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Micro-elemental Analysis of Statoliths as a Tool for Tracking the Stream Origins of Sea Lamprey (*Petromyzon marinus)* in Lake Huron

by

Carrol Hand

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ABSTRACT

Management of the invasive sea lamprey (*Petromyzon marinus*) in the Great Lakes currently costs millions of dollars annually, and has yet to fully control the species. The ability to determine natal origins of parasitic- and spawning- phase sea lamprey would greatly improve existing control efforts; one potential means to do so is statolith microchemistry. Herein I further developed methodology and explored its potential value for discriminating natal origins; specifically I compared two laser techniques, the effect of fish preservation, minimum sample size, and method of analysis (Chapter 2). Afterwards, I explored its application by determining our ability to discriminate among 45 potential production streams in Lake Huron (average classification accuracy 68%), geologic zones (69% accuracy) and watersheds (48% accuracy). For all analyses, manganese, rubidium and strontium were the most important elements, explaining the most variation. Ultimately, statolith microchemistry appears potentially useful, though requires further research prior to implementation.

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STATEMENT OF ORIGINALITY

I certify that this thesis, and the research to which it refers, are the product of my own work, and that any ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline. I acknowledge the helpful guidance and support of my supervisors, Dr. Brian Fryer (University of Windsor), Dr. Stuart Ludsin (NOAA's Great Lakes Environmental Research Lab) and Dr. Ellen Marsden (University of Vermont). In addition, I am indebted to Ed Brothers for permitting me to use his data in my analyses.

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Introduction

The problem.

Sea lamprey (*Petromyzon marinus*) first invaded the upper four Laurentian Great Lakes during the early 20th century following construction of the Welland Canal (Lawrie 1970). Since then, sea lampreys, normally anadromous, have adapted to the freshwater environment and extended their range to include all the Great Lakes, where their impact on native fish communities has been devastating (Weise and Pajos 1998). For example, sea lamprey predation on native fish (e.g. lake trout *Salvelinus namaycush* and lake whitefish *Coregonus clupeaformis*) in the open lakes has been attributed to causing more annual lake trout mortality than fishing and natural mortality combined (Schleen et al. 2003). Impact on the commercial fishing industry has been most noticeable, where sea lamprey predation caused the lake trout harvest to decline from 11 million kg to 3.6 million kg between 1930 and 1966 (Morse et al. 2003). The extent of the sea lamprey problem resulted in the creation of the Great Lakes Fishery Commission (GLFC), a bi-national agency that coordinates and manages control efforts in tributaries draining into the Great Lakes. These efforts include the application of lampricides (granular bayluscide and TFM), creation of physical and electrical barriers to prevent upstream migration of spawners, trapping of adult spawners, and sterile male release programs (Smith and Tibbles 1980; Twohey et al. 2003). Using such methods, the abundance of parasitic phase sea lampreys declined by as much as 90% in some lakes leading up to 1970, only to rebound and increase dramatically since that time in other systems (Young et al. 1996). Millions of dollars are currently spent each year on these control efforts. Clearly, a reliable method to identify important tributary sources of sea lamprey would be of great value, allowing GLFC to better prioritize control efforts (Schleen et al. 2003).

Background.

Since sea lamprey control efforts began in the 1950s, the primary focus has been on either preventing spawning, accomplished by stopping upstream migration of spawning adults using barriers and releasing sterile males into the environment, or killing larvae before metamorphosis, accomplished by applying lampricide to known production streams (Smith and Tibbles 1980).

Sea lampreys have a complex life cycle. Most Great Lakes fish have short larval stages (from weeks to months), while in contrast sea lampreys spend 3-7 years of their lives as larvae, only emerging as adults in their final 1-2 years (Figure 1.1) (Potter 1980; Manion and McLain 1971; Quintella et al. 2003*)*. To begin with, adults swim upstream and spawn, typically during spring or early summer, in habitats characterized by fine sand and silt substrate, and void of detritus and vegetation (Mullett and Bergstedt 2003). Fertilized eggs hatch in ~ 2 weeks, after which larvae burrow in the substrate within shallow streams (Manion and McLain 1971). Manion and McLain (1971) also noted a distinct pattern of larger larvae (>2 years) moving into deeper waters, where more organic detritus is present. This habitat preference is based on larval sea lampreys feeding on diatoms and organic detritus from their surrounding environment, only switching to blood and parasitism after metamorphosis (Manion 1967). When sea lampreys approach transformation, or metamorphosis, they begin accumulating fat reserves, allowing the progression from stream bed filter-feeding to open lake parasitism (Youson et al. 1979).

Typically, metamorphosis begins in early July, and lasts anywhere from 4 to 10 months (Potter 1980). Accompanying transformation is an ontogenetic habitat and diet shift from filter-feeding and burrowing in streams to parasitism on teleost fish (i.e., large bodied fish such as lake trout and lake whitefish) in the open lake. Although the parasitic phase for the anadromous sea lamprey lasts 23-28 months, it only lasts ~ 18 months in landlocked sea lamprey (Farmer 1980). Following the parasitic phase, sea lamprey return to tributaries, where they spawn and die (Applegate 1950). Sea lampreys do not home to their natal streams, but rather appear to choose spawning locations based on alternate cues, such as substrate, biota, or bile excreted by larvae, which might indicate availability of suitable larval habitat (Bergstedt and Seelye 1995) or where they end up in the lake post-parasitism.

The sea lamprey life cycle has had a great influence on the types of control methods applied, as well as their overall effectiveness. Electric and physical barriers, which are supposed to prevent adult sea lampreys from migrating upstream to spawn, are problematic because 1) their effect may take years to appear (since previous year-classes still exist), 2) they may not be effective at all if adults simply move to another stream to spawn (Smith and Tibbles 1980), and 3) they have the potential to limit migration of other native fishes. Focusing control on migrating, metamorphosing sea lampreys also is not practical, since metamorphosis occurs throughout a 6-month period (spring to fall), the time when the largest water volume must be screened (Smith and Tibbles 1980). Because of these drawbacks, the GLFC has moved towards trapping spawning adults, and more prominently targeting the larval stage using lampricides such as TFM and granular bayluscide.

Unfortunately, lampricides have many drawbacks as well, including costs for purchase and application, and mortality of non-target species (McLaughlin et al. 2003). Because of these costs, there is a need for methods to focus and prioritize control efforts on tributaries that contribute large numbers of parasitic and spawning phase lampreys. Currently, the primary method used to prioritize which streams will undergo lampricide treatment is an intensive survey of the larval distribution in a particular stream (using

Quantitative Assessment Surveys, QAS); lampricides are applied in streams with the highest larval density (Smith and Tibbles 1980). A complementary bioassay is also performed to determine the minimum amount of lampricide that must be applied to kill larvae and the maximum amount that can be applied without killing a significant number of non-target fish (Smith and Tibbles 1980). The QAS is based mostly on the presence, catch per unit effort and length frequency distribution of larvae, all factors which have proven difficult to quantify, especially for large streams. This approach also makes the potentially dangerous assumption that larvae will progress to the parasitic phase equally in all streams (i.e., survival is equal among streams), and therefore larval populations will correlate precisely with parasitic populations (Slade et al. 2003). Due to limitations of QAS and their impact on lampricide costs, other methods of identifying important sources of parasitic and spawning lampreys have been debated and in some cases tested. ,

One alternative for identifying which streams contribute parasitic sea lampreys and therefore are priorities for control efforts is the use of artificial tags. This approach has centered on coded wire tags for which a viable method of application was only recently developed (Bergstedt et al. 1993). Though this part of the technique has been mastered, even if tags are not lost physically from the sea lamprey, it likely will be difficult to recover tagged sea lampreys in sufficient numbers since they do not home to their natal streams (Bergstedt and Seelye 1995).

'Natural' tags offer an easier and more cost effective approach than artificial tags, since every individual is tagged at birth, and no application is required. Two methods are common in fisheries research: genetics and otolith microchemistry. The use of genetic markers for sea lamprey in the Great Lakes is not particularly feasible for two reasons. First, Great Lakes sea lamprey populations are recently established (only present since

~1920s), so they have not yet developed a clear genetic structure that would allow discrimination between individuals produced in different tributaries. Second, sea lampreys do not home to their spawning streams, preventing genetic differentiation among populations (Smith and Tibbles 1980). Thus, although some genetic structure was observed in Lake Superior sea lampreys, the relationship was weak, indicating several populations may possibly exist there (Krueger and Spangler 1981). Additionally, Jacobson et al. (1984) found sea lamprey ammocoetes (larvae) to be undesirable for stock identification studies since there was more allelic frequency variation within drainages than among them. Therefore, a natural tag that would indicate natal stream origins through environmental rather than genetic structure offers a preferable method.

One such natural tag whose application to fish stock delineation has been extensively explored is otolith microchemistry. Otoliths are the calcareous structures located in the inner ear of teleost fish, used for hearing and balance (Pannella 1971). Otolith research began when Pannella (1971) identified the structures as exhibiting daily growth rings which could be used to age fish. Since then, otoliths have been used for many fisheries related problems, such as stock delineation, tracing migration pathways, and reconstructing temperature and salinity histories (Campana 1999; Thresher 1999). Three unique properties of otoliths allow them to be used for this type of research: 1) they are metabolically inert (exhibit no reworking once layers are set down); 2) they continue to grow even when somatic growth is non-existent; and 3) their elemental composition reflects the physical and chemical environment in which the fish has resided in the past (Campana 1983; Campana and Nielson 1985; Campana and Thorrold 2001). Campana et al. (2000) found that specific trace elements show the physical and chemical characteristics of the surrounding water. Whether this would allow for discrimination between fish populations has been tested on several different species, such as American shad (*Alosa sapidissima),* which were classified back to their natal river with ~90% accuracy (Thorrold et al. 1998), and cutthroat trout (*Onchorhynchus clarki clarki),* which were reclassified with 100% accuracy (Wells et al. 2003).

Based on the ability of otolith microchemistry to discriminate between stocks of teleost fish, the extension of microchemistry to sea lamprey statoliths is logical. Statoliths are the calcified ear stones found in sea lampreys, analogous to the otoliths found in teleost fish (Carlstrom 1963). Whereas otoliths are comprised of calcium carbonate (usually aragonite), and typically continue growing in proportion to body size throughout the life of the fish, statoliths are 1) made of calcium phosphate (apatite), 2) are the only calcified structures found in an otherwise cartilaginous body, and 3) do not grow substantially post-metamorphosis (Volk 1986). Historically, statoliths were primarily used for aging. Sea lamprey, like most fish, display an internal banding pattern within their statoliths, with one opaque and one translucent band appearing each year (Volk 1986; Barker et al. 1997). However, although statolith growth and banding patterns are not significantly affected by photoperiod, sex, or age, when kept at a lower than natural temperature (8°C), no annuli form (Medland and Beamish 1991). In addition, Medland and Beamish (1991) found that sea lamprey continued producing bands through the final year of larval growth, even after the fish had begun storing lipids in preparation for metamorphosis.

Research on statolith aging has been important for our understanding of sea lamprey population structure, but up until recently has not directly affected sea lamprey control. To this end, preliminary work was conducted by Brothers and Thresher (2004) to determine whether the microchemistry of statoliths could be used to discriminate among sea lamprey from different spawning locations in Lake Huron and Lake Michigan. They concluded that 1) statoliths from different sites do show a difference in composition for some elements, 2) fish could be assigned to their natal streams with reasonable accuracy and 3) the St. Mary's River, a major producer of sea lampreys in Lake Huron, could be easily distinguished from other tributaries (Brothers and Thresher 2004). The sample sizes used, however, were very small (4-10 fish from each of five streams), and the instrument used for analysis, Particle Induced X-ray Emission (PIXE), limited their results due to poor detection capabilities for some elements and the long time required to analyze each sample (10-15 min) (Brothers 2003).

In the following studies, the methods behind the application of statolith microchemistry as a tool and the application of the tool at a large scale will be explored. In Chapter 2, we will develop the method through examination of several aspects, including method of analysis (Laser ablation inductively coupled plasma mass spectrometry vs. Particle induced x-ray emission), whether how the statolith is analyzed is important, whether preservation affects elemental concentrations, and how well streams from different lakes can be discriminated. In Chapter 3, we will focus on the large scale, and determine how well we can discriminate among streams in the Lake Huron watershed based on various groupings (geological zones, watersheds, and individual streams). In this section we ultimately define the application potential of this technique, as well as its limitations. Ultimately, we will make recommendations to management agencies (e.g., the GLFC) regarding their future implementation and integration of this technique into sea lamprey control efforts.

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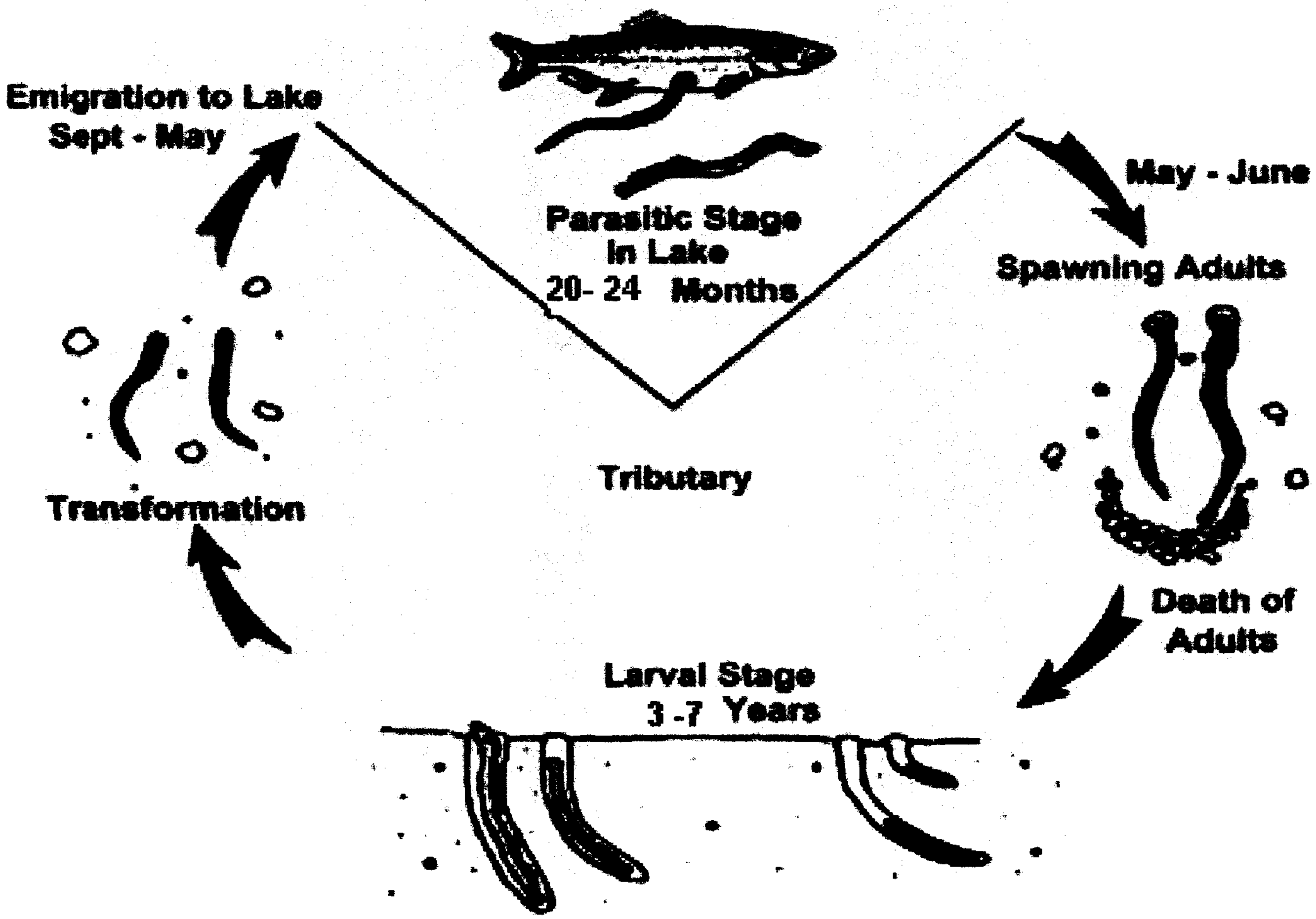

Figure 1.1. Sea lamprey life-cycle (Source: www.dnr.wi.gov).

CHAPTER 2:

Exploration of statolith microchemistry as a technique for identifying natal origins of sea lamprey (*Petromyzon marinus*)

Introduction

Sea lamprey (*Petromyzon marinus*) first invaded the upper Great Lakes during the early 20th century, following construction of the Welland Canal (Lawrie 1970). Since then, sea lampreys, normally anadromous, have adapted to the freshwater environment and extended their range to include all of the Great Lakes, where their impact on native fish communities has been devastating (Weise and Pajos 1998). The extent of the problem led to the creation of the bi-national Great Lakes Fishery Commission (GLFC), an agency that organizes and implements efforts to eradicate sea lamprey from the Great Lakes. Currently, control methods are based on larval distribution in production tributaries, where the streams with the highest larval density are qualified as most important and therefore a priority for treatment (Smith and Tibbles 1980). These Quantitative Assessment Surveys (QAS) are based on the presence of larvae, catch per unit effort and length-frequency distribution of larvae, but do not take into account that most likely larval populations will not correlate exactly with parasitic populations (Slade et al. 2003). Thus, with sea lamprey remaining a continual problem, the GLFC is still seeking a way to identify which streams are contributing the most parasites and spawning adults.

Tagging offers one possible method of identifying from which natal streams parasites and spawning adults are originating. Artificial tags are impractical for several reasons, the least of all being difficulty in application. Once sea lampreys have been tagged, there is a distinct likelihood that, even if tags are not lost physically, it will be difficult to recover tagged sea lampreys in sufficient numbers as they do not home to their natal streams and consequently there is substantial mixing among populations (Bergstedt et al. 1993; Bergstedt and Seelye 1995).

An alternative to artificial tags are natural tags, an area of research which includes genetics and otolith microchemistry. Genetics are not very feasible with sea lampreys, since the population in the upper Great Lakes has been present for less than a century, and, more importantly, sea lamprey do not home to their natal streams, so there is substantial mixing among populations (Bergstedt et al. 1993).

The more feasible alternative is otolith microchemistry. Otoliths are the calcareous structures located in the inner ear of teleost fish, used for hearing and balance (Pannella 1971). Otolith microchemistry has been used for many fisheries related problems, including stock delineation, tracing migration pathways, and reconstructing temperature and salinity histories (Campana 1999; Thresher 1999). Three unique properties of otoliths allow them to be used for this type of research: 1) they are metabolically inert (exhibit no reworking once layers are set down); 2) they continue to grow even when somatic growth is non-existent; and 3) their elemental composition reflects the physical and chemical environment in which the fish has resided in the past (Campana 1983; Campana and Thorrold 2001).

Herein we explore the potential extension of otolith microchemistry to statoliths, a calcified inner ear concretion found in sea lamprey that also exhibits annual banding patterns (Volk 1986; Barker et al 1997). Statoliths are analogous to the otoliths found in teleost fish (Carlstrom 1963). However, whereas otoliths are comprised of calcium carbonate (usually aragonite), and typically continue growing in proportion to body size throughout the life of the fish, statoliths are 1) made of calcium phosphate (apatite), 2) a fraction of the size of otoliths from most adult fish (averaging 50μm across) 3) the only calcified structures found in an otherwise cartilaginous body, and 4) do not grow significantly post-metamorphosis (Volk 1986). Statolith elemental chemistry is greatly influenced by the sea lamprey life cycle, which is dominated by a burrowing larval stage (3-7 years). Following the larval stage, sea lamprey spend up to two years as parasites before they become spawning adults and die, during which they add minimal material to the statolith. Consequently, the majority of the statolith material reflects the larval environment.

Only recently has preliminary work been conducted to determine whether statoliths could be used to discriminate between sea lamprey from different spawning locations and ultimately identify natal origins (Brothers and Thresher 2004). In their exploratory study, Brothers and Thresher (2004) used micro-PIXE analysis to demonstrate that statoliths from 4 different sites do show a difference in composition for some elements, and fish could be designated to their natal streams with reasonable accuracy (Brothers and Thresher 2004). Here we build on their findings, using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for analysis, which offers a method for examining trace elements at very low levels. In addition to determining if LA-ICP-MS can be used for analysis of larval sea lamprey statoliths, we further explore various factors influencing the technique, including storage method, sample size, ablation technique and method of analysis. Ultimately, we discuss the potential application of this technique for identifying natal origins of sea lamprey by quantifying our ability to discriminate larvae produced in lakes Huron, Michigan and Superior.

Materials and Methods

Field collections.

Sea lamprey larvae were collected from 17 streams within the Lake Huron, Lake Michigan and Lake Superior watersheds (Figure 2.1) by the Canadian Department of Fisheries and Oceans (Sault St. Marie, ON) and the U.S. Fish and Wildlife Service (Marquette and Luddington, MI field stations), as well as one stream (Lewis Creek) from Lake Champlain (NY-VT). All larval collections were made via electrofishing in the summers of 2004 and 2005 during post-lampricide surveys (biological collection and quantitative assessment surveys (QAS)) in recently treated streams. Larval samples were either provided to us stored in Nalgene® bottles preserved in 95% ethanol or frozen.

Larval sample preparation.

All statolith preparation took place in a Class 100 clean room. Prior to statolith removal, the total length (TL; to nearest millimeter) of each individual was measured, after which the head was removed. Bilaterally dissected heads were soaked in ultra-pure milli-Q water (MQW), and then both left and right statoliths were removed on a clean glass slide using clean glass probes. Removed statoliths were transferred using a clean glass probe to a drop of MQW in a clean, covered Petri dish. After 6 sets of statoliths had been removed, the covered Petri dishes were floated atop an ultra-pure MQW filled ULTRAsonik™ cleaner (model 57X; Ney Dental Inc. Bloomfield, CT, USA), where they were sonicated for 5 minutes (power = 0.5; degas = 0.75). Sonicated statoliths were then cleaned, and rinsed three times with MQW. Afterwards, the cleaned statoliths were mounted dorsal side up to a slide with Scotch™ double sided tape (Ludsin et al. 2006) for LA-ICP-MS analysis. No surface removal was necessary as the sea lamprey larvae were captured in their natal streams and therefore the desired signature is present throughout the entire statolith (Volk 1986).

All glassware and plastic-ware used was acid washed prior to use. Acid washing consisted of preliminary cleaning using Nitrox® soap, followed by a 24hr immersion in 13% nitric acid solution, a 24hr immersion in ultra-pure MQW water, and three final rinses with MQW. Finally, everything was dried over a 24hr period under a Class 100 laminar-flow fume hood.

Experimental set-up and data analysis.

Toward further developing micro-elemental analysis of statoliths as a technique that could be used by management agencies and researchers to identify natal origins of sea lamprey, we explored 1) multiple ablation techniques (drilling down versus across a transect), 2) the effects of ethanol vs. freezer storage as a preservation technique, 3) the likely minimum sample size needed to accurately represent a population, 4) differences between our LA-ICP-MS results and the PIXE results of Brothers and Threshers (2004) and 5) whether site-specific signatures differed among 3 of the Great Lakes, as well as within them.

LA- ICP-MS analysis.

Statoliths were analyzed using LA-ICP-MS. Our setup consisted of a Thermo Elemental X7 ICPMS, coupled with a Continuum solid state ND:YAG laser (wavelength: 266nm; max. power: 40mJ; pulse rate: 20Hz; beam width: 6mm). We quantified 11 elements (not including calcium, Ca) (Table 2.1), but only seven met our criteria for inclusion in analysis: magnesium (Mg), manganese (Mn), zinc (Zn), rubidium (Rb), strontium (Sr), barium (Ba) and lead (Pb). These criteria included a coefficient of variation (CV) that was less than 10% for individual isotopes and no more than two samples with concentrations below detection limits for the majority of streams. If a concentration was below detection limits for an element included in the analysis, a substitute was randomly generated between zero and the detection limit for that specific sample. All concentrations were calculated based on Calcium 43 normalization. To obtain elemental concentrations for statoliths, we traversed the entire width of the statolith (average integration time was 30 seconds), reducing the power to 1.10 kv and the beam diameter to 2mm to ensure that we did not burn through the statolith into the tape. We determined whether we burned through the statolith into the tape using the mass ^{120}Sn, representative of a carbon molecular ion (Ludsin et al. 2006). Data acquisition began with 60 seconds of background (using NIST-610 standard), followed by 10-60 seconds of sample analysis, and finished off with 30 additional seconds of background time.

Laser-ablation technique.

Statoliths grow in a conical shape, with the tip being the oldest material and the base being the most recently deposited. They do not grow substantially post-metamorphosis (Volk 1986). To ensure that the same elemental signature is found throughout the entire statolith, we compared elemental concentrations from a horizontal transect across the statolith to a vertical transect down through its apex. Left and right statoliths (from the same individual) from fish collected in the Sauble River and Lauzon Creek (n = 5 individuals per stream; Figure 2.1) were compared, using univariate paired t-tests (p = 0.05/ 7 elements = 0.007). To determine whether traversing the statolith or drilling down into the apex is the best approach for ablating statoliths with LA-ICP-MS, we compared differences in 1) average elemental concentrations, 2) average limits of detection and 3) average analysis duration. No data transformations were necessary (Kolmogorov-Smirnov test for normality, all $p \geq 0.20$). For all subsequent analyses we used traversed across the statolith.

Preservation method.

Due to logistical difficulties freezing larvae while in the field and difficulties (and cost) associated with preserving adults and parasites in ethanol, it has become clear that no single preservation technique for all life stages will suffice. Thus, we tested whether preservation (in ethanol versus freezing) has a significant effect on the trace elemental concentrations. Although preservation in ethanol does not appear to affect trace elemental concentrations in teleost fish (Milton and Chenery 1998; Proctor and Thresher 1998; Hedges et al. 2004), we tested the effects of ethanol preservation versus freezing on statoliths. To do so we used fish from both the Big Manistee River (Lake Michigan) and Lewis Creek (Lake Champlain) (Figure 2.1). For both streams, 30 larvae were preserved frozen, and another 30 were preserved in 95% ethanol. All statoliths were processed, mounted, and ablated as described above. Two sample t-tests ($p = 0.05/ 7$ elements $= 0.007$) were used to determine if elemental concentrations differed due to preservation technique. All data were log transformed to normalize them (Kolmogorov-Smirnov test for normality, all $p \geq 0.20$).

Sample size selection.

To determine the minimum sample size required to adequately represent a stream, we used larvae from Silver Creek, Lake Huron (n=45) (Figure 2.1). The minimum representative sample size was determined via bootstrapping, wherein random sub-samples consisting of 10, 15, 20, 25, 30 and 40 fish were drawn (n= 500 replicates per sample size). We compared individual element concentrations using a multivariate one-way analysis of variance (MANOVA, $p = 0.05$). Subsequently, we conducted a one-way ANOVA on individual elements. We log-transformed Mn, Zn, Rb and Sr, and took the reciprocal of Mg, Ba and Pb to normalize the data (Kolmogorov-Smirnov test for normality, all $p \geq 0.20$).

PIXE versus LA-ICP-MS.

Both particle induced x-ray emission (PIXE) and LA-ICP-MS have shown promise for trace-element analysis of otoliths (Campana et al. 1997). Previously, Brothers and Thresher (2004) used PIXE to successfully demonstrate that statolith microchemistry could be used to discriminate among sea lamprey collected in four Lake Huron tributaries: St. Mary's River (two sites), the Pigeon River, the Rifle River and the Black Mallard River (n= 4-10 individuals per site). We collected larvae from the same rivers (but different sites), except for substituting Loeb Creek for the Pigeon River (Figure 2.1). To evaluate similarities in our results, we compared untransformed values for both methods. We then performed a Linear Discriminant Function Analysis (LDFA) to compare data between the two analyses. LDFA predicts group membership for individuals based on a set of predictors, in this case trace elements.

Among- and within- lake comparison.

To explore whether sufficient variation exists with micro-elemental analysis of statoliths to differentiate among individuals spawned in different streams in the Great Lakes, we ran an analysis using larvae collected from several tributaries in three different Laurentian Great Lakes. We used two tributaries from Lake Superior (Bad River and

Brule River), four tributaries from Lake Michigan (Loeb Creek, Boardman River, Ford River, White River) and six tributaries from Lake Huron (Musquash River, Nottawasaga River, Saginaw River, St. Mary's River, Black Mallard Creek, Rifle River) (n = 10-25 for each stream) (Figure 2.1). The ability to discriminate among streams was tested using stepwise linear discriminant function analysis (LDFA). All data were log transformed to ensure normality (Kolmogorov-Smirnov test for normality, all $p \geq 0.20$).

Results

Laser ablation technique.

For the seven elements analyzed (Mg, Mn, Zn, Rb, Sr, Ba and Pb), no significant differences were found between the two ablation methods (Table 2.2). Limits of detection (LOD) also did not differ between methods for any element (Table 2.2). By contrast, however, we found that the average (+ 1 SE) ablation (analysis) time was significantly longer (22.9 +/- 8.3 seconds; ranging from 12.7 to 39.8 seconds) for statoliths that were traversed versus those that were ablated down through the apex (9.4 +/- 3.1 seconds; ranging from 4.2 to 14.9 seconds) ($p < 0.00022$).

Preservation.

For both Lewis Creek and the Big Manistee River, no difference between elemental concentrations of statoliths from fish stored differently was found for Mg, Mn, Zn, Sr, Ba, and Pb. However, for both streams Rb showed a statistical difference between frozen and ethanol stored samples ($p \leq 0.0047$). Rb concentrations (ppm) were higher in the fish preserved in ethanol than those frozen. Importantly, however, the average difference was small for both the Big Manistee River (average difference 0.552 ppm), and Lewis Creek (average difference 0.120 ppm), while the average differences between the two were 2.0 ppm for frozen fish and 1.3 ppm for ethanol preserved fish.

Sample size.

Analysis of the minimum sample size that could be used to represent a stream suggested that even a sample size as small as 10 individuals could be used, given that no difference in site-specific signatures were found among sample sizes of 10, 15, 20, 25, 30 and 40 individuals (MANOVA: p = 0.28). However, further inspection of univariate differences revealed that a sample size of 10 produced different results for Zn and Pb than for all larger size classes, whereas none of the larger samples sizes (15 to 40 individuals) differed (ANOVA, Tukey's post-hoc test: p = 0.007 and 0.012 for Zn and Pb, respectively).

PIXE vs LA-ICP-MS.

Brothers and Thresher (2004) used PIXE to analyze larval sea lamprey statoliths for 9 elements (other than Ca): Rb, Zn, Pb, Mn, Sr, Fe, Hg, Cu and Ni, but found that Ba data were not always reliable. We quantified 11 elements (Table 2.1), but found that only 7 (Mg, Mn, Rb, Sr, Zn, Ba, and Pb) were useable.

The ranges of concentrations were generally tighter for LA-ICP-MS than for PIXE analyses (Figure 2.2). For all four streams Rb, Sr, Pb and Ba are on the same scale as the Brothers and Thresher (2004) samples, but in each case the LA-ICP-MS samples fall within a tighter, lower range. For Zn, the values were also comparable, though LA-ICP-MS had a few instances of one extreme concentration. Manganese is the major exception to the trend, where LA-ICP-MS had two streams (St. Mary's River and Loeb Creek) with lower concentrations and smaller ranges, but for the two other streams

(Black Mallard River and Rifle River), PIXE concentrations were tighter. The LA-ICP-MS results do agree with Brothers and Thresher's (2004) observations that Rb values for the Black Mallard are higher in comparison with the other streams in this analysis, but disagree with Brothers and Thresher that the St. Mary's River has considerably lower Sr values than the other streams.

Brothers and Thresher (2004) plotted Sr against Rb (the two most important elements for discrimination in their study) to show effectively how their four streams can be distinguished (see Figure 5 in their study). We plotted the same elements, resulting in a virtually identical graph (Figure 2.3). Importantly, however, our x-axis (0-1200 ppm) and y-axis (0-10ppm) ranges were smaller than theirs (0-2400 ppm and 0-70 ppm for their x-axis and y-axis, respectively; see figure 5 in their study).

Brothers and Thresher (2004) ran two LDFAs, one for all four streams and one for the St. Mary's River versus the other three streams (all found in lower Michigan). In their LDFA analysis where all streams were discriminated, the first two roots were dominated by Rb, the third by Fe, Mn and Zn, and the fourth by Sr, with the first two roots explaining 89% of the variation. In our similar analysis, we found our first two roots were dominated by Rb, Sr, and Mn, and explained 96% of the variation, with the residual 4% being explained by one additional root (Table 2.3). Thus, both studies concur in that Rb is the most important discriminator, regardless of method (or year), and that Mn and Sr are somewhat important.

