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NWRI Contribution No. 05-321

NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

Environment Canada

Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau

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October 2005

ABSTRACT

There are elevated concentrations of mercury in sediments of Jellicoe Cove, a section of the Peninsula Harbour Area of Concern in Lake Superior that was exposed in the past to mercury-contaminated industrial effluents. To assess the bioavailability of this mercury and its potential for effects on fish, wildlife and humans through biomagnification, a study was conducted involving (a) comparisons of total and methyl mercury concentration in sediment and benthic invertebrates from Jellicoe Cove to those from reference locations, (b) analyses of the relationships of total and methyl mercury concentrations in invertebrates to those in sediment, and (c) predictions of concentrations of total and methyl mercury in representative consumers of benthic invertebrates and their predators using screening-level trophic transfer models.

In May 2002, sediment, overlying water and two benthic invertebrate taxa (midges and amphipods) were sampled from 25 locations in Jellicoe Cove and 13 reference site locations. Samples were analyzed for total and methyl mercury concentrations and a series of physico-chemical variables in the sediment and overlying water. Mercury concentrations in sediment and invertebrates in Jellicoe Cove were compared to concentrations in reference sites. Relationships between mercury in each invertebrate taxon and mercury in sediment were evaluated by regression analysis. Physico-chemical sediment and water variables were included as additional predictors. Concentrations of total and methyl mercury in the tissues of fish and wildlife receptors (Longnose Sucker, Yellow Perch, Lake Trout, Great Blue Heron, Mink) were predicted by multiplying measured body concentrations in the resident invertebrates by relevant biomagnification factors obtained from a review of pre-existing studies.

Total mercury concentrations in sediment, midges and amphipods at most sites in Jellicoe Cove are significantly elevated above concentrations at reference sites. Methyl mercury concentrations in sediment and amphipods from most Jellicoe Cove sites are also significantly higher than concentrations at reference sites. For midges, methyl mercury levels exceed the maximum for reference sites only at a few Jellicoe Cove sites. Total and methyl mercury concentrations in midges and amphipods from Jellicoe Cove and reference sites are significantly influenced by mercury in sediment ($r^2 = 0.11$ to 0.85), with the strongest relationships for total mercury and amphipods. In all multiple regression models, sediment mercury concentration is the most significant predictor of invertebrate mercury concentration. Predicted receptor mercury levels in a third (6-9) of the sites in Jellicoe Cove are greater than predicted receptor mercury levels for reference area sites. In almost all Jellicoe Cove sites, mercury concentrations in 1 or 2 of the 3 fish receptors could exceed tissue residue guidelines for the protection fish-consuming wildlife and humans. Among all predictions, $[MeHg]_{rec}$ for a group of seven sites in the southeastern section of Jellicoe Cove is consistently indicated to exceed both reference site conditions and tissue residue guidelines. Comparison of the predicted Hg concentration in fish receptors to actual mercury concentrations in fish collected from the AOC show that the model is not overestimating Hg accumulation. Using an "average concentration with area curve" exposure model, it is determined that reducing mercury to background level in the six most contaminated sites would result in mean methyl mercury concentrations in invertebrates for the whole area less than a determined critical value for consumer receptors.

Results of this assessment suggests that mercury is transferred from sediment to benthic invertebrates, and that under generally "intermediate" and "maximum" exposure and trophic transfer scenarios mercury could bioaccumulate in receptors to levels that are not protective of

adverse effects. However, the likelihood of realizing this degree of mercury biomagnification is not clear due to uncertainties associated with predicting receptor mercury concentrations.

RÉSUMÉ

Les concentrations de mercure sont élevées dans les sédiments de l'anse Jellicoe, une section du secteur préoccupant du havre Peninsula (lac Supérieur) exposée par le passé à des effluents industriels contaminés par le mercure. Pour évaluer la biodisponibilité de ce mercure et ses effets potentiels chez le poisson, les animaux et les êtres humains par bioamplification, les chercheurs ont mené une étude comportant a) des comparaisons de la concentration de mercure total et de méthylmercure dans les sédiments et chez les invertébrés benthiques de l'anse Jellicoe à celles de sites de référence, b) des analyses du rapport des concentrations de mercure total et des concentrations de méthylmercure chez les invertébrés et dans les sédiments et c) des prévisions des concentrations du mercure total et du méthylmercure chez des consommateurs représentatifs d'invertébrés benthiques et de leurs prédateurs à l'aide de modèles du transfert trophique du niveau de l'évaluation préalable.

