: Chromium concentrations in soil and sediment 1989-2011 (ppm).

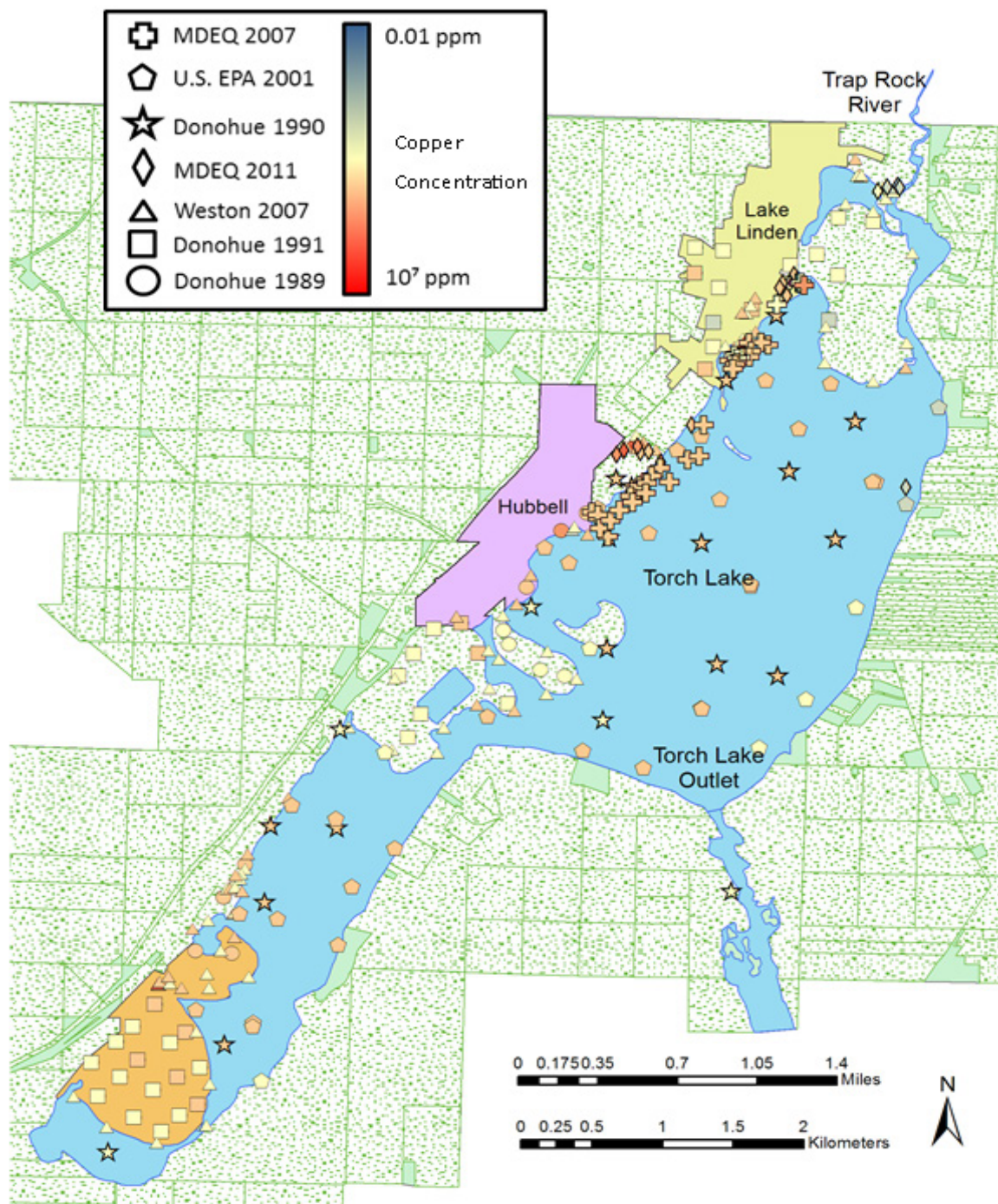


Figure 4.4: Copper concentrations in soil and sediment 1989-2011 (ppm).

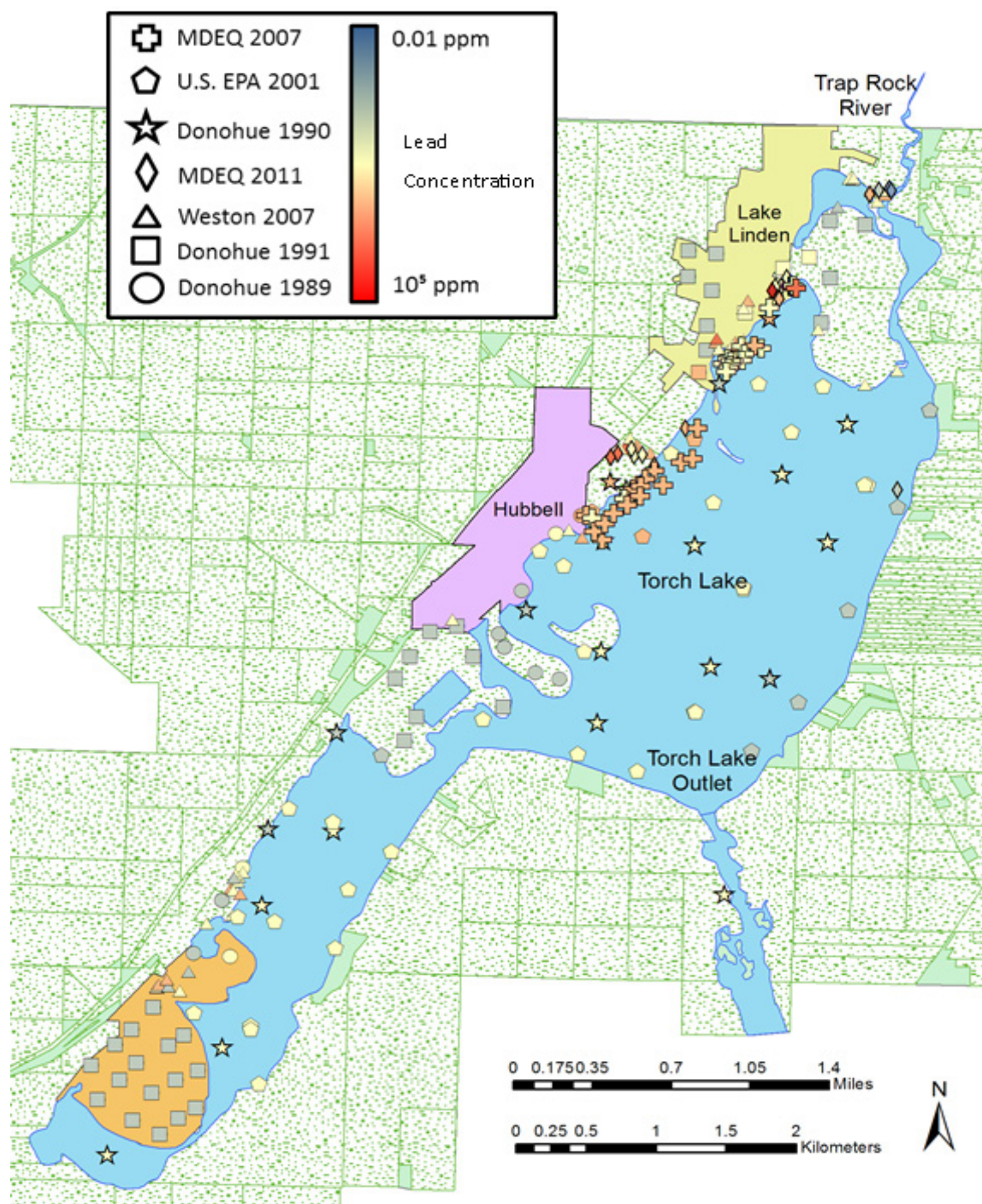


Figure 4.5: Lead concentrations in soil and sediment 1989-2011 (ppm).

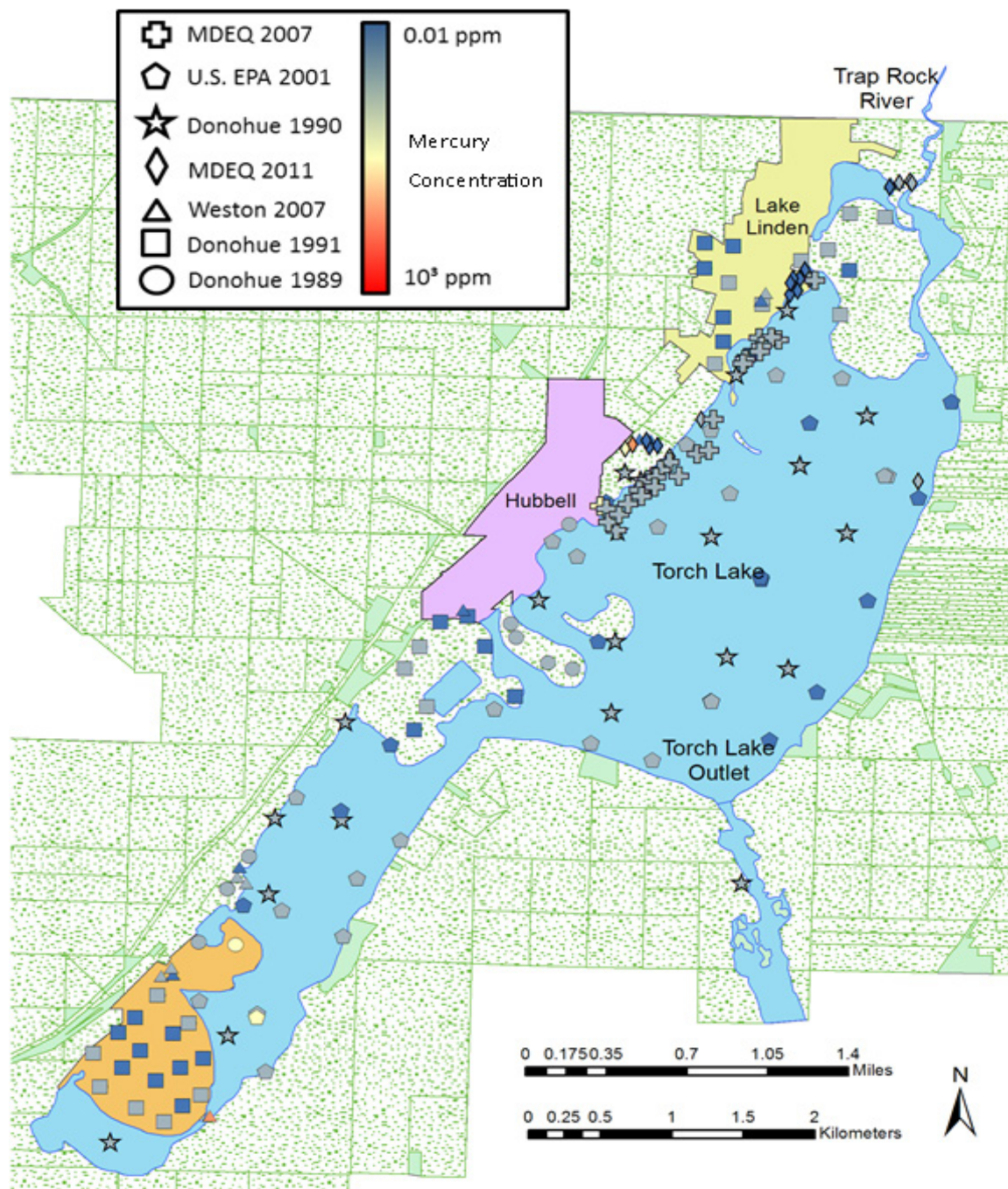


Figure 4.6: Mercury concentrations in soil and sediment 1989-2011 (ppm).

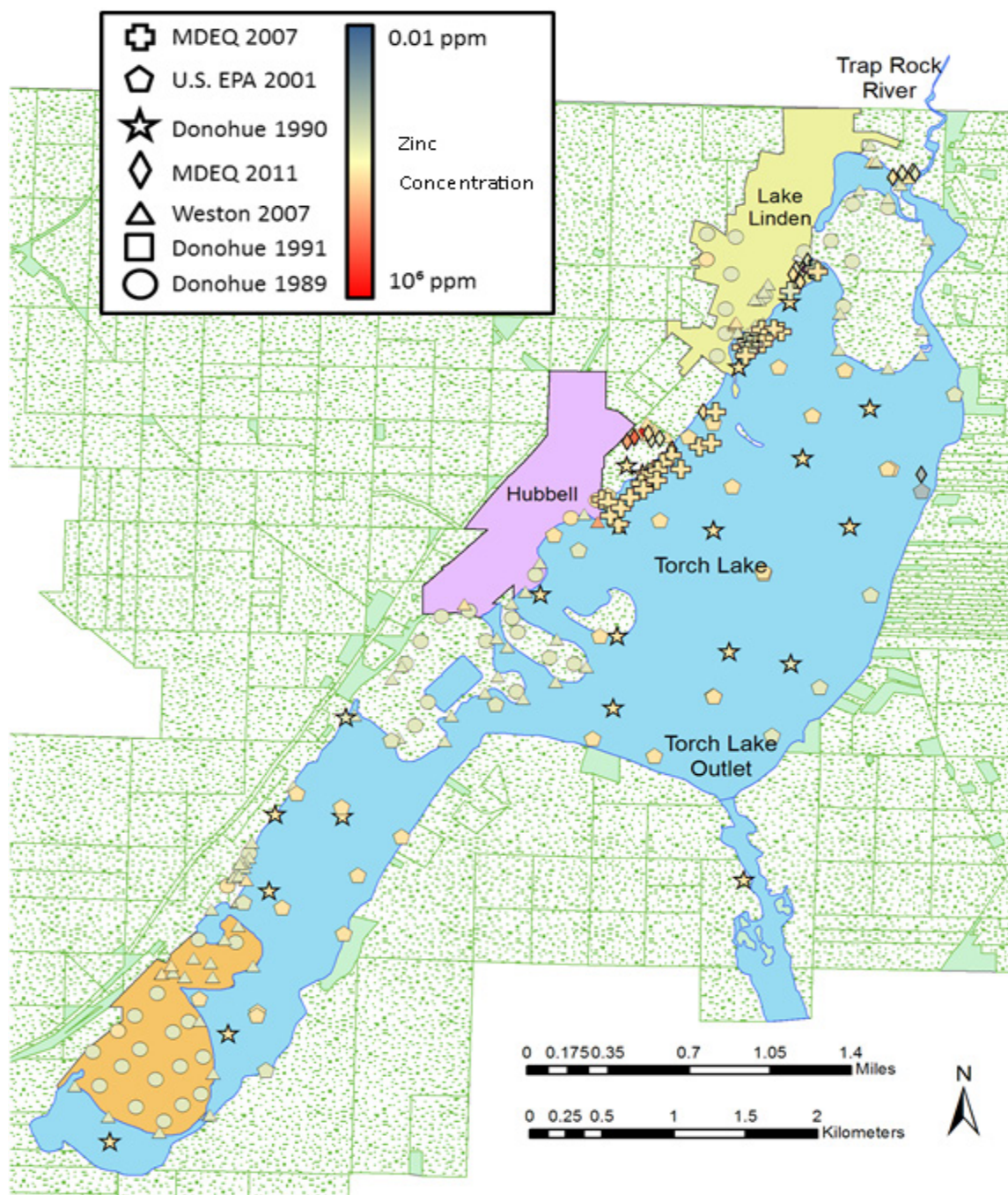


Figure 4.7: Zinc concentrations in soil and sediment 1989-2011 (ppm).

Table 4.6: Observations from Overview Analysis.

Metal	Spatial Observations			Temporal Observations
	Sediment vs. Soil	Spatial Variation Within the Lake	Variation among types of shore locations	
Arsenic (As)	Except for Emergency Removal locations, concentrations in the sediments tend to be higher than those in soil.		Concentrations in the Mason Tailings Pile tend to be lower than concentrations found anywhere else along the shore. Concentrations at the C&H Smelter site tend to be the highest.	At least in the sediment, it appears that the concentrations measured more recently are higher than those measured approx. 20 years ago.
Cadmium (Cd)	Except for Emergency Removal locations, Cadmium was not detected in the upland material.			Appears that concentrations measured in sediment more recently are higher than concentrations measured approx. 20 years prior.
Chromium (Cr)	Concentrations throughout sediments and soil show little spatial variability except for high concentrations near the Hubbell area.	Concentrations along the north basin's eastern shoreline tend to be about an order of magnitude less than concentrations in the rest of the north basin.	A couple of concentrations near the C&H Smelter site in Hubbell appear to be an order of magnitude higher than most of the upland concentrations.	No distinct temporal pattern was observed.

Metal	Spatial Observations		Temporal Observations
	Sediment vs. Soil	Spatial Variation Within the Lake	
Copper (Cu)	Concentrations in sediments appear to be about one order of magnitude higher than concentrations in soil.	Concentrations at the C&H Smelter site and in the vicinity of the Calumet and Hecla Stamp Mills in Lake Linden (the Emergency Removal sites) appear to be higher than most of the upland concentrations. Also, concentrations appear to be higher at the Quincy Reclamation Plant site in Mason.	In sediment there appears to be no significant difference between 1990 and 2001 observations. In soil, except for Emergency Removal locations, more recent concentrations appear to be an order of magnitude less than older concentrations. Emergency Removal concentrations tend to be the highest.

Metal	Spatial Observations			Temporal Observations
	Sediment vs. Soil	Spatial Variation Within the Lake	Variation among types of shore locations	
Lead (Pb)	Concentrations in sediment appear to increase with increasing proximity to the western shore, though concentrations in soil on the tailing piles are lower than sediment concentrations. The highest concentrations are observed in the Lake Linden to Hubbell area.	Concentrations along the north basin's eastern shoreline tend to be approx. an order of magnitude less than concentrations in the rest of the north basin.	Concentrations at the C&H Smelter site and in the vicinity of the Calumet and Hecla Stamp Mills in Lake Linden (the Emergency Removal sites) appear to be higher than most of the upland concentrations. Also, concentrations appear to be higher at the Quincy Reclamation Plant site in Mason.	In the sediment there appears to be no temporal pattern. In the soil it appears that concentrations observed more recently are higher than concentrations observed around 1990.

Metal	Spatial Observations			Temporal Observations
	Sediment vs. Soil	Spatial Variation Within the Lake	Variation among types of shore locations	
Mercury (Hg)	Concentrations in stamp sand piles tend to be low near the center of the piles and increase with increasing proximity to the water.	Concentrations in sediment tend to increase with increasing proximity to stamp sand piles.	High concentrations in soil were observed at the C&H Smelter site in Hubbell (an Emergency Removal site).	In sediments, concentrations observed in 1990 tend to be higher than concentrations observed in 2001. In soil, except for the Emergency Removal locations, there does not appear to be a significant difference between older and more recent observations.

Metal	Spatial Observations			Temporal Observations
	Sediment vs. Soil	Spatial Variation Within the Lake	Variation among types of shore locations	
Zinc (Zn)	There appears to be a general trend of both land and sediment concentrations being greater in the north basin compared to the south basin.	There appears to be a general trend of both land and sediment concentrations being greater in the north basin compared to the south basin.	Concentrations throughout the sediment and soil were generally uniform, except for Hubbell and Lake Linden in the vicinities of the C&H smelter site and the Calumet and Hecla Stamp mills, respectively (the Emergency Removal sites). These areas tend to have higher concentrations.	In sediments, especially close to the eastern shore, recent concentrations tend to be about an order of magnitude higher than older concentrations. In soils, there are some occasional locations where more recent concentrations are an order of magnitude higher than older concentrations. Emergency Removal concentrations were the highest observed.

Except for chromium and zinc, all analyzed metals seem to be present in higher concentrations in the sediments compared to the soil (this statement excludes the 2011 Emergency Removal concentrations in Lake Linden and Hubbell, which were generally higher than sediment concentrations). Cadmium, lead and mercury all displayed a pattern of concentrations in sediment increasing with increasing proximity to the western industrial shore. Chromium and zinc do not display obvious spatial trends.

Arsenic, cadmium and zinc concentrations in sediment all displayed the pattern of the recently sampled concentrations being higher than the older concentrations. Mercury displays the opposite pattern of the recently sampled concentrations being lower than the older concentrations in sediments. Chromium, copper and lead concentrations in sediment do not display any temporal pattern. Most of the analyzed metals did not show a temporal pattern in concentrations in soil; though recently measured copper, mercury and lead concentrations appear to be lower than older copper, mercury and lead concentrations.

4.3.2 Soil Concentration Analysis

The soil maps (Figure 4.8-Figure 4.14) of each metal show the locations where concentrations met or exceeded the Michigan Part 201 Residential Soil Direct Contact Criteria (DCC), fell below the criteria, or were not detected. Point layers are distinguished by source so that temporal observations can be made in addition to spatial observations. Observations for each metal are summarized in Table 4.7 (following Figure 4.14).

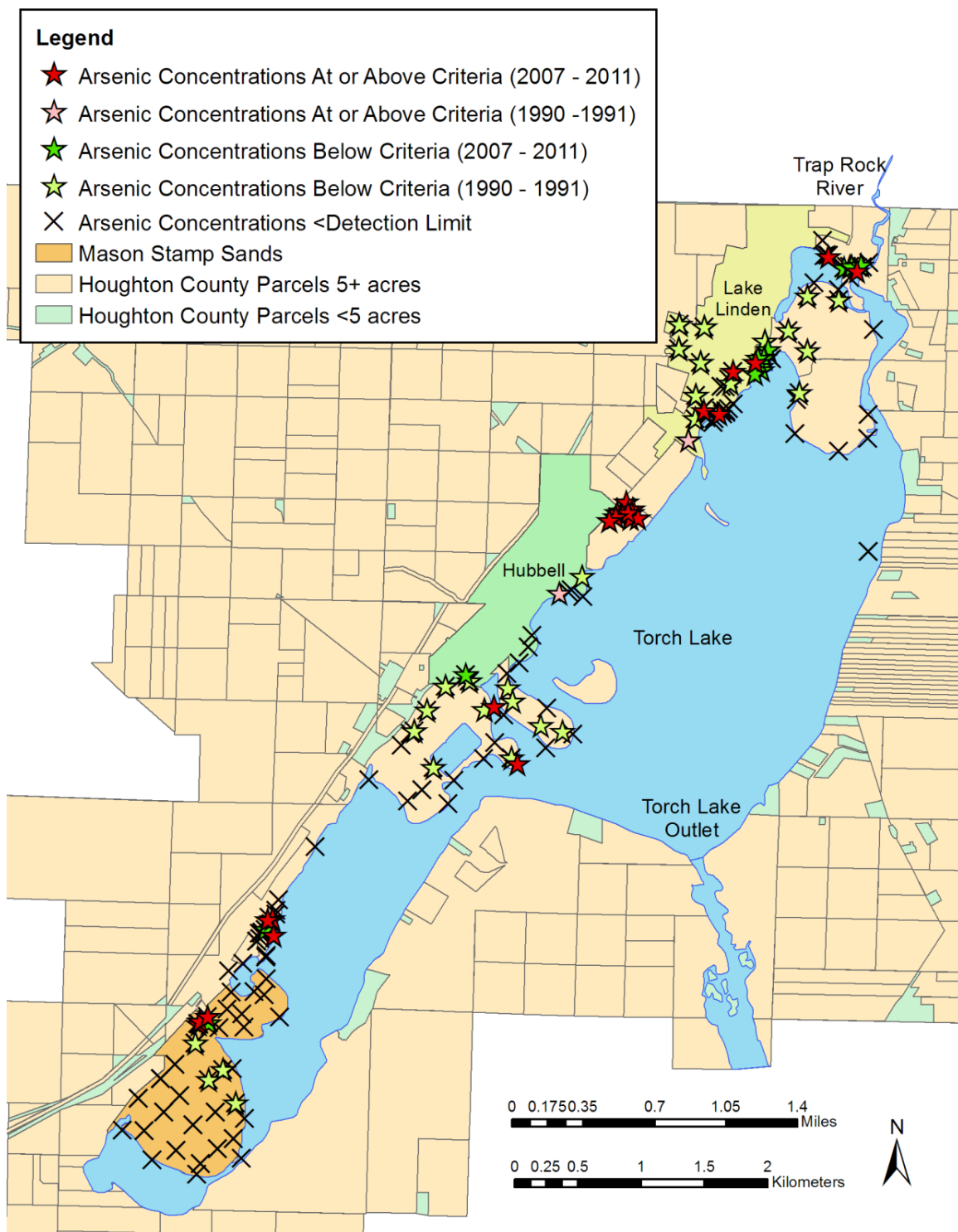


Figure 4.8: Arsenic in soil concentrations compared to Michigan cleanup criteria.

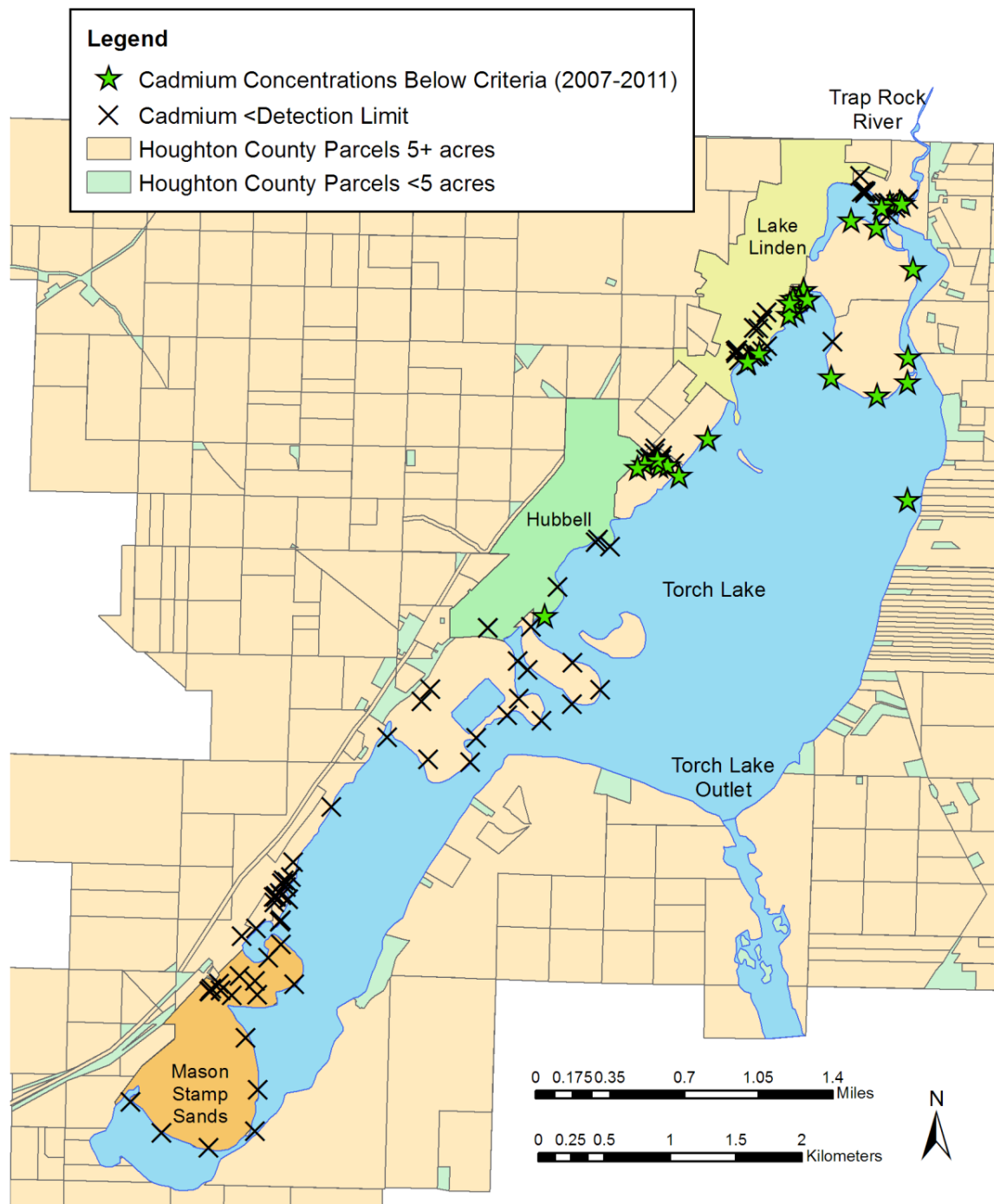


Figure 4.9: Cadmium in soil concentrations compared to Michigan cleanup criteria.

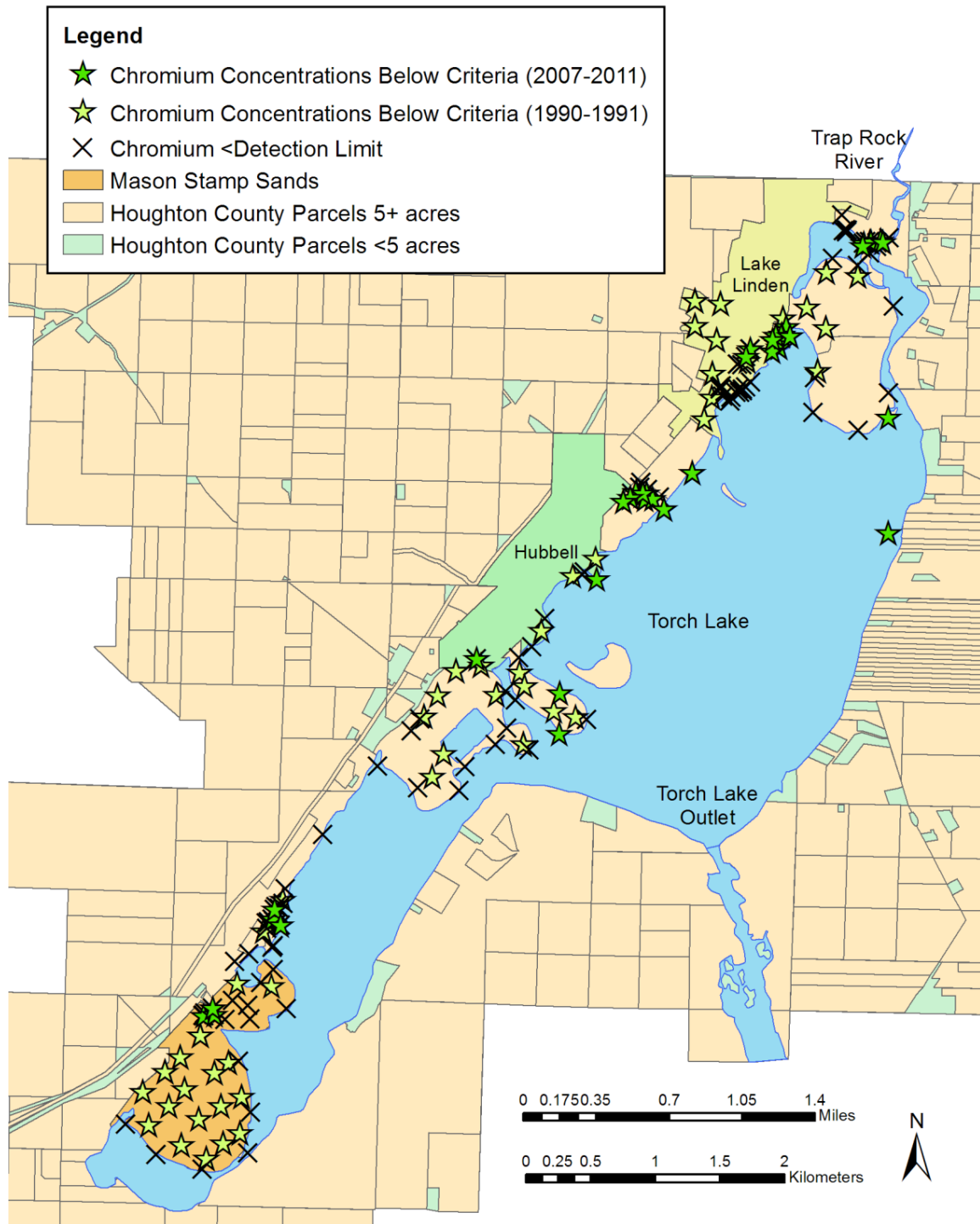


Figure 4.10: Chromium in soil concentrations compared to Michigan cleanup criteria.

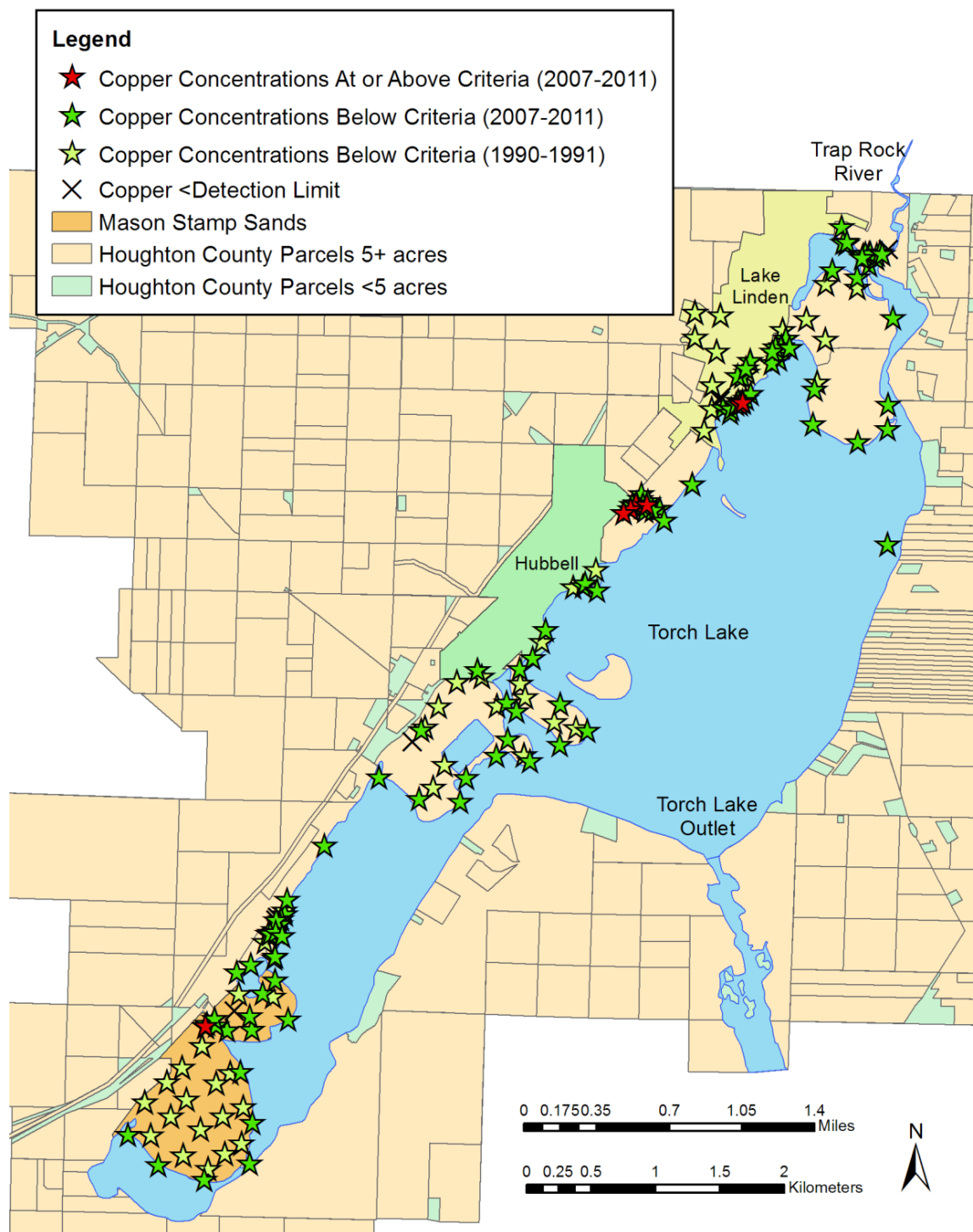


Figure 4.11: Copper in soil concentrations compared to Michigan cleanup criteria.

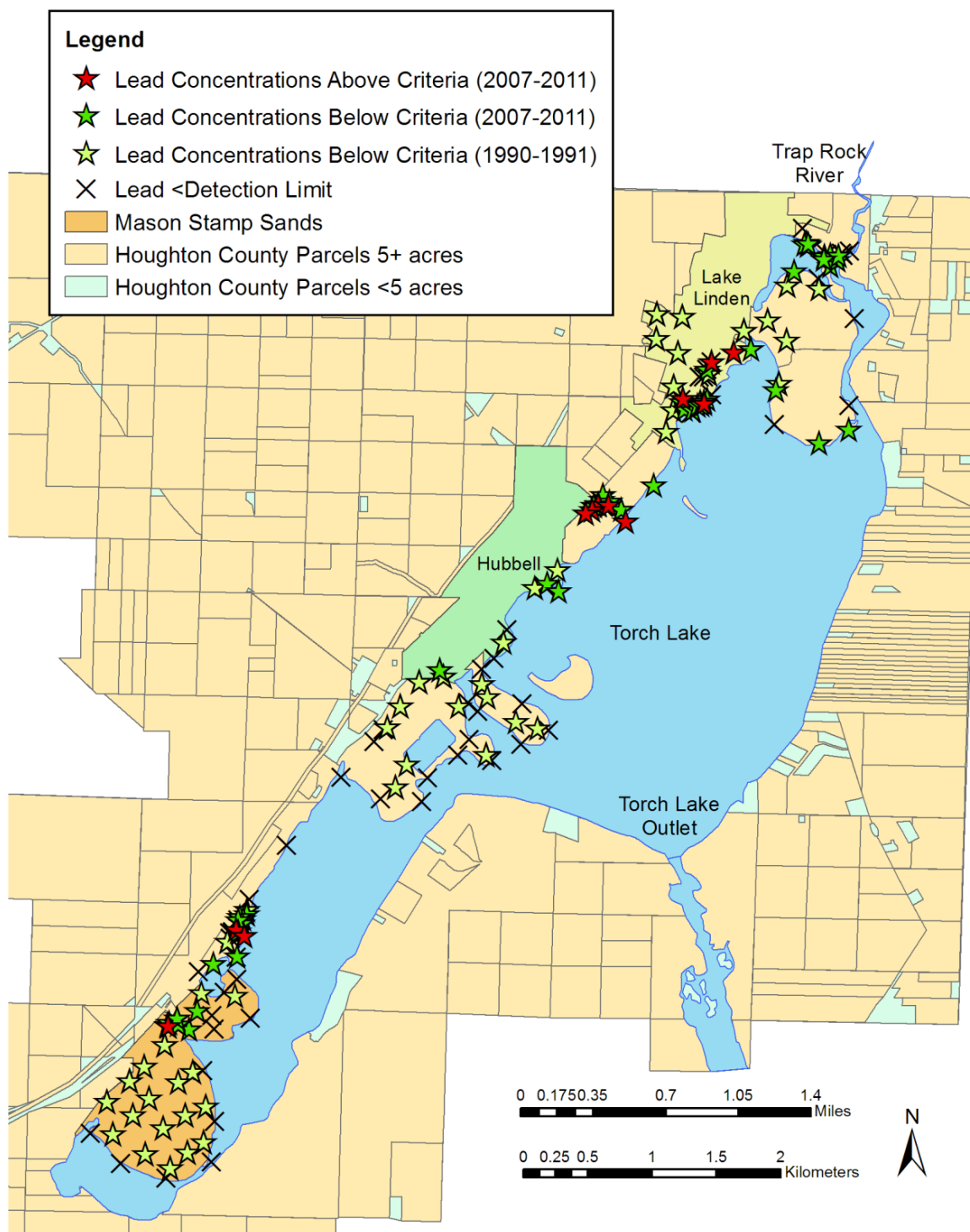


Figure 4.12: Lead in soil concentrations compared to Michigan cleanup criteria.

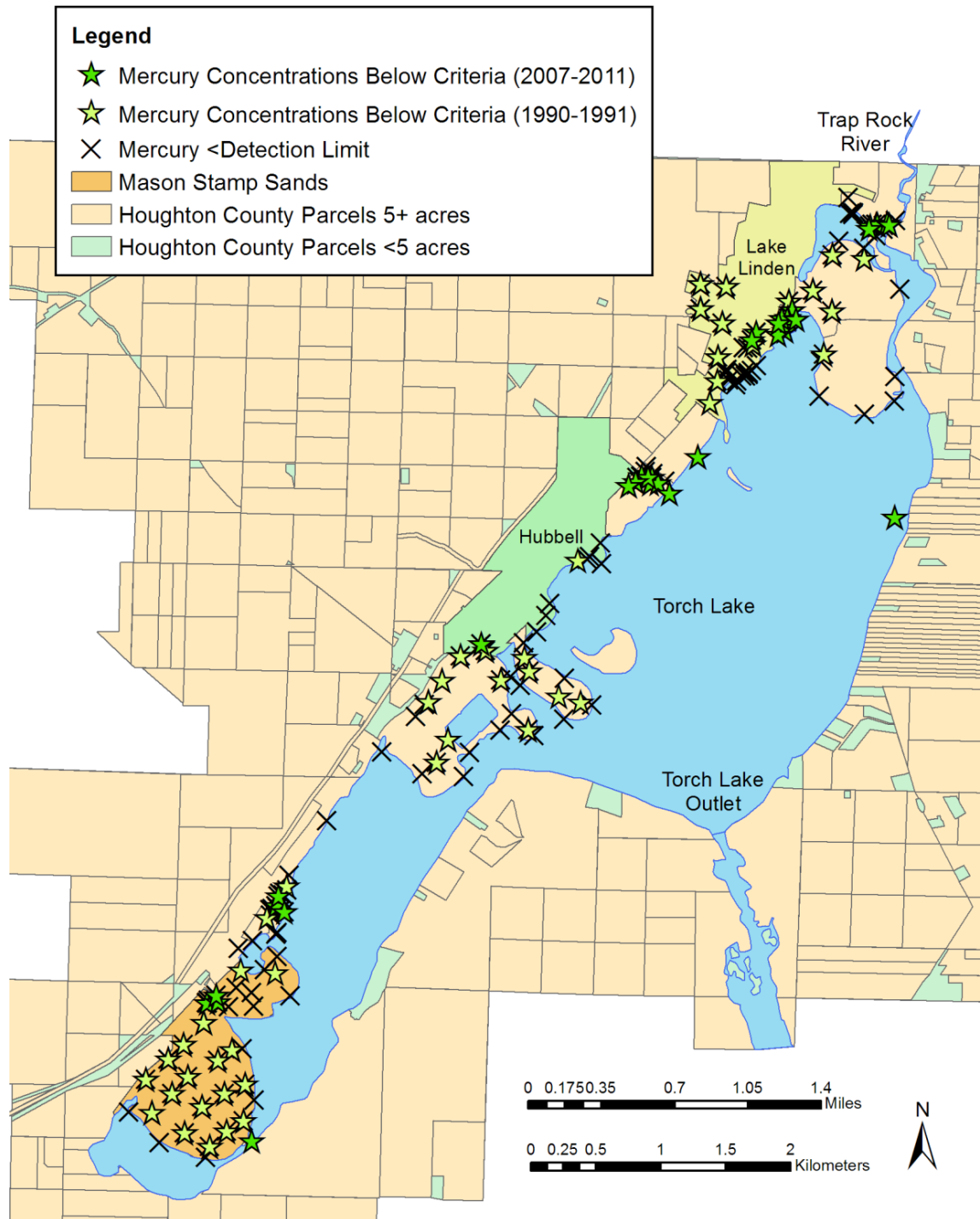


Figure 4.13: Mercury in soil concentrations compared to Michigan cleanup criteria.

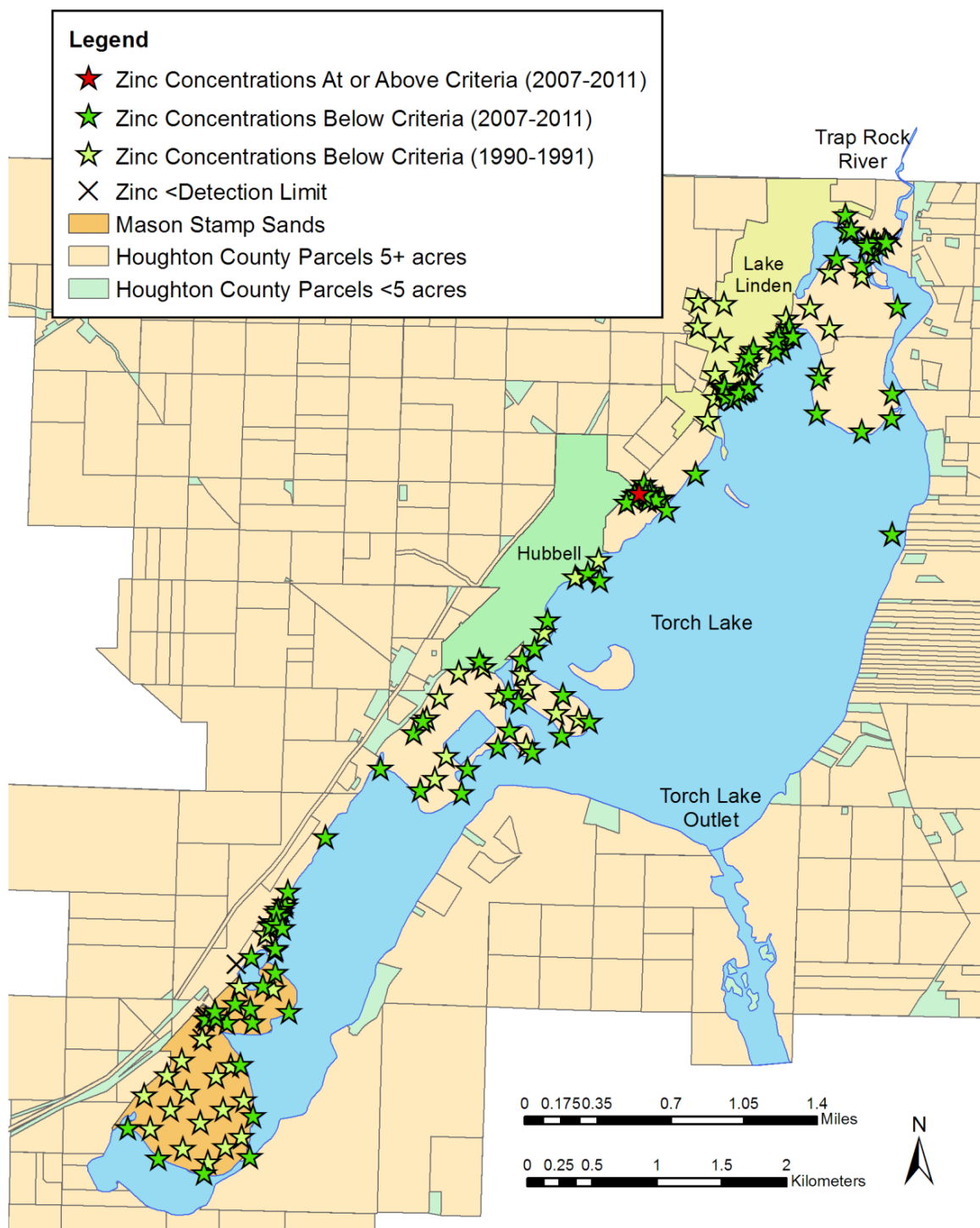


Figure 4.14: Zinc in soil concentrations compared to Michigan cleanup criteria.

Table 4.7: Observations from Soil Concentration Analysis.

Metal	Spatial Observation	Temporal Observation
Arsenic (As)	Locations where concentrations meet or exceed DCC are found all along the western shore except for between the Tamarack and Mason stamp sand piles, where not many samples were taken. Locations where concentrations are below the DCC are found in Lake Linden, the Tamarack stamp sands and the Mason stamp sands.	The majority of concentrations that meet or exceed the DCC were observed in 2007 or 2011. The majority of concentrations that fall below the DCC were observed in 1990-1991.
Cadmium (Cd)	All locations at which cadmium is detected fall below the DCC. Cd was detected at the mouth of the Trap Rock River, at the shoreline of Lake Linden and its stamp sands, and in the coal dock area between Lake Linden and Hubbell. There is one observed location in Hubbell.	Cadmium was not sampled in 1990-1991. The only measurements of Cd are from 2007 and 2011.
Chromium (Cr)	All locations at which chromium is detected fall below the DCC. Locations where chromium was detected are found along the western shore except for between the Tamarack and Mason stamp sand piles, where not many samples were taken.	Recent detections of chromium appear to be concentrated in the 2011 Emergency Removal locations, but this is likely due to a higher number of samples taken in these areas.

Metal	Spatial Observation	Temporal Observation
Copper (Cu)	Copper has been detected throughout the western shore at almost every location it was sampled. Concentrations that meet or exceed the DCC are found in southern Lake Linden, in the coal dock area between Lake Linden and Hubbell, and in the Mason stamp sands.	Concentrations that meet or exceed the DCC have been observed only recently. There is no pattern to the concentrations that fall below the DCC.
Lead (Pb)	Concentrations that meet or exceed the DCC have been observed in Lake Linden, the coal dock area between Lake Linden and Hubbell, just north of the Mason stamp sands and in the Mason stamp sands. Locations where Lead was detected are found all along the western shore except for between the Tamarack and Mason stamp sand piles, where not many samples were taken.	Concentrations that meet or exceed the DCC have been observed only recently. Recent concentrations detected below the DCC are concentrated at the mouth of the Trap Rock River, the 2011 Emergency Removal locations in Lake Linden and north of Hubbell, just north of the Mason stamp sands and in the northern part of the Mason stamp sands.
Mercury (Hg)	Concentrations that meet or exceed the DCC were not observed. Concentrations that fall below the DCC are found throughout the western shore. Mercury was not detected at a significant number of locations.	Recent concentrations detected below the DCC are concentrated at the mouth of the Trap Rock River, the 2011 Emergency Removal locations in Lake Linden and north of Hubbell, just north of the Mason stamp sands and in the northern part of the Mason stamp sands.

Metal	Spatial Observation	Temporal Observation
Zinc (Zn)	There has been only one observation of zinc that meets or exceeds the DCC. Zinc has been observed at almost every location it was sampled.	There is no observed temporal pattern to the detected zinc concentrations.

Cadmium, chromium and mercury did not display any concentrations at or above the DCC. Zinc displayed a concentration at or above the DCC at only one location.

Locations existed where lead, arsenic and copper concentrations met or exceeded the DCC at certain concentrated areas in or near the stamp sand piles. Lead, arsenic and copper concentrations at or above the DCC were generally observed in recent sampling events (as opposed to approx. twenty years prior). Otherwise, there was no distinct temporal pattern observed in the metals in soil concentrations.

4.3.3 Sediment Concentration Analysis

The sediment maps (Figure 4.15-Figure 4.21) of each metal show the locations where concentrations met or exceeded the PEC, met or exceeded the TEC but fell below the PEC, fell below the TEC, or were not detected. Point layers are distinguished by source so that temporal observations can be made in addition to spatial observations.

Observations noted for each metal are stated in the Table 4.8 (following Figure 4.21).

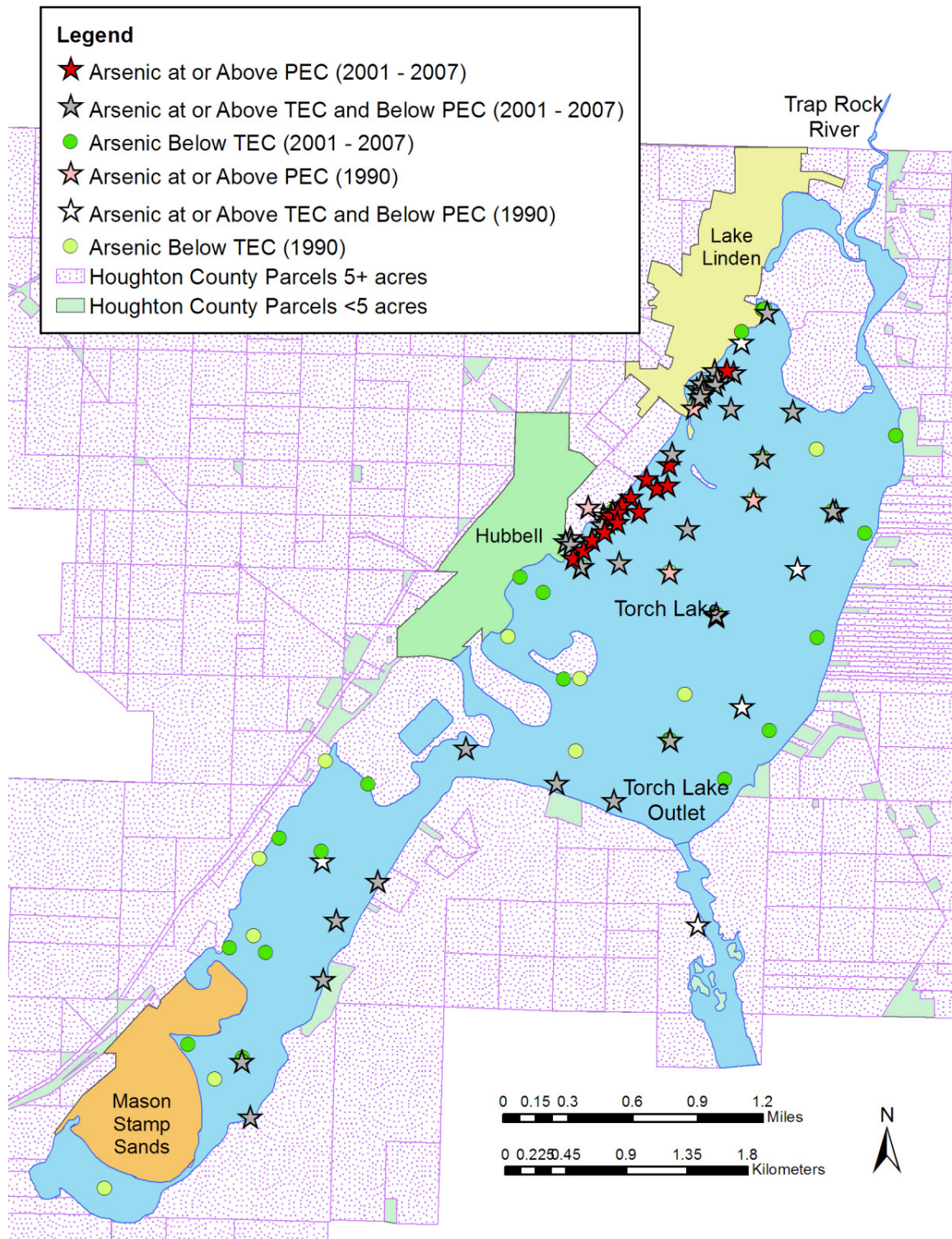


Figure 4.15: Measured arsenic concentrations compared to TEC and PEC.