Brothers and Thresher (2004) demonstrated success in their attempt to discriminate between the St. Mary's River and three (combined) streams in the lower peninsula of Michigan. In fact, they were able to discriminate with 94% accuracy, having only one sample from the St. Mary's River classified as from the lower peninsula (1 out of 18) and one sample from the lower peninsula misclassified as St. Mary's River (1 out of 17). We found similar (89%) discrimination success, with 3 of 35 Michigan fish classified as St. Mary's River individuals and 4 of 30 St. Mary's River fish classified as Michigan ones. Further, in both studies, Mn and Rb were the most important discriminators, explaining 100% of the variation between the St. Mary's River and Lower Peninsula streams.

Among- and within-system discrimination.

Our LDFA of 12 streams from Lake Superior, Lake Huron, and Lake Michigan allowed us to classify the larvae back to their correct stream with an average accuracy of ~80%, with individual stream accuracies ranging from 30% to 100% (Table 2.4). In fact, 7 of the 12 streams had ≥ 80% correct reassignment including two streams from Lake Superior, one from Lake Michigan and four from Lake Huron (Table 2.4). In figure 2.4 we see illustrated the difference between two streams with very good separation (Brule River and Black Mallard River) and two streams that consistently are misclassified as one another (Rifle River and Saginaw River). Our LDFA indicated that all seven elements (Mg, Mn, Zn, Rb, Sr, Ba, Pb) were important for explaining variation among streams. Though all were significant, we found that Mn, Sr and Rb were the most important elements, explaining 74% of the variation present within 2 roots. By adding root 3, dominated by Mn, an additional 12% of the variation was explained (cumulative ~86%); 100% of the variation can be explained with all 7 elements over a total of 7 roots (Table 2.5). Magnesium, Pb and Zn were largely unimportant for discriminating sites, being most related to axes that explained relatively little variation (<2%; table 2.5).

Discussion

Our investigation indicates promise for statolith microchemistry as a technique to discriminate among individuals produced in different streams, similar to the results of Brothers and Thresher (2004). Further, as we explain below, this technique seems robust in that there appears to be considerable flexibility in sample size requirements and how statoliths are preserved, ablated and analyzed (LA-ICP-MS versus PIXE).

We found no difference between elemental concentrations for statoliths ablated across (horizontal traverse) versus those that were ablated through the apex (vertically). This result was expected given that larval sea lampreys burrow into stream sediments for the entire larval period (Volk 1986). We found no significant difference between limits of detection either. The raw values show that the vertical LODs were slightly higher, but not significantly so. LA-ICP-MS has been shown, along with PIXE, to be effective at accurately quantifying trace elements in very small concentrations, and therefore a slight difference in LOD is inconsequential (Campana et al. 1997). We found only one significant difference between laser techniques, and that was in time for analysis. Not surprisingly, substantially more material is ablated with the horizontal traverse than the vertical. Analysis time for individual samples varied considerably, but the mean value for the horizontal traverse is almost 3 times longer than the vertical. Consequently, without affecting our concentrations or limits of detection, we can significantly increase the amount of data we are gathering by traversing across the statolith.

Analysis of statolith storage techniques demonstrated minimal difference between freezing and ethanol storage. Specifically we found no significant differences in concentrations of Mg, Mn, Zn, Sr, Ba, and Pb, which is consistent with previous findings that preservation method has no effect on otolith/statolith trace element concentrations (Milton and Chenery 1998; Proctor and Thresher 1998; Hedges et al. 2004; Brothers and Thresher 2004). The one deviation from these findings is that Rb is slightly higher in ethanol preserved fish than in frozen ones. Although this difference is statistically significant, it is small enough in magnitude that it should not prove biologically significant. Our two test streams demonstrate this, where the mean difference between freezing/ethanol within a stream was 0.12 ppm and 0.53 ppm, whereas the mean difference among streams is much greater (1.4 ppm for frozen fish; 1.9 ppm for ethanol-preserved). The issue of preservation is of particular concern for the use of statolith microchemistry as a tool, since it is logistically difficult and cost-prohibitive for regulatory agencies to preserve adults and larvae using the same method. For larvae it is difficult, due to space limitations, to have a cooler in the field, while for adult collection it is not cost-effective to store the fish in ethanol due to their size. Our analysis has shown that the necessity of employing different methods of preservation for larvae and adults in the field is acceptable, as preservation method has no significant impact on elemental concentrations.

The GLFC is currently seeking a cost effective method for identifying which natal streams are producing the most parasitic and spawning phase sea lamprey. Consequently, applying this technique requires comparison of a large number of streams. For this reason, we need to know the smallest possible sample size that will still accurately represent individual streams. The results of our multivariate analysis indicate that 10 fish should be sufficient, though due to some differences in univariate results we suggest using a minimum sample size of 15 fish.

Overall, comparison of our results with Brothers and Thresher's (2004) indicated that both techniques are suitable for trace-metal analysis of statoliths, but also that neither is perfect. For both methods, concentrations of elements were comparable, though LA-ICP-MS often exhibited a tighter range. Both techniques are able to analyze a large number of trace elements at low concentrations, though a major factor influencing both techniques is the limit of detection for individual elements. For example, PIXE was able to analyze Fe accurately and precisely, where LA-ICP-MS was not, due to its low abundance in statoliths and high LOD by LA-ICP-MS (Campana et al. 1997). Conversely, LA-ICP-MS was able to precisely and accurately analyze for Ba, an element PIXE is notoriously unable to analyze for at low levels (Campana et al. 1997; Brothers and Thresher 2004). While LA-ICP-MS has difficulty analyzing for certain elements like mercury (Hg), iron (Fe) and nickel (Ni), none of these elements were found to be major site discriminators by Brothers and Thresher (2004). For statolith microchemistry there are clear trade-offs to be made depending on which technique is used for analysis, but either way the pattern in the results is consistent.

Two major differences between analyzing statoliths using PIXE and using LA-ICP-MS are notable: time required for analysis and invasiveness of the technique. Not including sample preparation, PIXE requires between 10-15 minutes per sample, while LA-ICP-MS only requires 3-5 minutes. This difference in time may prove crucial, particularly when taking into account the number of necessary replications required to apply the technique to fisheries management. PIXE is relatively non-invasive, while LA-ICP-MS ablates the sample, destroying it in the process. In addition to technical differences between methods, a major advantage of LA-ICP-MS is the wider availability of machines and lower cost for analysis than PIXE, logistics that will greatly influence the implementation of statolith microchemistry as a technique by fisheries management agencies.

Overall, our results indicate that statolith microchemistry shows promise as a means to discriminate among individuals produced in different streams within the Great Lakes. The LDFA testing discrimination among lakes was only able to discriminate with ~60% classification accuracy. This poor discrimination demonstrates that streams within a lake basin vary substantially enough that no single stream could represent the entire lake. The LDFA to discriminate among streams within Lake Huron, Lake Michigan and Lake Superior improved classification dramatically, up to ~80% accuracy. This illustrates the fact that sufficient variation exists to discriminate among natal streams of parasitic and spawning phase sea lampreys. Our ability to discriminate among streams is not perfect; several streams share a common signature. This commonality may be dictated by the environmental factors influencing a stream, such as local geology or location in a watershed, since the larval period is spent burrowing in sediment. For example, in the stream LDFA, of the streams incorrectly classified, four streams located in close proximity and consistently misclassified as one another (Saginaw River, Loeb Creek, Rifle River and White River: Figure 2.1) share a common geological source. In contrast to this, two streams located in relatively close proximity but from different watersheds (Nottawasaga River and Musquash River) were not misclassified as one another and differentiated out almost perfectly. From this we see that relative location holds very little bearing over our ability to discriminate, but the importance of geology and watershed influences is significant.

Conclusion

Overall, from this study we can conclude that statolith microchemistry is a viable technique for discriminating among individuals produced in different streams. The method of storing the fish is not a significant factor, since there is little difference between elemental concentrations of ethanol-stored or frozen fish. For analyzing statoliths we advocate the use of LA-ICP-MS since, although PIXE is a valid method of analyzing for trace metals, LA-ICP-MS has lower limits of detection for elements significant for classification, is more widely available, is faster and has lower analytical costs. While our results suggested that 10 individuals per stream would be sufficient to accurately depict a stream, we recommend that a minimum of 15 fish are used. At present, from our small scale LDFA we conclude that streams do show sufficient variation to be discriminated amongst, and that variation is most likely influenced by local geology and watershed. Further experimentation is needed to fully explore the impact of these factors, as well as additional limitations of the application of the technique.

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Table 2.1. Isotopes quantified (not including calcium) using LA-ICP-MS. Mean limit of detection (LOD) was calculated based on all samples run. The coefficient of variation (CV) is the average for all runs, and was calculated as mean divided by standard deviation of NIST-610 standards. Isotopes shaded in gray met our criteria for inclusion in analysis.

Isotope	**^{7}Li**	[illegible]	[illegible]	**^{57}Fe**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**^{140}Ce**	[illegible]	**^{238}U**
Mean LOD (ppm)	0.750	13.6	0.466	77.9	0.671	0.291	2.09	0.234	0.516	0.143	0.575	0.528	0.023
CV (%)	6.03	3.52	3.18	12.9	6.32	5.25	2.50	2.22	3.33	3.52	3.67	6.16	5.39
% above LOD	3.1	100	100	72.7	96.0	99.1	100	100	100	100	32.0	82.4	4.2

Table 2.2. Comparison between average elemental concentrations and limits of detection (LOD) of paired statoliths traversed across versus drilled down (N=10).

Element	Method	Element Mean	SE	p	LOD Mean	SE	p
Mg	Across	3792	104.65		9.72	0.20	
Mg	Down	3324		0.022	10.6		0.412
Mn	Across	23.8	0.00		0.405	0.01	
Mn	Down	23.8		0.995	0.446		0.059
Zn	Across	20.7	1.90		0.576	0.06	
Zn	Down	29.2		0.564	0.833		0.097
Rb	Across	3.06	0.03		0.145	0.00	
Rb	Down	3.21		0.451	0.157		0.164
Sr	Across	367	4.25		0.300	0.02	
Sr	Down	348		0.027	0.371		0.488
Ba	Across	19.7	0.63		0.077	0.01	
Ba	Down	22.5		0.515	0.054		0.504
Pb	Across	0.202	0.00		0.024	0.00	
Pb	Down	0.206		0.944	0.02		0.366

Table 2.3. Standardized coefficients of variation from canonical analysis of St. Mary's River versus streams in the lower peninsula of Michigan. The cumulative proportion of variation is provided. Bolded values indicate values most strongly associated with that root.

Standardized Coefficients			
	Root 1	Root 2	Root 3
Rb	**-0.901**	-0.004	**-0.722**
Sr	**1.19**	0.252	**-0.83**
Mn	-0.243	**0.774**	**0.913**
Ba	-0.646	-0.154	0.316
Pb	0.196	-0.53	-0.345
Zn	-0.168	0.445	0.306
Mg	0.160	0.185	-0.358
Cum.Prop	0.654	0.955	1.00

Table 2.4. Classification matrix for 12 streams from Lake Huron, Lake Michigan and Lake Superior. Numeric designations to the left of the stream names are carried over along the top. Letters following stream name (H, M, S) denote which lake the stream drains into (see Figure 2.1). Correct classifications are shown in bold font.

	Classification Matrix													
	Stream	% Correct	1	2	3	4	5	6	7	8	9	10	11	12
1	Black Mallard R. (H)	100	**12**											
2	Loeb Cr. (M)	60.0		**6**	1		1	1		1				
3	Rifle R. (H)	30.8		2	**4**							1	4	2
4	St. Mary's R. (S/H)	90.0		1		**27**		1		1				
5	Bad R. (S)	80.0				1	**12**	1				1		
6	Boardman R. (M)	60.0		1				**6**	1			1		1
7	Brule R. (S)	100							**15**					
8	Ford River (M)	81.8	1							**9**			1	
9	Musquash R. (H)	100									**25**			
10	Nottawasaga R.(H)	93.3					1					**28**		1
11	Saginaw R. (H)	60.7			4					3			**17**	4
12	White R. (M)	70.0		1	1								1	**7**
	Total	80.4	13	11	10	28	14	9	16	14	25	31	23	15

Table 2.5. Standardized coefficients of variation from canonical analysis of 12 streams within the Great Lakes, with Lake Huron represented by 6 streams, Lake Michigan by 4 streams and Lake Superior by 2 streams. The cumulative proportion of variation explained by each axis is presented. Bolding indicated the elements most strongly associated with that root.

Standardized Canonical Scores	Root 1	Root 2	Root 3	Root 4	Root 5	Root 6	Root 7
Rb	0.239	**-0.743**	-0.535	0.281	0.311	0.033	-0.017
Sr	**0.893**	**0.757**	-0.264	0.156	0.080	0.253	0.309
Mn	0.559	-0.182	**0.811**	0.023	-0.276	-0.262	-0.039
Ba	-0.465	-0.53	-0.408	**-0.833**	-0.229	-0.564	-0.042
Mg	0.169	0.109	0.163	-0.507	**0.632**	0.400	-0.395
Pb	0.071	-0.243	0.017	-0.211	-0.641	**0.82**	0.103
Zn	-0.314	-0.01	0.23	0.105	0.591	-0.191	**0.842**
Cum.Prop	0.441	0.741	0.861	0.943	0.981	0.995	1.00

Figure 2.1. Sample site locations in Lake Huron, Lake Michigan and Lake Superior (designated as H, M and S, respectively). Streams are: 1) Sauble River (H), 2) Lauzon Creek (H), 3) Big Manistee River (M), 4) Silver Creek (H), 5) Loeb Creek (M), 6) St. Mary's River (S/H), 7) Black Mallard River (H), 8) Rifle River (H), 9) Bad River (S), 10) Brule River (S), 11) Boardman River (M), 12) Saginaw River (H), 13) Nottawasaga River (H), 14) Musquash River (H), 15) Ford River (M), and 16) White River (M).

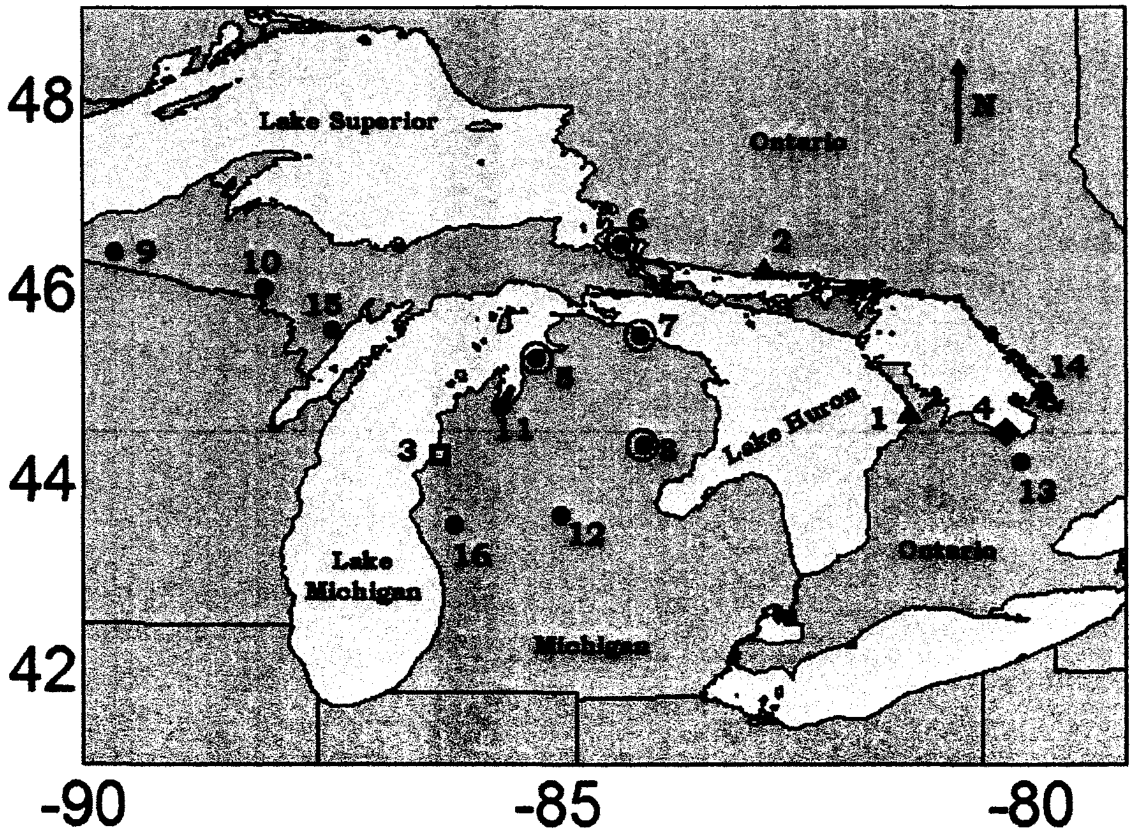


Figure 2.2. Plots of elemental concentrations for PIXE and LA-ICP-MS from four Lake Huron and Lake Michigan streams. The streams are: St. Mary's River (top row), Black Mallard River (2nd row), Rifle River (3rd row) and Pigeon River (PIXE)/Loeb Creek (LA-ICP-MS) (bottom row).

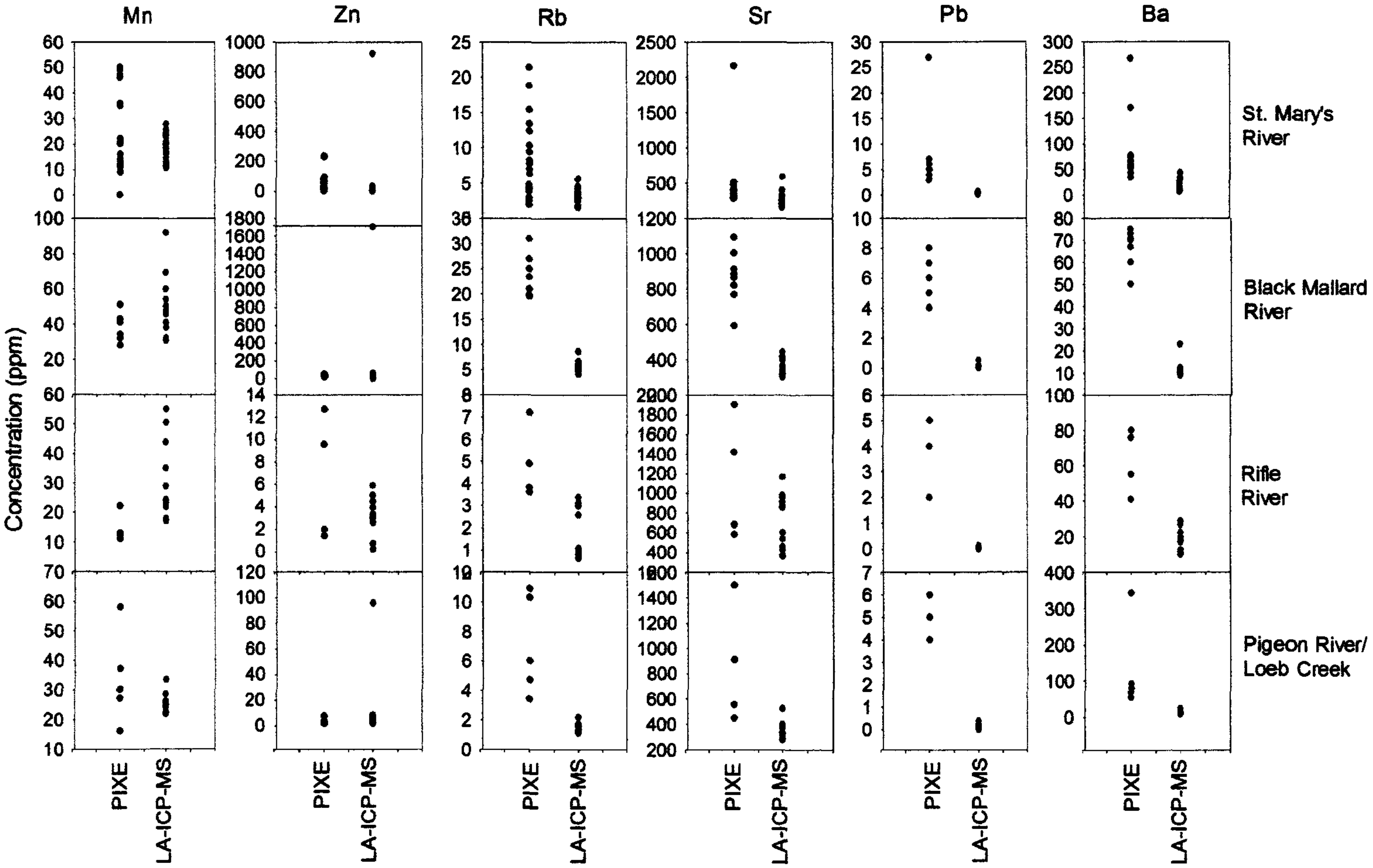


Figure 2.3. Strontium versus Rb concentrations for the four streams compared by Brothers and Thresher's (2004).

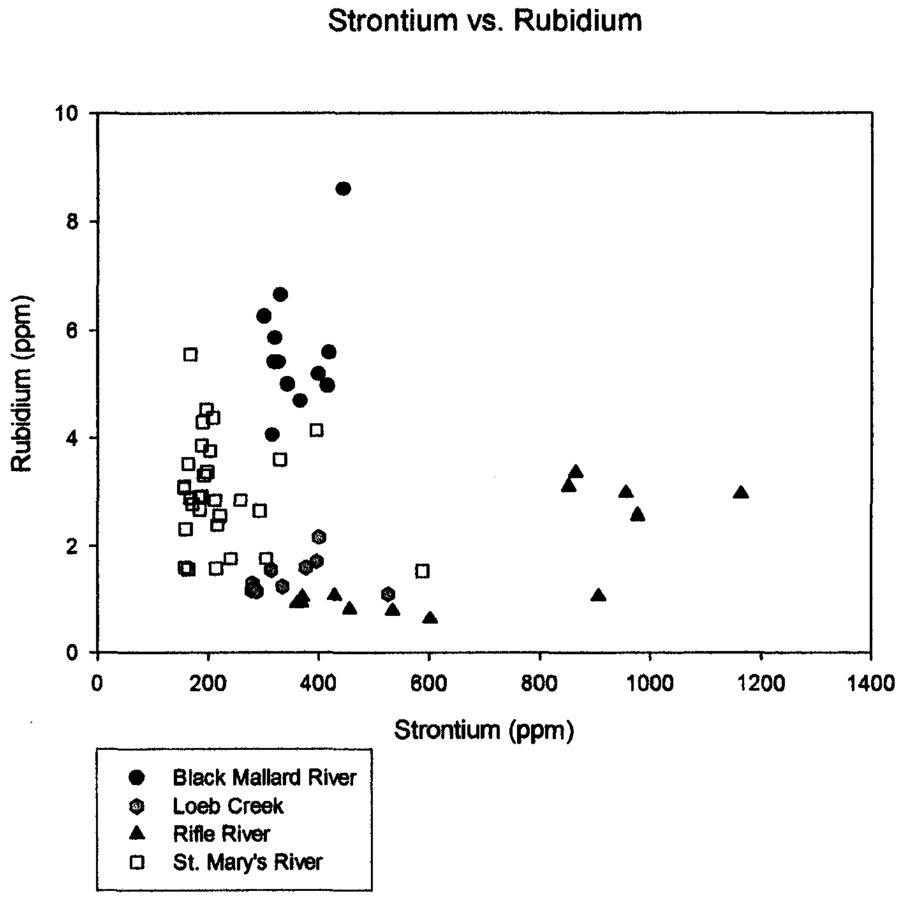
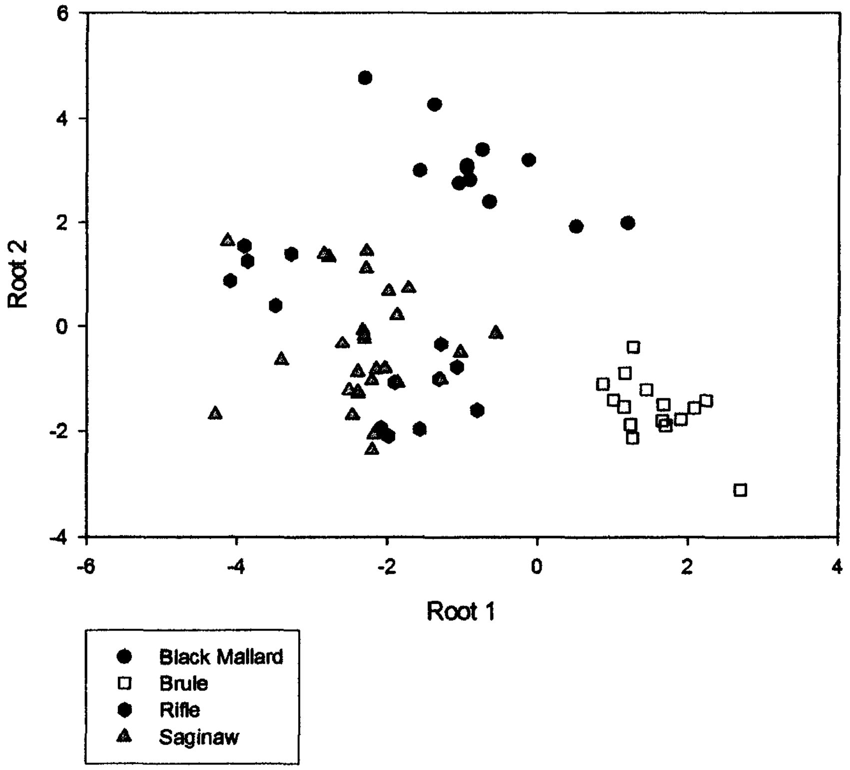


Figure 2.4. Graph of LDFA root 1 versus root 2, which combined explained 74% of the variation among streams. The four streams plotted here illustrate streams that discriminate well (Brule River (S) and Black Mallard River (H)), and streams that share a similar signature (Saginaw River (H) and Rifle River (H)).



Chapter 3:

Ability of Statolith microchemistry to discriminate amongst Sea lamprey (*Petromyzon marinus*) larvae from Lake Huron

Introduction

Sea lamprey (*Petromyzon marinus*) first invaded the upper four Laurentian Great Lakes following construction of the Welland Canal in the early 20th century (Lawrie 1970). Since that time, sea lampreys have adapted and extended their range to include all of the Great Lakes, where their impact on native fish communities has been devastating (Weise and Pajos 1998). The magnitude and extent of their impact resulted in the creation of the Great Lakes Fishery Commission (GLFC), a bi-national agency that oversees sea lamprey control efforts throughout the Great Lakes. These efforts include the creation of physical and electrical barriers to prevent upstream migration of spawners, trapping of adult spawners, sterile male release programs, and application of lampricides (i.e. granular bayluscide; 3-trifluoromethyl-4-nitrophenol TFM) to larval production streams (Smith and Tibbles 1980). In turn, the abundance of parasitic phase sea lampreys declined by as much as 90% in some lakes leading up to 1970, only to rebound and increase dramatically since that time in other systems (Young et al. 1996). As such, millions of dollars are still spent annually on these various control efforts. Given the expense of these efforts, the GLFC is seeking a reliable method to identify important tributary sources of sea lamprey so that control efforts can be better prioritized (Schleen et al. 2003).

Since sea lamprey control efforts began in the 1950s, the primary focus has been on either preventing spawning, accomplished by stopping upstream migration of spawning adults with barriers and releasing sterile males into the environment, or killing larvae prior to metamorphosis, accomplished by applying lampricides to known production streams (Smith and Tibbles 1980). Focusing control efforts on the larval stage is most sensible, however, since while most Great Lakes fish have short larval stages (from weeks to months), sea lampreys spend 3-7 years of their lives as larvae in a single tributary, only emerging as parasitic juveniles in the open lake during their final 1-2 years of life (Potter 1980; Manion and McLain 1971; Quintella et al. 2003).

Unfortunately, lampricides have drawbacks, including costs for purchase and application, and mortality of non-target species (McLaughlin et al. 2003). Owing to these costs, the GLFC is seeking methods to allow them to focus and prioritize control efforts such that only tributaries that contribute large numbers of parasitic and spawning phase sea lampreys are targeted. Currently, the primary method used to prioritize streams that will undergo lampricide treatment is an intensive survey of the larval distribution in streams (a Quantitative Assessment Survey, QAS). The QAS is based mostly on the presence of larvae and the length frequency distribution of larvae, both of which have proven difficult to quantify, particularly for large streams. This approach also assumes that all larvae will progress to the parasitic phase (i.e., survival is equal among streams), and therefore, the number of parasites emerging from streams correlates precisely with the number of larvae produced in those streams (Slade et al. 2003). In turn, streams with the highest larval density generally get highest priority for lampricide treatment (Smith and Tibbles 1980). Given the strong likelihood that larval survival varies among streams, the GLFC is seeking other methods of identifying important sources of parasitic and spawning lampreys.

Artificial tags offer one alternative for determining the differential contribution of larval production streams to parasitic and spawning adult populations. Toward this end, Bergstedt et al. (1993) developed a coded wire tagging program for Great Lakes sea lamprey. However, as with all artificial tagging programs in large systems, the likelihood of short-term success is low, owing to the difficulty and expense of tagging and recovering sufficient numbers of individuals. Recovering tagged individuals also seems especially difficult for sea lamprey, given that individuals do not home to their natal streams (Bergstedt and Seelye 1995).

'Natural' tags offer an easier and more cost effective approach, since every individual is tagged at birth, (i.e., no application is required). Two methods are common in fisheries research: genetics and otolith microchemistry. The use of genetic markers for sea lamprey in the Great Lakes is not particularly feasible since populations are recently established (only present since ~1920s), so they have not have developed a clear genetic structure, and sea lamprey do not home to their spawning streams, thereby preventing genetic differentiation among populations (Smith and Tibbles 1980). Indeed, Jacobson et al. (1984) found sea lamprey larvae to be undesirable for stock identification studies, given that allelic frequency variation within drainages was greater than among them.

Owing to the limitations of genetic approaches, the other natural tag, otolith microchemistry (statolith microchemistry in the case of sea lampreys), offers more promise. Statoliths are the calcified ear stones found in sea lampreys, analogous to the otoliths found in teleost fish (Carlstrom 1963). Whereas otoliths are comprised of calcium carbonate (usually aragonite), and typically continue growing in proportion to body size throughout the life of the fish, statoliths are made of calcium phosphate (apatite), are the only calcified structures found in an otherwise cartilaginous body, and do not grow substantially post-metamorphosis (Volk 1986). Preliminary work by Brothers and Thresher (2004) concluded that not only is it possible to use scanning proton microprobe (micro-PIXE) to discriminate among Lake Huron streams using statolith micro-elemental composition, but the St. Mary's River, a major producer of sea lampreys in Lake Huron, could be easily distinguished from other tributaries (Brothers and Thresher 2004). More recently, Hand et al. (submitted) explored the potential of laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) to quantify statolith microchemistry in Great Lakes sea lamprey, and arrived at a similar conclusion to Brothers and Thresher (2004). However, in both of these sea lamprey statolith investigations, less than 12 Lake Huron production streams were investigated, whereas >60 potential production streams exist in the Lake Huron watershed. As such, whether individual streams can be sufficiently discriminated from enough other streams to benefit sea lamprey control efforts in Lake Huron remains unknown.

Herein, we build on these two previous statolith microchemistry investigations by exploring variation in statolith micro-elemental signatures among 45 Lake Huron larval production streams. In addition to determining how well individual streams can be discriminated from one another, we explore the effects of local geology and watershed characteristics on our results, as well as quantify inter-annual variability in stream-specific signatures. Ultimately, we provide recommendations concerning the future use of this technique to eventually identify natal origins of parasitic- and spawning-phase sea lamprey in Lake Huron and other Great Lakes.

Materials and Methods

Field collections.

Sea lamprey larvae were collected from 45 Lake Huron tributaries by the Canadian Department of Fisheries and Oceans (Sault St. Marie, ON) and the U.S. Fish and Wildlife Service (Marquette, MI and Luddington, MI field stations) (Figure 3.1). All larvae were collected via electrofishing during post-lampricide surveys (biological collection and quantitative assessment surveys (QAS)) in 2004 and 2005. Larval samples were provided to us stored in 95% ethanol, which does not appear to affect trace elemental concentrations in sea lamprey statoliths (Brothers and Thresher 2004; Hand et al. submitted). For this study, we processed 6 to 30 individuals per stream, deviating from the suggested 15 samples (Hand et al. submitted) when a limited number of samples were available, there was more than one year of data, or ^{120}Sn concentrations were high enough to suggest possible contamination (Table 3.1).