En mai 2002, les chercheurs ont prélevé des échantillons dans les sédiments, dans la couche d'eau susjacente et chez deux taxons d'invertébrés benthiques (éphémères et amphipodes) à 25 endroits dans l'anse Jellicoe et dans treize (13) sites de référence. Ils ont mesuré la concentration de mercure total et la concentration de méthylmercure dans les échantillons et une série de variables physico-chimiques dans les sédiments et la couche d'eau susjacente. La concentration de mercure dans les sédiments et chez les invertébrés de l'anse Jellicoe a été comparée aux concentrations mesurées dans les sites de référence. Le rapport entre le mercure mesuré dans chaque taxon d'invertébré et le mercure mesuré dans les sédiments a été évalué par une analyse de régression. Les variables physico-chimiques des sédiments et de l'eau ont été incluses comme variables indépendantes supplémentaires. La concentration de mercure total et la concentration de méthylmercure dans les tissus des poissons et chez les récepteurs animaux (meunier rouge, perchaude, touladi, grand héron bleu, vison) avaient été prédites en multipliant les concentrations corporelles chez les invertébrés résidents par des facteurs appropriés de bioamplification obtenus à partir d'un examen des études antérieures.

La concentration de mercure total dans les sédiments, chez les éphémères et chez les amphipodes, mesurée dans la plupart des sites de l'anse Jellicoe est significativement plus élevée que celle relevée dans les sites de référence. La concentration de méthylmercure relevée dans les sédiments et chez les amphipodes dans la plupart des sites de l'anse Jellicoe est également significativement plus élevée que celle mesurée dans les sites de référence. Dans le cas des éphémères, seuls quelques sites dans l'anse présentent un taux de méthylmercure supérieur à la valeur maximale établie pour les sites de référence. Le mercure dans les sédiments ($r^2 = 0{,}11$ à 0,85) influe énormément sur la concentration de mercure total et la concentration de méthylmercure chez les éphémères et les amphipodes de l'anse et aux sites de référence, le rapport étant le plus fort pour le mercure total et les amphipodes. Dans tous les modèles de régression multiple, la concentration de mercure dans les sédiments est le prédicteur le plus important de la concentration de mercure chez les invertébrés. Les taux prévus de mercure dans les récepteurs dans un tiers (6 à 9) des sites dans l'anse Jellicoe sont supérieurs aux taux prévus dans les sites des zones de référence. Dans presque tous les sites de l'anse Jellicoe, les concentrations de mercure chez 1 ou 2 des trois récepteurs ichtyens pourraient dépasser les

quantités recommandées de résidus dans les tissus qui visent à protéger les animaux et les êtres humains qui consomment du poisson. Parmi toutes les prévisions, la recommandation à l'égard du $[MeHg]_{rec}$ pour un groupe de sept sites dans la partie sud-est de l'anse Jellicoe dépasse régulièrement les conditions du site de référence et les recommandations de résidus dans les tissus. Une comparaison de la concentration de Hg prévue chez les poissons récepteurs par rapport aux concentrations réelles de mercure chez les poissons prélevés dans le secteur préoccupant montre que le modèle ne surestime pas l'accumulation de mercure. À l'aide d'un modèle de l'exposition utilisant la concentration moyenne avec aire sous la courbe, on a établi qu'en réduisant le mercure au niveau de fond dans les six endroits les plus contaminés, on obtiendrait des concentrations moyennes de méthylmercure chez les invertébrés de l'ensemble du secteur qui seraient inférieures à la valeur critique calculée pour les récepteurs consommateurs.