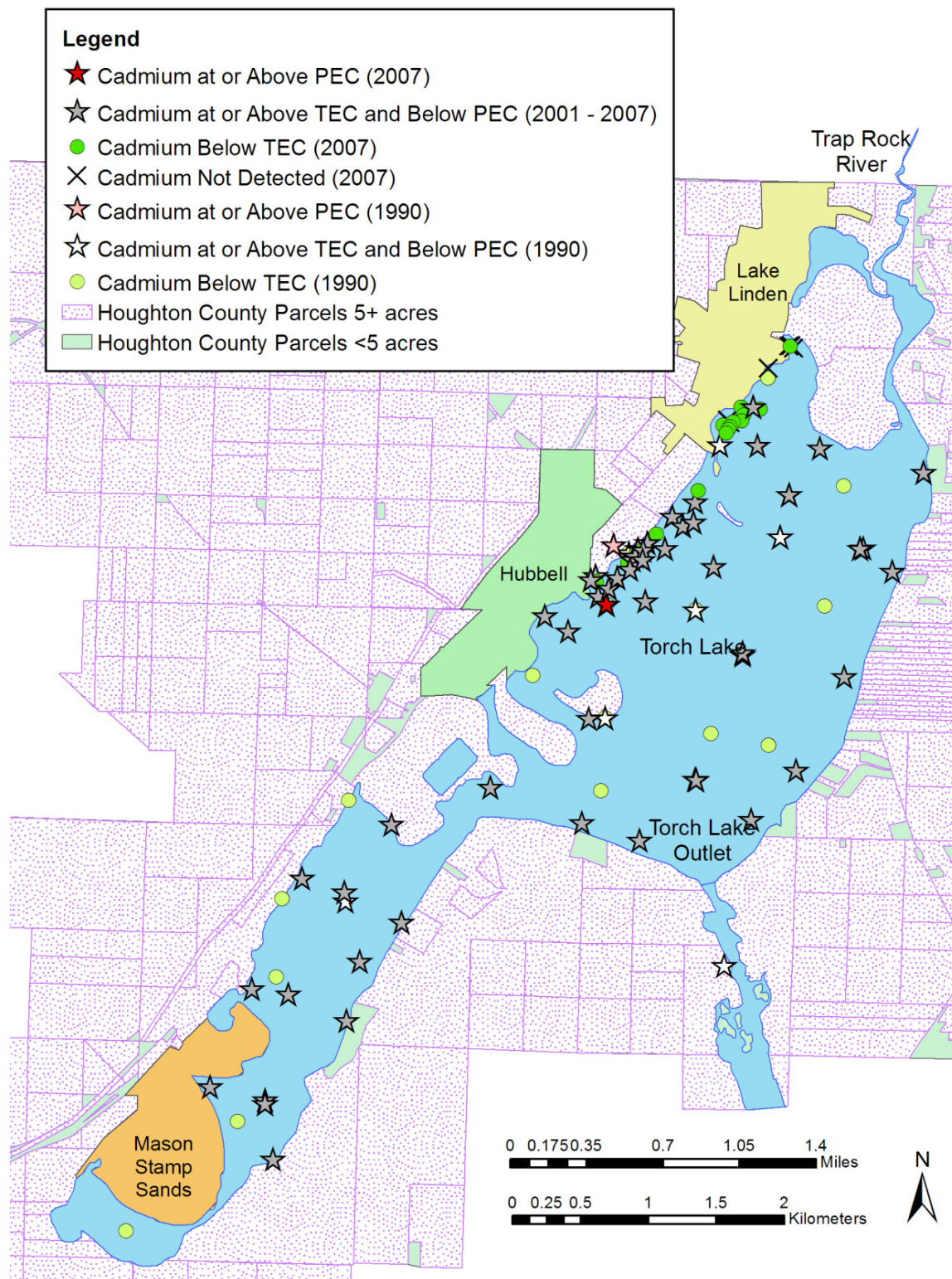


Figure 4.16: Measured cadmium concentrations compared to TEC and PEC.

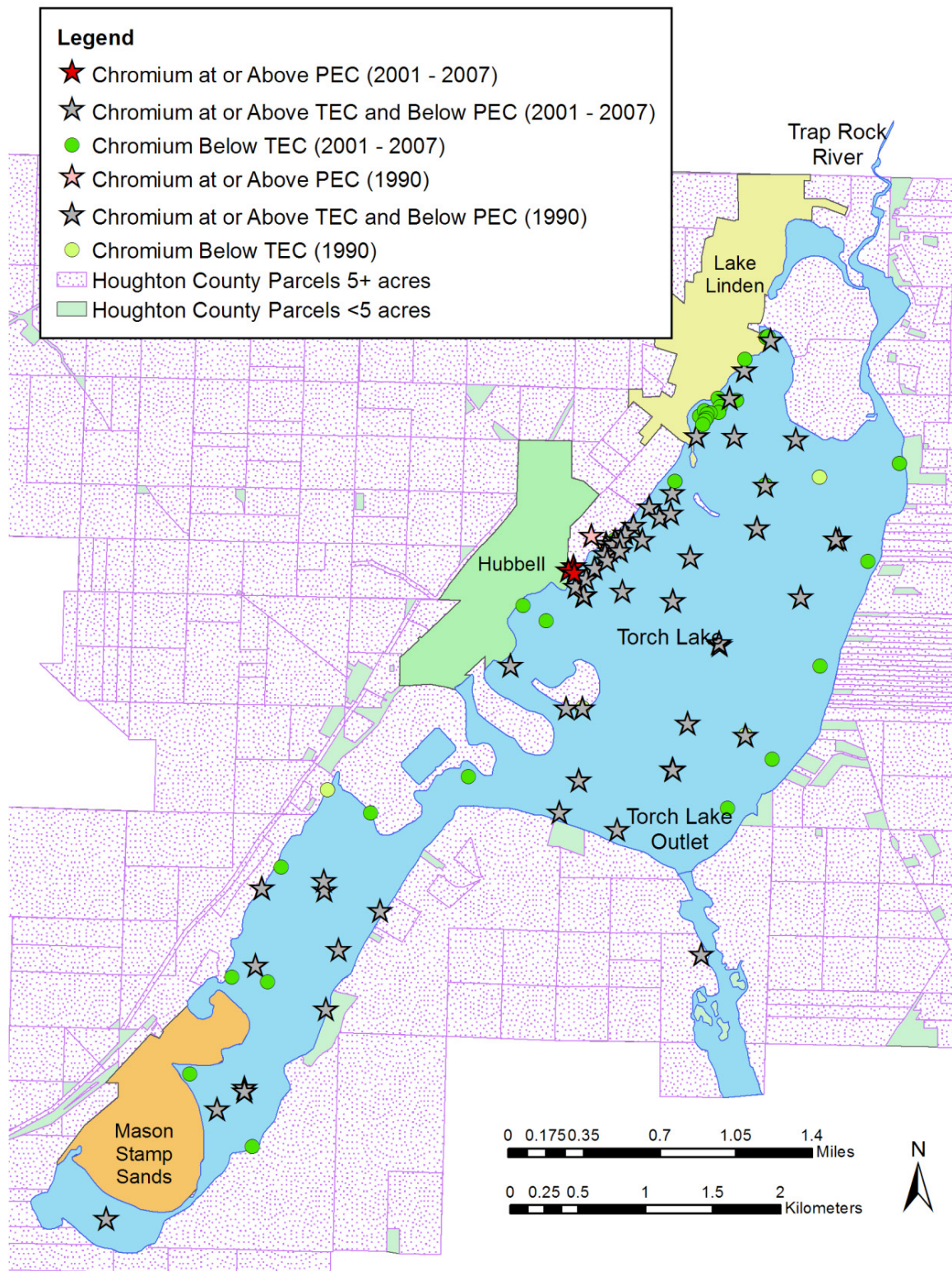


Figure 4.17: Measured chromium concentrations compared to TEC and PEC.

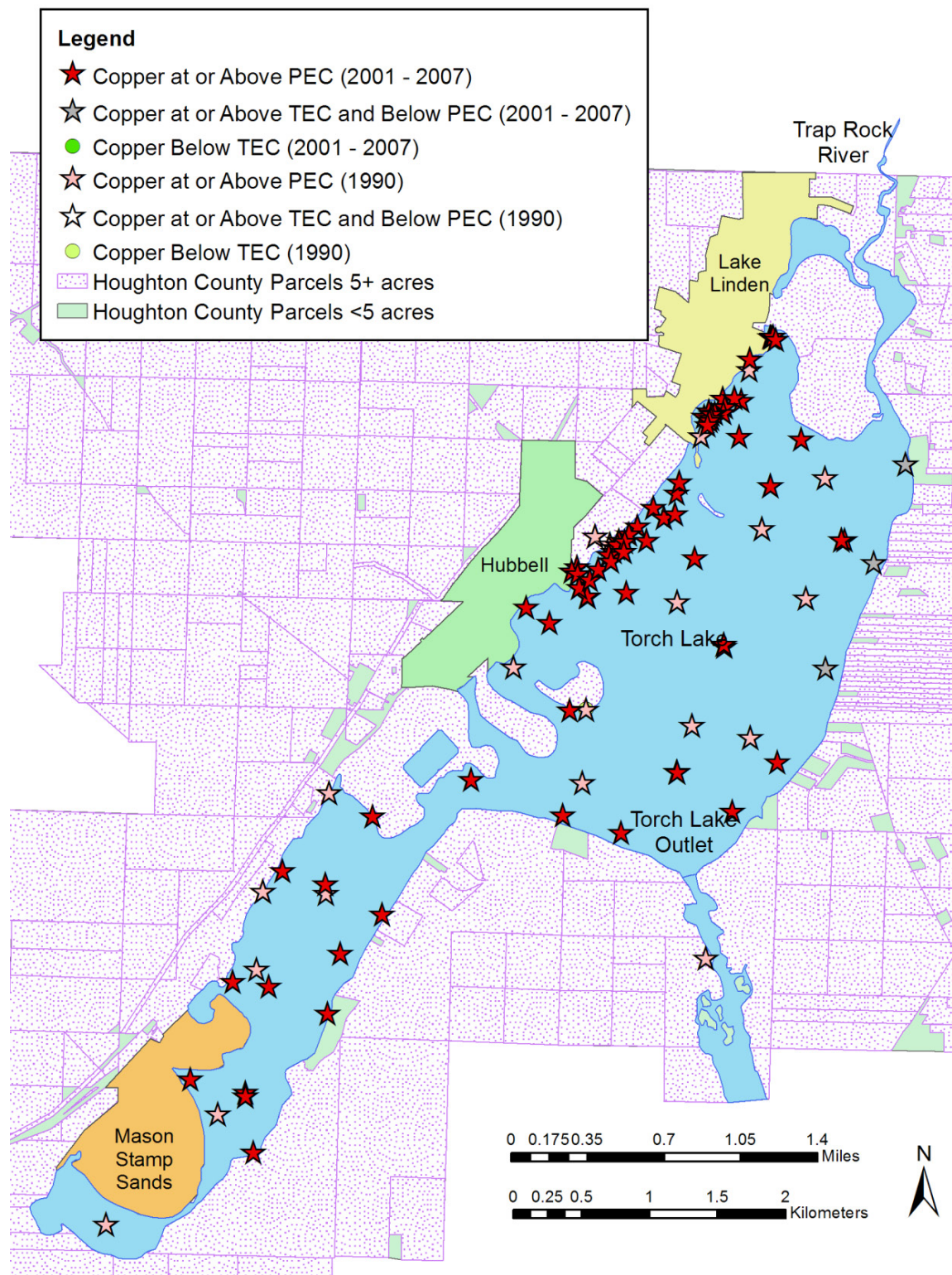


Figure 4.18: Measured copper concentrations compared to TEC and PEC.

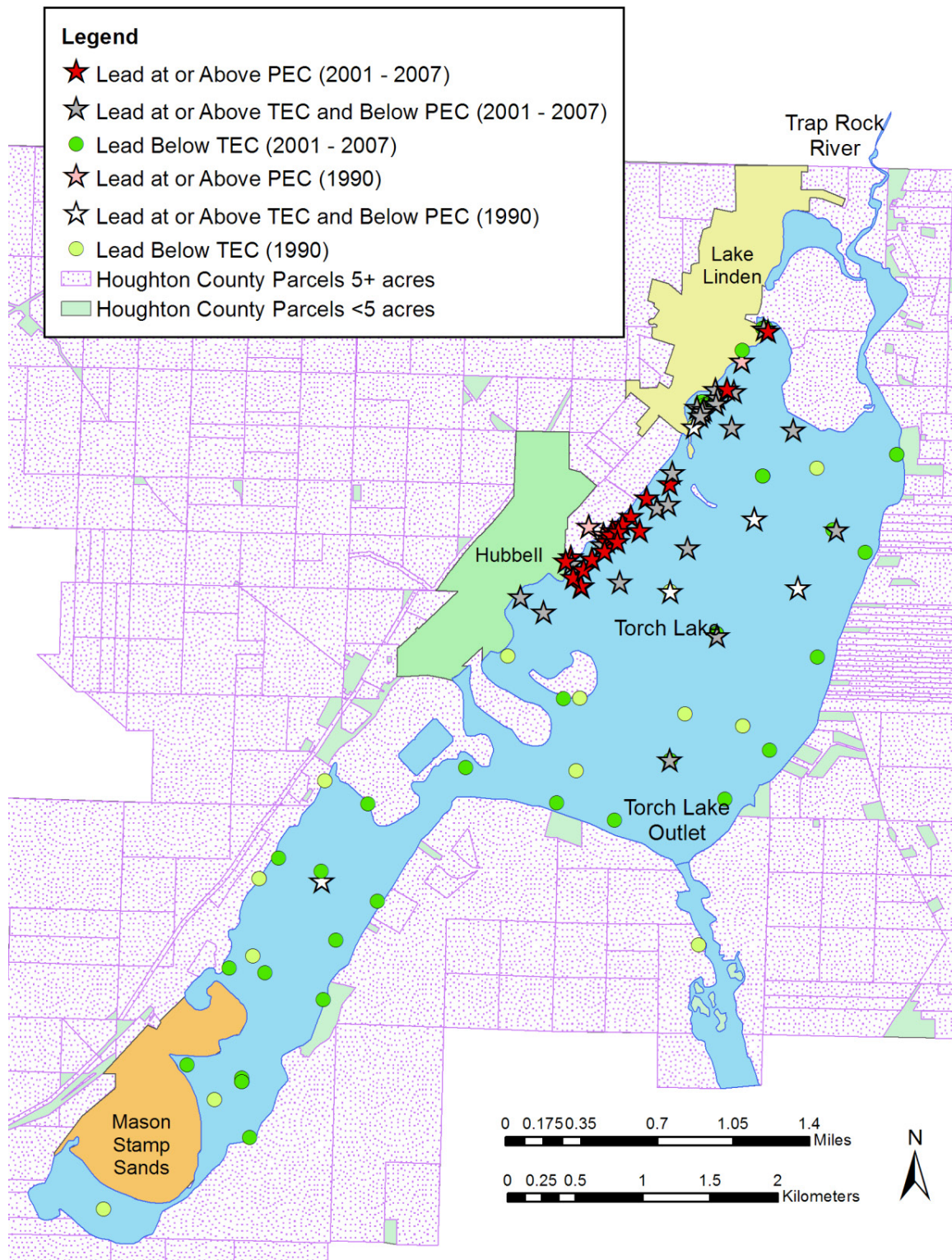


Figure 4.19: Measured lead concentrations compared to TEC and PEC.

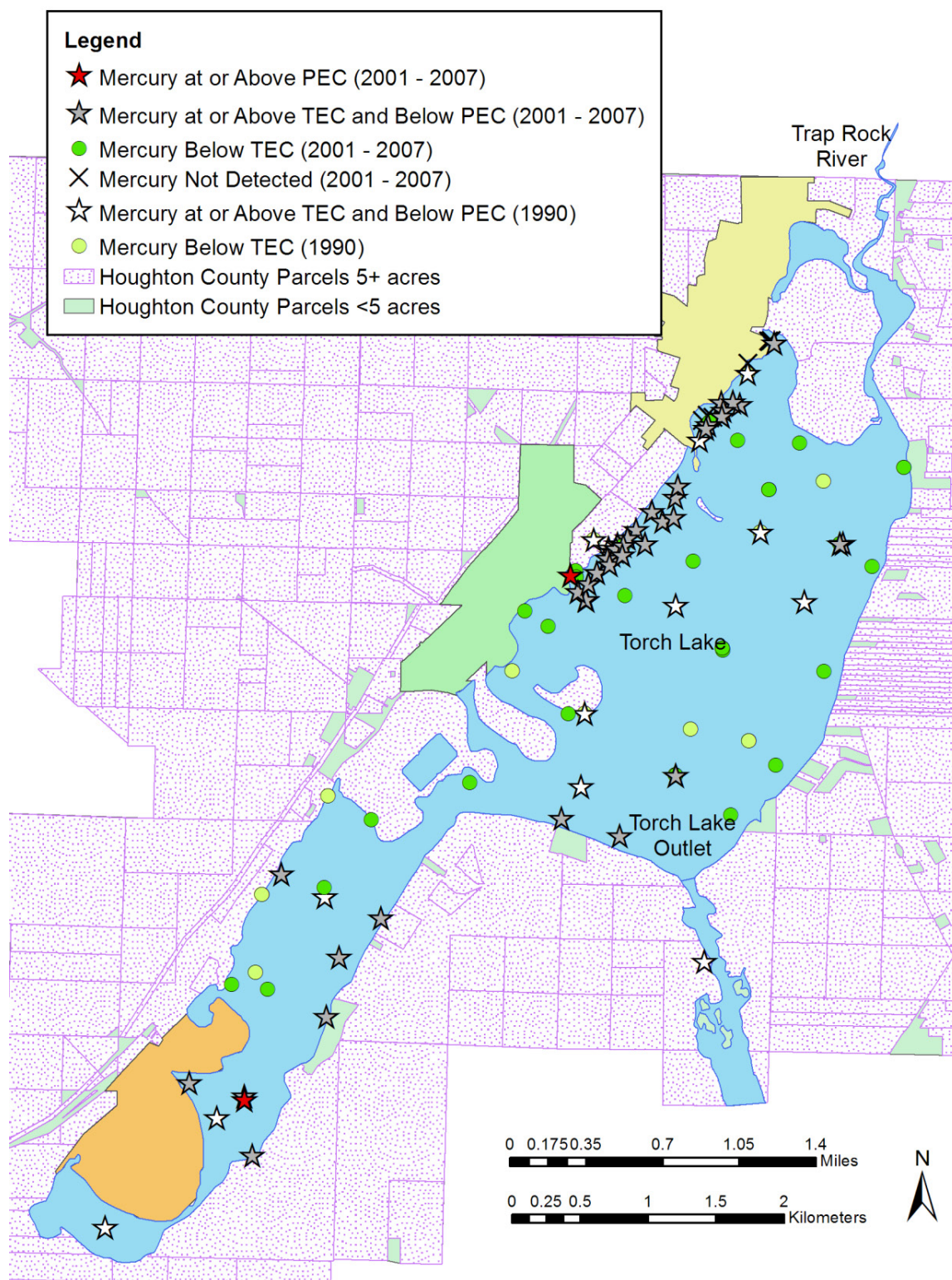


Figure 4.20: Measured mercury concentrations compared to TEC and PEC.

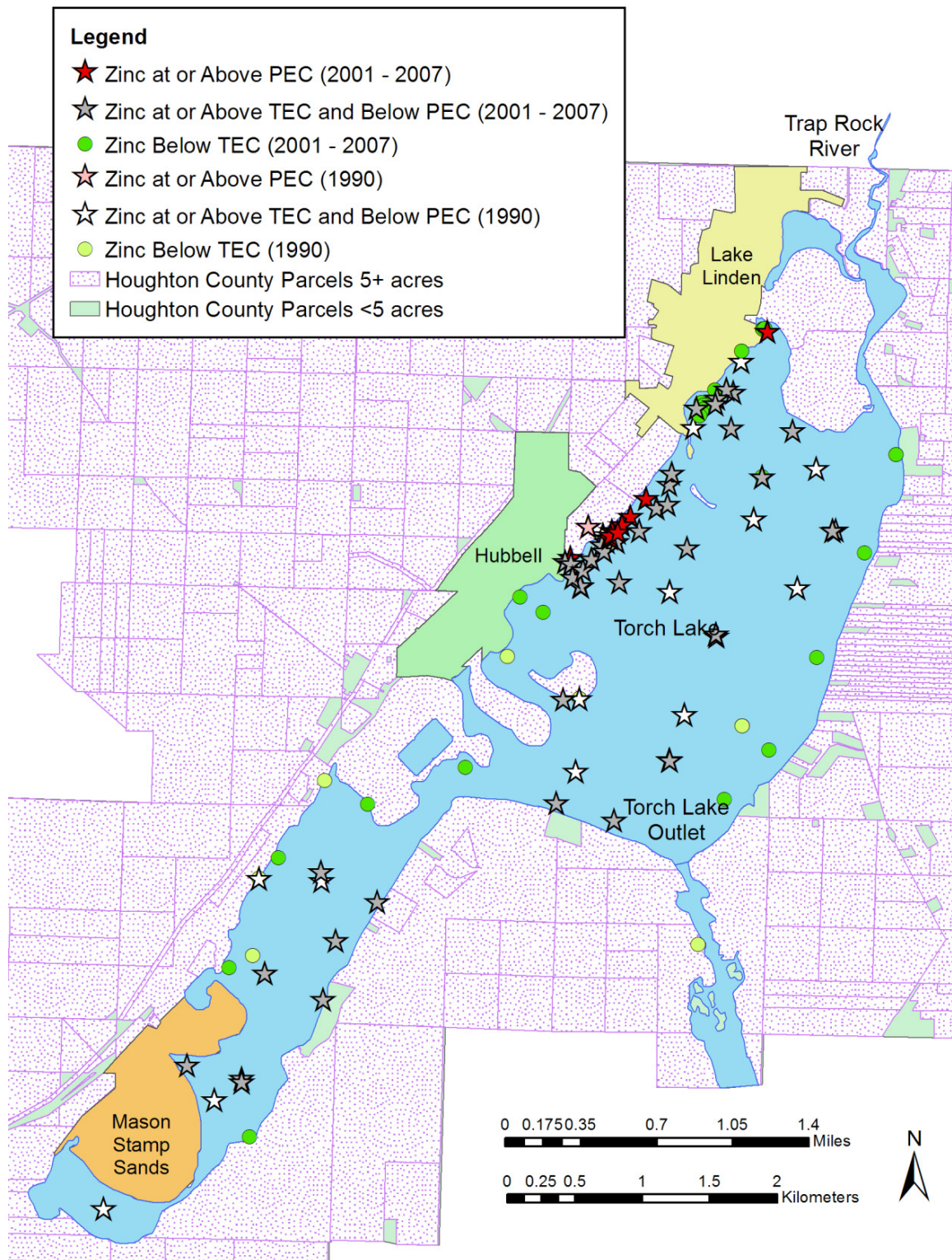


Figure 4.21: Measured zinc concentrations compared to TEC and PEC.

Table 4.8: Observations from Sediment Concentration Analysis.

Metal	Spatial Observation	Temporal Observation
Arsenic (As)	Locations where Arsenic meets or exceeds the PEC are located between Lake Linden and Hubbell. Locations where concentrations are between the TEC and PEC are located throughout the lake, and locations where As falls below the TEC are located throughout the lake.	The recent concentrations that meet or exceed the PEC are mostly found in the coal dock area between Lake Linden and Hubbell. There is no distinct pattern to the other observations.
Cadmium (Cd)	There is one location where Cadmium meets or exceeds the PEC just north of Hubbell. Most other locations detected concentrations between the TEC and the PEC. A few locations detected concentrations below the TEC. There is no distinct pattern to the locations of the detected concentrations.	There is no distinct pattern between the 2001 and the 1990 observations.
Chromium (Cr)	There are two locations where concentrations meet or exceed the PEC just north of Hubbell. Most locations where Cr falls below the TEC are found along the shoreline of the lake. Most of the locations in the middle contain concentrations between the PEC and the TEC.	There is no distinct temporal pattern.
Copper (Cu)	Most of the observed concentrations are above the PEC.	There is no distinct temporal pattern.

Metal	Spatial Observation	Temporal Observation
Lead (Pb)	<p>Concentrations that meet or exceed the PEC are observed mostly near the coal dock area north of Hubbell. Two additional locations were found near Lake Linden.</p> <p>Concentrations between the TEC and PEC are found mostly in the western half of the northern basin. The majority of the remainder of the sample sites contain concentrations that fall below the TEC.</p>	There is no distinct temporal pattern.
Mercury (Hg)	<p>One location near the Mason stamp sands contains a concentration that meets or exceeds the PEC. All other observed concentrations are dispersed throughout the lake, though the majority are found along the lake's western shoreline.</p>	There is no distinct temporal pattern.
Zinc (Zn)	<p>Concentrations that meet or exceed the PEC are observed along the western shore just north of Hubbell. Concentrations that fall below the TEC are found along the perimeter of the lake. The remainder of the observed concentrations is dispersed throughout the lake and fall between the TEC and the PEC.</p>	There is no distinct temporal pattern.

Generally, concentrations of metals in sediments that meet or exceed the PEC were found along the western shore between Lake Linden and Hubbell, usually close to Hubbell. The exceptions to these observations are for copper and mercury. Copper concentrations that meet or exceed the PEC are found throughout the lake area. Mercury is on the other end of the spectrum with only one observation meeting or exceeding the PEC near the Mason stamp sands. Chromium, mercury and zinc exhibited concentrations that were below the TEC near the perimeter of the lake while concentrations between the TEC and PEC were located in the middle. Lead displayed the pattern of concentrations falling between the TEC and PEC in the western half of the northern basin. There were no significant temporal patterns.

4.4 Conclusion

The results from the metals analysis give several insights about spatial and temporal patterns of the concentrations in the sediment and upland material. In general, based on the mapping, concentrations of metals in the sediments are higher than those in the upland material. Cadmium, lead and mercury displayed the pattern of concentrations within the sediments increasing with increasing proximity to the industrial shore. This implies that though the sediments are more contaminated with metals than the upland material, the sources of contamination are likely located in the upland area.

Comparing the metals concentrations to the DCC helps to understand trends in the concentrations in the upland material. Out of the seven metals analyzed, lead, arsenic and copper had concentrations that were equal to or exceeded the DCC. These concentrations were observed in the sampling events that took place from 2007-2011; and they were located in or near the exposed mine tailings piles along the western shore. This implies that the source of lead, arsenic and copper contamination is in the exposed mine tailings piles and that contamination has increased between around 1990 and around

2011. To confirm this conclusion, it would be helpful to analyze more of the available data to determine if these patterns are observed with any other metals. The other metals included in this analysis generally did not display concentrations at or above the DCC; nor did they display distinct temporal patterns. Based on the observations of lead and arsenic concentrations compared to the DCC, and that these lead and arsenic concentrations have increased over time, the shoreline cannot be safely developed. Lead and arsenic are both substances that are poisonous to humans (GreenFacts, 2001-2015) (EPA), as discussed in the introduction.

In general, concentrations of metals in sediments that equal or exceed the PEC were found along the western shore between Lake Linden and Hubbell. The exceptions to this rule are copper (whose concentrations exceed the PEC throughout the lake) and mercury (whose concentrations generally do not exceed the PEC). This implies that the sources of metals contamination are in or near the exposed mine tailings piles. Chromium, mercury and zinc all displayed the pattern of concentrations existing below the TEC near the perimeter of the lake and concentrations existing between the TEC and the PEC near the center of the lake, which may be due to focusing of the sediments. There were no significant temporal patterns.

In addition to examining the spatial and temporal trends of the metals concentrations in the soil and sediments of Torch Lake, a few characteristics of sediments and the historical activities which produced the metals should be considered. Metals tend to be more mobile in fine particles found in the deeper areas of lakes compared to coarse particles found in littoral zone of lakes, which may explain the finding that some of the metals displayed higher concentrations in the sediment rather than in the upland material, and especially in patterns out from the exposed mine tailings piles. As mentioned at the beginning of this chapter, industrial waste besides the mine tailings produced lead, zinc and chromium in addition to copper (Urban et al., 2016 (Expected)), (Rose et al., 1986

(inferred)), and this waste was dispersed from the C&H smelter in Hubbell in the form of slag and fly ash. Copper and arsenic were natural enrichments of amygdaloid and conglomerate ore tailings, therefore it makes sense that they are found everywhere throughout the mine tailings (Rose et al., 1986 (inferred)). Conglomerate ore tended to have higher copper content compared to amygdaloid ore. C&H's mine tailings were from conglomerate rock, while Quincy's mine tailings were from amygdaloid ore; which may explain why exposed mine tailings in Mason have lower copper content than exposed mine tailings in Tamarack, Hubbell and Lake Linden. (Urban et al., 2016 (Expected))

The results of the analysis of metals concentrations in the soil and sediments of Torch Lake provide several insights about the current state of metals contamination in the Torch Lake system, its implications for human and ecosystem health, and potential for remediation. Due to recent concentrations of lead and arsenic found in soil exceeding DCC, the western shoreline cannot be safely developed, because of the hazardous nature of these substances to human health. People who presently reside on these properties need to take great care in digging groundwater wells and during activities such as gardening and children playing on the ground. Many of the concentrations of the metals in sediment are above the TEC; average concentrations of the metals in the sediment likely explain the lack of benthos at the lake bottom.

Analysis of the locations of heavy metals, combined with analysis of the historical industrial activities at these locations tell how the metals came to be there, and also give insights into how remediation actions could be improved. The remediation method implemented at the exposed mine tailings piles was capping, which was considered the most viable remediation method compared to dredging the lake's contaminated sediment. Given the information that some of heavy metals contamination is not naturally tied to the mine tailings, it may be worth considering concentrated dredging of the slag near

Hubbell and removal or capping of industrial soils near the Quincy Reclamation Plant, the Hecla Stamp Mill, and the Smelter and C&H coal dock area. A recent Side Scan Sonar search near the Hubbell C&H Coal Dock site revealed significant quantities of debris (Appendix A.13). The Torch Lake Integrated Assessment report and the 1986 report on heavy metals in sediments (part of a large Michigan Tech report about Torch Lake) discuss that some of the heavy metals analyzed are from debris; for this reason, debris removal from the area may be considered.

In short, based on the results of this analysis, two main conclusions are drawn: 1) that some locations along the western shoreline are not safe for development, and 2) that further remediation for OUs I and II should be considered. At least some locations along the western shoreline are not safe for development (in particular, residential development) because arsenic, lead and copper are present in concentrations that exceed the DCC. A declaration that all areas without exceedances are safe for development would require the assumption that the intensity of sampling was adequate to detect all elevated concentrations. Some of the exceedance locations are in the immediate vicinity of former buildings or activity centers where no remediation was performed; other exceedances are on stamp sand piles that were capped. The current methods of remediation for OUs I and II (vegetated soil cap and natural sedimentation, respectively) may be failing and a more effective solution is needed. The findings of this analysis suggest that many of the industrial sites need to be remediated and that some of the capping was ineffective in burying all high concentrations.

4.5 References

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5 ANALYSIS OF POLYCHLORINATED BIPHENYL COMPOUNDS

5.1 Introduction

5.1.1 Objectives

This chapter summarizes the polychlorinated biphenyl (PCB) compound analysis that was performed as part of the Torch Lake Integrated Assessment. The objectives of this chapter are to: 1) summarize prior assessments of the PCB problem in Torch Lake and the existing data on PCB contamination; and 2) evaluate the evidence for local inputs of PCBs to the lake and for ongoing, unidentified inputs to the lake. Objective 1 will be accomplished by discussing the timeline of the PCB investigation and describing what was reported previously. Objective 2 will be accomplished by synthesizing the results of past PCB studies in Torch Lake and reference lakes, discussing the use of PCBs in historical mining activities, synthesizing the locations of likely historical PCB use with recent soil contamination data, and comparing SPMD-estimated truly dissolved PCB concentrations to mass balance model-predicted ones.

5.1.2 Research Approach

The approach to this research began with going through documents about Torch Lake to gather qualitative and quantitative information related to PCBs in the lake system. (NB: lake system here refers to the lake water and sediments, the upland soil in the lake's immediate vicinity, the groundwater flowing into the lake, the lake's airshed, and sometimes the watershed of the lake and its tributaries). Existing information was gathered, compiled, summarized, and interpreted. As part of this process, comparisons

were made of the concentrations of PCBs in fish to safe consumption levels, of aqueous concentrations and isomer distributions in Torch Lake to those of other area waterbodies, and of locations of elevated concentrations of PCBs in soil and sediment to locations of historical industrial buildings. Because this research is a part of an integrated assessment, no new PCB measurements were taken.

After the PCB information was compiled, a mass-balance model was constructed to evaluate the internal consistency of the data and the possible existence of ongoing, unidentified inputs to the lake. Some of the quantitative data that were compiled, specifically the sediment and groundwater concentrations, were used as inputs for the mass-balance model. The conclusions drawn from the compilation of PCB information contribute to both Objectives 1 and 2. The results of the mass-balance modeling were compared to the other estimates of aqueous concentrations to evaluate if unknown, ongoing sources of PCBs to the lake exist.

5.1.3 Structure of this Chapter

This chapter is made up of five sections in the following order: this introduction, the methods, results, discussion and conclusions. The methods section describes the methods used to compile and map existing data on PCBs concentrations in various media, construct and evaluate the mass balance of PCBs in the Torch Lake system, and estimate aqueous concentrations from passive sampler measurements. In the results section, the maps of the SPMD and sediment concentration data, the fish PCB concentration analysis, and the outputs of the mass balance model and its evaluation are presented. The discussion section ties these results together with analysis done outside of this thesis to describe what was known about Torch Lake PCB contamination prior to this research and to evaluate the evidence for local and ongoing, unidentified inputs of PCBs to the lake. The conclusions section summarizes the findings and new insights from this research.

5.2 Methods

5.2.1 PCB Concentration Data Compilation

The first step in compiling data was to go through all of the documents that were available on Torch Lake and to find quantitative or qualitative information on PCBs. Qualitative information was noted and quantitative data were compiled in Excel spreadsheets. The quantitative data were organized by medium and then by sampling; e.g., data were sorted by medium (fish, SPMDs, sediment, soil and groundwater), then sorted by investigation such as the 2007 MDEQ sediment chemistry survey or the 2008 EPA sediment Aroclor investigation. The U.S. EPA provided 2 datasets of sediment samples, one of which was developed by a contractor. The MDEQ provided 1 dataset of SPMD samples, 3 datasets of sediment samples, 4 datasets of upland material samples, and 6 datasets of fish samples.

For the fish PCB concentration measurements, all of the available data for Torch Lake, Portage Lake and Huron Bay were compiled into Excel. Portage Lake and Huron Bay data were compiled to serve as control sites for Torch Lake. In Torch Lake, the MDEQ sampled Walleye, Northern Pike, Smallmouth Bass, and White Sucker for PCB content. They also sampled Walleye and Northern Pike from Portage Lake, and Walleye, Rainbow Trout and Northern Pike in Huron Bay. The different species of fish were also classified into different size classes, as presented in Table 5.1:

Table 5.1: Size classes of fish.

Species/Size	Small	Medium	Large
Smallmouth Bass	20 – 29.9 cm	30 – 39.9 cm	>40 cm
Walleye	30 – 44.9 cm	45 – 64.9 cm	>65 cm
Northern Pike	30 – 44.9 cm	45 – 64.9 cm	>65 cm
White Sucker	500 – 750g	N/A	900 – 1410 g

Source of Data: (Bohr, 2010) Information also available through the MDEQ Fish Contaminant Monitoring Program (<http://www.deq.state.mi.us/fcmp/>).

Before 2000, PCB concentrations were measured in terms of Aroclor mixtures. From 2000 on, PCB concentrations in fish were measured in terms of congeners. For the purpose of this research, the totals and averages of totals of the reported concentrations were analyzed. An analysis of the trend of the PCB concentrations by specimen length over time for Torch Lake Walleye and Northern Pike is presented.

For the sediment, soil, and groundwater concentrations, specific data extracted for this study included sample PCB concentration, measurement or analysis notes (usually with regards to sample detection limit), geographic coordinates, sample ID and date sampled. Information that was compiled in Excel was transferred into ArcGIS. ArcGIS was used to produce maps of the PCB homolog distribution at each of the 2005 MDEQ SPMD study sample locations and locations of elevated concentrations of PCBs found in sediment, soil and groundwater. These maps are presented in the Discussion section.

5.2.2 PCB Mass-Balance Model

The objective of constructing a mass-balance model for PCBs in Torch Lake is to evaluate whether the existing measurements of PCBs in different environmental media around the lake (air, water, fish, and sediments) are internally consistent. Because PCBs partition from one medium to another, it would likely not be possible to have high concentrations in fish if concentrations in the lake water were very low; similarly, it would likely not be possible to have high concentrations in the sediments and low concentrations in the fish. The mass balance model can be used to evaluate whether known sources of PCBs can account for known sinks or losses of PCBs from the lake. If measured losses are greater than the known sources, the existence of an additional, unknown source might be indicated. The mass balance model can also be used to estimate the time required for recovery of the lake from historical contamination.

The mass balance model for PCBs in Torch Lake is set up essentially as a two-box model, though one of the two boxes is actually three boxes in parallel. As shown in Figure 5.1 below, the top box represents the water column. Also shown in Figure 5.1, the bottom three boxes exist in parallel to each other and represent the three different sediment exchange regions. The reason that a two-box structure was chosen for the mass balance model is because a box representing the sediment column can account for burial of PCBs into the refractory sediment layers, while a one-box structure representing only the water column would not be able to account for a sink of PCBs out of the labile sediment layer. One of the major assumptions in applying this model is that sediment exchange regions 1 and 2 (shown in Figure 5.2), where the concentrations of PCBs are known, provide a constant input of PCBs into the water column. Due to this assumption, some of the terms in this model that rely on the concentration of PCBs in the sediment being known quantities are calculated differently between sediment exchange regions 1 and 2, and 3. In particular, the sediment-to-water diffusion terms and the resuspension terms are calculated as flux values in sediment exchange regions 1 and 2, but as a flow

value in sediment exchange region 3. In this model, “flux” terms are expressed in units of mass/time and “flow” terms are expressed in units of volume/time; therefore, flux values require a concentration of PCB congener in the medium/media involved in the term, where flow values do not. The designations of the sediment exchange regions are discussed later in this section.

This model was constructed under two major assumptions: 1) Torch Lake water column is well-mixed; and 2) the PCB loadings to the lake system are not changing. The PCBs in the lake system are assumed not to be changing because it is assumed that changes in input loadings of PCBs to Torch Lake have not occurred since at least the 1970s. This assumption is the control condition; the comparison of the model-predicted truly dissolved concentrations to SPMD-estimated truly dissolved concentrations is used to evaluate if an unidentified, ongoing source of PCBs to Torch Lake exists.

5.2.2.1 Model overview

As shown in Figure 5.1, the water-column box has the following inputs: atmospheric deposition, absorption, groundwater input, sediment diffusion of both the truly dissolved and DOC-bound phases, and resuspension. Outputs include: volatilization, outflow, sediment diffusion of both the truly dissolved and DOC-bound phases, and settling. Also shown in Figure 5.1 are the inputs and outputs of the sediment box that include the following: sediment diffusion of the truly dissolved and DOC-bound phases, settling, resuspension and burial.

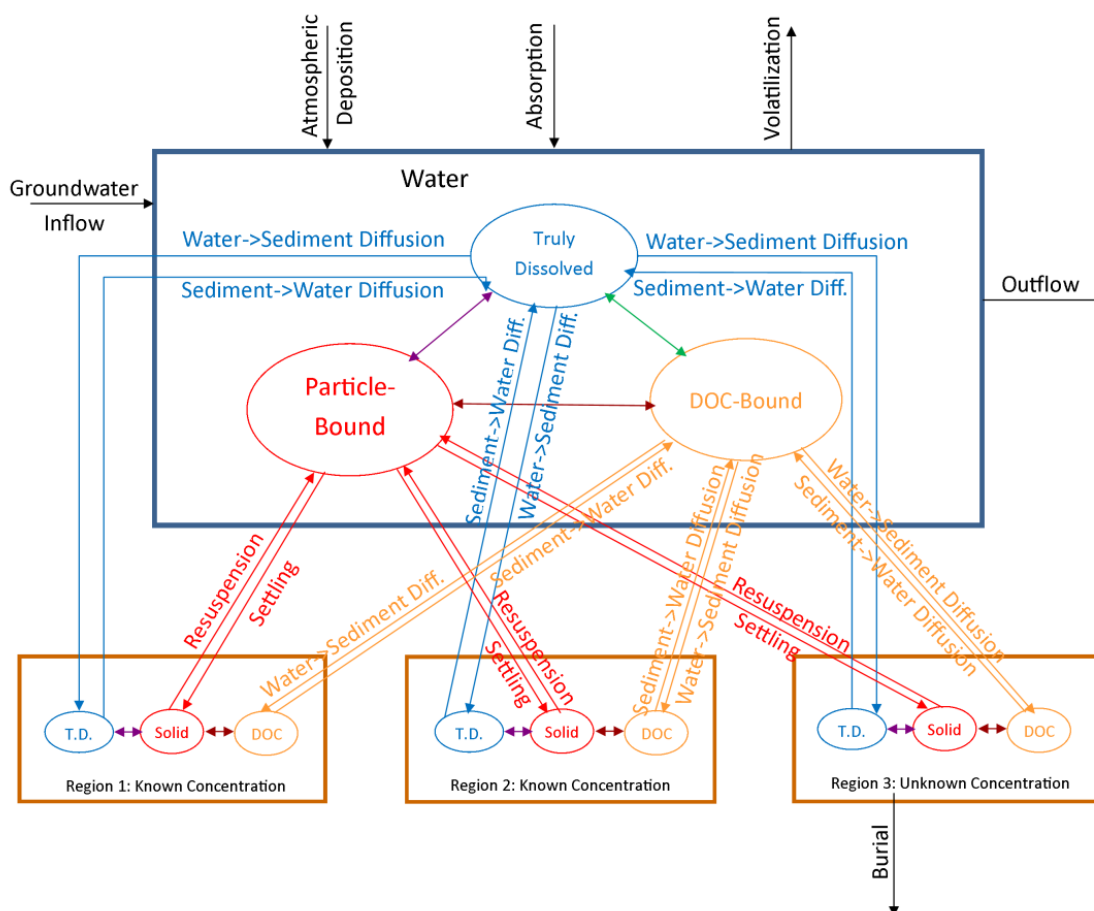


Figure 5.1: Torch Lake PCB mass balance model schematic.

All inputs and outputs for both boxes, along with the partitioning of PCBs into three different phases (truly dissolved, particulate-bound and DOC-bound) are explained in more detail below.

5.2.2.2 Phase-naming conventions

In this analysis, concentrations and fractions of concentrations of PCBs are considered in three different phases: the truly dissolved phase, PCBs bound to dissolved organic carbon (DOC-bound) and particle-bound PCBs. To clarify, dissolved organic carbon is carbon

material in water that is small enough to pass through a filter. (Schwarzenbach, 2003)

The DOC-bound fraction is considered in this model because it is the fraction that is not available for bioaccumulation, and must be accounted for as such. In addition to these phases, groups of these phases are referred to as follows: aqueous PCB concentration, which is the sum of the truly dissolved phase + DOC-bound phases; total water PCB concentration, which equals truly dissolved + DOC-bound + particle-bound in the water column; and total sediment PCB concentration, which equals truly dissolved + DOC-bound + particle-bound in the sediment column. The equations for the phase fractions are described after Table 5.3 of this chapter. Total water PCB concentration and total sediment PCB concentration are the state variables of the system. To clarify, total sediment PCB concentration usually refers to the unknown concentration of PCBs in the sediments in sediment exchange region 3 (explained following this section), unless otherwise noted in this chapter.

5.2.2.3 Sediment Exchange Regions

Upon examination of the locations of elevated PCB concentrations in the sediment, it was determined that there were two main, known regions of sediment contamination. For the purpose of providing accurate input to the mass balance model of PCB flux from the sediments, rather than having one average sediment concentration over the entire lake (which would be biased due to the large area of the lake without elevated PCB concentrations), there are two average sediment PCB concentrations over smaller areas that are higher than those in the remainder of the lake bottom and more representative of the actual PCB concentrations found in these locations. Regions of sediments designated for modeling purposes are shown in Figure 5.2.

The selection of the sediment exchange regions was based on the extents of the two areas of positive PCB concentrations (where concentrations that met or exceeded detection limits were found). Circles were drawn around the points, and using the scale of the map, the areas of the circles were estimated. Because the areas of the regions included land, the area values were multiplied by estimated fractions of the water in the circles to give a more accurate estimate of the sediment exchange area. Sediment exchange region 1 is the water section of the southern circle, sediment exchange region 2 is the water section of the northern circle, and sediment exchange region 3 is the remainder of the lake area not included in either circle.

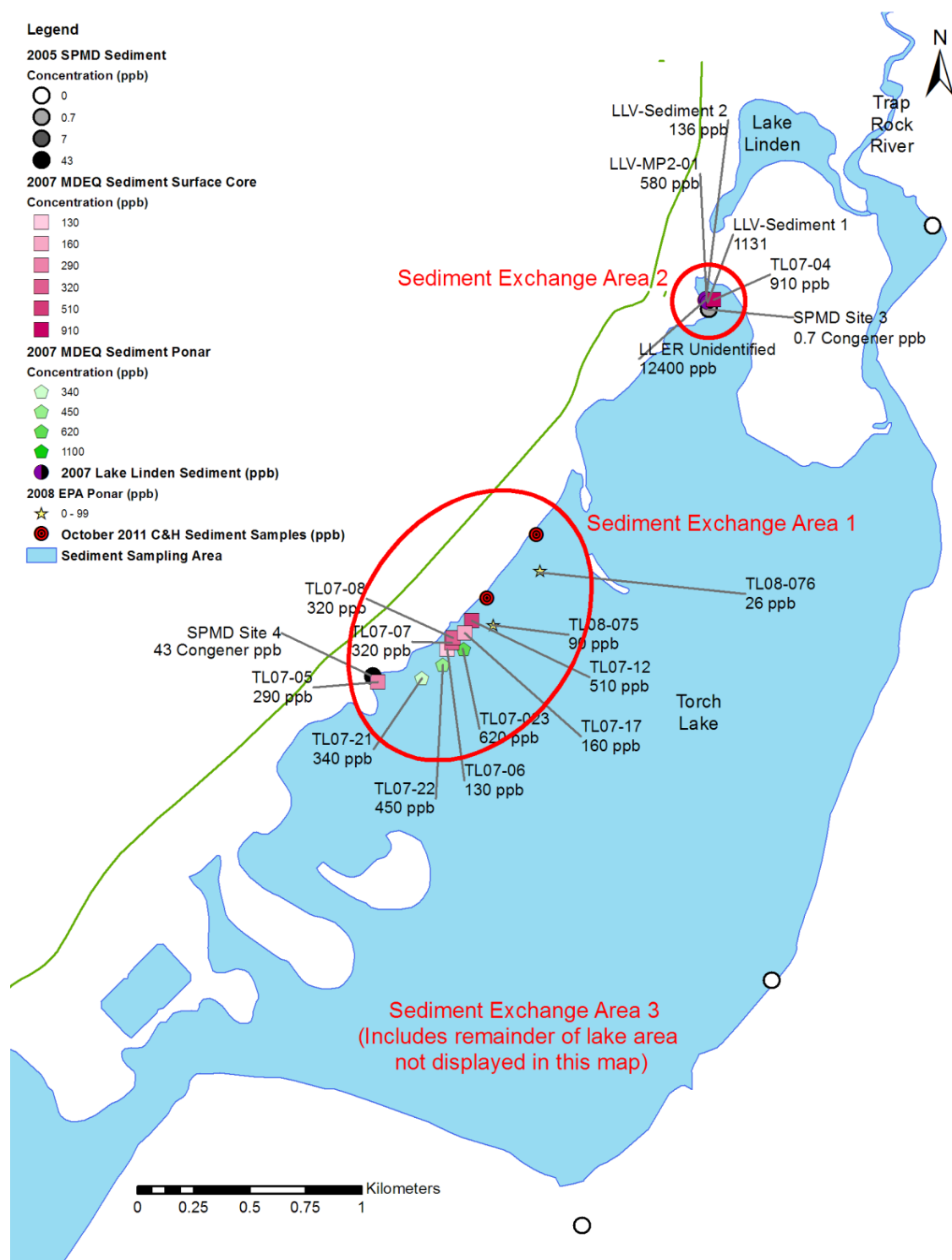


Figure 5.2: Sediment region definitions.

5.2.2.4 Model Construction

The mass balance model for PCBs in Torch Lake was constructed in Microsoft® Excel. Calculated inputs (such as groundwater concentration or resuspension flux), lake properties, chemical properties of PCBs, loading calculations and concentration calculations were implemented in separate tabs. Calculations in later steps reference calculations or variables in earlier steps; for example, the calculation of the concentration of PCBs in water references the calculation of absorption, and the calculation of absorption references independent variables that are properties of Torch Lake and the PCB congeners.

Terms that are congener-specific are indexed, e.g., the truly dissolved fraction of the congener is described as f_{iw} , where i represents the congener number. We follow the convention of designating mass flux (J , mass/time) into the control volume (lake or sediment), flows (Q , volume/time) out of the control volume.

The system of equations that represent the two boxes and govern the entire model is given below:

$$\begin{aligned} \frac{VdC_{iwater}}{dt} = 0 = & J_{iAD} + J_{iabs} + J_{igw} + J_{isedexSW1} + J_{isedexDOCSW1} + J_{isedexSW2} + \\ & J_{isedexDOCSW2} + J_{iresus1} + J_{iresus2} - Q_{ivol}C_{iwater} - Q_{iset}C_{iwater} - Q_{out}C_{iwater} - \\ & Q_{isedexWS1}C_{iwater} - Q_{isedexDOCWS1}C_{iwater} - Q_{isedexWS2}C_{iwater} - \\ & Q_{isedexDOCWS2}C_{iwater} - Q_{isedexWS3}C_{iwater} - Q_{isedexDOCWS3}C_{iwater} + \\ & Q_{isedexDOCSW3}C_{ised} + Q_{iresus3}C_{ised} \end{aligned} \quad [1]$$

$$V \frac{dC_{ised}}{dt} = 0 = -Q_{iburial3}C_{ised} - Q_{isedexSW3}C_{ised} - Q_{isedexDOCWS3}C_{ised} - \\ Q_{iresus3}C_{ised} + Q_{iset}C_{iwater} + Q_{isedexWS3}C_{iwater} + Q_{isedexDOCWS3}C_{iwater} \\ [2]$$

where variables are defined in Table 5.2.

Table 5.2: Sediment region definitions

Quantity	Symbol	Units
Total PCB concentration in the water column	C_{iwater}	$\text{mg}/\text{m}^3_{\text{water}}$
Total PCB concentration in the sediment column	C_{ised}	$\text{mg}/\text{m}^3_{\text{sed}}$
Atmospheric deposition flux input to water column	J_{iAD}	mg/yr
Absorption flux into water column	J_{iabs}	mg/yr
Groundwater flux into water column	J_{igw}	mg/yr
Sediment exchange diffusion flux of truly dissolved PCB from sediment exchange region 1 to the water column	$J_{isedexSW1}$	mg/yr
Sediment exchange diffusion flux of DOC-bound PCB from sediment exchange region 1 to the water column	$J_{isedexDOCSW1}$	mg/yr
Sediment exchange diffusion flux of truly dissolved PCB from sediment exchange region 2 to the water column	$J_{isedexSW2}$	mg/yr
Sediment exchange diffusion flux of DOC-bound PCB from sediment exchange region 2 to the water column	$J_{isedexDOCSW2}$	mg/yr
Resuspension flux of particle-bound PCB from sediment exchange region 1 to water column	$J_{iresus1}$	mg/yr
Resuspension flux of particle-bound PCB from sediment exchange region 2 to water column	$J_{iresus2}$	mg/yr
Volatilization flow out of the water column into the air (not modeled)	Q_{ivol}	$\text{m}^3_{\text{water}}/\text{yr}$
Settling flow of particle-bound PCB from the water column to the sediment column	Q_{iset}	$\text{m}^3_{\text{water}}/\text{yr}$

Quantity	Symbol	Units
Outflow of PCB from Torch Lake to the Portage Canal (not modeled)	Q_{out}	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of truly dissolved PCB from the water column to sediment exchange region 1	$Q_{isedexWS1}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of DOC-bound PCB from the water column to sediment exchange region 1	$Q_{isedexDOCWS1}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of truly dissolved PCB from the water column to sediment exchange region 2	$Q_{isedexWS2}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of DOC-bound PCB from the water column to sediment exchange region 2	$Q_{isedexDOCWS2}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of truly dissolved PCB from the water column to sediment exchange region 3	$Q_{isedexWS3}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of DOC-bound PCB from the water column to sediment exchange region 3	$Q_{isedexDOCWS3}$	$\text{m}^3_{\text{water}}/\text{yr}$
Sediment exchange diffusion flow of truly dissolved PCB from sediment exchange region 3 to the water column	$Q_{isedexSW3}$	$\text{m}^3_{\text{sed}}/\text{yr}$
Sediment exchange diffusion flow of DOC-bound PCB from sediment exchange region 3 to the water column	$Q_{isedexDOCSW3}$	$\text{m}^3_{\text{sed}}/\text{yr}$
Resuspension flow of particle-bound PCB from sediment exchange region 3 to water column	$Q_{iresus3}$	$\text{m}^3_{\text{sed}}/\text{yr}$
Burial flow of PCB from labile sediment to refractory sediment (not modeled)	$Q_{iburial3}$	$\text{m}^3_{\text{sed}}/\text{yr}$

The equations used to calculate the steady-state concentration of total PCB in the water and sediment column are:

$$C_{iwater\infty} = \frac{J_1 * (k_{22} + k_{21})}{(k_{11} + k_{12}) * (k_{22} + k_{21}) - k_{21} * k_{12}} \quad [3]$$

$$C_{ised\infty} = \frac{J_1 * k_{12}}{(k_{11} + k_{12}) * (k_{22} + k_{21}) - k_{21} * k_{12}} \quad [4]$$

where:

$$J_1 = \frac{J_{iAD} + J_{iabs} + J_{igw} + J_{isedexSW1} + J_{isedexDOCSW1} + J_{isedexSW2} + J_{isedexDOCSW2} + J_{iresus1} + J_{iresus2}}{V_{lake}} \quad [5]$$

$$J_2 = 0 \quad [6]$$

$$k_{11} = \frac{Q_{ivol} + Q_{iset} + Q_{out} + Q_{isedexWS1} + Q_{isedexDOCWS1} + Q_{isedexWS2} + Q_{isedexDOCWS2}}{V_{lake}} \quad [7]$$

$$k_{12} = \frac{Q_{iset} + Q_{isedexWS3} + Q_{isedexDOCWS3}}{V_{lake}} \quad [8]$$

$$k_{21} = \frac{Q_{isedexSW3} + Q_{isedexDOCSW3} + Q_{iresus3}}{V_{sedex3}} \quad [9]$$

$$k_{22} = \frac{Q_{iburial3}}{V_{sedex3}} \quad [10]$$

Table 5.3 and Table 5.4 below list the equations and variables used in the model. The sections below these tables discuss some of the model terms in more detail.