Larval sample preparation.

All statoliths were prepared in a Class 100 clean room. Prior to removal, the total length (TL; to nearest mm) of each individual was measured, after which both statoliths were removed and rigorously cleaned according to the protocol in Hand et al. (submitted). Afterwards statoliths were mounted dorsal side up to a glass slide with Scotch^{TM} double sided tape (Ludsin et. al. 2006). Statoliths were analyzed with LA-ICP-MS, using a Thermo Elemental X7 ICPMS coupled to a Continuum solid state ND:YAG laser (wavelength: 266nm; max power: 40mJ; pulse rate: 20 Hz; beam width: 6mm). We quantified 11 elements with LA-ICP-MS (Table 3.1) by traversing the entire width of the statolith, only finding the following seven (not including calcium) suitable for analysis, using the criteria of Ludsin et al. (2006) and Hand et al. (submitted): magnesium (Mg), manganese (Mn), zinc (Zn), rubidium (Rb), strontium (Sr), barium (Ba) and lead (Pb).

Data analysis.

To identify the resolution at which streams can be discriminated, and also to determine the effect of watershed and geology bedrock record on our discrimination ability, we used forward stepwise linear disriminant function analysis (LDFA; Statistica software, Statsoft Inc., Tulsa, OK). We ran three separate LDFAs to explore our ability to discriminate individuals collected in different groupings: 1) geologic zones (n=4 zones: older Paleozoic, Southern/Superior, Grenville and younger Paleozoic (Figure 3.2)); 2) major watershed (n=9 watersheds: Lone Lake Ocqueoc, North Lake Huron, Carp-Pine, Aues Gres-Rifle, East Georgian Bay, St. Mary's, Titabawasee, East Lake Huron and Wanipiti-French (Figure 3.1)); and 3) streams (n=45 streams) (Table 3.2; Figure 3.1). In each LDFA, our suite of seven elements (Table 3.1) was used to predict group membership. In addition, because larval sea lamprey total length varied among streams (ANOVA: F= 14.21, p= 0.00; Table 3.1), we used average stream total length as a covariate in all analyses (Ludsin et al. 2006) to guard against potential physiological effects on site-specific signatures. For entry into our model, a predictor had to have a minimum F-value and tolerance equal to one. Classification accuracies were determined by a jackknifing procedure, conducted as part of a default stepwise LDFA. In instances where an element was below the sample limit of detection (LOD; see Ludsin et al. 2006 for its determination), we replaced each missing value with a random value generated from between that sample's LOD and 0 (using a uniform probability distribution).

All elements were natural-log transformed prior to analysis to normalize the data (Kolmogorov-Smirnov test for normality: all p>0.20). Alpha levels were set at 0.05.

Results

Geology

When streams were grouped according to geologic zone, Sr, Mn, Rb and Zn were most important for discrimination, all being negatively correlated with LDFA root (axis) 1 (Table 3.3). Strontium also was positively related to LDFA root 2, while Rb also was negatively related to it (Table 3.3). In total, the first two roots explained 93% of the variation among geologic zones. Root 3, which explained the remaining variation, was dominated by Mn (negatively related) and total length (TL) (positively related). Lead also was statistically significant in our model, but its relative importance for explaining variation among streams within different geologic zones was minimal.

Using geologic zones as a grouping variable, we were able to correctly classify 69.7% of the individuals, with classification success for individual zones ranging from 66% to 81% (Table 3.4). From analysis of our classification matrix, we could distinguish the Grenville effectively from both younger Paleozoic and older Paleozoic due to high levels of Mn, Rb and Sr and low Zn, and we could distinguish the younger Paleozoic from Grenville and Southern/Superior due to low Mn and Rb and high Sr and Zn values (Table 4; Figure 3.3). By contrast, fish from older Paleozoic substrates were consistently mistaken for all other zones, owing to the large range of elemental concentrations in individuals collected throughout this region (Mn: 7-360 ppm, Zn: 0.05-1704 ppm, Rb: 0.4-11 ppm, Sr:95-1468 ppm). Ultimately, the two geologic zones we could reliably discriminate from all others were the Grenville (81%) and the younger Paleozoic (78%) (Table 3.4).

To assess our confidence in these classifications, we averaged the posterior probabilities for each correctly classified individual by geologic zone. This analysis suggests that we can have confidence in our classifications, especially for the Grenville zone (average posterior probability = 0.89; Table 3.4).

Major watershed

When the fish were grouped by major watershed, all seven elements and TL were included (and significant) in the final model (Table 3.5). However, TL was largely unimportant, being correlated with LDFA root 5, which explained less than 4% of the variation among watersheds (Table 3.5). Similarly, Ba, Pb, and Mg were relatively unimportant, being correlated with LDFA roots 5, 6 and 7, which combined explained less than 6% of the variation among watersheds (Table 3.5; Figure 3.4). Thus, similar to our analysis of geologic zones, Sr, Rb and Mn were the most important elements. The first two roots were dominated by Sr (strongly, negatively correlated to LDFA root 1) and Rb (strongly, positively correlated to LDFA root 2) and described ~73% of the variation, whereas LDFA root 3 was most highly (positively) correlated with Mn (Table 3.5).

For the nine major watersheds, the overall classification accuracy was 48%, with success for individual watersheds ranging from ~31% (Lone Lake Ocqueoc) to 100% (Wanipiti-French and East Lake Huron) (Table 3.6). From analysis of misclassifications, we could clearly distinguish 1) the Wanipitai-French (located near Georgian Bay; Figure 3.1) from most other watersheds based on high Mn and Rb and low Sr values, 2) the East Lake Huron (located near Georgian Bay; Figure 3.1) from most others due to low Mn, Rb and Sr values, and 3) the Titabawasee (located in the lower peninsula of Michigan; Figure 3.1) from all but the Aues-Gres Rifle (also located in the lower peninsula of

Michigan; Figure 3.1) due to intermediate Mn, low Rb and high Sr. Lone Lake Ocqueoc, North Lake Huron and Carp-Pine, all of which are located in Michigan or along the top of the basin (Figure 3.1), had the worst classification success (Table 3.6). All three watersheds were frequently mistaken for one another, as well as the St. Mary's, due to similar intermediate levels of Sr and Rb (Table 3.6; Figure 3.4). Many sea lamprey were misclassified to the St. Mary's watershed, but the St. Mary's watershed discriminated fairly well (70% correct), most likely due to low Rb and Sr values. Ultimately, we could fully distinguish both the Wanipitai-French and East Lake Huron watersheds from all others based on high Rb and Mn and low Sr, and low Mn, Sr and Rb, respectively (Table 3.6; Figure 3.4).

As with the LDFA based on geologic zones, we assessed our confidence in our classification success by averaging posterior probabilities for correctly classified individuals in each watershed. Average posterior probabilities ranged from a less certain 0.43 (North Lake Huron) to fairly certain 0.85 (Wanipitai-French) (Table 3.6). Thus, even though individuals were re-classified with 100% accuracy for the Wanipitai-French and East Lake Huron watersheds, our confidence in these classifications is a bit lower (Table 3.6).

Individual Streams

Similar to previous analyses, all factors were significant in our final model, with Mn, Rb, Sr and Zn once again being the most important for discriminating among streams (Table 3.7). Manganese, Rb and Sr dominated the first three LDFA roots, with Mn and Sr positively related to LDFA root 1, Rb positively and Sr negatively related to LDFA root 2 and Mn positively and Sr negatively related to LDFA root 3 (Table 3.7).

Sixty-four percent of the variation among streams was explained by the first two roots, with an additional 15% explained with LDFA root 3. Total length (TL) and Ba were both important as well, dominating roots 4 and 5, respectively, and explaining a combined 12% of the variation among streams (Table 3.7). Magnesium and Pb, dominating LDFA roots 7 and 8, were relatively unimportant, as combined they described only 5% of the variation among streams (Table 3.7).

Overall, we were able to classify fish back to their natal streams with 68% accuracy. Individual stream classification rates ranged from 6% to 100%, with four streams exhibiting perfect classification: Browns Creek (#7 on Figure 3.1), French River (13), Manitou River (23) and Thessalon River (41) (Table 3.8). Of the 45 streams, 11 had ≤ 60% correct classification accuracy, seven had between 60 and 70%, four had between 70 and 80%, nine had between 80 and 90%, and 14 had 90% or higher (Table 3.8). Due to the impracticality of graphing all individuals for each of the 45 streams (1000+ samples), we instead provide a ternary plot of the mean Sr, Rb and Mn concentrations for each of the streams that demonstrates how well some streams discriminate (Figure 3.5). The streams with 100% correct classification had similar concentrations for the most significant elements, with all values being intermediate except for low Mn and Zn in the Manitou River (23), low Sr in the Thessalon River (41), and high Rb and low Sr in the French River (13) (Table 3.2). As shown in figure 3.1, the four streams come from 3 different geologic zones, one older Paleozoic (Manitou River (23)), two Southern/Superior (Browns Creek (7) and Thessalon River (41)) and one Grenville (French River (13)).

Using two separate data sources, a case study of Lake Huron 1979 to 1999 (Morse et al. 2003) and the 2003 GLFC Sea Lamprey Annual Report (Young and Klar 2003), we were able to determine streams which have historically been major producers in Lake Huron. Morse et al. (2003) indicate that 32 of our 45 streams are considered Category 1 streams (i.e., highly productive for sea lampreys). Of these 32 streams, we are able to discriminate eight with 90% or higher accuracy, including Albany Creek (1), Blue Jay Creek (5), Manitou River (23), Serpent River (35), Thessalon River (41), Browns Creek (7), Gawas River (15) and Garden River (14). All of these streams, with the exception of Albany Creek, are located either in the Canadian Shield (Grenville or Southern/Superior) or on Manitoulin Island (older Paleozoic). Figure 3.6 demonstrates how well those 8 streams discriminate from one another. Albany Creek, in particular, has been slated as a large producer, and it was completely discriminated with high Mn, low Rb and intermediate Sr and Zn, with the exception of one sample misclassified as Gordon Creek (16) (also an important producer) (Table 3.2).

Two additional streams that have been designated as important producers are the Cheboygan River (9) and the St. Mary's River (38) (Morse et al. 2003). The Cheboygan River, located in the lower peninsula of Michigan, was classified with 86% accuracy, and had low Mn and Rb concentrations and intermediate Sr and Zn concentrations (Table 3.2). Two Cheboygan River samples were misclassified, one as the Mindemoya River (25) and one as the Manitou River (23), both of which also exhibit low Mn. The St. Mary's River, acknowledged as the single leading producer of parasites and spawners, was misclassified as McKay Creek (24) several times, and vice versa. Both streams have low levels of Sr, and comparable low levels of Rb and Mn (Table 3.2).

The 2003 GLFC Sea Lamprey Annual Report (Young and Klar 2003) estimated larval year class size for 2003, and 14 of our streams are on that list as Category 1 streams. Of those 14 streams, six with large estimated populations have $\leq$ 60% classification accuracy, while three streams have 80-90%. Of the poorly classified streams, the Echo (11) and Mississagi Rivers (26) are of particular concern, the Echo having < 7% correct classification (and nearly 10,000 larvae estimated in 2003), while the Mississagi had 40% classification, but nearly 430,000 larvae estimated (Young and Klar 2003). The Echo River was characterized by intermediate concentrations for all elements, and was misclassified as any of 14 different streams, without any particular pattern as to location. The stream with which the Echo River was most misclassified was Grace Creek (17), a category 3 stream (not very productive) in the Lower Peninsula. The Mississagi River, in contrast, was characterized by high levels of Mn, Rb and Sr, but intermediate levels of Zn. The Mississagi River was misclassified as 6 other streams, but four of those streams are category 2 (less productive for sea lamprey), such that only two samples were classified as other streams of concern (Albany Creek (1) and Black Mallard River (4)). Figure 3.7 shows both poorly classified streams, and the streams they are misclassified as, illustrating the overlap.

Analysis of average posterior probabilities of correct classifications for each stream demonstrates that 25 streams had posterior probabilities $\geq$ 0.7, while the remaining 20 had between 0.24 and 0.69 likelihood of being classified to that particular stream. A distinct pattern emerged for posterior probabilities, where we were generally very confident in our classifications for streams that also exhibited good discrimination

(> 70%), but were much less confident in our streams with low classification rates. This is illustrated by a R^2 value of 0.58 for correct classification versus posterior probability.

Inter-annual variation

Closer inspection of our individual stream analysis revealed that nearly half of the streams with larvae sampled during both 2004 and 2005 (5 of 11 streams) had classification accuracies less than 60%. To assess the potential influence of inter-annual variation in stream-specific signatures on our ability to discriminate, we removed one year of data from a stream sampled during both 2004 and 2005, and re-ran the LDFA without it. We did this for both years for all 11 streams sampled in both 2004 and 2005 (22 analyses in total) and then compared classification accuracies for those streams when only 2004 data, 2005 data or both years of data were included (Table 3.9).

Overall, our results suggest that inter-annual variation in stream-specific signatures may reduce our discrimination abilities, given that classification accuracies were potentially much higher when one year of data had been removed from analysis. For example, the Echo River (11) had ~7% correct classification with both years, but increased to ~67% when only 2005 data were present and increased to 60% when 2004 data were present. This pattern was also evident in the Naiscoot River (28) (improved by 16% when either year was removed), the Trout River (44) (improved by 10% in both cases) and the St. Mary's River (38) (improved by 26% when only 2005 data and by 6% when only 2004 data) (Table 3.9). Nine of the 11 streams had classification accuracies that stayed the same or improved when one year of data was removed. In contrast, the Tawas River (40) improved by 20% with only 2004 data, but decreased by 13% with only 2005 data. The Pine River (30) was the prime example where both an increase and a decrease occurred, with classification accuracy improving to 100% with only 2004 data, but decreasing to 0% with only 2005 (Table 3.9). With few exceptions, there was a clear increase in classification accuracy when one year of data (whether 2004 or 2005) was removed.

Discussion

Sea lampreys have been a major problem in the Great Lakes for over a century. Current control efforts have substantially improved the situation, but there is still a need for a method to identify important production tributaries. With this project we tested statolith microchemistry as a tool, determining our ability to discriminate individuals produced in different streams in different geologic zones, and watersheds. Below, we discuss the effectiveness of this technique for discriminating known production tributaries, and then possible effects of inter-annual variability on our ability to discriminate. Afterwards, we use our findings to provide recommendations to those interested in using statolith microchemistry as a tool to identify natal origins of sea lamprey in the Great Lakes.

Regardless of how the data were grouped (geology, watershed or stream), Mn, Rb, and Sr consistently dominated the first several LDFA roots, and thus were the most important elements for discriminating among individuals produced in different areas. Our results are supported by Brothers and Thresher (2004), who found the same three elements to be the primary site discriminators in their pilot work with micro-PIXE, and found Pb and Ba to be relatively unimportant. Brothers and Thresher (2004) also found Zn to be somewhat important, especially for distinguishing the St. Mary's River (38) from other streams. By contrast, Zn was relatively unimportant in our analyses, perhaps due to the many streams we sampled, but Brothers and Thresher (2004) did not, and those streams having similar levels of Zn to those of the St. Mary's River. Further, because Zn can change due to physiology and fish size (Renfro et al. 1975), it also may be possible that high levels of Zn relative to other systems in Brothers and Threshers (2004) work may have been due to physiology and not water chemistry. The fact that Zn and TL are positively correlated to one another, and also highly correlated with LDFA root 4 in our individual stream analysis (Table 3.7), supports this contention.

The consistent pattern of important elements is very clearly influenced by geology. In our results we saw high values for all three major elements in the Grenville (Table 3.4), results which are consistent with the high Rb and areas of high Sr expected for Precambrian rocks. In contrast, for limestones we expect high Sr and Zn, both of which we found in the older and younger Paleozoic zones. While these generalities direct what we can expect for these geologic zones, the areas are large and do not take into account local influences of water and sediments.

While the important elements for discrimination were fairly consistent regardless of how the data were grouped, our classification accuracy varied drastically. We were able to discriminate with fair accuracy both geological zones and individual streams; however, at the watershed level, our accuracy was generally poor. This fact is due to the tendency of one watershed to incorporate multiple geologic zones, such that fish being classified collectively are exposed to a wide array of geologic influences. Importantly, while geology does appear to be a driving influence on our ability to discriminate, high classification accuracies for more than a dozen streams also indicates the significant influence of local water chemistry.

Aside from Brothers and Thresher (2004) and Hand et al. (submitted), no previous work has been done on statolith microchemistry as a method for discriminating among natal streams of sea lamprey. However, previous work with teleost fish has explored the ability of otolith elemental composition to discriminate among individuals produced in different spawning areas of the Great Lakes. For example, similar to our work, Brazner et al. (2004) found Sr and Mn to be important for discriminating among age-0 yellow perch (*Perca flavescens*) produced in different Lake Superior wetlands, though they also found Ba, Mg and K to be important. Likewise, Ludsin et al. (2006) found Sr, Ba, Zn and Mg to be useful for discriminating larval yellow perch produced in different spawning areas in Lake Erie. In both studies site discriminators were consistent with what we found, with the exception of K, which we did not analyze.

The usefulness of statolith microchemistry as a technique should not be defined by the average classification accuracy, but rather how well individual production streams can be discriminated. Our ability to discriminate eight major production streams with 90% or greater accuracy (i.e., Albany Creek (1), Blue Jay Creek (5), Manitou River (23), Serpent River (35), Thessalon River (41), Browns Creek (7), Gawas River (15) and Garden River (14)) is very promising, particularly when three of these eight streams are classified perfectly (100%) and have high posterior probabilities of classification. Thus, we are optimistic that our results can provide immediate value to the GLFC efforts to identify contributions from these streams.

Unfortunately, other important production streams appear more problematic. For example, the Cheboygan River (9) had a successful classification rate of 86%, yet the misclassified fish were consistently classified as originating from other important production tributaries. Likewise the Echo River (11) also was consistently misclassified as other major producers. The St. Mary's River (38), which is the largest producer of parasitic sea lamprey in Lake Huron (Young and Klar 2003), could only be discriminated with 67% success, oftentimes being confused with McKay Creek (24), also an important producer of sea lamprey (Morse et al. 2003). Thus, whereas Brothers and Thresher (2004) found that the St. Mary's River could easily be discriminated from three streams in the lower peninsula of Michigan (Rifle River (31), Black Mallard River (4), and Pigeon Creek), it is likely the case that the St. Mary's River cannot be discriminated well using just elemental concentrations when the majority of other Lake Huron streams are included in the analysis.

In a study by Kennedy et al. (2000), Sr isotopes were found to be stable over time, and allow for effective discrimination (83%) among juvenile salmon. Strontium isotopes were stated to be the most effective for several different reasons, but most applicable to this study is that $^{87}Sr/^{86}Sr$ ratios arise from differences in bedrock geology. Preliminary data suggest this usefulness for discrimination extends to statolith microchemistry, as stream water from our different geologic zones exhibit distinct Sr isotopic signatures (Fryer, unpublished data).

Because it is not feasible to sample all sea lamprey-producing streams in the Lake Huron watershed every year, a potential limitation to using statolith elemental concentrations to discriminate among production areas is inter-annual variability in stream-specific signatures. From our analyses of streams sampled in multiple years, it is evident that inter-annual variation is affecting classification accuracy. Several of our most poorly classified streams were ones that were sampled over multiple years. Further, classification rates almost universally improved when one year was removed, indicating that variation in site-specific signatures between years can be greater than signatures among streams sampled in the same year.

Previous otolith microchemistry work with teleost fishes also has documented temporal variation in site-specific signatures, with variation occurring at daily, weekly, monthly, seasonal and annual time scales. For example, Elsdon and Gillanders (2006), in their exploration of water samples in Gulf St. Vincent, Australia, found that Ca, Ba, Sr and Mn concentrations varied on the scale of days and weeks, while Sr also varied seasonally. Hatje et al. (2001) also found that Cu, Pb and Zn varied on the scale of hours and days in their study of 3 rivers draining into the Port Jackson Estuary, Australia. An important conclusion in this second study was that small scale variability becomes more important as the size of the natural system decreases (Hatje et al 2001). In a freshwater study performed on the Mississippi River, it was found that Mn, Zn and Pb were highly variable seasonally, while Rb and Ba were fairly stable seasonally (Shiller 1997). No inter-annual variability was found, though Shiller (1997) suggested that hydrologic factors such as mixing of tributaries or changes in discharge rates did have an impact on inter-annual variability.

For our study, we only had a small subset of streams (n=11) with two years of data; however, we observed at least some inter-annual variation for each of them, despite the fact that they varied tremendously in both location and size. Further, Young and Klar (2003) projected that 8 of the 11 streams for which we had two years of data would produce parasitic sea lamprey the following year, a further illustration of the need to continue exploring the influence of inter-annual variation. Overall, before this technique is implemented, this phenomenon needs to be examined further, as our evidence of inter-annual variability could be due to real variation in site-specific signatures, due to varying water chemistry, or due to samples coming from different locations within the stream. Clearly, assessment of how site-specific signatures vary over a longer time span (5 to 10 years) would allow us to place our observed variation in a better context.

Conclusions

Herein, we explored statolith microchemistry as a technique to identify natal origins of sea lamprey, and ultimately help prioritize sea lamprey control efforts in Lake Huron. Overall, our results demonstrate promise, given that we could accurately discriminate a substantial number of streams within the Lake Huron basin, many of which have been identified as likely contributors of parasitic- and spawning-phase sea lamprey, based on QAS estimates of larval abundance (Young and Klar 2003). However, statolith microchemistry seems far from perfect as a technique, as demonstrated by our inability to successfully discriminate some other important production tributaries (i.e., the St. Mary's River (38) and Echo River (11)). Also, inter-annual variation in site-specific stream signatures poses a major problem, since it will prohibit the development of statolith microchemical 'libraries' with only a few years of data (i.e., larvae would need to be sampled every year on a continuous basis to develop a signature). Most certainly, however, the potential of the technique would increase with the ability to sample larvae from all of the production streams in a single year. We also suggest that future studies explore the possibility of integrating discrimination techniques, such as analysis of elemental composition and stable isotopes and/or larval growth rates. In this way, localized effects from water chemistry/pollution or the larval growth environment can be captured with analysis of elemental concentration and growth rate, respectively, and large-scale effects due to geology could be captured using isotope data. Work by Kennedy et al. (2000) has shown that $^{87}Sr/^{86}Sr$ ratios are effective for discriminating among juvenile salmon from 18 different tributaries, and Fryer (unpublished data) has found isotopic signatures to be distinct for a selection of streams scattered around Lake Huron. Since Sr isotopes are directly attributable to the underlying bedrock, differences among statolith signatures that we have found to be strongly influenced by local geology should be reflected in the $^{87}Sr/^{86}Sr$ ratios. Ultimately, the use of Sr isotopes (Kennedy et al. 2000) would effectively deal with the primary problem we have identified with the technique, i.e., inter-annual variability. We are optimistic that combining isotopic data (or perhaps larval growth data, as recorded in statoliths) with already fairly distinctive elemental signatures would provide the GLFC with a means to prioritize sea lamprey control efforts throughout the Great Lakes without unwanted assumptions about larval survival.

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Table 3.1. Isotopes quantified (not including calcium) using LA-ICP-MS. Mean limit of detection (LOD) was calculated based on all samples run. The coefficient of variation (CV) is the average for all runs, and was calculated as mean divided by standard deviation of NIST-610 standards. Isotopes shaded in gray met our criteria for inclusion in analysis.

Isotope	^{7}Li	[illegible]	[illegible]	^{57}Fe	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	^{140}Ce	[illegible]	^{238}U
Mean LOD (ppm)	0.750	13.6	0.466	77.9	0.671	0.291	2.09	0.234	0.516	0.143	0.575	0.528	0.023
CV (%)	6.03	3.52	3.18	12.9	6.32	5.25	2.50	2.22	3.33	3.52	3.67	6.16	5.39
% above LOD	3.1	100	100	72.7	96.0	99.1	100	100	100	100	32.0	82.4	4.2

Table 3.2. Background information on all 45 streams, including location on Figure 3.1, stream name, year collected, number of samples (N), average total length of larvae and standard deviation (TL), geologic zone, watershed designation, and mean stream concentrations and standard deviations of magnesium (Mg), manganese (Mn), zinc (Zn), rubidium (Rb), strontium (Sr), barium (Ba) and lead (Pb).

Map	Stream	Year	# samples	TL	Geologic Age	Major Watershed
1	Albany Cr.	2005	12	92.3 ± 27.5	Older Paleozoic	Carp-Pine
2	Beavertail Cr.	2004	15	78.9 ± 20.3	Older Paleozoic	Carp-Pine
3	Bighead R.	2005	15	91.0 ± 23.1	Older Paleozoic	East Lake Huron
4	Black Mallard R.	2005	12	84.8 ± 7.9	Older Paleozoic	Lone Lake Ocqueoc
5	Blue Jay Cr.	2005	15	67.6 ± 11.8	Older Paleozoic	North Lake Huron
6	Boyne R.	2005	15	60.9 ± 18.4	Grenville	East Georgian Bay
7	Browns Cr.	2005	9	144 ± 8	Older Paleozoic	North Lake Huron
8	Caribou Cr.	2004	15	99.1 ± 23.7	Older Paleozoic	Carp-Pine
9	Cheboygan R.	2005	14	107 ± 13	Older Paleozoic	Lone Lake Ocqueoc
10	Devils R.	2004	15	114 ± 21	Older Paleozoic	Lone Lake Ocqueoc
11	Echo R.	2004/2005	30	91.8 ± 42.9	Southern/Superior	North Lake Huron
12	Elliot Cr.	2004	15	109 ± 16	Older Paleozoic	Lone Lake Ocqueoc
13	French R.	2005	15	146 ± 13	Grenville	Wanipitai-French
14	Garden R.	2005	15	77.7 ± 18.4	Southern/Superior	North Lake Huron
15	Gawas R.	2005	15	135 ± 7	Older Paleozoic	North Lake Huron
16	Gordon Cr.	2005	13	51.8 ± 30.6	Older Paleozoic	North Lake Huron
17	Grace Cr.	2004	15	72.4 ± 22.9	Older Paleozoic	Lone Lake Ocqueoc
18	Hessel Cr.	2004	15	99.9 ± 27.6	Older Paleozoic	Carp-Pine
19	Koshkawong R.	2005	6	62.0 ± 32.3	Older Paleozoic	North Lake Huron
20	Lauzon Cr.	2004	15	127 ± 10	Southern/Superior	North Lake Huron
21	Little Monkscong R.	2004	10	122 ± 18	Older Paleozoic	St. Marys
22	Magnetewan R.	2004	15	78.5 ± 21.4	Grenville	East Georgian Bay
23	Manitou R.	2005	15	95.4 ± 18.9	Older Paleozoic	North Lake Huron
24	McKay Cr.	2004	15	117 ± 9	Older Paleozoic	Carp-Pine
25	Mindemoya R.	2004/2005	30	82.5 ± 16.1	Older Paleozoic	North Lake Huron
26	Mississagi R.	2004	15	120 ± 20	Southern/Superior	North Lake Huron
27	Musquash R.	2004/2005	25	103 ± 30	Grenville	East Georgian Bay
28	Naiscoot R.	2004/2005	30	75.3 ± 32.7	Grenville	East Georgian Bay
29	Nottawasaga R.	2004/2005	30	114 ± 22	Older Paleozoic	East Georgian Bay
30	Pine R.	2004/2005	19	91.9 ± 40.0	Older Paleozoic	Carp-Pine
31	Rifle R.	2005	13	82.2 ± 23.7	Younger Paleozoic	Aues Gres-Rifle
32	Saginaw R.	2004/2005	28	95.9 ± 20.6	Younger Paleozoic	Titabawasee
33	Sauble R.	2004	15	108 ± 15	Older Paleozoic	East Lake Huron
34	Schmidt Cr.	2004	15	110 ± 14	Older Paleozoic	Lone Lake Ocqueoc
35	Serpent R.	2005	15	131 ± 6	Southern/Superior	North Lake Huron
36	Silver Cr.	2004	15	108 ± 36	Older Paleozoic	East Georgian Bay
37	Spanish R.	2004	15	91.3 ± 9.8	Southern/Superior	North Lake Huron
38	St. Marys R.	2004/2005	30	103 ± 22	Older Paleozoic	St. Marys
39	Steeles Cr.	2004	15	105 ± 17	Older Paleozoic	Carp-Pine
40	Tawas R.	2004/2005	30	97.8 ± 21.6	Younger Paleozoic	Aues Gres-Rifle
41	Thessalon R.	2005	15	144 ± 11	Southern/Superior	North Lake Huron
42	Timber Bay Cr.	2004/2005	30	89.2 ± 16.9	Older Paleozoic	North Lake Huron
43	Trout Cr.	2004	15	79.9 ± 36.6	Older Paleozoic	Carp-Pine
44	Trout R.	2004/2005	30	80.5 ± 24.4	Older Paleozoic	Lone Lake Ocqueoc
45	Watson Cr.	2005	15	73.7 ± 8.9	Older Paleozoic	North Lake Huron

Map	Mg	Mn	Zn	Rb	Sr	Ba	Pb
1	4090 ± 1090	186 ± 93	39.7 ± 31.7	2.81 ± 0.96	382 ± 168	26.8 ± 6.1	0.134 ± 0.103
2	3080 ± 511	25.9 ± 3.2	4.69 ± 8.93	7.09 ± 1.27	181 ± 56	19.4 ± 23.7	0.052 ± 0.030
3	4240 ± 538	16.6 ± 3.6	1.62 ± 1.15	0.63 ± 0.16	310 ± 119	7.98 ± 4.96	0.055 ±0.035
4	4150 ± 288	50.4 ± 17.0	157 ± 488	5.64 ± 1.16	358 ± 49	11.6 ± 3.7	0.120 ± 0.133
5	3300 ± 410	23.7 ± 8.2	2.11 ± 1.56	1.94 ± 0.34	203 ± 44	6.68 ± 2.62	0.044 ± 0.020
6	3810 ± 358	76.5 ± 22.6	0.76 ± 0.47	4.95 ± 0.42	1110 ± 115	32.0 ± 6.4	0.044 ± 0.022
7	4300 ± 575	29.9 ± 6.8	7.44 ± 5.77	2.84 ± 0.22	307 ± 19	19.3 ± 4.4	0.320 ± 0.165
8	3760 ± 531	52.9 ± 13.2	12.3 ± 5.9	4.30 ± 1.04	285 ± 86	21.2 ± 9.2	0.071 ± 0.032
9	4190 ± 706	10.6 ± 2.8	11.6 ± 14.5	1.74 ± 0.25	311 ± 55	11.2 ± 3.0	0.804 ± 0.770
10	4380 ± 638	24.9 ± 5.8	20.4 ± 8.3	2.88 ± 0.38	388 ± 90	13.8 ± 4.8	0.134 ± 0.129
11	3860 ± 606	33.6 ± 10.2	7.39 ± 10.2	3.31 ± 1.57	425 ± 209	14.7 ± 6.9	0.102 ± 0.087
12	3520 ± 486	18.4 ± 2.4	38.7 ± 21.1	3.19 ± 0.65	255 ± 67	16.4 ± 6.3	0.290 ± 0.137
13	4240± 526	50.2 ± 9.7	11.7 ± 14.2	6.31 ± 1.04	255 ± 32	17.0 ± 3.1	0.195 ± 0.076
14	3490 ± 417	23.3 ± 6.9	11.3 ± 14.3	10.1 ± 1.0	486 ± 160	53.4 ± 104	0.072 ± 0.034
15	4460 ± 569	29.1 ± 5.8	13.8 ± 6.2	2.62 ± 0.29	201 ± 12	7.61 ± 0.84	0.140 ± 0.044
16	3370 ± 635	51.1 ± 27.9	7.65 ± 12.2	4.04 ± 2.62	402 ± 107	17.1 ± 10.1	0.071 ± 0.056
17	3260 ± 509	29.9 ± 4.9	4.01 ± 7.78	5.12 ± 1.08	372 ± 82	19.8 ± 25.7	0.138 ± 0.142
18	5590 ± 469	83.3 ± 10.5	32.5 ± 18.2	6.29 ± 1.06	550 ± 132	39.7 ± 39.2	0.201 ± 0.097
19	3510 ± 562	37.2 ± 6.8	19.9 ± 28.4	4.28 ± 0.72	203 ± 21	19.9 ± 8.9	0.090 ± 0.690
20	4400 ± 623	29.7 ± 9.7	39.2 ± 19.4	6.14 ± 1.13	572 ± 138	34.6 ± 7.1	0.339 ± 0.193
21	4110 ± 642	67.7 ± 41.9	65.1 ± 52.6	2.45 ± 0.85	237 ± 50	16.0 ± 5.0	0.224 ± 0.135
22	4340 ± 604	183 ± 73	8.09 ± 11.3	8.35 ± 2.87	829 ± 165	59.6 ± 14.6	0.239 ± 0.084
23	3780 ± 388	17.1 ± 3.6	2.88 ± 2.21	3.32 ± 0.28	449 ± 104	11.7 ± 4.3	0.062 ± 0.029
24	3780 ± 624	27.8 ± 11.2	24.9 ± 10.0	1.72 ± 0.21	205 ± 44	9.76 ± 3.53	0.141 ± 0.064
25	3990 ± 504	12.8 ± 3.4	6.82 ± 9.41	2.11 ± 0.64	382 ± 158	11.3 ± 6.8	0.135 ± 0.143
26	5180 ± 809	84.7 ± 47.9	30.5 ± 12.5	7.02 ± 1.49	646 ± 691	58.8 ± 101	0.273 ± 0.228
27	4580 ± 653	65.0 ± 29.4	7.58 ± 9.87	6.99 ± 1.31	741 ± 61	39.0 ± 9.3	0.269 ± 0.281
28	3970 ± 730	148 ± 130	12.9 ± 37.3	8.36 ± 2.07	964 ± 221	52.4 ± 23.9	0.282 ± 0.802
29	4020 ± 523	14.8 ± 3.1	9.91 ± 16.5	1.52 ± 0.39	483 ± 149	20.2 ± 9.8	0.070 ± 0.056
30	3930 ± 942	33.5 ± 15.3	26.0 ± 45.0	4.98 ± 3.46	485 ± 289	31.5 ± 23.0	0.152 ± 0.146
31	3980 ± 854	29.5 ± 12.7	3.44 ± 1.65	1.71 ± 1.08	680 ± 281	18.5 ± 5.4	0.066 ± 0.033
32	4570 ± 578	34.4 ± 19.2	9.94 ± 9.00	1.60 ± 0.76	579 ± 192	18.4 ± 11.8	0.152 ± 0.210
33	4520 ± 667	30.6 ± 6.7	12.8 ± 24.5	0.85 ± 0.27	253 ± 40	5.90 ± 1.67	0.104 ± 0.065
34	3790 ± 861	42.2 ± 10.6	41.7 ± 44.2	2.72 ± 0.86	216 ± 30	12.1 ± 2.2	0.078 ± 0.055
35	3550 ± 390	68.7 ± 26.5	31.2 ± 19.5	5.73 ± 0.52	540 ± 91	20.6 ± 7.7	0.186 ± 0.117
36	5090 ± 1240	29.8 ± 9.4	78.0 ± 88.8	5.91 ± 1.50	463 ± 110	8.60 ± 3.44	0.320 ± 0.182
37	3780 ± 608	24.0 ± 9.3	3.90 ± 2.86	4.20 ± 0.98	467 ± 106	26.9 ± 7.9	0.179 ± 0.218
38	3800 ± 432	19.4 ± 4.9	41.7 ± 167	3.01 ± 1.00	222 ± 89	15.7 ± 8.4	0.237 ± 0.133
39	3730 ± 549	43.1 ± 10.8	6.46 ± 10.3	3.94 ± 0.90	111 ± 14	8.74 ± 5.04	0.052 ± 0.031
40	4060 ± 725	20.9 ± 3.6	53.0 ± 51.4	2.61 ± 0.71	873 ± 896	29.9 ± 17.7	0.267 ± 0.207
41	3720 ± 357	26.9 ± 6.5	11.5 ± 5.6	3.79 ± 0.74	261 ± 11	7.28 ± 1.15	0.164 ± 0.057
42	3390 ± 733	36.1 ± 11.5	9.43 ± 25.3	5.56 ± 2.01	231 ± 64	36.3 ± 61.7	0.146 ± 0.254
43	4690 ± 1020	65.8 ± 16.5	9.20 ± 8.52	7.08 ± 1.36	578 ± 292	27.4 ± 10.3	0.147 ± 0.116
44	4440 ± 774	27.8 ± 7.5	26.6 ± 42.1	2.53 ± 0.48	275 ± 57	10.3 ± 4.9	0.146 ± 0.078
45	4140 ± 336	27.2 ± 7.5	1.81 ± 0.74	5.47 ± 0.72	263 ± 58	13.1 ± 5.4	0.027 ± 0.012

Table 3.3. Correlations between elements and LDFA roots (axes) for geologic zones. The percentage of variation that each axis (root) explained is provided in the bottom row.