Les résultats de cette évaluation font ressortir que le mercure est transféré des sédiments vers les invertébrés benthiques, et que, dans les scénarios d'exposition et de transfert trophique de niveau globalement « intermédiaire » et « maximal », le mercure pourrait être bioaccumulé dans ces récepteurs à des concentrations qui dépassent le niveau des effets néfastes. Toutefois, la probabilité d'atteindre ce degré de bioamplication du mercure n'est pas établie, étant donné les incertitudes associées à la prévision des concentrations de mercure dans les récepteurs.

ACKNOWLEDGEMENTS

This project was sponsored by the Government of Canada's Great Lakes Basin 2020 Action Plan and the Great Lakes Sustainability Fund, a component of the Great Lakes program. The Sustainability Fund provides resources to demonstrate and implement technologies and techniques to assist in the remediation of Areas of Concern and other priority area in the Great Lakes. The report that follows addresses sediment quality issues in the Peninsula Harbour Area of Concern in Marathon, Ontario. Although the report was subject to technical review, it does not necessarily reflect the views of the Sustainability Fund or Environment Canada.

Advice on the study design was received from Roger Santiago (Environmental Conservation Branch – Ontario Region). Technical support for the field sampling was provided by Sherri Thompson, Tim Pascoe, Jennifer Dow, Jennifer Webber, and Mark Pokorski (National Water Research Institute, Environment Canada). Study maps for the report were provided by Tim Pascoe.

Comments on an earlier draft of the report were contributed by Rein Jaagumagi, Lisa Richman, Conrad Debarros, Pat Inch, Anne Borgmann, Don Hart, Jerry Fitchko, Kai Chen and Janette Anderson.

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ABBREVIATIONS, ACRONYMS AND SYMBOLS

adj	adjusted
AOC	Area of Concern
BEAST	BEnthic Assessment of SedimenT
BMF	biomagnification factor
BSAF	biota-sediment accumulation factor
dw	dry weight
FCM	food chain multiplier
GLWQA	Great Lakes Water Quality Agreement
Hg	mercury; used where form (MeHg or THg) is unspecified
IJC	International Joint Commission
inv	invertebrate
LEL	lowest effect level
max	maximum
med	medium
MeHg	methyl mercury
min	minimum
PCB	polychlorinated biphenyl
PEL	probable effect level
QA/QC	quality assurance/quality control
RAP	Remedial Action Plan
rec	receptor
ref	reference
reg	regression
sed	sediment
SEL	severe effect level
THg	total mercury
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TP	total phosphorus
TRG	tissue residue guideline
wt	weight
ww	wet weight
$[x]_i$	concentration of substance *x* in matrix *i*

1 INTRODUCTION

1.1 Background and Mandate

In the 1970s, 42 locations in the Great Lakes where the aquatic environment was severely degraded were identified as "problem areas" by the International Joint Commission (IJC). Of these, 17 are along Canadian lakeshores or in boundary rivers shared by the US and Canada. The IJC's Great Lakes Water Quality Board recommended in 1985 that a Remedial Action Plan (RAP) be developed and implemented for each problem area. The RAP approach and process is described in the 1987 Protocol to the *Great Lakes Water Quality Agreement* (GLWQA). The goal is to restore the "beneficial uses" of the aquatic ecosystem in each problem area, which were now called "Areas of Concern" (AOCs). Fourteen possible "impairments of beneficial use", which could be caused by alterations of physical, chemical or biological conditions in the area, are defined in Annex 2 of the GLWQA.

The Canadian government's commitment to the GLWQA was renewed in 2000 with the Great Lakes Basin 2020 (GL2020) Action Plan, under which the efforts of eight federal departments to "restore, conserve, and protect the Great Lakes basin" over the next five years were to be co-ordinated. Environment Canada's contribution included the funding of detailed chemical and biological assessments of sediments in each of the remaining Canadian AOCs. The National Water Research Institute (NWRI) was given the responsibility of conducting and reporting on these assessments.