Table 5.3: Equations used in Torch Lake mass balance on PCBs.

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
<i>Air-Water Gas Exchange</i>				
Gas absorption (Input)	mg _{PCB} /yr	$J_{iabs} = \frac{v_{iaw}A_{lake}C_{ia}}{K_{iaw}}$		11
Gas volatilization (Output)	m ³ /yr	$Q_{ivol} = v_{iaw}A_{lake}f_{iw}$		12
Air-water exchange velocity	m/yr	$\frac{1}{v_{iaw}} = \left(\frac{1}{v_{ia}K_{iaw}} + \frac{1}{v_{iw}}\right)^{-1}$	1	13
Air-phase transfer velocity	m/yr	$v_{ia} = \left(\frac{D_{ia}}{D_{wa}}\right)^{0.67}v_{wa}$	1	14
Diffusivity in air	cm ² /s	$D_{ia} = D_{wa}\left(\frac{M_i}{M_{H_2O}}\right)^{-1/2}$	1	15
Diffusivity of water in air	cm ² /s	$D_{wa} = \frac{1.55}{M_{H_2O}^{0.65}}$	1	16
Air-phase transfer velocity of water vapor	m/yr	$v_{wa} = 0.2u_{10} + 0.3 * \left(\frac{31536000sec}{yr}\right) * \left(\frac{1m}{100cm}\right)$	1	17
Water-phase transfer velocity	m/yr	$v_{iw} = \left(\left(\frac{Sc_{iw}}{780}\right)^{-a_{sc}}\right) * v_{CO_2w} * \left(\frac{31536000sec}{yr}\right) * \left(\frac{1m}{100cm}\right)$	1	18
Schmidt number (applied value for 15°C)	-	$Sc_{iw} = \frac{v_w}{D_{iw}}$	1	19

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
Diffusivity in water – truly dissolved phase (Reference substance is CO ₂ at 5°C)	cm ² /s	$\frac{D_{iw}}{D_{ref}} = \left[\frac{M_i}{M_{ref}}\right]^{-1/2}$	1	20
Dimensionless Henry's Law Constant	-	$K_{iaw} = \frac{K_{iH}}{R \cdot T_{AW}}$		21
Henry's Law Constant	Pa*m ³ /mol	$\log K_{iH} = A_{iH} - \frac{B_{iH}}{T_{AW}}$	2	22
Groundwater Input				
Groundwater Input	mg/yr	$J_{igw} = Q_{igw} C_{igw}$		23
Groundwater Flow (Darcy's Law; divide by 52 to get weekly flux, multiply by 6 for number of weeks to which this quantity actually applies (assumption))	m ³ /yr	$Q_{igw} = K \times D_{WT} \times W \times S * \left(\frac{6 \text{ weeks}}{52 \text{ weeks}}\right)$		24
Settling				
Settling Flow	m ³ /yr	$Q_{iset} = f_{is} A_{lake} v_{set} * \frac{365 \text{ days}}{\text{yr}}$		25

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
<i>Sediment Exchange</i>				
Truly dissolved phase sediment-to-water flux (applies to regions 1 and 2)	mg/yr	$J_{isedexSWX} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * A_{sedexX} * C_{isedwX}}{\Delta_z}$		26
Truly dissolved phase sediment-to-water flow (applies to region 3)	m ³ /yr	$Q_{isedexSW3} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * A_{sedex3} * f_{isedw}}{\Delta_z}$		27
DOC-bound phase sediment-to-water flux (applies to regions 1 and 2)	mg/yr	$J_{isedexDOCSWX} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * A_{sedexX} * C_{isedDOCX}}{\Delta_z}$		28
DOC-bound phase sediment-to-water flow (applies to region 3)	m ³ /yr	$Q_{isedexSW3} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * A_{sedex3} * f_{isedDOC}}{\Delta_z}$		29
Truly dissolved phase water-to-sediment flow (applies to all regions)	m ³ /yr	$Q_{isedexSWX} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * f_{iw} * A_{sedexX}}{\Delta_z}$		30

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
DOC-bound phase water-to-sediment flow (applies to all regions)	m ³ /yr	$Q_{isedexDOCSWX} = \frac{D_{ieff} * \frac{31536000sec}{1yr} * f_{iDOC} * A_{sedexX}}{\Delta_z}$		31
Molecular mass of congener + organic carbon	g/mol	$M_{iOC} = M_i + M_{OC}$		32
Diffusivity in water – DOC-bound phase (Reference substance is CO ₂ at 5°C)	cm ² /s	$\frac{D_{iwOC}}{D_{ref}} = [\frac{M_{iOC}}{M_{ref}}]^{-1/2}$		33
Effective diffusivity – truly dissolved phase	m ² /s	$D_{ieff} = D_{iw} \varphi * \left(\frac{1m^2}{10000cm^2} \right)$	1	34
Effective diffusivity – DOC-bound phase	m ² /s	$D_{ieffOC} = D_{iwOC} \varphi * \left(\frac{1m^2}{10000cm^2} \right)$	1	35
Sediment exchange area 3	m ²	$A_{sedex3} = A_{lake} - (A_{sedex1} + A_{sedex2})$		36
Concentration of truly dissolved PCB in sediment exchange areas 1 or 2	mg _{PCB} /m ³ _{sed}	$C_{isedwX} = C_{isedtX} f_{isedw}$		37

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
Concentration of DOC-bound PCB in sediment exchange areas 1 or 2	$\text{mg}_{\text{PCB}}/\text{m}^3_{\text{sed}}$	$C_{isedDOCX} = C_{isedtX}f_{isedDOC}$		38
Concentration of total PCBs in Sediment Exchange Region 1 or 2	$\text{mg}_{\text{PCB}}/\text{m}^3_{\text{sed}}$	$C_{isedtX} = C_{isedX}\rho_{bulk}\left(\frac{kg_{solids}}{1000g_{solids}}\right)\left(\frac{10^6cm^3_{sed}}{m^3_{sed}}\right)$		39
<i>Resuspension</i>				
Resuspension flux	mg/yr	$J_{iresusX} = v_{resus}A_{sedexX}C_{isedsX}$		40
Resuspension flow	m^3/yr	$Q_{iresus3} = v_{resus}A_{sedex3}f_{iseds}$		41
Concentration of particle-bound PCB in sediment exchange areas 1 or 2	$\text{mg}_{\text{PCB}}/\text{m}^3_{\text{sed}}$	$C_{isedsX} = C_{isedtX}f_{iseds}$		42
<i>Burial</i>				
Burial flow	m^3/yr	$Q_{iburial3} = v_{burial}A_{sedex3}$		43

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
<i>Partition Fractions and Other Chemical or Physical Properties</i>				
Fraction of PCB bound to DOC in water column	-	$f_{iDOC} = \frac{K_{iDOC}C_{DOCW}}{1+K_{id}r_{swW}+K_{iDOC}C_{DOCW}}$	1	44
Fraction of truly dissolved PCB in water column	-	$f_{iw} = \frac{1}{1+K_{id}r_{swW}+K_{iDOC}C_{DOCW}}$	1	45
Fraction of particle-bound PCB in water column	-	$f_{is} = \frac{K_{id}r_{swW}}{1+K_{id}r_{swW}+K_{iDOC}C_{DOCW}}$	1	46
Solid-water distribution coefficient	L _w /kg _{solids}	$K_{id} = f_{ocW}K_{ioc}$		47
Organic carbon normalized solid-water partition coefficient	L _w /kg _{oc}	$\log K_{ioc} = 0.74\log K_{iow} + 0.15$	1	48
Log of octanol-water partition coefficient		$\log K_{iow} = A_{iow} - \frac{B_{iow}}{T}$	2	49
Octanol-water partition coefficient	L _w /L _o	$K_{iow} = 10^{\log K_{iow}}$		50
Equilibrium DOC-water partition coefficient	L _w /kg _{oc}	$K_{iDOC} = 0.08K_{iow}$	3	51

Equation Description	Units	Equation	Eqn. Source	Eqn. No.
Solid-water distribution coefficient (sediment)	L _w / kg _{solids}	$K_{id\text{sed}} = f_{oc\text{sed}}K_{ioc}$		52
Water-to-solids ratio (sediment)	g _{solids} / cm _w ³	$r_{sw\text{sed}} = \frac{\rho_{bulk}}{\varphi}$		53
Volume of lake	m ³	$V_{lake} = A_{lake}D_{lake}$		54
Volume of Sediment Exchange Region 3	m ³	$V_{sedex3} = A_{sedex3}\Delta z$		55

Source References Used in this Table

Equation Source Number	Equation Source
1	(Schwarzenbach, 2003)
2	(Paasivirta & Sinkkonen, 2009)
3	(Burkhard, 2000)

The equations for the fractions of PCB in each phase are given below.

Fraction of PCB bound to DOC in sediment column:

$$f_{isedOC} = \frac{K_{iDOC}C_{DOCsed}\left(\frac{1kg_{OC}}{10^6mg_{OC}}\right)}{1 + K_{idsed}r_{swsed}\left(\frac{1000cm^3_W}{L_W}\right)\left(\frac{1kg_{solids}}{1000g_{solids}}\right) + K_{iDOC}C_{DOCsed}\left(\frac{1kg_{OC}}{10^6mg_{OC}}\right)} \quad [56]$$

(Schwarzenbach, 2003)

Fraction of truly dissolved PCB in sediment column:

$$f_{isedw} = \frac{1}{1 + K_{idsed}r_{swsed}\left(\frac{1000cm^3_W}{L_W}\right)\left(\frac{1kg_{solids}}{1000g_{solids}}\right) + K_{iDOC}C_{DOCsed}\left(\frac{1kg_{OC}}{10^6mg_{OC}}\right)} \quad [57]$$

(Schwarzenbach, 2003)

Fraction of particle-bound PCB in sediment column:

$$f_{iseds} = \frac{K_{idsed}r_{swsed}\left(\frac{1000cm^3_W}{L_W}\right)\left(\frac{1kg_{solids}}{1000g_{solids}}\right)}{1 + K_{idsed}r_{swsed}\left(\frac{1000cm^3_W}{L_W}\right)\left(\frac{1kg_{solids}}{1000g_{solids}}\right) + K_{iDOC}C_{DOCsed}\left(\frac{1kg_{OC}}{10^6mg_{OC}}\right)} \quad [58]$$

(Schwarzenbach, 2003)

Table 5.4: Independent parameters used in Torch Lake mass balance on PCBs.

Variable Name	Units	Symbol	Value	Source	Notes
Atmospheric deposition flux intensity	ng/m ² /yr	F_{iAD}	Varies with congener	1	See text for details
Molecular mass of water	g/mol	M_{H_2O}	18		
Molecular mass of congener	g/mol	M_i	Varies with congener		
Molecular mass of carbon dioxide	g/mol	M_{CO_2}	44		
Molecular mass of organic carbon	g/mol	M_{OC}	1000		
Wind speed at 10 m above water surface	m/s	u_{10}	3.60		Assumed to be the average wind speed measured at the Hancock airport weather station from April through October 2005
		a_{Sc}	0.67	2	Constant related to the Schmidt number.
Water-phase velocity of carbon dioxide	cm/s	v_{CO_2w}	$6.5 \cdot 10^{-4}$	2	
Viscosity of water at 15°C	cm ² /s	ν_w	0.01139	2	
Diffusivity of carbon dioxide in water	cm ² /s	D_{CO_2w}	$1.45 \cdot 10^{-5}$	2	Value at 15°C
Bulk density	g _{solids} /cm ³ _{sed}	ρ_{bulk}	0.2	3	

Variable Name	Units	Symbol	Value	Source	Notes
Burial velocity	m/yr	v_{burial}	0.0011	3	
Resuspension velocity	m/yr	v_{resus}	$4.05 \cdot 10^{-4}$		See text for details
Concentration of truly dissolved organic carbon in sediments (pore water)	mgOC/L _w	C_{DOCsed}	40	4	
Ideal Gas Constant	(Pa*m ³)/(mol*K)	R	8.314	2	
Regression constants to calculate $\log K_{iH}$		A_{iH}, B_{iH}	Varies with congener	5	
Temperature of air-water gas exchange	K	T_{AW}	288	6	Assumed value based on measurements of the water temperature taken in the fall over several years
Concentration of congener in air	ngPCB/ m ³ _{air}	C_{ia}	Varies with congener	1	Average of all values measured by IADN at Eagle Harbor of the congener's concentration in air from April-October of 2005
Area of Torch Lake	m ²	A_{lake}	$9.82 \cdot 10^6$		Measurement of polygon taken from Michigan Geographical Database Library
Concentration of congener in groundwater	mgPCB/ m ³ _{water}	C_{igw}	Varies with congener		See text for details

Variable Name	Units	Symbol	Value	Source	Notes
Hydraulic conductivity of soil/upland material	m/d	K	8	7	
Depth to the water table	m	D_{WT}	2.39	8	Calculated based on sparse data from monitoring wells at the Calumet & Hecla Power Plant
Width of contaminated upland area	m	W	180		Determined by using GIS to measure the length from the northernmost upland sample point (in Lake Linden) to the southernmost upland sample point (near Hubbell)
Slope of hydraulic gradient	ft/ft	S	0.0429	8	Calculated from MDEQ data
Settling velocity	m/d	v_{set}	0.85	3	
Outflow	m ³ /yr	Q_{out}	1.02*10 ⁸		Taken from water balance calculated in Fall 2012 by N. Urban
Area of sediment exchange region 1	m ²	A_{sedex1}	3.11*10 ⁵		
Area of sediment exchange region 2	m ²	A_{sedex2}	8.63*10 ⁴		

Variable Name	Units	Symbol	Value	Source	Notes
Average concentration of PCB congener in sediment exchange region 1 or 2	mg _{PCB} / kg _{solids}	C_{isedX}	$8.63 \cdot 10^4$		Average of sediment concentrations measured in sediment exchange region 1 or 2
Porosity	kg _w / kg _{sed}	φ	0.8	3	
Thickness of the layer of sediment participating in diffusion	m	Δ_z	0.01		Assumed value
Fraction of organic carbon in sediments	kg _{oc} / kg _{sed}	f_{ocsed}	0.14		Value is based on measurements in Torch Lake sediments.
Average depth of lake	m	D_{lake}	15.2		
Dissolved organic carbon concentration in water	kg _{oc} /L _w	C_{DOCW}	$7.90 \cdot 10^{-6}$		Average of measurements taken over 10 years
Ratio of solids-to-water in water / concentration of suspended solids	kg _{solids} / L _w	r_{sww}	$8.5 \cdot 10^{-7}$		Measured quantity
Fraction of organic carbon in suspended particles in the lake		f_{ocw}	0.25		This value was taken to be typical of medium-sized lakes.
Regression constants to calculate $\log K_{iow}$		$A_{iow},$ B_{iow}	Varies with congener	5	

Variable Name	Units	Symbol	Value	Source	Notes
Temperature of DOC partitioning	K	T_{part}	288		

Source References Used in this Table

Variable Source Number	Variable Source
1	(Blanchard et al., 2005)
2	(Schwarzenbach, 2003)
3	(McDonald et al., 2010)
4	(Cusack & Mihelcic, 1999)
5	(Paasivirta & Sinkkonen, 2009)
6	(The Weather Channel)
7	(NRCS)
8	Unpublished MDEQ data

5.2.2.5 Model Term Details

5.2.2.5.1 Water Column Terms

Atmospheric Deposition (Input)

Wet atmospheric deposition flux is calculated using the following equation:

$$J_{iAD} = F_{iAD} \times A_{lake} \quad [59]$$

where F_{iAD} is the annual atmospheric deposition (AD) flux in ng/m²/yr. Measured F_{iAD} values for congeners 52 and 101 for the year 2005 were reported in the 2005 International Atmospheric Deposition Network (IADN) report (Blanchard et al., 2005). Specific values for the other congeners in the mass-balance model were not reported, so they were calculated or assumed. For congener 33, F_{iAD} was assumed to be the same as that of congener 52 because both of these congeners are relatively light. For congener 99, F_{iAD} was assumed to be the same as that of congener 101 because both 99 and 101 have five chlorines attached to their phenyl rings. The atmospheric deposition flux value for congener 180 is assumed to be zero because compared to the atmospheric deposition flux values of less chlorinated congeners, which are more likely to volatilize, its concentration in air is very small.

For congeners 149 and 153, F_{iAD} was estimated by calculating the ratio of the weight fractions of Aroclor 1242 represented by congeners 149 or 153 to the weight fraction of Aroclor 1242 represented by congener 101. The reasoning behind this calculation is that congeners 149 and 153 are not similar to congener 101 enough to assume that the flux for

congener 101 applies to them. It was assumed that because Aroclor 1242 is a mixture of mostly less-chlorinated congeners that are more likely to volatilize, the ratios of the congeners in this particular mixture can be representative of the ratio of congeners in the air. To determine if this assumption was reasonable, the distribution of congener weight fractions in Aroclor 1242 and the distribution of congener concentrations (specifically, the averages of concentrations reported by the IADN Project from April-October of 2005) were compared. In both distributions, the values of all congener concentrations were normalized to the value of the concentration of congener 4. As shown in Figure 5.3 and Figure 5.4 below, the distributions are similar, but only vaguely. It was decided that the distributions were similar enough to allow calculation of the AD flux values for congeners 149 and 153.

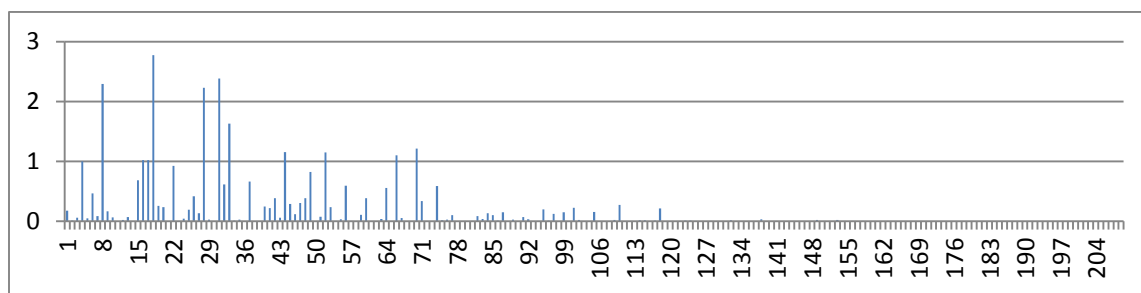


Figure 5.3: Distribution of congener weight fractions in Aroclor 1242, normalized to the %weight fraction of PCB 4.

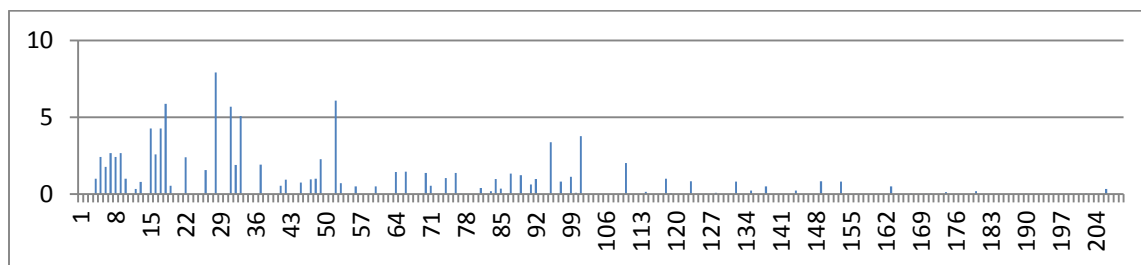


Figure 5.4: Distribution of average congener concentration from April-October 2005 at Eagle Harbor, MI, normalized to the concentration of PCB 4.

Air-Water Gas Exchange

Historically, it has been common to consider air-water exchange to be the net process that encompasses volatilization (lake to air) and absorption (air to lake) (Schwarzenbach, 2003). In this model, the two sub-processes are quantified separately; absorption is calculated using equation 11, and volatilization is calculated using equation 12.

Measured air concentrations are not available for all PCB congeners – out of the 209 congeners, the concentrations of only 77 congeners were measured in air. In regards to this thesis, the concentrations of the two hexachlorinated congeners (PCB 149 and PCB 153) were reported as concentrations co-eluted with other congeners during lab analysis.

Groundwater (Input)

Groundwater input, as used in the model, is calculated by multiplying the groundwater flow by the concentration of congener in the groundwater:

$$J_{igw} = Q_{igw}C_{igw} \quad [23]$$

The concentrations of PCBs in groundwater were reported as concentrations of Aroclor mixtures 1254 or 1260. In order to incorporate these concentrations into the model, the Aroclor mixture concentrations were converted into congener concentrations using weight fractions of congeners in the Aroclor mixtures reported in Frame et al., 1996. Once the congener concentrations at each sample location were calculated, these concentrations were averaged to obtain the concentration of congener in groundwater. Q_{igw} was calculated using Darcy's Law:

$$Q_{igw} = K \times D \times W \times S \quad [24]$$

where K is the hydraulic conductivity of the soil, D is the depth to the water table, W is the width of the contaminated area and S is the slope of the hydraulic gradient. The hydraulic conductivity is an assumed value based on hydraulic conductivity for coarse sand (NRCS). The depth of the water table, 2.39 m, is calculated based on sparse data from monitoring wells at the Calumet and Hecla Power Plant provided by the MDEQ. The width of the contaminated upland soil area was determined by using GIS to measure the length from the northernmost upland sample point (in Lake Linden) to the southernmost upland sample point (near Hubbell). Finally, the slope of the hydraulic gradient is calculated from MDEQ data. It was assumed that groundwater input is only relevant for 6 weeks of the year, during snowmelt. It is assumed that snowmelt is the only time of year when the ground is saturated enough for groundwater to be transported to the lake. Otherwise, groundwater input is assumed to be negligible.

Sediment-Water Exchange

The governing equation for Sediment-Water Exchange in this model is:

$$J_{sedex} = D_{ieff} \left(\frac{C_{sed} \times f_{sedw} - C_{water} f_{iw}}{\Delta z} \right) \quad [60]$$

In this model, there are 12 separate terms for sediment-water exchange. Sediment exchange is considered over three separate regions of the lake based on the areas in the sediment where PCBs were detected by sampling. These regions are displayed in Figure 5.2, which is displayed earlier in this section. Region 1 is located in the Tamarack/Hubbell area, region 2 is located in Lake Linden, and region 3 is the remaining area of the lake.

For each region, sediment-water diffusion exchange is considered for the truly dissolved and DOC-bound phases of each congener. In regions 1 and 2, for both the truly dissolved and DOC-bound phases, Equation 59, shown above, was split into a flux equation from

the sediment column to the water column (Equations 26 and 28) and a flow equation from the water column to the sediment column (Equations 30 and 31), all described below. For region 3, both sediment-to-water (Equations 27 and 29) and water-to-sediment diffusion (Equations 30 and 31) are expressed as flow because the concentration of PCB contamination in the sediment is a state variable of the model.

All of the sediment-water exchange diffusivity terms for the truly dissolved phase rely on the effective diffusivity of the congeners. The effective diffusivity of each congener in the sediment, D_{ieff} , is calculated using the following equation: $D_{ieff} = D_{iw}\varphi$, where D_{iw} is the diffusivity of each congener in the water and φ is the porosity of the lake sediments. D_{iw} is calculated using a relationship between the diffusivity and molar mass of the congener and the diffusivity and molar mass of a reference substance. For the purpose of this model, the reference substance for sediment-water exchange is CO₂. The relationship used to calculate D_{iw} is the following equation:

$$\frac{D_{iw}}{D_{ref}} = \left[\frac{M_i}{M_{ref}}\right]^{-1/2} \quad [20]$$

where D_{iw} is the diffusivity of the congener in water, D_{ref} is the diffusivity of CO₂ at 5°C (the assumed temperature at which sediment-exchange takes place), M_i is the molar mass of the congener, and M_{ref} is the molar mass of CO₂ (Schwarzenbach, 2003).

For diffusivity of the DOC-bound congeners, the calculations of the sediment-water exchange diffusivity terms were identical to those for the truly dissolved phase of the congeners, except rather than using the molecular mass of the congener to calculate its diffusivity in water and effective diffusivity, the sum of the molecular masses of the congener and organic carbon were used, as shown in Equations 32 – 34 below:

$$M_{iOC} = M_i + M_{OC} \quad [32]$$

$$\frac{D_{iwOC}}{D_{ref}} = \left[\frac{M_{iOC}}{M_{ref}} \right]^{-1/2} \quad [33]$$

$$D_{ieffOC} = D_{iwOC} \varphi \quad [34]$$

A_{sedex1} and A_{sedex2} were assigned as the areas in which measurable PCB concentrations were found in the lake sediments. A_{sedex1} is the area near Hubbell, and A_{sedex2} is the area near Lake Linden. A_{sedex3} is calculated as shown in Equation 36 below:

$$A_{sedex3} = A_{lake} - (A_{sedex1} + A_{sedex2}) \quad [36]$$

Δ_z is an assumed value of 0.01 m. C_{ised1} and C_{ised2} are average concentrations of the congener in sediment regions 1 and 2. The concentrations were taken from measurements conducted by the Michigan Department of Environmental Quality (MDEQ), the U.S. Environmental Protection Agency (U.S. EPA) and their contractors. (MDEQ, 2008b; EPA, 2009) These data were usually reported as concentration of Aroclor 1254. The Aroclor concentrations were converted to congener concentrations using the average weight percentages reported in Frame et al., 1996. In each region, the congener concentrations for all positive sampling points were averaged over the area of the region. The concentrations that were reported include the truly dissolved, DOC-bound and particle-bound concentration of each congener. To get the truly dissolved phase concentration in the sediment column, the reported total congener concentration in the sediment column was multiplied by the fraction of the truly dissolved phase congener in the sediment column.

Because C_{ised3} is one of the state variables of the model, the sediment-to-water exchange term of region 3 is calculated as a flow rather than a flux. This means that the C_{isedw3} term is split into its sub-terms, f_{isedw3} and C_{isedt3} . $C_{isedt3} = C_{ised3}$ is a state variable of the model, therefore it is removed from the equation so that the equation represents a flow coefficient to the state variable.

5.2.2.5.2 Sediment Column Terms:

For a 2-box mass-balance model, some of the terms from the water column are identical to those for the sediments. In particular, settling and all of the sediment-water exchange terms are identical except for sign. Since these terms were described in the Water Column Terms section, they are not described here.

Resuspension

For sediment-exchange regions 1 and 2, resuspension is calculated as a flux because the concentration of PCB in the sediment is assumed to be a known, continuous input. The equation for resuspension flux is:

$$J_{iresusX} = v_{resus}A_{sedexX}C_{isedsX} \quad [40]$$

The v_{resus} value for the entire lake is calculated by taking the weighted average of v_{resus} for different sedimentation zones of the lake. The different zones were established based on the locations of sediment cores taken as described in the 2010 paper by McDonald et al. The average settling flux for the entire lake and burial fluxes for each zone were also taken from this paper. The flux intensities were reported in units of g/(cm²-yr); they were converted into fluxes (mass/time) by multiplying by the area of the appropriate zone.

The resuspension fluxes (g/yr) were calculated by subtracting the burial fluxes (g/yr) from the settling flux, and the differences were converted into flux intensities by dividing by the area (in cm²) of the zone to which they applied. The overall resuspension flux intensity (g/(cm²-yr)) for the lake was calculated by taking the area-weighted average of the resuspension flux intensities (g/(cm²-yr)) for the individual zones. The resuspension flux intensity was converted into a velocity by dividing the flux by the bulk density of the sediment.

For sediment exchange region 3, resuspension is expressed as a flow because the concentration of PCB in the sediment is a state variable of the model rather than a measured parameter. The equation for resuspension flow in region 3 is:

$$Q_{iresus3} = v_{resus} A_{sedex3} f_{iseds} \quad [41]$$

Burial

Burial is calculated only for sediment exchange region 3; while it occurs in the other two regions of the lake, due to the areas of regions 1 and 2 relative to region 3, the fluxes are so small as to not influence the overall mass balance for either the lake or total sediment compartments. The v_{burial} value is taken from McDonald et al., 2010.

PCB Phase-Partitioning in the Water Column:

The T_{part} value for DOC partitioning is assumed to be 9°C based on temperature measurements of the water column in the early fall over several years. T_{part} is used in the regression equations to determine $\log K_{low}$. Concentration of dissolved organic carbon in the water column, C_{DOCW} , is an average of multiple measurements made over a 10-year period.

5.2.3 Sensitivity Analysis

The sensitivity analysis was performed by changing the values of 31 independent parameters and determining the percent change in the modeled total water and total sediment (region 3) PCB concentrations. An Excel spreadsheet containing three sections was built: the control, in which no values were changed, the section that displayed the values of water and sediment total PCB concentrations due to a 10% increase in each independent parameter, and the section that displayed the values of water and sediment total PCB concentrations due to a 10% decrease in each independent parameter. The percent changes in water and sediment total PCB concentrations were calculated in the last step.

Table 5.5 below presents the independent parameters.

Table 5.5: Parameters manipulated in the sensitivity analysis.

Parameter Name	Symbol	Units
Concentration of PCB in sediment in sediment exchange region 1	C_{ised1}	$\mu\text{gPCB}/\text{kg}_{\text{solids}}$
Concentration of PCB in sediment in sediment exchange region 2	C_{ised2}	$\mu\text{gPCB}/\text{kg}_{\text{solids}}$
Total concentration of PCB in sediment in sediment exchange region	C_{isedt1}	$\text{mgPCB}/\text{m}^3_{\text{sed}}$
Total concentration of PCB in sediment in sediment exchange region	C_{isedt2}	$\text{mgPCB}/\text{m}^3_{\text{sed}}$
Concentration of PCB in groundwater	C_{igw}	$\text{mgPCB}/\text{m}^3_{\text{water}}$
Concentration of PCB in air	C_{ia}	$\text{ngPCB}/\text{m}^3_{\text{air}}$
Resuspension velocity	v_{resus}	m/yr
Lake area	A_{lake}	m^2
DOC concentration in water column	C_{DOCw}	kgoc/Lw
Solid:Water ratio in water column	r_{sww}	$\text{kg}_{\text{solids}}/\text{Lw}$
Temperature of DOC partitioning	T_{part}	K
Fraction of organic carbon in suspended particles of the lake water	f_{ocw}	$\text{kgoc}/\text{kg}_{\text{water}}$
Temperature of air-water gas exchange	T_{AW}	K
Windspeed at 10 m above lake	u_{10}	m/s
Hydraulic conductivity	K	m/d
Depth of water table	D_{WT}	m
Width of shoreline over which groundwater flow occurs	W	m
Slope of western shore	S	ft/ft
Particle settling velocity (in water column)	v_{set}	m/d
Outflow	Q_{out}	m^3/yr
Area of sediment exchange region 1	A_{sedex1}	m^2

Parameter Name	Symbol	Units
Area of sediment exchange region 2	A_{sedex2}	m^2
Porosity	φ	-
Depth of sediment exchange layer	Δ_z	m
Fraction of organic carbon in sediment column	f_{ocsed}	kgOC/kg _{sed}
Bulk density of sediments	ρ_{bulk}	g _{solids} /cm ³ _{sed}
DOC concentration in sediment column	C_{DOCsed}	mgOC/L _w
Burial velocity	v_{burial}	m/yr
PCB atmospheric deposition flux	F_{iAD}	ng/m ² /day
Log of octanol-water partitioning coefficient	$\log K_{iow}$	Lo/L _w
Henry's Law Constant	K_{iH}	Pa-m ³ /mol

All variables were increased and decreased individually by 10% of the value implemented in the model. The corresponding PCB in water and PCB in sediment concentrations (C_{iwater} and C_{ised} , respectively) were recorded for each congener. The percent change in C_{iwater} and C_{ised} due to the 10% change in each parameter was calculated. The maximum and minimum changes in C_{iwater} and C_{ised} were noted, as well as “significant” and “more significant” changes. “Significant changes” were considered to be in the range of 5-10%, and “more significant” changes were 10% or more.

5.2.4 Uncertainty Analysis

Uncertainty analysis was executed using first-order uncertainty propagation. The control variables in the uncertainty analysis are the same as the ones analyzed in the sensitivity analysis, except for the total PCB concentrations in the region 1 and region 2 sediments. Partial derivatives of the C_{iwater} and C_{ised} equations (Equations 3 and 4) with respect to the control variables were calculated in MATLAB and applied in Excel. The standard error of each variable was chosen as the representation of error to be propagated. It was determined that conducting the uncertainty analysis for congeners 33 and 153 would give an acceptable description of how the chlorination level of the congeners affects the uncertainty of the mass-balance.

5.2.5 Validation of the PCB Mass Balance Model by Application to Other Lakes

The PCB Mass Balance model was applied to Lake Superior and Dollar Bay. These lakes were chosen because in the MDEQ's 2005 SPMD study, control sites were located in Huron Bay, Dollar Bay, and the north and south entrances of the Portage Canal. Portage Lake was not used for model validation because the physical properties of the entrances of the Portage Canal (where SPMD samples were taken) are not representative of the physical properties of Portage Lake; and for validation purposes, the PCB mass balance for Torch Lake could only be applied to other lakes. For Lake Superior and Dollar Bay, several steps were taken to apply the model. The physical properties of Torch Lake were replaced with those of the lake in question.

Table 5.6 below lists the parameters and their values for each of the lakes:

Table 5.6: Parameters manipulated to apply mass balance on PCBs to Lake Superior and Dollar Bay.

Parameter Name	Symbol	Units	Torch Lake	Lake Superior	Dollar Bay
Lake area	A_{lake}	m^2	$9.82 \cdot 10^6$	$8.21 \cdot 10^6$	$1.42 \cdot 10^5$
Dissolved organic carbon concentration in water	C_{DOCw}	kgOC/L _W	$7.90 \cdot 10^{-6}$	$1.60 \cdot 10^{-6}$	$7.00 \cdot 10^{-6}$
Ratio of solids-to-water in water/ concentration of suspended solids	r_{sww}	kg _{solids} /L _W	$8.50 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$	$1.83 \cdot 10^{-6}$
Temperature of DOC partitioning	T_{part}	K	288	283	281
Fraction of organic carbon in suspended particles of the lake water	f_{ocw}	kgOC/kg _{water}	0.25	0.2	0.43
Temperature of air-water gas exchange	T_{AW}	K	288	283	288
Windspeed at 10 m above lake	u_{10}	m/s	3.60	5.00	2.98
Water-phase transfer velocity of carbon dioxide	v_{CO_2w}	cm/s	$6.50 \cdot 10^{-4}$	$1.27 \cdot 10^{-3}$	$6.50 \cdot 10^{-4}$
Air-phase transfer velocity of water vapor	v_{wa}	m/yr	$3.22 \cdot 10^5$	$4.10 \cdot 10^{-5}$	$2.82 \cdot 10^5$

Parameter Name	Symbol	Units	Torch Lake	Lake Superior	Dollar Bay
Particle settling velocity	v_{set}	m/d	0.85	1.37	0.9
Outflow	Q_{out}	m ³ /yr	1.02*10 ⁸	7.10*10 ¹⁰	0
Sediment exchange region 3 area (area of undetermined PCB in sediment concentrations)	A_{sedex3}	m ²	9.43*10 ⁶	4.86*10 ¹⁰	1.42*10 ⁵
Porosity of sediments	φ	-	0.8	0.8	0.95
Depth of sediments participating in exchange	Δ_Z	m	0.01	0.04	0.01
Fraction of organic carbon in sediments	f_{ocsed}	kgOC/kg _{sed}	0.14	0.03	0.4
Mean depth of lake	D_{lake}	m	15.2	149	3
Volume of lake	V_{lake}	m ³	1.49*10 ⁸	1.22*10 ¹³	4.26*10 ⁵
Viscosity of water at T_{AW}	ν_w	cm ² /s	1.14*10 ⁻²	0.01307	0.01139
Diffusivity of carbon dioxide in water at T_{AW}	D_{CO_2w}	cm ² /s	1.46*10 ⁻⁵	1.26*10 ⁻⁵	1.46*10 ⁻⁵
Bulk density of sediments	ρ_{bulk}	g _{solids} /cm ³ _{sed}	0.2	0.352	0.11

Parameter Name	Symbol	Units	Torch Lake	Lake Superior	Dollar Bay
Ratio of solids to water in sediments	r_{swsed}	g_{solids}/cm^3_w	0.25	0.44	0.12
Burial Velocity	v_{burial}	m/yr	0.0011	$4.69 \cdot 10^{-4}$	0.01
Resuspension Velocity	v_{resus}	m/yr	$4.05 \cdot 10^{-4}$	87.5	88.06
Concentration of dissolved organic carbon in sediments	C_{DOCsed}	mgOC/L _w	40	0.625	7
Density of solids	ρ_{solids}	Kg_{solids}/m^3_{solids}	1000	1760	900

In addition to changing the values of these properties, the groundwater inflow and sediment exchange involving regions with known concentrations of PCBs were eliminated. (To be clear, in the Lake Superior and Dollar Bay models, the volume of sediments represented by v_{sedex3} is the total volume of surface sediments.) The groundwater inflow was considered negligible for Lake Superior and Dollar Bay. Unlike the model for Torch Lake, the models for Lake Superior and Dollar Bay did not take into account special regions with measured concentrations of PCBs in the sediment.

5.2.6 Comparison to Fugacity Model

Obviously, there is large scope for error in writing the code for all of the equations, in selecting appropriate coefficients, and in insuring that proper units are used for all parameters. To help to insure that all equations were written properly, the model was run under “equilibrium” conditions to verify that the fugacity in each phase was, in fact, equal. Fugacity refers to the chemical potential of a substance; at equilibrium, the

chemical potential of a substance in all phases must be equal. Formulations for fugacity expressions were taken from Mackay et al., 1983. For this approach to be valid, the mass-balance model was modified to include only equilibrium processes of sorption, volatilization and truly dissolved-phase sediment exchange.

5.2.7 Validation of SPMD Model

In order to draw conclusions from the mass balance of PCBs in Torch Lake, the results need to be compared to measured values. In Torch Lake, however, PCB concentrations in the water column have not been directly measured. A search through environmental studies conducted on Torch Lake for direct measurements of truly dissolved PCBs in the surface water resulted in finding that the closest anyone has come to obtaining direct measurements of truly dissolved PCBs in Torch Lake is the MDEQ's use of semi-permeable membrane devices (SPMDs) in 2005 (GLEC, 2006), in which concentrations in the devices following one month of in situ exposure to lake water were reported.

The SPMDs were deployed at 10 locations – six within Torch Lake and four at control sites located in the Keweenaw Waterway, Dollar Bay and Huron Bay – in the summer of 2005. To estimate the concentration of PCB congeners in Torch Lake, reported concentrations from four of the six Torch Lake sites considered representative of PCB contamination in Torch Lake were averaged together. The results from laboratory analysis of SPMD extracts are concentrations of PCBs in SPMD extracts. Because of the way SPMDs work to take up the chemical being sampled - by diffusion between the water and membrane followed by diffusion between the membrane and lipid – the reported concentrations in the SPMD extracts are an indirect measure of the truly dissolved phase PCB concentrations in the lake. A model was used to estimate the truly dissolved concentration of PCBs in the lake from the SPMD extract concentrations.

The model used to estimate truly dissolved concentrations of PCBs in water from the reported SPMD extract concentrations is in a spreadsheet developed by the United States Geological Survey (USGS). The USGS spreadsheet uses SPMD uptake models based on first order kinetics in which the three phases of the uptake isotherm (linear, curvilinear and equilibrium) are calculated separately (USGS, 2010). The inputs to the model spreadsheet include one of three temperature options (user chooses the temperature closest to sampling temperature), the number of days of SPMD deployment, the mass of the SPMD, the volumes of the lipid, membrane and total SPMD, and the mass of analyte (USGS, 2010). Ideally, performance reference compounds (PRCs) would have been used to more accurately determine the uptake rate of the congeners into the SPMDs in situ (Huckins et al., 2006). Because PRCs were not used in the 2005 MDEQ study, rate constants for congeners are taken from the literature and used in the model (USGS, 2010). A full explanation of the SPMD model is given by Huckins et al., 2006.

The mass of each PCB congener at each sample site was determined by multiplied the concentration in the SPMD extract by the volume of the solvent, hexane. Because the congener concentration reported for each site was actually a composite of the extracts of four devices, the mass of the congener in the extract was divided by 4. The mass of each congener was then put into the model, and the model output was the estimated concentration of that congener in the water. These concentrations were used to compare with PCB concentrations predicted by the mass balance model.

Because the SPMD-estimated concentrations are not direct measurements, the accuracy of SPMD-estimated concentrations in Huron Bay were assessed by comparing them to directly-measured concentrations in Lake Superior in 2006 (Simcik, 2010). A chi-squared analysis was performed on the datasets to determine if the SPMD estimates of the truly dissolved concentration were different from the directly measured values.

It should be noted that, given the methodology used to collect and process aqueous samples collected from Lake Superior for the Great Lakes Aquatic Contaminants Survey (Simcik, 2010), the measured concentration values may actually be aqueous (truly dissolved + DOC-bound) concentrations rather than truly dissolved concentrations only, whereas the SPMD-estimates represent truly dissolved concentrations. The concentrations of the truly dissolved and DOC-bound phases are not distinguished in the reported data or in the report narrative; and in the report it is stated that “Partitioning of PCBs to organic carbon associated with suspended particulate matter in neither Lake Michigan nor Lake Superior correlate well with the octanol-water partition coefficient” (Simcik, 2010), which implies that the concentrations of the truly dissolved and DOC-bound phases would be difficult to predict. That we do not know the fraction of the aqueous concentration that is bound to DOC is extremely important because the DOC-bound fraction is not available for bioaccumulation. For the congeners considered in the mass balance, the percent of the total congener estimated to be bound to DOC ranges from 4-74% in Lake Superior. For the purpose of comparison, due to lack of data on how much of the reported concentrations are truly dissolved or DOC-bound, it was assumed that the reported concentrations were truly dissolved only.

5.3 Results

5.3.1 Semi-Permeable Membrane Device (SPMD) –Estimated Results

The SPMD-estimated results were taken from the output of the USGS spreadsheet model described in the methods section. Also as described in the methods section, the results from Torch Lake are the averages of the concentrations estimated at four locations in the north basin of the lake. The concentrations displayed in Figure 5.5, Figure 5.7 and Figure 5.8 below are the concentrations of the truly dissolved-phase PCBs in water estimated by the SPMD model at Torch Lake, Huron Bay and Dollar Bay. “N/A” indicates that a truly

dissolved concentration could not be estimated for the congener because the concentration in the SPMD extract was reported by the MDEQ contractor that conducted the study (either GLEC or their subcontractor EST) as “0”. A reported concentration of 0 could mean one of two things: 1) that the results were below the quantitation limit or 2) the concentration could not be determined due to interference (GLEC, 2006).

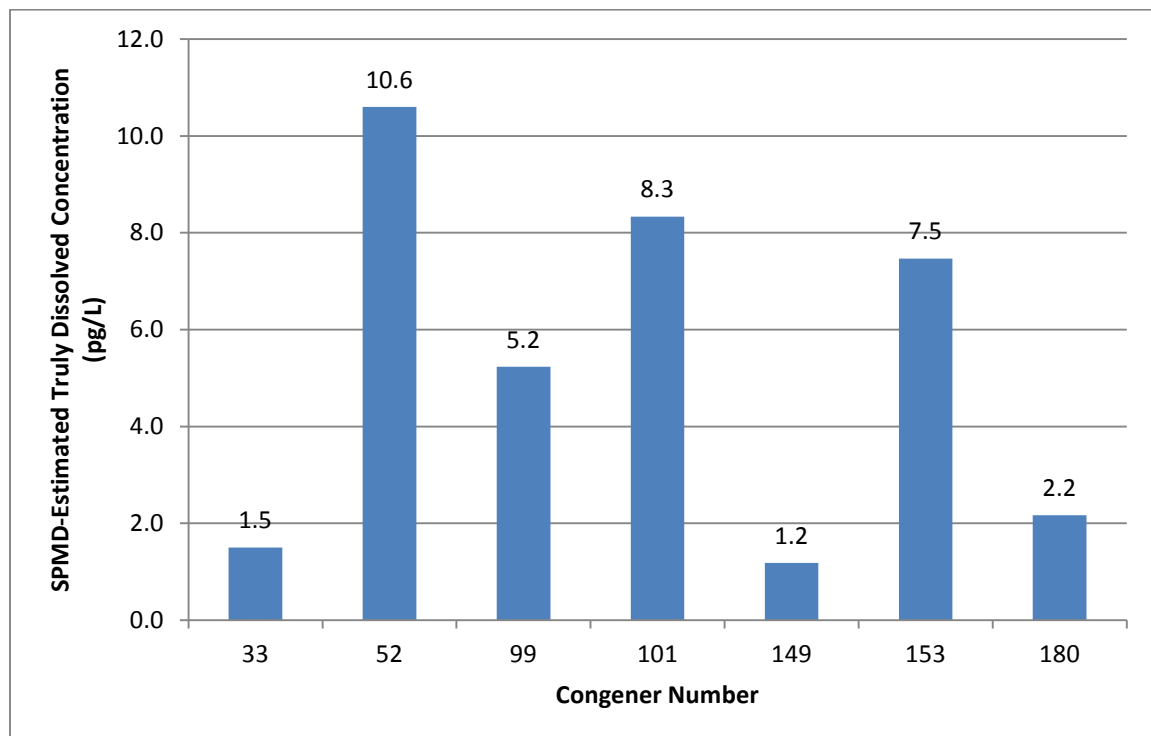


Figure 5.5: SPMD-estimated truly dissolved concentrations in Torch Lake.

To provide a frame of reference for the PCB congener concentrations (both SPMD-estimated and mass-balance modeled, which are presented later), the estimated amount of PCB contamination in sediment by the spill of oil from 1 transformer was modeled in the Torch Lake mass balance (Figure 5.6). It was assumed that a spill of 21 gallons, or 0.0795 m^3 , of oil contaminated an area of 0.652 m^2 of sediment at a depth of 0.1524 m (6 inches). Based on these assumptions, it was assumed that the concentration of total PCBs in the sediment was $2.989 \text{ } \mu\text{g}_{\text{PCB}}/\text{kg}_{\text{solids in sediment}}$. The weight fractions of congeners in

Aroclor mixture 1260, as determined by Frame et al., 1996, were used to determine the concentrations of each modeled congener in the sediment. These concentrations, along with their associated contaminated area, were substituted into the Torch Lake mass balance as the sediment exchange region 1 concentrations and area (while these values for sediment exchange region 2 were forced to equal zero) and the mass balance was calculated. The resulting truly dissolved congener concentrations are displayed in Figure 5.6.

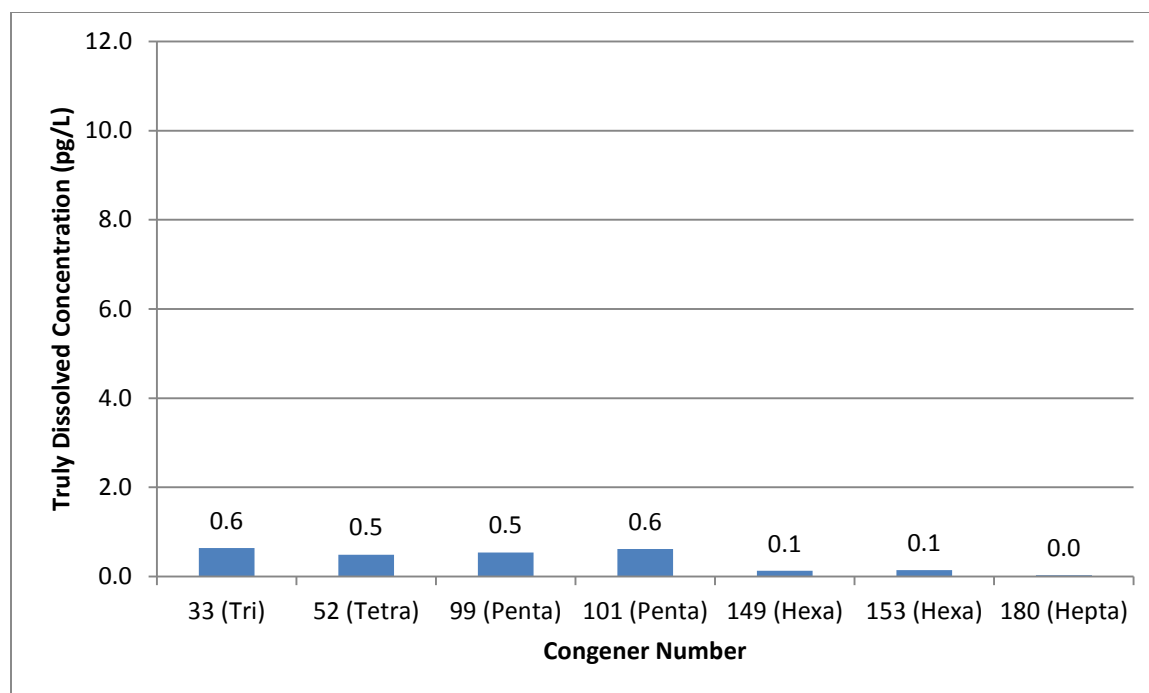


Figure 5.6: Mass-balance modeled truly dissolved congener concentrations in Torch Lake water column due to oil spill from 1 transformer.

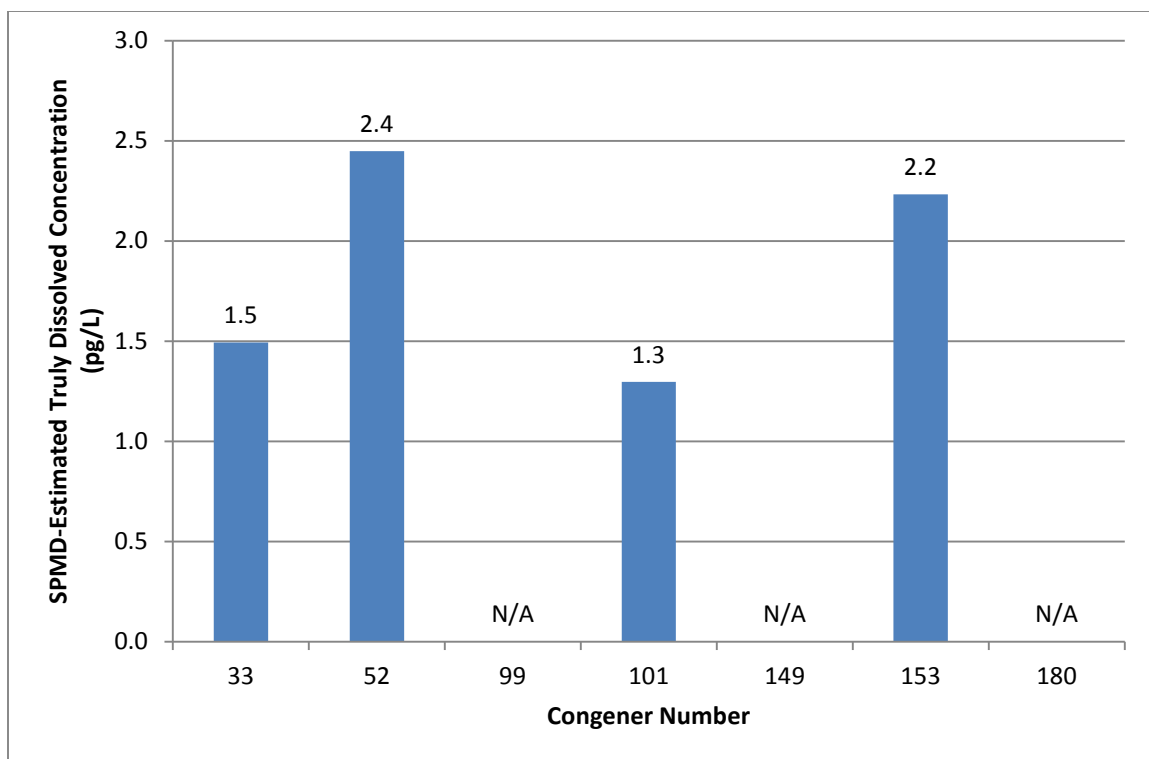


Figure 5.7: SPMD-estimated truly dissolved concentrations in Huron Bay.