	Root 1	**Root 2**	**Root 3**
Sr	**-0.640**	**0.710**	0.160
Rb	**-0.512**	**-0.576**	0.219
Mn	**-0.571**	-0.175	**-0.476**
Zn	0.145	0.182	0.338
TL (mm)	0.007	-0.084	**0.532**
Pb	-0.127	0.078	0.131
Mg	-0.076	0.168	-0.112
Ba	-0.524	0.234	-0.016
Cum.Prop	0.73	0.93	1.00

Table 3.4. Background information on geologic zones, including sample size per region (N), percent of correct classifications, average posterior probability, and mean values plus one standard deviation for key important elements.

Geologic Zone	**N**	**% correct**	**posterior probability**	**Mn**	**Rb**	**Sr**	**Zn**
Grenville	100	81.00	0.89	107 ± 92	7.20 ± 2.13	804 ± 300	8.84 ± 22.2
Younger Paleozoic	71	78.87	0.78	27.8 ± 14.6	2.05 ± 0.93	722 ± 615	26.9 ± 40.5
Southern/Superior	120	68.33	0.67	40.6 ± 29.6	5.45 ± 2.48	478 ± 294	17.8 ± 18.0
Older Paleozoic	500	66.40	0.71	35.2 ± 33.6	3.53 ± 2.11	322 ± 162	22.8 ± 90.9

Table 3.5. Correlations between elements and LDFA roots (axes) for watersheds. The percentage of variation that each axis (root) explained is provided in the bottom row.

	Root 1	Root 2	Root 3	Root 4	Root 5	Root 6	Root 7	Root 8
Sr	**-0.721**	0.660	-0.130	0.085	-0.140	0.016	-0.022	0.027
Rb	0.438	**0.832**	0.000	0.123	0.140	-0.253	-0.067	-0.116
Mn	-0.003	0.433	**0.598**	**0.521**	-0.052	-0.326	-0.022	0.273
Zn	0.090	-0.111	-0.343	**0.528**	-0.364	-0.320	**0.590**	-0.004
TL (mm)	0.134	-0.046	0.129	-0.241	**-0.669**	0.076	**0.671**	0.029
Ba	-0.155	0.590	-0.009	0.476	-0.424	0.324	-0.308	-0.148
Pb	0.029	0.039	-0.263	0.034	**-0.721**	**-0.620**	-0.144	-0.044
Mg	-0.195	-0.006	0.255	0.083	-0.227	-0.407	0.317	**-0.757**
Cum.Prop	0.41	0.73	0.86	0.94	0.97	0.99	1.00	1.00

Table 3.6. Background information on watersheds, including sample size per region (N), percent of correct classifications, average posterior probability, and mean values plus one standard deviation for key important elements.

Watershed	**N**	**% correct**	**posterior prob**	**Mn**	**Rb**	**Sr**	**Zn**
East Lake Huron	30	100.00	0.82	23.6 ± 8.9	0.74 ± 0.25	282 ± 92	7.23 ± 18.0
Wanipiti-French	15	100.00	0.85	50.2 ± 9.7	6.31 ± 1.05	255 ± 32	11.7 ± 14.2
Titabawasee	28	82.14	0.63	34.4 ± 19.2	1.60 ± 0.76	579 ± 192	9.94 ± 9.00
St. Marys	40	70.00	0.55	31.4 ± 29.6	2.87 ± 0.98	226 ± 81	47.6 ± 146
East Georgian Bay	130	64.62	0.79	83.5 ± 90.9	5.84 ± 3.06	754 ± 274	16.7 ± 42.0
Aues Gres-Rifle	43	58.14	0.75	23.5 ± 8.4	2.33 ± 0.92	814 ± 765	38.0 ± 48.5
Carp-Pine	121	39.67	0.54	60.7 ± 54.8	4.83 ± 2.44	351 ± 239	19.2 ± 25.0
North Lake Huron	268	33.58	0.43	33.4 ± 23.8	4.43 ± 2.36	379 ± 235	12.0 ± 16.9
Lone Lake Ocqueoc	116	31.90	0.45	28.6 ± 13.9	3.25 ± 1.42	305 ± 84.5	38.1 ± 159

Table 3.7. Correlations between elements and LDFA roots (axes) for all 45 streams. Elements most highly correlated with each axis are bold, and indicate their importance in discrimination (bottom). The percentage of variation that each axis (root) explained is provided in the bottom row.

	Root 1	Root 2	Root 3	Root 4	Root 5	Root 6	Root 7	Root 8
LnMn	**0.697**	-0.116	**0.675**	0.172	-0.041	0.013	0.074	-0.090
LnRb	**0.685**	**0.566**	-0.263	-0.247	-0.207	-0.064	0.172	0.066
LnSr	0.419	**-0.668**	**-0.477**	-0.005	0.269	0.161	-0.225	-0.027
LnZn	0.024	0.093	-0.048	**0.789**	0.093	**-0.594**	-0.060	-0.009
TL (mm)	-0.059	0.140	-0.035	**0.738**	-0.183	**0.505**	-0.298	0.231
LnBa	0.394	-0.094	-0.150	0.035	**0.829**	0.190	0.068	0.290
LnMg	0.058	-0.205	-0.040	0.384	-0.332	-0.060	**0.545**	**0.628**
LnPb	0.068	0.037	-0.193	0.574	0.126	0.103	**0.639**	-0.439
Cum.Prop	0.44	0.64	0.80	0.87	0.92	0.95	0.98	1.00

Table 3.8. Posterior probabilities and classification accuracies for 45 Lake Huron streams.

% Correct	Stream	Mean posterior prob
6.67	Echo River	0.30
10.53	Pine River	0.24
30.77	Gordon Creek	0.72
30.77	Rifle River	0.63
33.33	Trout Creek	0.39
36.67	Naiscoot River	0.56
40.00	Little Monkscong River	0.79
40.00	Mississagi River	0.55
53.33	Devils River	0.61
53.33	Timber Bay Creek	0.56
56.67	Trout River	0.68
60.00	Grace Creek	0.72
60.00	Hessel Creek	0.61
60.00	Schmidt Creek	0.60
60.71	Saginaw River	0.59
64.00	Musquash River	0.69
66.67	Spanish River	0.57
66.67	St. Marys River	0.63
73.33	Caribou Creek	0.57
73.33	McKay Creek	0.58
73.33	Tawas River	0.83
75.00	Black Mallard River	0.70
80.00	Beavertail Creek	0.76
80.00	Elliot Creek	0.72
80.00	Magnetewan River	0.79
80.00	Mindemoya River	0.69
80.00	Nottawasaga River	0.70
83.33	Koshkawong River	0.68
85.71	Cheboygan River	0.93
86.67	Sauble River	0.89
86.67	Silver Creek	0.91
91.67	Albany Creek	0.98
93.33	Bighead River	0.88
93.33	Blue Jay Creek	0.77
93.33	Boyne River	0.96
93.33	Garden River	0.85
93.33	Gawas River	0.69
93.33	Lauzon Creek	0.84
93.33	Serpent River	0.89
93.33	Steeles Creek	0.87
93.33	Watson Creek	0.83
100.00	Browns Creek	0.76
100.00	French River	0.88
100.00	Manitou River	0.59
100.00	Thessalon River	0.79

Table 3.9. Eleven streams with data collected in both 2004 and 2005. Shown are classification accuracies for individual streams when both years of data are present, when 2004 data are removed and when 2005 data are removed.

		% Correct	
Stream	**2004 and 2005**	**2005 only**	**2004 only**
Echo River	6.67	66.7	60.0
Pine River	10.5	0.00	100
Naiscoot River	36.7	53.3	53.3
Timber Bay Creek	53.3	73.3	53.3
Trout River	56.7	66.7	66.7
Saginaw River	60.7	84.6	60.0
Musquash River	64.0	86.7	80.0
St. Marys River	66.7	93.3	73.3
Tawas River	73.3	60.0	93.3
Mindemoya River	80.0	86.7	86.7
Nottawasaga River	80.0	93.3	80.0

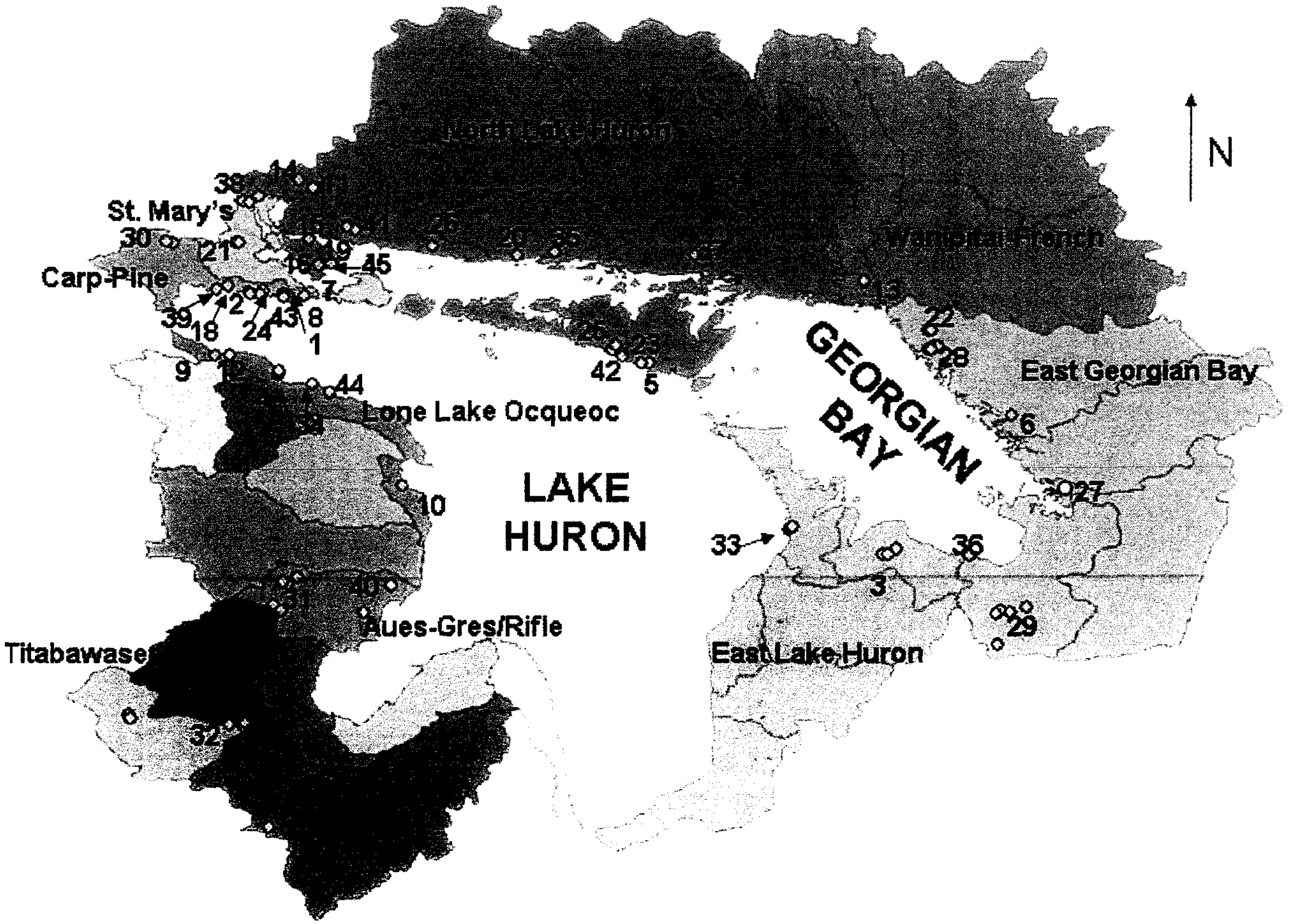

Figure 3.1. Map of sample locations for 45 Lake Huron streams, and their respective locations in nine major watersheds (those 9 watersheds are labeled). The streams include: 1) Albany Creek, 2) Beavertail Creek, 3) Bighead River, 4) Black Mallard River, 5) Blue Jay Creek, 6) Boyne R, 7) Browns Creek, 8) Caribou Creek, 9) Cheboygan River, 10) Devils River, 11) Echo River, 12) Elliot Creek, 13) French River, 14) Garden River, 15) Gawas River, 16) Gordon Creek, 17) Grace Creek, 18) Hessel Creek, 19) Koshkawong River, 20) Lauzon Creek, 21) Little Monkscong River, 22) Magnetewan River, 23) Manitou River, 24) McKay Creek, 25) Mindemoya River, 26) Mississagi River, 27) Musquash River, 28) Naiscoot River, 29) Nottawasaga River, 30) Pine River, 31) Rifle River, 32) Saginaw River, 33) Sauble River, 34) Schmidt Creek, 35) Serpent River, 36) Silver Creek, 37) Spanish River, 38) St. Marys River, 39) Steeles Creek, 40) Tawas River, 41) Thessalon River, 42) Timber Bay Creek, 43) Trout Creek, 44) Trout River, and 45) Watson Creek.

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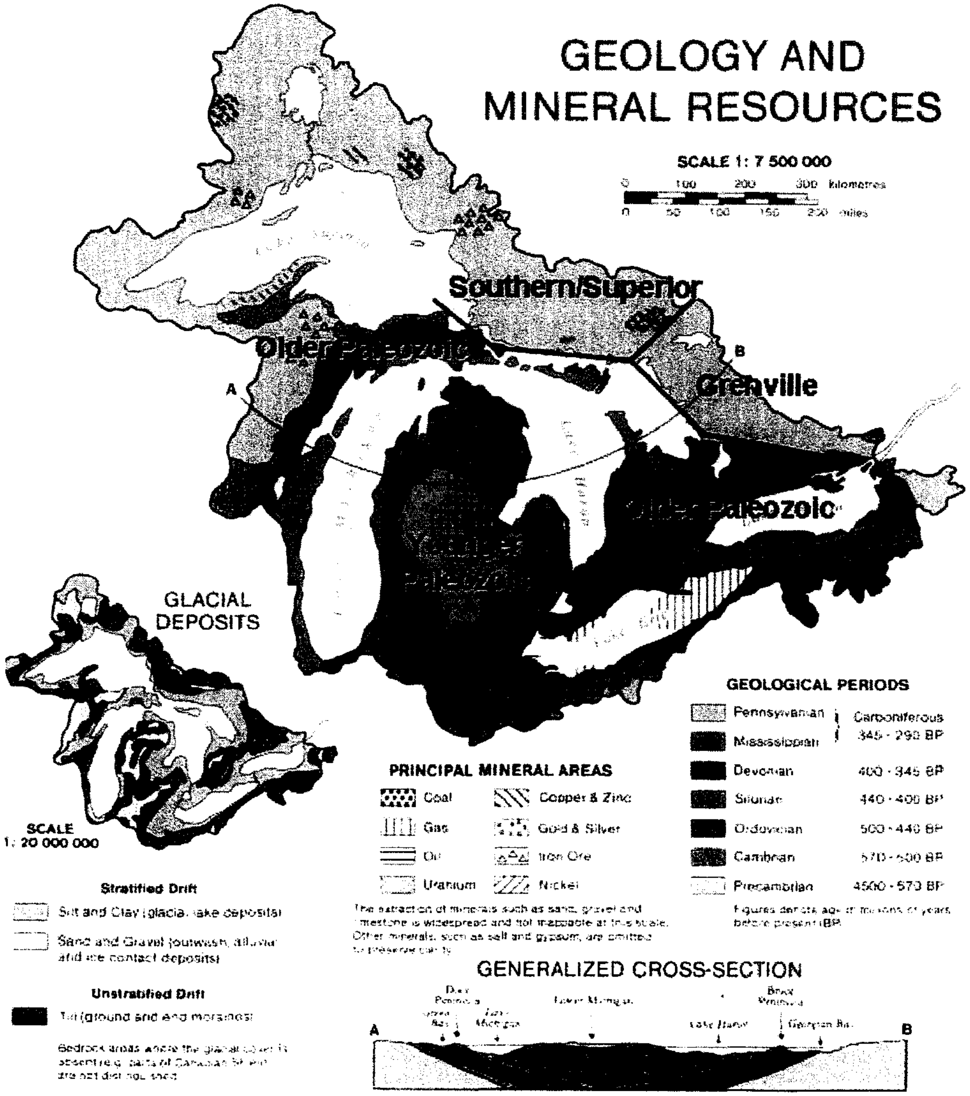


Figure 3.2. Map of geologic zones in Lake Huron watershed. (source: www.epa.gov)

Figure 3.3. LDFA root 1 versus root 2 for geologic zones. Sr, Rb and Mn decrease along the x-axis. Strontium increases on root 2, whereas Rb decreases along it.

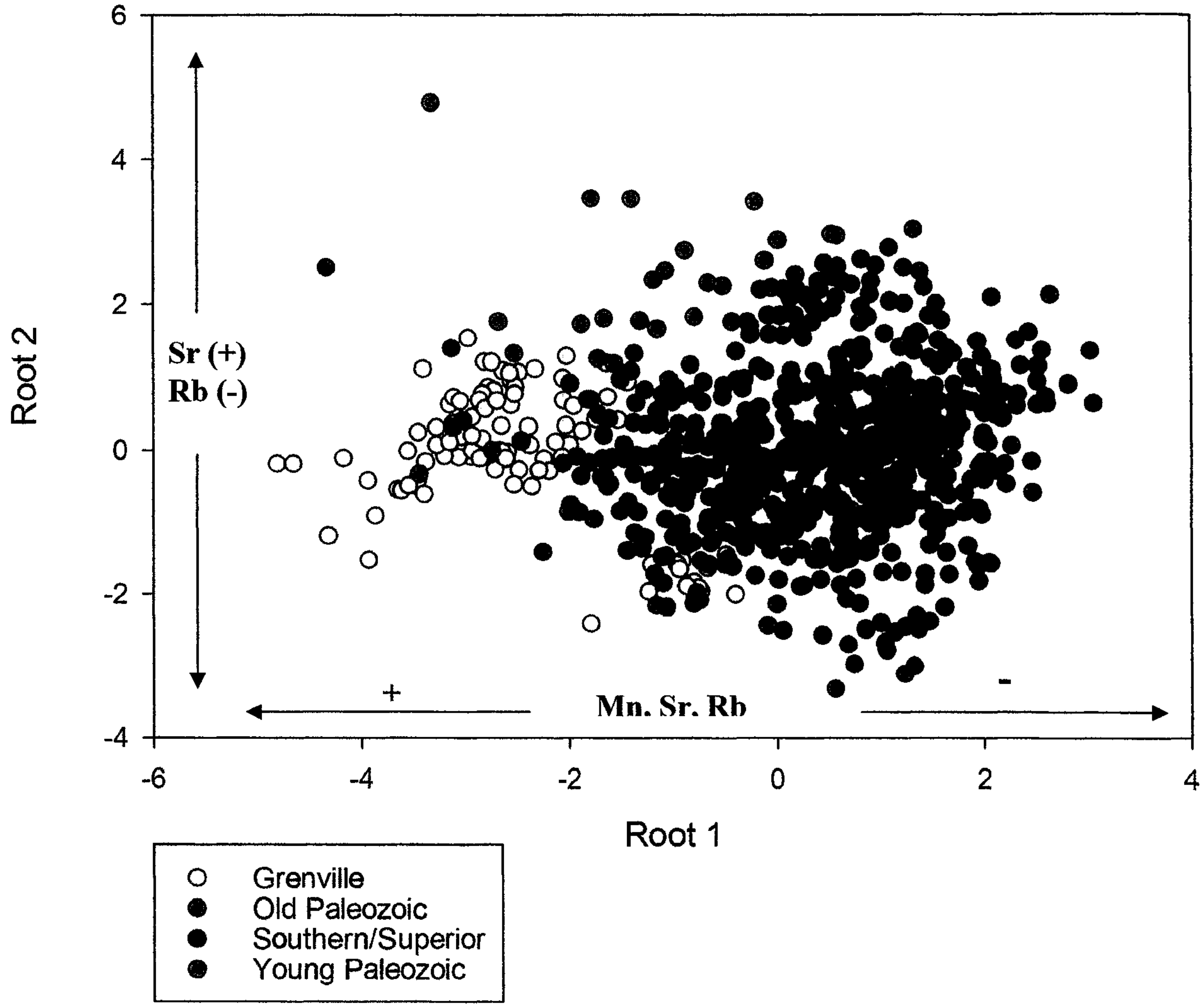


Figure 3.4. LDFA root 1 versus root 2 for watersheds. which combined explain 73% of the variation among watersheds. Samples decrease in Sr along the x-axis and increase Rb along the y-axis.

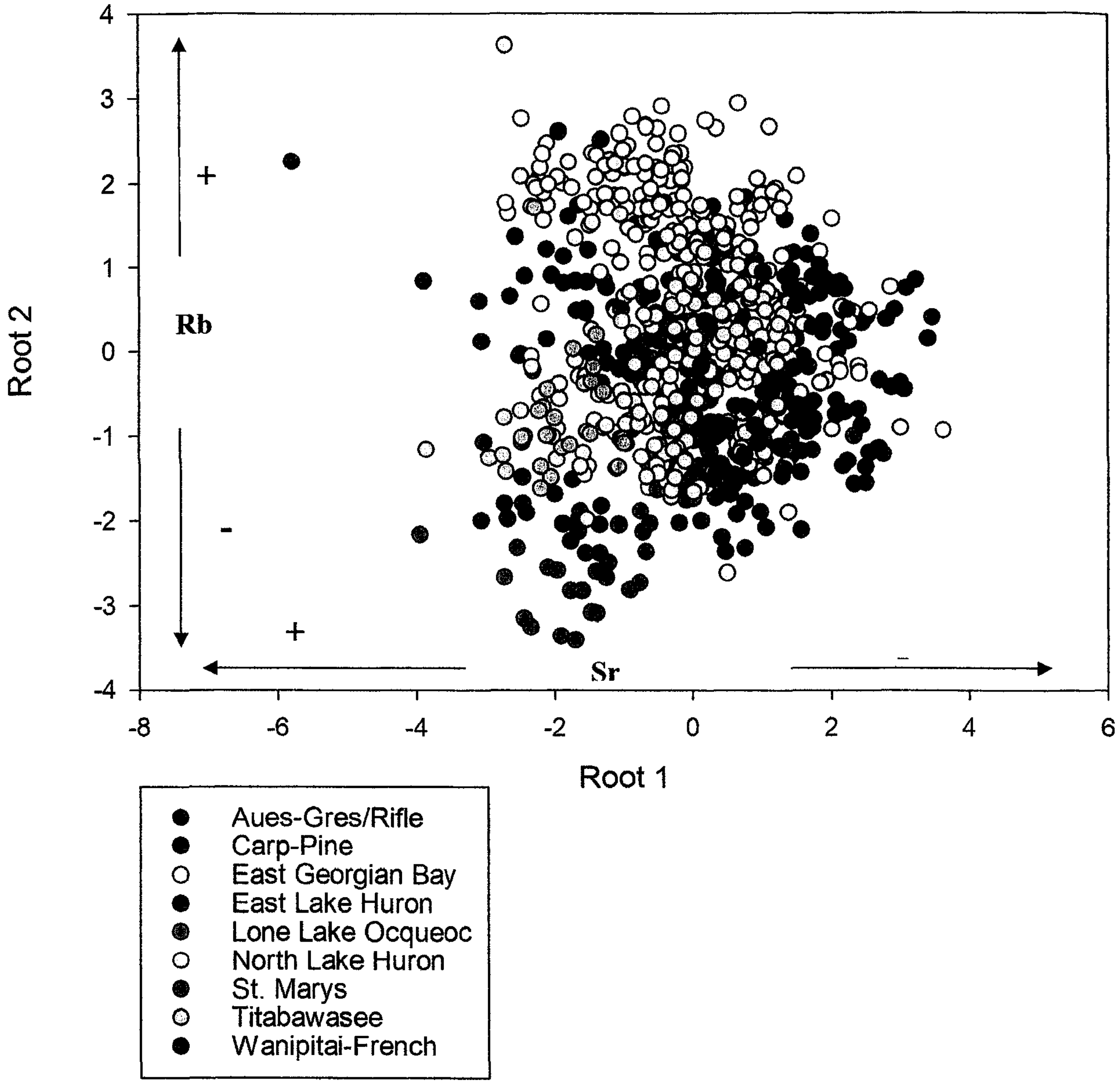


Figure 3.5. Ternary graph of mean Rb, Mn (divided by 10) and Sr (divided by 100) concentrations (ppm) for all 45 streams analyzed.

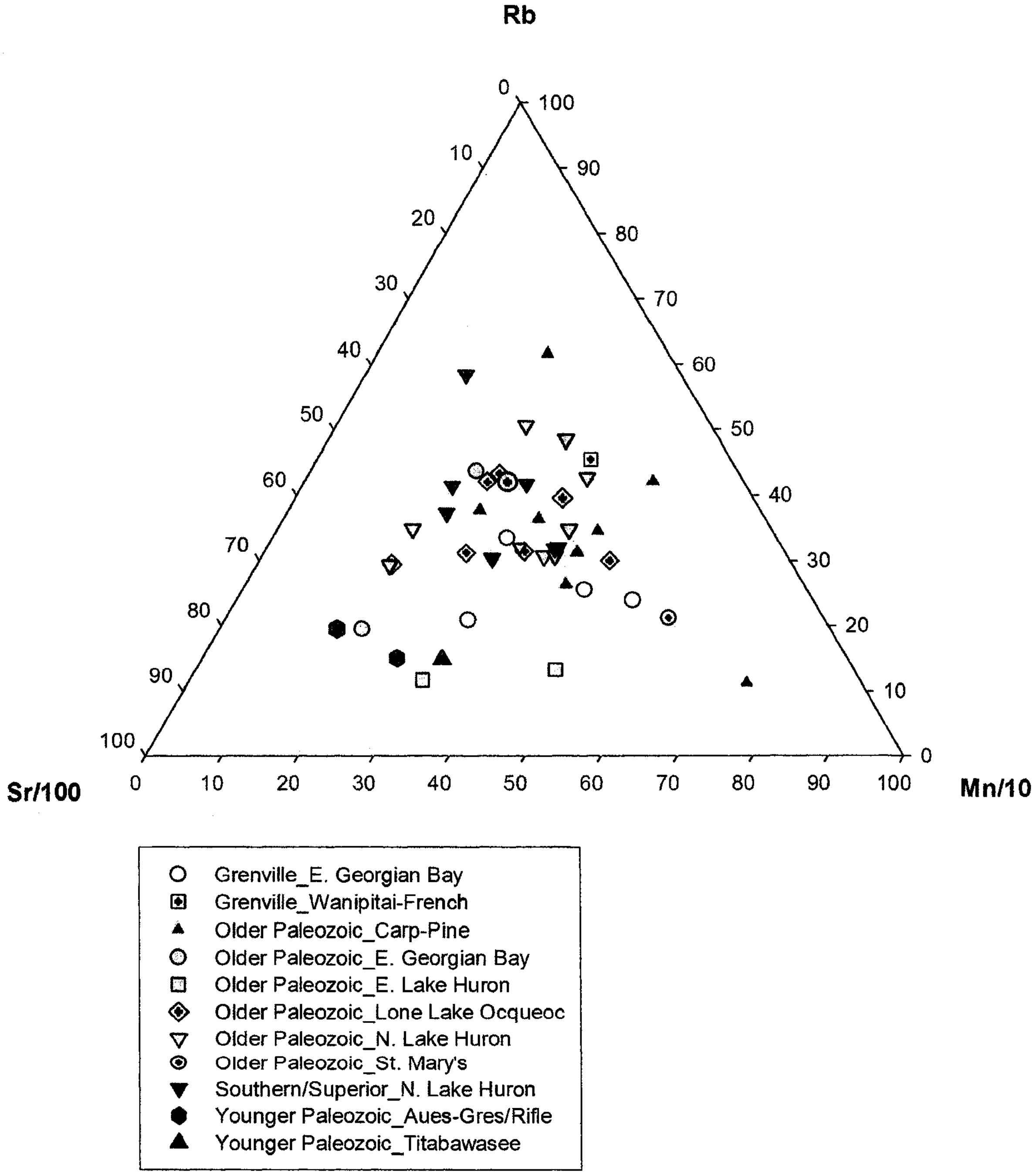


Figure 3.6. LDFA root 1 versus root 2 for eight major production streams with between 90% and 100% classification accuracy. Mn and Rb increase along the x-axis. Rubidium increases along root 2, whereas Sr decreases along it.