Under the terms of reference for the NWRI's mandate, the BEnthic Assessment of SedimenT (BEAST) methodology of Reynoldson et al. (1995; 2000) is to be applied to the AOC assessments. To date, the methodology has involved evaluation of sediment contaminant concentration, laboratory toxicity, and benthic invertebrate community structure. Recent reviews of the BEAST framework have recommended the inclusion of an additional line of evidence – information on the bioaccumulation of contaminants liable to biomagnify (Grapentine et al. 2002). To obtain this additional information, support has been received from the Great Lakes Sustainability Fund for work in AOCs, including Peninsula Harbour, Ontario. The study described in this document was conducted to supplement existing data to complete an assessment

of sediments in Jellicoe Cove, Peninsula Harbour, that were historically exposed to industrial effluents.

1.2 Decision Framework for Sediment Assessment

The underlying philosophy of the NWRI's approach to sediment assessment is that observations of elevated concentrations of contaminants alone are not indications of ecological degradation. Rather, it is the biological responses to these contaminants that are the concern. A recommendation on remedial activity requires evidence to be provided of an adverse biological effect either on the biota resident in the sediment, or on biota that are affected by contaminants originating from the sediment, either by physical, chemical or biological relocation.

It is recognized that to make decisions on sediment quality and the need to remediate, four components of information (in addition to knowledge on the stability of sediments) are required (Krantzberg et al. 2000):

- ***Sediment chemistry and grain size*** – Quantifies the degree to which sediments are contaminated. Indicates exposure (or at least potential exposure) of organisms to contaminants (with consideration of exposure pathways). Provides information on physicochemical attributes of the sediment to assist in the interpretation any observed biological effects.

- ***Benthic invertebrate community structure*** – Used to determine whether natural faunal assemblages in contaminated sediments differ from those in uncontaminated reference locations. Can indicate a biological response to sediment conditions. Organisms which reside in and ingest sediments experience the most ecologically relevant exposures to contaminants present, and represent important food web components.

- ***Sediment toxicity*** – Differences in resident invertebrate communities between contaminated and uncontaminated sites alone cannot be conclusively attributed to toxic chemicals.

Sediment toxicity data provide supporting evidence that responses observed in the community are associated with sediment contaminants rather than other potential stressors.

- ***Invertebrate body burdens*** – Measurements of contaminants in tissues of resident benthic fauna provide evidence of bioavailability, and that the contaminants are responsible for observed effects on the organisms (Borgmann et al. 2001). In addition, the information can be used to assess the risk to higher trophic levels due to biomagnification. Some contaminants, although bioavailable, may not accumulate in benthic invertebrates to sufficient concentrations to induce effects. A few of these contaminants (e.g., mercury) have the property of biomagnifying up the food chain to produce adverse responses in higher trophic level organisms.

Overall assessment of a site is achieved by integrating the information obtained both within and among the above four lines of evidence. The decision framework was developed from the Sediment Triad (Long and Chapman 1985; Chapman 1996) and the BEAST (Reynoldson et al. 1995; 2000) frameworks, and is described in detail elsewhere (Grapentine et al. 2002).

1.3 The Peninsula Harbour Area of Concern

The Peninsula AOC has been the subject of two major RAP reports – Stage 1: Environmental Conditions and Problem Definition (Peninsula Harbour RAP Team 1991) and Stage 2: Remedial Strategies for Ecosystem Restoration (Peninsula Harbour RAP Team 1998). The environmental issues of concern identified for Peninsula Harbour are:

- Mercury contamination,
- PCB contamination,
- Presence of other contaminants (trace metals, oil and grease),
- Bacterial contamination,
- Aesthetic impairment,
- Habitat destruction and degradation (due to accumulation of wood fibres and bark),
- Exotic species (sea lamprey), and
- Fish health problems related to contaminants.