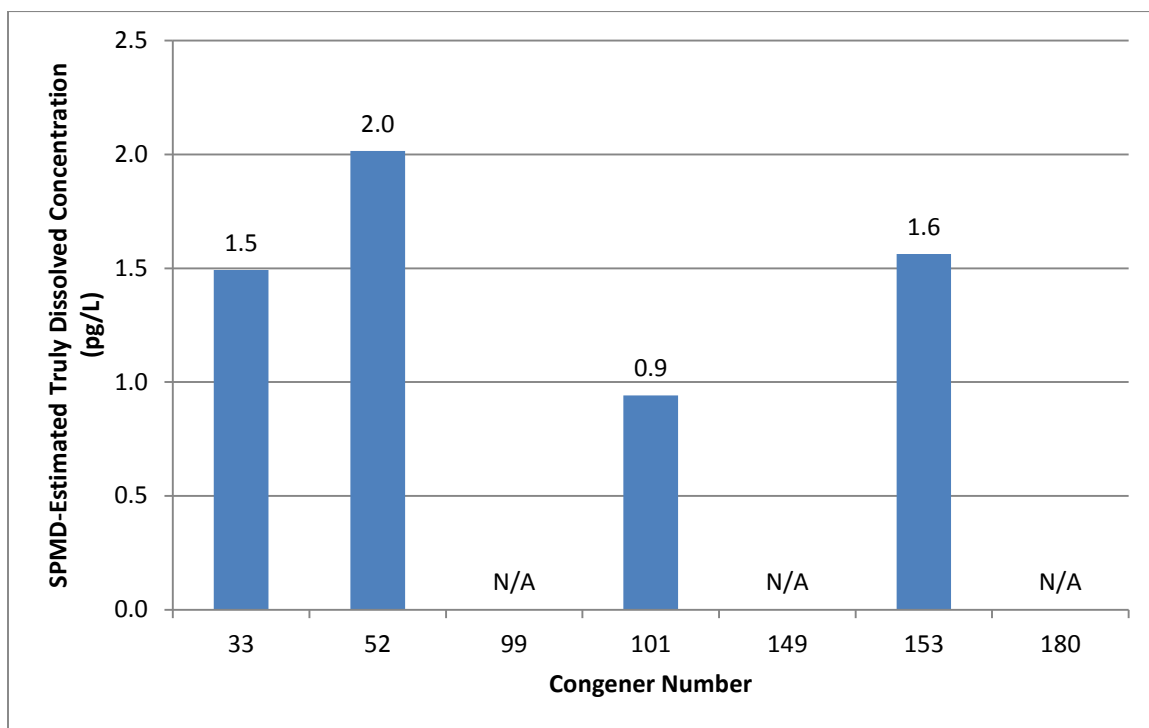


Figure 5.8: SPMD-estimated truly dissolved concentrations in Dollar Bay.

5.3.2 Validation of SPMD Estimates

Because the truly dissolved PCB concentrations determined by SPMDs are estimates, it is necessary to validate the SPMD model against measured values. To clarify, SPMD-estimated concentrations are used in Torch Lake to compare against the mass balance model because measured concentrations are not available for Torch Lake. In order to validate the SPMD-estimated concentrations, the non-zero SPMD-estimated concentrations from Huron Bay were compared to measured concentrations of PCBs in Lake Superior measured in the Great Lakes Aquatic Contaminants Survey (GLACS) performed in 2006 (Simcik, 2010).

To perform the validation, first, only the congeners detected by the SPMDs in Huron Bay were considered to eliminate differences due to including zero-values for SPMD-estimated concentrations. From the GLACS data, only concentrations reported as being measured from XAD-resin were considered to be representative of the truly dissolved concentrations. Because there were concentrations reported from multiple sample sites throughout Lake Superior, the values for each congener were averaged. The averages were then compared to the concentrations estimated by SPMDs in Huron Bay.

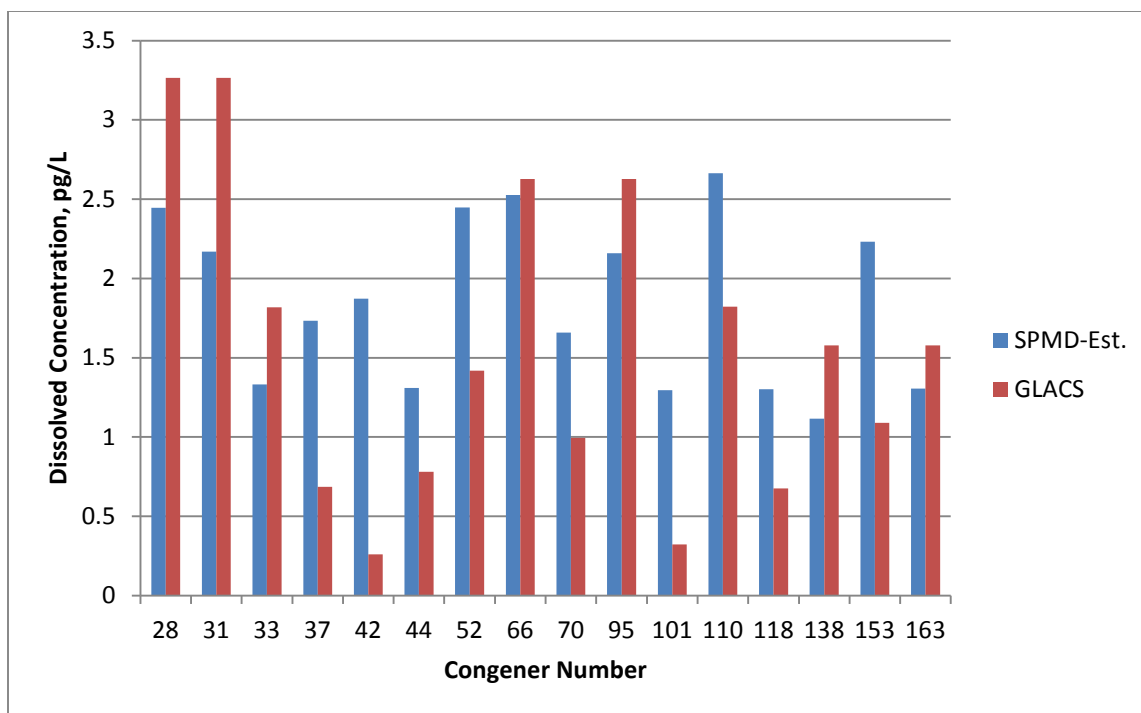


Figure 5.9: Comparison of SPMD-estimated concentrations measured at Huron Bay in 2005 to measured concentrations in Lake Superior in 2006 from the GLACS study (Simcik, 2010).

A chi-square analysis was performed on the two datasets compared in Figure 5.9. After omitting outliers, the analysis showed that the X^2 (19) was less than the critical value (25) for 15 degrees of freedom, indicating that the SPMD-estimated concentrations are statistically similar to the measured concentrations. Outliers were determined roughly as congeners whose measured aqueous concentrations were less than 25% of the SPMD-estimated concentrations. It is speculated that the correlation might be improved if there were more SPMD-estimated concentrations to compare to the concentrations measured by GLACS.

5.3.3 Mass Balance Model Results

The results of the mass balance on PCBs in Torch Lake are displayed in Table 5.7 and Figure 5.10. The implications of these results will be discussed in the discussion section; they are presented here to accompany the results of the sensitivity analysis, the uncertainty analysis, and the validation of the model to other lakes.

Table 5.7: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved PCB concentrations estimated from SPMD measurements in Torch Lake.

	Modeled Truly Dissolved Concentration in Water	SPMD-Estimated Truly Dissolved Concentration in Water	Ratio of SPMD- Estimated/Modeled Truly Dissolved Concentrations
Units	pg/L	pg/L	-
Congener			
33	1.0	1.5	1.5
52	2.0	10.6	5.3
99	2.2	5.2	2.4
101	3.7	8.3	2.2
149	2.2	1.2	0.5
153	2.5	7.5	3.1
180	1.5	2.2	1.5

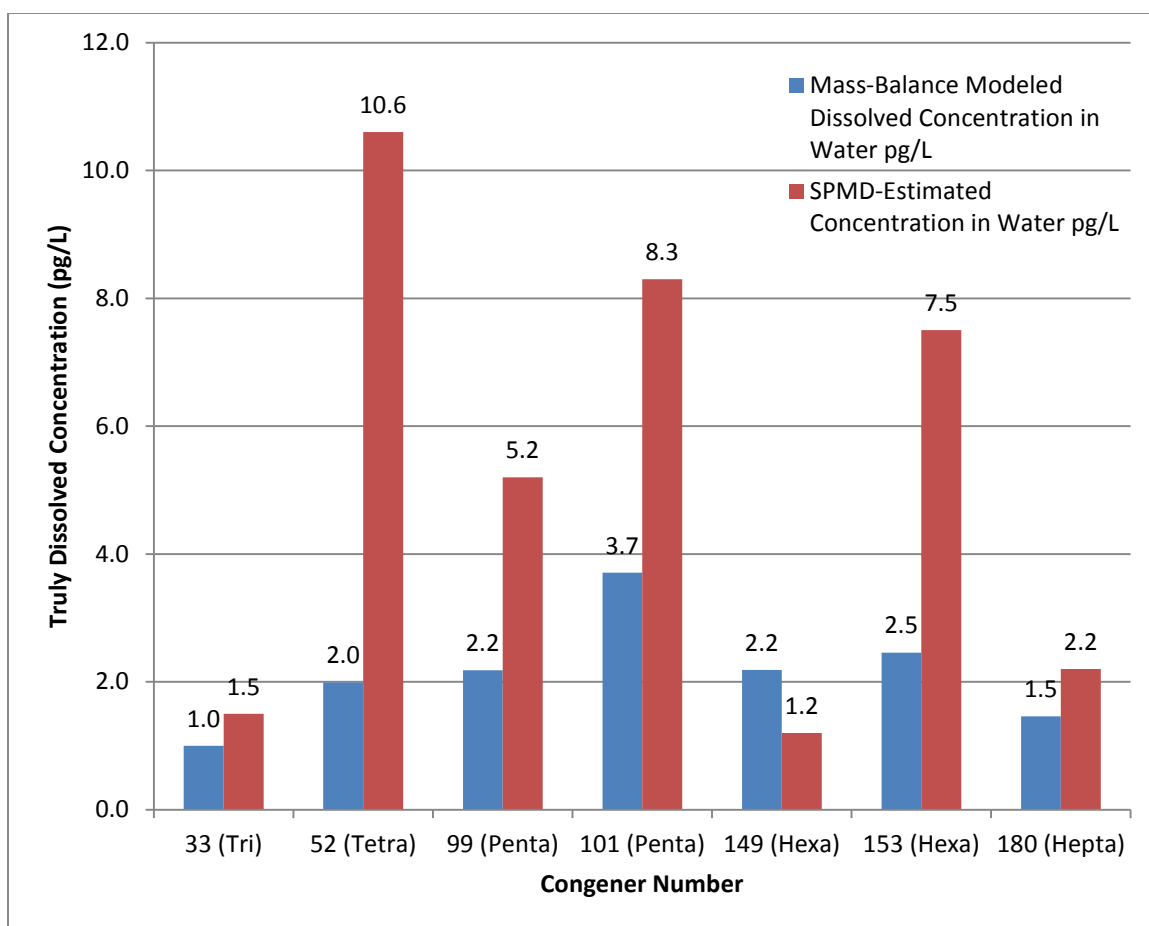


Figure 5.10: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved concentrations estimated from SPMD measurements in Torch Lake.

5.3.4 Sensitivity Analysis

The results of the sensitivity analysis indicate that the total PCB concentration in the water column (C_{iwater}) is most sensitive to porosity (ϕ) and least sensitive to both the ratio of solids to water in the water column (r_{sww}) and the fraction of organic carbon in the water column (f_{ocw}). The range of change in C_{iwater} due to a 10% increase in ϕ is 14% to 19%. The range of change in C_{iwater} due to a 10% decrease in ϕ is 12% to 17%. The range of change in C_{iwater} due to a 10% change in either r_{sww} or f_{ocw} is 0.01% to 0.2%. The results also indicate that the total PCB concentration in the sediment column is most sensitive to the concentration of PCB in region 1 sediments (C_{ised1}) and

the least sensitive to the resuspension velocity (v_{resus}). The range of change in C_{ised} due to a 10% change in C_{ised1} is 6% to 10%, and the range of change in C_{ised} due to a 10% change in v_{resus} is 0.04% to 0.41%. The sensitivity of the total PCB concentration in the water column to porosity may be due to porosity being a factor in all of the sediment exchange diffusion terms. Also of note is that the sensitivity analysis revealed that the total water PCB concentration and total sediment PCB concentration (region 3) is sensitive to the concentration of PCBs in sediment exchange region 1, but not sediment exchange region 2. This is likely due to the approximately 4-fold difference in area between sediment exchange regions 1 and 2, which are $3.11 \times 10^5 \text{ m}^2$ and $8.63 \times 10^4 \text{ m}^2$, respectively.

Parameters that caused significant or more significant change in the total PCB concentration in the water include those listed in Table 5.8 below. “Significant changes” were considered to be in the range of 5-10%, and “more significant” changes were 10% or more. The percent change in the total PCB concentration in water by each of these parameters is displayed in Figure 5.11 and Figure 5.12 below.

Table 5.8: Parameters that caused significant or more significant change in the total PCB concentration in water (parameters marked with ‘*’ caused more significant change).

Parameter Name	Symbol	Units
Concentration of PCB in sediment in region 1	C_{ised1}	$\mu\text{gPCB/kg}_{\text{solids}}$
Lake area	A_{lake}	m^2
Area of region 1	A_{sedex1}	m^2
Porosity*	φ	-
Depth of sediment exchange layer	Δ_Z	m
Fraction of organic carbon in sediment column	f_{ocsed}	$\text{kgOC/kg}_{\text{sed}}$
Bulk density of sediments	ρ_{bulk}	$\text{g}_{\text{solids}}/\text{cm}^3_{\text{sed}}$
DOC concentration in sediment column	C_{DOCsed}	mgOC/L_w
Dissolved organic carbon - water partitioning coefficient*	K_{iDOC}	L_w/kgOC
Octanol-water partitioning coefficient*	K_{iow}	L_w/L_o

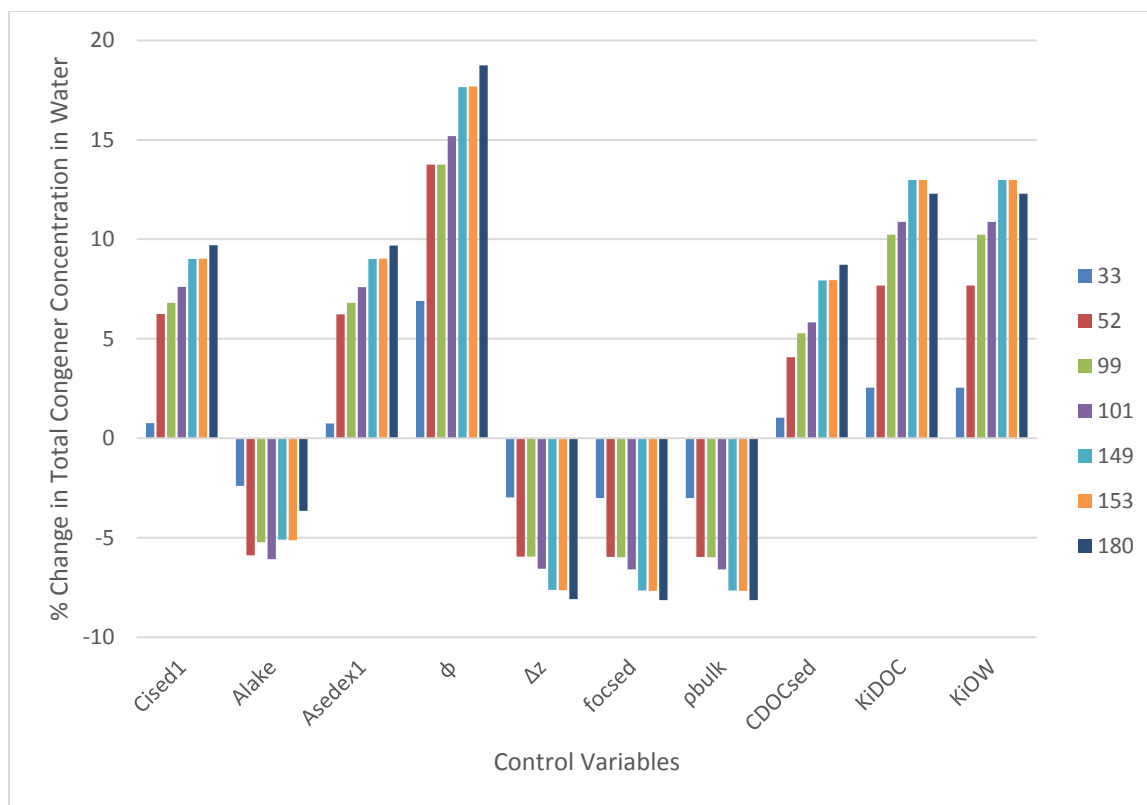


Figure 5.11: Percent change in predicted total water PCB concentration due to a 10% increase in independent parameters. Only parameters causing significant or more significant change are displayed.

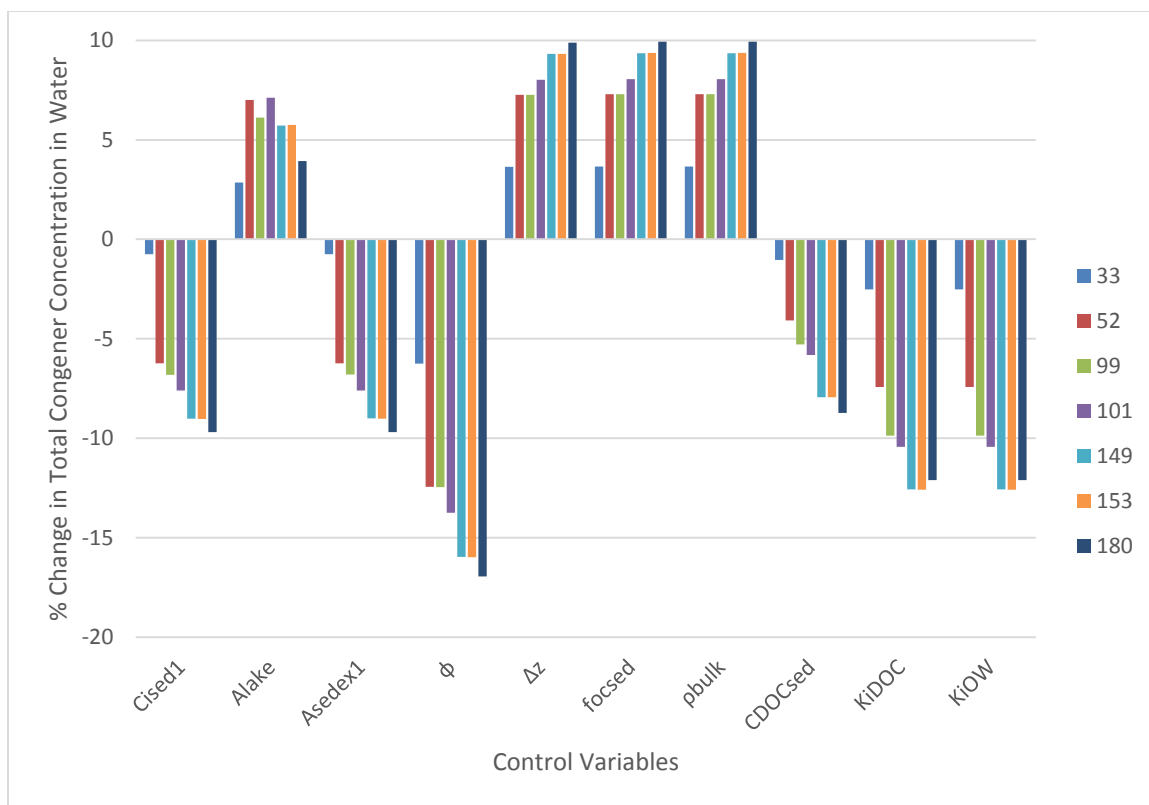


Figure 5.12: Percent change in predicted total water PCB concentration due to a 10% decrease in independent parameters. Only parameters causing significant or more significant change are displayed.

Parameters that caused significant or more significant change in the total PCB concentration in the sediment include the parameters listed in Table 5.9 below. “Significant changes” were considered to be in the range of 5-10%, and “more significant” changes were 10% or more. The percent change in the total PCB concentration in sediment by each of these parameters is displayed in Figure 5.13 and Figure 5.14:

Table 5.9: Parameters that caused significant or more significant change in the total PCB concentration in Region 3 sediment (parameters marked with ‘*’ caused more significant change).

Parameter Name	Symbol	Units
Concentration of PCB in sediment in region 1	C_{ised1}	$\mu\text{g}_{\text{PCB}}/\text{kg}_{\text{solids}}$
Lake area	A_{lake}	m^2
Solid:Water ratio in water column	r_{sww}	$\text{kg}_{\text{solids}}/\text{L}_W$
Fraction of organic carbon in suspended particles of the lake water	f_{ocw}	$\text{kg}_{\text{OC}}/\text{kg}_{\text{water}}$
Particle settling velocity (in water column)	v_{set}	m/d
Area of sediment exchange region 1	A_{sedex1}	m^2
Porosity	φ	unitless
Depth of sediment exchange layer	Δ_z	m

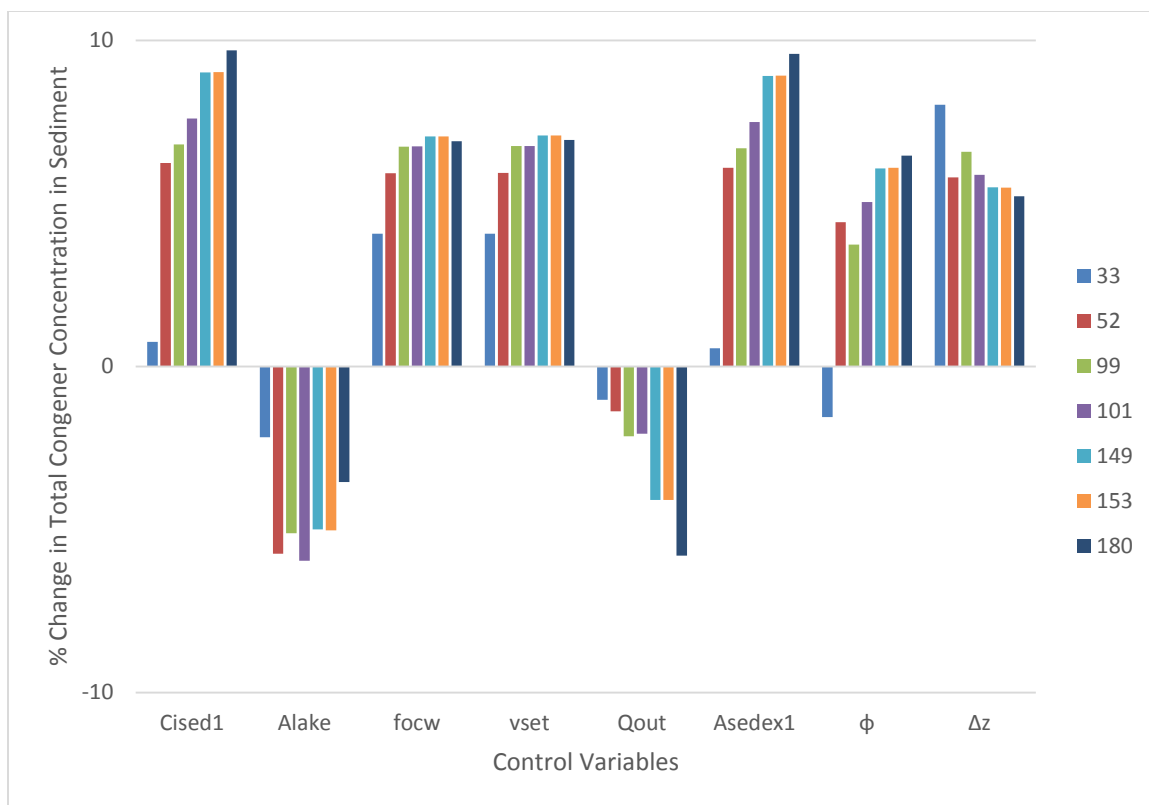


Figure 5.13: Percent change in predicted region 3 sediment PCB concentration due to a 10% increase in independent parameters. Only parameters causing significant or more significant change are displayed.

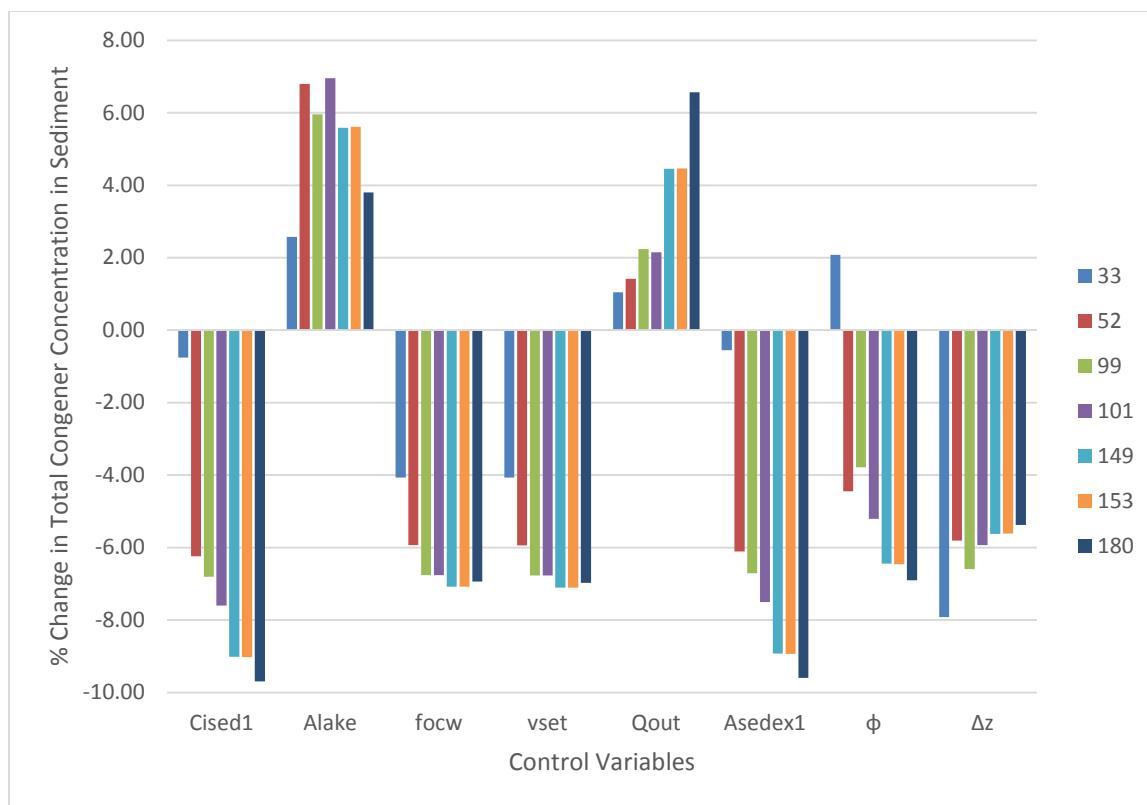


Figure 5.14: Percent change in predicted region 3 sediment concentration due to a 10% decrease in independent parameters. Only parameters causing significant or more significant change are displayed.

5.3.5 Uncertainty Analysis Results

Uncertainty analysis indicated a large uncertainty exists in model predictions for both the total water PCB concentration and the total sediment PCB concentration in sediment exchange region 3. The uncertainty in the total congener-specific PCB concentration in the water column is 62,249 pg/L for congener 33 and 338,230 pg/L for congener 153. The uncertainty in the total PCB concentration in the region 3 sediments is 1.19×10^5 gPCB/kg_{solids} for congener 33 and 6.62×10^5 gPCB/kg_{solids} for congener 153. Uncertainty is represented by the standard error about the mean model prediction. Table 5.10 provides the estimated propagated uncertainties in model predictions due to estimated uncertainties in individual model parameters, in which estimation was done by first-order error propagation. The complete uncertainty analysis can be found in electronic Appendix A.8.

Table 5.10: Overall Uncertainty in Water and Sediment Column Concentrations in Torch Lake.

	Mass-Balance Modeled Total Water Concentration	Uncertainty in Total Water Concentration	Mass-Balance Modeled Concentration in Region 3 Sediments	Uncertainty in Concentration in Region 3 Sediments
	pg/L	pg/L	gPCB/kg_{solids}	gPCB/kg_{solids}
33	1.35	62249	1.56	1.19E+05
153	30.52	338230	44.53	6.62E+05

Both the total PCB concentration in water and PCB concentrations in Region 3 sediments equations have the same most uncertain and least uncertain terms. The term with the smallest range of uncertainty is the width of the Torch Lake western shoreline over which groundwater is assumed to flow (W, m). The term with the widest range of uncertainty is Henry's Law Constant (K_{iH} , Pa*m³/mol). The ranges in uncertainty for these terms are shown in Table 5.11.

Table 5.11: Ranges of Uncertainty in PCB Concentration in Air and DOC-Partitioning Temperature.

Congener	Uncertainty in predicted congener concentration in the water column due to uncertainty in Henry's Law Constant	Uncertainty in predicted congener concentration in the sediment column due to uncertainty in Henry's Law Constant	Uncertainty in predicted congener concentration in the water column due to uncertainty in shoreline width of groundwater flow	Uncertainty in predicted congener concentration in the sediment column due to uncertainty in shoreline width of groundwater flow
	pg/L	gPCB/kg solids	pg/L	gPCB/kg solids
33	3.94E+04	5.60E+01	2.30E-04	3.19E-04
153	3.35E+05	6.37E+02	4.57E-02	8.71E-02

The small range in uncertainty in the predicted congener concentrations in the water and sediment columns due to uncertainty in the shoreline width of groundwater flow is explained by the small range in values between the minimum and maximum shoreline widths, which is 7m. The wide range in uncertainty in the predicted congener concentrations in the water and sediment columns due to uncertainty in the Henry's Law Constant reflects the wide variability in the literature values of Henry's Law Constant.

Due to the way the code to calculate the derivatives for the uncertainty analysis was written, the derivative of the system equations with respect to the octanol-water coefficient (K_{ow}) was calculated to be zero; however, the sensitivity analysis showed that K_{ow} is one of the two terms to which the mass-balance-calculated congener concentration in water is most sensitive. A modified sensitivity analysis, based on the ranges of values for K_{ow} found in the literature, shows that the range of the mass-balance-calculated congener concentration in water is 1.2 – 1.6 pg/L for congener 33 and 6.7 – 32.8 pg/L for congener 153. The calculated ranges suggest that K_{ow} has potentially little impact on the uncertainty about the total concentration of congener 33 in water, but potentially significant impact on the uncertainty about the total concentration of congener 153 in water.

From the uncertainty analysis, we learn how much uncertainty exists in the mass balance model. The uncertainty in the total water PCB water concentrations is approximately 4 orders of magnitude greater than the predicted values. The uncertainty in the sediment concentrations is approximately 4-5 orders of magnitude greater than the predicted values. The high uncertainty reflects the high uncertainty in many of the model terms, which in many cases can be attributed to the fewness of data available with which the terms could be calibrated. It should also be considered that the uncertainty analysis was done in a conservative manner; that is, equal weight was given to all values considered for control parameters, making the uncertainty a large overestimate of the potential errors of the model.

5.3.6 Fugacity Results

The truly dissolved concentrations of PCBs in the water modeled by the modified mass balance model (the version of the model which only took into account equilibrium processes) match those calculated using fugacity (Figure 5.15); and the calculated fugacities in sediment match those calculated using the modified mass balance model (Figure 5.16). The near-perfect matches between the truly dissolved PCB concentrations calculated with the modified mass balance model and the fugacity approach were achieved because both the modified mass balance and the fugacity models assume that PCBs in sediment, water, and air are in equilibrium with each other.

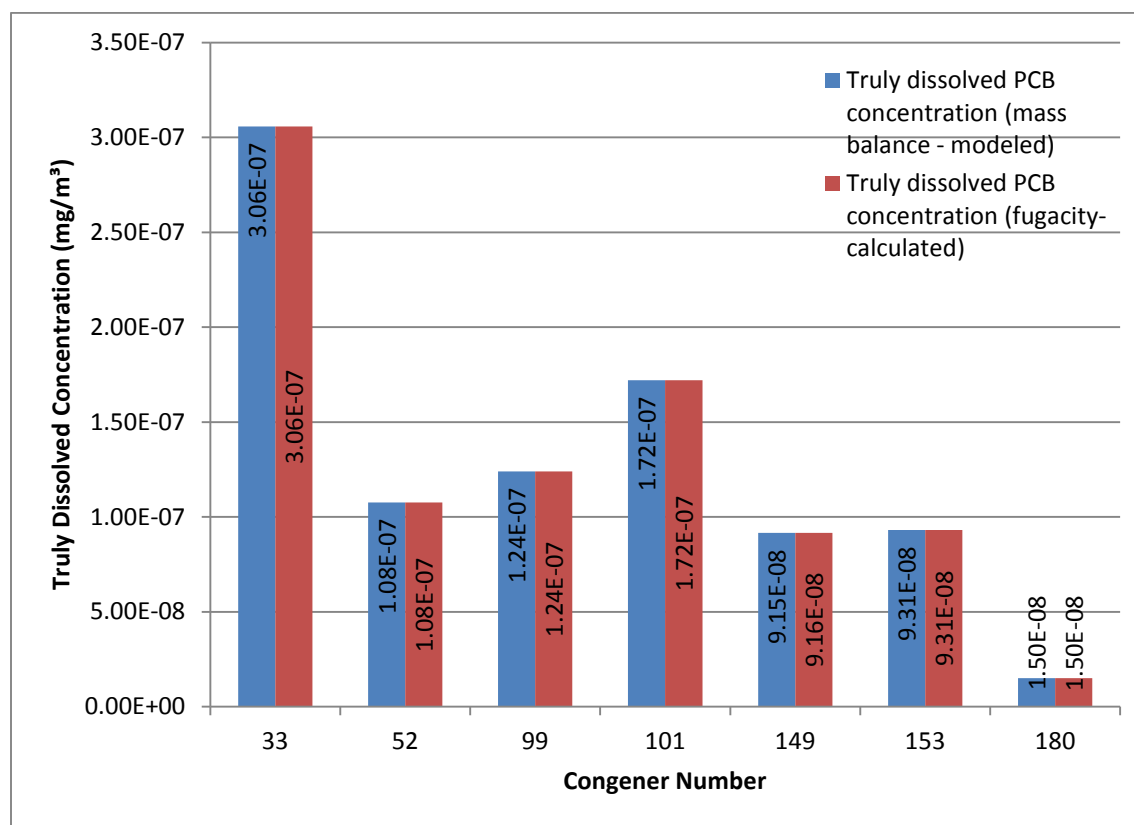


Figure 5.15: Comparison of truly dissolved PCB Concentrations calculated with a fugacity model and a modified mass balance model for Torch Lake.

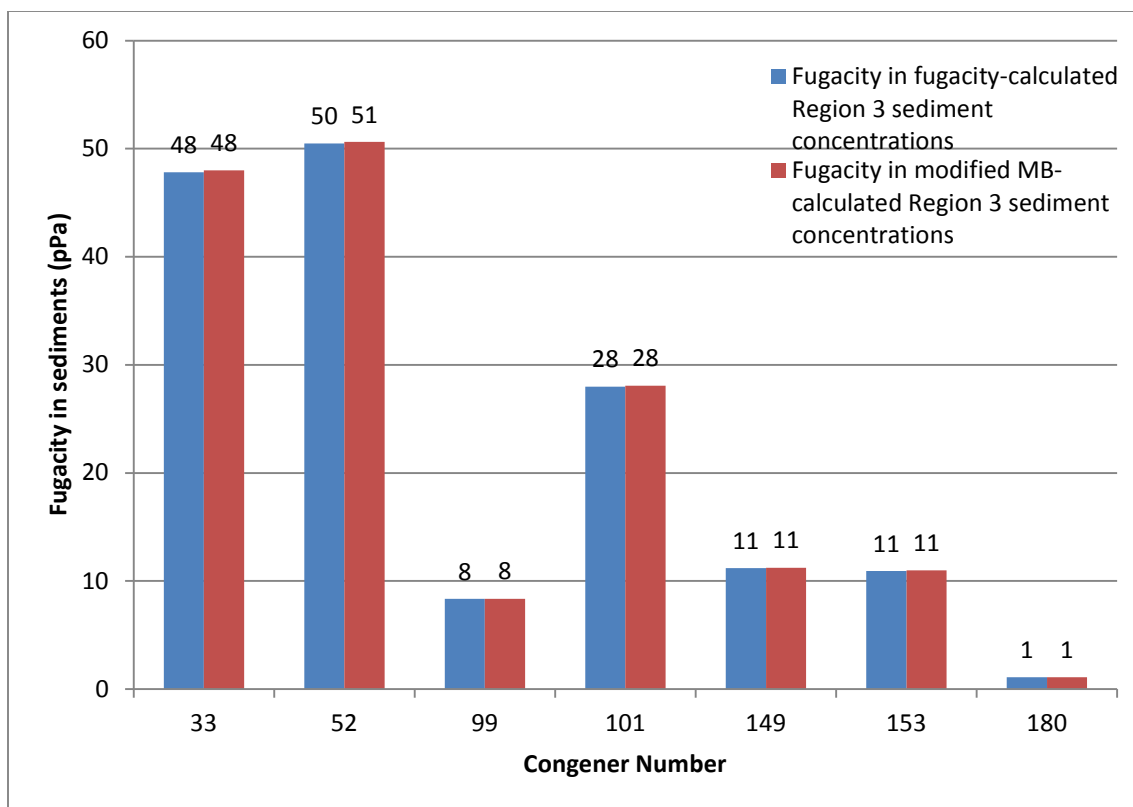


Figure 5.16: Comparison of sediment fugacities from fugacity-model and from modified mass-balance model.

5.3.7 *Comparison of modeled truly dissolved concentrations and fluxes to SPMD-estimated truly dissolved concentrations and fluxes*

To test the validity of the mass balance on PCBs in Torch Lake, the mass balance model was applied to Lake Superior and Dollar Bay, for which truly dissolved concentration results were available from the MDEQ's 2005 SPMD study. In general, the modeled and SPMD-estimated truly dissolved concentrations did not agree. In both lakes, the mass balance model predicts truly dissolved concentrations less than those estimated from concentrations in the SPMDs. The results of application of the mass balance to PCBs in Lake Superior and Dollar Bay are shown in Table 5.12 and Table 5.13, respectively, and Figure 5.17 and Figure 5.18, respectively.

Lake Superior Mass Balance Results

Table 5.12: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved PCB concentrations estimated by SPMDs in Lake Superior.

	Modeled Truly Dissolved Concentration in Water	SPMD-Estimated Truly Dissolved Concentration in Water	Ratio of SPMD- Estimated/Modeled Truly Dissolved Concentrations
Units	pg/L	pg/L	--
Congener			
33	0.8	1.3	2.1
52	0.4	2.4	7.3
99	0.6	N/A	-
101	0.6	1.3	2.8
149	0.2	N/A	-
153	0.2	2.2	14.4
180	0.0	N/A	-

N/A = Not Available

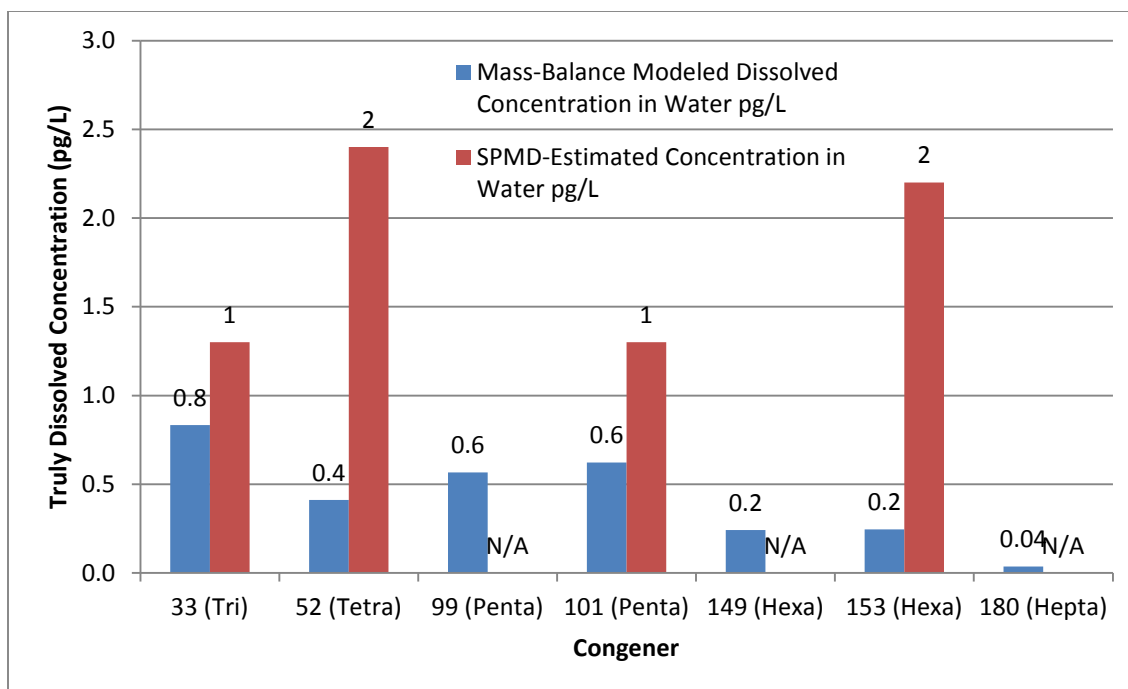


Figure 5.17: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved concentrations estimated by SPMDs in Lake Superior.

Dollar Bay Mass Balance Results

Table 5.13: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved PCB concentrations estimated by SPMDs in Dollar Bay.

	Modeled Truly Dissolved Concentration in Water	Measured Truly Dissolved Concentration in Water	Ratio of Measured/Modeled Truly Dissolved Concentrations
Units	pg/L	pg/L	--
Congener			
33	0.69	1.5	2.2
52	0.47	2.0	4.2
99	0.52	N/A	N/A
101	0.54	0.9	1.7
149	0.08	N/A	N/A
153	0.08	1.6	18.2
180	0.007	N/A	N/A

N/A = Not Available

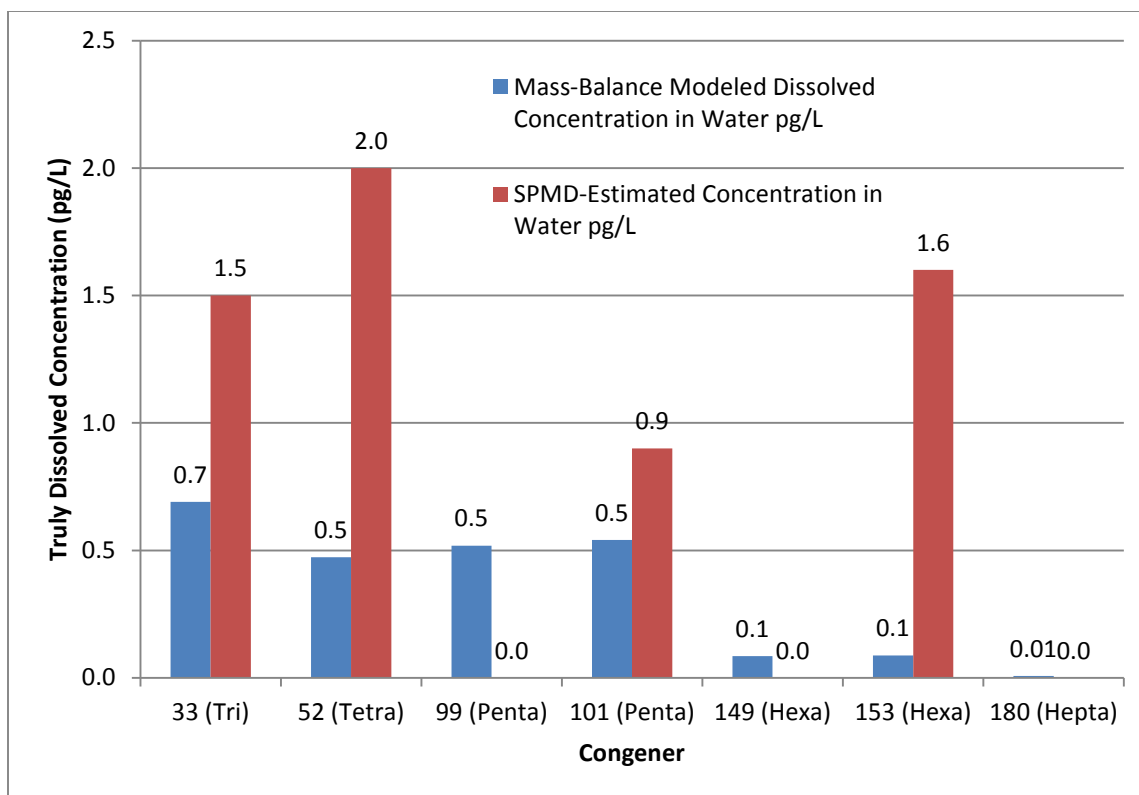


Figure 5.18: Truly dissolved PCB concentrations modeled by mass balance compared to truly dissolved concentrations estimated by SPMDs in Dollar Bay.

The SPMD concentrations are considered valid as demonstrated in the SPMD model validation section. For Lake Superior, the ratios of measured to modeled concentrations range from 2.1 to 14.4, suggesting that the model under-predicted the steady-state concentrations in Lake Superior. For Dollar Bay, the ratios of measured to modeled concentrations range from 1.4 to 18.2, suggesting that the model under-predicted the steady-state concentrations in Dollar Bay. There are several possible reasons for this disagreement. Measured rates of atmospheric deposition were only available for congeners 52 and 101; assumptions made for atmospheric deposition rates of other congeners may explain part of the error in model predictions for those congeners. The uncertainty analysis indicates that the disagreement between model predictions and measurements is small compared to the uncertainty in the predictions; alternatively, the relatively good agreement of model predictions with measurements might suggest that

the uncertainty in predictions is much smaller than indicated by the uncertainty analysis. Simplifications in the model (e.g., lack of seasonality, complete mixing in the water column) may result in the model underpredictions. Alternatively, lack of steady state may also contribute to the discrepancy between model predictions and SPMD measurements; the lake, as reflected in the SPMD-based concentrations, still contains PCBs from previous years when rates of atmospheric deposition and absorption were higher. Steady state with the 2006 rate of atmospheric deposition would result in lower concentrations in the lake as predicted by the mass balance model. Given the differences between the mass balance-predicted concentrations and the SPMD-estimated concentrations in sites having only atmospheric deposition and gas exchange as a possible source of PCBs, caution must be applied to interpretation of the mass balance model predictions in Torch Lake.

Differences between the mass balance-predicted truly dissolved concentrations and the SPMD concentrations might occur if the SPMDs took up the truly dissolved- and DOC-bound phases of PCBs. In an effort to determine if the SPMDs took up the truly dissolved-phase and DOC-bound phase concentrations of PCBs, the mass-balance modeled truly dissolved and DOC-bound phase concentrations were compared to the SPMD-estimated concentrations, as shown in Figure 5.19 to Figure 5.21 below. To be clear, SPMDs do not take up the DOC-bound phase of PCBs. As explained further in this section, if DOC partitioning was not taken into account during SPMD calibration experiments, the SPMD estimates may be greater than actual truly dissolved congener concentrations in the water column.

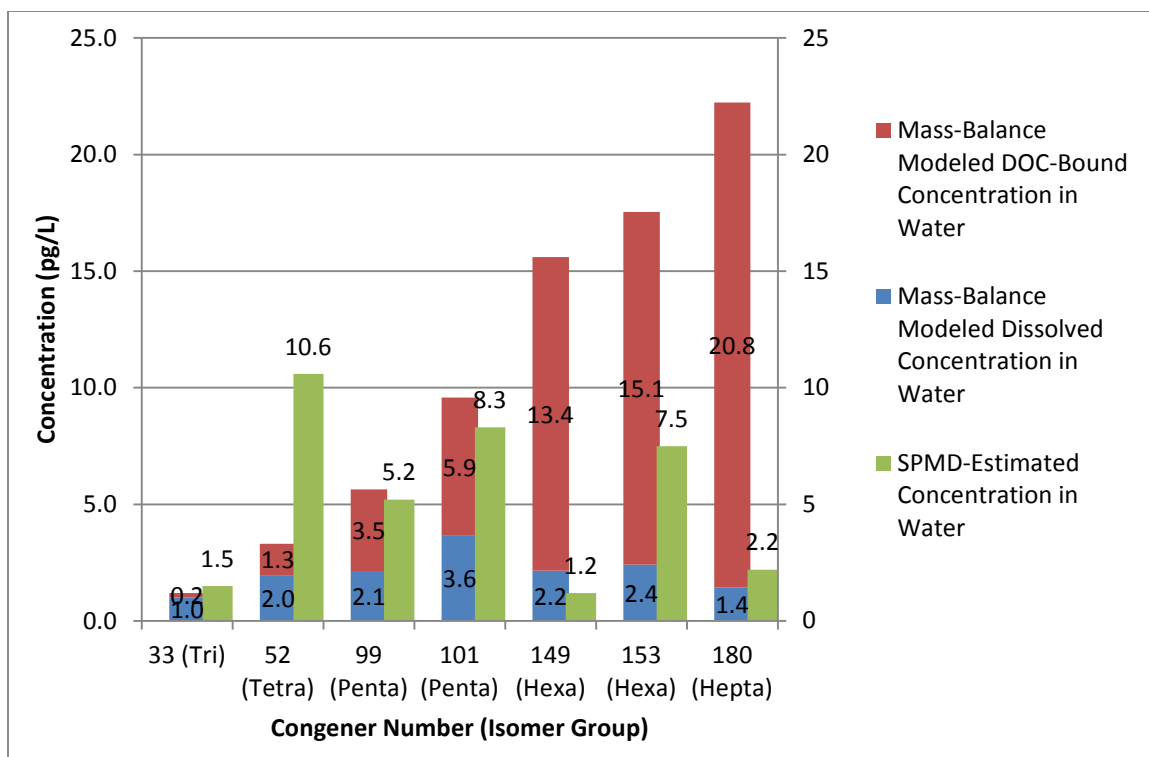


Figure 5.19: Comparison of (truly dissolved + DOC-bound) concentrations predicted by the mass balance model with SPMD-estimated concentrations in Torch Lake.

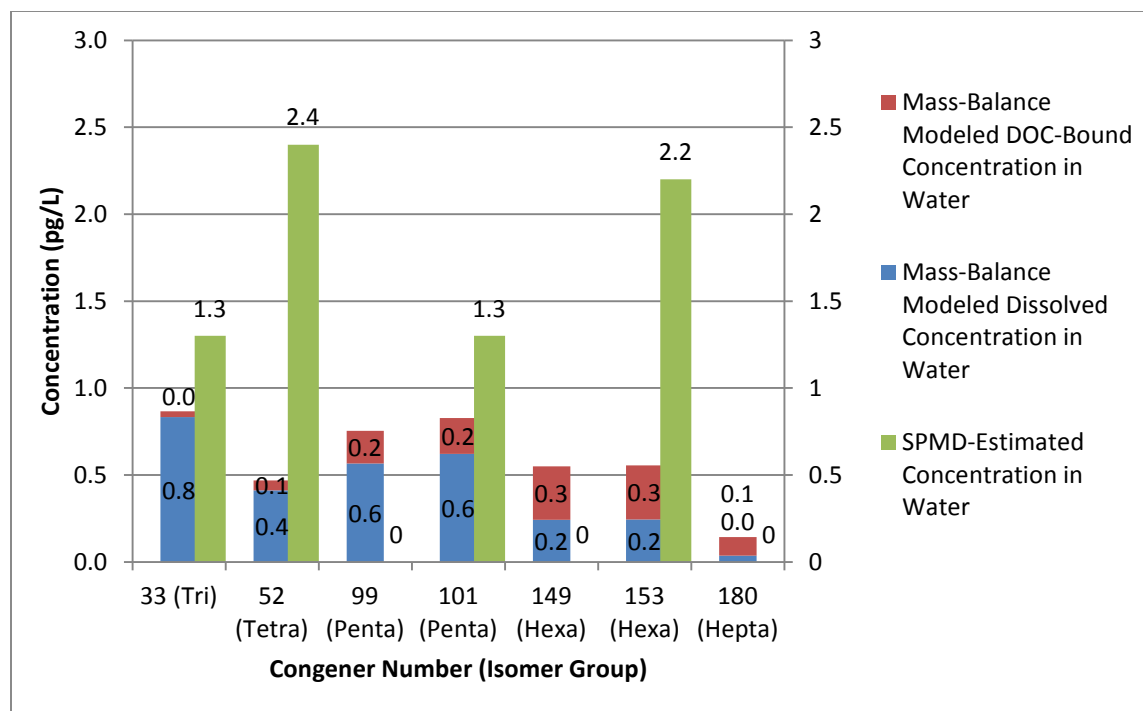


Figure 5.20: Comparison of (truly dissolved + DOC-bound) phase concentrations predicted by the mass balance model with SPMD-estimated concentrations in Lake Superior.

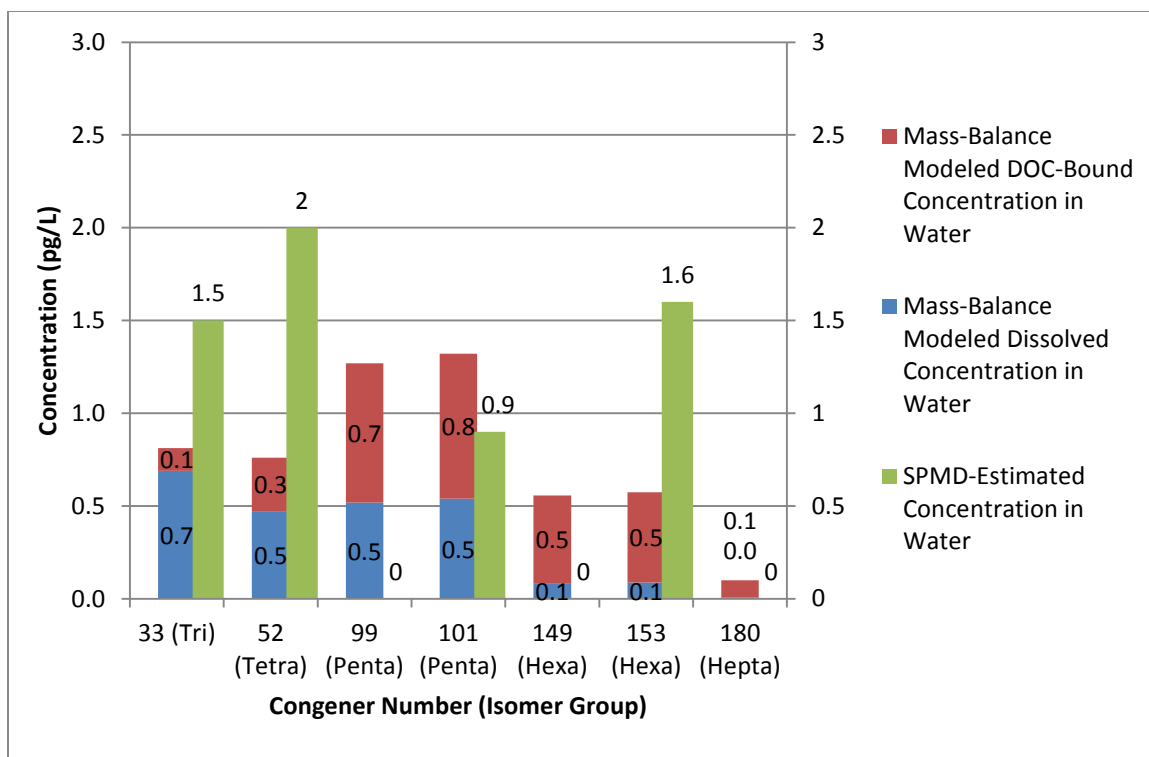


Figure 5.21: Comparison of (truly dissolved + DOC-bound) phase concentrations predicted by the mass balance model with SPMD-estimated concentrations in Dollar Bay.