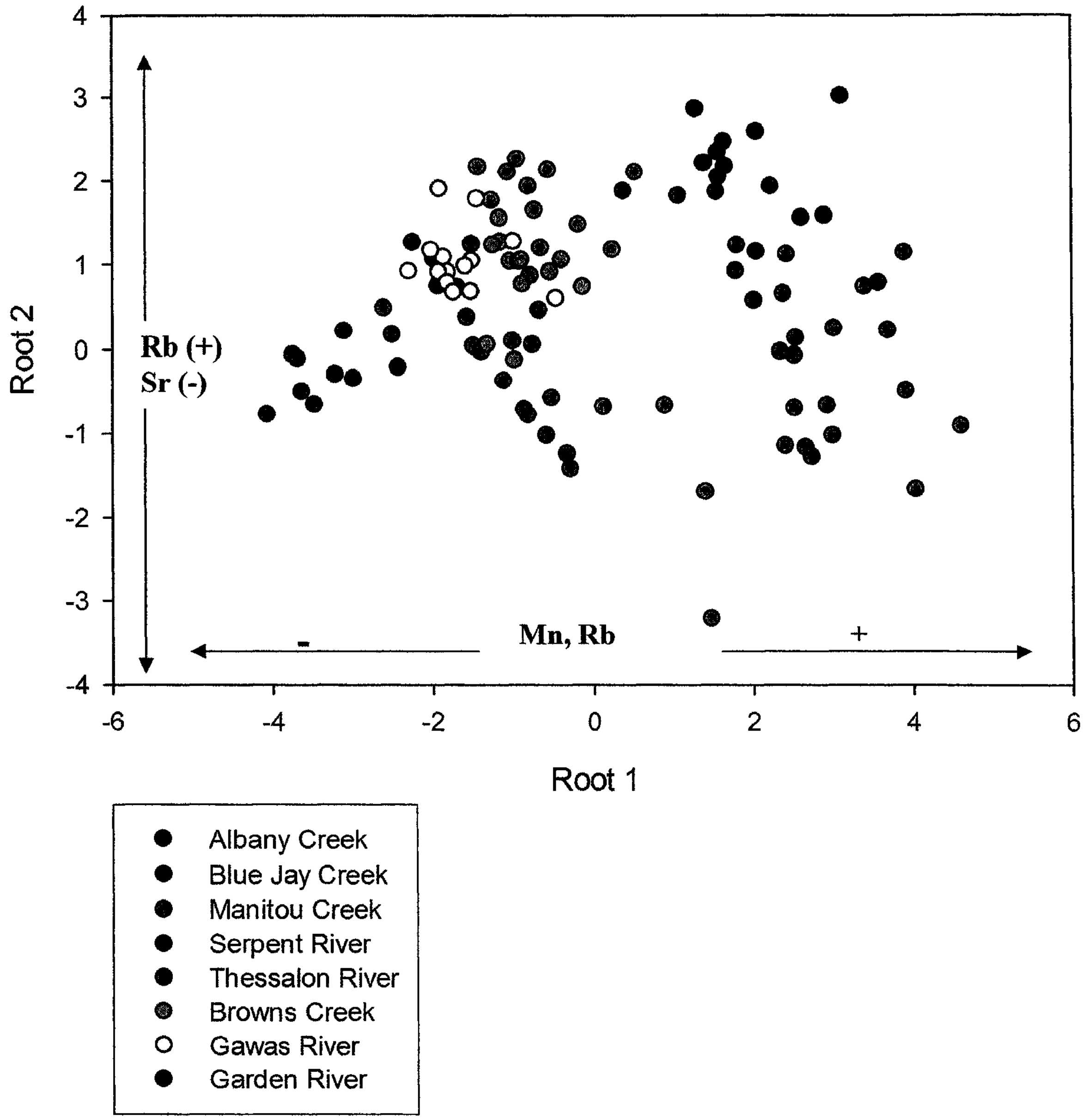
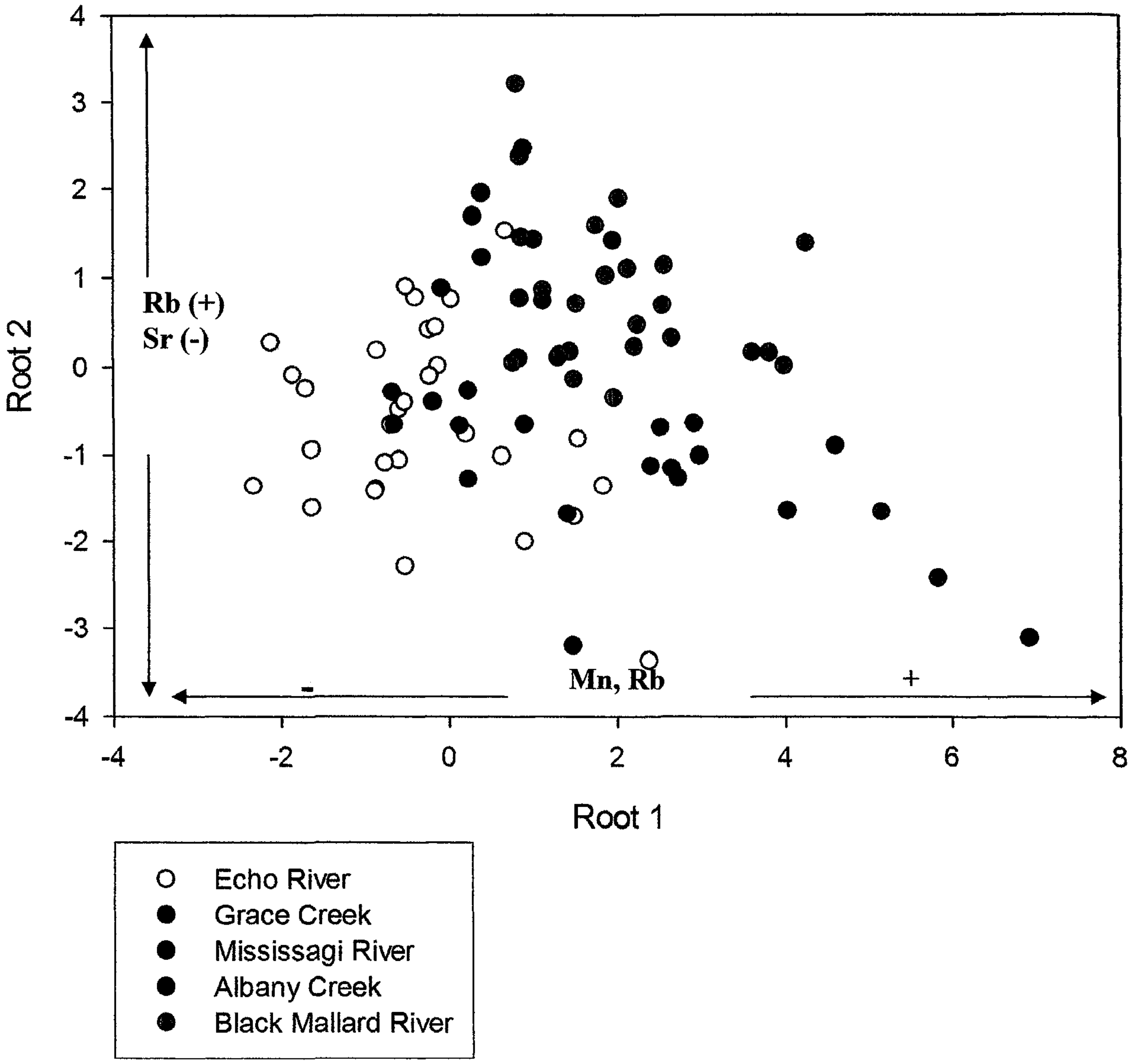


Figure 3.7. LDFA root 1 versus root 2 for the Echo River and Mississagi River, along with the streams they are consistently misclassified with (Grace Creek, Albany Creek and Black Mallard River). Mn and Rb increase along the x-axis. Rubidium increases along root 2, whereas Sr decreases along it.



Conclusion

The ultimate goal of this study was to determine whether statolith microchemistry is a viable technique for discriminating among sea lamprey production streams in Lake Huron so that contributions from natal streams could eventually be determined. Toward this end, I helped further develop the technique and explored some of its potential limitations (see Chapter 2). From this effort, I learned that preserving fish by freezing versus in 95% ethanol had little effect on statolith elements concentrations. Thus, the current agency protocol of storing larvae in ethanol and adults/parasites frozen should not cause significant bias. Second, I demonstrated that the use of LA-ICP-MS is preferable to PIXE due to 1) lower limits of detection for elements significant for classification, 2) its wide availability at lower costs for analysis and 3) the reduced time (and hence money) to process samples. Importantly, however, the frequently elevated elemental concentrations produced by PIXE in Brothers and Thresher's (2004) analysis relative to LA-ICP-MS may very well have been attributable to different cleaning techniques (i.e. contamination may have been a problem in their analysis), not technological limitations. Further work should be conducted to better determine whether PIXE always produces higher elemental concentrations than LA-ICP-MS, holding all other things (e.g., cleaning process) constant. Third, while I found that 10 individuals per stream would probably be sufficient to accurately represent a stream, I recommend using a minimum of 15 fish due to differences found for some elements. And finally, using a small subset of streams from lakes Superior, Michigan and Huron, I demonstrated that sufficient statolith elemental differences exist among production streams, but that discrimination may not be perfect for all streams owing to the effects of local geology and watershed inputs.

In Chapter 3, I further explored statolith microchemistry as a technique, focusing on my ability to discriminate among 45 sea lamprey producing tributaries in the Lake Huron basin. When samples were grouped either by geology or by watershed in our analyses, I expected to find higher levels of discrimination ability (classification accuracy) than when all 45 streams were looked at individually. While my expectation held true for the analysis involving geologic zones, it did not hold true for the watershed comparison. While I cannot fully explain our inability to discriminate among all watersheds, it is likely that past glacial movements and relative location in the watershed are important. For example, streams in the southern Lake Huron basin likely cannot be discriminated because of sediment deposits originating from similar glacial origins. Further, lamprey from the St. Mary's watershed, which historically has produced the most sea lamprey larvae in the Lake Huron basin, it likely cannot be discriminated because the St. Mary's River serves as a depository of water and sediments from many different watersheds (i.e., all water draining from Lake Superior runs through the St. Mary's watershed). Our analysis of individual streams demonstrated both successes (e.g., 12 streams with perfect classification accuracy, including 8 that are known to be large producers of larvae) and failures (8 with <50% classification accuracy).

While an inability to discriminate among some streams may simply be attributable to insufficient variation in ambient element concentrations, my analysis also suggests that inter-annual variation in stream-specific signatures is important. However, the exact cause of high variation in stream-specific signatures between sampling years is unknown. While it is possible that water chemistry does vary enough annually to drive differential variation in statolith micro-elemental signatures, other possibilities exist as well. While I have ruled out the likelihood that age-specific physiological effects are responsible for inter-annual differences within streams, given that sea lamprey length was not correlated strongly with any element (all Pearson r values < 0.1) and length was also largely unimportant as a covariate in our LDFA models, there are two other possibilities that cannot be ruled out as of yet. First, it is possible that larval collection site differences between years may have played a role, especially in large tributaries with numerous reaches that may be exposed to different geologies or pollutants. Second, LA-ICP-MS measurement error may have also influenced my results. I am confident in the measurement precision, given that all elements used in analysis had a coefficient of variation of < 5% based on the NIST-610 standards. However, because 2004 and 2005 samples were run at different times (i.e., 2004 samples first, then 2005), a whole-sale shift in the ability of our instrument to quantify one or more elements could have occurred. To explore potential importance of instrument error, I plan to simultaneously analyze 2004 and 2005 samples from the same streams (using both statoliths).

Though statolith microchemistry as a technique shows a lot of promise, the evidence of inter-annual variation in stream-specific signatures highlights the need for additional research before this technique could be used for management purposes. Most importantly, it is critical that we understand how much variation in signatures occurs, since larvae spend between 3 and 7 years residing there. If indeed inter-annual variation can be greater within streams than among them, this would cause major difficulties when assigning unknown parasites/spawners back to their natal stream. Currently, only two years of data have been explored from any tributary. I suggest that at least 5 years of data would be needed to help place these two years in context. I also recommend that research be conducted to explore the potential use of other approaches for discrimination, including stable isotope analysis, larval growth rates and statolith morphology. I am optimistic that the addition of another discrimination technique (e.g., stable isotopes) to our already fairly distinctive elemental signatures would provide the GLFC and other management agencies with a means to prioritize sea lamprey control efforts throughout the Great Lakes without unwarranted assumptions about larval survival.

APPENDIX A

My data from LA-ICP-MS analyses, 2004-2005 (concentrations in ppm)

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1480	Old Paleozoic	Carp-Pine	Albany Cr.	61	2005	4282	182.3	44.4	3.1	315	25.7	0.02
PEMA-1485	Old Paleozoic	Carp-Pine	Albany Cr.	62	2005	3981	252.5	54.2	3.0	283	27.7	0.11
PEMA-1486	Old Paleozoic	Carp-Pine	Albany Cr.	64	2005	4372	134.4	60.2	3.3	355	25.6	0.28
PEMA-1477	Old Paleozoic	Carp-Pine	Albany Cr.	69	2005	2470	93.5	30.2	1.6	281	17.6	0.01
PEMA-1483	Old Paleozoic	Carp-Pine	Albany Cr.	69	2005	2767	80.2	14.9	1.6	872	38.2	0.25
PEMA-1479	Old Paleozoic	Carp-Pine	Albany Cr.	91	2005	4851	199.1	25.2	3.2	259	25.6	0.10
PEMA-1478	Old Paleozoic	Carp-Pine	Albany Cr.	97	2005	4063	151.3	12.8	3.8	368	24.1	0.06
PEMA-1475	Old Paleozoic	Carp-Pine	Albany Cr.	100	2005	5211	337.1	36.6	4.8	337	29.6	0.20
PEMA-1482	Old Paleozoic	Carp-Pine	Albany Cr.	104	2005	2879	104.2	5.9	1.9	340	24.1	0.03
PEMA-1473	Old Paleozoic	Carp-Pine	Albany Cr.	126	2005	5407	360.1	123.1	2.9	374	37.6	0.26
PEMA-1474	Old Paleozoic	Carp-Pine	Albany Cr.	130	2005	5686	222.0	51.1	2.8	286	20.3	0.24
PEMA-1472	Old Paleozoic	Carp-Pine	Albany Cr.	134	2005	3122	109.8	17.7	1.7	512	25.4	0.05
PEMA-112	Old Paleozoic	Carp-Pine	Beavertail Cr.	49	2004	2501	28.8	2.0	5.7	255	97.8	0.04
PEMA-109	Old Paleozoic	Carp-Pine	Beavertail Cr.	59	2004	3710	22.4	3.8	8.8	185	41.3	0.09
PEMA-101	Old Paleozoic	Carp-Pine	Beavertail Cr.	61	2004	3438	27.9	0.90	6.3	167	9.9	0.03
PEMA-110	Old Paleozoic	Carp-Pine	Beavertail Cr.	61	2004	3156	27.7	1.8	6.2	164	12.1	0.01
PEMA-114	Old Paleozoic	Carp-Pine	Beavertail Cr.	67	2004	2630	26.4	0.79	5.8	181	9.5	0.02
PEMA-108	Old Paleozoic	Carp-Pine	Beavertail Cr.	68	2004	2996	27.0	0.34	6.8	174	14.1	0.07
PEMA-111	Old Paleozoic	Carp-Pine	Beavertail Cr.	72	2004	2539	24.9	3.0	6.7	192	15.2	0.05
PEMA-113	Old Paleozoic	Carp-Pine	Beavertail Cr.	75	2004	2833	24.9	36.3	6.7	135	5.2	0.08
PEMA-107	Old Paleozoic	Carp-Pine	Beavertail Cr.	78	2004	2815	20.4	1.9	9.6	165	16.5	0.03
PEMA-105	Old Paleozoic	Carp-Pine	Beavertail Cr.	84	2004	2597	28.8	7.6	8.6	193	27.6	0.07
PEMA-103	Old Paleozoic	Carp-Pine	Beavertail Cr.	88	2004	3441	25.0	1.3	6.1	104	5.3	0.03
PEMA-106	Old Paleozoic	Carp-Pine	Beavertail Cr.	90	2004	2780	25.6	1.1	8.9	123	6.0	0.05
PEMA-102	Old Paleozoic	Carp-Pine	Beavertail Cr.	98	2004	3628	19.3	4.6	6.0	339	13.1	0.09
PEMA-104	Old Paleozoic	Carp-Pine	Beavertail Cr.	115	2004	4256	29.9	2.3	7.4	184	8.0	0.11
PEMA-100	Old Paleozoic	Carp-Pine	Beavertail Cr.	119	2004	2920	29.6	2.6	6.6	156	10.0	0.03
PEMA-1400	Old Paleozoic	East Lk. Huron	Bighead R.	64	2005	3599	10.5	0.69	0.91	290	16.0	0.04
PEMA-1387	Old Paleozoic	East Lk. Huron	Bighead R.	68	2005	4304	16.3	0.77	0.49	691	13.0	0.16

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1399	Old Paleozoic	East Lk. Huron	Bighead R.	70	2005	3393	15.7	0.86	0.73	345	16.5	0.05
PEMA-1398	Old Paleozoic	East Lk. Huron	Bighead R.	71	2005	3924	18.8	0.06	0.91	297	16.5	0.06
PEMA-1397	Old Paleozoic	East Lk. Huron	Bighead R.	81	2005	3534	10.3	0.39	0.78	313	6.7	0.01
PEMA-1389	Old Paleozoic	East Lk. Huron	Bighead R.	82	2005	4396	16.8	0.82	0.43	243	3.5	0.01
PEMA-1390	Old Paleozoic	East Lk. Huron	Bighead R.	83	2005	4537	16.3	1.2	0.69	288	3.6	0.04
PEMA-1386	Old Paleozoic	East Lk. Huron	Bighead R.	87	2005	3982	16.8	1.2	0.45	212	4.9	0.03
PEMA-1392	Old Paleozoic	East Lk. Huron	Bighead R.	87	2005	4948	19.0	2.3	0.68	376	6.9	0.04
PEMA-1388	Old Paleozoic	East Lk. Huron	Bighead R.	90	2005	4461	18.0	3.0	0.63	211	3.8	0.04
PEMA-1391	Old Paleozoic	East Lk. Huron	Bighead R.	90	2005	3958	11.0	2.4	0.62	299	4.3	0.04
PEMA-1396	Old Paleozoic	East Lk. Huron	Bighead R.	98	2005	3935	15.8	1.3	0.44	382	7.1	0.06
PEMA-1395	Old Paleozoic	East Lk. Huron	Bighead R.	121	2005	5021	20.4	3.8	0.57	214	5.5	0.09
PEMA-1394	Old Paleozoic	East Lk. Huron	Bighead R.	134	2005	4458	21.4	2.1	0.54	231	3.2	0.06
PEMA-1393	Old Paleozoic	East Lk. Huron	Bighead R.	139	2005	5115	21.5	3.5	0.51	265	8.0	0.08
PEMA-1520	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	67	2005	4640	53.9	8.2	5.4	327	10.6	0.11
PEMA-1519	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	78	2005	4361	38.1	10.3	6.3	301	9.8	0.06
PEMA-1517	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	82	2005	3814	69.1	2.5	6.6	330	8.9	0.14
PEMA-1527	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	82	2005	3861	32.0	6.2	5.6	418	23.0	0.07
PEMA-1521	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	83	2005	3883	91.8	11.3	8.6	443	10.0	0.09
PEMA-1524	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	83	2005	4125	50.1	6.8	5.0	342	10.5	0.12
PEMA-1529	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	84	2005	3877	47.5	22.9	4.7	365	10.9	0.06
PEMA-1526	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	85	2005	4121	59.8	19.2	5.0	415	11.7	0.10
PEMA-1525	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	91	2005	4517	45.7	61.7	4.1	315	9.7	0.14
PEMA-1522	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	93	2005	3919	45.8	2.4	5.9	320	10.7	0.00
PEMA-1523	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	94	2005	4182	40.8	27.2	5.2	398	11.0	0.03
PEMA-1531	Old Paleozoic	Lone Lk. Ocqueoc	Black Mallard R.	95	2005	4460	30.7	1704.6	5.4	318	12.3	0.52
PEMA-1296	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	55	2005	2517	21.2	0.64	1.8	199	4.9	0.02
PEMA-1300	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	55	2005	3352	12.2	1.4	1.6	273	9.5	0.02
PEMA-1299	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	58	2005	3010	17.5	0.27	1.8	179	3.0	0.03
PEMA-1310	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	60	2005	4067	25.4	2.2	1.5	132	5.4	0.05

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1302	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	61	2005	3177	17.6	0.33	1.7	254	11.9	0.07
PEMA-1298	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	62	2005	3459	13.4	0.46	1.5	212	3.6	0.01
PEMA-1301	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	62	2005	2881	19.0	1.4	1.7	252	6.2	0.06
PEMA-1297	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	63	2005	3789	14.9	1.3	1.7	246	7.4	0.05
PEMA-1308	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	64	2005	3589	24.8	4.6	2.0	212	6.0	0.07
PEMA-1306	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	69	2005	3393	36.4	2.3	2.5	152	5.4	0.03
PEMA-1303	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	72	2005	3496	26.1	1.4	2.1	192	6.6	0.05
PEMA-1307	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	76	2005	2663	25.0	2.4	2.4	221	8.6	0.06
PEMA-1309	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	78	2005	3471	38.0	4.1	2.3	124	5.1	0.05
PEMA-1305	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	80	2005	3446	30.5	4.5	2.4	176	5.4	0.04
PEMA-1304	Old Paleozoic	North Lk. Huron	Blue Jay Cr.	99	2005	3164	33.8	4.3	2.1	216	11.3	0.05
PEMA-1352	Grenville	East Georgian Bay	Boyne R.	44	2005	3320	84.3	0.31	5.3	1170	39.2	0.06
PEMA-1348	Grenville	East Georgian Bay	Boyne R.	46	2005	4167	43.1	0.42	4.4	1223	25.1	0.02
PEMA-1355	Grenville	East Georgian Bay	Boyne R.	46	2005	4136	57.1	0.48	5.5	1202	33.6	0.04
PEMA-1353	Grenville	East Georgian Bay	Boyne R.	47	2005	3478	66.8	0.77	4.4	1084	34.8	0.05
PEMA-1354	Grenville	East Georgian Bay	Boyne R.	53	2005	4142	100.1	1.9	5.2	1142	27.1	0.06
PEMA-1343	Grenville	East Georgian Bay	Boyne R.	56	2005	3836	85.5	0.70	4.1	1234	28.0	0.05
PEMA-1350	Grenville	East Georgian Bay	Boyne R.	56	2005	4118	60.5	0.34	5.2	1161	30.6	0.06
PEMA-1351	Grenville	East Georgian Bay	Boyne R.	57	2005	3363	73.1	0.81	5.3	1128	32.7	0.02
PEMA-1344	Grenville	East Georgian Bay	Boyne R.	59	2005	3753	75.7	0.82	5.4	1185	24.6	0.04
PEMA-1345	Grenville	East Georgian Bay	Boyne R.	60	2005	3569	94.2	0.54	5.2	1168	32.2	0.01
PEMA-1341	Grenville	East Georgian Bay	Boyne R.	64	2005	3314	134.4	0.92	4.7	1049	22.4	0.05
PEMA-1349	Grenville	East Georgian Bay	Boyne R.	66	2005	3637	70.8	0.18	4.9	1025	45.8	0.06
PEMA-1347	Grenville	East Georgian Bay	Boyne R.	67	2005	4183	63.5	1.1	5.0	1159	38.0	0.05
PEMA-1346	Grenville	East Georgian Bay	Boyne R.	73	2005	3784	51.4	0.52	4.8	1003	28.1	0.01
PEMA-1342	Grenville	East Georgian Bay	Boyne R.	120	2005	4384	86.2	1.6	4.8	782	38.0	0.10
PEMA-1123	Old Paleozoic	North Lk. Huron	Browns Cr.	126	2005	4898	32.4	4.8	2.5	301	17.0	0.20
PEMA-1119	Old Paleozoic	North Lk. Huron	Browns Cr.	137	2005	4929	22.5	3.3	2.6	338	19.5	0.06
PEMA-1122	Old Paleozoic	North Lk. Huron	Browns Cr.	142	2005	4331	40.1	20.4	2.8	326	29.0	0.58

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1121	Old Paleozoic	North Lk. Huron	Browns Cr.	143	2005	3928	40.1	5.8	3.0	271	15.5	0.34
PEMA-1117	Old Paleozoic	North Lk. Huron	Browns Cr.	145	2005	4689	31.0	13.7	3.1	308	23.0	0.52
PEMA-1116	Old Paleozoic	North Lk. Huron	Browns Cr.	147	2005	4433	29.6	5.9	2.8	301	17.8	0.43
PEMA-1120	Old Paleozoic	North Lk. Huron	Browns Cr.	150	2005	4056	22.3	5.0	3.0	300	16.1	0.25
PEMA-1124	Old Paleozoic	North Lk. Huron	Browns Cr.	150	2005	3066	24.3	4.3	2.7	322	19.5	0.28
PEMA-1118	Old Paleozoic	North Lk. Huron	Browns Cr.	154	2005	4364	26.4	3.8	3.1	299	15.7	0.23
PEMA-374	Old Paleozoic	Carp-Pine	Caribou Cr.	45	2004	3593	33.2	7.6	2.8	504	50.8	0.04
PEMA-375	Old Paleozoic	Carp-Pine	Caribou Cr.	54	2004	2508	54.0	5.0	2.7	357	18.5	0.07
PEMA-366	Old Paleozoic	Carp-Pine	Caribou Cr.	79	2004	4443	35.2	4.6	2.8	272	12.8	0.06
PEMA-367	Old Paleozoic	Carp-Pine	Caribou Cr.	81	2004	4371	31.7	6.7	4.5	203	17.6	0.05
PEMA-369	Old Paleozoic	Carp-Pine	Caribou Cr.	101	2004	3391	47.4	14.0	4.2	252	13.5	0.10
PEMA-371	Old Paleozoic	Carp-Pine	Caribou Cr.	101	2004	4277	69.4	26.4	3.7	207	22.0	0.10
PEMA-361	Old Paleozoic	Carp-Pine	Caribou Cr.	109	2004	3741	58.4	17.8	3.8	262	20.8	0.10
PEMA-370	Old Paleozoic	Carp-Pine	Caribou Cr.	109	2004	3670	66.7	11.4	4.9	239	21.6	0.07
PEMA-360	Old Paleozoic	Carp-Pine	Caribou Cr.	110	2004	3850	56.6	10.6	4.6	291	16.0	0.10
PEMA-365	Old Paleozoic	Carp-Pine	Caribou Cr.	113	2004	3559	49.3	8.6	5.3	205	15.1	0.03
PEMA-362	Old Paleozoic	Carp-Pine	Caribou Cr.	114	2004	4412	59.8	11.6	5.2	243	19.6	0.07
PEMA-373	Old Paleozoic	Carp-Pine	Caribou Cr.	114	2004	4045	53.5	19.7	3.7	232	22.5	0.09
PEMA-368	Old Paleozoic	Carp-Pine	Caribou Cr.	115	2004	3300	66.3	15.8	5.1	357	25.7	0.14
PEMA-363	Old Paleozoic	Carp-Pine	Caribou Cr.	118	2004	3236	72.3	11.6	5.2	409	26.5	0.04
PEMA-364	Old Paleozoic	Carp-Pine	Caribou Cr.	124	2004	3989	40.5	12.6	6.2	242	14.4	0.03
PEMA-1516	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	83	2005	3334	6.9	31.8	1.6	356	14.2	0.22
PEMA-1513	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	91	2005	4469	7.7	9.1	1.9	339	12.4	1.14
PEMA-1510	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	97	2005	3699	7.4	3.9	1.6	324	14.9	0.55
PEMA-1507	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	100	2005	5165	10.1	8.1	1.9	318	10.3	0.41
PEMA-1508	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	101	2005	5083	11.9	4.8	1.8	291	10.6	0.71
PEMA-1514	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	102	2005	4422	11.1	6.0	1.4	293	11.3	0.36
PEMA-1505	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	103	2005	3766	7.8	55.1	1.7	255	5.8	0.13
PEMA-1511	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	104	2005	3100	9.0	2.0	1.7	304	12.3	0.41

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1515	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	108	2005	4595	13.8	8.8	1.9	308	13.3	1.89
PEMA-1503	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	116	2005	3375	16.9	1.7	2.3	468	7.6	0.17
PEMA-1506	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	116	2005	4749	11.9	9.6	1.6	264	13.2	2.57
PEMA-1504	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	117	2005	3555	10.3	2.9	1.4	314	15.6	0.30
PEMA-1509	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	124	2005	5022	12.9	9.2	1.7	264	7.5	1.89
PEMA-1502	Old Paleozoic	Lone Lk. Ocqueoc	Cheboygan R.	129	2005	4365	10.8	8.8	1.7	259	8.1	0.52
PEMA-896	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	88	2004	4498	36.0	30.6	2.5	317	11.4	0.13
PEMA-1076	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	90	2004	3934	23.4	9.2	2.6	346	21.8	0.09
PEMA-897	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	92	2004	3128	27.8	19.7	2.3	501	16.5	0.56
PEMA-1077	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	93	2004	3639	17.4	8.1	2.8	503	18.4	0.08
PEMA-894	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	94	2004	3774	25.5	23.7	2.2	340	13.3	0.15
PEMA-1078	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	96	2004	4210	23.0	11.3	2.6	425	14.5	0.11
PEMA-889	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	106	2004	5004	32.3	13.8	3.5	354	12.7	0.01
PEMA-1075	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	111	2004	3936	23.9	17.1	3.0	289	7.3	0.06
PEMA-895	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	111	2004	5066	26.8	17.2	2.9	506	22.6	0.12
PEMA-888	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	133	2004	4914	22.0	27.0	2.9	342	9.8	0.07
PEMA-887	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	134	2004	4784	23.9	32.8	3.3	530	17.5	0.02
PEMA-893	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	136	2004	4909	32.4	13.7	3.0	393	12.8	0.17
PEMA-892	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	137	2004	3785	26.8	23.2	3.3	243	9.8	0.15
PEMA-890	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	139	2004	5034	17.3	31.7	3.3	308	6.3	0.11
PEMA-891	Old Paleozoic	Lone Lk. Ocqueoc	Devils R.	144	2004	5014	15.5	26.4	2.8	423	12.1	0.17
PEMA-691	South./Sup.	North Lk. Huron	Echo R.	87	2004	3377	43.9	1.4	1.8	354	13.6	0.02
PEMA-693	South./Sup.	North Lk. Huron	Echo R.	97	2004	3102	24.0	2.0	1.4	394	12.5	0.16
PEMA-692	South./Sup.	North Lk. Huron	Echo R.	109	2004	3872	36.2	2.5	1.6	605	31.5	0.03
PEMA-701	South./Sup.	North Lk. Huron	Echo R.	132	2004	3994	51.9	35.8	2.0	282	8.1	0.20
PEMA-698	South./Sup.	North Lk. Huron	Echo R.	133	2004	4880	30.7	11.0	2.6	383	16.2	0.26
PEMA-794	South./Sup.	North Lk. Huron	Echo R.	133	2004	4229	35.3	17.8	1.7	470	33.5	0.28
PEMA-696	South./Sup.	North Lk. Huron	Echo R.	134	2004	4302	24.2	2.9	1.9	388	12.5	0.10
PEMA-795	South./Sup.	North Lk. Huron	Echo R.	136	2004	3216	29.9	17.3	1.7	292	7.1	0.19