Of the 14 beneficial uses evaluated for the Peninsula Harbour AOC, 5 were determined as "impaired". All are associated with sediment contaminants:

- Degradation of benthos,
- Restrictions on fish consumption,
- Degradation of fish populations,
- Loss of fish and wildlife habitat, and
- Restrictions on dredging activities

Assessments of sediments and contaminants in depositional areas of the Peninsula Harbour, specifically Jellicoe Cove, were most recently performed in 2000 (Burt and Fitchko 2001, Milani et al. 2002). Key conclusions were from these studies were:

- Total mercury concentrations in Jellicoe Cove are elevated and generally increase with sediment depth.
- A similar pattern is evident with methyl mercury, which is generally higher in the deeper sediments.
- Direct toxicity of sediment-bound contaminants in Jellicoe Cove is not evident based on laboratory toxicity tests and assessment of resident benthic communities in Jellicoe Cove. Resident benthic communities show a general trend towards greater diversity and abundance at test sites compared to reference sites.
- Bioavailability of mercury from sediments and the potential for food chain effects are of concern and need to be investigated in Jellicoe Cove.

Discharges of mercury from the former chlor-alkali plant (closed 1977) were released directly into Jellicoe Cove. Currently, the two point sources (pulp and paper mill and the WPCP) discharge into the open lake; however, a mill sump overflow discharges into Jellicoe Cove. The current chief environmental issue of concern is the elevated concentration of mercury in remaining sediment due to past discharges from local sources, and the potential risk to fish, wildlife and humans through biomagnification. The bioaccumulation component of the assessment framework is important to consider where concern exists for contaminants such as mercury and chlorinated organic compounds that can be highly concentrated in the food web

without inducing effects on survival, reproduction or growth at the lower trophic levels (which are typically examined for sediment assessments). Measurement of invertebrate body burdens allows assessment of the potential for effects on higher trophic level organisms (which are more difficult to measure and typically not examined in sediment assessments) resulting from the transfer of contaminants through dietary sources. Measurement of body burdens of benthic organisms was identified as requiring further assessment (Peninsula Harbour RAP Team 1998).

1.4 Purpose of the Study

The purpose of this study is to determine if deleterious amounts of mercury from sediments in Jellicoe Cove could potentially be transferred through benthic invertebrates to fish, wildlife or humans. In other words: Is there evidence that mercury biomagnification is an environmental issue of concern? The results of this study should lead to one of two alternate conclusions: (a) mercury is unlikely to concentrate in the food web at levels that can cause adverse effects, or (b) mercury **could** concentrate in the food web at levels that can cause adverse effects. The determination of whether mercury biomagnification and adverse effects to higher trophic level organisms (fish, wildlife, human) are actually occurring in Jellicoe Cove is beyond the scope of this study, and would need to be addressed by a more comprehensive assessment such as a detailed risk assessment. The latter conclusion (b) is of **potential** biomagnification, but does not determine actual biomagnification.

2 OBJECTIVES AND APPROACH

2.1 Objectives of Study

The purpose of the study was achieved through two objectives:

A. Determining if benthic invertebrates in locations where mercury is elevated are a potential source of mercury to higher trophic levels.
B. Determining if the amount of mercury potentially available is of concern.

The first objective was addressed by comparing concentrations of mercury (Hg) in benthic invertebrates from sites in Jellicoe cove to those from reference sites, and by determining whether sediment Hg concentration is related to invertebrate (whole body) Hg concentration. For the second objective, the concentrations of Hg in selected trophically linked receptor species (i.e., consumers of benthic invertebrates and their predators) were predicted based on measured Hg in invertebrates and literature-derived biomagnification factors. (Traas et al. (2002) is an example of an application of this approach.). The predicted Hg concentrations in the selected receptors were compared to appropriate tissue mercury guidelines established for the protection of higher trophic level organisms. Whereas predictions of receptor tissue mercury concentrations focused on methyl mercury (MeHg) because it is the most toxicologically relevant and predominant form of mercury in tissues of fishes and higher trophic level receptors (USEPA 1997b; Environment Canada 2002), determinations of Hg distributions and bioaccumulation in sediment and invertebrates were made on the basis of both total mercury (THg) and MeHg to allow comparisons with results from other studies and guidelines that involve THg.

The biomagnification modelling was broken down into four steps:

- Identification of receptors of potential concern.
- Measurement of contaminant concentrations in invertebrates and sediment.
- Selection of biomagnification factors.
- Prediction of possible receptor species tissue concentrations.