In Lake Superior and Dollar Bay, the SPMD-estimated concentrations are greater than the mass balance modeled concentrations as well as the sum of the mass balance modeled (truly dissolved + DOC-bound, “aqueous”) concentrations – this shows that the discrepancy between the mass balance modeled dissolved concentrations and the SPMD-estimated concentrations are not just the result of a methodological issue. As seen in Figure 5.19, the SPMD-estimated concentrations in Torch Lake are less than the sum of the mass balance modeled aqueous concentrations (except for the lightest congeners, PCB-33 and PCB-52). A couple of observations can be drawn from these results: 1) The DOC-content of Torch Lake is higher than the DOC content of Lake Superior or Dollar Bay; and 2) The conditions in Torch Lake are different than those in the control sites.

A comparison of the ratios of SPMD-estimated concentrations to mass balance modeled truly dissolved concentrations in Torch Lake to the control lakes further proves that something different is occurring in Torch Lake. As shown in Figure 5.10, the SPMD-estimated concentrations are lower than the mass balance modeled concentrations, which is the same result observed in the control sites. The ratios of SPMD-estimated concentrations to mass balance modeled truly dissolved concentrations are lower in Torch Lake compared to the ratios observed in Lake Superior and Dollar Bay. Combined with the results of examining the mass balance modeled aqueous concentrations to the SPMD-estimated concentrations, it can be concluded that something different is going on in Torch Lake.

Accounting for the DOC-bound congener concentrations affected the comparison of mass balance-modeled concentrations to SPMD-estimated concentrations differently in Torch Lake compared to Lake Superior and Dollar Bay. In all three lakes, the mass balance-modeled truly dissolved concentrations (blue bars) are less than the SPMD-estimated concentrations (green bars). In Torch Lake, the sums of the mass balance-modeled truly dissolved and DOC-bound concentrations tend to agree with the SPMD concentrations for congeners 33-101, but then these sums exceed the SPMD concentrations for congeners 149-180. In Lake Superior, for the comparable congeners (33, 52, 101, and 153), the sums of the mass balance-modeled truly dissolved and DOC-bound concentrations are less than the SPMD-estimated concentrations. (Average ratio SPMD : mass balance-modeled (truly dissolved + DOC-Bound) = 3.04, S.D. = 1.79) In Dollar Bay, for the comparable congeners (33, 52, 101, and 153), except for congener 101, the sums of the mass balance-modeled truly dissolved and DOC-bound concentrations are less than the SPMD-estimated concentrations. (Average ratio SPMD : mass balance-modeled (truly dissolved + DOC-Bound) = 1.98, S.D. = 0.96)

Comparison of the terms in the mass balance provides an indication of their relative contributions (Figure 5.22 to Figure 5.24; Table 5.14 to Table 5.16). Comparing the mass balance terms of the three lakes, volatilization is large compared to all other fluxes in each lake, except for diffusion of DOC-bound PCB from sediment to water in region 1 of Torch Lake. It was found that reducing the volatilization flux improved the results of the model (for all lakes) – that the mass balance modeled concentrations are at least within the same order of magnitude as the SPMD-concentrations. Furthermore, it was found that reducing the air-water exchange velocity also improved the agreement of the model with the SPMD measurements (for all lakes). Additional scrutiny should be given to the estimation of the air-water exchange velocity to improve the accuracy of the mass balance model.

As shown in Figure 5.22 below, the diffusion of DOC –bound PCB from sediment to water in region 1 is also large compared to other fluxes in the mass balance. A comparable value for Lake Superior and Dollar Bay does not exist because these lakes do not have regions of high concentrations of PCBs in the sediments serving as potential inputs of PCBs to the lake. Future work should include an examination of this parameter to ensure that it is estimated correctly.

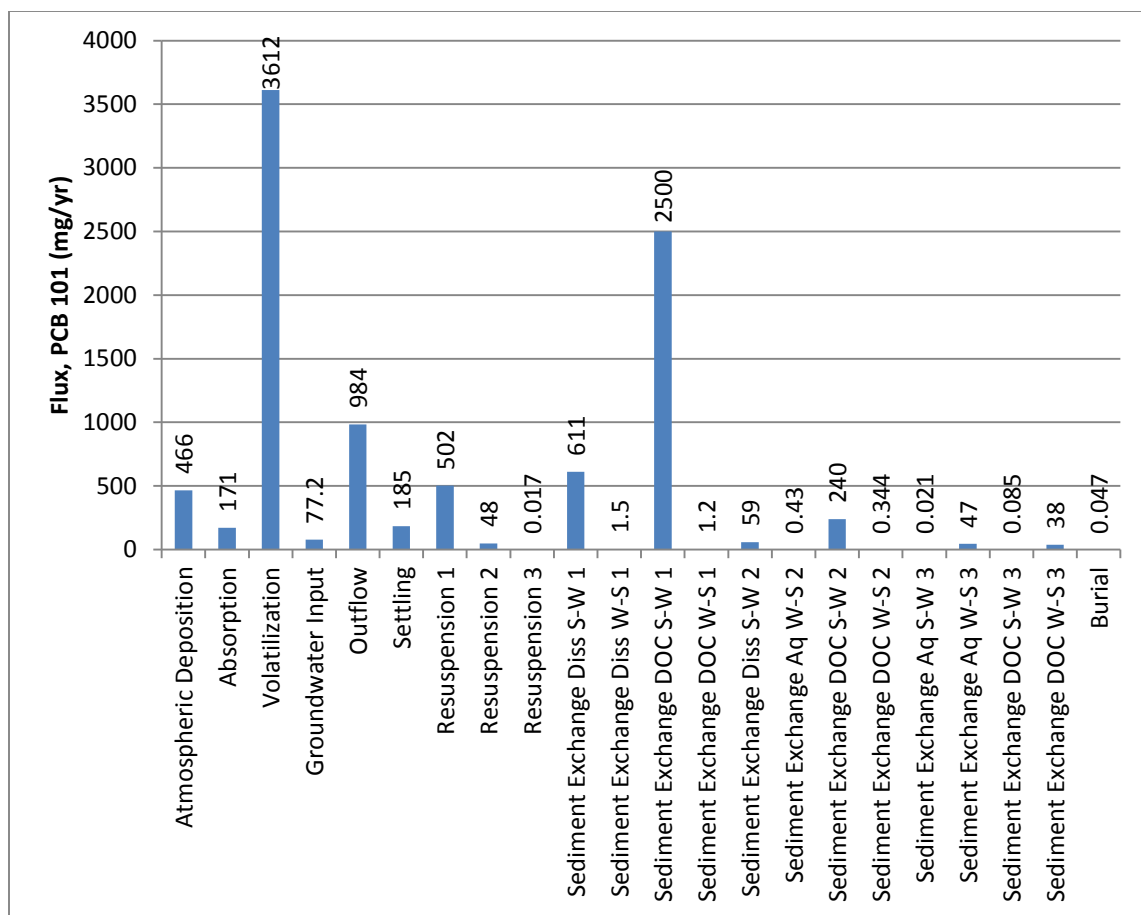


Figure 5.22: Magnitude of the components in the mass balance model for Torch Lake.

Table 5.14: Comparison of PCB Inputs and Outputs for Torch Lake.

Congener	Inputs	Outputs	Output - Input	Output/Input
	mg/yr	mg/r	mg/yr	
33	1185	1206	21	1.02
52	2434	2498	64	1.03
99	2648	2762	115	1.04
101	4674	4869	195	1.04
149	3755	4064	309	1.08
153	4216	4560	344	1.08
180	3703	4104	401	1.11

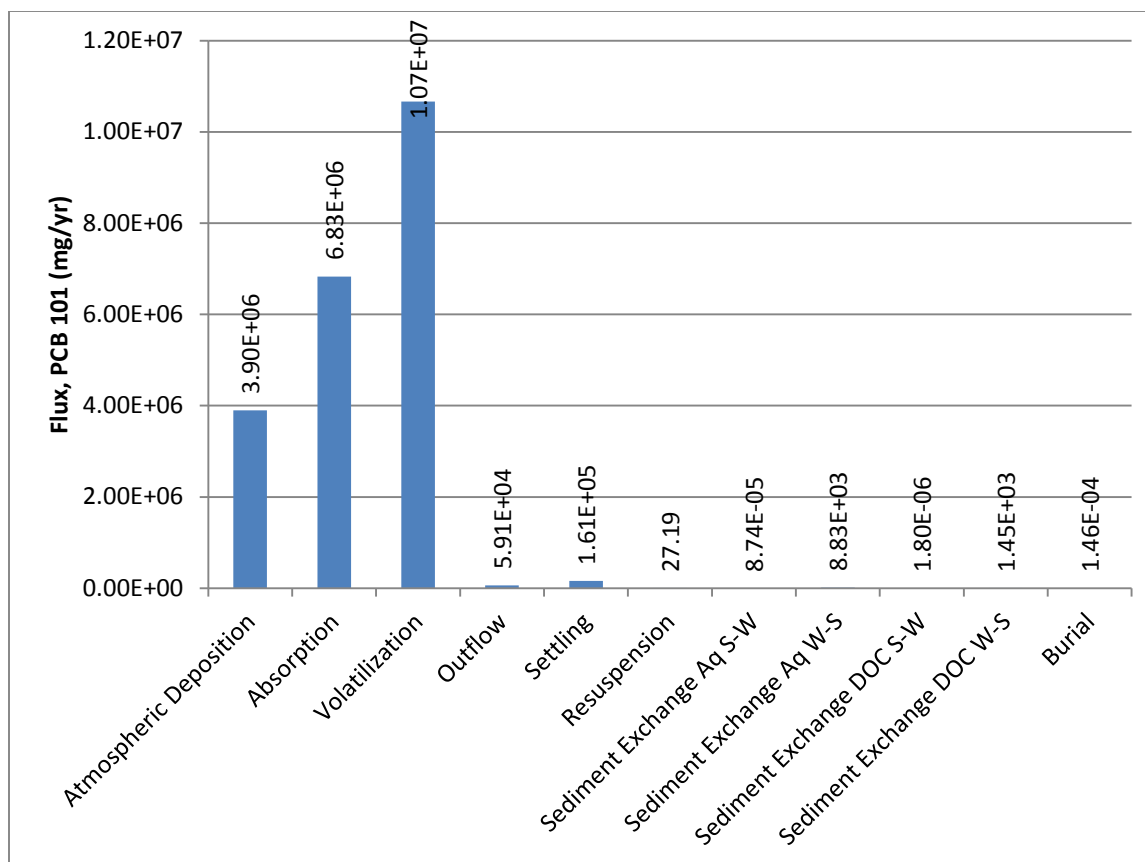


Figure 5.23: Magnitude of the components in the mass balance model for Lake Superior.

Table 5.15: Comparison of PCB Inputs and Outputs for Lake Superior.

Congener	Inputs mg/yr	Outputs mg/yr	Outputs-Inputs mg/yr	Output/Input
33	1.49E+07	1.49E+07	5.94E+04	1.00
52	8.03E+06	8.09E+06	6.28E+04	1.01
99	8.09E+06	8.24E+06	1.56E+05	1.02
101	1.07E+07	1.09E+07	1.71E+05	1.02
149	3.93E+06	4.11E+06	1.74E+05	1.04
153	3.96E+06	4.13E+06	1.76E+05	1.04
180	5.34E+05	5.83E+05	4.83E+04	1.09

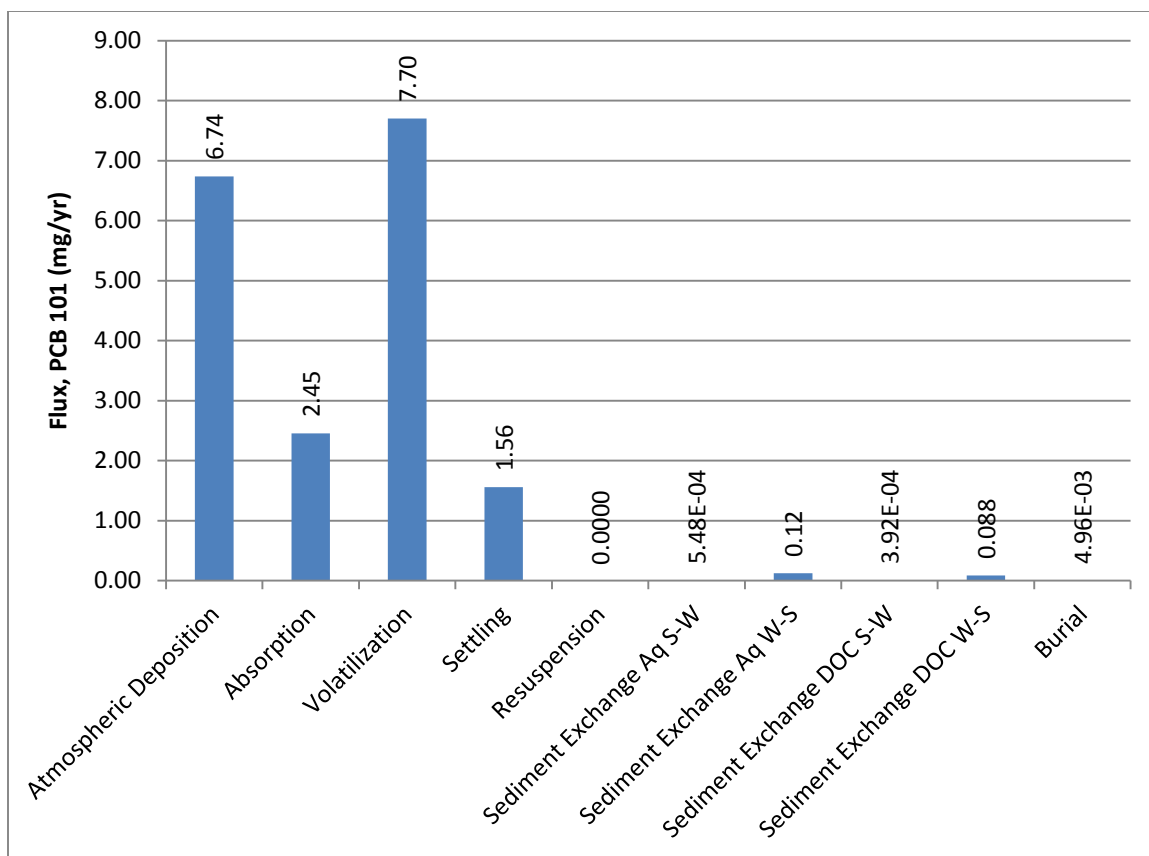


Figure 5.24: Magnitude of the components in the mass balance model for Dollar Bay.

Table 5.16: Comparison of PCB Inputs and Outputs for Dollar Bay.

Congener	Inputs mg/yr	Outputs mg/yr	Outputs - Inputs mg/yr	Output/Input
33	10.87	11.11	0.24	1.02
52	7.85	8.05	0.19	1.02
99	8.41	8.68	0.27	1.03
101	9.19	9.48	0.29	1.03
149	1.81	1.90	0.10	1.05
153	1.86	1.96	0.10	1.05
180	0.19	0.21	0.02	1.08

As shown in Figure 5.22 to Figure 5.24 and Table 5.14 to Table 5.16 above, the input and output fluxes balance in all three lakes. Since the model assumed steady state, this balance merely shows that no errors were made in calculations. In addition to the comparison of mass balance modeled concentrations to SPMD-estimated concentrations and the examination of flux balance, the times to steady-state of the congeners were calculated using an equation presented in Schwarzenbach et al. (2003), with some modifications to allow for my definition of the rate equations. The times to steady state in Torch Lake ranged from 5.7 – 7 years, in Lake Superior ranged from 2.1 – 9.9 years, and in Dollar Bay ranged from 4.7 – 7 years.

It was concluded that the assumption that conditions are at steady-state for PCBs, while valid for Torch Lake, is not valid in Lake Superior or Dollar Bay. The reason for this is that it is known that over time, the concentration of PCBs in the air has been decreasing. Given that the half-life of PCBs in the atmosphere is 5-12 years, and that the time to steady state for all congeners is less than this range of time, the atmospheric inputs are changing too rapidly to allow the lakes to reach steady state. Because it is assumed that the only inputs of PCBs to Lake Superior and Dollar Bay are atmospheric, Lake Superior and Dollar Bay are not at steady state. This lack of steady state also contributes to the discrepancy between model predictions and SPMD measurements; the lake, as reflected in the SPMD-based concentrations, still contains PCBs from previous years when rates of atmospheric deposition and absorption were higher. Steady state with the 2006 rate of atmospheric deposition would result in lower concentrations in the lake as predicted by the mass balance model.

Torch Lake is likely closer to steady state than are the other two lakes because the declining atmospheric inputs represent a smaller fraction of total inputs for Torch Lake. If only atmospheric inputs of PCBs to Torch Lake existed, one would expect similar ratios of SPMD-estimated to model-predicted truly dissolved PCB concentrations as are observed in Lake Superior and Dollar Bay. As displayed in Figure 5.10, this is not the case.

In addition, reviewing the book Monitors of Organic Chemicals in the Environment by Huckins et al., 2006 (the text that explains the USGS SPMD spreadsheet model), and the GLEC report for the 2005 SPMD study, it is not clear that partitioning of PCBs between the truly dissolved and DOC-bound phases was taken into account. According to Huckins et al., in theory, whether or not DOC is taken up by the SPMD should not affect the apparent water sampling rate (R_s), but “the fractional amount of chemical sorbed to DOC can affect the accuracy of SPMD calibration experiments, which in turn can affect SPMD-derived estimates of truly dissolved environmental concentrations.” (Huckins et al., 2006) If the DOC-bound phase was not accounted for in SPMD calibration experiments (but was present), then the R_s values would be too low, based on the equation for aqueous concentration as defined by Huckins et al.:

$$C_w = \frac{N}{V_s K_{sw} \left(1 - e^{-\frac{R_s t}{V_s K_{sw}}} \right)} \quad [61]$$

where:

Table 5.17: Variables in Equation for Aqueous Phase Concentration.

Symbol	Quantity
C_w	Aqueous phase concentration
N	Amount absorbed into the SPMD
V_s	Volume of SPMD
K_{sw}	SPMD-water partition coefficient
R_s	Apparent water sampling rate
t	Exposure time

As seen in the equation above, if the R_s value is too low, this could cause the SPMD-estimated concentration to be higher than expected.

5.4 Discussion

5.4.1 Summary of Existing Knowledge

Prior to this research, it was known that PCBs were a problem in Torch Lake, but the extent to which they were a problem was not clear. Until the early 1990s, PCBs were not considered a problem in Torch Lake. As part of the Remedial Investigation in 1989-1990, PCBs were sampled and high levels were found in one sample location offshore of the former C&H smelter in Hubbell (Donohue and Associates, 1992; EPA, 1994).

Because they were found in one concentrated area near what is now the Koppers site (the former site of the C&H smelter, displayed in Figure 5.25) only, the EPA concluded that the contamination found in that small area could not be causing the frequency of fish tumors occurring in Torch Lake (EPA, 1994) (MDEQ, 2007). The EPA explored the idea of placing a polyvinyl chloride cap over the contaminated location, but it was decided that this measure would be cost prohibitive (EPA, 1994).

Legend

■ Historical Industrial Building Locations



Figure 5.25: Locations of historical industrial buildings where PCBs have been found.

Though PCBs were sampled in the upland material as part of the OUI Remedial Investigation and in drums of contaminated material found near Hubbell/Tamarack and Mason, they were detected in only one barrel between all sampled media (Geraghty & Miller, 1992). Two of three soil samples were collected near the Ahmeek stamp mill site (Figure 5.25) in Tamarack in the vicinity of a transformer pad and a drum. Neither of these samples yielded positive concentrations of PCBs. Recent soil sampling efforts for PCBs have not occurred near the Ahmeek stamp mill. An effort to locate the Mason soil sample site was made by the author, but it could not be located based on comparison of the schematic drawing provided in the Remedial Investigation and modern-day maps of the area. None of these sample locations had influence on the recent upland sampling for PCBs, which is discussed further below. The area of concentrated contamination in the sediment may have influenced the locations of recent U.S. EPA and MDEQ sediment sampling efforts, which were launched by the need to find a possible local source of PCB contamination that may be affecting concentrations found in fish caught from Torch Lake.

PCBs became recognized as a more prominent problem when fish caught from Torch Lake were collected and found to contain PCBs. PCBs were detected in fish caught from Torch Lake as early as 1986 (Bohr, 2010). In 1998, when the MDCH established revised safe consumption levels for PCBs, the concentrations previously measured were found to exceed these revised safe consumption levels. The current Beneficial Use Impairment due to restriction on fish consumption exists because the Torch Lake fish consumption advisories based on PCBs and mercury in fish are more restrictive than those of their associated Great Lake, Lake Superior. According to the 2007 Torch Lake AOC Remedial Action Plan Update, the next step to delisting the Fish Consumption BUI is identifying and remediating the source of PCBs driving the Fish Consumption Advisories (MDEQ, 2007). It was hypothesized that the concentrations found in the Torch Lake fish were actually a result of exposure to PCBs in Lake Superior because a barrier for fish movement between Torch Lake and Lake Superior does not exist (MDEQ, 2008a).

To determine if this hypothesis was correct, several studies were conducted by the MDEQ and the EPA. The results of these studies are discussed in the following sections. From the 2005 SPMD study, it was concluded that “a source of PCBs does exist in the Torch Lake watershed” (MDEQ, 2006). This viewpoint appeared to be reinforced by the findings of the MDEQ’s 2008 fish study, which looked at the concentrations of PCBs in Walleye caught in Torch Lake compared to Walleye caught in Portage Lake and Huron Bay. The fish study was done to determine if a hypothesis about the cause of elevated concentrations of PCBs found in Torch Lake fish due to exposure in Lake Superior was true. The findings of this report appeared to not confirm the hypothesis as it was found that the concentrations of PCBs in fish caught from Portage Lake were similar to those of fish caught from Huron Bay, while the Torch Lake fish concentrations were elevated (MDEQ, 2008a).

In addition to the MDEQ’s fish study, both the MDEQ and the EPA conducted sediment sampling to determine if the level of PCB contamination in the sediment would contribute to the elevated PCB concentrations found in the fish. Based on the fact that the concentrations found in surficial sediment samples were generally below project detection limits (samples: 0.7-12400 ppb, mean=972 ppb, median=320 ppb; DLs: 25 - 760 ppb), the EPA determined that “the surficial sediment PCB concentrations detected in 2007 and 2008 in the Hubbell/Tamarack area... are generally at or below the ranges of concentrations expected to impact aquatic species” (EPA, 2009), but that “an ongoing source of PCBs to Torch Lake cannot be ruled out” (EPA, 2009).

As the planned MDEQ and EPA studies were coming to a close, sampling for PCBs was conducted in upland material as part of Emergency Removal actions. The triggers for the Emergency Removal actions are discussed in chapter 3. As a result of the sampling, PCBs were detected in soil and groundwater mostly in Lake Linden, Hubbell, Tamarack and Mason near the former C&H Lake Linden Power Plant, C&H Smelter, Tamarack Leaching Plant and Quincy Reclamation Plant, respectively. The conclusions drawn from these detections are described in detail later in this discussion.

In short, before this thesis research was conducted, it was known that PCBs were present in the Torch Lake system at levels higher than those found at control sites, however it was concluded that the concentrations in the lake sediments were too low to cause elevated concentrations in the fish. The work done in this thesis research helps to link the PCB concentrations measured/estimated in the sediment, groundwater, shoreline soil, and atmosphere to the PCB concentrations estimated from the SPMD samples to be present in the truly dissolved phase in the lake water, which represents the fraction of the total aqueous concentration available for bioaccumulation. Work that links the truly dissolved PCB concentrations to PCB concentrations in fish is discussed in E. Sokol's thesis (Sokol, 2015). Table 5.18 summarizes the timeline of the events discussed above.

Table 5.18: Timeline of PCB-related government agency investigation activities in Torch Lake prior to this research.

Year	Study; Agency/Contractor	Result	Reference
1984	Clean up of the present-day Koppers site due to oil discharge; MDNR/Michigan Tech	PCBs were found in fuel tanks on the site and treated by Michigan Tech.	(Swift, 1984)
1988	Fish Survey; MDNR	PCBs reported, but concluded to be “some of the lowest contamination levels found in the state.”	(MDNR, 1990)
1989-1990	Operable Unit II Remedial Investigation; U.S. EPA/Donohue & Associates	PCBs were detected in one site sampled near the C&H Smelter in Hubbell.	(Donohue and Associates, 1992)
1991	Risk Assessment; U.S. EPA/Life Systems, Inc.	It was stated that the consumption of PCB-contaminated fish is one of the highest risks to the local population.	(Life Systems, 1991)
1994	OUII ROD; U.S. EPA/Donohue & Associates	It was concluded that the PCB contamination observed could not be the cause of the frequency of fish tumors in Torch Lake.	(EPA, 1994)

Year	Study; Agency/Contractor	Result	Reference
1998	MDCH	A fish consumption advisory was established due to new guidelines for PCB and mercury consumption.	(Baker, 2007)
2005	SPMD Study; MDEQ/GLEC	"A source of PCBs does exist in the watershed."	(Center, 2006)
2007	Torch Lake Area Assessment; MDEQ/Weston	PCBs were located near in soil near Hubbell	(Weston Solutions, 2007)
2007	Sediment Chemistry Survey; MDEQ, U.S. EPA	It was concluded that concentrations in sediment were too low to cause PCB contamination in fish.	(MDEQ, 2008b)
2008	Aroclor Sediment Investigation; U.S. EPA		(EPA, 2009)
2008	Fish Study; MDEQ	It was concluded that it was likely that "the elevated concentrations of PCBs measured in [walleye caught from Torch Lake] are a result of sources within the Torch Lake watershed over and above atmospheric inputs."	(MDEQ, 2008a)
2011- 2013	Emergency Removals; U.S. EPA	PCBs were detected in the basement of the C&H Lake Linden Power Plant and at the Hubbell Smelter	(EPA, 2015)

5.4.2 Evidence of Local and Ongoing Source(s) of PCBs to Torch Lake

5.4.2.1 Evidence of a Local Source

Further examination of the results of the previous studies on PCBs in Torch Lake, combined with new research on the historical use of PCBs in the Torch Lake system, points to evidence of a local source of PCBs to Torch Lake. The results of SPMD, fish and sediment sampling show that a local source does exist. These results and their associated conclusions will be described in further detail in the following sections. The results of the historical investigation, combined with the results of collection and analysis of upland materials, help to determine possible local sources of PCBs to the lake.

5.4.2.1.1 Truly Dissolved Congener Concentrations

As part of the overall goal to determine if a local source or sources of PCBs to Torch Lake exists, in 2005, the MDEQ contracted Great Lakes Environmental Center (GLEC) to conduct collect samples of PCB from the lake water using SPMDs. SPMDs were deployed in 2005 in six locations in Torch Lake and four control sites located in the Keweenaw Waterway, Dollar Bay and Huron Bay, which are shown in Figure 5.26. More details about this study can be found in the methods section or in the GLEC report (GLEC, 2006). Two findings of the MDEQ 2005 SPMD study clearly show that a local source of PCBs exists in Torch Lake.

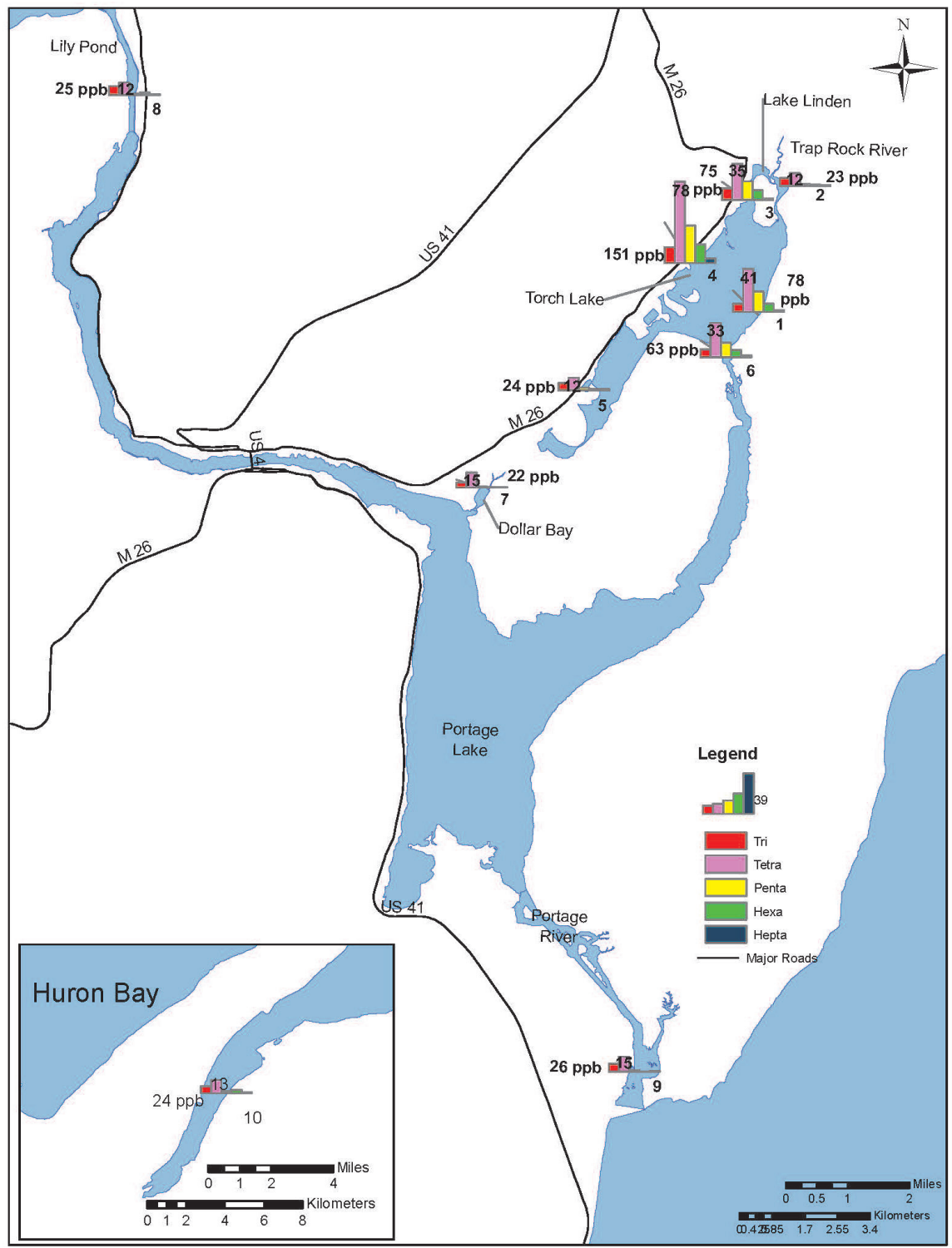


Figure 5.26: Isomer PCB concentrations in SPMDs. Numbers at the bottom right of each bar graph are the site numbers. Total PCB concentrations in the SPMDs at each site are reported in ppb. Numbers above the tallest bar in each graph give the total concentration for the most prominent isomer at that site.

First, PCB concentrations in the Torch Lake SPMDs were considerably higher than the concentrations found in the control sites (60-150 ppb vs. 22-26 ppb). The similarity in total PCB concentrations at all control sites is noteworthy; such similarity is expected if lake water at the control sites is near equilibrium with PCBs in the air. Higher concentrations in Torch Lake imply that this water body is not near equilibrium with the atmosphere, but rather that PCBs are volatilizing into the atmosphere. Indeed, of the seven congeners measured in the SPMDs and used in the mass balance model, all seven had fugacities in the water that are higher than the fugacity in the air (assumed equal to those measured at the Eagle Harbor IADN site in the year of the SPMD study, 2005). The differences in total PCB concentrations observed in Torch Lake and the control sites suggest that Torch Lake has a PCB source other than the atmosphere.

Second, the isomer distributions in the SPMDs clearly show that the PCB source for Torch Lake is compositionally different than the source for the control sites. The PCBs in Torch Lake SPMDs were dominated by heavier congeners relative to those in the control sites. While tetra-chlorinated PCB isomers were the most abundant of all isomers in all sites, penta- through hepta-chlorinated isomers contributed approx. 50% of total PCBs in Torch Lake sites but only 16-29% in the control sites. Hence, the SPMD study revealed that not only were the concentrations of total PCBs higher in Torch Lake water, but the PCBs were also compositionally different in Torch Lake than in the control sites.

5.4.2.1.2 Concentrations in Fish

The results from fish sampling performed in Torch Lake, Portage Lake and Huron Bay in 2000, 2007 and 2013 show that despite changing trends of PCBs in fish over time, the concentrations of PCBs in fish caught in Torch Lake were consistently higher than PCB concentrations in fish caught from the control sites. Due to limits of available data, only concentrations in Walleye could be compared among the lakes in Table 5.19.

Table 5.19: Comparable fish sample data. Codes: TL = Torch Lake, HB = Huron Bay, PL = Portage Lake. Huron Bay was sampled in 2006 instead of 2007.

Sampling Year	Walleye	Northern Pike	Smallmouth Bass	White Sucker
2000	TL	TL	TL	
2007	TL, HB (2006), PL	TL		TL
2013	TL, HB	TL, HB	TL	

As mentioned above and as shown in Figure 5.27, concentrations in Walleye in Torch Lake are usually higher than concentrations in Walleye in Portage Lake or Huron Bay. Concentrations reported are in terms of wet weight in fillets.

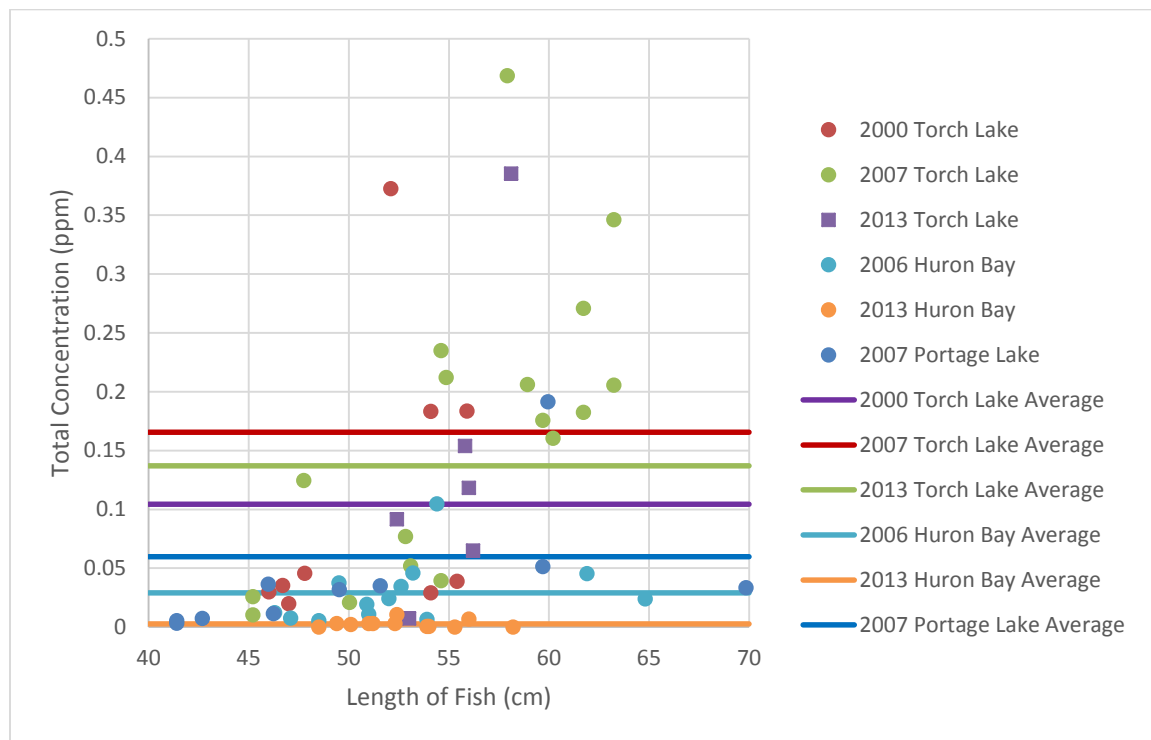


Figure 5.27: Concentrations of PCBs in Walleye 45-65 cm in length of fish.

The fact that the concentrations of PCBs in fish caught from Torch Lake are higher than those caught from Huron Bay or Portage Lake suggests that a difference may exist between sources of PCBs to Torch Lake fish compared to sources of PCBs in fish from other lakes. If the sources in Torch Lake were the same as those in the control sites, it could be expected that the concentrations in fish from Torch Lake would be similar to concentrations in fish from other lakes rather than greater. However, the expectation that the concentrations in fish in Torch Lake would be similar to concentrations in Huron Bay or Portage Lake would also rely on accounting for physical differences between Torch Lake and the control lakes; such as lake size, flushing rate, sedimentation rate, surface area, food web structure, and others.

5.4.2.1.3 Sediment Sampling

The MDEQ conducted sediment sampling in 2007 focused near the western shore of Torch Lake and found clusters of elevated concentrations of PCBs in close proximity to the former Calumet & Hecla (C&H) Lake Linden Power Plant and to the Coal Dock and former C&H Smelter in Hubbell, as shown in Figure 5.28. The EPA conducted sediment sampling in 2008 that spatially covered the entire lake area, but at only two of the 80 locations were concentrations above detection limits for that campaign (the detection limits in the EPA study ranged from 25 – 530 ppb and the sample depth consisted of the top 1-2 inches of organic material). The two locations where PCBs exceeded detection limits were near Hubbell.

The sediment mapping supports the conclusion from the SPMD study that local sources of PCBs to the lake exist. As shown in Figure 5.28, areas of elevated concentrations are located close to the industrial western shore. Specifically, the elevated concentrations in sediment are found in proximity to C&H operations that likely used PCBs, such as the C&H Lake Linden Power Plant and the C&H Smelter in Hubbell. Though the contaminated areas in the sediment suggest sources near the C&H operations, the low concentrations (0.7-12400 ppb, mean=972 ppb, median=320 ppb) suggest that either PCBs were highly diluted with other materials dumped into the lake, or that very little PCB was dumped into the lake. The existence of these localized, concentrated areas of elevated concentration clearly indicate local sources, as atmospheric deposition would spread PCBs throughout the lake subject only to sediment focusing.

Legend

- Positive Lake Sediment Samples
- Historical Industrial Building Locations

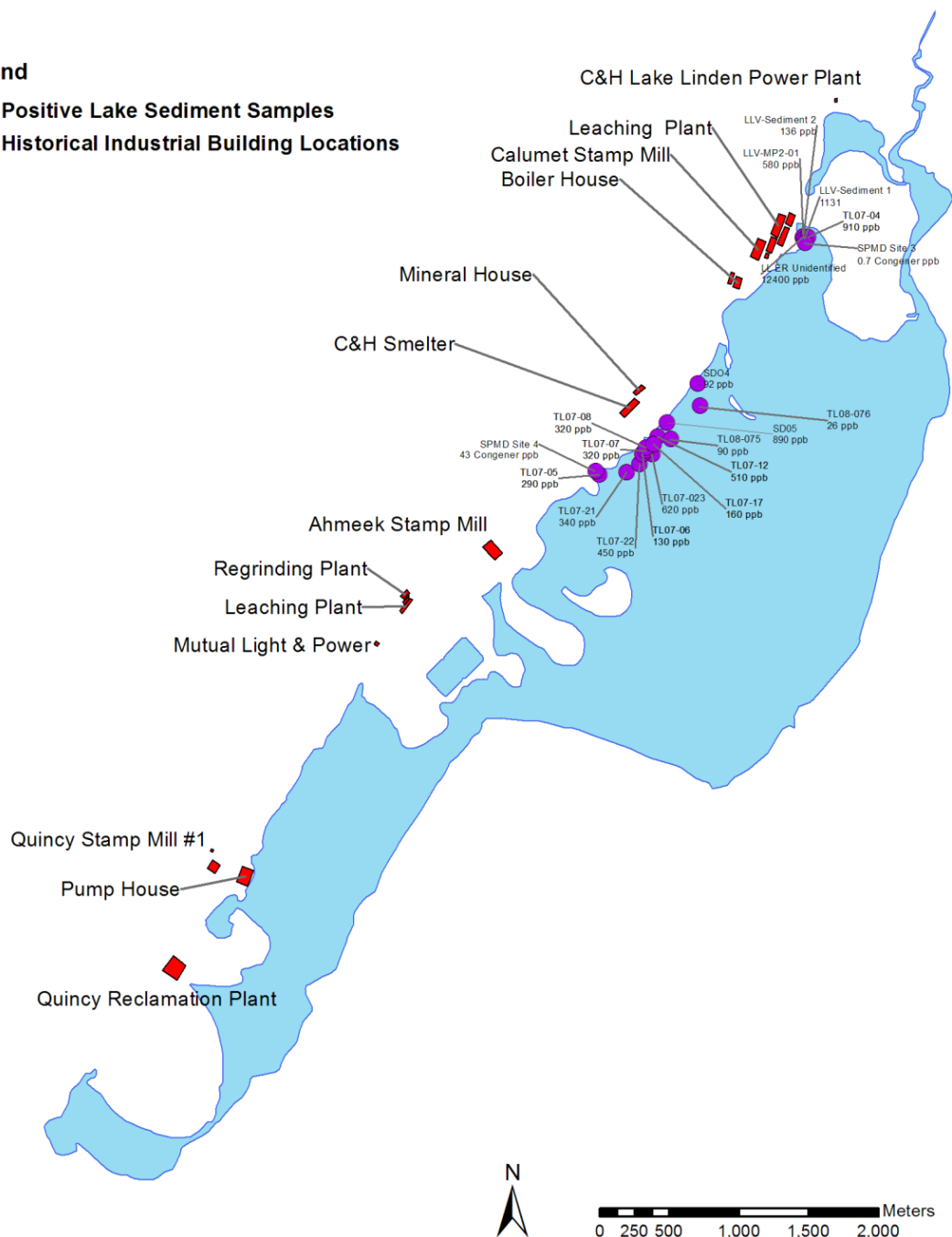


Figure 5.28: Positive PCB concentrations in sediment and industrial copper processing industry along the western shore of Torch Lake.

5.4.2.1.4 Summary of Historical PCB Use on the shore of Torch Lake

Examining how and where PCBs were used in historical industrial activities helps to identify possible local sources of PCBs to Torch Lake. A detailed analysis of PCB use in historical mining activities was conducted by E. Schwaiger Zawisza, M.S. student, Social Sciences (Industrial Archaeology). Through this work, the locations of buildings and equipment in which PCBs were used were identified. Schwaiger Zawisza's process was first to identify all of the industrial buildings along the western shore, then to narrow the findings by identifying which buildings were in use between 1930-1970 (the time period during which PCBs were in use), and then to focus on the electrical distribution system and where transformers were located. By combining the results of her mapping industrial building locations and her schematic of the electrical distribution system along the western shoreline, the general locations of transformers were identified.

The C&H Lake Linden Power Plant provided electricity for most, if not all, of the industrial operations along the western shore (Schwaiger Zawisza, 2016 (Expected)). From the Lake Linden power plant, electricity was provided to the Lake Linden Reclamation Plant, the Lake Linden substation, the Coal Dock substation and the Ahmeek Mill Power Plant and Quincy Reclamation Plant in Mason (after 1943). The Coal Dock substation in Hubbell provided power to the C&H Smelting works. The Ahmeek Mill Power Plant in Tamarack City provided power to the Ahmeek Mill Pump House, Mutual Water, Light and Power Co. Pump House, and the Tamarack Reclamation Plant substation (Schwaiger, 2014) (see Figure 5.25 for reference; the site of the Ahmeek Mill is the in the vicinity of the locations of the Ahmeek Mill Power Plant and the Ahmeek Mill Pump House). A schematic of the electrical distribution system is shown Figure 5.29.

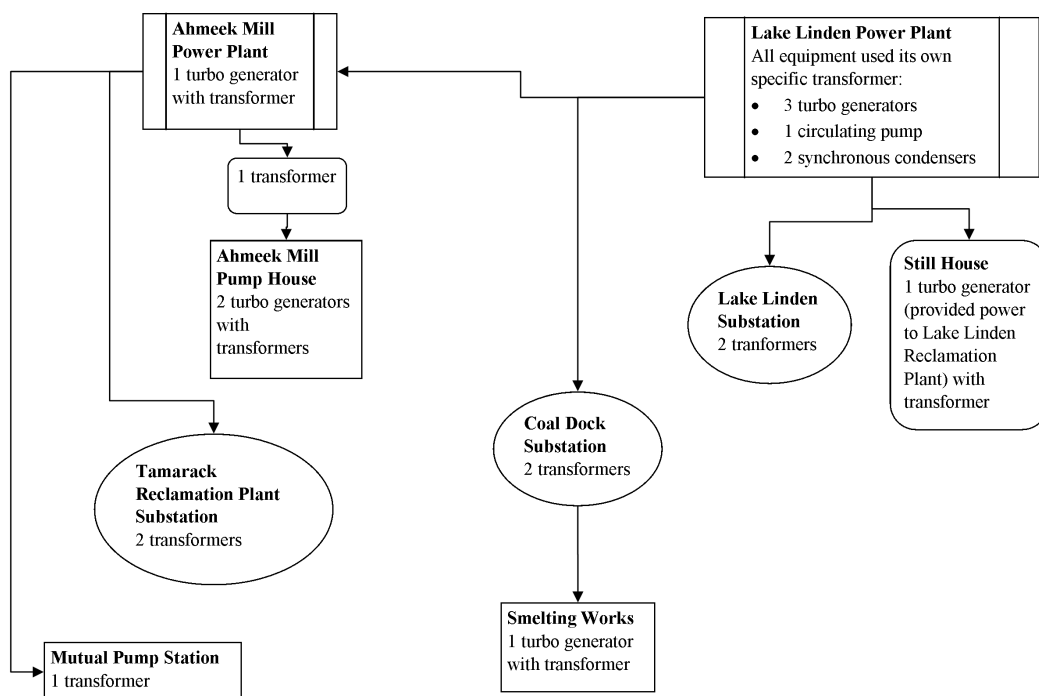


Figure 5.29: Schematic of the electrical distribution system along western shore of Torch Lake in the early 1930s identifying buildings in which electrical transformers are known to be located (Adapted from McIntosh & Borgan, 1931; Schwaiger Zawisza, 2016 (Expected)).

As shown in Figure 5.30, it is apparent that the clusters of PCB concentrations above detection limits in the soil and groundwater correspond to the locations of the Calumet & Hecla Lake Linden Power House (“Houghton County Electric Co”), the C&H Smelter in Hubbell (“Smelting and Refining”), the Tamarack Leaching Plant (“Leaching Plant”), and the Quincy Reclamation Plant in Mason (“Quincy Reclamation Plant”, not shown in Figure 5.30). As shown in Figure 5.28, clusters of PCB concentrations above detection limits in the sediment are located near the electrical substation in Lake Linden and near the C&H Smelter in Hubbell. The fact that PCBs were found in the sediment at these locations suggests that waste oils from these buildings may have been discarded into the lake. The correlation between the transformer locations and the elevated PCB concentration clusters supports the hypothesis that an upland source of PCBs to Torch Lake exists; and that the PCBs found in the upland material may have been spilled from

transformers, as this equipment contained PCBs and was located in the industrial buildings. More discussion on industrial PCB use along Torch Lake can be found in Schwaiger Zawisza (2016, expected).

5.4.2.1.5 Soil and Groundwater Sampling

Based on the proximity of the PCB concentrations above detection limits in soil and groundwater to historical industrial sites, it is likely that the source of PCBs to Torch Lake is electrical equipment (probably transformers, but also remnants of burning reclaimed electrical equipment) that are or were near the lake. Removed equipment may have leaked PCBs into the soil/sediment before it was removed, and this soil/sediment then may continue to be a source of PCBs to the lake. The most recent soil contamination data consists of the analysis results from sampling performed by Weston Solution, Inc. in 2007 (Weston Solutions, 2007) and the MDEQ in 2011. Most of Weston samples that were taken along the Torch Lake western shoreline did not yield concentrations of PCBs above the detection limits, except for one in Hubbell. The MDEQ samples yielded a number of PCB concentrations above detection limits, as displayed in Figure 5.30.

Legend

- ▲ Positive Upland Soil Samples
- Positive Upland Groundwater Samples
- Historical Industrial Building Locations

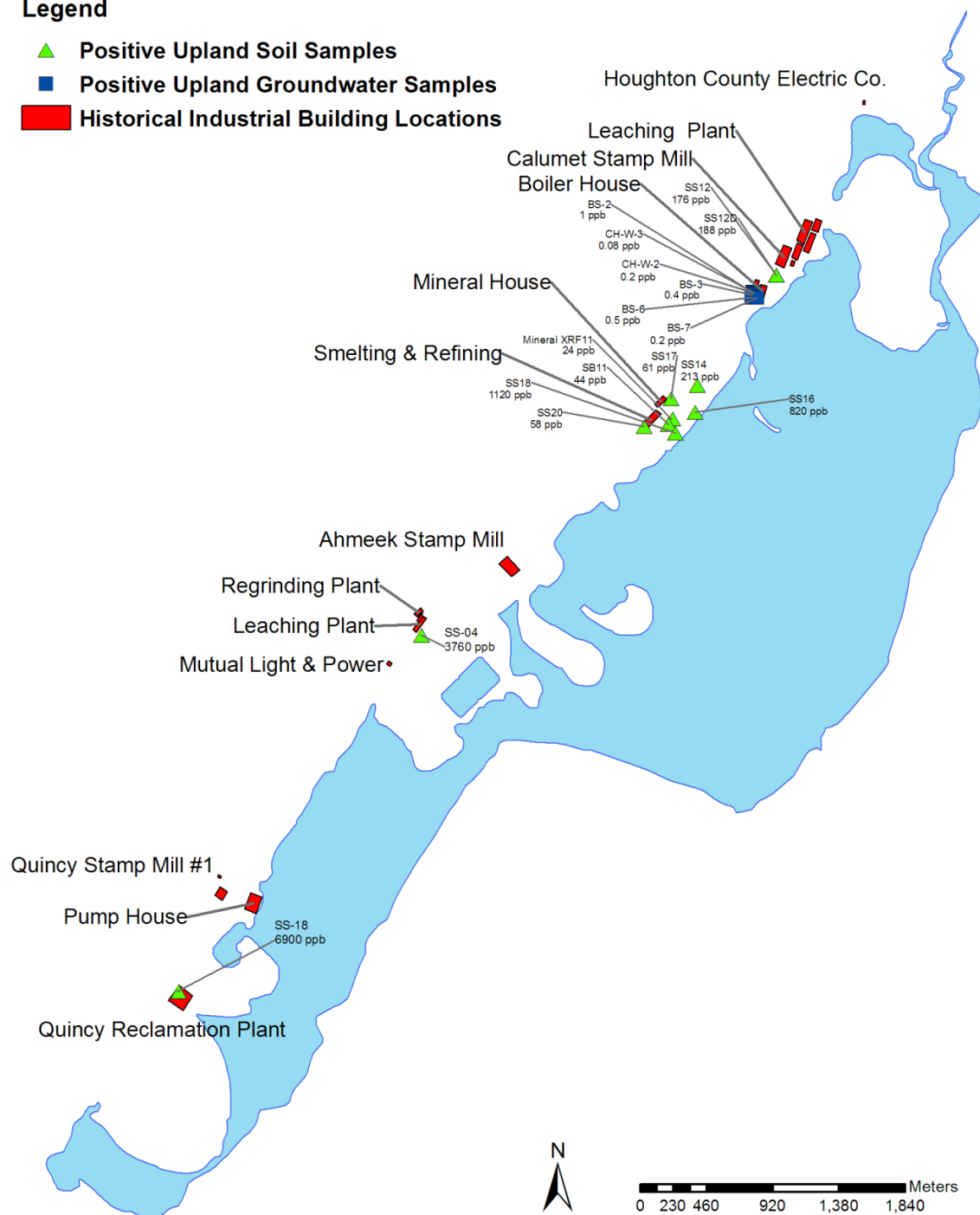


Figure 5.30: Locations of PCB concentrations above detection limits in soil and groundwater relative to historical industrial buildings.

In Lake Linden and Hubbell, the locations of the PCB concentrations above detection limits in soil are at or near the C&H Lake Linden Power Plant and the C&H Smelting Works and Coal Docks, respectively, where transformers were once located (Schwaiger Zawisza, 2016 (Expected)). In Lake Linden, PCB concentrations above detection limits in groundwater were located in the basement of the C&H Power Plant. The range of concentrations for these samples was 0.08 - 1 ppb. PCBs were detected in a soil sample collected from between the C&H Boiler House and the Calumet Stamp Mill, though the C&H Power Plant was located adjacent to the boiler house on its northwest side.

In Hubbell, where there are seven locations at which PCBs were detected (concentration range 24 – 1120 ppb), the concentrations tend to be higher towards the northern and southern ends of the cluster, near the locations of the Coal Dock and the Smelter Power Plant, respectively. In Tamarack, PCBs were detected in a soil sample (3760 ppb) located in the open area just southeast of the Tamarack Leaching Plant. In Mason, PCBs were detected in a soil sample (6900 ppb) located at the site of the Quincy Reclamation Plant. Electrical transformers were located in all of the buildings mentioned above.

Based on the preceding observations, the spatial trends in the soil concentrations and their correlation to the locations of transformers support the hypothesis that the source of the PCBs to the lake is electrical equipment that was located along the western, industrialized shoreline of Torch Lake. It is likely that waste oils containing PCBs were dumped or otherwise discarded into the lake. It is well documented that PCBs were widely used in electrical transformers, capacitors, and in hydraulic fluids between 1930 and 1979. Industrial records show business transactions with General Electric, one of the main suppliers of PCB-filled transformers. The low concentrations found in the sediment (relative to the concentrations found in the upland material) may be due to dilution by other materials dumped into the lake, or simply because very little PCB was discarded.