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-699	South./Sup.	North Lk. Huron	Echo R.	138	2004	4615	38.0	8.0	1.3	301	9.8	0.00
PEMA-695	South./Sup.	North Lk. Huron	Echo R.	139	2004	4939	56.9	31.3	1.8	289	10.6	0.17
PEMA-792	South./Sup.	North Lk. Huron	Echo R.	139	2004	3448	20.8	24.1	1.8	321	11.3	0.12
PEMA-694	South./Sup.	North Lk. Huron	Echo R.	140	2004	3737	56.4	8.8	2.2	381	13.1	0.03
PEMA-700	South./Sup.	North Lk. Huron	Echo R.	140	2004	4388	32.4	20.8	2.0	405	19.4	0.04
PEMA-697	South./Sup.	North Lk. Huron	Echo R.	141	2004	5478	37.3	7.4	1.9	376	14.3	0.24
PEMA-793	South./Sup.	North Lk. Huron	Echo R.	144	2004	4096	30.6	20.2	1.8	291	9.0	0.30
PEMA-1154	South./Sup.	North Lk. Huron	Echo R.	39	2005	4168	33.3	1.0	4.6	432	12.7	0.08
PEMA-1147	South./Sup.	North Lk. Huron	Echo R.	43	2005	3446	27.8	0.66	3.7	268	8.7	0.12
PEMA-1149	South./Sup.	North Lk. Huron	Echo R.	43	2005	3284	41.2	0.04	4.7	1187	15.8	0.03
PEMA-1143	South./Sup.	North Lk. Huron	Echo R.	44	2005	3423	22.8	0.40	4.7	398	14.4	0.05
PEMA-1144	South./Sup.	North Lk. Huron	Echo R.	45	2005	3469	28.4	0.04	5.3	291	9.7	0.10
PEMA-1148	South./Sup.	North Lk. Huron	Echo R.	45	2005	2962	31.2	1.3	4.5	307	12.9	0.06
PEMA-1150	South./Sup.	North Lk. Huron	Echo R.	45	2005	3786	23.0	0.41	4.3	838	25.2	0.02
PEMA-1152	South./Sup.	North Lk. Huron	Echo R.	46	2005	3248	29.9	0.66	4.5	298	10.2	0.04
PEMA-1145	South./Sup.	North Lk. Huron	Echo R.	47	2005	3163	22.6	1.3	4.8	283	7.6	0.03
PEMA-1151	South./Sup.	North Lk. Huron	Echo R.	47	2005	3854	24.0	0.12	5.1	337	8.9	0.02
PEMA-1146	South./Sup.	North Lk. Huron	Echo R.	50	2005	3711	36.2	0.17	5.6	687	22.7	0.02
PEMA-1153	South./Sup.	North Lk. Huron	Echo R.	52	2005	3352	31.1	0.27	4.5	841	28.1	0.04
PEMA-1142	South./Sup.	North Lk. Huron	Echo R.	54	2005	4151	52.0	0.76	5.1	416	14.1	0.07
PEMA-1141	South./Sup.	North Lk. Huron	Echo R.	99	2005	3963	21.5	1.4	4.4	361	16.0	0.11
PEMA-1140	South./Sup.	North Lk. Huron	Echo R.	113	2005	4265	34.1	2.2	6.0	286	12.0	0.14
PEMA-609	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	78	2004	3469	16.2	17.0	3.1	196	10.4	0.24
PEMA-601	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	83	2004	3002	24.1	4.4	2.3	201	13.4	0.16
PEMA-608	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	98	2004	3733	16.0	28.1	3.7	311	28.4	0.30
PEMA-610	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	104	2004	3093	16.6	53.5	3.6	164	14.0	0.46
PEMA-1054	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	105	2004	3412	19.7	17.6	2.7	230	13.5	0.26
PEMA-605	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	105	2004	4918	22.1	79.2	4.2	268	27.0	0.58
PEMA-604	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	106	2004	3503	15.8	26.7	2.2	450	12.3	0.02

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-602	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	109	2004	3423	18.7	24.7	3.7	266	21.1	0.30
PEMA-606	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	114	2004	3094	19.3	39.8	4.1	242	15.4	0.21
PEMA-1057	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	116	2004	3542	19.3	39.3	3.6	233	11.2	0.48
PEMA-607	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	116	2004	3516	19.4	47.2	2.5	249	12.7	0.25
PEMA-1053	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	117	2004	3070	16.7	80.6	3.0	290	21.5	0.30
PEMA-1056	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	117	2004	4034	18.9	45.5	3.2	273	24.0	0.20
PEMA-1055	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	121	2004	3166	16.6	39.0	2.5	199	8.6	0.31
PEMA-603	Old Paleozoic	Lone Lk. Ocqueoc	Elliot Cr.	148	2004	3768	17.4	37.1	3.5	254	12.9	0.28
PEMA-1321	Grenville	Wanipiti-French	French R.	130	2005	4074	52.9	4.4	6.0	267	17.2	0.12
PEMA-1322	Grenville	Wanipiti-French	French R.	133	2005	5423	65.0	9.3	7.3	281	20.6	0.30
PEMA-1319	Grenville	Wanipiti-French	French R.	134	2005	4388	48.6	2.4	5.4	242	15.2	0.09
PEMA-1320	Grenville	Wanipiti-French	French R.	135	2005	3998	34.3	4.0	6.9	256	16.3	0.24
PEMA-1324	Grenville	Wanipiti-French	French R.	135	2005	4791	59.8	7.2	8.4	263	18.5	0.23
PEMA-1315	Grenville	Wanipiti-French	French R.	143	2005	4078	41.9	10.6	6.5	206	13.2	0.20
PEMA-1313	Grenville	Wanipiti-French	French R.	144	2005	3418	37.3	5.5	6.4	238	12.1	0.18
PEMA-1317	Grenville	Wanipiti-French	French R.	146	2005	4092	65.1	28.9	5.4	233	13.9	0.19
PEMA-1323	Grenville	Wanipiti-French	French R.	147	2005	3731	39.8	7.8	5.7	253	16.5	0.16
PEMA-1325	Grenville	Wanipiti-French	French R.	147	2005	5104	49.5	15.5	7.8	232	17.7	0.30
PEMA-1312	Grenville	Wanipiti-French	French R.	149	2005	4037	48.3	9.4	6.7	227	18.4	0.17
PEMA-1316	Grenville	Wanipiti-French	French R.	153	2005	4414	48.9	7.1	5.6	273	15.7	0.14
PEMA-1318	Grenville	Wanipiti-French	French R.	154	2005	4222	49.3	5.7	5.1	347	23.5	0.16
PEMA-1311	Grenville	Wanipiti-French	French R.	167	2005	4103	63.6	56.8	6.8	258	21.4	0.35
PEMA-1314	Grenville	Wanipiti-French	French R.	178	2005	3749	49.2	0.68	4.6	245	15.6	0.10
PEMA-1195	South./Sup.	North Lk. Huron	Garden R.	55	2005	3238	19.7	0.62	9.8	515	56.1	0.05
PEMA-1199	South./Sup.	North Lk. Huron	Garden R.	59	2005	3622	30.9	1.1	9.8	436	15.4	0.04
PEMA-1198	South./Sup.	North Lk. Huron	Garden R.	60	2005	2896	28.9	0.60	9.1	389	25.9	0.04
PEMA-1192	South./Sup.	North Lk. Huron	Garden R.	61	2005	3453	26.0	16.8	10.8	464	21.3	0.10
PEMA-1197	South./Sup.	North Lk. Huron	Garden R.	62	2005	3164	20.1	28.4	12.1	812	422.0	0.08
PEMA-1194	South./Sup.	North Lk. Huron	Garden R.	63	2005	3276	20.4	0.78	9.5	363	9.7	0.01

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-1193	South./Sup.	North Lk. Huron	Garden R.	68	2005	3903	15.5	18.5	7.8	374	15.3	0.11
PEMA-1191	South./Sup.	North Lk. Huron	Garden R.	72	2005	3000	22.1	0.92	9.6	405	17.1	0.02
PEMA-1196	South./Sup.	North Lk. Huron	Garden R.	76	2005	3672	22.5	1.2	10.5	402	28.8	0.07
PEMA-1189	South./Sup.	North Lk. Huron	Garden R.	94	2005	3080	18.3	1.3	10.6	417	19.7	0.10
PEMA-1190	South./Sup.	North Lk. Huron	Garden R.	95	2005	4459	42.9	3.4	10.6	439	30.3	0.09
PEMA-1185	South./Sup.	North Lk. Huron	Garden R.	96	2005	3929	16.5	22.8	10.8	917	85.1	0.11
PEMA-1187	South./Sup.	North Lk. Huron	Garden R.	98	2005	3705	23.7	1.6	9.9	407	11.2	0.06
PEMA-1188	South./Sup.	North Lk. Huron	Garden R.	99	2005	3616	20.4	46.8	11.0	489	24.6	0.11
PEMA-1186	South./Sup.	North Lk. Huron	Garden R.	108	2005	3274	20.9	24.2	9.2	466	18.3	0.10
PEMA-1168	Old Paleozoic	North Lk. Huron	Gawas R.	122	2005	3810	34.8	16.0	2.3	207	6.8	0.15
PEMA-1167	Old Paleozoic	North Lk. Huron	Gawas R.	123	2005	4329	45.4	10.0	3.0	224	8.3	0.15
PEMA-1169	Old Paleozoic	North Lk. Huron	Gawas R.	125	2005	4013	25.6	17.8	3.2	197	8.6	0.14
PEMA-1159	Old Paleozoic	North Lk. Huron	Gawas R.	130	2005	4507	34.7	16.0	3.1	200	9.0	0.22
PEMA-1160	Old Paleozoic	North Lk. Huron	Gawas R.	131	2005	4304	27.2	7.3	2.6	191	6.9	0.11
PEMA-1161	Old Paleozoic	North Lk. Huron	Gawas R.	135	2005	4558	23.2	11.3	2.6	217	7.6	0.12
PEMA-1163	Old Paleozoic	North Lk. Huron	Gawas R.	136	2005	4527	30.4	13.1	2.6	193	6.6	0.09
PEMA-1157	Old Paleozoic	North Lk. Huron	Gawas R.	137	2005	4171	21.9	10.8	2.2	216	7.7	0.11
PEMA-1162	Old Paleozoic	North Lk. Huron	Gawas R.	137	2005	3354	23.6	10.8	2.6	207	9.1	0.22
PEMA-1155	Old Paleozoic	North Lk. Huron	Gawas R.	138	2005	4447	30.1	11.1	2.7	199	6.8	0.13
PEMA-1165	Old Paleozoic	North Lk. Huron	Gawas R.	138	2005	5048	29.1	18.1	2.4	203	8.1	0.17
PEMA-1164	Old Paleozoic	North Lk. Huron	Gawas R.	139	2005	4563	29.1	7.4	2.4	200	7.4	0.08
PEMA-1156	Old Paleozoic	North Lk. Huron	Gawas R.	141	2005	4663	27.5	7.7	2.5	199	7.4	0.09
PEMA-1166	Old Paleozoic	North Lk. Huron	Gawas R.	143	2005	4639	27.7	18.2	2.4	179	6.8	0.13
PEMA-1158	Old Paleozoic	North Lk. Huron	Gawas R.	144	2005	5913	26.3	31.2	2.7	184	7.0	0.19
PEMA-1201	Old Paleozoic	North Lk. Huron	Gordon Cr.	27	2005	3561	54.1	3.1	1.7	407	16.9	0.02
PEMA-1205	Old Paleozoic	North Lk. Huron	Gordon Cr.	28	2005	3341	29.7	1.4	1.1	320	11.0	0.03
PEMA-1203	Old Paleozoic	North Lk. Huron	Gordon Cr.	28	2005	3156	47.5	1.2	1.6	637	15.1	0.05
PEMA-1206	Old Paleozoic	North Lk. Huron	Gordon Cr.	30	2005	3048	37.0	43.5	1.5	556	16.8	0.12
PEMA-1204	Old Paleozoic	North Lk. Huron	Gordon Cr.	32	2005	3093	29.4	4.3	1.7	441	23.4	0.02

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1207	Old Paleozoic	North Lk. Huron	Gordon Cr.	35	2005	3214	26.0	1.1	1.4	375	8.2	0.02
PEMA-1210	Old Paleozoic	North Lk. Huron	Gordon Cr.	51	2005	3346	61.9	14.4	6.7	371	15.1	0.18
PEMA-1208	Old Paleozoic	North Lk. Huron	Gordon Cr.	57	2005	2456	107.4	1.2	6.7	414	37.3	0.05
PEMA-1211	Old Paleozoic	North Lk. Huron	Gordon Cr.	59	2005	3370	98.7	6.5	7.3	291	9.2	0.05
PEMA-1212	Old Paleozoic	North Lk. Huron	Gordon Cr.	61	2005	3179	32.7	0.53	6.2	252	8.4	0.04
PEMA-1214	Old Paleozoic	North Lk. Huron	Gordon Cr.	61	2005	3855	79.5	2.4	5.1	307	10.0	0.17
PEMA-1209	Old Paleozoic	North Lk. Huron	Gordon Cr.	64	2005	2944	30.7	0.69	7.7	469	38.0	0.11
PEMA-1200	Old Paleozoic	North Lk. Huron	Gordon Cr.	141	2005	5176	29.9	19.2	3.8	383	12.5	0.07
PEMA-825	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	44	2004	3413	20.1	1.2	4.1	382	4.6	0.05
PEMA-757	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	50	2004	3225	25.8	1.3	3.8	557	9.5	0.08
PEMA-821	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	52	2004	3295	26.0	4.3	4.2	440	11.5	0.04
PEMA-822	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	53	2004	2882	26.7	0.52	3.7	330	4.3	0.09
PEMA-756	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	54	2004	3870	30.5	0.70	6.7	375	6.5	0.58
PEMA-761	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	54	2004	2768	36.0	3.3	5.2	331	8.0	0.01
PEMA-823	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	55	2004	2621	27.5	1.1	3.5	446	9.4	0.11
PEMA-824	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	59	2004	2949	31.5	1.6	4.5	287	8.4	0.09
PEMA-760	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	88	2004	3183	26.5	2.2	6.6	365	48.4	0.10
PEMA-759	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	89	2004	2800	33.4	1.5	5.7	333	37.1	0.09
PEMA-755	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	90	2004	2892	36.9	0.49	5.8	364	17.3	0.11
PEMA-752	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	92	2004	3229	34.5	1.0	5.3	268	11.2	0.13
PEMA-753	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	92	2004	3295	29.0	3.2	5.9	284	11.6	0.08
PEMA-754	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	101	2004	4395	37.3	31.6	6.1	496	101.3	0.30
PEMA-758	Old Paleozoic	Lone Lk. Ocqueoc	Grace Cr.	113	2004	4091	27.1	6.2	5.8	318	7.0	0.23
PEMA-350	Old Paleozoic	Carp-Pine	Hessel Cr.	61	2004	5149	80.5	56.5	5.8	708	24.2	0.13
PEMA-358	Old Paleozoic	Carp-Pine	Hessel Cr.	65	2004	5055	88.1	31.5	6.5	539	18.4	0.16
PEMA-357	Old Paleozoic	Carp-Pine	Hessel Cr.	66	2004	5537	87.7	7.4	6.0	776	26.5	0.12
PEMA-351	Old Paleozoic	Carp-Pine	Hessel Cr.	68	2004	5717	84.7	25.8	6.7	516	13.0	0.08
PEMA-333	Old Paleozoic	Carp-Pine	Hessel Cr.	69	2004	5390	104.8	14.6	8.7	579	18.8	0.14
PEMA-328	Old Paleozoic	Carp-Pine	Hessel Cr.	102	2004	6409	80.4	60.6	4.6	786	37.4	0.28

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-334	Old Paleozoic	Carp-Pine	Hessel Cr.	104	2004	5495	98.7	11.4	5.5	489	30.1	0.11
PEMA-340	Old Paleozoic	Carp-Pine	Hessel Cr.	104	2004	5528	76.2	34.9	6.4	411	31.5	0.16
PEMA-318	Old Paleozoic	Carp-Pine	Hessel Cr.	105	2004	5031	66.7	65.1	4.9	584	27.9	0.34
PEMA-347	Old Paleozoic	Carp-Pine	Hessel Cr.	105	2004	6069	77.7	43.0	6.8	559	174.3	0.26
PEMA-314	Old Paleozoic	Carp-Pine	Hessel Cr.	124	2004	6672	67.2	34.1	6.6	420	33.2	0.40
PEMA-316	Old Paleozoic	Carp-Pine	Hessel Cr.	127	2004	5603	74.2	20.1	6.0	534	28.6	0.18
PEMA-313	Old Paleozoic	Carp-Pine	Hessel Cr.	128	2004	5402	89.6	23.9	8.0	590	66.9	0.23
PEMA-329	Old Paleozoic	Carp-Pine	Hessel Cr.	130	2004	5286	83.1	42.8	6.1	442	24.6	0.31
PEMA-312	Old Paleozoic	Carp-Pine	Hessel Cr.	141	2004	5451	90.1	15.3	5.6	315	40.4	0.11
PEMA-1219	Old Paleozoic	North Lk. Huron	Koshkawong R.	33	2005	3108	42.2	32.5	3.7	169	8.7	0.05
PEMA-1220	Old Paleozoic	North Lk. Huron	Koshkawong R.	38	2005	3450	36.7	3.1	3.7	223	19.2	0.06
PEMA-1217	Old Paleozoic	North Lk. Huron	Koshkawong R.	54	2005	2786	29.7	0.82	3.9	187	13.0	0.04
PEMA-1218	Old Paleozoic	North Lk. Huron	Koshkawong R.	59	2005	3516	44.3	0.09	5.6	219	34.0	0.07
PEMA-1216	Old Paleozoic	North Lk. Huron	Koshkawong R.	65	2005	4418	41.9	10.6	4.3	212	24.9	0.10
PEMA-1215	Old Paleozoic	North Lk. Huron	Koshkawong R.	123	2005	3765	28.6	72.2	4.4	209	19.9	0.22
PEMA-708	South./Sup.	North Lk. Huron	Lauzon Cr.	109	2004	4725	22.3	44.5	6.8	672	35.8	0.45
PEMA-796	South./Sup.	North Lk. Huron	Lauzon Cr.	117	2004	4375	29.9	90.9	5.5	630	40.3	0.32
PEMA-703	South./Sup.	North Lk. Huron	Lauzon Cr.	119	2004	3941	23.3	22.5	5.3	428	38.9	0.28
PEMA-798	South./Sup.	North Lk. Huron	Lauzon Cr.	120	2004	4286	30.6	21.5	6.4	674	33.4	0.26
PEMA-706	South./Sup.	North Lk. Huron	Lauzon Cr.	122	2004	4677	19.0	21.7	6.7	389	29.7	0.43
PEMA-800	South./Sup.	North Lk. Huron	Lauzon Cr.	125	2004	3622	20.6	31.0	5.3	701	42.5	0.26
PEMA-702	South./Sup.	North Lk. Huron	Lauzon Cr.	126	2004	4317	46.5	36.7	9.0	523	23.1	0.12
PEMA-797	South./Sup.	North Lk. Huron	Lauzon Cr.	127	2004	3675	39.7	63.5	4.9	699	36.9	0.49
PEMA-709	South./Sup.	North Lk. Huron	Lauzon Cr.	128	2004	3520	33.4	21.9	4.8	856	44.1	0.17
PEMA-799	South./Sup.	North Lk. Huron	Lauzon Cr.	128	2004	5843	50.4	61.2	5.8	657	45.4	0.54
PEMA-711	South./Sup.	North Lk. Huron	Lauzon Cr.	130	2004	5377	18.8	41.7	6.5	392	28.8	0.14
PEMA-710	South./Sup.	North Lk. Huron	Lauzon Cr.	132	2004	4202	22.7	27.6	5.5	429	21.5	0.86
PEMA-705	South./Sup.	North Lk. Huron	Lauzon Cr.	134	2004	4418	32.5	32.6	7.0	540	30.0	0.35
PEMA-707	South./Sup.	North Lk. Huron	Lauzon Cr.	135	2004	4586	30.0	38.0	7.3	476	35.1	0.19

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-704	South./Sup.	North Lk. Huron	Lauzon Cr.	151	2004	4369	25.6	33.2	5.3	520	34.1	0.23
PEMA-298	Old Paleozoic	St. Marys	Little Monkscong R.	96	2004	3805	37.3	78.6	2.2	244	11.9	0.19
PEMA-293	Old Paleozoic	St. Marys	Little Monkscong R.	97	2004	3476	45.7	27.4	2.0	218	15.8	0.10
PEMA-273	Old Paleozoic	St. Marys	Little Monkscong R.	112	2004	4320	52.8	21.3	2.1	225	14.9	0.12
PEMA-287	Old Paleozoic	St. Marys	Little Monkscong R.	113	2004	3422	43.1	0.75	1.5	191	13.5	0.18
PEMA-284	Old Paleozoic	St. Marys	Little Monkscong R.	118	2004	4754	64.4	70.5	2.2	207	13.5	0.18
PEMA-274	Old Paleozoic	St. Marys	Little Monkscong R.	127	2004	5285	81.0	68.2	4.5	200	16.9	0.49
PEMA-308	Old Paleozoic	St. Marys	Little Monkscong R.	129	2004	3467	72.1	181.4	2.0	218	13.9	0.04
PEMA-302	Old Paleozoic	St. Marys	Little Monkscong R.	142	2004	3627	32.3	33.6	2.0	281	17.3	0.30
PEMA-301	Old Paleozoic	St. Marys	Little Monkscong R.	144	2004	4536	70.4	115.3	2.9	232	13.3	0.37
PEMA-286	Old Paleozoic	St. Marys	Little Monkscong R.	145	2004	4385	177.9	53.7	3.0	359	29.6	0.26
PEMA-627	Grenville	East Georgian Bay	Magnetewan R.	47	2004	5480	239.1	10.1	8.3	939	69.9	0.15
PEMA-630	Grenville	East Georgian Bay	Magnetewan R.	52	2004	3442	94.8	4.5	6.0	678	38.8	0.26
PEMA-1044	Grenville	East Georgian Bay	Magnetewan R.	63	2004	4016	126.5	1.0	5.2	878	51.2	0.12
PEMA-1045	Grenville	East Georgian Bay	Magnetewan R.	64	2004	4263	101.3	43.4	5.8	798	50.1	0.39
PEMA-624	Grenville	East Georgian Bay	Magnetewan R.	67	2004	4954	210.2	1.3	14.0	758	60.8	0.19
PEMA-626	Grenville	East Georgian Bay	Magnetewan R.	68	2004	4283	170.5	6.6	7.6	645	69.7	0.28
PEMA-622	Grenville	East Georgian Bay	Magnetewan R.	75	2004	3063	98.0	0.33	14.1	692	51.9	0.25
PEMA-1041	Grenville	East Georgian Bay	Magnetewan R.	78	2004	4333	142.1	3.2	6.8	902	59.8	0.18
PEMA-625	Grenville	East Georgian Bay	Magnetewan R.	82	2004	4151	325.5	2.4	9.0	963	78.5	0.12
PEMA-1042	Grenville	East Georgian Bay	Magnetewan R.	83	2004	4786	306.0	3.2	5.3	760	81.2	0.27
PEMA-1043	Grenville	East Georgian Bay	Magnetewan R.	84	2004	4244	150.6	7.5	6.4	988	45.8	0.18
PEMA-628	Grenville	East Georgian Bay	Magnetewan R.	84	2004	4448	177.9	23.0	8.2	1273	87.2	0.31
PEMA-629	Grenville	East Georgian Bay	Magnetewan R.	91	2004	5093	132.8	1.4	7.8	753	45.9	0.34
PEMA-623	Grenville	East Georgian Bay	Magnetewan R.	105	2004	4371	234.0	9.0	9.7	715	53.8	0.21
PEMA-621	Grenville	East Georgian Bay	Magnetewan R.	134	2004	4107	234.1	4.3	11.1	700	49.3	0.35
PEMA-1287	Old Paleozoic	North Lk. Huron	Manitou R.	65	2005	3478	22.0	1.5	3.1	487	13.4	0.04
PEMA-1290	Old Paleozoic	North Lk. Huron	Manitou R.	69	2005	3545	14.6	1.3	3.6	444	9.8	0.02
PEMA-1289	Old Paleozoic	North Lk. Huron	Manitou R.	71	2005	3131	16.9	1.9	4.0	408	6.5	0.02

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1292	Old Paleozoic	North Lk. Huron	Manitou R.	80	2005	4000	22.2	2.1	3.2	539	13.9	0.08
PEMA-1294	Old Paleozoic	North Lk. Huron	Manitou R.	88	2005	3290	15.4	3.4	3.2	339	6.5	0.03
PEMA-1295	Old Paleozoic	North Lk. Huron	Manitou R.	91	2005	4253	8.1	1.0	3.6	332	6.6	0.04
PEMA-1286	Old Paleozoic	North Lk. Huron	Manitou R.	97	2005	4257	17.1	2.9	3.2	328	8.1	0.07
PEMA-1291	Old Paleozoic	North Lk. Huron	Manitou R.	98	2005	4405	17.2	1.7	3.3	483	14.0	0.06
PEMA-1285	Old Paleozoic	North Lk. Huron	Manitou R.	100	2005	3341	20.1	4.4	3.5	407	13.7	0.08
PEMA-1288	Old Paleozoic	North Lk. Huron	Manitou R.	101	2005	4162	19.4	4.5	3.3	510	16.1	0.12
PEMA-1293	Old Paleozoic	North Lk. Huron	Manitou R.	103	2005	3842	15.3	2.0	3.2	400	9.8	0.05
PEMA-1281	Old Paleozoic	North Lk. Huron	Manitou R.	106	2005	3835	20.1	0.86	2.9	701	22.2	0.05
PEMA-1284	Old Paleozoic	North Lk. Huron	Manitou R.	107	2005	3828	17.2	4.1	3.4	417	11.0	0.09
PEMA-1283	Old Paleozoic	North Lk. Huron	Manitou R.	124	2005	3790	17.2	1.9	2.9	585	13.5	0.10
PEMA-1282	Old Paleozoic	North Lk. Huron	Manitou R.	131	2005	3523	13.6	9.7	3.4	355	10.0	0.07
PEMA-787	Old Paleozoic	Carp-Pine	McKay Cr.	101	2004	4486	12.1	21.1	1.7	253	18.2	0.11
PEMA-788	Old Paleozoic	Carp-Pine	McKay Cr.	104	2004	3199	29.5	32.0	1.8	169	7.4	0.14
PEMA-789	Old Paleozoic	Carp-Pine	McKay Cr.	105	2004	4513	43.6	16.5	1.6	197	8.4	0.20
PEMA-785	Old Paleozoic	Carp-Pine	McKay Cr.	113	2004	2918	37.1	8.0	2.0	163	7.7	0.08
PEMA-783	Old Paleozoic	Carp-Pine	McKay Cr.	114	2004	3537	48.2	30.9	1.6	185	9.4	0.18
PEMA-836	Old Paleozoic	Carp-Pine	McKay Cr.	114	2004	3479	23.9	33.8	1.6	215	11.0	0.18
PEMA-837	Old Paleozoic	Carp-Pine	McKay Cr.	115	2004	4240	17.4	20.3	1.3	224	6.7	0.16
PEMA-839	Old Paleozoic	Carp-Pine	McKay Cr.	115	2004	4804	14.5	24.1	1.6	267	13.7	0.10
PEMA-782	Old Paleozoic	Carp-Pine	McKay Cr.	116	2004	3051	34.8	6.6	2.1	226	15.2	0.02
PEMA-791	Old Paleozoic	Carp-Pine	McKay Cr.	121	2004	2894	24.9	34.7	1.9	279	9.4	0.13
PEMA-840	Old Paleozoic	Carp-Pine	McKay Cr.	122	2004	4035	23.0	41.2	1.5	155	5.2	0.25
PEMA-786	Old Paleozoic	Carp-Pine	McKay Cr.	123	2004	3454	39.2	34.4	1.8	125	6.3	0.11
PEMA-838	Old Paleozoic	Carp-Pine	McKay Cr.	123	2004	3590	32.7	28.3	2.0	203	10.6	0.19
PEMA-790	Old Paleozoic	Carp-Pine	McKay Cr.	126	2004	4333	14.6	24.7	1.7	239	9.2	0.22
PEMA-784	Old Paleozoic	Carp-Pine	McKay Cr.	138	2004	4099	20.7	17.1	1.8	175	8.0	0.04
PEMA-644	Old Paleozoic	North Lk. Huron	Mindemoya R.	59	2004	4692	18.8	0.63	3.1	604	22.1	0.14
PEMA-807	Old Paleozoic	North Lk. Huron	Mindemoya R.	61	2004	4116	11.1	10.5	2.1	434	8.7	0.10

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-641	Old Paleozoic	North Lk. Huron	Mindemoya R.	62	2004	4269	11.5	0.17	2.6	374	9.2	0.02
PEMA-642	Old Paleozoic	North Lk. Huron	Mindemoya R.	64	2004	3781	12.8	6.3	2.3	385	8.6	0.20
PEMA-645	Old Paleozoic	North Lk. Huron	Mindemoya R.	64	2004	3505	15.8	1.6	2.5	453	26.6	0.50
PEMA-809	Old Paleozoic	North Lk. Huron	Mindemoya R.	68	2004	3302	12.7	1.4	1.9	387	13.2	0.06
PEMA-806	Old Paleozoic	North Lk. Huron	Mindemoya R.	69	2004	3195	9.6	0.88	1.9	411	8.4	0.05
PEMA-810	Old Paleozoic	North Lk. Huron	Mindemoya R.	69	2004	3820	13.9	1.3	2.0	465	10.7	0.06
PEMA-649	Old Paleozoic	North Lk. Huron	Mindemoya R.	69	2004	3422	21.9	29.4	4.1	367	22.4	0.16
PEMA-648	Old Paleozoic	North Lk. Huron	Mindemoya R.	71	2004	5382	16.7	1.4	2.4	526	17.3	0.16
PEMA-643	Old Paleozoic	North Lk. Huron	Mindemoya R.	74	2004	4459	17.9	12.5	3.3	357	10.8	0.42
PEMA-808	Old Paleozoic	North Lk. Huron	Mindemoya R.	74	2004	3913	11.5	10.0	2.5	984	28.5	0.11
PEMA-650	Old Paleozoic	North Lk. Huron	Mindemoya R.	76	2004	4474	8.9	20.3	2.0	332	7.2	0.10
PEMA-647	Old Paleozoic	North Lk. Huron	Mindemoya R.	84	2004	4259	9.1	1.8	2.8	236	7.6	0.13
PEMA-646	Old Paleozoic	North Lk. Huron	Mindemoya R.	87	2004	3842	16.9	1.1	3.1	415	15.9	0.66
PEMA-1253	Old Paleozoic	North Lk. Huron	Mindemoya R.	83	2005	4359	9.0	1.9	1.6	351	11.6	0.05
PEMA-1248	Old Paleozoic	North Lk. Huron	Mindemoya R.	84	2005	3912	10.9	4.8	1.7	287	6.8	0.14
PEMA-1251	Old Paleozoic	North Lk. Huron	Mindemoya R.	84	2005	3667	12.3	2.3	1.7	300	6.9	0.05
PEMA-1242	Old Paleozoic	North Lk. Huron	Mindemoya R.	87	2005	3784	9.2	18.3	1.6	252	4.5	0.10
PEMA-1247	Old Paleozoic	North Lk. Huron	Mindemoya R.	87	2005	3226	9.1	1.5	1.6	282	7.2	0.06
PEMA-1252	Old Paleozoic	North Lk. Huron	Mindemoya R.	87	2005	4565	12.0	6.2	1.7	291	7.3	0.11
PEMA-1244	Old Paleozoic	North Lk. Huron	Mindemoya R.	88	2005	4067	11.1	6.3	1.5	251	8.2	0.06
PEMA-1250	Old Paleozoic	North Lk. Huron	Mindemoya R.	88	2005	3953	14.7	1.6	1.6	698	10.8	0.08
PEMA-1241	Old Paleozoic	North Lk. Huron	Mindemoya R.	90	2005	4181	14.5	1.2	1.7	251	4.6	0.04
PEMA-1240	Old Paleozoic	North Lk. Huron	Mindemoya R.	101	2005	3543	11.6	1.6	1.5	392	22.2	0.08
PEMA-1249	Old Paleozoic	North Lk. Huron	Mindemoya R.	104	2005	3319	11.2	3.2	1.8	350	9.6	0.08
PEMA-1243	Old Paleozoic	North Lk. Huron	Mindemoya R.	105	2005	4375	10.5	41.3	1.8	238	5.8	0.15
PEMA-1245	Old Paleozoic	North Lk. Huron	Mindemoya R.	105	2005	4040	10.8	6.2	1.7	286	9.4	0.08
PEMA-1239	Old Paleozoic	North Lk. Huron	Mindemoya R.	108	2005	3605	9.2	1.8	1.7	283	5.5	0.05
PEMA-1246	Old Paleozoic	North Lk. Huron	Mindemoya R.	123	2005	4593	17.7	7.2	1.7	222	2.9	0.06
PEMA-534	South./Sup.	North Lk. Huron	Mississagi R.	81	2004	5471	35.0	21.3	8.1	396	29.9	0.42

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-529	South./Sup.	North Lk. Huron	Mississagi R.	100	2004	6364	43.2	12.7	10.3	260	16.1	0.31
PEMA-532	South./Sup.	North Lk. Huron	Mississagi R.	100	2004	4736	76.7	26.2	7.0	297	16.6	0.23
PEMA-525	South./Sup.	North Lk. Huron	Mississagi R.	105	2004	5655	90.4	18.1	6.1	288	25.3	0.13
PEMA-527	South./Sup.	North Lk. Huron	Mississagi R.	110	2004	4058	46.5	27.9	6.4	326	16.8	0.11
PEMA-1046	South./Sup.	North Lk. Huron	Mississagi R.	113	2004	5625	72.3	16.0	8.1	526	35.4	0.18
PEMA-1047	South./Sup.	North Lk. Huron	Mississagi R.	114	2004	3886	38.8	35.7	6.5	702	31.7	0.13
PEMA-530	South./Sup.	North Lk. Huron	Mississagi R.	116	2004	4005	191.3	48.5	5.2	377	19.9	0.26
PEMA-1034	South./Sup.	North Lk. Huron	Mississagi R.	122	2004	6495	95.8	18.1	9.0	975	35.9	0.46
PEMA-533	South./Sup.	North Lk. Huron	Mississagi R.	122	2004	4888	148.2	46.9	6.2	1318	62.1	0.17
PEMA-1040	South./Sup.	North Lk. Huron	Mississagi R.	135	2004	5504	76.8	35.4	5.2	333	13.3	0.10
PEMA-526	South./Sup.	North Lk. Huron	Mississagi R.	140	2004	5851	61.9	47.5	6.4	307	15.8	0.27
PEMA-528	South./Sup.	North Lk. Huron	Mississagi R.	145	2004	4592	27.8	33.7	5.7	333	132.8	0.26
PEMA-1033	South./Sup.	North Lk. Huron	Mississagi R.	146	2004	5324	129.2	24.0	6.4	2898	408.4	0.09
PEMA-531	South./Sup.	North Lk. Huron	Mississagi R.	149	2004	5196	137.4	46.0	8.7	349	22.0	0.99
PEMA-731	Grenville	East Georgian Bay	Musquash R.	53	2004	4230	60.2	1.7	8.1	691	33.6	0.17
PEMA-726	Grenville	East Georgian Bay	Musquash R.	56	2004	5293	78.2	49.8	6.4	688	29.1	1.53
PEMA-724	Grenville	East Georgian Bay	Musquash R.	60	2004	4401	81.4	2.2	9.2	715	37.7	0.51
PEMA-729	Grenville	East Georgian Bay	Musquash R.	62	2004	3964	48.1	12.4	9.9	776	55.6	0.16
PEMA-730	Grenville	East Georgian Bay	Musquash R.	65	2004	5107	76.3	7.2	8.5	916	48.8	0.04
PEMA-728	Grenville	East Georgian Bay	Musquash R.	68	2004	5160	92.2	1.4	7.0	745	41.9	0.03
PEMA-725	Grenville	East Georgian Bay	Musquash R.	73	2004	5683	71.6	8.3	8.6	736	37.7	0.16
PEMA-727	Grenville	East Georgian Bay	Musquash R.	80	2004	3100	73.8	3.8	7.7	802	27.7	0.20
PEMA-723	Grenville	East Georgian Bay	Musquash R.	95	2004	4915	52.2	3.5	9.1	699	44.9	0.24
PEMA-722	Grenville	East Georgian Bay	Musquash R.	114	2004	4409	52.4	3.2	7.3	763	48.8	0.29
PEMA-1369	Grenville	East Georgian Bay	Musquash R.	96	2005	4569	50.8	4.4	6.5	695	28.8	0.23
PEMA-1365	Grenville	East Georgian Bay	Musquash R.	104	2005	4678	43.2	3.9	6.9	742	33.8	0.19
PEMA-1362	Grenville	East Georgian Bay	Musquash R.	106	2005	4244	44.1	2.3	6.5	658	27.6	0.24
PEMA-1366	Grenville	East Georgian Bay	Musquash R.	112	2005	4586	40.9	5.3	5.4	743	43.5	0.15
PEMA-1361	Grenville	East Georgian Bay	Musquash R.	116	2005	3905	176.9	7.0	5.1	740	58.1	0.19

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1367	Grenville	East Georgian Bay	Musquash R.	117	2005	4575	41.0	20.3	5.8	793	45.1	0.27
PEMA-1360	Grenville	East Georgian Bay	Musquash R.	124	2005	4531	68.5	2.8	5.5	745	46.7	0.19
PEMA-1370	Grenville	East Georgian Bay	Musquash R.	126	2005	4014	43.1	13.1	5.3	819	37.2	0.24
PEMA-1368	Grenville	East Georgian Bay	Musquash R.	127	2005	3661	76.5	5.7	5.6	731	28.0	0.23
PEMA-1359	Grenville	East Georgian Bay	Musquash R.	131	2005	4419	41.3	2.2	6.7	765	26.8	0.11
PEMA-1363	Grenville	East Georgian Bay	Musquash R.	132	2005	4433	49.9	2.7	7.2	696	31.4	0.13
PEMA-1357	Grenville	East Georgian Bay	Musquash R.	133	2005	4626	49.4	8.5	6.8	687	39.0	0.31
PEMA-1358	Grenville	East Georgian Bay	Musquash R.	134	2005	4830	108.8	10.7	6.5	724	45.3	0.37
PEMA-1364	Grenville	East Georgian Bay	Musquash R.	138	2005	4890	56.5	2.1	6.1	838	48.6	0.27
PEMA-1356	Grenville	East Georgian Bay	Musquash R.	146	2005	6331	47.6	4.9	7.1	628	29.8	0.29
PEMA-659	Grenville	East Georgian Bay	Naiscoot R.	69	2004	3965	78.4	6.4	11.2	807	35.7	0.27
PEMA-670	Grenville	East Georgian Bay	Naiscoot R.	80	2004	3031	78.1	19.0	9.7	1110	44.6	0.18
PEMA-652	Grenville	East Georgian Bay	Naiscoot R.	85	2004	4356	95.3	29.7	12.1	803	37.8	0.22
PEMA-658	Grenville	East Georgian Bay	Naiscoot R.	87	2004	3945	450.7	4.8	10.9	1051	70.1	0.16
PEMA-654	Grenville	East Georgian Bay	Naiscoot R.	89	2004	3992	157.4	8.8	9.5	864	100.4	0.19
PEMA-653	Grenville	East Georgian Bay	Naiscoot R.	94	2004	3726	145.1	6.4	8.1	857	66.2	0.27
PEMA-1052	Grenville	East Georgian Bay	Naiscoot R.	96	2004	5123	46.3	6.9	7.2	1741	36.0	0.14
PEMA-657	Grenville	East Georgian Bay	Naiscoot R.	96	2004	3975	63.2	10.1	5.3	947	44.4	0.13
PEMA-1048	Grenville	East Georgian Bay	Naiscoot R.	99	2004	4835	51.7	11.5	11.0	1027	43.6	0.29
PEMA-656	Grenville	East Georgian Bay	Naiscoot R.	100	2004	4554	137.6	15.6	6.6	982	38.5	0.04
PEMA-655	Grenville	East Georgian Bay	Naiscoot R.	103	2004	4175	99.5	11.0	8.4	899	39.6	0.25
PEMA-1049	Grenville	East Georgian Bay	Naiscoot R.	108	2004	4618	106.0	11.3	12.1	964	47.3	0.14
PEMA-651	Grenville	East Georgian Bay	Naiscoot R.	115	2004	4732	140.7	206.6	10.1	712	43.2	4.51
PEMA-1050	Grenville	East Georgian Bay	Naiscoot R.	118	2004	4426	106.7	5.7	7.7	974	134.9	0.20
PEMA-1051	Grenville	East Georgian Bay	Naiscoot R.	123	2004	6372	127.2	22.0	6.7	946	60.6	0.26
PEMA-1333	Grenville	East Georgian Bay	Naiscoot R.	25	2005	3082	135.1	0.79	6.0	942	43.6	0.03
PEMA-1337	Grenville	East Georgian Bay	Naiscoot R.	30	2005	3448	165.4	0.13	9.1	924	67.4	0.08
PEMA-1339	Grenville	East Georgian Bay	Naiscoot R.	31	2005	3355	145.2	0.45	7.3	784	40.6	0.04
PEMA-1336	Grenville	East Georgian Bay	Naiscoot R.	32	2005	3555	295.6	1.0	9.8	696	35.8	0.08

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-1340	Grenville	East Georgian Bay	Naiscoot R.	32	2005	3320	617.4	0.34	8.1	984	109.2	0.10
PEMA-1338	Grenville	East Georgian Bay	Naiscoot R.	34	2005	3640	138.2	0.21	8.2	919	56.1	0.04
PEMA-1335	Grenville	East Georgian Bay	Naiscoot R.	38	2005	3376	208.7	0.68	9.6	808	31.1	0.08
PEMA-1332	Grenville	East Georgian Bay	Naiscoot R.	41	2005	2986	391.2	0.32	5.9	663	40.3	0.04
PEMA-1331	Grenville	East Georgian Bay	Naiscoot R.	50	2005	3450	51.5	0.65	5.8	1404	50.1	0.05
PEMA-1329	Grenville	East Georgian Bay	Naiscoot R.	55	2005	3544	87.6	1.5	6.4	813	46.7	0.09
PEMA-1330	Grenville	East Georgian Bay	Naiscoot R.	56	2005	3288	78.3	1.5	7.3	1092	39.3	0.06
PEMA-1328	Grenville	East Georgian Bay	Naiscoot R.	60	2005	3955	40.0	0.60	6.2	1365	43.9	0.04
PEMA-1334	Grenville	East Georgian Bay	Naiscoot R.	80	2005	4681	101.6	1.0	11.5	875	54.1	0.22
PEMA-1327	Grenville	East Georgian Bay	Naiscoot R.	93	2005	3836	57.6	1.0	6.8	907	31.4	0.13
PEMA-1326	Grenville	East Georgian Bay	Naiscoot R.	139	2005	3858	54.6	1.0	5.9	1048	38.6	0.13
PEMA-734	Old Paleozoic	East Georgian Bay	Nottawasaga R.	75	2004	4798	10.0	2.1	1.6	277	10.9	0.09
PEMA-815	Old Paleozoic	East Georgian Bay	Nottawasaga R.	79	2004	3246	10.6	8.8	1.4	736	34.2	0.09
PEMA-738	Old Paleozoic	East Georgian Bay	Nottawasaga R.	82	2004	3720	13.9	4.8	1.5	654	27.4	0.13
PEMA-811	Old Paleozoic	East Georgian Bay	Nottawasaga R.	85	2004	4350	12.8	3.2	1.5	454	14.5	0.06
PEMA-740	Old Paleozoic	East Georgian Bay	Nottawasaga R.	88	2004	4042	12.6	5.9	1.7	493	24.6	0.04
PEMA-736	Old Paleozoic	East Georgian Bay	Nottawasaga R.	90	2004	4688	17.9	2.3	1.9	292	7.8	0.15
PEMA-733	Old Paleozoic	East Georgian Bay	Nottawasaga R.	91	2004	3551	20.1	2.7	1.6	606	32.8	0.09
PEMA-814	Old Paleozoic	East Georgian Bay	Nottawasaga R.	93	2004	4107	13.5	5.8	1.1	627	37.2	0.28
PEMA-741	Old Paleozoic	East Georgian Bay	Nottawasaga R.	96	2004	4223	15.9	6.1	2.3	485	36.0	0.11
PEMA-739	Old Paleozoic	East Georgian Bay	Nottawasaga R.	97	2004	4868	10.4	1.4	1.5	376	19.2	0.07
PEMA-812	Old Paleozoic	East Georgian Bay	Nottawasaga R.	101	2004	2481	13.9	2.6	1.6	451	15.1	0.03
PEMA-732	Old Paleozoic	East Georgian Bay	Nottawasaga R.	110	2004	4991	17.7	12.1	1.8	817	26.0	0.16
PEMA-735	Old Paleozoic	East Georgian Bay	Nottawasaga R.	124	2004	3975	16.4	3.4	2.0	475	16.9	0.11
PEMA-737	Old Paleozoic	East Georgian Bay	Nottawasaga R.	124	2004	4005	18.6	4.1	2.2	569	24.0	0.01
PEMA-813	Old Paleozoic	East Georgian Bay	Nottawasaga R.	133	2004	4097	18.3	89.9	1.6	652	22.7	0.07
PEMA-1378	Old Paleozoic	East Georgian Bay	Nottawasaga R.	113	2005	3621	12.6	17.5	0.90	426	14.8	0.03
PEMA-1384	Old Paleozoic	East Georgian Bay	Nottawasaga R.	114	2005	3644	9.6	1.4	1.8	325	7.3	0.03
PEMA-1377	Old Paleozoic	East Georgian Bay	Nottawasaga R.	117	2005	4532	15.2	0.80	1.6	339	8.5	0.04

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-1380	Old Paleozoic	East Georgian Bay	Nottawasaga R.	117	2005	3844	14.8	15.4	1.0	581	28.7	0.03
PEMA-1385	Old Paleozoic	East Georgian Bay	Nottawasaga R.	122	2005	4027	9.5	1.5	1.6	322	9.9	0.09
PEMA-1374	Old Paleozoic	East Georgian Bay	Nottawasaga R.	128	2005	3636	14.4	10.1	1.0	354	10.1	0.03
PEMA-1383	Old Paleozoic	East Georgian Bay	Nottawasaga R.	129	2005	3840	13.7	0.31	1.9	378	10.2	0.03
PEMA-1382	Old Paleozoic	East Georgian Bay	Nottawasaga R.	131	2005	3498	14.4	1.3	1.9	365	13.9	0.03
PEMA-1375	Old Paleozoic	East Georgian Bay	Nottawasaga R.	134	2005	4558	13.4	0.83	1.9	369	10.0	0.06
PEMA-1381	Old Paleozoic	East Georgian Bay	Nottawasaga R.	134	2005	3972	19.5	17.7	0.88	453	27.5	0.06
PEMA-1376	Old Paleozoic	East Georgian Bay	Nottawasaga R.	136	2005	3665	15.0	18.6	1.0	720	39.3	0.03
PEMA-1379	Old Paleozoic	East Georgian Bay	Nottawasaga R.	140	2005	3925	15.8	1.9	1.8	330	9.0	0.04
PEMA-1372	Old Paleozoic	East Georgian Bay	Nottawasaga R.	141	2005	4325	20.4	21.8	1.2	496	23.3	0.07
PEMA-1373	Old Paleozoic	East Georgian Bay	Nottawasaga R.	141	2005	3988	16.5	13.2	1.0	694	26.6	0.04
PEMA-1371	Old Paleozoic	East Georgian Bay	Nottawasaga R.	159	2005	4488	15.8	19.9	1.0	377	16.1	0.01
PEMA-636	Old Paleozoic	Carp-Pine	Pine R.	34	2004	4633	38.6	1.3	10.3	470	45.0	0.14
PEMA-631	Old Paleozoic	Carp-Pine	Pine R.	37	2004	3277	54.6	3.3	6.7	303	20.2	0.01
PEMA-632	Old Paleozoic	Carp-Pine	Pine R.	41	2004	3313	22.9	2.7	7.7	400	30.7	0.09
PEMA-635	Old Paleozoic	Carp-Pine	Pine R.	41	2004	3104	33.4	2.2	6.4	491	38.6	0.06
PEMA-633	Old Paleozoic	Carp-Pine	Pine R.	42	2004	3135	29.7	1.8	11.7	322	20.4	0.11
PEMA-634	Old Paleozoic	Carp-Pine	Pine R.	50	2004	3442	28.4	0.67	10.1	395	47.4	0.13
PEMA-1537	Old Paleozoic	Carp-Pine	Pine R.	62	2005	3532	88.6	90.4	1.9	189	12.8	0.13
PEMA-1542	Old Paleozoic	Carp-Pine	Pine R.	98	2005	4459	32.9	2.2	0.91	745	25.8	0.28
PEMA-1533	Old Paleozoic	Carp-Pine	Pine R.	106	2005	3817	25.7	3.1	6.1	369	102.5	0.06
PEMA-1543	Old Paleozoic	Carp-Pine	Pine R.	109	2005	4837	23.0	3.1	1.1	604	15.1	0.37
PEMA-1532	Old Paleozoic	Carp-Pine	Pine R.	110	2005	3702	28.6	6.7	5.4	335	53.5	0.03
PEMA-1534	Old Paleozoic	Carp-Pine	Pine R.	114	2005	3029	34.9	4.5	6.1	523	60.0	0.02
PEMA-1544	Old Paleozoic	Carp-Pine	Pine R.	115	2005	5421	25.6	70.3	0.87	553	22.3	0.32
PEMA-1545	Old Paleozoic	Carp-Pine	Pine R.	119	2005	5717	32.2	26.2	1.1	549	14.0	0.39
PEMA-1538	Old Paleozoic	Carp-Pine	Pine R.	121	2005	5896	35.3	47.6	0.81	532	16.1	0.50
PEMA-1546	Old Paleozoic	Carp-Pine	Pine R.	121	2005	3308	29.4	3.3	4.8	1469	31.6	0.05
PEMA-1539	Old Paleozoic	Carp-Pine	Pine R.	132	2005	3608	27.6	1.4	4.0	649	27.3	0.01

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-1535	Old Paleozoic	Carp-Pine	Pine R.	147	2005	3366	21.8	175.7	2.2	189	8.2	0.15
PEMA-1540	Old Paleozoic	Carp-Pine	Pine R.	148	2005	2979	24.2	48.0	6.4	133	6.7	0.06
PEMA-1428	Young Paleozoic	Aues Gres-Rifle	Rifle R.	41	2005	3030	24.0	3.1	0.62	602	22.2	0.05
PEMA-1427	Young Paleozoic	Aues Gres-Rifle	Rifle R.	47	2005	2836	17.7	0.12	0.94	368	10.2	0.01
PEMA-1415	Young Paleozoic	Aues Gres-Rifle	Rifle R.	67	2005	4703	17.0	3.3	1.1	429	17.1	0.07
PEMA-1416	Young Paleozoic	Aues Gres-Rifle	Rifle R.	68	2005	4848	24.4	5.0	1.0	370	12.7	0.13
PEMA-1414	Young Paleozoic	Aues Gres-Rifle	Rifle R.	71	2005	3584	23.1	3.3	0.93	360	11.7	0.10
PEMA-1417	Young Paleozoic	Aues Gres-Rifle	Rifle R.	78	2005	4518	24.2	2.6	0.78	534	19.4	0.11
PEMA-1425	Young Paleozoic	Aues Gres-Rifle	Rifle R.	80	2005	2095	17.8	0.70	1.1	905	26.7	0.05
PEMA-1418	Young Paleozoic	Aues Gres-Rifle	Rifle R.	82	2005	4805	21.9	2.9	0.81	456	18.1	0.09
PEMA-1423	Young Paleozoic	Aues Gres-Rifle	Rifle R.	100	2005	4092	50.5	5.0	3.0	1163	28.7	0.03
PEMA-1420	Young Paleozoic	Aues Gres-Rifle	Rifle R.	103	2005	4355	55.1	5.9	3.1	851	17.7	0.07
PEMA-1419	Young Paleozoic	Aues Gres-Rifle	Rifle R.	104	2005	4163	35.0	3.9	3.4	864	17.0	0.06
PEMA-1422	Young Paleozoic	Aues Gres-Rifle	Rifle R.	109	2005	4593	28.9	4.5	2.6	977	19.8	0.06
PEMA-1421	Young Paleozoic	Aues Gres-Rifle	Rifle R.	118	2005	4126	43.9	4.4	3.0	955	19.1	0.05
PEMA-228	Young Paleozoic	Titabawasee	Saginaw R.	58	2004	3971	28.4	11.9	1.7	564	22.2	1.04
PEMA-265	Young Paleozoic	Titabawasee	Saginaw R.	62	2004	5203	41.9	8.4	1.9	623	24.2	0.19
PEMA-230	Young Paleozoic	Titabawasee	Saginaw R.	71	2004	4049	30.7	12.9	1.5	564	14.0	0.12
PEMA-227	Young Paleozoic	Titabawasee	Saginaw R.	74	2004	3736	51.1	1.4	1.6	398	9.4	0.06
PEMA-261	Young Paleozoic	Titabawasee	Saginaw R.	75	2004	5590	32.2	1.8	2.7	578	22.9	0.05
PEMA-231	Young Paleozoic	Titabawasee	Saginaw R.	75	2004	4324	31.7	18.1	1.6	624	30.8	0.16
PEMA-262	Young Paleozoic	Titabawasee	Saginaw R.	77	2004	4741	43.2	9.2	3.0	505	13.5	0.00
PEMA-266	Young Paleozoic	Titabawasee	Saginaw R.	80	2004	5083	40.3	13.0	2.7	480	12.9	0.01
PEMA-229	Young Paleozoic	Titabawasee	Saginaw R.	80	2004	4576	31.2	42.2	1.8	402	16.3	0.63
PEMA-263	Young Paleozoic	Titabawasee	Saginaw R.	82	2004	4898	34.4	4.6	2.3	442	13.8	0.05
PEMA-264	Young Paleozoic	Titabawasee	Saginaw R.	87	2004	5757	39.2	4.4	2.7	457	9.7	0.09
PEMA-260	Young Paleozoic	Titabawasee	Saginaw R.	96	2004	5235	34.2	2.3	1.3	652	16.6	0.10
PEMA-257	Young Paleozoic	Titabawasee	Saginaw R.	124	2004	4228	41.4	5.3	1.4	327	9.0	0.03
PEMA-258	Young Paleozoic	Titabawasee	Saginaw R.	130	2004	4946	42.0	6.3	1.6	482	18.6	0.01

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-259	Young Paleozoic	Titabawasee	Saginaw R.	131	2004	5289	115.7	12.8	1.4	667	69.0	0.11
PEMA-1431	Young Paleozoic	Titabawasee	Saginaw R.	89	2005	4527	21.2	2.3	0.75	869	13.7	0.09
PEMA-1434	Young Paleozoic	Titabawasee	Saginaw R.	93	2005	4374	20.6	30.5	1.0	485	9.6	0.11
PEMA-1404	Young Paleozoic	Titabawasee	Saginaw R.	98	2005	4539	26.7	15.7	0.87	731	30.4	0.12
PEMA-1405	Young Paleozoic	Titabawasee	Saginaw R.	101	2005	4045	24.1	4.2	0.79	601	17.5	0.10
PEMA-1406	Young Paleozoic	Titabawasee	Saginaw R.	105	2005	4136	21.9	6.7	0.83	667	22.3	0.10
PEMA-1433	Young Paleozoic	Titabawasee	Saginaw R.	106	2005	5083	24.6	15.6	1.1	505	13.2	0.13
PEMA-1430	Young Paleozoic	Titabawasee	Saginaw R.	107	2005	3944	13.7	0.28	1.1	510	7.6	0.02
PEMA-1432	Young Paleozoic	Titabawasee	Saginaw R.	107	2005	3396	60.9	14.4	3.8	1378	28.4	0.30
PEMA-1408	Young Paleozoic	Titabawasee	Saginaw R.	108	2005	4752	22.1	6.9	1.1	614	16.2	0.13
PEMA-1407	Young Paleozoic	Titabawasee	Saginaw R.	110	2005	3878	17.3	6.7	0.90	477	10.1	0.13
PEMA-1403	Young Paleozoic	Titabawasee	Saginaw R.	115	2005	4862	18.5	6.8	1.1	600	13.4	0.15
PEMA-1402	Young Paleozoic	Titabawasee	Saginaw R.	119	2005	4381	28.1	7.0	1.1	489	14.6	0.12
PEMA-1401	Young Paleozoic	Titabawasee	Saginaw R.	125	2005	4522	25.8	6.6	1.1	532	13.8	0.09
PEMA-746	Old Paleozoic	East Lk. Huron	Sauble R.	68	2004	3962	26.4	1.1	1.2	214	5.1	0.04
PEMA-742	Old Paleozoic	East Lk. Huron	Sauble R.	91	2004	5467	35.5	7.8	1.5	218	6.3	0.07
PEMA-748	Old Paleozoic	East Lk. Huron	Sauble R.	94	2004	3920	41.9	3.4	0.75	245	7.9	0.13
PEMA-747	Old Paleozoic	East Lk. Huron	Sauble R.	100	2004	5228	44.4	4.1	1.0	303	8.7	0.05
PEMA-816	Old Paleozoic	East Lk. Huron	Sauble R.	101	2004	3819	26.6	18.3	1.1	230	4.8	0.14
PEMA-743	Old Paleozoic	East Lk. Huron	Sauble R.	111	2004	5450	27.5	3.3	0.89	232	6.1	0.10
PEMA-749	Old Paleozoic	East Lk. Huron	Sauble R.	111	2004	5193	27.3	15.7	0.45	286	6.1	0.01
PEMA-750	Old Paleozoic	East Lk. Huron	Sauble R.	112	2004	4819	36.0	3.6	0.80	234	4.2	0.10
PEMA-820	Old Paleozoic	East Lk. Huron	Sauble R.	113	2004	5102	30.7	3.2	0.88	252	5.6	0.12
PEMA-817	Old Paleozoic	East Lk. Huron	Sauble R.	115	2004	4839	26.6	12.4	0.83	207	4.8	0.16
PEMA-744	Old Paleozoic	East Lk. Huron	Sauble R.	116	2004	4112	34.7	4.5	0.71	328	8.6	0.11
PEMA-818	Old Paleozoic	East Lk. Huron	Sauble R.	122	2004	3511	19.2	99.7	0.75	218	3.7	0.04
PEMA-751	Old Paleozoic	East Lk. Huron	Sauble R.	122	2004	4188	26.9	6.5	0.74	287	4.8	0.15
PEMA-819	Old Paleozoic	East Lk. Huron	Sauble R.	123	2004	3807	25.8	3.3	0.81	316	7.8	0.27
PEMA-745	Old Paleozoic	East Lk. Huron	Sauble R.	125	2004	4404	29.7	5.9	0.42	229	4.0	0.05

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-777	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	89	2004	4181	51.6	33.9	2.3	214	13.5	0.06
PEMA-776	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	91	2004	3305	45.5	66.4	5.3	235	14.1	0.09
PEMA-833	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	97	2004	4857	28.3	5.7	2.0	187	11.3	0.07
PEMA-774	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	98	2004	3734	47.8	20.1	2.6	207	13.0	0.04
PEMA-780	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	101	2004	3491	47.7	32.2	3.0	178	11.7	0.06
PEMA-831	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	103	2004	4333	35.8	74.6	2.8	251	17.1	0.15
PEMA-772	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	108	2004	2660	41.7	34.3	1.7	213	12.6	0.01
PEMA-834	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	113	2004	3281	32.5	7.9	1.9	184	7.8	0.02
PEMA-832	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	114	2004	3626	36.5	17.5	3.1	224	11.6	0.08
PEMA-778	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	116	2004	5064	69.3	178.4	3.0	220	11.1	0.22
PEMA-835	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	118	2004	2425	36.4	6.5	1.9	188	9.6	0.06
PEMA-781	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	122	2004	3241	45.1	49.4	3.1	283	12.2	0.06
PEMA-773	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	126	2004	3133	30.9	37.6	2.3	216	9.6	0.13
PEMA-775	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	130	2004	5382	50.9	60.1	2.8	252	13.5	0.10
PEMA-779	Old Paleozoic	Lone Lk. Ocqueoc	Schmidt Cr.	131	2004	4170	33.1	1.3	3.1	185	12.2	0.02
PEMA-1274	South./Sup.	North Lk. Huron	Serpent R.	121	2005	3280	43.7	24.1	5.7	422	13.3	0.17
PEMA-1275	South./Sup.	North Lk. Huron	Serpent R.	124	2005	3912	63.1	46.8	6.3	531	13.9	0.14
PEMA-1276	South./Sup.	North Lk. Huron	Serpent R.	124	2005	3592	40.3	11.9	6.3	601	24.0	0.08
PEMA-1273	South./Sup.	North Lk. Huron	Serpent R.	126	2005	3619	58.7	20.2	6.1	414	16.7	0.09
PEMA-1277	South./Sup.	North Lk. Huron	Serpent R.	126	2005	4500	52.3	18.3	5.6	581	25.5	0.18
PEMA-1279	South./Sup.	North Lk. Huron	Serpent R.	128	2005	3370	118.1	20.4	5.0	658	27.6	0.24
PEMA-1238	South./Sup.	North Lk. Huron	Serpent R.	130	2005	3123	87.0	29.1	6.0	506	18.0	0.11
PEMA-1278	South./Sup.	North Lk. Huron	Serpent R.	130	2005	3215	92.9	31.0	6.1	515	22.5	0.19
PEMA-1270	South./Sup.	North Lk. Huron	Serpent R.	133	2005	3345	103.5	79.5	6.2	526	42.6	0.55
PEMA-1237	South./Sup.	North Lk. Huron	Serpent R.	134	2005	3307	38.9	23.3	5.3	751	18.0	0.13
PEMA-1272	South./Sup.	North Lk. Huron	Serpent R.	136	2005	3684	102.9	59.0	5.8	524	17.6	0.22
PEMA-1271	South./Sup.	North Lk. Huron	Serpent R.	137	2005	4080	42.3	52.5	5.5	520	17.1	0.29
PEMA-1236	South./Sup.	North Lk. Huron	Serpent R.	138	2005	3765	47.1	17.5	5.2	438	16.9	0.20
PEMA-1269	South./Sup.	North Lk. Huron	Serpent R.	138	2005	3197	59.3	19.4	4.6	626	23.8	0.10

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1280	South./Sup.	North Lk. Huron	Serpent R.	140	2005	3207	81.1	14.5	6.1	492	11.7	0.10
PEMA-538	Old Paleozoic	East Georgian Bay	Silver Cr.	48	2004	4736	18.7	8.1	3.1	310	4.6	0.06
PEMA-541	Old Paleozoic	East Georgian Bay	Silver Cr.	66	2004	4719	31.0	11.3	6.3	420	6.3	0.06
PEMA-537	Old Paleozoic	East Georgian Bay	Silver Cr.	76	2004	3715	26.9	10.0	6.3	442	6.5	0.19
PEMA-543	Old Paleozoic	East Georgian Bay	Silver Cr.	82	2004	4089	29.2	45.7	5.1	421	6.8	0.22
PEMA-561	Old Paleozoic	East Georgian Bay	Silver Cr.	85	2004	4084	50.7	156.1	8.9	277	9.9	0.28
PEMA-564	Old Paleozoic	East Georgian Bay	Silver Cr.	87	2004	4241	25.7	65.3	5.9	443	5.6	0.15
PEMA-536	Old Paleozoic	East Georgian Bay	Silver Cr.	89	2004	4752	24.6	22.6	6.6	760	18.3	0.43
PEMA-539	Old Paleozoic	East Georgian Bay	Silver Cr.	112	2004	3796	30.8	9.7	5.4	564	7.8	0.18
PEMA-542	Old Paleozoic	East Georgian Bay	Silver Cr.	113	2004	6061	24.6	37.7	6.9	481	8.0	0.35
PEMA-563	Old Paleozoic	East Georgian Bay	Silver Cr.	117	2004	4182	32.7	85.2	5.9	483	7.1	0.36
PEMA-565	Old Paleozoic	East Georgian Bay	Silver Cr.	129	2004	7592	28.5	307.9	3.1	469	12.3	0.64
PEMA-540	Old Paleozoic	East Georgian Bay	Silver Cr.	150	2004	4725	33.4	125.7	5.5	508	9.2	0.61
PEMA-535	Old Paleozoic	East Georgian Bay	Silver Cr.	156	2004	6958	20.5	21.9	7.4	479	6.8	0.41
PEMA-544	Old Paleozoic	East Georgian Bay	Silver Cr.	156	2004	6218	20.3	42.9	5.3	494	11.8	0.35
PEMA-562	Old Paleozoic	East Georgian Bay	Silver Cr.	158	2004	6505	49.8	220.6	6.8	402	8.1	0.52
PEMA-714	South./Sup.	North Lk. Huron	Spanish R.	66	2004	3214	19.7	2.9	2.2	367	15.1	0.15
PEMA-715	South./Sup.	North Lk. Huron	Spanish R.	78	2004	3915	17.5	1.7	3.4	308	12.9	0.09
PEMA-712	South./Sup.	North Lk. Huron	Spanish R.	81	2004	3864	26.1	3.0	4.8	509	38.8	0.14
PEMA-720	South./Sup.	North Lk. Huron	Spanish R.	88	2004	3647	28.2	1.3	5.1	483	29.1	0.02
PEMA-716	South./Sup.	North Lk. Huron	Spanish R.	90	2004	4857	20.5	4.1	4.7	365	21.2	0.92
PEMA-802	South./Sup.	North Lk. Huron	Spanish R.	90	2004	3280	17.6	11.8	3.4	449	25.5	0.07
PEMA-721	South./Sup.	North Lk. Huron	Spanish R.	93	2004	3373	22.8	2.2	4.8	526	42.6	0.07
PEMA-717	South./Sup.	North Lk. Huron	Spanish R.	95	2004	3830	17.5	9.0	4.1	372	18.5	0.27
PEMA-805	South./Sup.	North Lk. Huron	Spanish R.	95	2004	3909	24.8	2.0	5.0	343	30.1	0.14
PEMA-803	South./Sup.	North Lk. Huron	Spanish R.	96	2004	3423	37.9	2.6	3.8	497	25.8	0.06
PEMA-804	South./Sup.	North Lk. Huron	Spanish R.	96	2004	2707	23.4	3.8	3.2	669	28.8	0.31
PEMA-713	South./Sup.	North Lk. Huron	Spanish R.	97	2004	5091	20.7	4.7	4.8	492	29.7	0.09
PEMA-718	South./Sup.	North Lk. Huron	Spanish R.	100	2004	4001	50.5	3.1	3.9	474	25.8	0.14