5.4.2.2 Evidence of an Ongoing Source

A closer study of the results from the SPMD and fish sampling, combined with the results of the mass balance on PCBs in Torch Lake, points to evidence of an ongoing source of PCBs to Torch Lake. The results of the SPMD and fish sampling suggest that an ongoing source exists by comparing concentrations found in these media in Torch Lake to concentrations found in the same media in control sites in Huron Bay and Portage Lake. The concentrations in water predicted by the mass balance on PCBs in Torch Lake are lower than the concentrations in water estimated by SPMDs, which further suggests the existence of an ongoing source or sources.

As discussed in the section presenting evidence of a local source, the concentrations of PCBs in SPMDs in Torch Lake are higher than the concentrations of PCBs in SPMDs in the control sites (Torch Lake: 1-6 pg/L, Huron Bay: 0.0-0.6 pg/L, Dollar Bay: 0.0-0.7 pg/L). Also, the isomer distributions found in the SPMDs in Torch Lake are compositionally different from those found at the control sites. Specifically, heavier congeners were found more frequently in SPMD samples in Torch Lake compared to those in the control sites. These pieces of evidence not only support the hypothesis that a local source or sources of PCBs to Torch Lake exists, but that the source(s) continue to exist as well. If the only source of PCBs to Torch Lake were atmospheric (re)deposition, the concentrations and isomer distributions measured in the SPMDs in Torch Lake would closely resemble those in the control sites, where it is more certain that the only source of PCBs is the atmosphere.

Also, as previously discussed, the PCB concentrations in fish from Torch Lake are higher than PCB concentrations in fish from Huron Bay. As with the SPMDs, the same evidence presented to prove local source(s) can be used to prove the existence of an ongoing source or sources of PCBs to Torch Lake. Regardless of the trend in PCB

concentrations in Walleye in both Torch Lake and Huron Bay, the concentrations in fish from Torch Lake remain higher than concentrations in fish from Huron Bay. If the source of PCBs to Torch Lake was not ongoing, the PCB concentrations in fish from Torch Lake may have shown similar concentrations to PCB concentrations in fish from Huron Bay, provided that other inlake processes and physical characteristics were analyzed in such a way that they were comparable.

5.4.2.2.1 Mass Balance on PCB Compounds in Torch Lake

The concentrations predicted by the PCB mass balance model for Torch Lake are less than the concentrations estimated by the SPMDs, except for congener 149 (Table 5.7; Figure 5.10). In addition, the distribution of the truly dissolved concentrations of the heavier congeners (congeners 101-180) tended to dominate based on the mass balance model, while the lighter congeners (congeners 33-99) tended to be less present in the lake water. This finding is consistent with that of the SPMD study in that heavier congeners tend to make up more of the composition of truly dissolved congeners than the lighter ones.

The fact that the model predicts concentrations that are less than those estimated by the SPMDs supports the idea that an ongoing source of PCBs to the lake exists. It is assumed that the PCB loadings to the system are not changing. That the steady-state model predicts concentrations lower than those estimated based on the SPMD samples shows that the SPMD-estimated truly dissolved concentrations are higher than they are expected to be at steady-state. This difference suggests that an input or inputs that has/have not yet been accounted for exists in the Torch Lake system.

The distribution of the modeled congeners suggests that the source(s) is not atmospheric deposition. If this source was atmospheric deposition, the distribution of congeners would be such that the lighter congeners dominate in the water rather than the heavier congeners. The fact that the heavy congeners dominate correlates well with the fact that the Aroclor mixtures used in the electrical industry tended to contain heavier congeners, and that heavier Aroclor mixtures were identified in positive PCB concentrations in the sediment. The distribution of the modeled congeners also supports the hypothesis that a local source of PCBs to Torch Lake exists.

While evidence of a local source of PCBs is strong and independent of the model, the conclusion that the local source continues to this day relies principally upon the robustness of the model results. As shown in the Results section, the uncertainty of the model predictions could be many orders of magnitude, and the accuracy of the model was not proven unequivocally by results for Dollar Bay and Lake Superior. However, the results for both Lake Superior and Dollar Bay (i.e., model predictions with a factor of 10 of the measured concentrations) suggests that the precision of the model is within one order of magnitude. Furthermore, the lack of steady state conditions suggests that model predictions should differ from the SPMDs by about a factor of 2. For Dollar Bay and Lake Superior; the accuracy of the model; for 2 of 4 measured congeners, the agreement was within that range. Hence the accuracy of the model may be acceptable. Application of the model to Torch Lake results in lower ratios of measured to model-predicted concentrations than for either Dollar Bay or Lake Superior, particularly for heavier congeners. This is the primary basis for asserting that there is an ongoing source in Torch Lake. Clearly, more robust support for this conclusion is desirable. Such support could be obtained by measuring more congener concentrations in the truly dissolved phase in Torch Lake.

5.4.2.3 Closing Discussion

This research has shown that transport and transformation modeling of a contaminant is necessary to explain the impact of the contamination of one medium on the contamination of other media. An extremely important example of this in Torch Lake is how the potential impact of the sediment contamination of PCBs on the fish was dismissed. The EPA twice deemed the concentrations of PCBs found in the sediment not high enough to cause contamination in fish (EPA, 1994; 2009). When this conclusion was drawn in 2008, the PCB concentrations in Torch Lake fish exceeded safe consumption levels, concentrations in SPMDs in Torch Lake were elevated compared to SPMD concentrations in control sites, and the composition of truly dissolved congeners in Torch Lake contained a higher percentage of heavy congeners compared to the congener composition of the control sites. Of particular importance is the congener composition in Torch Lake SPMDs, specifically the presence of higher heavy isomer concentrations, which is consistent with the Aroclor mixture compositions in use in the electrical and mining industries at the time, both of which occurred on the western shore of Torch Lake. The inconsistency in these results is apparent from the mass balance model for Torch Lake: the sediment and groundwater concentrations that have been discovered so far cannot fully account for the truly dissolved PCBs found in the water. There must be an unknown, local, ongoing source(s) of PCBs to Torch Lake.

The most recent soil sampling shows extremely elevated concentrations of PCBs near the Tamarack Electric Substation and in the Quincy Reclamation Plant in Mason, as seen in Figure 5.30. In the sediments near both of these locations, more sampling could be done to search for PCBs – in particular, efforts might focus on sampling closer to the shoreline than where past sampling occurred. It is possible that concentrations of PCBs will be found in these sediments that could help account for the truly dissolved concentrations estimated based on the SPMD samples.

In general, this research shows that cleanup criteria need to account for a site's unique conditions. It is not accurate to conclude that because concentrations at one site are orders of magnitude less than concentrations at other sites where the same type of contamination occurs, the contaminant does not need to be cleaned up or the site does not need to be remediated; the EPA implied this conclusion in the 2008 Aroclor study, claiming that cleanup criteria for PCBs in the Fox and Ashtabula Rivers were much higher than the average PCB concentrations they found in Torch Lake (EPA, 2009). There is no basis for comparison among these sites because they differ greatly in their magnitude of contamination and their physical characteristics. Along the same lines, it is also not accurate to assume that because two sites have similar physical characteristics they will suffer from contamination of the same chemical in the same way. Modeling the transport and transformation of a chemical is important to understand how characteristics of a site and of the contaminant in question act together to transport contamination from one medium or location to another medium/location.

5.5 Summary

This research indicates that an unknown, local, ongoing source(s) of PCBs exists in Torch Lake. Evidence of a local source(s) has been demonstrated by differences in PCB concentrations in fish and SPMDs in Torch Lake compared to control sites; the existence of PCB contamination in the sediment, soil and groundwater and their proximities to sites where PCB-containing equipment was once used; and by differences in the distribution of congeners in the SPMD samples in Torch Lake compared to those in SPMD samples at the control sites. Evidence of an ongoing source is provided by the difference between the mass-balance model predicted PCB concentrations and the SPMD-estimated concentrations, and the differences in concentrations in the fish in Torch Lake compared to control sites. It is recommended that further sampling of Torch Lake sediments and soils be conducted to search for PCBs, and that this search start near the sites of the Tamarack Electric Plant and the Quincy Reclamation Plant.

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6 CONCLUSION

The objectives of this thesis are to summarize the status of contamination and remediation activities in Torch Lake and to estimate the magnitude of potential sources of PCBs to Torch Lake. The overall question guiding this research is the following: what is the status of remediation efforts in Torch Lake with regards to metals and PCBs? Specifically, there are two parts to this question: 1) are the implemented methods of remediation for copper, other metals, and PCBs effective; and 2) can the identified sources of PCBs explain the aqueous concentrations estimated to be in the water?

Chapters 2 and 3 are history chapters which describe the activities that led to the present-day conditions in Torch Lake. Chapter 2 described the Torch Lake industrial history, described the activities that generated metal contamination and described the impact of dumping mine tailings and other industrial waste into the lake. Chapter 3 summarized the history of remediation at Torch Lake. Chapters 2 and 3 provide a context for the content and characteristics of the metal and PCB contamination analyzed in Chapters 4 and 5. After reading Chapters 2 and 3, readers should be able to better understand observations made in Chapters 4 and 5.

Chapter 4 summarized the measurements of heavy metals in the sediment and soil of Torch Lake, and examined the spatial and temporal distribution of these concentrations and the occurrence of criteria concentration exceedances. Several conclusions were drawn from the observations. Due to the recent concentrations of lead and arsenic exceeding the Michigan Part 201 Soil Direct Contact Criteria (DCC), it was concluded that currently not all of the western shore can be safely developed for residential use; and that people who presently reside on properties near the contamination need to take great care in digging groundwater wells and during activities such as gardening and children playing on the ground. The concentrations of heavy metals in the sediment above the

Threshold Effect Concentration (TEC) likely explain the lack of benthos at the lake bottom. A couple of considerations for future remediation were provided, including dredging the slag near Hubbell, and removing debris from the lake bottom.

Chapter 5 focused on the contamination of Torch Lake with PCBs. This chapter included a summary of the mapping of PCB concentrations found in the sediment, soil and groundwater; a discussion of the SPMD sampling analysis, from which aqueous PCB concentrations were estimated; and the results of the mass balance of PCBs in Torch Lake and inferred local sources. The analysis in Chapter 5 concludes that an unknown, local, ongoing source(s) of PCBs exists in Torch Lake. It was recommended that further sampling of Torch Lake sediments and soils should be conducted to search for PCBs, and that this search start near the sites of the Tamarack Electric Plant and the Quincy Reclamation Plant.

Nothing about improving Torch Lake's environmental problems is short work. Contamination occurred over a period of approximately 100 years. While the goal of activities remained the same over those 100 years (to extract copper from various sources), the technology used to achieve that goal evolved during that time, which affected the content and characteristics of the waste disposed into Torch Lake such that these are not uniform throughout the lake and its shore. Remediation has been taking place over the past approximately 35 years. The sheer volume and diversity of the type, source and location of contaminants does not make locating, identifying, and remediating them simple tasks. To further complicate matters, the transport and transformation of chemicals can cause the characteristics of the contamination to change over time from when it was first disposed into the lake.

It is suggested that examining the site as a whole, rather than individual parts of the contamination, would lead to developing more effective remedial actions. Previous efforts to remediate Torch Lake have not provided adequate solutions, as demonstrated by the need for recent emergency removal actions on the site, and the continued existence of two BUIs. Examining the historical activities that caused the contamination, combined with examining the transport and transformation of the contaminants, gives valuable context to contamination location, quantity and content; as demonstrated in the analysis of metals and PCB contamination. This context should be used to help investigators focus their sampling and remediation efforts. This thesis contributes to a holistic examination of the contamination and remediation activities in Torch Lake.

APPENDICES

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- A.4 GIS file for maps
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- A.6 Mass Balance model for Torch Lake, Lake Superior, Dollar Bay
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- A.13 Side Scan Sonar data and map, Summer 2013

APPENDIX A.1: Documentation for Figures

Documentation for Figures 1.3 and 1.4:

2/21/2016

Michigan Technological University Mail - RE: Torch Lake Figures permission to use



Ankita Mandelia <ajmandel@mtu.edu>

RE: Torch Lake Figures permission to use

2 messages

Baker, Sharon (DEQ) <BAKERS9@michigan.gov>
To: Ankita Mandelia <ajmandel@mtu.edu>

Tue, Feb 16, 2016 at 12:56 PM

Ankita,

Good Afternoon!

It is a state and federal policy that you may copy and use at will, all **published** state or federal government reports, guidance documents, data, etc. You may also use information found on public websites, whether they are generated by state or federal agencies. This information may include, but is not limited to: Area of Concern (AOC) guidance documents; AOC Remedial Action Plans (RAPs) or RAP Updates; Superfund (SF) Site Remedial Investigations/Feasibility Studies; SF Records of Decision (ROD); SF ROD Five Year Reviews; SF Emergency Removal Reports; topical white papers; brochures; etc.

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From: Ankita Mandelia [mailto:ajmandel@mtu.edu]
Sent: Tuesday, February 16, 2016 10:01 AM
To: Baker, Sharon (DEQ)
Subject: Torch Lake Figures

Hi Sharon,

<https://mail.google.com/mail/u/0/?ui=2&ik=30e400433f&view=pt&search=inbox&th=152eb39c551a9e7a&siml=152eb39c551a9e7a&siml=152eb3fe10483d33>

1/2

Fair Use Statement for Figures 2.1 and 5.29

Figures 2.1 and 5.29 are the same figure: they are a simplification of the electrical schematic for the system along Torch Lake as of 1931. The data for this figure came from the original electrical schematic in McIntosh and Bergan, 1931. Schwaiger Zawisza, 2016 is cited because her interpretation of the data helped me with my interpretation of the data; but ultimately my interpretation of the data is another, original representation of the data. The electrical schematic in McIntosh and Bergan, 1931, is a traditional electrical schematic, using appropriate symbols to indicate the location of transformers in the system, and showing the complete system, rather than only what was along Torch Lake. McIntosh and Bergan also included more detail than what is included in my thesis figure. The figure originally created by Schwaiger Zawisza calls out by name only the locations of the transformers and other equipment. The figure created by the author for this thesis distinguishes power sources (i.e. power plants), electrical substations, and ultimate electrical destinations in the figure nodes themselves.

APPENDIX A.2: Annotated Bibliography

A Mining Legacy: Torch Lake, An Area of Concern: Its History and Future.

Pamphlet. Houghton-Keweenaw Soil and Water Conservation District. Torch Lake, Area of Concern, Houghton-Keweenaw Soil and Water Conservation District, Public outreach.

Pamphlet contains timeline up to 1995 of activities on Torch Lake.

Map: Laurium Quadrangle. Map., Torch Lake.

Map showing town of Laurium and most of Torch Lake. Appears to be an early map due to lack of mapped stamp sand piles on western shore.

NPL Candidate Narrative Summary. U.S. EPA (inferred), Torch Lake, Superfund.

A one-paragraph description of Torch Lake, the historical mining activities, the sediment contamination, and the fish tumors.

U.S. EPA. **EPA Preliminary Assessment Site Investigation.** Superfund, Lake Linden, Calumet & Hecla.

A completed site assessment form about the Calumet & Hecla site in Lake Linden to determine what contamination and hazards are present. Notes copper and other metals contamination, fish tumors, and C&H leachate spill.

D. Chellaraj, U.S. EPA. **Superfund Preliminary Site Closeout Report Final Remedial Action for Torch Lake Superfund Site, Houghton County, Michigan.** Torch Lake, U.S. EPA, Superfund.

P. Gallichio and D. Novak. **Torch Lake: EPA Superfund Site Monitored by Michigan Students.** Pamphlet. U.S. EPA. Torch Lake, stamp sands, monitoring, public outreach.

Pamphlet gives an overview of the history of mining activities, Torch Lake contamination, remediation actions taken by the EPA, and organized monitoring of this remediation by local high-school students.

City of Hancock, et al. **General Comments Of The Community Regarding EPA's Proposed Remedy.** Personal Communication. J. Kuhns, U.S. EPA, D. Novak, U.S. EPA and R. Campbell, Michigan Department of Natural Resources. Torch Lake, Superfund, Operable Unit II, public outreach.

All authors of these comments support the no action alternative for OU II.

U.S. Department of the Interior. **National Wetlands Inventory, Houghton County Road Systems.** Map. Torch Lake, map, wetlands, roads.

File includes two maps: one of the wetlands surrounding Torch Lake, and another one of the roads surrounding Torch Lake.

T. Kipela. **The native copper mining era of the Keweenaw copper country : lodes and mining locations, 1846-1968 / drawn & prepared by Tauno Kilpela.** Map.

Copper, mining history, map.

Map of principal lodes on the Keweenaw Copper Range.

Life Systems Inc., U.S. EPA (assumed). **ICAIR Responses To EPA And MDNR Comments On Torch Lake OUII Draft Baseline Risk Assessment.**

NPS. **Timeline of Michigan Copper Mining.**

<http://www.nps.gov/kewe/learn/historyculture/copper-mining-timeline.htm>. 4/30/2015.

Summary of major events within and affecting the life of the mining industry in the Keweenaw Peninsula.

WUPPDR, Torch Lake Township. **Torch Lake Township Recreation Plan 2009-2013.**

A. F. Taggart, John Wiley & Sons, Inc., Chapman & Hall, Limited. **Floatation.** 12-01 to 12-10. industrial process, floatation.

Chapter from a book explaining the process of floatation in detail.

Weston, Inc. **Project Plan for Characterization of Bank Anomalies.** Torch Lake, Weston, copper.

Plan for a project to characterize bank anomalies detected through a proton magnetometer operation performed by EPA Region 5 and to identify a gradient of copper contamination within the sediment and determine its impact upon aquatic biota.

Weston Solutions, Inc. **SITE LAYOUT MAP, Quincy Smelter Site, Franklin Township, Houghton County, Michigan.** Map. Quincy Smelter, map.

(After 1940 (inferred)). Quincy Mining Company Stamp Mill Branch, **Assay of Waste Sands.** copper, stamp sands, Quincy Mining Company.

Report generated by Quincy Mining Company summarizing copper content of stamp sands from 1902 to 1940.

(1888). L. G. Emerson. **Topographical Map of the Portage Lake Mining District.** Map. mining history, map.

(1909). Gay and Sturgis (inferred). **Direct Exclusive Private Wires to the Lake Superior District.** Map. Houghton County, Keweenaw County.

Map of Houghton and Keweenaw Counties, showing towns within the counties.

(1910, 1920, 1930, 1940). USGS, Washington Government Printing Office. copper, financial reports.

Summary of mining output and production costs and returns in various states, including Michigan.

(1911). **Plat Book of Houghton Co. MI.** Torch Lake, Boston Pond, mining history, plat book.

Plat map of northern Houghton County from 1911.

(1955, 1960, 1975). U.S. Bureau of Mines, copper, financial reports.

U.S. Bureau of Mines reports on production and output of mines throughout the country, including Michigan.

(1960 to 1980). U.S. Census Bureau, **Table 5: Population of Places.**

Table showing populations of various cities in Michigan in 1960, 1970 and 1980.

(1967, 1957, 1947, 1937, 1927, 1917, 1907). Calumet & Hecla. **Annual Report.** Calumet & Hecla.

Annual Reports for C&H company stakeholders.

(1969). J. M. Yanko. **The Biological and Chemical Effects of Saline Mine Water on the Receiving Water System.** Thesis. Michigan Technological University, Master of Science.

This research examined the effect of saline waters pumped from the Osceola Mine No.13 on the distribution of invertebrates in Torch Lake and other connected waters. In the thesis it stated "In the lakes affected by the saline waters the distribution of invertebrates appears to be dependent on the substrate rather than the chloride or calcium concentrations.

(1969, 1984). *Moody's Industrial Manual pages on Universal Oil Products for years 1969 and 1984.*

(1970). C. J. Doonan et al., MDNR, U.S. Department of the Interior. **Ground Water and Geology of Keweenaw Peninsula, Michigan**. Keweenaw Peninsula, groundwater.

Report by MDNR and USGS to determine what groundwater can be used for drinking water in the Keweenaw Peninsula. The following is a part of the summary of the report:

“About half the wells in Houghton County and a few in Keweenaw County obtain water from sand and gravel. The Jacobsville Sandstone underlies the glacial drift in most of the southern and southeastern parts of Keweenaw and Houghton counties. It yields small to moderate supplies of fresh water to most wells drilled into it. Water from most wells in drift and bedrock is satisfactory for domestic use, but many yield water with objectional amounts of iron. A few of the deeper wells in bedrock yield water too salty for drinking. Most public water supplies in the two counties are obtained from Lake Superior or from mine shafts, but a few are obtained from wells and springs.”

(1970). A. D. Kennedy, Michigan Technological University. **Recovery of Copper From Michigan Stamp Sands: Volume II: Physical and Chemical Properties of Stamp Sand**.

(1970). A. D. Kennedy and F. J. Chernosky, Michigan Technological University. **Recovery of Copper From Michigan Stamp Sands: Concentration Tests**.

(1970). Michigan Water Resources Commission, MDNR. **Biological Evaluation of Torch Lake, Houghton Michigan, October 1970**. Torch Lake, copper, benthics.

This evaluation was designed to assess the effect of both the original and reprocessed stamp sand tailings on the physical environment and biological community of Torch Lake. On October 26-28, 1970, the following water quality indicators were sampled in Torch Lake: 1. water chemistry, 2. sediments, 3. coliform, 4. algae, 5. benthic invertebrates, 6. fish. Analyses of chemical and bacteriological water samples indicate that copper and chlorides were substantially elevated above normal background levels. Most of the lake bottom is covered in stamp sands. Benthic community reflects an early stage of redevelopment and does not appear to play a vital role in the existing food chain in Torch Lake. Phytoplankton is diverse but not dense. 17 species of fish are present in the lake. Copper concentration in Torch Lake fish ranged from 0.5-4.5 mg/L with a mean of 2.05 mg/L. Discharge of stamp sands has had significant effects on the lake ecosystem.

(1972). R. M. Wilson. **The Effects of Fertilization on Interstitial Water Quality in Copper Mine Tailings**. Thesis. Michigan Technological University, Master of Science. Torch Lake, groundwater.

From the thesis:

"This project was designed to determine if significant amounts of these nutrients (phosphorus and nitrates), as well as copper, were leaching through the sands and entering Torch Lake.... It appears that applied fertilizer is not entering the lake, but that the sands themselves are contributing nutrients and other dissolved solids to the lake through natural processes."

(1973). D. J. Brandt. **Factors Controlling Soluble Copper(II) Levels in the Keweenaw Waterway**. Thesis. Michigan Technological University, Master of Science.

This thesis examines the copper content and the factors controlling it in Torch Lake and the remainder of the Keweenaw Waterway.

(1973). E. Evans, Michigan Water Resources Commission, MDNR. **An Evaluation of a Cupric Ammonium Carbonate Spill Into Torch Lake, Houghton County, Michigan, September 29, 1972.** Torch Lake, emergency removal, Lake Linden Leach Liquor Spill.

Summary from Document:

"1. Personnel of the Michigan Water Resources Commission from Lansing conducted an investigation on September 29, 1972 of a spill of cupric ammonium carbonate in Torch Lake, Houghton County. The discharge of at least 27,000 gallons was from the Lake Linden Leaching Plant of the Calumet Division of Universal Products. Discoloration of several acres of lake bottom indicated previous discharges of a larger magnitude.
2. Due to the delay between the spring spill and the time of this investigation, no deleterious effects to the lakes waters, algae, benthic macroinvertebrates or fish could be ascertained.
3. Since 1970 chloride concentrations have decreased by more than a third to about 25 mg/l, due to lake flushing and the termination of mine dewatering.
4. Dissolved copper concentrations have remained relatively high (.04 - .08 mg/L) and similar to the 1970 levels of .05 mg/L."

(1973). I. B. Joralemon, Howell North Books. **The Copper Country**. 41-69. copper, Keweenaw Peninsula, history.

Historical overview of copper use and mining in the Keweenaw Peninsula from early Native American use through the 1930s.

(1973). D. G. Leddy, Michigan Technological University. **Factors Controlling Copper(II) Concentrations in the Keweenaw Waterway: A Project Completion Report**. Keweenaw Waterway, copper.

From the document:

"This study attempts to describe the most important factors involved in the solution chemistry of copper in the aquatic environment of the Keweenaw Waterway. Observations of Torch Lake from July, 1972 through January, 1973 suggest that a number of physical and chemical parameters have undergone striking changes since 1970."

(1973). J. M. Lopez Diaz. **Aqueous environmental chemistry of copper and other heavy metals in Torch Lake and selected waters of the Keweenaw Peninsula area of Lake Superior**. Thesis. University of Wisconsin, Master of Science. copper.

University of Wisconsin master's thesis analyzing the water quality of Torch Lake, particularly for copper and other heavy metals.

(1973). J. G. Prather. **Vegetative stabilization of reclaimed copper stamp-sands**. Thesis. Michigan Technological University, Master of Science.

(1973). T. D. Wright, et al, **Water Quality Alternation of Torch Lake, Michigan by Copper Leach Liquor**. Torch Lake, copper.

From the document:

"In the summer of 1972, Torch Lake was found to have very high levels of copper, carbonate alkalinity, pH and ammonia nitrogen in comparison to previous years. In addition, unusual oxygen depletion in the hypolimnion was noted. Bioassays indicated that portions of the lake were toxic to macroinvertebrates. Behavior of the chlorides in the lake indicated that observed conditions were not caused by accumulation in the basin, but probably resulted from spills of cupric ammonium carbonate known to have occurred in late fall 1971 and early summer 1972. Volumetric calculations indicate that the spill could have resulted in copper values much greater than those observed and could have (through conversion of ammonia nitrogen to nitrate nitrogen) been significantly involved in oxygen depletion. There is also evidence of change in the phytoplankton community, but the causal mechanism is not clear. Theoretical calculations indicate that Torch Lake, which has one of the highest copper concentrations in the United States, should not support aquatic life. That it does illustrates a hiatus in the role of various ionic species of copper and aquatic life."

(1974). D. A. Tomljanovich. **Growth Phenomena and Abnormalities of the Sauger, Stizostedion Canadense (Smith), of the Keweenaw Waterway.** Thesis. Michigan Technological University, Master of Science. fish.

From the abstract:

"This study began as an attempt to determine whether distinct populations of sauger, Stizostedion canadense (Smith), exhibiting different growth rates, existed within the Keweenaw Waterway and adjoining waters.... However, significant sexual differences in size prevailed throughout the waterway."

(1974). T. T. Virnig. **Long-Term Water Quality Analysis of Torch Lake, Michigan.** Thesis. Michigan Technological University, Master of Science.

From the abstract:

"This study was meant to elucidate the chemical condition of Torch Lake and the impact of past mining practices on it."

J. M. Lopez and G. F. Lee, ENVIRONMENTAL CHEMISTRY OF COPPER IN TORCH LAKE, MICHIGAN. *Water Air and Soil Pollution* **1977**, 8 (4), 373-385.

(1977). S. G. Shetron, et al, MDNR. **Establishing Vegetation on Alkaline Iron and Copper Tailings.**

The objective of this research was to determine if vegetation could be established on Alkaline Iron and Copper Tailings, and if so, how to effectively execute this vegetation. According to the Summary and Conclusions section of the report, it was found that "[the] wastes are capable of supporting vegetation, with additions of fertilizer to raise the available macronutrients to meet the demands of plants to be established."

(1977). R. H. Sypniewski. **Benthos, particle size composition, and sediment copper comparisons between the North and South Keweenaw Waterway Entries.** Thesis. Michigan Technological University, Master of Science.

K. J. Kraft, Pontoporeia distribution along the Keweenaw shore of Lake Superior affected by copper tailings. *Journal of Great Lakes Research* **1979**, 5 (1), 28-35.

(1981). L.M. Miller and Associates Consulting Engineers and Geologists. **Hydrogeological Evaluation for Houghton County Wastewater Disposal.** Lake Linden stamp sands, Tamarack stamp sands, wastewater treatment plant.

The purpose of this investigation is to determine the propriety of operating the wastewater treatment facilities utilizing one lined cell, one seepage cell and irrigation. Conclusions:

- 1) The utilization of a seepage cell at the Tamarack and Lake Linden disposal sites will maximize the aerobic soil zone beneath the wastewater lagoons.*
- 2) Maintenance of an aerobic soil zone aids in the renovation of wastewaters and thus minimizes affects on ground and surface water quality.*

3) Modest rates of irrigation ($1 \pm$ "/week) during the warm summer month periods of low soil moisture and high evapotranspiration will serve to provide an effective sink for the water applied and will further the management goal of maximizing the unsaturated zone thickness.

4) Irrigation would also serve to maintain the existing grasslands and therefore limit aeolian soil erosion potentials.

5) The overall quality of Torch Lake is good and will not be substantially altered as a result of implementing the proposed seepage cell disposal plan.

K. J. Kraft and R. H. Sypniewski, Effect of Sediment Copper on the Distribution of Benthic Macroinvertebrates in the Keweenaw Waterway. *Journal of Great Lakes Research* **1981**, 7 (3), 258-263.

From the document abstract:

"Benthic macroinvertebrates, sediment copper, and sediment particle size were examined in two areas of the Keweenaw Waterway. The north area is downdrift from deposits of copper tailings. South area sediment averaged 27% silt and clay and north area sediment 66%. South area sediment had an average copper content of 33 mg/kg and north area sediment 589 mg/kg. The number of invertebrates was 4.3 times greater in the south than the north. The average number of taxa at south stations was 20 and at north stations 8."

(1981). L. D. Lankton and C. K. Hyde, 78-83, 127, 133 144, 146, 147, 149, 151-154. Quincy Mining Company.

Overview of Quincy Mining Company operations.

(1981). B. M. Sabol. **Effects of copper-bearing stamp sands on benthic microbial decomposition**. Thesis. Michigan Technological University, Master of Science.

J. J. Black, et al, EPIZOOTIC NEOPLASMS IN FISHES FROM A LAKE POLLUTED BY COPPER MINING WASTES. *Journal of the National Cancer Institute* **1982**, 69 (4), 915-926.

Article discusses details of contamination of Torch Lake sauger and walleye. A revised manuscript of this article can also be found in the EPA disk.

(1983). J. Goffin, **Are Lake Linden residents drinking Torch Lake water?** Lake Linden, drinking water.

Article discusses residents' issues with quality of their drinking water (specifically taste and smell). Residents express concern that the cause is the use of water from the test wells, which are located "near Torch Lake in an area where water coming down from Calumet to the Traprock River and Hammel Creek empties into the lake."

(1983). G. R. Smith, Director of Michigan Department of Public Health. Personal Communication. R. W. Davis, U.S. Congressperson for Lake Linden in 1983. Lake Linden, drinking water.

Letter from MDPH to Congressman Davis explaining that despite pollution in Torch Lake, the public drinking water supply in Lake Linden is safe for consumption.

(1984). L. V. Coppa, U.S. Bureau of Mines. **Division of Minerals Availability Open File Report: Waste Disposal Activities and Practices: Copper, Lead, Zinc, Gold, and Silver Waste Disposal Activities and Practices in the United States.** copper disposal output.

Abstract from Report:

"This Bureau of Mines open file report is an inventory of the amount and type of mill tailings created from the lode-mine commodities (copper, lead, zinc, gold, and silver) on a State and county basis between the years 1911 and 1981. The report contains tables and base maps cataloging the amounts of tailings created in each county on a decade basis. Mine waste and mill tailings disposal practices and technological advances and changes in the milling are discussed. Also included is a discussion of the material content typical to tailings produced from these five commodities".

(1984). C. Courchaine, Chief, MDPH Division of Upper Peninsula. Personal Communication. A. C. Sause. Lake Linden, drinking water.

Information regarding safety of groundwater well in Lake Linden.

J. M. Glime and R. E. Keen, The importance of bryophytes in a man-centered world (Proceedings of the World Conference of Bryology, Tokyo, Japan, May 23-28, 1983. Part 1.) -- (Recent Aspects of Physiology and Ecology. (Symposium 2)). *Journal of the Hattori Botanical Laboratory* **1984**, p133-146.

(1984). T. R. Harvey. Personal Communication. Village of Lake Linden. Torch Lake, Lake Linden, fish.

Letter from descendant of Lake Linden residents giving the Village of Lake Linden to use family health records to "help establish proof needed to get a massive clean-up of your lake to protect present and future generations there."

(1984). R. P. Juetten, District Fisheries Biologist, MDNR. Personal Communication. J. M. Aittama, Chairman, Lake Linden Village Water Committee. Torch Lake, Lake Linden, fish.

Letter from MDNR to Lake Linden explaining that restocking Torch Lake is not possible at this time due to tumors on fish and associated human health hazards.

(1984). D. G. Leddy. Personal Communication. S. Haralson, Village Clerk. Torch Lake, Lake Linden, recreation.

Letter from Michigan Tech to Lake Linden confirming Western Upper Peninsula District Health Department's decision that the beach may remain open despite the existence of the fish consumption advisory.

(1984). D. G. Leddy. Personal Communication. T. Thomas, U.S. EPA. sediment.

Letter enclosure includes data from a sediment study conducted by Michigan Tech in the Keweenaw Waterway.

(1984). C. Levin, U.S. Senator for Michigan. Personal Communication. J. M. Aittama, Chairman, Lake Linden Village Water Committee. Lake Linden, drinking water.

Letter from Senator Levin to Mr. Aittama regarding continued funding of studies of the water pollution problem in Torch Lake.

K. W. Malueg, et al., Toxicity of sediments from three metal-contaminated areas. *Environmental Toxicology and Chemistry* **1984**, 3 (2), 279-291.

From the abstract:

"Sediments from Phillips Chain of Lakes (Wisconsin), Torch Lake (Michigan), and Little Grizzly Creek System (California) were tested for acute toxicity using the water flea, Daphnia magna, and the burrowing mayfly nymph, Hexagenia limbata.... In general, numbers of organisms, biomass, species diversity and dominant types of organisms correlated with metal content and acute laboratory toxicity."

(1984). K. E. Rowe, Medical Director, WUPPDR. Personal Communication. V. Jolly, President, Village of Lake Linden. Torch Lake, Lake Linden, recreation.

Letter from WUPDHD to Village of Lake Linden confirming decision that the beach may remain open despite the fish consumption advisory.

(1984). A. C. Sause. **Preliminary Assessment, Michigan/R05-8312-05-327: Hubbell/Torch Lake (No U.S.E.P.A. Identification Number Assigned)**. Personal Communication. File/U.S. EPA Region V.

From document:

"The Michigan Dept. of Natural Resources (MDNR) has taken many samples of the water, fish and lake sediments with the last sampling in October, 1982. While the sediment and water samples from Torch Lake have a greater copper concentration than background sample from Lake Superior, the MDNR feels the copper concentration is not at a level which would be toxic to humans. Tumors have been detected in two species of fish, Saugers and Walleyes, and the MDNR has thoroughly investigated the triggering mechanisms of these tumors. To date, they do not know what has triggered the tumors in these fish, but feel it is not the copper concentration per se."

(1984). B. Swift, The Daily Mining Gazette. **Industrial discharge copper contaminated**. Torch Lake, PCI, wastewater.

PCI discharged copper-contaminated process waters into the sewer system.

(1984). B. Swift, The Daily Mining Gazette. **Copper-laden lagoon concerns Torch Lake officials**. Torch Lake, PCI, wastewater.

(1984). B. Swift, **Torch clean-up hits snag with PCB discovery**.

(1984 (inferred)). Lake Linden Village Water Committee. **Re: Torch Lake Trout Stocking**. Personal Communication. MDNR. Torch Lake, Lake Linden, fish.

Request to restock Torch Lake with Trout so that sport fishing can be restored, despite studies suggesting that this should not happen due to tumors found on fish.

(1986). D. H. Clarke, **Copper Mines of Keweenaw No. 14 Albany and Boston Mining Company**. 1-19. Copper, mining history

Synopsis of the operations of the Albany and Boston Mining Company.

(1986). E. D. Evans. Personal Communication. J. M. Aittama. Torch Lake, Lake Linden, fish.

Letter from MDNR to Village of Lake Linden stating conditions for fishing in Torch Lake. At this time, the tumors in the fish were subsiding, and the water quality was improving.

(1986). D. G. Leddy, et al., Michigan Technological University. **Torch Lake study: a project completion report prepared for the Michigan Department of Natural Resources**.

The report is comprised of 5 studies. Brief notes from each study follow:

1) Tumor Induction Study: Recognizing the high incidence of liver tumors in Torch Lake sauger and walleye, research was conducted to explore the possible connection between exposure to the flotation agents (xanthates and creosote) and the occurrence of liver tumors. Given the limited duration of this experiment, and the possibility that the micronodules could further differentiate, it is possible that exposure to/creosote could result in liver tumors.

2) Environmental Fate of Xanthates and Creosotes: Xanthates and creosotes, were studied to determine what their expected lifetimes would be in the Torch Lake environment and if they still persist in that environment. Xanthates would not be expected to persist in the environment beyond one year. The source of the PAH present could not be determined from this study but it is suspected that PAH detected came from combustion of solid and liquid fuels.

3) Tumor Incidence and Parasite Survey of Perch, Walleye and Sauger from Torch Lake: Twenty-five perch, walleye, and eleven sauger were examined for the presence and possible interrelationship of parasites and tumors. A direct relationship between the parasites and host tumors was not found. However, a physio-chemical association cannot be ruled out as the possibility of a

cocarcinogenic relationship between hosts, parasites, and environmental pollutants exists.

4) Heavy Metals in Sediments and Mining Wastes of Torch Lake: Sediments and tailings adjacent to Torch Lake and airborne dust samples from above the tailings have been analyzed for metal concentrations and mineral compositions. Even though the sediments are contaminated with heavy metals, the metals do not readily dissolve into the water and Torch Lake is not directly contaminated with heavy metals. Winds from the lake stir up dust clouds from stamp sands around the lake, but the most highly contaminated areas around Hubbell do not contribute much and it is unlikely that airborne heavy metals represent a serious human health problem.

5) Copper Budget for Torch Lake: A hydrologic and copper budget have been calculated to determine the amount and source of copper entering Torch Lake via its watershed and sediments. The budget shows that 32 of the total mass of copper input comes from precipitation on the lake surface, 96.5% is from surface runoff, while only 0.5% is from the ground water. The annual input of dissolved copper from external sources is 2470 kilograms.

(1986 (inferred)). U.S. EPA (inferred). **National Priorities List Site**. Torch Lake, Superfund.

Paragraph describing the Torch Lake Superfund site. States presence of sediment contamination and fish tumors, status of remediation and reason for listing as a Superfund site.

(1986 (inferred)). W. I. Rose, Michigan Technological University. **Heavy Metals in Sediments and Mining Wastes of Torch Lake, Michigan**. Torch Lake, sediment, copper, metals.

From the document:

“The main objectives of this study are: 1) to determine the bulk chemical composition of the Torch Lake stamp sands and sediments; 2) record the distribution and identify the source or sources of any enriched toxic and/or mutagenic elements that occur in the Torch Lake sands and sediments; and 3) determine whether there is a potential health hazard to residents in the area as a result of the proximity of several towns to the stamp sand areas and the transport of tailings by wind. The sediments and sands of Torch Lake are significantly enriched in Cu, Pb, Sn, Zn, As, Rb, La, Cr, K, Zr, Ce, and Ba when compared to the local basalt bedrock of the area. These enrichments are probably natural. Large enrichments of Pb, Sn, Zn, and Cr in Torch Lake sediments are apparently due to dispersal of contaminated wastes (electrical debris and associated slag) at the old Torch Lake Copper Reclamation Plant near Hubbell. The heavy metals do not readily dissolve into the Torch Lake water and the water is not directly contaminated. Winds at Torch Lake stir up dust clouds from stamp sands around the lake, but the most strongly contaminated areas around Hubbell do not contribute much to the dust clouds and it is unlikely that airborne heavy metals

represent a serious human health problem.”

(1987). D. Klemans, State of Michigan Areas of Concern Coordinator. **Update on the Torch Lake AOC**. Personal Communication. Individuals interested in the Torch Lake Area of Concern. Torch Lake, Area of Concern, Beneficial Use Impairment, Fish Tumors.

Letter includes a status update on the Torch Lake AOC. It is recommended at this time that the fish consumption advisory be lifted based on the absence of tumors in the Sauger and Walleye. Particularly, they may have been caused by the presence of floatation chemicals in the lake, but those chemicals are no longer present in the water or sediment, and they should have degraded after six months. The enclosure also mentions the construction of wastewater lagoons on the stamp sands and the plan to provide wastewater treatment on the Trap Rock River.

(1987). MDNR. **Michigan Department of Natural Resources Remedial Action Plan for Torch Lake Area of Concern**. MDNR, Torch Lake, Area of Concern, Fish Tumors.

From the document summary:

“Two Impaired uses exist in Torch Lake at this time: a consumption advisory based on tumors in sauger and walleye and a degraded benthic macroinverte community due to sediment copper toxicity.... A high incidence of liver tumors have been found in sauger (100%) with lower incidences in walleye.... Tumor induction studies using fish revealed liver abnormalities when exposed to xanthates and creosote.... Copper concentrations in the water of Torch Lake are high due to natural loadings from its major tributary, the Trap Rock River, and the release of sediment bound copper. Copper concentrations in the water exceed the IJC water quality objective and Michigan's Water Quality Standard NPDES permit limitations. High concentrations of copper are widespread in Torch Lake and Portage Lake sediments. Near the smelter site on Torch Lake, lead, tin and zinc are also elevated in the sediments. The biotic communities of Torch Lake, other than benthic macroinvertebrates, do not seem to be greatly inhibited by the unusually high copper concentrations.”

(1987). J. A. Spence. Personal Communication. T. D. Martin, Director, Office of the Great Lake, MDNR. Torch Lake, barrels.

Letter from Michigan Tech to MDNR requesting the investigation of barrels and other debris dumped into Torch Lake. Letter explains where barrels were found and that they may be linked a continued release of carcinogenic substances to the lake.

(1987). P. D. Zugger. **Michigan Water Resources Commission Authorization to Discharge Under the National Pollutant Discharge Elimination System**. Michigan Water Resources Commission. Torch Lake, PCI, NPDES.

Permit to PCI granted by the Michigan Water Resources Commission to discharge effluent via storm sewer into Torch Lake.

(1987, 2005). MDNR. **Torch Lake, Michigan Area of Concern**. Map. Torch Lake, Area of Concern.

Map of the Torch Lake Area of Concern

W. H. Clements, D. S. Cherry and J. Cairns, Structural alterations in aquatic insect communities exposed to copper in laboratory streams. *Environmental Toxicology and Chemistry* **1988**, 7 (9), 715-722.

From the abstract:

"The effects of copper on aquatic insect communities were examined using rock-filled trays colonized in the field for 30 d, transferred to laboratory streams, and dosed with CuSO₄.... results [of the study] indicate that the artificial substrates employed in this study are amenable to experimental manipulation and will provide a unique opportunity to examine the community responses of aquatic insects to toxicants under environmentally realistic conditions."

(1988). C. Courchaine and D. J. De Grand. Personal Communication. J. Lee. Torch Lake, groundwater.

Enclosure contains the following:

- 1. Water well records for Sections 5-8, 17, and 19, T55N, R32W; Sections 12-14, 23, 24, 26, and 27, T55N, R33W; and Sections 31 and 32, T56N, R32W.*
- 2. Copies of plat book pages for that area.*
- 3. Lake Linden water supply Inventory (partial).*
- 4. Chemical analysis results for Lake Linden wells including volatile organic chemicals, metals, herbicides, pesticides, and inorganic chemistry.*
- 5. Mason (Osceola Township) water supply inventory.*
- 6. Mason water supply chemical analysis results including volatile 1 organic chemicals, metals, and inorganic chemistry.*

(1988). Donohue and Associates, Inc. **Torch Lake, Michigan Compository Summary**. U.S. EPA

This document is an overview of several aspects of the Torch Lake site. The summary includes overview of the following: history of environmental problems and studies, history of regulatory actions, history of response actions, hazardous materials sources and affected media, and regional and local site characteristics.

(1988). The Center for the Great Lakes and The Centre for the Great Lakes Foundation, **Fact Sheet Great Lakes Areas of Concern: Torch Lake, Michigan**. Torch Lake, Area of Concern.

Fact sheet describes BUIs and progress on the remedial action plan. At the time the IJC was concerned that the cause of the fish tumors had not been identified, that there was a lack of a plan to achieve the goal of eliminating the fish tumors, and that no monitoring, surveillance or remedial actions had been planned.

(1988). NPS. **Options for National Park Service Involvement in the Management of Historic Copper Mining Resources on Michigan's Keweenaw Peninsula**. mining history, National Park Service, Quincy, C&H.

From the document:

"This report presents several options for preserving and managing the historic copper mining resources on the Keweenaw Peninsula of Michigan. The document summary states the following options with the site designated as a National Historic Landmark: 1. Advisory/Coordinating Council with Congressional Trust; 2. Foundation with Recurring Funding; 3. National Historic Sites with Historic Preservation Commission; 4. National Historical Park."

(1988). J. A. Spence, **THE KEWEENAW WATERWAY: A status report with suggested remedial investigation and feasibility study options for developing a comprehensive remedial action plan**. Keweenaw Waterway, remedial investigation.

Report describes physical conditions in Torch Lake and also status of investigations on benthics. Summary from Report:

"An extensive body of information exists concerning the many environmental problems of Torch Lake (see attached bibliography). However, the causative agent(s) for tumors in the resident fish populations has not yet been identified and conflicting evidence exists for both increases and decreases in tumor incidence. One preliminary study indicated that bottom sediments may be carcinogenic in mammals but more carefully controlled studies have not been carried out. Vegetative stabilization of the stampsands has not been very successful though experience to date has delineated problem areas and points to possible solutions. The existence of heavy metal contaminants in enriched onshore stampsands and lake sediments has been verified qualitatively but not yet quantified. Magnetometry studies along the perimeter of a rumored barrel dump site in the Tamarack stampsands has revealed the presence of several magnetic anomalies which have a high probability of being barrels."

(1989). U.S. EPA **Superfund Fact Sheet Torch Lake Superfund Site Houghton County, Michigan**. U.S. EPA. Torch Lake, U.S. EPA, Superfund.

This appears to be the first Superfund Fact Sheet created about Torch Lake. The sheet gives background on the industrial history of the site, what contamination the industrial activities caused, and what Remedial Investigation / Feasibility Study activities are planned for the site.

(1989). A. A. Anderson and F. C. Beodray. **Re: Torch Lake**. Personal Communication. J. B. Lee. Torch Lake, groundwater.

Enclosure contains well/sample data sheets that were completed from July 17-21, 1989.

(1989). Donohue and Associates, U.S. EPA. **Volume 2: Field Sampling Plan: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan Revision I.**

From the document:

“The purpose of the RI field investigation activities described in this Field Sampling Plan (FSP) is to satisfy the data needs associated with the following objectives:

- 1. Characterize the nature and extent of contaminant sources in Operable Unit (OU) I and II.*
- 2. Determine the potential for contaminant migration by identifying and evaluating chemical and physical processes affecting migration.*
- 3. Provide data needed to evaluate human health risk associated with the site.*
- 4. Provide data necessary to assess the feasibility and cost effectiveness of remedial action alternatives.”*

The field investigation activities described include sampling the following media: drums, tailings, soil, air, sediment, floc, surface water, groundwater, and biota.

(1989). Donohue and Associates, Inc., U.S. EPA. **Volume 1a: Final Work Plan: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan Revision 1.** Torch Lake, Superfund, Remedial Investigation.

From the document:

“Donohue & Associates, Inc. (Donohue) is submitting this Work Plan to the U.S. Environmental Protection Agency (EPA) to conduct a Remedial Investigation/Feasibility Study (RI/FS) for the Torch Lake site in response to Work Assignment No. 02-5LS8 under Region V ARCS Program Contract No. 68-W8-0093....

This Work Plan and the associated project control plans are contained in five volumes. Volume 1A presents the technical scope of work and includes a discussion of the site background and setting, an initial evaluation of the site including the types and volumes of waste present and the potential pathways of contaminant migration, the Work Plan rationale including data quality objectives and data needs, and the Work Plan approach. Also included in Volume 1A are a discussion of the 15 RI/FS tasks to be completed, a schedule for completion of the tasks, and a discussion of project management. The Preliminary Endangerment Assessment and Endangerment Assessment Plan are included in Appendices A and B, respectively. The costs and key assumptions associated with the RI/FS are contained in Volume IB.”

(1989). Donohue and Associates, Inc. U.S. EPA. **Volume 4: Health And Safety Plan: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan Revision 1.** Torch Lake, Superfund, Remedial Investigation.

From the document:

"This Health and Safety Plan (HASP) has been prepared in accordance with the ARCS V Program Health and Safety Guideline HAS-1, and the regulatory requirements of 29 CFR 1910.120, "Hazardous Waste Operations and Emergency Response." It addresses those activities associated with the Remedial Investigation/Feasibility Study (RI/FS) to be conducted at Torch Lake in Houghton County, Michigan, under U.S. Environmental Protection Agency (EPA) Work Assignment 02-5LS8. The HASP will be implemented by the Health and Safety Officer (HSO) and the Assistant HSO during site work."

(1989). Donohue and Associates, Inc. U.S. EPA. **Volume 3: Quality Assurance Project Plan For Phase 1 Remedial Investigation Activities: Torch Lake Remedial Investigation/Feasibility Study, Houghton County, Michigan, Revision 1.** Torch Lake, Superfund, Remedial Investigation.

From the document:

"The purpose of a Quality Assurance Project Plan (QAPP) is to present the planned system of activities and expected level of data quality for the site. The precision, accuracy, completeness, representativeness, and comparability of the environmental data collected must be known and documented according to this plan. Presented in this QAPP are the personnel responsible for quality assurance, the data quality objectives, and the specific quality control measures to be taken to reach the objectives."

(1989). Donohue and Associates, Inc., U.S. EPA. **Revisions/Additions to Field Sampling Plan.** Torch Lake, Superfund, Remedial Investigation.

Describes revisions to soil and air sampling plans that were outlined in Volume 2 of the final work plan: the Field Sampling Plan.

(1989). U. S. EPA, **EPA: Water From Mason and Lake Linden Municipal Wells OK To Drink.** Torch Lake, groundwater.

This was an EPA news release.

(1989). E. Evans. **Review Comments MTU Torch Lake Report.** Personal Communication. J. M. Aittama. Torch Lake, MTU report.

Contains comments on the 1986 MTU report. Critiques on sampling and analysis methods as well as flaws in the report are provided by MDNR staff.

(1989). E. Evans. **Torch Lake — Portage Lake Fish Tumor Data.** Personal Communication. J. Hesse. Torch Lake, fish tumors.

Data strongly suggest that liver tumor inducing agents above background concentrations no longer exist in the Torch Lake — Portage Lake fishery.

(1989). Weston/Gulf Coast Laboratories. Personal Communication. M. O'Mara, Roy F. Weston Incorporated.

Sample analysis results from what appears to be a groundwater study conducted by Weston.

(1989). T. Irvin. **Torch Lake Air Monitoring**. Personal Communication. D. Gruben. Torch Lake, air sampling.

Enclosure contains data from air sampling.

(1989). J. D. Maletzke. **Documentation of Soil/Tailings Samples during Phase 1 RI Work at the Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.031**. Personal Communication. L. Ransome, et al.. Torch Lake, Remedial Investigation, sampling.

This memo details the documentation of the samples, Including sample identification numbers, completion of EPA sample tags, chain-of-custody forms, and packing and transport to Donohue Analytical in Sheboygan, Wisconsin.

(1989). J. D. Maletzke. **Operable Unit III (OU-III) Archive Search and Field Reconnaissance (August 24 and 25, 1989) Torch Lake Superfund Site Houghton County, Michigan Donohue Project Mo. 20011.031**. Personal Communication. L. Ransome, et al..

The source of OU-III tailings and stamp sand piles were from various stamp mills and smelters associated with respective mines. OU-III tailings and stamp sands apparently do not represent any reprocessing and subsequent redistribution.

(1989). J. D. Maletzke. **Soil/Tailings Sample Shipment Phase I RI Work Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.031**.

Personal Communication. L. Ransome, L. Trick, R. Stenson, M. Whittington and J. Lee. mine tailings.

Memo concerns logistics of sample transport from field to lab.

(1989). P. B. Markelz, Donohue, U.S. EPA (inferred). **Site-Specific Health and Safety Plan Torch Lake Geophysical Investigation**. Superfund.

(1989). Roy F. Weston, Inc., U.S. EPA. **Drum Search: Torch Lake Drum, Houghton Michigan.**

From the document:

"The objective of this investigation was to locate submerged drums in Torch Lake. Once these drums were located, a Remotely Operated Vehicle (ROV) with a video camera was used to enumerate and determine whether the drums were intact. Water samples were obtained to help determine whether any hazardous substances had entered the lake environment.

The drums found both on shore and in the lake were either empty or contained solidified substances. Since the water analysis and water quality study did not indicate any disturbances, the contents of the drums were either diluted below the detection limits, were not soluble in water, or were contaminants that would not be detected by the analysis used."

(1989). D. Ray. Personal Communication. J. Lee. Torch Lake, Area of Concern.
Enclosure contains fact sheet about Torch Lake AOC, the BUIs and the RAP.

(1989). D. Rector, Deputy Director, MDNR. Personal Communication. V. V. Adamkus, Regional Administrator, U.S. EPA, Region V. Torch Lake, air sampling.
Enclosed is the State of Michigan's Multi-Site Cooperative Agreement, Amendment V005843-01-6, for Technical Assistance to the U.S. Environmental Protection Agency on the Torch Lake air sampling program.

(1989). S. Reith. **EPA Region V ARCS Contract 68-W8-0093, EPA Work Assignment No. 02-5LS8, Donohue Project No. 20011.002, Torch Lake CR Trip Information.** Personal Communication. M. A. Croce et al.. Torch Lake, community relations.

Memo from Donohue to EPA concerning a community relations trip in Houghton County in March 1989.

(1989). D. Richardson. **Health and Safety Program at Torch Lake (Donohue Project No. 20011).** Personal Communication. P. Markelz, et al.. Torch Lake, Remedial Investigation, health and safety.

This memorandum describes the health and safety procedures Implemented during the Phase I Field Program at Torch Lake, Houghton, Michigan.