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-801	South./Sup.	North Lk. Huron	Spanish R.	100	2004	3525	14.9	4.1	3.7	665	30.8	0.07
PEMA-719	South./Sup.	North Lk. Huron	Spanish R.	104	2004	4116	18.2	2.1	6.2	481	28.4	0.14
PEMA-524	Old Paleozoic	St. Marys	St. Marys R.	54	2004	2884	25.5	14.5	4.5	196	7.1	0.32
PEMA-517	Old Paleozoic	St. Marys	St. Marys R.	62	2004	3977	24.9	923.2	3.8	203	14.3	0.20
PEMA-522	Old Paleozoic	St. Marys	St. Marys R.	66	2004	3058	19.6	6.2	2.9	187	10.9	0.09
PEMA-520	Old Paleozoic	St. Marys	St. Marys R.	76	2004	4061	26.0	7.5	1.6	164	8.6	0.19
PEMA-518	Old Paleozoic	St. Marys	St. Marys R.	80	2004	3904	24.3	23.1	5.6	168	9.1	0.21
PEMA-516	Old Paleozoic	St. Marys	St. Marys R.	87	2004	4060	23.1	13.2	4.3	190	16.0	0.65
PEMA-1023	Old Paleozoic	St. Marys	St. Marys R.	88	2004	3925	13.0	14.0	2.4	217	12.4	0.08
PEMA-1032	Old Paleozoic	St. Marys	St. Marys R.	99	2004	4431	17.6	9.3	2.8	212	15.3	0.14
PEMA-519	Old Paleozoic	St. Marys	St. Marys R.	102	2004	4286	20.9	32.8	3.5	163	10.2	0.27
PEMA-1025	Old Paleozoic	St. Marys	St. Marys R.	104	2004	3673	14.1	18.8	3.3	192	16.4	0.37
PEMA-1024	Old Paleozoic	St. Marys	St. Marys R.	105	2004	3240	16.4	9.5	2.3	159	8.7	0.13
PEMA-523	Old Paleozoic	St. Marys	St. Marys R.	111	2004	3902	20.3	8.4	3.9	188	12.6	0.23
PEMA-1031	Old Paleozoic	St. Marys	St. Marys R.	120	2004	4036	20.6	17.7	2.7	293	21.7	0.41
PEMA-521	Old Paleozoic	St. Marys	St. Marys R.	121	2004	3973	24.3	7.1	3.6	329	43.2	0.50
PEMA-515	Old Paleozoic	St. Marys	St. Marys R.	122	2004	3507	24.7	9.9	3.4	198	13.5	0.34
PEMA-1139	Old Paleozoic	St. Marys	St. Marys R.	80	2005	3775	22.9	2.1	4.1	395	21.9	0.13
PEMA-1138	Old Paleozoic	St. Marys	St. Marys R.	83	2005	3417	17.1	3.2	2.9	167	11.7	0.16
PEMA-1137	Old Paleozoic	St. Marys	St. Marys R.	102	2005	4279	15.8	2.0	4.4	208	11.4	0.12
PEMA-1128	Old Paleozoic	St. Marys	St. Marys R.	105	2005	3985	23.7	15.9	1.8	240	16.6	0.18
PEMA-1129	Old Paleozoic	St. Marys	St. Marys R.	107	2005	4192	17.2	14.3	2.6	221	16.2	0.24
PEMA-1134	Old Paleozoic	St. Marys	St. Marys R.	107	2005	3168	21.1	27.1	1.6	214	16.7	0.36
PEMA-1126	Old Paleozoic	St. Marys	St. Marys R.	109	2005	3461	18.5	27.6	1.6	158	8.0	0.14
PEMA-1136	Old Paleozoic	St. Marys	St. Marys R.	116	2005	3518	20.8	2.9	2.8	172	12.5	0.20
PEMA-1131	Old Paleozoic	St. Marys	St. Marys R.	119	2005	3815	11.5	3.6	2.7	185	11.1	0.07
PEMA-1135	Old Paleozoic	St. Marys	St. Marys R.	119	2005	4985	20.2	5.4	2.9	258	30.1	0.39
PEMA-1125	Old Paleozoic	St. Marys	St. Marys R.	129	2005	3742	27.8	12.7	1.5	588	34.3	0.21
PEMA-1132	Old Paleozoic	St. Marys	St. Marys R.	130	2005	3561	10.8	1.9	3.1	156	9.3	0.20

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1127	Old Paleozoic	St. Marys	St. Marys R.	131	2005	3678	11.0	3.9	3.1	156	14.1	0.10
PEMA-1130	Old Paleozoic	St. Marys	St. Marys R.	131	2005	3964	12.4	10.7	1.8	304	27.3	0.23
PEMA-1133	Old Paleozoic	St. Marys	St. Marys R.	132	2005	3643	14.6	3.1	2.9	183	10.2	0.23
PEMA-199	Old Paleozoic	Carp-Pine	Steeles Cr.	70	2004	3141	36.3	9.3	3.3	112	8.3	0.07
PEMA-195	Old Paleozoic	Carp-Pine	Steeles Cr.	90	2004	3622	38.9	8.6	3.1	109	15.6	0.07
PEMA-186	Old Paleozoic	Carp-Pine	Steeles Cr.	92	2004	4034	41.4	2.1	4.0	101	7.9	0.05
PEMA-190	Old Paleozoic	Carp-Pine	Steeles Cr.	95	2004	3658	73.1	2.2	3.9	150	5.4	0.10
PEMA-197	Old Paleozoic	Carp-Pine	Steeles Cr.	95	2004	3791	44.7	1.8	4.2	100	7.6	0.08
PEMA-188	Old Paleozoic	Carp-Pine	Steeles Cr.	98	2004	3364	39.8	1.1	3.8	114	8.7	0.00
PEMA-192	Old Paleozoic	Carp-Pine	Steeles Cr.	99	2004	4221	52.4	1.7	4.6	103	5.4	0.02
PEMA-198	Old Paleozoic	Carp-Pine	Steeles Cr.	104	2004	4263	48.9	5.0	5.9	120	21.3	0.04
PEMA-193	Old Paleozoic	Carp-Pine	Steeles Cr.	106	2004	3567	31.1	4.4	2.7	120	15.2	0.02
PEMA-196	Old Paleozoic	Carp-Pine	Steeles Cr.	108	2004	2551	30.6	42.2	3.5	119	5.6	0.07
PEMA-185	Old Paleozoic	Carp-Pine	Steeles Cr.	112	2004	4328	37.5	3.1	3.9	101	11.3	0.10
PEMA-187	Old Paleozoic	Carp-Pine	Steeles Cr.	125	2004	4146	48.2	3.0	5.5	96	5.6	0.01
PEMA-191	Old Paleozoic	Carp-Pine	Steeles Cr.	126	2004	4621	51.4	1.5	3.2	101	5.1	0.07
PEMA-194	Old Paleozoic	Carp-Pine	Steeles Cr.	127	2004	3352	34.3	9.2	3.0	103	4.2	0.06
PEMA-189	Old Paleozoic	Carp-Pine	Steeles Cr.	129	2004	3262	37.5	1.9	4.7	114	3.7	0.02
PEMA-498	Young Paleozoic	Aues Gres-Rifle	Tawas R.	53	2004	3295	22.0	42.9	2.6	644	32.4	0.12
PEMA-502	Young Paleozoic	Aues Gres-Rifle	Tawas R.	62	2004	4129	25.1	59.4	3.5	841	29.2	0.16
PEMA-500	Young Paleozoic	Aues Gres-Rifle	Tawas R.	69	2004	3350	23.1	86.3	2.8	370	15.9	0.13
PEMA-1038	Young Paleozoic	Aues Gres-Rifle	Tawas R.	76	2004	4171	16.8	46.7	3.1	558	17.7	0.11
PEMA-504	Young Paleozoic	Aues Gres-Rifle	Tawas R.	77	2004	4477	22.8	74.3	4.4	328	12.7	0.16
PEMA-495	Young Paleozoic	Aues Gres-Rifle	Tawas R.	78	2004	3645	21.7	85.0	1.8	1161	69.6	1.03
PEMA-497	Young Paleozoic	Aues Gres-Rifle	Tawas R.	80	2004	3221	17.4	14.6	2.3	514	19.2	0.11
PEMA-1037	Young Paleozoic	Aues Gres-Rifle	Tawas R.	82	2004	3528	16.0	18.9	3.0	901	28.0	0.06
PEMA-1036	Young Paleozoic	Aues Gres-Rifle	Tawas R.	84	2004	3426	12.9	25.8	2.6	476	20.6	0.08
PEMA-501	Young Paleozoic	Aues Gres-Rifle	Tawas R.	84	2004	4257	18.4	51.6	3.9	806	31.0	0.25
PEMA-1039	Young Paleozoic	Aues Gres-Rifle	Tawas R.	85	2004	3876	20.5	30.2	3.2	703	34.2	0.08

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-1035	Young Paleozoic	Aues Gres-Rifle	Tawas R.	92	2004	4057	18.7	31.7	2.4	667	21.5	0.17
PEMA-503	Young Paleozoic	Aues Gres-Rifle	Tawas R.	93	2004	4824	18.6	30.9	3.0	487	12.6	0.27
PEMA-499	Young Paleozoic	Aues Gres-Rifle	Tawas R.	98	2004	4142	18.6	50.0	2.9	873	40.2	0.39
PEMA-496	Young Paleozoic	Aues Gres-Rifle	Tawas R.	109	2004	3088	27.1	28.1	3.3	607	19.5	0.63
PEMA-1559	Young Paleozoic	Aues Gres-Rifle	Tawas R.	96	2005	4020	20.8	32.1	2.7	344	17.4	0.14
PEMA-1558	Young Paleozoic	Aues Gres-Rifle	Tawas R.	98	2005	3863	17.8	7.4	2.5	461	24.5	0.07
PEMA-1557	Young Paleozoic	Aues Gres-Rifle	Tawas R.	99	2005	3974	15.6	190.2	2.3	226	10.2	0.20
PEMA-1561	Young Paleozoic	Aues Gres-Rifle	Tawas R.	99	2005	3694	24.0	71.7	2.4	359	23.2	0.32
PEMA-1553	Young Paleozoic	Aues Gres-Rifle	Tawas R.	108	2005	3791	20.7	37.8	2.6	252	12.5	0.16
PEMA-1560	Young Paleozoic	Aues Gres-Rifle	Tawas R.	108	2005	3801	25.0	197.0	2.6	930	50.9	0.43
PEMA-1555	Young Paleozoic	Aues Gres-Rifle	Tawas R.	110	2005	4875	21.9	8.8	2.8	922	46.2	0.14
PEMA-1551	Young Paleozoic	Aues Gres-Rifle	Tawas R.	114	2005	6758	19.6	86.3	2.7	817	22.5	0.40
PEMA-1554	Young Paleozoic	Aues Gres-Rifle	Tawas R.	114	2005	5409	26.0	173.9	3.0	656	24.0	0.51
PEMA-1552	Young Paleozoic	Aues Gres-Rifle	Tawas R.	115	2005	3860	17.4	7.2	1.9	1190	34.1	0.25
PEMA-1549	Young Paleozoic	Aues Gres-Rifle	Tawas R.	121	2005	3689	23.6	12.1	1.3	1127	22.7	0.19
PEMA-1556	Young Paleozoic	Aues Gres-Rifle	Tawas R.	122	2005	3817	24.8	26.7	2.4	337	15.4	0.38
PEMA-1547	Young Paleozoic	Aues Gres-Rifle	Tawas R.	131	2005	4632	22.0	15.2	1.5	1902	44.0	0.42
PEMA-1550	Young Paleozoic	Aues Gres-Rifle	Tawas R.	136	2005	3774	26.9	39.2	1.4	1568	82.1	0.45
PEMA-1548	Young Paleozoic	Aues Gres-Rifle	Tawas R.	142	2005	4282	21.1	8.2	1.5	5156	63.2	0.20
PEMA-1233	South./Sup.	North Lk. Huron	Thessalon R.	125	2005	3269	27.7	16.3	3.4	259	9.0	0.13
PEMA-1228	South./Sup.	North Lk. Huron	Thessalon R.	128	2005	4266	28.4	18.0	3.7	251	7.6	0.28
PEMA-1224	South./Sup.	North Lk. Huron	Thessalon R.	135	2005	3706	31.5	15.5	5.8	272	7.0	0.18
PEMA-1227	South./Sup.	North Lk. Huron	Thessalon R.	137	2005	3856	20.3	8.7	4.4	271	8.6	0.18
PEMA-1231	South./Sup.	North Lk. Huron	Thessalon R.	139	2005	3859	29.3	7.0	3.3	245	5.5	0.12
PEMA-1221	South./Sup.	North Lk. Huron	Thessalon R.	139	2005	3305	16.9	8.8	4.6	282	6.6	0.12
PEMA-1226	South./Sup.	North Lk. Huron	Thessalon R.	139	2005	3113	19.2	4.0	3.6	255	8.4	0.21
PEMA-1230	South./Sup.	North Lk. Huron	Thessalon R.	140	2005	4046	27.7	10.7	3.1	254	7.2	0.20
PEMA-1222	South./Sup.	North Lk. Huron	Thessalon R.	147	2005	3584	19.1	8.4	4.1	263	6.9	0.20
PEMA-1234	South./Sup.	North Lk. Huron	Thessalon R.	148	2005	3814	31.5	8.0	3.0	269	6.9	0.09

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1235	South./Sup.	North Lk. Huron	Thessalon R.	153	2005	4199	35.6	14.1	3.8	253	8.9	0.22
PEMA-1229	South./Sup.	North Lk. Huron	Thessalon R.	155	2005	3505	21.7	7.4	3.4	255	6.2	0.12
PEMA-1223	South./Sup.	North Lk. Huron	Thessalon R.	157	2005	4182	40.1	25.1	3.9	277	7.2	0.20
PEMA-1232	South./Sup.	North Lk. Huron	Thessalon R.	158	2005	3440	28.2	6.1	2.9	251	5.2	0.11
PEMA-1225	South./Sup.	North Lk. Huron	Thessalon R.	161	2005	3653	26.8	14.0	3.9	250	7.9	0.08
PEMA-617	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	62	2004	3897	41.6	1.2	6.9	208	64.9	0.01
PEMA-620	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	64	2004	2793	42.5	2.1	7.2	252	328.4	0.13
PEMA-619	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	70	2004	3654	36.2	3.3	10.3	291	23.4	0.13
PEMA-612	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	71	2004	3807	40.7	139.7	7.6	128	9.0	1.42
PEMA-614	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	73	2004	2786	19.7	33.6	6.2	268	9.6	0.10
PEMA-616	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	76	2004	2885	52.6	1.1	10.7	279	16.8	0.03
PEMA-611	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	79	2004	3610	35.6	8.0	9.1	198	19.0	0.20
PEMA-1027	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	86	2004	4772	44.2	5.0	6.0	221	10.4	0.12
PEMA-1028	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	87	2004	3508	49.3	6.3	6.1	193	9.9	0.19
PEMA-1026	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	90	2004	3483	43.3	3.2	4.8	265	13.0	0.11
PEMA-1030	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	91	2004	2927	24.5	3.3	6.1	220	27.3	0.08
PEMA-613	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	91	2004	4149	25.7	7.1	4.4	203	38.6	0.12
PEMA-1029	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	93	2004	4571	43.4	3.7	4.0	193	12.1	0.12
PEMA-615	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	93	2004	4603	78.5	7.8	8.8	200	23.7	0.46
PEMA-618	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	96	2004	4714	25.2	1.5	6.0	131	7.9	0.03
PEMA-1268	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	72	2005	2674	34.1	2.9	3.7	260	21.1	0.05
PEMA-1254	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	78	2005	3846	35.9	4.8	4.1	154	18.9	0.14
PEMA-1267	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	78	2005	3178	27.5	2.3	4.7	289	33.0	0.09
PEMA-1261	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	82	2005	3100	31.1	1.3	4.1	235	23.1	0.02
PEMA-1265	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	84	2005	4331	26.5	8.4	4.8	248	38.7	0.09
PEMA-1264	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	86	2005	2541	19.8	1.8	4.6	345	11.5	0.06
PEMA-1266	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	91	2005	3246	29.0	2.8	3.8	114	152.2	0.09
PEMA-1257	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	97	2005	2269	30.8	2.2	4.1	349	11.4	0.07
PEMA-1262	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	100	2005	2991	38.8	2.5	3.9	246	10.2	0.06

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1259	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	101	2005	3151	37.2	3.2	4.1	246	17.4	0.08
PEMA-1263	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	104	2005	3889	33.8	2.7	4.8	173	19.4	0.11
PEMA-1258	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	112	2005	2619	28.9	9.0	4.2	349	19.4	0.06
PEMA-1256	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	113	2005	2656	43.4	3.3	4.1	169	16.6	0.07
PEMA-1260	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	116	2005	2742	30.1	4.5	3.8	190	17.2	0.06
PEMA-1255	Old Paleozoic	North Lk. Huron	Timber Bay Cr.	140	2005	2404	33.9	4.1	3.7	319	65.4	0.07
PEMA-182	Old Paleozoic	Carp-Pine	Trout Cr.	36	2004	4609	47.8	27.4	4.6	468	21.6	0.31
PEMA-184	Old Paleozoic	Carp-Pine	Trout Cr.	38	2004	3080	53.2	4.5	7.4	539	26.5	
PEMA-181	Old Paleozoic	Carp-Pine	Trout Cr.	40	2004	3776	57.2	1.4	6.0	993	37.7	0.06
PEMA-179	Old Paleozoic	Carp-Pine	Trout Cr.	41	2004	3631	62.1	5.8	6.0	506	22.9	0.04
PEMA-180	Old Paleozoic	Carp-Pine	Trout Cr.	43	2004	4398	60.5	2.6	6.7	292	17.6	0.03
PEMA-161	Old Paleozoic	Carp-Pine	Trout Cr.	72	2004	6544	56.2	18.0	8.9	669	22.5	0.10
PEMA-152	Old Paleozoic	Carp-Pine	Trout Cr.	73	2004	5050	69.5	4.2	5.8	309	16.3	0.06
PEMA-160	Old Paleozoic	Carp-Pine	Trout Cr.	73	2004	4281	75.6	24.8	5.3	1146	57.3	0.14
PEMA-157	Old Paleozoic	Carp-Pine	Trout Cr.	76	2004	4515	58.6	0.16	7.9	985	34.6	0.08
PEMA-153	Old Paleozoic	Carp-Pine	Trout Cr.	80	2004	4111	61.7	1.2	7.6	882	30.3	0.11
PEMA-141	Old Paleozoic	Carp-Pine	Trout Cr.	118	2004	6321	109.2	10.0	8.6	207	20.6	0.44
PEMA-137	Old Paleozoic	Carp-Pine	Trout Cr.	122	2004	5707	93.3	15.3	8.6	456	22.3	0.20
PEMA-136	Old Paleozoic	Carp-Pine	Trout Cr.	126	2004	4612	72.7	10.0	6.4	431	22.2	0.08
PEMA-138	Old Paleozoic	Carp-Pine	Trout Cr.	127	2004	3824	54.9	6.8	7.7	503	26.2	0.22
PEMA-135	Old Paleozoic	Carp-Pine	Trout Cr.	133	2004	5822	54.1	5.9	8.8	289	32.6	0.19
PEMA-766	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	54	2004	2659	26.2	4.1	3.2	367	14.9	0.25
PEMA-690	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	68	2004	5191	25.8	1.8	1.5	251	11.9	0.10
PEMA-683	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	76	2004	3603	37.5	3.6	2.1	289	16.1	0.12
PEMA-765	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	79	2004	4255	27.5	2.8	2.4	232	10.5	0.05
PEMA-682	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	81	2004	5076	35.1	2.9	2.1	262	5.2	0.10
PEMA-685	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	82	2004	4713	37.2	1.8	2.2	287	10.6	0.18
PEMA-687	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	82	2004	3175	26.2	1.8	2.5	442	14.8	0.08
PEMA-684	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	86	2004	3433	33.1	0.94	2.0	327	13.3	0.13

Fish ID	**Geologic zone**	**Major Watershed**	**Stream**	**TL (mm)**	**Year**	**Mg**	**Mn**	**Zn**	**Rb**	**Sr**	**Ba**	**Pb**
PEMA-686	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	98	2004	3586	21.4	1.3	1.8	257	8.4	0.04
PEMA-763	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	99	2004	3366	24.1	5.3	2.7	273	6.0	0.07
PEMA-681	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	102	2004	5027	30.5	8.0	2.7	225	5.2	0.06
PEMA-688	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	110	2004	5029	56.5	12.5	2.6	222	7.2	0.20
PEMA-764	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	113	2004	5037	26.9	8.8	3.4	235	10.5	0.24
PEMA-689	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	122	2004	4136	24.5	2.4	2.3	228	6.0	0.19
PEMA-762	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	141	2004	5235	18.6	5.6	2.4	406	9.1	0.06
PEMA-1566	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	51	2005	4965	29.0	88.1	2.8	259	8.6	0.15
PEMA-1569	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	51	2005	3860	17.2	1.8	2.1	345	9.7	0.03
PEMA-1576	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	51	2005	4408	26.0	1.9	2.9	282	23.2	0.11
PEMA-1568	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	55	2005	5081	31.5	91.1	2.7	233	6.5	0.23
PEMA-1570	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	56	2005	3926	19.2	4.6	3.2	263	4.8	0.15
PEMA-1573	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	56	2005	3570	25.8	2.6	2.1	218	5.5	0.06
PEMA-1575	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	58	2005	4196	28.8	66.6	2.8	313	12.3	0.29
PEMA-1565	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	66	2005	4205	28.1	82.7	2.1	272	7.8	0.14
PEMA-1564	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	71	2005	5077	21.2	22.9	2.3	234	8.8	0.09
PEMA-1567	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	71	2005	4845	25.5	19.3	2.8	301	14.8	0.10
PEMA-1572	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	71	2005	4103	20.4	9.7	2.2	264	24.6	0.28
PEMA-1571	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	76	2005	5448	31.7	188.7	3.5	212	5.6	0.28
PEMA-1563	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	79	2005	5021	32.3	59.3	2.5	203	7.7	0.18
PEMA-1574	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	80	2005	5231	24.6	36.2	2.7	260	8.5	0.15
PEMA-1562	Old Paleozoic	Lone Lk. Ocqueoc	Trout R.	130	2005	5604	21.8	58.5	3.2	296	10.2	0.25
PEMA-1182	Old Paleozoic	North Lk. Huron	Watson Cr.	61	2005	3878	28.4	2.5	5.9	222	9.9	0.05
PEMA-1183	Old Paleozoic	North Lk. Huron	Watson Cr.	61	2005	4386	18.6	1.2	5.0	271	13.3	0.01
PEMA-1179	Old Paleozoic	North Lk. Huron	Watson Cr.	63	2005	4097	21.4	1.7	6.1	220	10.9	0.04
PEMA-1184	Old Paleozoic	North Lk. Huron	Watson Cr.	68	2005	3595	21.5	1.2	5.3	250	15.6	0.03
PEMA-1176	Old Paleozoic	North Lk. Huron	Watson Cr.	69	2005	3964	18.8	2.5	6.0	267	11.0	0.02
PEMA-1180	Old Paleozoic	North Lk. Huron	Watson Cr.	69	2005	4358	39.1	2.6	4.8	268	18.7	0.02
PEMA-1173	Old Paleozoic	North Lk. Huron	Watson Cr.	73	2005	3962	24.1	1.0	4.7	210	10.0	0.04

Fish ID	Geologic zone	Major Watershed	Stream	TL (mm)	Year	Mg	Mn	Zn	Rb	Sr	Ba	Pb
PEMA-1177	Old Paleozoic	North Lk. Huron	Watson Cr.	73	2005	4629	28.9	1.9	5.8	227	13.5	0.02
PEMA-1178	Old Paleozoic	North Lk. Huron	Watson Cr.	73	2005	3828	36.3	3.0	4.9	391	28.6	0.04
PEMA-1181	Old Paleozoic	North Lk. Huron	Watson Cr.	77	2005	4145	24.4	1.8	6.3	231	9.2	0.02
PEMA-1170	Old Paleozoic	North Lk. Huron	Watson Cr.	79	2005	4147	32.4	0.11	6.9	299	11.2	0.01
PEMA-1175	Old Paleozoic	North Lk. Huron	Watson Cr.	79	2005	4824	43.6	2.1	5.0	391	18.3	0.02
PEMA-1171	Old Paleozoic	North Lk. Huron	Watson Cr.	83	2005	3726	23.4	1.5	4.7	245	8.8	0.02
PEMA-1172	Old Paleozoic	North Lk. Huron	Watson Cr.	87	2005	4237	22.6	2.1	4.7	207	8.0	0.04
PEMA-1174	Old Paleozoic	North Lk. Huron	Watson Cr.	90	2005	4375	24.9	2.0	5.9	239	9.9	0.03

APPENDIX B

Brothers and Thresher's data from PIXE analyses (concentrations in ppm) (Brothers and Thresher 2004)

Sample ID	Stream	site	Mn	Fe	Ni	Cu	Zn	Rb	Sr	Hg	Pb	Ba
A230a	St. Marys 1	1	16	35	0	2	51.9	4.2	297	8	5	53
A229a	St. Marys 1	1	35	30	1.3	3	96	9.4	322	5	3	75
A228a	St. Marys 1	1	46	134	1.5	2	236	8.1	277	8	4	58
A227a	St. Marys 1	1	47	121	2.5	2.5	97	6.3	385	9	3	54
A226a	St. Marys 1	1	50	89	1.6	3.5	232	8.2	398	7	5	59
A225a	St. Marys 1	1	21	29	2.1	3.9	86	10.3	374	7	4	54
A224a	St. Marys 1	1	20	25	2	2.5	59.7	7.7	314	6	6	78
A333b	St. Marys 1	1	49	16	4.2	6.9	68	21.4	413	22	4	58
A334	St. Marys 1	1	0	8	1.8	1.4	29.6	2.9	2163	7	3	268
A125a	St. Marys 2	2	9	14	1.6	2.7	4.1	2	310	4.5	6	35
A124a	St. Marys 2	2	12	32	2.1	4.6	17	4.4	344	5	7	67
A123a	St. Marys 2	2	36	38	5	31	26	7	393	12	27	171
A122a	St. Marys 2	2	12	12.8	2.1	2.6	12.2	2.6	282	5	5	43
A117a	St. Marys 2	2	11	12	2.4	3.3	62	15.4	471	8	7	64
A118a	St. Marys 2	2	13	27	2.7	1.9	16.8	4.8	325	9	6	52
A101	St. Marys 2	2	0	6	2.7	1.3	9.5	3.8	405	6	4	54
A102	St. Marys 2	2	14	12	1.5	4.7	34	12.4	319	7	4	65
A103b	St. Marys 2	2	9	8	1.6	3.3	51	18.8	507	8	5	64
A104a	St. Marys 2	2	22	11	2.1	4.2	79	13.4	411	9	4	74
A411	Black Mallard larvae	3	32	7	1.6	3.3	38.7	19.9	592	10	5	60
A412a	Black Mallard larvae	3	51	10	0.7	5.2	55	21	913	11	5	75
A414a	Black Mallard larvae	3	43	9	2.8	4	30.9	31	884	11	6	67
A415	Black Mallard larvae	3	28	6	2.1	2.3	35	25	767	14	7	50
A416a	Black Mallard larvae	3	34	6	2.2	4	54	23.4	821	12	4	71
A417a	Black Mallard larvae	3	28	8	2.5	3.8	16.7	19.6	1091	2	6	70
B401a	Black Mallard larvae	3	41	13	1.9	4.1	31.3	21	865	11	5	.
B403a	Black Mallard larvae	3	41	15	2.7	4.4	49	27	1004	10	8	73

Sample ID	Stream	site	Mn	Fe	Ni	Cu	Zn	Rb	Sr	Hg	Pb	Ba
B426	Black Mallard adults	4	45	31	1.6	5	173	22.9	644	8	4	80
B427	Black Mallard adults	4	13	9	1	1.5	6.5	8.1	635	10	4	51
B428	Black Mallard adults	4	86	12	1.5	5.4	99	30.8	548	11	6	55
B429	Black Mallard adults	4	65	9	0	13	46	19	513	8	6	118
B430	Black Mallard adults	4	62	20	1.3	5.4	145	20.3	624	9	5	62
B431	Black Mallard adults	4	43	12	1.6	4.2	84	32	1071	11	6	80
B432	Black Mallard adults	4	37	11	2	2.6	24.4	12.8	742	8	5	36
B433	Black Mallard adults	4	91	13	3	4	51	25.3	616	26	3	207
B434	Black Mallard adults	4	62	9	2.1	2.9	32.9	22	936	13	6	568
B435	Black Mallard adults	4	101	116	3.5	5.7	268	39	795	14	4	142
B436	Black Mallard adults	4	13	21	2.2	5.9	16.2	8.1	727	9	4	62
B437	Black Mallard adults	4	31	20	1.6	4	30.9	15	584	9	4	77
B438	Black Mallard adults	4	29	11	1.6	3.3	26	13	1189	14	6	155
B439	Black Mallard adults	4	85	12	2	5.8	31.4	16.9	620	9	3	64
B440	Black Mallard adults	4	50	20	1.4	4.1	72	29	805	9	5	105
B444	Black Mallard adults	4	41	31	3	14	70	66	934	17	14	219
B445	Black Mallard adults	4	31	13	2.1	3.9	17.7	18	707	10	5	67
B302	Black Mallard adults	4	48	19	2	3	46	16	842	15	12	159
R13	Rifle River	5	12	5	1.5	1.4	2	4.9	581	8	5	41
R14	Rifle River	5	22	8	.	2.4	9.6	7.2	681	7	4	55
R29	Rifle River	5	13	9	1.4	2.4	12.7	3.6	1419	3	2	76
r20	Rifle River	5	11	6	1.5	2.7	1.4	3.8	1900	6	5	80
P15	Pigeon River	6	58	4	1.4	2.3	3.7	6	450	8	5	55
P31	Pigeon River	6	30	4	1.2	2.7	7.9	10.9	912	11	4	343
P36	Pigeon River	6	37	4	1.3	1.5	2.2	4.7	554	9	4	70
P49	Pigeon River	6	27	6	1.7	3.2	3.1	10.3	910	12	6	93
p53	Pigeon River	6	16	5	2.6	1.5	2.5	3.4	1500	4	6	80

VITA AUCTORIS

Carrol Hand was born in Detroit, Michigan, USA in 1981. She graduated from high school at The Roeper School (Birmingham, MI) in 1999. From there she went on to Barnard College of Columbia University (New York, NY) and graduated with a B.A. in 2003, majoring in Environmental Science with a minor in English. She is currently a candidate for a Masters degree in Science from the Great Lakes Institute for Environmental Research at the University of Windsor, and plans to graduate in the fall of 2006.