(1989). D. Richardson et al. **Surface Tailing Sampling at Torch Lake, Houghton, Michigan.** Personal Communication. L. Ransome, R. Stenson and L. Trick. Torch Lake, sediment, sampling procedures.

This memorandum describes the procedures, documentation, packaging, and decontamination of equipment employed during the surface tailings sampling at

Torch Lake, Houghton, Michigan.

(1989). R. Stenson. **U.S. Bureau of Mines Site Visit Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.031**. Personal

Communication. L. Ransome. Torch Lake, mine tailings, U.S. Bureau of Mines.

Communication within Donohue & Associates that the U.S. Bureau of Mines is visiting Torch Lake as part of their research on mine tailings disposal in water as a means of eliminating the oxidation and leaching which occurs when tailings are exposed to the atmosphere.

(1989). R. Stenson. **Torch Lake Superfund Site Houghton County, MI Donohue Project No. 20011.031: Shallow Surface Tailings Sampling**. Personal Communication.

L. Ransome. Torch Lake, mine tailings.

This memo describes the shallow subsurface tailing sampling program.

(1989). R. Stenson and D. Richardson. **EPA Region V ARCS Program Donohue Project No. 20011.031: Inventory of Existing Wells, Torch Lake. Torch Lake Superfund Site Houghton County, Michigan**. Personal Communication. L. Ransome.

Torch Lake, groundwater.

"This memorandum describes the well inventory conducted from August 22 to August 24, 1989. The Lake Linden Lagoon water table varies from 604.12 feet in L-1 (background well) to 601.32 feet in L-3 which is a difference of 2.8 feet. Wells L-2 through L-6 are in the lagoon area and the water table elevation varies by 1.15 feet. The depth of the wells vary from 1982 to the present (Table 1). The maximum change is 5.91 feet in L-2. It is unclear if the well has silted in or if our popper was caught on the top of the screen. Water level measurements at the Tamarack Lagoon monitoring wells indicate a 3-foot difference in the water table from 604.16 feet in T-1 (background well) and T-6 to 600.85 feet in T-4. The depth to the bottom of the wells has changed since 1982 by approximately 4 to 4.5 feet (Table 2). It is unclear if the well has filled with sediment or if the popper was caught on top of the screen. However T-1, the background well, has not changed in depth since 1982".

(1989). R. Teoh. **RI/FS air sampling at Torch Lake site, Houghton County**. Personal Communication. D. Gruben. Torch Lake, Superfund, Remedial Investigation, air sampling.

Communication within MDNR containing Torch Lake air sampling program.

(1989 (inferred)). ATSDR, United States Public Health Service. **Preliminary Health Assessment for Torch Lake, CERCLIS No. MID980901946, Houghton County, Michigan.** Torch Lake, public health.

From the document:

"Based upon the information reviewed, this site is of potential public health concern because of the risk to human health that could result from the possible exposure to presently unknown etiologic agents at the levels that may result in adverse health effects over time.... Although Torch Lake is polluted with copper and other contaminants, no known health effects have been linked to the problem. The incidence of cancer deaths over a period from 1970 to 1981 Indicates that all but stomach cancer were at or below the state average for age-adjusted cancer mortality.... Rumors regarding the dumping of chemicals and barrels into the lake during the 1950's and 1960's should be investigated.... Fish populations in Torch Lake should be studied to determine: (1) if other species have abnormally high incidence of tumors, as do the walleye and sauger, (2) the causative agent of the tumors, (3) why certain species are apparently unable to reproduce in the lake, and (4) the risk to human health from the consumption of the fish...."

(1989 (inferred)). T. J. Kubiak, U.S. Fish and Wildlife Service. **PROPOSAL: Reproduction in Gulls and Bald Eagles in the High Copper Environment of Torch Lake, Michigan.** Torch Lake, copper, Gulls, Bald Eagles.

The objectives of the study, as detailed in the following section of the proposed monitoring program, are as follows:

- o Determine reproductive success in resident colonies of Herring gull and ring-billed gull.*
- o Measure exposure via forage items and embryonic exposure via egg content analyses of copper.*
- o Compare productivity and egg copper levels on site and with existing information- base.*

(1990). **Federal Register.** Health Hazards.

Federal register entry on the system to rank human health hazards through overland/flood migration and groundwater to surface water migration.

(1990). P. C. Baumann, et al., U.S. EPA. **Effects of High Copper Concentrations on Reproduction by Yellow Perch in Torch Lake, Michigan**. Torch Lake, Superfund, copper, fish.

From the document:

*"It was hypothesized that the elevated levels copper in Torch Lake led to the decline of the Walleye and Sauger populations with little or no recruitment. This study used yellow perch (*Perca flavescens*) to determine if chronic exposure to elevated copper concentrations has reduced the reproductive success of percids. Although copper concentrations found in Torch Lake did not significantly reduce hatching success, a larger sample size may have revealed different results. P values of $p = 0.157$ and $p = 0.10$ suggest that more data may indicate a significant difference in hatching success. Duration of hatching was significantly longer for Torch Lake egg masses than was for reference lake egg masses, indicating that copper may be affecting hatching rates."*

(1990). Donohue and Associates, Inc., U.S. EPA. **Final Community Relations Plan Torch Lake Superfund Site Houghton County, Michigan**. Superfund, community relations.

From the document:

"This Community Relations Plan (CRP) presents an overview of the community concerns regarding the Torch Lake Superfund site and a description of community relations activities that the U.S. Environmental Protection Agency (U.S. EPA) will conduct during the Remedial Investigation/Feasibility Study (RI/FS) process." (page 1) Planned activities listed on pages 14-16 of the document are the following: "(1) Designate a central contact person at U.S. EPA... (2) Establish an information repository... (3) Develop a mailing list of individuals and organizations interested in receiving information regarding the site... (4) Contact local newspapers, radio stations, and television stations for news releases... (5) Develop and distribute fact sheets during the RI/FS process... (6) Provide information about public health... (7) Hold public meetings... (8) Provide opportunities for the public to comment on the remedial actions proposed for the site... (9) Prepare a responsiveness summary... (10) Announce and explain the selected remedial action."

(1990). Donohue and Associates, Inc., U.S. EPA. **Volume 3 Final Quality Assurance Project Plan for Operable Unit II Remedial Investigation Activities - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**.

(1990). Donohue and Associates, Inc., U.S. EPA. **Volume 2: Final Field Sampling Plan Revision 2 - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**. Superfund, remedial investigation.

Describes activities planned for sampling tailings, soil, air, surface water, sediment, and groundwater. Addendum appears to include revisions to the following sections: Section 4 - Media Specific Sampling Plans; Section 5 - Sample Identification Numbers; Section 6 - Chain of Custody; Section 7 - Packaging and

Shipping; and the appendices.

(1990). Donohue and Associates, Inc., U.S. EPA. **Volume 4: Final Health And Safety Plan Revision 2 - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.**

(1990). Donohue and Associates, Inc., U.S. EPA. **Volume IA: Final Work Plan Revision 2 - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Superfund, remedial investigation.

From the document executive summary (page vi):

"This work plan and the associated project control plans are contained in five volumes. Volume 1A presents the technical scope of work and includes a discussion of the site background and setting/ an initial evaluation of 'the site including the types and volumes of waste present and potential pathways of contaminant migration/ and the work plan rationale and approach. Also included in Volume 1A are a discussion of the 15 RI/FS tasks to be completed, a schedule for completion of the tasks, and a discussion of project management."

Also according to the document, Revision 2 specifically accounts for the addition of project plans for OU II.

(1990). Donohue and Associates, Inc., U.S. EPA. **Final Remedial Investigation Report Operable Unit I - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.**

Conclusions from the remedial investigation include the level of human health risk of surface tailings and slag materials, debris and drum deposits, physical characteristics of submerged tailings, groundwater contamination by inorganic compounds, contamination at a "hot spot" at Hubbell, contamination of surface waters, and human health risk of groundwater.

(1990). U. S. EPA. **Guidance on Remedial Actions for Superfund Sites with PCB Contamination.** Superfund, PCB, groundwater MCL.

(1990). U. S. EPA. **Early Findings from 1989 Torch Lake Investigation Available; Further Studies Planned For This Summer.** United States Environmental Protection Agency, R. Office of Public Affairs. Torch Lake, Superfund, public outreach.
News release.

(1990). D. Gruben. Personal Communication. B. Wilder.

(1990). E. Helmer, Ecologist. **Torch Lake NPL Site Photos from Wetlands Investigation.** Personal Communication. J. Lee, remedial Project Manager. Torch Lake, Superfund, wetlands, photos.

Enclosure includes photos taken during August, 1990 wetlands investigation.

These photos go with the Wetlands Investigation Report dated October 19, 1990.

(1990). E. Helmer and D. Beltman, U.S. EPA. **Torch Lake NPL Site Wetlands Investigation**. Superfund, wetlands, OU I, OU II.

There is a memo at the beginning of the document that summarizes the report.

The findings include the following:

- "1. Wetlands were developing over some tailings around Torch Lake, usually near stream inlets.*
- 2. Natural wetland area near the southern and southeastern portion of the lake do not seem to be affected by tailings deposits.*
- 3. Some possible natural wetlands near Lake Linden may be affected by tailings deposits.*
- 4. Wetland areas around Boston Pond may have been filled in with tailings."*

Recommendations include the following:

- "1. Apparent natural wetland areas around Boston Pond, the Portage Canal and the "MTU pile" may require restoration and enhancement activities depending on their size.*
- 2. Boston Pond does not necessarily require restoration/enhancement activities because filling occurred before 1975 (and therefore the filling activities were not subject to Section 404 of the Clean Water Act)."*

(1990). J. L. Hesse. Personal Communication. W. F. Nied. Torch Lake, AOC, BUI, fish consumption advisory.

Letter stating that the fish consumption advisory can be removed and that the sunken drums need to be further investigated before determining if they must be removed.

(1990). R. T. Kavetsky, Acting Field Supervisor, USFWS. Personal Communication. J. Lee, Remedial Project Manager, U.S. EPA. Superfund, eagles, gulls.

Memo from USFWS to U.S. EPA describes sampling of eagles, gulls and yellow perch. Hatching rates for eagles and gulls were at normal levels, while the hatching rate for yellow perch increased.

(1990). M. A. Kuehl and I. Donohue and Associates, U.S. EPA. **Addendum No. 1 To Quality Assurance Project Plan For Phase 1 Remedial Investigation Activities Torch Lake RI/FS Houghton County, Michigan**. Superfund, remedial investigation.

This addendum to the QAPP was prepared as a result of a meeting regarding data quality objectives and format involving the EPA RPM.

(1990). J. D. Maletzke. **Boring Geotechnical Sampling and Monitoring Well Installation, Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.230**. Personal Communication. L. Ransome, Site Manager. Superfund, OUII.

Sampling locations and methods are described. Enclousre includes field forms.

(1990). J. D. Maletzke, et al.. **Operable Unit III Tailings Sampling Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.330.**

Personal Communication. L. Ransome. Superfund, OUIII.

Sampling procedures and locations were described.

(1990). MDNR, **Staff Report: Fish Growth Anomalies in Torch and Portage Lakes 1974-1988 Houghton County, Michigan.** Torch Lake, fish.

"The purpose of this report is to present the fish contaminant and tumor data and compare it to other data where appropriate. Only four (4) of the 56 fish samples analyzed for mercury had concentrations that exceeded the 0.5 mg/kg consumption advisory action limit and none exceeded 1.0 mg/kg. The incidence of liver neoplasms has apparently declined and may now be near normal background levels, however, additional study is needed to more accurately determine normal or background tumor frequencies, especially in older and larger fish. Saugers were not collected in 1988 following an extended period of population decline which began in the 1960's. Sauger are a turbid water fish and once the waters cleared, as copper ore milling decreased and then stopped, sauger were apparently no longer able to outcompete other game fish. Bioassays of the water and sediments of Torch Lake, have not indicated the presence of a carcinogenic substance. The data do not support the basis for the continuance of this specific fish consumption advisory."

(1990). U.S. Bureau of Mines. **Torch Lake Tailings Leachability Evaluation.** Torch Lake, metals, U.S. Bureau of Mines.

From the document overview (page 1):

"The Spokane Research Center (SRC) has performed laboratory evaluations of tailings and water samples from Torch Lake and vicinity to aid in determining the potential for metals to adversely affect Torch Lake. This laboratory evaluation does not include an assessment of potential discharge from drums or other industrial chemicals within the tailings or potential for concentration of metals in lake waters through metal-organic complexation or other biological processes."

From the document conclusions (page 6):

"In general, metal concentrations in leachates from the samples were extremely low when compared[sic] to tailings at over 30 other sites studied at SRC (see reference list). This is attributable to the tailings being highly oxidized and originating from a non-sulfide ore body. Results indicate that very little metal is being released from the Torch Lake tailings."

However, this evaluation did not include an assessment of potential discharge from drums or other industrial chemicals within the tailings or potential for concentration of metals in lake waters through metal-organic complexation or other biological processes."

(1990). U.S. Bureau of Mines. **Metal Contamination Characteristics of Subaqueous Tailings at Torch Lake**. Torch Lake, metals, U.S. Bureau of Mines.

This document is a duplicate of the Torch Lake Tailings Leachability Evaluation with a cover letter from the Bureau of Mines to the EPA attached. There are also six pages of what appears to be another document, which is what this entry is named for.

(1990). K. Rubsam. **Groundwater Sampling Torch Lake Superfund Site Houghton County, Michigan Donohue Project No. 20011.230**. Personal Communication. L. Ransome, Site Manager. Torch Lake, Superfund, OPERable Unit II, groundwater.

This technical memorandum describes sampling procedures, documents data collection, and notes deviation from project plans. Prior to sample collection, static water levels and depth to bottom measurements were recorded for each well. The pump was started and initial pH, conductivity, temperature, color, odor, and turbidity measurements were recorded.

(1990). P. C. Eder Associates Consulting Engineers, **Draft Health and Safety Plan, Torch Lake, Keweenaw Peninsula, Michigan**. Superfund, remedial investigation.

(1990). Weston, Inc., U.S. EPA. **Site Assessment for Torch Lake, Houghton County, Michigan**. Superfund.

This report includes an overview of the physical conditions of the site, the results and methods of the drum, groundwater and soil sampling that has taken place up to that time, and the concluded threats to human health and the environment.

(1990). Weston, Inc.. **Torch Lake Site Investigation, Hubbell, Michigan**. Personal Communication. D. Heaton and U.S. EPA. Superfund, OUI, drums.

Report on methods, locations and results of drum sampling. Various organic chemicals, including VOCs, were found.

(1990 (inferred)). M. Vendl, U.S. EPA. **TORCH LAKE HOUGHTON COUNTY, MICHIGAN Ground Penetrating Radar Survey May 9-11, 1989**. Torch Lake, drums.

A ground penetrating radar (GPR) survey was conducted at Torch Lake, Houghton County, Michigan on May 9-11, 1989. This survey was conducted by geologists with the Technical Support Unit, Waste Management Division, Region V, U.S. Environmental Protection Agency, with the purpose of locating possible buried drums at three separate locations near Torch Lake as well as in the lake itself. It was found that a number of point targets were located both on the bottom of Torch Lake, and in the mine tailings at the three sites which may or may not be drums. The targets on the bottom of Torch Lake and at the Sewage Pond site have the most likelihood of being drums. Only test pits can verify this.

(1991). Ebasco Environmental (inferred) and Donohue and Associates, Inc., U.S. EPA. **Alternative Array Memo: Torch Lake RI/FS Houghton County, Michigan.** Superfund, OUI, OUIII, Feasibility Study.

Purpose, from page 1-1 of the document:

"The purpose of this alternative array memo is to summarize the identification, screening and evaluation of remedial technologies, and to present preliminary potential Applicable or Relevant and Appropriate Requirements (ARARs) which are relevant for the feasibility study of residual copper tailings and slag piles at the Torch Lake Site."

(1991). R. E. Bartlet, Geraghty & Miller, Inc. **Scope of Work Outline for Drum Removal Effort.** Personal Communication. W. Nied, On-Scene Coordinator, U.S. EPA and P. Felitti, Assistant Regional Counsel, U.S. EPA. Torch Lake, drums.

Outlines drum sampling plan. Proposed date of sampling not specified. Activities outlined in the document include the following (from the document):

"1) Stage all visible drums, sample the drums, and remove those containing hazardous materials.

2) Sample drum location soils and remove aft soils contaminated with Hazardous Substances.

3) Conduct a geophysical investigation to determine If any buried drums are located on site including offshore to a depth of 30 feet.

4) Conduct an underwater survey to determine if any drums are located along the shoreline in Torch Lake to a depth of 30 feet contiguous to Respondent's property or place of business operation."

(1991). S. Casey. Personal Communication. R. H. Haralson. Torch Lake, PCI, wastewater.

Enclosure gives results of PCI wastewater sample analysis. To PCI from MDNR.

(1991). Donohue and Associates, Inc., U.S. EPA. **Volume 2 Appendices A, B, and C, Draft Remedial Investigation Report Operable Unit II, Torch Lake Remedial Investigation / Feasibility Study, Houghton County, Michigan.** Superfund, remedial investigation, Operable Unit II.

Appendices for the OU II Remedial Investigation report. Appendix A consists of technical memoranda associated with field sampling. Appendix B consists of technical evaluation memoranda. Appendix C consists of analytical chemistry data tables, in which metal and organic chemical sampling results can be found.

(1991). Donohue and Associates, Inc., U.S. EPA. **Final Remedial Investigation Report Operable Unit I - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**. Superfund, remedial investigation, Operable Unit I.

From the document:

"This baseline risk assessment (risk assessment) is an analysis of the potential adverse health effects (current and future) resulting from releases of hazardous substances from tailings deposited on the western shore of Torch Lake." (page 1-1)

"Based on a review of site conditions including land use, contamination patterns and human activity patterns, the populations most likely to be exposed are:

- Current and future off-site residents (adults and children).*
- Workers - lagoon and sludge spreaders.*
- Campers (adults and children).*
- Future on-site residents.*

The most important exposure pathways are judged to be

- Inhalation of particulates from the contaminated tailings.*
- Ingestion of contaminated tailings." (page 7-2)*

(1991). Donohue and Associates, Inc., U.S. EPA. **Amendment No. 1 To Final Work Plan (Revision 2) - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**. Superfund, remedial investigation.

From the document:

"This Amendment (No. 1) to the FINAL WORK PLAN (Revision 2) for the Torch Lake Remedial Investigation/Feasibility Study addresses changes to the Work Plan as authorized in Work Authorization Form (WAF) 02-5LS8, Revision 12. These changes include proposed supplemental sampling of surface waters and sediments along the Keweenaw Waterway as part of the Operable Unit II Remedial Investigation and limited approach feasibility study for a slag pile in Operable Unit I. In addition/ this addendum addresses changes for the baseline risk assessment for OU I, as specified and authorized by the RPM. The costs and LOE associated with this amendment are presented in the Cost Pricing Proposal, Revision 3." (page 1)

(1991). Donohue and Associates, Inc., U.S. EPA. **Addendum No. 1: Final Remedial Investigation Report Operable Unit I - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Superfund, remedial investigation, Operable Unit I, drums.

From the document:

"This addendum summarizes test pit excavations performed to supplement geophysical data to locate potential buried drums in OU I tailings. This introductory section briefly summarizes the 1989 geophysical survey activities documented in the Torch Lake Superfund RI Report (Donohue, 1990) .

Subsequent addendum sections present details of test pit excavation procedures, results, and conclusions." (page 1)

(1991). Donohue and Associates, Inc., U.S. EPA. **Addendum No. 1: Final Field Sampling Plan Revision 2 - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.**

The difference between this document and its original is unclear.

(1991). Donohue and Associates, Inc., U.S. EPA. **Addendum: Final Quality Assurance Project Plan For Operable Unit II Remedial Investigation Activities - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Superfund, Remedial investigation, OUII.

From Section 3.1: Project Description Introduction:

"The purpose of this Quality Assurance Project Plan {QAPPJ Addendum is to document the necessary modifications to the existing approved QAPP dated June 1990 to provide for the collection and chemical analysis of additional surface water, sediment, and smelter slag samples to further define the Operable Unit II Keweenaw Waterway as described in the Work Plan Addendum. Only those sections of the approved QAPP that apply to the addition of surface water, sediment, and slag locations to the sampling and analysis program are included in this addendum."

(1991). Donohue and Associates, Inc., U.S. EPA. **Amendment No. 1a To Final Work Plan (Revision 2) Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Superfund, remedial investigation.

From the document:

"This Amendment (No. 1) to the FINAL WORK PLAN (Revision 2) for the Torch Lake Remedial Investigation/Feasibility Study addresses changes to the Work Plan as authorized in Work Authorization Form (WAF) 02~5LS8, Revision 12. These changes include proposed supplemental sampling of surface waters and sediments along the Keweenaw Waterway as part of the Operable Unit II Remedial Investigation and limited approach feasibility study for a slag pile in Operable Unit X. In addition, this addendum addresses changes for the baseline risk assessment for OU I, as specified and authorized by the RPM. The costs and LOB associated with this amendment are presented in the Cost Pricing Proposal,

Revision 3." (page 1)

(1991). P. Drake, U.S. Bureau of Mines. Personal Communication. J. B. Lee, U.S. EPA. Torch Lake, stamp sands.

Enclosure includes the assay results for the twenty-four solid samples that were collected during the February 1991 sampling trip. The results of a "maximum leachability assay" on each of the solid samples are given in the attached table.

(1991). E. J. Dupuis. **Torch Lake Superfund Site (Public Input)**. Personal Communication. U.S. EPA. Torch Lake, drums, public outreach.

Letter from resident requesting that an area near the Lake Linden swim area be investigated due to the presence of heavy black sludge found there during the recovery of a dead body a few years earlier.

(1991). U. S. EPA. **Superfund Program Information Update: Torch Lake Superfund Site, Houghton County, Michigan**. Torch Lake, Superfund.

Fact sheet updating stakeholder on status of Superfund actions on Torch Lake. Includes a description of the Superfund process, what the individual Operable Units are, the announcement that the first cleanup plan should be complete by the next year, a discussion of the drum removal, and the announcement of a public meeting.

(1991). Geraghty & Miller, Inc., Universal Oil Products Company, Inc. et al. **Final Work Plan Torch Lake Drum Removal Houghton County, Michigan**. Superfund, drums.

This is the Work Plan developed by the lawyers of the parties identified as responsible for the cleanup of the drums in the Torch Lake site. The plan describes the following tasks: contractor procurement, terrestrial drum removal, contaminated soil removal, offshore geophysical investigation, underwater survey, underwater drum removal, hazardous material disposal, and reporting. Also included in the report is a Health and Safety Plan and a Sampling and Analysis Plan.

(1991). D. Gruben. Personal Communication. J. Lee. Torch Lake, soil samples.

Enclosure contains various soil sample results.

(1991). T. Hartsig, Donohue Site Manager. **EPA Region V ARCS Contract No.- 68-W8-0093, EPA Work Assignment No. 02-5LS8, Donohue Project No. 20011, Torch Lake RI/FS: Addendum No. 2. Final Field Sampling Plan Smelter Slag and Groundwater Sampling Plan Torch Lake Superfund Site Houghton County, Michigan**. Personal Communication. J. Lee, EPA Region V RPM. Torch Lake, Superfund, Remedial Investigation.

This memorandum describes standard procedures to be followed while collecting soil samples at OU III Location 6 (Quincy Smelter) and groundwater samples at OU III Location 7 (Isle Royale Tailings).

(1991). T. Irvin, Site Management Unit 3 ERD. **Torch Lake**. Personal Communication.
D. Gruben, Site Management Unit 2 ERD. Torch Lake, Superfund, arsenic, cyanide.

Memo within DNR stating that an informant told the author of arsenic and cyanide discharge points to the Portage Canal that existed during the operation of the Quincy stamp mill and smelter.

(1991). R. Komula, **EPA Finds Barrels in Torch Lake**. Torch Lake, barrels.

Article describes drum search and removal activities in Mason, Hubbell, Tamarack City and Lake Linden.

(1991). K. D. Kozie and T. J. Kubiak, USFWS, U.S. EPA. **Reproduction in Bald Eagles and Gulls in the High Copper Environment of Torch Lake, Michigan**.

Gulls and Bald Eagles feed on Torch Lake fish. Short-term reproductive biology appears normal. Long-term productivity on Portage Lake Bald Eagle nest is poor but this is an old problem (since at least 1981) but this may be due to organochlorine and/or PCB contamination. In short, analysis results do not show that copper contamination is the cause for reproductive issues in gulls and Bald Eagles, but contaminants such as PCBs and PAHs may be.

(1991). J. B. Lee. Personal Communication. Various families within Torch Lake Superfund site boundaries. Torch Lake, groundwater.

Gives results of residential well sample analysis.

(1991). Life Systems, Inc., Donohue and Associates, Inc. **Final Baseline Risk Assessment Report For Torch Lake, Operable Unit I**. Superfund, OUI, risk assessment

From the summary of this document:

"This baseline risk assessment is an analysis of the potential adverse health effects (both current and future) resulting from exposures to hazardous substances in tailings along the western shore of Torch Lake (OUI)....

The most important exposure pathways are judged to be

- Inhalation of particulates from the contaminated tailings.*
- Ingestion of contaminated tailings....*

No calculated chronic hazard indices exceed one for any exposure pathway evaluated at Torch Lake.

Calculated subchronic hazard indices exceed one for several exposure pathways involving children at the campground, at current residences near the slag pile/beach and future residences assumed to be built on the tailings piles. Only one chemical, copper, at the slag pile/beach scenario contributed an HQ that exceeded one...."

It... appears that lead is not a source of concern at this site."
(1991). K. Manty, The Daily Mining Gazette. **Torch Lake drum removal complete.**
Torch Lake, emergency removal, drums.

This articles states that the drum investigation results are expected soon.

(1991). Soil Conservation Service, USDA. **Preliminary Cost Estimates for the Vegetation of the Copper Mine Tailings at Torch Lake.** Torch Lake, mine tailing vegetation.

Presents cost estimates for various vegetation options.

(1991). W. S. Sottile, MDPH Upper Peninsula Laboratory. Personal Communication. D. Gruben, MDNR Environmental Response Division. Lake Linden, waste removal.

Letter from MDPH to MDNR that medical waste found in Lake Linden is not hazardous.

(1991). E. Zahl and P. Drake. Personal Communication. J. B. Lee.

U.S. Bureau of Mines September Status Report

(1991 (inferred)). The Daily Mining Gazette. **Editorial: Wrong place & time.** Torch Lake, public outreach.

Editorial states that U.S. EPA should have public meetings about Torch Lake within the region of Torch Lake so that residents who are most affected by the problem have more accessibility to the meeting.

(1991 (inferred)). D. W. Charters, Environmental Response Team, U.S. EPA. **Final Report for Torch Lake, Michigan**. Torch Lake, drums.

From the document:

"Objectives of the Study

The objective of the study was to determine both acute and toxic effect levels in the sediments of Torch Lake. The study was devised to evaluate, not only copper toxicity "but if other variables such as mercury and variations ' in site sediment parameters were contributing to or ameliorating toxic effects. Sediment samples were collected, screened by X-Ray Fluorescence (XRF) for copper and stored so that a site specific gradient of copper could be evaluated for toxicity. Other tasks included, collection of surface water samples for metals analysis and toxicity testing by the U.S. EPA Region V."

CONCLUSIONS

"Based on the toxicity evaluation of Torch Lake and the extent of contamination survey delivered to ERT by Region V Project Manager Jae Lee, it is apparent that the vast majority of the sediments in Torch Lake are toxic and not able to support a normal benthic community. The benthic macroinvertebrate community is an integral part of the base of a complex foodweb in a lacustrine system and a severely impacted benthic community would impact the entire foodweb. Unfortunately, the area impacted by the copper contamination may make a complete restoration of the lake to a pre-mining state unfeasible. Alternate proposals should be entertained including remediation of portions of the lake. Studies of these alternate possibilities should be undertaken as soon as possible."

(1991 (inferred)). K. Manty, The Daily Mining Gazette. **Torch Lake plan done by September: EPA**. Torch Lake, Superfund, U.S. EPA.

Discusses EPA contaminant findings and community meeting.

(1991 (original), 1992 (revision)). T. Hartsig. **Occurrence of Polynuclear Aromatic Hydrocarbons (PAHs) in Residential Soils at Torch Lake, Michigan**. Personal Communication. J. B. Lee. Torch Lake, PAH.

The purpose of this technical memorandum is to address the occurrence of polynuclear aromatic hydrocarbon (PAH) compounds in the soils of local residences along the western shore of Torch Lake, Houghton County, Michigan. Polynuclear aromatic hydrocarbons were identified in soil samples from Hubbell and Mason. The geographic distribution of these compounds does not readily suggest derivation from a single contaminant source.

(1992). U.S. EPA (assumed). **U.S. EPA Proposed Plan for Torch Lake Site**. Torch Lake, Superfund, public outreach.

This document is a fact sheet explaining the remediation decision for Operable Units I and III and the reasoning behind them. The remediation option chosen for Operable Unit I is the soil and vegetation cap of the protruding stamp sand piles in Torch Lake itself. The remediation option chosen for Operable Unit III is the soil and vegetation cap of the slag piles and the beach in Hubbell. It was determined that these options were the most practicable and beneficial to the protection of human health.

(1992). C. R. Baillod, Portage Lake Water and Sewage Authority, **Comments on USEPA Proposed Cover-Up Plan for the Torch Lake Superfund Site**. Torch Lake, Portage Lake Water & Sewage Authority, U.S. EPA, Superfund.

Document states that separation of Operable Units I and III from II is not logical. Also states that risk and toxicity from various contaminants including background concentrations of metals and other elements in soils, airborne particulates, copper, and chromium and human ingestion of stamp sand are grossly over estimated. Concludes that the cover-up plan is not justifiable as remedial action and urges the EPA to select the "No Action" alternative and to proceed to remove the Torch Lake Site from the NPL.

(1992). D. Christian, Lake Linden - Hubbell Public Schools. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Request to extend public comment period on proposed plan because the comments and questions from the May 12, 1992 demonstrated a "profound misunderstanding of the EPA remediation proposal and also reflect fears of possible liability litigation threatened by one of the PRPs.

(1992). D. Christian, Lake Linden - Hubbell Public Schools. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Request from Lake Linden - Hubbell Public Schools to EPA to have a second public meeting about the Torch Lake proposed plan for OUs I and III.

(1992). Donohue and Associates, Inc., U.S. EPA. **Appendix C: Final Baseline Risk Assessment Final Remedial Investigation Report Operable Unit III Torch Lake Remedial Investigation / Feasibility Study Houghton County, Michigan**. Torch Lake, U.S. EPA, Superfund.

"This document is an analysis of the potential adverse health effects (current and future) resulting from releases of hazardous substances from and direct exposure to tailings deposited at 12 locations on the Keweenaw Peninsula...." The carcinogenic risks for residents are generally 1-2 orders of magnitude greater than the values required to be considered not significant, 1 order of magnitude greater than this value for current workers, and not significant to just greater than significant for scavengers and recreational visitors. There is some risk from gastrointestinal irritation in children due to copper ingestion and hematological

effects due to antimony, but it is not certain that these would occur.
(1992). Donohue and Associates, Inc., U.S. EPA. **Volume 1: Final Remedial Investigation Report Operable Unit II: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Torch Lake, Superfund, Remedial Investigation.

From the Executive Summary (pages vii-viii):

"The OU II RI was performed to collect and evaluate data to assess the physical characteristics of OU II, the type and extent of contamination of OU II, environmental and human health risks associated with OU II, and the need for and methods to remediate OU II. Activities documented in this report include waste characterization of groundwater chemistry, evaluation of aquifer characteristics, and assessment of human health impact....

Inorganic contaminants of potential concern in groundwater samples were generally above background concentrations and for a limited number of analytes, above maximum concentration limits (MCLs).

Both inorganic and organic analytical results for Torch Lake sediment samples suggest a "hot spot" directly offshore- of the Hubbell area.... However, with the exception of this single sampling location, contaminant levels detected in Torch Lake sediment were not dramatically higher than those reported for background samples....

A baseline risk assessment for the Torch Lake Superfund Site was conducted to analyze the potential adverse health effects resulting from exposures to hazardous substances in groundwater, surface water, and sediment at the site. Risk associated with dermal contact of surface water is attributable to arsenic and beryllium. Risk associated with ingestion of sediment is attributable to arsenic. Noncarcinogenic risk exists via ingestion of groundwater by hypothetical future residents."

(1992). Donohue and Associates, Inc., U.S. EPA. **Final Remedial Investigation Report Operable Unit III Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**. Superfund, remedial investigation, OUIII.

From the Executive Summary of the Document:

"This report summarizes the RI performed for OU III which includes primary contaminant sources in surface tailings in Houghton County. The OU III RI was performed to collect and evaluate data to assess the physical characteristics of OU III, the type and extent of contamination of OU III, environmental and human health risks associated with OU III, and the need for and methods to remediate OU III. Activities documented in this report include waste characterization of OU III tailings, limited characterization of soil, and assessment of human health impacts."

"The compounds detected in OU III surface and subsurface tailings included bis(2-ethylhexyl)phthalate, polycyclic aromatic hydrocarbon (PAH) compounds, and inorganic compounds. The concentration and distribution of metals appeared similar among surface and subsurface tailings. Slag material exhibited higher concentrations of arsenic, chromium, copper, and lead. Neither the semi-volatile organic nor inorganic compound levels measured on OU III tailings are dramatically higher than those found in naturally occurring soils. Metal levels were generally similar in background soil samples and tailings samples."

(1992). Donohue and Associates, Inc., U.S. EPA, **Addendum No. 1: Final Remedial Investigation Report Operable Unit II - Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan**. Superfund, remedial investigation, OUII.

From Section 1.1 - Purpose of Addendum:

"This addendum summarizes surface water and sediment sample collection performed to supplement analytical data presented in the OU II RI Report (Donohue, 1992a). Activities documented in this addendum include characterization of Keweenaw Waterway surface water, submerged tailings, and sediment."

From Section 7.1 - Summary:

"A variety of inorganic (most notably arsenic, barium, chromium, nickel, vanadium, and zinc) and organic (acetone and PAHs) contaminants were found in concentrations higher than background at locations along the Keweenaw Waterway. In addition, metals including aluminum/arsenic, barium, chromium, copper, iron, lead, and vanadium were present in Keweenaw Waterway sediments in higher concentrations than found in Torch Lake sediments (except for location SD-9 at Torch Lake). Most of the inorganic and organic contamination in the Keweenaw Waterway is found adsorbed to sediments."

(1992). SEC Donohue, U.S. EPA. **Final Feasibility Study Report Operable Units I and II Torch Lake Remedial Investigation / Feasibility Study Houghton County, Michigan**. Torch Lake, U.S. EPA, Superfund, Copper.

Presents the results of the Feasibility Study completed for Operable Units I and III. The study identifies and evaluates applicable technologies and process options. Options are first identified based on site-specific information and human health and environmental considerations. They are then screened based on technical feasibility, then implementability, effectiveness and cost. The alternatives considered for the tailings are: 1. No Action and 2. Soil Cover/Vegetation/Deed Restrictions. The alternatives considered for the slag piles/beaches are: 1. No Action, 2. Fencing / Deed Restrictions, 3. Soil Cover and Vegetation / Deed Restrictions, and 4. Excavation and Off-Site Disposal.

(1992). J. A. Duchene. **Revision of RfD - Arsenic**. Personal Communication. J. Lee. Torch Lake, arsenic.

Revision of Torch Lake arsenic hazard quotient based on change in Arsenic reference dose.

(1992). J. A. Duchene, Life Systems, Inc. **Torch Lake Risk Assessment Issue - Tailings as Road Friction Material**. Personal Communication. J. Lee, U.S. EPA. Torch Lake, Superfund, stamp sands, roads.

Letter to EPA from Life Systems, Inc., stating that the use of stamp sands as road friction material in the winter is not a cause for health concern. This is because (1) the tailings themselves are not highly contaminated, and (2) the road-spreading scenario provides a low potential for exposure.

(1992). Life Systems, Inc., **ADDENDUM TO THE DRAFT BASELINE RISK ASSESSMENT REPORT FOR TORCH LAKE OPERABLE UNIT III: Assessment of Potential Risks Based on Development of Quincy Smelting Works as Part of a National Historical Park Torch Lake Risk Assessment Support**. Superfund, public health, Operable Unit III.

From the document:

"This addendum to the baseline RA assesses potential risks to future populations who might be exposed to the tailings and slag deposited at the Quincy Smelting Works if the site were developed as a national historical park. This assessment is limited to potential exposures after the park development is completed; populations potentially exposed during construction and development are not considered. Potential risks from other media (surface water, sediments, groundwater) are not addressed in this assessment or in the OUIII RA." (page I-I)

(1992). Environmental Consultations, Inc., Michigan Technological University. **Public Comments Relative to the US EPA Proposed Plan and Supporting Documentation - Operable Units I, II and III Torch Lake Superfund Site Houghton County, Michigan**. Torch Lake, Superfund, public outreach.

This document was prepared on behalf of the MTU administration. The MTU administration agreed with the drum removal completed by the EPA in 1991. They do not support the planned activities in any of the three Operable Units in the Houghton/Hancock area because the planned activities are "based upon a data base and health/risk assessment porcess which appear to have significant shortcomings..." (Section III, Summary). "The MTU administration recommends that the US ERA fully review their data and evaluations of the Torch Lake Site and significantly modify their existing planning to reflect the realities of local remediation and restoration efforts, the native geology of the region and the historical and economic resources of the region." (Section III, Summary) Based on the data available at that time, the MTU administration believed that a "no action" Record of Decision was warranted. (Section III, Summary)

(1992). U. S. EPA. **Guidance for Performing Site Inspections Under CERCLA**. U.S. EPA, CERCLA, Site inspections.

(1992). U. S. EPA. **U.S. EPA Proposed Plan for Torch Lake Site**. Torch Lake, U.S. EPA, Superfund, copper.

This is a fact sheet that presents the chosen remedial actions for the Torch Lake Superfund site. The fact sheet explains the criteria the EPA used to reach its decision and presents a cost analysis of the different alternatives. Site background and a summary of the Remedial Investigation are included. Also, a space for comment is provided.

(1992). U. S. EPA. **Responsiveness Summary Torch Lake Superfund Site Operable Units I and III Houghton County, Michigan**. Torch Lake, U.S. EPA, MDEQ, Superfund.

Public comments to Torch Lake remediation options presented to them by the U.S. EPA and the MDEQ at a public meeting on May 12, 1992.

(1992). U. S. EPA. **Torch Lake Site, MI Operable Units I and III Declaration for the Record of Decision**. Torch Lake, U.S. EPA, Superfund, Operable Unit I, Operable Unit III.

This document states the selected remedial action for Operable Units I and III. The action includes the following: deed restrictions to control the use of tailing piles, removal of debris in the tailing piles to effectively implement the soil cover with vegetation, and implement soil cover with vegetation in the Lake Linden, Hubbell/Tamarack City and Mason Tailings in OU I, Calumet Lake, Boston Pond, Michigan Smelter, Dollar Bay and Grosse-Point Tailings in OU III, and the slag pile/beach in Hubbell in OU I. The Isle-Royale Tailings are included in parts.

(1992). U. S. EPA, **Record of Decision: Decision Summary Torch Lake Site Operable Units I and III Houghton County, Michigan**. Torch Lake, U.S. EPA, Superfund, Operable Unit I, Operable Unit III.

There are two parts of this document: the Declaration of the Record of Decision for Operable Units I and III, and the Record of Decision itself. The Declaration states the chosen remediation options for OUs I and III. As stated in the Declaration, the major components of the selected remedy include the following: 1. Deed restriction to control the use of tailing piles, 2. Removal of debris from the tailing piles, 3. Soil cover with vegetation on tailing piles in OUs I and III, 4. Slag pile in Quincy Smelter area will either be developed as a national park or otherwise prevented from development as residences, 5. North Entry, Redridge and Freda mine tailings will not be covered. The sections included in the ROD are the following: I. Site Name, Location and Description, II. Site History and Enforcement Activities, III. Community Relations History, IV. Scope and Role of Remedial Actions, V. Site Characteristics, VI. Summary of Site Risks, VII. Description of Remedial Alternatives, VIII. Summary of the Comparative Analysis of Alternatives, IX. The Selected Remedy, X. Statutory Determinations Summary, XI. Documentation of Significant Changes.

(1992). U. S. EPA, **Extension of the Public Comment Period on the Feasibility Study and Proposed Plan for Operable Units 1 and 3 for the Torch Lake Superfund Site Houghton County, Michigan**. Torch Lake, Superfund, public outreach.

States that public comment period on the feasibility study and the proposed plan for OUs I and III will be extended until July 1, 1992.

(1992). U. S. EPA, **Extension of the Public Comment Period on the Feasibility Study and Proposed Plan for Operable Units 1 and 3 for the Torch Lake Superfund Site**. Torch Lake, Superfund, public outreach.

Notice that public comment period on feasibility study and proposed plan for Operable Units I and III is extended a second time to July 13, 1992.

(1992). U. S. EPA, **THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY announces a PUBLIC COMMENT PERIOD and PUBLIC MEETING on the Feasibility Study and Proposed Plan for Operable Units 1 and 3 for the Torch Lake Superfund Site, Houghton County, Michigan**. Torch Lake, Superfund, Operable Units I and III, public outreach.

Notice to public about public meeting and opportunity to comment on the proposed plan for Operable Units I and III. States the remediation alternatives and what the EPA's preferred alternatives are.

(1992). R. Erkkila, Village of Calumet. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter from Village of Calumet to EPA stating that the village approves of the No Action alternative.

(1992). The Daily Mining Gazette, **EPA, go home**. Torch Lake, Superfund, public reaction.

Editorial by the Gazette expressing concern that cost to taxpayers to vegetate the stamp sands is more than the public health or environmental benefit of doing so.

(1992). Geraghty & Miller, Inc., et al.. **Final Drum Removal Report - Torch Lake Drum Removal Houghton County, Michigan**.

The parties responsible for the removal of drums found onshore and underwater in Torch Lake near Lake Linden "Respondents" conducted terrestrial and underwater searches for drums. 103 drums were removed (83 terrestrial drums and 20 underwater drums). 4 out of the 103 drums that were removed contained hazardous waste, but all drums that were removed "were disposed of in a licensed hazardous waste storage facility." (page 36)

(1992). Geraghty & Miller, Inc., Paul, Weiss, Rifkind, Wharton & Garrison. **Alternatives Evaluation Report for Operable Units I and III - Torch Lake Superfund Site Houghton County, Michigan**. Superfund, Operable Units I and III, Proposed Alternative.

(paraphrased from the document) The purpose of this evaluation report is to find information that the US EPA did not consider in its Proposed Alternative for OUs I and III and to compare the Proposed Alternative to the No Action Alternative (Section 1.1: Purpose of Report). The authors conclude that the No Action Alternative is the best solution for remediation. They claim the following: "...the USEPA Proposed Alternative is inferior to the No Action Alternative for the primary balancing and modifying criteria of short term effectiveness, implementability, cost and public acceptance, and provides no significant additional protection of human health or the environment." (Section 6.0: Conclusions and Recommendations, page 48)

(1992). G. Gwathmey, Paul, Weiss, Rifkind, Wharton & Garrison. **Re: Torch Lake NPL Site**. Personal Communication. F. H. Habicht, U.S. EPA. Torch Lake, Superfund, public outreach.

The lawyers of UOP claim that Torch Lake is not degraded and that the EPA is demonstrating bias in making UOP and two other large businesses the Potentially Responsible Parties for the site. They are urging the EPA to adopt the "No Action" remediation alternative.

(1992). G. Gwathmey, Paul, Weiss, Rifkind, Wharton & Garrison. **Comments Submitted on Behalf of Universal Oil Products, Inc. ("UOP") Relating to the Torch Lake Superfund Site.** Personal Communication. Superfund, UOP.

UOP's lawyers present UOP's comments on the proposed plan, which consist of the following:

- 1. EPA's proposed plan violates CERCLA (page 10): a. There are no unacceptable health risks presented by Torch Lake; accordingly, the proposed plan is unjustifiable (page 10). b. Torch Lake is a healthy and productive environment; accordingly the proposed plan is unjustifiable (page 14).*
- 2. The inappropriateness of the proposed plan is demonstrated by other RODs where the No Action remedy was selected (page 18).*
- 3. EPA unlawfully biased the community during the public comment period (page 21).*

(1992). R. J. Harding, MDNR. Personal Communication. V. V. Adamkus, Regional Administrator, U.S. EPA, Region V. Torch Lake, Superfund, Record of Decision.

Letter to the EPA from the MDNR stating that they accept the ROD with conditions. The MDNR concurs with the remedy proposed in the ROD for OU I and OU III to the extent that it can be shown that the risk level exceeds one in 1,000,000.

(1992). T. Hartsig, R. M. Gau, M. L. Crosser and I. Donohue and Associates, U.S. EPA. **Addendum No. 3: Final Field Sampling Plan Revision 2: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Torch Lake, Superfund, Remedial Investigation.

The addendum includes a description of extended sediment sampling in OUII. The purpose of this additional sampling is "...to determine the extent of contamination to provide data necessary to assess the feasibility and cost-effectiveness of remedial action alternatives." (page 2-1)

(1992). T. Hartsig and P. Markelz, U.S.EPA. **Addendum No. 1: Final Health And Safety Plan Revision 2: Torch Lake Remedial Investigation/Feasibility Study Houghton County, Michigan.** Torch Lake, Superfund, Remedial Investigation.

From page 1-1: "This addendum addresses continued sampling of Torch Lake sediments in Operable Unit II (OU II) for the Torch Lake, Houghton County, Michigan RI/FS."

(1992). C. Jacobson, U.S. EPA. **Remedy Delegation for Torch Lake, MI Site RODs.** Personal Communication. D.A. Ullrich, U.S. EPA. Torch Lake, Superfund.

Memo within the EPA stating that the Torch Lake Superfund site is listed in CERCLIS as a planned completion. Enclosure contains supporting documentation.

(1992). V. Jolly, Village of Lake Linden. **Torch Lake Site EPA Proposed Plan.** Personal Communication. J. B. Lee, U.S. EPA. Torch Lake, Superfund, public outreach. *Village of Lake Linden concisely states that they approve of the EPA plan but they do not believe that their residents should be held liable.*

(1992). R. C. Krestner, City of Houghton. **Re: Torch Lake Superfund Site, Houghton County, Michigan.** Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach. *Letter from the City of Houghton urging the U.S. EPA to adopt the No Action alternative and delist the Torch Lake Superfund Site from the NPL as soon as possible.*

(1992). Life Systems, Inc., U.S. EPA (Inferred). **Final Ecological Assessment for the Torch Lake Superfund Site: Torch Lake Risk Assessment Report.** Torch Lake, Superfund, Donohue, ecological assessment.

From the Executive Summary:

"Objectives of the Ecological Assessment

The objectives of this Report are as follows:

- 1. Provide a summary of existing ecological studies which have been performed at the site or included samples of contaminated environmental media from the site.*
- 2. Perform an evaluation based on existing studies and additional site information to estimate the magnitude and extent of actual impacts and potential risks at the site....*

Severe degradation of benthic communities and absence of wetlands in shallow areas are the most obvious ecological impacts associated with tailings deposits and contaminated sediments in Torch Lake and other surface waters in the study area.

*Very few locations where sediment was sampled in Torch Lake have sediment copper concentrations that are below laboratory estimates of the LC50 (AOO to 630 mg/kg) for *Hyalella* exposed to copper in contaminated sediments. These include three areas farthest removed from tailings deposits: in the mouth of the Trap Rock River; near the mouth of the Trap Rock River; and in the south-central area of the lake near the entrance to drainage into Portage Lake.... Extremely high concentrations of lead and arsenic in submerged tailings near Hubbell are likely to enhance copper toxicity, so this area presents the greatest risk to aquatic life in Torch Lake. All other areas of the lake where tailings have been deposited are likely to be too toxic for development of pollution intolerant benthic organisms....*

Reduction in nutrient cycling, mineralization and productivity in fish populations that feed on bottom dwelling organisms are possible secondary results of

degraded benthic communities.

The primary ecological impact of tailings deposits on land is significant habitat loss due to a variety of chemical and nonchemical stresses....

The extent of adverse impacts to terrestrial organisms living in areas surrounding tailings is expected to be minimal. Bald eagles and other birds are not likely to be affected by the primary metals of concern at this site since the metals do not biomagnify in their food webs. Plant species of special concern to the State of Michigan may be exposed to site related stresses in the study area, but information on populations potentially exposed to tailings is not available for evaluation....

Greatest risks to aquatic life in Torch Lake are posed by the area of elevated levels of arsenic and lead in tailings near Hubbell...."

(1992). Life Systems, Inc., U.S. EPA. **Appendix D: Final Baseline Risk Assessment Draft Remedial Investigation Report Operable Unit II.** Torch Lake, Superfund, Operable Unit II, U.S. EPA.

Evaluates potential risks from Operable Unit II to humans in Torch Lake. Carcinogenic risks are typically 1-3 orders of magnitude higher than the risk value considered small enough to be of no practical concern. Hypothetical future residents using groundwater for drinking water may have some risk of the effects associated with exposure to these chemicals. Lead is not a source of concern at this site.

(1992). M. D. Lydon. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter from Torch Lake Township to U.S. EPA stating that they do not believe that they should have to pay for the remediation of the stamp sands.

(1992). J. B. Manderfield, County Road Commissioners, Houghton County. **Public comments Torch Lake Superfund Site, Houghton County, Michigan.** Personal Communication. P. Schutte, U.S. EPA. stamp sands, roads, Superfund, public outreach.

The Houghton County Board of Road Commissioners strongly opposes the proposed plan to cover up the stamp sands. They are used as road abrasives and also as subbase in construction.

(1992). J. B. Manderfield, County Road Commissioners, Houghton County. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter to EPA from Houghton County Board of Road Commissioners stating their opposition to cover and vegetate the Grosse Pointe No. 10 stamp sands.

(1992). MDNR. **A Biological Survey of the Trap Rock River and its Tributaries, July 29-30, 1991 Houghton County, Michigan.**

Objective of study was to qualitatively evaluate whether historical copper mining operations have adversely impacted the biological integrity and physical habitat conditions of Slaughterhouse Creek, Scales Creek, Kearsarge Creek, and/or the Trap Rock River. Results among the eight sampling stations are mixed.

(1992). F. J. Musich, Village of Laurium. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter from the Village of Laurium to the EPA stating that the village approves of the No Action alternative.

(1992). J. A. Niemi, Houghton County Board of Commissioners. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter from Houghton County Board of Commissioners to U.S. EPA expressing its support of a letter dated June 24, 1992 sent to the EPA by Commissioner Gerard Perreault and urging the EPA to choose the No Action alternative.

(1992). G. Perreault, Houghton County Board of Public Works. Personal Communication. P. Schutte, U.S. EPA. Torch Lake, Superfund, public outreach.

Letter from the Houghton County Board of Public Works to the EPA stating that they approve of the No Action alternative.

(1992). L. Smith, Donohue and Associates, Inc., U.S. EPA. **Addendum to Final Quality Assurance Project Plan for Operable Unit II Remedial Investigation Activities Torch Lake Remedial Investigation/Feasibility Study, Houghton County, Michigan.**

This addendum accounts for sediment sampling activities in OUII.

(1992). M. Tuisku, Mayor of Hancock. Personal Communication. U.S. EPA (assumed). Torch Lake, Superfund, public outreach.

Letter to the EPA (assumed) stating that Hancock residents cannot afford to pay for the remediation of the Isle Royale Stamp Sands.

(1992). K. B. Vettori, Court Reporter, CER-2517, **Public Meeting Torch Lake Superfund Site.** Torch Lake, Superfund, public outreach.

Transcript from the public meeting concerning the cleanup plan for OUs I and III. This meeting took place on May 12, 1992 in Hancock, MI.

(1992 (inferred)). Geraghty & Miller, Inc., **Public Comment Document Operable Units I and III.** Superfund, OUI, OUIII, public comments, potentially responsible parties.

Extensive comments developed by a contractor for Universal Oil Products on the following documents: 1) Remedial Investigations for OUs I and III; 2) Risk Assessments for OUs I and III; 3) Ecological Assessment; 4) Feasibility Study; 5)

Proposed Plan; in addition to other summary comments.
(1992 (inferred)). USDA Soil Conservation Service, U.S. EPA. **Report of the Phase I Literature Search**. mine tailing vegetation.
Findings of literature search conducted by Soil Conservation Service for EPA on the subject of vegetating mine tailings.

G. T. Ankley, V. R. Mattson, E. N. Leonard, C. W. West and J. L. Bennett,
PREDICTING THE ACUTE TOXICITY OF COPPER IN FRESH-WATER
SEDIMENTS - EVALUATION OF THE ROLE OF ACID-VOLATILE SULFIDE.
Environmental toxicology and chemistry **1993**, 12 (2), 315-320.

Research evaluated role of acid-volatile sulfide in determining copper toxicity in sediments. Results indicated that AVS alone is not an appropriate partitioning phase for predicting copper bioavailability in freshwater sediments (from article abstract).

(1993). R. Campbell, MDNR. **Re: Institutional Controls on the Public Use of Groundwater Torch Lake Superfund Site**. Personal Communication. G. Shebuski, Houghton County Department of Public Health and M. Webber, Michigan Department of Public Health.

This letter discusses the results of a meeting between the EPA, the MDPH and the Houghton County Department of Public Health to strengthen Institutional Controls on groundwater to ensure that drinking water wells do not draw from contaminated sources in the stamp sands. In addition to screening drinking water wells in the sandstone aquifer and rigorous testing by the State and the County, and heightened awareness by the affected communities in permitting construction on the stamp sands, the following enhancements to the institutional controls will be made (from the document):

"1) The County Health Department and the Michigan Department of Public Health (MDPH) could stipulate the use of municipal water supplies, where available, for any residential developments on stampsands. A likely first candidate for this would be the development currently underway on the Isle Royale sands.

2) The County Health Department could formalize the practice of prohibiting the installation of drinking water wells which would be screened so as to draw groundwater from stampsands. Wells installed on stampsands would be required to extend down through the sands and to be screened in the underlying sandstone.

3) The County could adopt the practice of making the granting of building permits for work to be undertaken on the stampsands contingent upon County Health Department approval. County Health Department approval would depend upon the provision of satisfactory drinking water supply plans."

The above constitute the institutional controls to which the Record of Decision for Operable Unit II refers.

(1994). D. Banette (inferred), UPPCO. **Re; Torch Lake Superfund Site**. Personal Communication. D. Novak, U.S. EPA. Torch Lake, Superfund, Operable Unit II, public outreach.

Author expresses his support of the no action alternative for Operable Unit II.

(1994). A. J. Birnbaum, Paul. Weiss. Rifkind, Wharton & Garrison, **UOP's Public Comments on EPA's Proposed Plan for OU II at the Torch Lake Superfund Site**. Torch Lake, Superfund, Operable Unit II, public outreach.

Comments from UOP about Operable Unit II. The conclusion, from the document, states:

"The extensive scientific data in the Administrative Record clearly demonstrates that OU II poses no meaningful risk to people or the environment. EPA's Proposed Plan selecting the No Action Alternative therefore is in complete accordance with the Administrative Record. In fact, for the reasons identified herein and by EPA, the No Action Alternative — overwhelmingly supported by the public and by local and state government officials — is the only response that is consistent with the NCP and valid under CERCLA."

(1994). B. Darling, Friends of the Land of Keweenaw. Personal Communication. J. Kuhns, U.S. EPA. Torch Lake, Superfund, Operable Unit II, public outreach.

Letter from FOLK to the U.S. EPA commenting on the "No Action" alternative to remediate OUII.

(1994). Environmental Consultations, Inc., Michigan Technological University. **Public Comments Relative To The US EPA Proposed Cleanup Remedy for Torch Lake Operable Unit II Torch Lake Superfund Site Houghton County, Michigan**. Torch Lake, Superfund, public outreach.

The Michigan Tech administration fully supported the "no-action" alternative for OU II.

(1994). U. S. EPA, **Record of Decision: Decision Summary: Torch Lake Superfund Site Operable Unit II, Houghton County, Michigan**. Torch Lake, Superfund, Operable Unit II, Record of Decision.

From the document:

"This decision document presents the selected remedial action for the Torch Lake Superfund Site, Operable Unit (OU) II (OU II consists of groundwater, surface water, and sediments associated with the site), in Houghton County, Michigan, which was chosen in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA), and is consistent with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) to the extent practicable. This decision is based upon the contents of the Administrative Record for the site. The attached index identifies the items which comprise the Administrative Record upon which the selection of the remedial action is based. The State of Michigan concurs with the selected remedy.

DESCRIPTION OF THE SELECTED REMEDY:

U.S. EPA has selected a "No Action" remedy for OU II. The remedy selected for OU n takes into consideration and relies upon:

- The reduction of stampsand loading to surface water bodies expected as a result of the remedial action which will be taken at OUs I & III.*
- Ongoing natural sedimentation and detoxification such as that which is occurring in other surface water bodies in the area.*
- Institutional programs and practices controlling potential future exposure to site affected groundwater which are administered at the county and state level.*

The long-term monitoring and the five year review process monitoring requirements of the remedy selected for OUs I & III under a previous Record of Decision for this site."

(1994). U. S. EPA. **Torch Lake Superfund Site Operable Unit II Final Remedy Position Paper**. Superfund, Operable Unit II, ROD.

Paper summarizes remediation decision for Operable Unit II. It was decided that no action would be taken to remediate the lake sediment, with the assumption that a natural sediment layer would cap the contaminated sediment over time as what was occurring in Portage Lake. It was also decided that existing institutional controls would suffice to protect human health, but that these controls should be monitored for effectiveness over time.

(1994). R. J. Harding, MDNR. Personal Communication. V. V. Adamkus, U.S. EPA, Region V. Torch Lake, Superfund, Operable Unit II, Record of Decision, public outreach. *Letter states that the MDNR supports the No Action alternative for OU II provided that certain other criteria are met.*

(1994). J. H. Hartig and N. L. Law, Wayne State University. **Progress in Great Lakes Remedial Action Plans: Implementing the Ecosystem Approach in Great Lakes Area of Concern**. Area of Concern, Torch Lake.

*Provides an overview of progress in all Great Lakes Areas of Concern as of 1992. W. C. Kerfoot, G. Lauster and J. A. Robbins, Paleolimnological Study of Copper Mining Around Lake Superior: Artificial Varves from Portage Lake Provide a High Resolution Record. *Limnology and Oceanography* 1994, 39 (3), 649-669.*

(1994). H. D. Paikala, Notary Public Houghton County, **Declaration of Restrictive Covenant**. Torch Lake, Superfund, stamp sands, Lake Linden.

Lake Linden owns the stamp sands, but if, in the process of construction, the stamp sands are uncovered, they must be recovered after construction.

(1994). J. A. Spence. Personal Communication. D. Novak, U.S. EPA. Torch Lake, Superfund, Operable Unit II, public outreach.

A resident (specifically James Spence) provides comments on the EPA's selection of the no-action remediation alternative. The comments are extensive. The conclusion from his comments are found below:

"In conclusion, the Final Remedy Position Paper argues that "...the nature and extent of the TL sediment would render attempts to actively remediate impracticable." In the case of the hot spot I would argue Just the opposite. When compared to the remainder of TL, the nature and extent of the sediments in the hot spot offer an opportunity to remediate. Many of the hot spot contaminants are significantly more toxic than copper; In combination, they may create an even greater risk. If not remediated, the composition of the hot spot will significantly delay any natural remediation process. Consequently, the contaminants would be available for uptake over a longer period of time. If, however, analysis of the geomembrane cap proves it to be technically feasible, It would appear to offer a very cost-effective remediation alternative that would expedite rather than delay the lake's eventual recovery."

(1994). M. C. Stearns, CER-3917, **Public Meeting & Public Comments Regarding Operable Unit #2 Torch Lake Superfund Site Houghton, Michigan**. Torch Lake, Superfund, Operable Unit II, public outreach.

Transcript of Public Meeting about Operable Unit II that took place at Michigan Tech on March 3, 1994.

(1994). United Salvage & Reclamation Co.; et al. **Re: EPA's P(r)oposed Plan For Torch Lake Remedy Of All Operating Units ('Ou's 1-3) ,'" A Non-Action Plan "**. Personal Communication. Superfund, community relations.

This comment seems like it may have been received or sent well after the decisions on OUs I and III were made, but in response to the selection of the no-action alternative for OU II. The commenters disagree with the selection of this alternative.

(1994). U.S. EPA. **EPA Proposes Cleanup Remedy at Torch Lake Superfund Site Operable Unit II**. U.S. EPA. Torch Lake, Superfund, Operable Unit II, public outreach. *This Fact Sheet describes the plan recommended by the U.S. Environmental Protection Agency (EPA) as the most appropriate remedy option for dealing with the contamination associated with Operable Unit (OU) II at the Torch Lake site. It also summarizes the reasoning behind this recommendation.*

(1994 (inferred)). USDA Soil Conservation Service. **Treatability Study to Determine the Effectiveness of Vegetation on Stabilizing Mine Tailings at the Torch Lake Site**.

(1995). N. Boersma, Michigan Technological University. **An Analysis of Copper in Torch Lake**. Torch Lake, Copper, sediment. *Report analyzes the "natural attenuation" of Torch Lake sediments. Conclusion states that while improving the vegetation and stabilization of Torch Lake shores is the most logical remediation at the time, it may not be adequate to accelerate the remediation of the sediments.*

(1995). C. C. Cusack. **Sediment toxicity from copper in the Torch Lake (MI) Area of Concern**. Thesis. Michigan Technological University, Master of Science in Civil Engineering. Torch Lake, copper, sediment. *Thesis by C.C. Cusack studying the sediment toxicity from in Torch Lake. Reduction of copper toxicity in the sediments is occurring. Torch Lake's low productivity level and 1-year residence time may account for the slow recovery by natural attenuation compared to Portage Lake.*

(1995). Houghton-Keweenaw Soil and Water Conservation District, **August 9, 1995 Torch Lake Remediation Tour Itinerary Guide**. Torch Lake, Superfund, Area of Concern, stamp sands, Houghton-Keweenaw Soil and Water Conservation District. *Tour included: Portage Cove (Isle Royale Stamp Sands), Mason Sands, Tamarack Sands, Tamarack City M-26 Bypass, Hubbell Slag Pile and Slag Sands, Lake Linden private properties, and Lake Linden Stamp Sands.*

(1995). Houghton-Keweenaw Soil and Water Conservation District, **Houghton/Keweenaw Soil and Water Conservation District Public Meeting Agenda for the purpose of discussing the Torch Lake Superfund Site Remediation Plan**. Torch Lake, Superfund, Houghton-Keweenaw Soil and Water Conservation District. *Agenda for the meeting and a summary of the planned remediation activities for the Superfund site stamp sands including debris removal, stamp sand pile shaping for future use, soil treatment, tree planting and operation and maintenance.*

(1996). **History of Boston Pond and Area**. Copper, mining history, Boston Pond. *Describes brief history of land ownership and mill construction, milling processes, mineralogy of area, site accessibility and briefly addresses lack of remediation by revegetation of stamp sands.*

(1996). U. S. EPA. **Soil Screening Guidance: User's Guide**. Superfund, soil.

From Page 1 of document:

"The Soil Screening Guidance is a tool that the U.S. Environmental Protection Agency (EPA) developed to help standardize and accelerate the evaluation and cleanup of contaminated soils at sites on the National Priorities List (NPL) with future residential land use. This guidance provides a methodology for environmental science/engineering professionals to calculate risk-based, site-specific, soil screening levels (SSLs) for contaminants in soil that may be used to identify areas needing further investigation at NPL sites."

(1999). M. Lyons, **Design Report: Lake Linden Sands, Torch Lake EPA Superfund Site**. Torch Lake, Superfund, stamp sands, Lake Linden.

Describes plan to vegetate stamp sands in Lake Linden and possibly use the sands as a park.

(1999). M. Lyons, USDA NRCS. **Construction Completion Report: Lake Linden Stamp Sands, Torch Lake EPA Superfund Site, Houghton County, Michigan**. Torch Lake, Superfund, stamp sands, Lake Linden.

As-built documents and drawings for restoration work completed at the Lake Linden stamp sands.

(1999). D. J. Quirk. **Copper from Sand: A History of Copper Reclamation on Torch Lake, Houghton County, Michigan**. Thesis. Michigan Technological University, Master of Science in Industrial Archaeology. Torch Lake, copper, copper reclamation.

Explains the industrial processes, stamping and milling, how they were conducted by C&H and Quincy, economic importance and the impacts on the population, economy and the environment.

(2000). USDA NRCS, **Design Report: Tamarack City, Torch Lake EPA Superfund Site**. Torch Lake, Superfund, stamp sands, Tamarack.

Construction plan for stream stabilization, vegetation and debris removal at Tamarack stamp sands.

(2000). USDA. NRCS. **Operation and Maintenance Plan: Torch Lake Superfund Site, Tamarack City**. Torch Lake, Superfund, stamp sands, Tamarack.

This document describes the monitoring and maintenance activities to be performed at the Tamarack stamp sands site. The establishment period activities, establishment period inspections, and post-establishment period inspections are described. The vegetation is also described in case repairs to it are necessary.

(2000). USDA. **Operation and Maintenance Plan: Torch Lake Superfund Site, Lake Linden Stamp Sands**. Torch Lake, Superfund, stamp sands, Lake Linden.

This document describes the monitoring and maintenance activities to be performed at the Lake Linden stamp sands. The establishment period, establishment period inspections, and post-establishment period inspections activities are stated.

(2001). J. A. Blair, Michigan Technological University. **The Quincy Mining Company Torch Lake Smelter & Reclamation Plant At Mason Sands Torch Lake EPA Superfund Site**. OUI.

Archaeological survey report on the Quincy Smelter and Reclamation Plant at the Mason Stamp Sands.

(2001). U. S. EPA. **Baseline Study Report: Torch Lake Superfund Site, Houghton County, MI**. Torch Lake, Superfund.

The purpose of the Baseline Study is to establish the conditions of Torch Lake and the nearby groundwater before remedial actions were taken, and to establish methods and baseline data for future sampling efforts. Baseline Study work included assessing the benthic community populations, measuring sediment toxicity to benthic invertebrates, measuring concentrations of metals and semi-volatile organic compounds in sediment, surface water and groundwater, and studying the sedimentation process in lake sediments. Several results are discussed in the document. Analysis of results of sediment sampling show that metals (particularly copper) are high in concentration and persistent both in the surface and at depth. It was determined that the sediments are toxic to benthic organisms, and that the abundance and diversity of benthic species are low. Surface water samples indicate a relatively uniform distribution of metals, none of the metals detected in groundwater samples exceeded federal drinking water levels (at that time), and SOC's were not detected in the sediments. Semi-volatile organic compounds detected in surface water and groundwater samples were not significant (few detects and at low concentrations).

(2001). A. J. Howard, MDEQ. **Plan for Deletion of the Torch Lake Site from the National Priorities List**. Personal Communication. J. Mayka, U.S. EPA, Region 5. Torch Lake, Superfund, delisting.

This letter to the EPA from the MDEQ outlines the schedule for Torch Lake Superfund site parcels to be delisted as and when they are remediated.

(2002). U. S. EPA. **Torch Lake Superfund Site Remediation Monitoring: Fall, 2002 Sampling Overview and Results**. Microsoft PowerPoint. Torch Lake, Superfund, U.S. EPA.

Slideshow by B. Jones providing an overview of fall 2002 sampling efforts and a summary of the results from this sampling. Surveys of small mammals, plants and birds were conducted, as well as a GPS survey of the entire site and all sampling locations. The survey results show that the number of species and number of individuals [plants and animals] increased from the time that the protruding stamp sands were capped and vegetated. It was also shown that soil fertility increased after remedy.

(2002). G. V. Gulezian, U.S. EPA Region V. **ENVIRONMENTAL PROTECTION AGENCY 40 CFR Part 300 [FRL ———] National Oil and Hazardous Substance Pollution Contingency Plan; National Priorities List**. Torch Lake, Superfund, delisting.

Direct final notice of deletion of the Lake Linden parcel and Operable Unit 2 of Torch Lake Superfund Site from the National Priorities List. Gives detail of deletion procedures, the basis for site deletion, and deletion action.

(2002). G. V. Gulezian, U.S. EPA Region V, **ENVIRONMENTAL PROTECTION AGENCY 40 CFR Part 300 [FRL-7136-7] National Oil and Hazardous Substance Pollution Contingency Plan; National Priorities List**. Torch Lake, Superfund, delisting.

Notice of intent to delete the Lake Linden parcel and Operable Unit 2 of the Torch Lake Superfund Site from the National Priorities List published in the Federal Register.

(2002). G. V. Gulezian, U.S. EPA Region V, **ENVIRONMENTAL PROTECTION AGENCY 40 CFR Part 300 [FRL-7136-6] National Oil and Hazardous Substance Pollution Contingency Plan; National Priorities List**. Torch Lake, Superfund, delisting.

Direct final notice of deletion of the Lake Linden parcel and Operable Unit 2 of Torch Lake Superfund Site from the National Priorities List with details about deletion procedures, basis for site deletion, and deletion action published in the Federal Register.

(2002). B. R. Jones. **Torch Lake Superfund Site Remediation Monitoring: Fall, 2002 Sampling Overview and Results**. Microsoft PowerPoint. Torch Lake, Superfund, USEPA, natural attenuation.

Presentation summarizing ecological monitoring of vegetation on Gay, Lake Linden, Hubbell/Tamarack, Mason and Point Mills stamp sands piles. Presentation states that biodiversity at each site has improved.

(2002). Michigan Technological University. **The Quincy Mining Company Smelting Works, 1898 Historical Land Use Survey Project**. MTU, OUIII.

The report discusses the historical land use of the Quincy Smelting Works site to assist Franklin Township with the redevelopment of the site.

(2002). S. Padovani, U.S. EPA. **RE: Response to February 17, 2002 letter Concerning the Torch Lake Superfund Site, Houghton County, Michigan**. Personal Communication. V. Troesch and K. Troesch. Torch Lake, stamp sands, vegetation, public outreach.

EPA response to resident letter opposing vegetation of stamp sand on resident property.

(2002). S. Padovani, U.S. EPA. **Discussion of Shoreline Protection and Gravel Driveways at the Point Mills Portion of the Torch Lake Superfund Site, Houghton County, Michigan**. Personal Communication. File. Point Mills stamp sands.

This memo is intended to provide a summary and explanation of additional remedial action (RA) costs as a result of the extensive use of shoreline protection, two types of shoreline protection used, and the installation of gravel driveways for some landowners at the Point Mills portion of the Torch Lake Superfund Site, Houghton County, Michigan.

(2002). S. Padovani, U.S. EPA. **No Action at the Coal Dock Property Located at the Hubbell/Tamarak Portion of the Torch Lake Superfund Site, Houghton County, Michigan**. Personal Communication. File. Torch Lake, Superfund, Operable Unit I.

This memo provides an explanation for taking no action at the coal dock property. The debris (including the coal) is of a relatively large size and would likely not be subject to wind erosion. In addition, the NRCS conducted soil borings through the debris and observed native soil within 6 to 10 inches of the surface. surface water runoff from the property did not enter Torch Lake. The agencies confirmed the presence of only a thin layer of surface debris (mainly coal pieces) which contains only minor amounts of stamp sand. Based on this observation, the agencies concluded that the volume of waste material is not significant enough to be a significant contaminant source to Torch Lake. Also, no significant contamination was detected in the two soil samples collected by the MDEQ. The MDEQ analytical results, along with field observations, support the conclusion that the coal dock property is not likely a significant potential source of contamination to Torch Lake. (Text from document)

(2002). S. Padovani, U.S. EPA. **Vegetation Planting at Gull Island, Torch Lake Superfund Site, Houghton County, Michigan.** Personal Communication. File. stamp sands, Gull Island.

From the first page of the memorandum:

"This memo provides an explanation for the planting of vegetation as a way to stabilize stamp sands at Gull Island (see attached figure), Torch Lake Superfund Site (the Site), Houghton County, Michigan."

There are two main reasons that it was decided that only a vegetation cover (as opposed to a vegetation and soil cover) was necessary: 1) The water table was high enough to reside in the rooting zone for vegetation and 2) the species of plants being installed are known for their ability to fix their own nitrogen from the atmosphere.

(2002). T. V. Skinner, U.S. EPA. **Responsiveness Summary Torch Lake Superfund Site Deletion of Lake Linden Parcel and Operable Unit 2 Houghton County, Michigan.** Torch Lake, Superfund, Operable Unit II, delisting.

The EPA responds to two comments regarding the delisting of OUII from the NPL. The first comment expresses concern about contaminants spreading from uncapped areas of surface stamp sands. The resident was confused about the definition of OUII. The second comment is extremely extensive:
"A resident raises three general concerns: 1) Unclear Site definitions presented in the 2/5/02 issue of the Federal Register, 2) the inappropriateness of delisting OU2 because of the lack of measurable [natural recovery] progress and 3) inappropriateness of delisting OU2 because of the need for institutional controls in OU2. The resident strongly recommends U.S. EPA consider placing institutional controls on "Torch Lake's OU2" and supports the need with detailed technical information."

The EPA response is extensive and generally defends the EPA's decision to delist OUII.

(2002). V. Troesch and K. Troesch. **TORCH LAKE EPA SUPERFUND SITE ENGINEERING DESIGN LANDOWNER REVIEW.** Personal Communication. G. Aho, USDA and S. Padovani, U.S. EPA. Torch Lake, stamp sands, vegetation, public outreach.

Resident letter opposing the vegetation of stamp sands on their property, citing the degradation of the wildlife habitat that currently exists on the stamp sands on their property.

(2002 (inferred)). G. V. Gulezian, U.S. EPA Region V. **ENVIRONMENTAL PROTECTION AGENCY 40 CFR Part 300: National Oil and Hazardous Substance Pollution Contingency Plan National Priorities List.** Torch Lake, Superfund, delisting.

Notice of intent to delete the Lake Linden parcel and Operable Unit 2 of the

Torch Lake Superfund Site from the National Priorities List
(2003). D. W. Charters, U.S. EPA, et al.. **Final Report Torch Lake Stamp Sand Evaluation Torch Lake Site Keweenaw, Michigan.**

Text from the Executive Summary of the document is found below:

In 1998, the U.S. EPA selected a remedy which included the installation of a soil cap over shoreline deposits of stamp sand and the establishment of a vegetative cover to stabilize the soil. This project evaluated the success of this portion of the remedy by monitoring the development of habitat, as well as plant, bird and mammal communities over time in remediated and un-remediated areas. During August 2002, a field investigation was conducted to characterize the ecological setting and resources of the site. The field activities include a small mammal, bird and plant survey, and an evaluation of soil fertility, plant biomass, plant root penetration, and percent soil coverage by vegetation....

In summary, the establishment of a soil and vegetative cover over the shoreline deposits of stamp sand areas has resulted in the development of a soil-stabilizing plant community and habitat which has attracted birds and small mammals.

(2003). U. S. EPA. **First Five-Year Review Report for the Torch Lake Superfund Site, Houghton County, Michigan.** Superfund, U.S. EPA.

Document discusses whether or not chosen remedy (in this case "natural attenuation") is protective of human health and the environment. It was determined that the chosen remedy will be effective once it is complete. Document also gives progress of remediation activities. The document states the following as of 2003:

"Issues:

- 1) Need to complete all remedy requirements in accordance with the 1992 ROD and memoranda to Site file.*
- 2) Need to ensure deed restrictions are in place in accordance with the 1992 ROD and 1994 AOC (see Section III - Initial Response). To date, only a small number of these restrictions have been verified to be in place.*
- 3) Need to conduct a periodic review of groundwater uses at the Site and the effectiveness of the county well permitting process in preventing drinking water well installation in tailings at the Site. Currently, EPA is not aware of any drinking water wells at the Site that use tailings as a potable water source.*
- 4) Need to make repairs to cover material and shoreline protection, as necessary, to ensure long-term integrity of remedy.*
- 5) Need to investigate MDEQ observation that tailings have been applied around recently installed culverts and on the surface of trails and campground pads at the Lake Linden parcel.*
- 6) Need to complete restoration of Mason borrow-soil source.*
- 7) Need to complete evaluation of North Entry and Scales Creek for possible elimination from remediation plans.*

- 8) *Need to resolve access issues at Point Mills (summary in attachment 6).*
 - 9) *Need to evaluate long-term access for conducting monitoring and O&M activities.*
 - 10) *Need to evaluate Houghton County Road Commission's road traction tailing excavation practices at Point Mills relative to 1992 ROD requirements.*
 - 11) *Evaluate the need for deed restrictions to prevent the development of residences in the slag area of Quincy Smelter...*
- Recommendations and Follow-up Actions:*
- 1) *Maintain current IAG contract with USDA-NRCS and work cooperatively with USDA-NRCS to ensure the work is adequately completed.*
 - 2) *Continue to seek documentation from landowners at the Site to verify proper deed restrictions have been put in place, and if they are not, work with the landowners and/or county to ensure deed restrictions are put in place.*
 - 3) *Conduct periodic on-Site inspections of groundwater use and work with county officials to evaluate the effectiveness of the county well permitting process in preventing the installation of drinking water wells in tailings.*
 - 4) *Conduct routine inspections and coordinate repair work with USDA-NRCS and/or State.*
 - 5) *Conduct Site inspection and if tailings are confirmed, evaluate the potential for the tailings to enter Torch Lake.*
 - 6) *Ensure USDA-NRCS addresses and adequately completes this work in 2003.*
 - 7) *Review State response to EPA's 12/27/02 letter and establish a final position in a letter to the State.*
 - 8) *Continue to work with the Office of Region Counsel, Department of Justice, and the Federal court system to enforce two Administrative Orders for Access dated April 2002.*
 - 9) *Review 1994 AOC and other access agreements for applicability to long-term access. Seek additional/updated access agreements where necessary.*
 - 10) *Work with the Houghton County Road Commission to ensure practices are consistent with the 1992 ROD and/or evaluate the need for possible modification of the specific 1992 ROD requirements on this issue to better reflect current engineering and protectiveness needs.*
 - 11) *Work with landowner and stakeholders to determine Historical Park redevelopment schedule. If a redevelopment schedule cannot be committed to by the end of 2003, work with the landowner and/or county to have deed restrictions immediately in place to prevent residential development of the slag area."*

(2003). Exponent, MDEQ. **Fish Contaminant Monitoring Program: Review and Recommendations.**

The purpose of this document is for the MDEQ's consultant, Exponent, to present the results of its review of the trends monitoring elements of the Fish Consumption Monitoring Program (FCMP). They provide recommendations to make trends analyses more robust.

(2004). C. Flaga and S. Hession. **Quincy Smelter Evaluation**. Personal Communication. A. Keranen. Superfund, OUIII, Soil DCC.

Discusses soil sampling completed at the Quincy Smelter in OUIII in 1990, 1991, 1997 and 2002, and compares concentrations to soil direct contact criteria (SDCC). The memo also discusses the estimated cancer risk for visitors to and workers at the property should the smelter site be developed into a national historical park. It was concluded that arsenic levels were unacceptable for residential use, but were acceptable for high soil intensive groundskeeping activities and visitors. Additional sampling is recommended. Asbestos abatement activities should be started. Substances that exceed the groundwater surface water interface criteria were listed.

(2005). L. Anderson et al., Michigan Technological University. **Accelerating the Natural Remediation of Torch Lake**. Torch Lake, Copper, sediment cap.

Senior design project exploring remediation options for copper contamination in Torch Lake. A sediment cap consisting of sand with a thickness of 40cm was is predicted to be the best solution.

(2005). P. Blanchard et al., Environment Canada, U.S. EPA. **Atmospheric Deposition of Toxic Substances to the Great Lakes: IADN Results through 2005**. Great Lakes, IADN.

Reports contaminant air deposition data collected by the IADN from 2001-2005. PCB deposition measured at Eagle Harbor, MI is included in this report.

(2005). Great Lakes Environmental Center, MDEQ. **Quality assurance project plan (QAPP) for project number 05-25: PCB study using semi-permeable membrane devices in Torch Lake, Houghton County**.

Torch Lake, Semi-Permeable Membrane Devices

(2006). **Standard Operating Procedure for the Measurement of WHO/NIST/NOAA List Polychlorinated Biphenyl Congeners and Polybrominated Diphenyl Ethers in Water, Soils and Sludge Extracts by Gas Chromatography Using Both Ion Trap Tandem Mass Spectrometry and Quadrupole Negative Chemical Ionization Mass Spectrometry**. U.S. EPA Region 5 Chicago Regional Laboratory. Operating procedure, WHO, NIST, NOAA, polychlorinated biphenyl congeners, polybrominated diphenyl ethers, gas chromatography, mass spectrometry.

(2006). Great Lakes Environmental Center and MACTEC Engineering and Consulting, Inc. MDEQ. **Torch Lake Sediment Flux and Metals Analysis Study Houghton Co., MI.** Torch Lake, metals, natural attenuation.

This is a study of the concentrations of metals found in the "natural" sediment cap in 2006. The conclusions and recommendations are stated in the "Recommendations for future work" section of the document:

"Several metals appear to be at sufficient concentrations in the suspended sediment to cause adverse effects on aquatic life. However, there is anecdotal evidence that suggests a relatively health fishery, plankton populations and forage fish base exist in Torch Lake despite the relatively high metal concentration. Additional work is necessary to completely understand the bioavailability and subsequent effect of the metals on aquatic life in Torch Lake."

(2006). S. DeLong, NPS. Personal Communication. F. Fiala, NPS. Superfund, OUIII. *Summary from the document:*

"Following recent heavy rainfalls I visited areas in the park associated with stormwater drainage projects to examine how they performed. An area that I remain concerned about is the culvert on the Quincy Smelter site installed as part of an EPA project in 2004. While placement of the culverts has effectively rerouted drainage, erosion continues in this location and has led to sediment basins filling after less than one season. Seeking answers for why this occurred, I explored the drainage area south of the culvert that passes below highway M-26. The photos I have included below are useful to examine change in the landscape and to identify issues to be resolved."

(2006). Great Lakes Environmental Center, MDEQ. **PCB study using semipermeable membrane devices in Torch Lake, Houghton County (MDEQ project number 05-25).** Torch Lake, MDEQ, PCB, SPMD, water.

This report describes the study the MDEQ conducted using Semi-Permeable Membrane Devices to determine congener concentrations in the Torch Lake water column compared to control sites on the Portage Canal and in Huron Bay. The concentrations of PCBs were generally higher, and high concentrations found in tetra- and penta- chlorinated congeners were generally higher than others. The results of the study suggest that there is a source of PCBs at the northern side of Torch Lake. GLEC is the contractor that carried out the work and their report provides additional detail to what is provided in the MDEQ report on the same study.

(2006). Great Lakes Environmental Center, MDEQ. **Development of a Copper Criteria Adjustment Procedure for Michigan's Upper Peninsula Waters**. copper, MDEQ.

From the Executive Summary from the document:

"Results of laboratory tests and water quality monitoring revealed that elevated copper concentrations in several Upper Peninsula (U.P.), Michigan....suggest that Michigan's current copper standard may be overprotective for streams and rivers in the U.P., and perhaps in other State waters as well. This research program was designed to develop a copper criteria adjustment procedure for U.P. waters using a scientifically defensible approach that accounts for site-specific conditions.... The data indicate that i) a single standard for copper in the U.P. is not appropriate; ii) copper toxicity in U.P. waters is highly dependent on DOC concentration; iii) copper toxicity in U.P. waters is poorly correlated with water hardness (also alkalinity and pH); and iv) the copper BLM consistently overestimates observed LC50 values and WERs in U.P. waters. Modification of Michigan's copper standard at any given U.P. site appears to be best achieved by linear graphic interpolation of the WER from measured DOC concentrations."

(2006). R. M. Hobrla, MDEQ. Quality. Personal Communication. D. Lorenzetti.

(2006). D. S. Ireland. **Torch Lake PCB/SPMD results**. Personal Communication. M. Elster. PCB, PCBs in SPMDs.

Interpretation of results from study 2005 MDEQ study of PCBs in semi-permeable membrane devices.

(2006). MDEQ. **Guidance for Delisting Michigan's Great Lakes Areas of Concern**. Torch Lake, Great Lakes, Area of Concern.

From the Purpose section of the document:

"The purpose of this document is to: 1) provide guidance to AOC communities about the State's process for delisting AOCs; and 2) identify specific quantitative or qualitative criteria which the State will use to determine when BUIs have been restored."

(2006). MDEQ. **Torch Lake SPMD study cover letter 3-29-06**. Personal Communication. D. Lorenzetti. PCB, PCBs in SPMDs.

Letter from MDEQ Water Bureau to D. Lorenzetti, a member of the Torch Lake PAC. Letter updates the PAC about the status of the assessment of the Beneficial Use Impairment covering Restrictions on Fish and Wildlife Consumption in the Torch Lake Area of Concern (AOC).

(2006). MDEQ, **PCB concentrations in Torch Lake using semi-permeable membrane devices.**

This report describes the study the MDEQ conducted using Semi-Permeable Membrane Devices to determine congener concentrations in the Torch Lake water column compared to control sites on the Portage Canal and in Huron Bay. The concentrations of PCBs were generally higher, and high concentrations found in tetra- and penta- chlorinated congeners were generally higher than others. The results of the study suggest that there is a source of PCBs at the northern side of Torch Lake.

(2006). M. B. Schafer. **Subject: Sediment Core Studies of Biotic Recovery Following Mining Perturbations in Torch Lake Superfund Site.** Personal Communication. W. C. Kerfoot. Torch Lake, sediment, natural attenuation.

Comments on MTU report on sediment core studies in Torch Lake from MDEQ Water Bureau and Superfund staff. Among other items, they seemed to be unclear on the type of model used to understand copper dynamics in Torch Lake and what is the CRS model.

(2006). U.S. EPA, **Exception to CRL QA Procedure.** PCB, fish.

Explanation for a performed exception to the CRL QA procedure related to the PCB sampling in fish.

(2006). W. J. Whipple, CRL. **Case Narrative.** PCB, PCBs in passive samples.

Includes Case Description, Quality Controls, and Sample Results for soil sample analysis. Soil samples were taken from same locations as SPMD samples during the 2005 SPMD study in Torch Lake.

(2007). M. A. Gade. Personal Communication. S. E. Chester. Torch Lake, Area of Concern, Beneficial Use Impairment, Fish Tumors.

Letter from U.S. EPA stating that they approve the MDEQ's request for the delisting of the Fish Tumors and Other Deformities Beneficial Use Impairment in Torch Lake

(2007). MDEQ. **The Michigan Department of Environmental Quality Biennial Remedial Action Plan Update for the Torch Lake Area of Concern.**

The purpose of the document is to determine if Torch Lake can be delisted as an AOC. When Torch Lake was established as an AOC, three BUIs were identified: Fish Tumor or Other Deformities, Restrictions on Fish and Wildlife Consumption and Degraded Benthos. The Fish Tumor or Other Deformities BUI was delisted in 2007. The other two BUIs still remain. This document explains in detail the status of the three BUIs. It also gives a summary of the Superfund remedial actions.

The document states that the Fish Tumor BUI can be delisted. Degradation of Benthos is addressed by the natural attenuation of Torch Lake sediment and will only be improved once the sediment is no longer toxic to benthos. To address the Restriction on Fish and Wildlife Consumption BUI, the local source of PCBs to the lake must be identified and removed.

(2007). M. Schafer and B. Vetort, **Torch Lake.** Torch Lake, Superfund, sediment, metals, PCB.

2007 sediment sampling in Lake Linden Park for metals and PCBs. Several metals and Aroclors 1248 and 1254 were found.

(2007). Weston Solutions, Inc., U.S. EPA. **Summary Report for the Torch Lake Area Assessment Torch Lake NPL Site and Surrounding Areas Keweenaw Peninsula, Michigan.** Torch Lake, Superfund, metals, PCB, Weston.

This is the Weston report from 2007 that measured metals and PCB concentrations in 17 different Areas of Investigation within the Torch Lake Superfund site.

(2008). U. S. EPA. **Second Five-Year Review Report for the Torch Lake Superfund Site, Houghton County, Michigan.** Torch Lake, Superfund, Five-Year Report.

The second five-year report describes progress on the Superfund-required remediation activities. The issues and recommendations to addresses these issues are as follows (from the document):

"Issues:

- 1. Based upon the IC evaluation activities thus far, follow-up actions are required to assure that Deed Restrictions on the remaining private properties are implemented. Further review of the institutional controls is needed to assure that the remedy is functioning as intended with regard to the ICs and to ensure effective procedures are in place for long term stewardship at the Site.*
- 2. Possible exposures for groundwater and the effectiveness of the county well permitting process in preventing drinking water well installation in tailings at the Site requires evaluation. EPA has recently been informed that there may be drinking water wells at the Site that use tailings as a potable water source.*

Specifically evaluate residential areas within the Site. (Isle-Royale, Dollar Bay, Mason Sands, Point Mills)

- 3. Possible groundwater exposures/complete GSI pathway, GSI needs to be evaluated*
- 4. Mining related wastes have been left in place and unaddressed in the Lake Linden Recreational Area.*
- 5. Lack of cover and sedimentation basin issues at Quincy Smelter to prevent further erosion of stampsands into surface water.*
- 6. Continued Deterioration of Buildings and structural safety concerns. Friable asbestos exists in some buildings at the Quincy Smelter facility.*
- 7. Possible additional contaminant sources at Mason Sands. The need for additional work will be determined.*
- 8. Need to determine if additional areas from the Torch Lake Area Assessment Report (TLAA Report) need assessing or remediation (Attachment 6- "Attachment A" from MDEQ – MDEQ's list of concerns).*
- 9. Long-term access for conducting monitoring and O&M activities has not been formally established.*
- 10. Houghton County Road Commission's road traction tailing excavation practices at Point Mills relative to 1992 ROD requirements are a possible concern.*
- 11. Deed restrictions to prevent the development of residences in the slag area of Quincy Smelter were not implemented.*
- 12. Slow-sedimentation and lack of detoxification of sediments in Torch Lake as assumed in OU2 ROD, leading to a current estimate of natural recovery in excess of several hundred years.*
- 13. A next round of monitoring and data collection for Torch Lake is required by 2009.*
- 14. Lack of acceptable vegetative cover establishment in certain areas of Point Mills....*

Recommendations and Follow-up Actions:

- 1. Continue to seek documentation from landowners at the Site to verify proper deed restrictions have been put in place, and if they are not, work with the landowners and/or county to ensure deed restrictions are put in place.*
- 2. Evaluate groundwater data and uses at the Site, as well as develop a plan for periodic on-Site inspections of groundwater use and work with county officials to evaluate the effectiveness of the county well permitting process in preventing the installation of drinking water wells in tailings.*
- 3. Groundwater exposures/complete GSI pathway, needs to be evaluated.*
- 4. Further assessment, evaluation and remediation as necessary in the Lake Linden Area.*
- 5. Prepare and Finalize a Decision Document (ROD Amendment) to implement appropriate remedy at Quincy Smelter.*
- 6. Building and structural stability along with asbestos removal will be assessed.*
- 7. Further assessment, evaluation and remediation as necessary in the Mason*

Sands parcel.

8. Determine if any areas from the TLAA Report need additional evaluation.

9. Review 1994 AOC and other access agreements for applicability to long-term access. Seek appropriate long term solution for access agreements where necessary. Evaluate the need for additional ICs.

10. Work with the Houghton County Road Commission to ensure practices are consistent with the 1992 ROD.

11. Work with Franklin Township to ensure they record appropriate deed restrictions at Quincy Smelter.

12. Determine and develop alternative studies or measures for OU#2, Torch Lake, as appropriate.

13. Develop Data collection plan/Monitoring for Torch Lake.

14. Evaluate vegetative cover establishment in certain areas of Point Mills and determine possible solution."

(2008). U. S. EPA.. **Proposed Plan for Record of Decision Amendment for Operable Unit 3 at Torch Lake Superfund Site.** Superfund, OUIII, Record of Decision.

This amendment describes a revised plan for the Quincy Smelter site in OUIII. The reason a revision was necessary is that the site was supposed to become a national park, but it did not. The revised plan consists of soil and vegetative cover at the smelter and improved erosion control along the shoreline.

(2008). U.S. EPA. **Planning for the Future: Reuse Assessment for the Quincy Smelter Site Torch Lake Superfund Site, Houghton County, Michigan.** Superfund, OUIII.

This document is a concept plan for the reuse of the Quincy Smelter site (OUIII) as a more functional park space.

(2008). B. Kelly, U.S. EPA. **Initial/Final - Asbestos Removal Complete Quincy Smelter 48991 Maple Street, Ripley, Franklin TWP, MI Latitude: 47.12 Longitude: -88.54.** Personal Communication. Various. Superfund, OUIII, Emergency Removal.

Report discussing actions taken in removing and abating asbestos from the Quincy Smelter (OUIII) site.

(2008). MACTEC Engineering and Consulting of Michigan, Inc., MDEQ. **MONITORING REPORT TORCH LAKE SUPERFUND SITE.** Torch Lake, Superfund.

Conclusions include the following:

1. Natural recovery of sediments is not occurring at an appreciable rate. Based on a study by Dr. Kerfoot, the estimated time for natural sediment recovery to occur is 800 years.

2. There has been some improvement in pelagic fish species.

3. Sources of copper, mercury and other contamination remain uncontrolled. A persistent source of copper is present.

4. No conclusions were drawn from any evaluation of bioavailability.

5. Copper concentrations in surficial sediment layer have increased; specifically they have increased to concentrations above those found in the deeper sediments.
6. The benthic organism community remains low in abundance and richness, and is not improved by natural recovery of sediments.

Recommendations include the following:

1. Rates of copper concentration and deposition over time should be determined.
2. Biotic recovery should be evaluated.
3. Nature and extents of the contaminants should be characterized.
4. Conduct modeling on copper and metals to determine their transport and transformation.
5. Conduct an investigation on PCBs at the site.
6. Generally implement monitoring and modeling of transport and fate of contaminants so that all possible sources of contamination are accounted for. Once this has been accomplished, do the remediation.

(2008). MDEQ. **A sediment chemistry survey of Torch Lake**. Torch Lake, AOC, MDEQ, PCB, sediment.

The purpose of this study is to follow up to the one completed in 2005 using Semi-Permeable Membrane Devices to determine PCB concentrations in the water. The results of that study indicated that a source of PCBs exists within the lake, therefore the purpose of this study was to determine where in the sediment elevated concentrations of PCBs are found.

Conclusions from this study include the following (from the summary of the document):

- "2. The metals analysis demonstrated elevated concentrations of copper and lead consistent with the historical sampling activities.
3. PCBs were detected in 16 of the 71 discrete samples, with quantified concentrations ranging from 130 micrograms/kilogram (ug/kg) to 8,900 ug/kg. PCBs were also detected at 11 of the 36 surficial sampling locations.
4. Surficial sediments in the Hubbell area in Torch Lake appear to have low levels (1,000 ug/kg or less) of PCB concentrations. PCB concentrations in the deeper sediments, except at the very northern end of the sample area (Figure 2), were predominantly below reporting limits.
5. Based on the data collected, the PCB sediment concentrations in the north/northwest basin of Torch Lake are below levels requiring remedial action. However, given that low levels of PCBs are detected in the surficial sediment in the Hubbell sampling area an ongoing upland source of PCBs to Torch Lake can not be ruled out."

(2008). MDEQ. **PCB concentrations in Walleye collected from Torch Lake (Houghton County) and Lake Superior.** Torch Lake, AOC, MDEQ, BUI, fish consumption advisory, PCB.

This study was conducted as a follow up to the Semi-Permeable Membrane Device study completed by the MDEQ in 2005 and the Sediment Chemistry Survey completed by the MDEQ in 2007. The objective of this study was to determine if PCB concentrations found in fish caught from Torch Lake were greater than PCB concentrations found in fish caught from Lake Superior.

Conclusions of the study include the following (from the document summary):
"3. Total PCB and lipid-normalized total PCB concentrations in Torch Lake walleye collected in 2007 were equivalent to the concentrations in walleye collected in 2000.

4. Total PCB and lipid-normalized total PCB concentrations in walleye collected from Torch Lake were higher than concentrations in walleye collected from Huron Bay, and the data suggest that walleye from the two areas represent distinct groups.

5. Total PCB concentrations in Portage Lake walleye appear similar to the concentrations in walleye collected from Huron Bay, but the comparisons are weak due to a small Portage Lake sample.

6. The MDCH fish consumption advisories for Torch Lake and Portage Lake walleye are unlikely to be relaxed based on the total PCB concentrations measured in the 2007 samples."

(2008). Weston Solutions, Inc. U.S. EPA. **FINAL LETTER REPORT FOR THE QUINCY SMELTER SITE RIPLEY, FRANKLIN TWP., HOUGHTON COUNTY, MICHIGAN.**

WESTON START conducted a time-critical removal of asbestos at the Quincy Smelter Site in April 2008. This report discusses the specific activities performed. (From page 3 of the document) Activities include the following:

- reducing the height of the Reverbatory Furnace Building smoke stack*
- asbestos removal*
- air monitoring*
- health and safety removal oversight*

(2008 (inferred)). B. Kelly, U.S. EPA. **ACTION MEMORANDUM - Request for a Time Critical Removal Action at the Quincy Smelter Area of the Torch Lake Superfund Site, Franklin Township, Houghton County, Michigan (Site ID B57M).**

Personal Communication. R. C. Karl, U.S. EPA. Superfund, OUIII, Emergency Removal.

The purpose of this memo was to request approval from the EPA for an emergency removal of asbestos from the Quincy Smelter site.

(2009). U.S. EPA. **Aroclor sediment investigation Torch Lake area of concern**. Torch Lake, sediment, PCB, MDEQ, EPA.

From the Project Goals and Objectives Section (page 3):

"The objective of this study was to evaluate surficial sediments throughout the Lake to determine if there are areas of higher PCB concentrations that might indicate a terrestrial and/or aquatic source of PCBs to the lake. This report presents the results of the 2008 sediment sampling event and provides some context for those results."

From the Results and Discussion:

"Of the eighty nine samples collected and analyzed, only two had detectable concentrations of PCBs, sample TL08-75 (90 micrograms per kilogram [$\mu\text{g/kg}$] J) and TL08-76 (26 $\mu\text{g/kg}$ J). The J flag, in both cases indicates that the values are estimated because they are below the contract required detection limits, as required by the EPA CLP program."

(2009). B. Vetort. **Residential Wells Evaluation, Torch Lake Superfund Site Houghton County, Michigan**. Personal Communication. S. Cornelius. Torch Lake, Superfund, groundwater.

Summary of residential and municipal groundwater well monitoring on Torch Lake Superfund site locations.

(2009). B. Vetort-Tiffany, MDEQ. **Groundwater Sampling Investigation Report for Village of Lake Linden Torch Lake Superfund Site Lake Linden, Michigan**. Torch Lake, Lake Linden, Superfund, metals, groundwater.

Purpose of this document (from the General Summary on page 1):

"This work was conducted to further evaluate exposure pathways identified during the United States Environmental Protection Agency (U.S. EPA) August 2007 emergency removal action, and to investigate agency and citizen reports of "blue water" discharging onto the Lake Linden beach and into the creek adjacent to the beach. This sampling effort is designed to screen for likely groundwater discharge locations along the Lake Linden stampsands, and to collect samples of groundwater prior to its discharging into the Torch Lake surface water body."

From the results and discussion section (page 8):

"The MDEQ identified several areas of preferential flow. The most significant of these groundwater discharge locations are where the field screening data coincide with upward hydraulic gradients. Sample locations were biased to these locations. Field screening data, especially specific conductance and temperature measurements, were used to identify where to collect samples."

Recommendations for next steps are given in the document.

(2009). B. Vetort-Tiffany, MDEQ. **Groundwater Sampling Investigation Report for Michigan Smelter, Torch Lake Superfund Site, Houghton County, Michigan.**

Superfund, groundwater, Michigan Smelter.

Sampling was conducted to find potential discharge sources of groundwater from the smelter site and to collect samples prior to their discharge into the Portage Canal. According to the document, "The MDEQ identified several areas of preferential flow. The most significant of these groundwater discharge locations are where the field screening data coincide with upward hydraulic gradients. Sample locations were biased to these locations. Field screening data, especially specific conductance and temperature measurements, were used to identify where to collect samples." Recommendations for next steps are given in the document.

(2010). MDEQ. **Michigan Department of Environmental Quality Fish Contaminant Monitoring Program 2010 Annual Edible Portion Report Recommendations for Changes to the 2011 Michigan Department of Community Health Fish Consumption Advisory.**

(2011). B. R. Jones, U.S. EPA. **Torch Lake Area of Concern: Current Status.** Torch Lake, Area of Concern.

Slideshow introduces the Torch Lake Area of Concern and describes ecological monitoring that took place at the site.

(2011). N. R. Urban et al., **Integrated Assessment of Torch Lake Area of Concern.** Torch Lake, Michigan Sea Grant.

Michigan Sea Grant Integrated Assessment project proposal.

(2011). USACE. **Keweenaw Stamp Sands Ecosystem Restoration, Keweenaw and Houghton Counties, MI.** stamp sands, Gay, USACE

USACE study to determine effects of Gay stamp sands on ecosystem and benthics.

(2011 (Accessed)). U.S. EPA. **MID980901946, NPL Fact Sheet | Region 5 Superfund | US EPA.** November 2, 2011. Torch Lake, Superfund.

EPA online summary description of the Torch Lake Superfund Site.

(2012). T. Lipsey. **Development of Site-Specific Aquatic Values for Total Copper for Water Bodies in the Upper Peninsula of Michigan.** Personal Communication.

Stakeholders. Keweenaw Peninsula, copper.

This letter explains what the copper criteria document is, tells the stakeholder where online they can find the document, and asks for comments.

(2012). T. Lipsey. **"Two Total Maximum Daily Loads (TMDLs) for Total Copper for the Owl Creek Watershed, Keweenaw County, Michigan" and "Three TMDLs for Total Copper for portions of the Trap Rock River Watershed, Houghton County, Michigan"**. Personal Communication. Stakeholders. copper, TMDL, MDEQ.

Letter informing stakeholders of development of TMDLs
(2012). MDCH. **Health Consultation: Technical Support Document for a Polychlorinated Biphenyl Reference Dose (RfD) as a Basis for Fish Consumption Screening Values (FCSVs)**. MDCH, U.S. Department of Health and Human Services, PCB, fish, MDCH.

From the document:

"The purpose of this document is to review the recent literature on PCBs and recommend changes in the MFCAP, if necessary, to ensure that the consumption advice remains protective of public health and the basis of the screening levels can be evaluated and updated as needed." (page 10) Conclusions: "MDCH concludes that eating unlimited amounts of certain fish from lakes in Michigan throughout the year could harm people's health. This is a public health hazard." (page 9) Next steps: "Use the proposed reference dose (RfD), protective of immunological effects and other non-carcinogenic effects, to develop updated PCB fish contaminant screening values (FCSVs) and utilize these values to provide fish consumption advice in Michigan.... Continue monitoring of fish in Michigan for PCBs.... Provide the Fish and Wildlife Contaminant Advisory Committee (FAWCAC) and other relevant groups (Great Lakes Sport Fish Advisory Task Force and Great Lakes Human Health Network) with a copy of this document." (page 9)

(2012). N. R. Urban, **ENVE4505 Fall 2012 Modeling Project 2**. copper.

Description of term-project assignment consisting of calculating the mass balance of copper in Torch Lake.

(2012 (Inferred)). MDCH, U.S. Department of Health and Human Services. **Public Health Assessment Initial/Public Comment Release: Evaluation of Municipal and Residential Drinking Water around Torch Lake**. Torch Lake, groundwater.

In 1989, 1995 and 1998, the MDCH produced several documents discussing public health issues at the Torch Lake Superfund site. In 2007, the MDEQ requested updated information. According to the document, "This document addresses potential contaminant exposure from municipal or residential wells in the Torch Lake area. This document does not include any ecological assessments, such as discussion of impacts to wildlife or benthic communities." (page 7) According to the summary of the document, the following conclusions concerning drinking water wells at the Torch Lake site were made: 1) "MDCH concludes that drinking municipal drinking water is not expected to harm people's health." (page 7) and 2) "MDCH is unable to determine if contaminants present in private residential wells installed or screened in stampsand may harm people's health." (page 7)

(2012 (Inferred)). MDCH, U.S. Department of Health and Human Services. **Public Health Assessment Initial/Public Comment Release: Physical hazards in the Torch Lake Superfund site and surrounding area, Houghton and Keweenaw Counties, Michigan.** Torch Lake, Superfund, MDCH, U.S. Department of Health and Human Services, physical hazards.

This document evaluates the physical hazards present throughout the entire Torch Lake Superfund Site. The study concludes that many physical hazards are present throughout the site and that the degree of human protection varies throughout the site. Physical hazards need to be removed, corrected or better restricted.

(2012 (Inferred)). MDCH. **Torch Lake Superfund Site and Surrounding Areas Drinking Water.** M. D. o. C. Health. Torch Lake, groundwater.

Fact Sheet summarizing results of 2010 municipal and residential groundwater monitoring. Tells residents they should only consume water from well-constructed wells.

(2012 (Inferred)). MDCH, MDEQ. **Two Total Maximum Daily Loads for Total Copper for the Owl Creek Watershed, Keweenaw County, Michigan.** TMDL, Owl Creek.

(2012 (Inferred)). MDCH, MDEQ. **Three Total Maximum Daily Loads for Total Copper for Portions of the Trap Rock River Watershed, Houghton County, Michigan.** Trap Rock River, TMDL.

(2013). U.S. EPA. **Five-Year Review Report for the Torch Lake Superfund Site, Houghton County, Michigan.** Torch Lake, Superfund, Five-Year Report.

The third five-year report describes progress on the Superfund-required remediation activities. The issues and recommendations to addresses these issues are as follows (from the document):

"Issues:

1) Lack of vegetative cover establishment at certain properties at the Point Mills. Also, minor areas need repair and additional reseeded and fertilization at Point Mills.

2) A determination needs to be made that the required restrictive covenants on residential properties and permitting restrictions on wells screened in the stamp sands are in place and effective to ensure long-term protectiveness of human health and the environment for the groundwater.

3) Houghton County Road Commission is currently using tailing material at Point Mills to spread on roads during winter to provide traction for motor vehicles.

4) Site-wide O&M Plan have not been finalized. Existing residential wells are screened in the stamp sands. While these wells are not contaminated above drinking water standards, monitoring is necessary to ensure remedy continued protectiveness....

Follow-up Recommendations:

- 1) U.S. EPA and MDEQ will work with property owners to find a cost-effective solution to the vegetation problem at Point Mills.*
- 2) U.S. EPA and MDEQ will review the required restrictive covenants on residential properties and the permitting restrictions on wells screened in the stamp sands and confirm that they are necessary, in place and effective. U.S. EPA and will prepare an IC plan for the Site which will include a plan for long-term stewardship.*
- 3) U.S. EPA and MDEQ will work with the Houghton County Road Commission to ensure that road traction tailing excavation practices are consistent with the 1992 ROD.*
- 4) MDEQ will finalize the Site-wide O&M Plan. MDEQ will revise the O&M Plan to include monitoring of residential wells screened in the stamp sands."*

(2013). LimnoTech, MDEQ, U.S. EPA. **Statewide Michigan PCB TMDL**. TMDL, PCB, Michigan.

From Page 1 of the document:

"The 2010 Sections 303(d), 305(b), and 314 Integrated Report (Michigan Department of Environmental Quality² [MDEQ], 2010a) identified 21,923 miles of rivers and streams and 144,693 acres of inland lakes and reservoirs as not supporting their designated use due to high concentrations of polychlorinated biphenyls (PCBs) in fish tissue. In addition, 49,551 miles of rivers and streams and 125 acres of lakes are not supporting their designated use due to PCBs in the water column (MDEQ, 2010a).

The scope of this PCB TMDL covers inland water bodies in the state of Michigan, primarily impacted by atmospheric deposition of PCBs. These water bodies are described further in Section 2 and Appendix A. This document describes the statewide approach that Michigan has taken to develop a TMDL for PCBs."

(2013 (Inferred)). MDCH, U.S. Department of Health and Human Services. **Public Health Assessment Public Comment Release: Evaluation of recreational uses at beach areas at Lake Linden and along Torch Lake, Houghton County, Michigan**. Torch Lake, Lake Linden, MDCH, U.S. Department of Health and Human Services, beaches.

The purpose of this document is to identify potentially harmful exposures and actions that would minimize those exposures. The MDCH was unable to determine if the chemicals found the the Lake Linden, Hubbell beach areas and Boston Pond and Calumet Lake were harmful to human health. They determined that the chemicals found in the Mason stamp sand area are not harmful to human health, and that unlimited consumption of fish from Torch Lake is harmful to human health.