Knowledge of the food web structure of a site is needed to determine relevant receptor species (fish, bird, mammal). These are identified in the following subsection. Determinations of concentrations of mercury in sediment ($[Hg]_{sed}$) and invertebrates ($[Hg]_{inv}$) are described in the sampling design and methods sections. The identified receptors determined what biomagnification factors (BMFs) to use for predicting receptor mercury concentrations and what guideline to use (e.g., guidelines for protection of wildlife consumers of aquatic biota; human health guidelines for protection from fish consumption) for comparison. The review and selection of BMFs are discussed in the data analyses (subsection 3.4.2.1.) and Appendix A, and the estimation of [Hg] in the tissues of receptor species is described in subsection 3.4.2.2.

If the predicted contaminant concentration in a receptor for a Jellicoe Cove site exceeded the guideline *and* the maximum predicted concentration for the reference sites, a potential risk of adverse effects due to biomagnification was concluded. Alternatively, if the predicted contaminant concentration in the receptor for a Jellicoe Cove site was less than the guideline *or* the maximum predicted concentration for the reference sites, no potential risk was concluded.

2.2 Identification of Receptors of Concern

Based on generic food webs for the Great Lakes (e.g., Diamond et al. 1994), information on fauna resident in the Peninsula Harbour AOC (RAP Team 1991, 1998) and guidelines from Environment Canada (2000), receptors representative of four trophic levels were selected for biomagnification modelling:

- Benthic Invertebrates (trophic level 1): ***amphipods*** and ***midges (chironomids)***.
- Benthivorous fish (trophic level 2): ***Longnose Sucker***. Total mercury concentrations in 45 cm suckers collected from Peninsula Harbour show a decrease from 2020 ng/g to 640 ng/g ww for the period of 1975 to 2002, but on average, concentrations are higher than other areas in Lake Superior, which show a range of concentrations from 80 ng/g ww to 490 ng/g ww over the period of 1985 to 2001 (MOE 2002).
- Small piscivorous fish (trophic level 3): ***Yellow Perch***. The yellow perch have been observed in netting surveys in the Peninsula Harbour AOC (Peninsula Harbour RAP Team 1991). Regular collections for the determination of total mercury concentrations do not take place for this species.
- Large piscivorous fish (trophic level 4): ***Lake Trout***. Total mercury concentrations in 50 cm lake trout collected from the Peninsula Harbour AOC show an overall decrease from 1010 ng/g to 220 ng/g ww for the period of 1975 to 2002. Recent data (fish sampled in the 2000 to 2002 period) show that, on average, Hg concentrations in trout collected from Peninsula Harbour are slightly higher than those collected from six other areas in Lake Superior (range 120 to 210 ng/g ww) (MOE 2002).

- Piscivorous bird (trophic level 4): ***Great Blue Heron***. Great blue herons are widespread, and are known to breed along the shores of Lake Superior. Fishes (mostly <25 cm in length) are the preferred prey (CWS 2002).
- Piscivorous mammal (trophic level 4): ***mink***. Mink are associated with numerous aquatic habitats and are opportunistic feeders (CWS 2002). Mink inhabit areas throughout central and northern Ontario.

As part of the Sport Fish Contaminant Monitoring Program, regular collections of Lake Trout and Longnose Sucker (as well as other fish species) are collected from the Peninsula Harbour AOC. Sport fish consumption restrictions for total mercury begin at 450 ng/g and total restriction is advised for levels above 1570 ng/g (MOE 2003). Total mercury concentrations are at levels that warrant consumption advisories for both these species. For the sucker, consumption restrictions commence for fish 35-45 cm long, and total restriction imposed for fish 45-55 cm long. For the trout, restrictions commence for fish 45-55 cm long with total restriction for fish 65-75 cm long (MOE 2003).

A model of the feeding relationships linking these receptors with each other and benthic invertebrates and sediment is shown in Figure A1 (Appendix A).

2.3 Study Area

Background information on environmental conditions in the Peninsula Harbour AOC is given in Peninsula Harbour RAP Team (1991). Previous sediment surveys (Burt and Fitchko 2002, Milani et al. 2002; Appendix B: Table B1) performed in Peninsula Harbour, specifically in Jellicoe Cove, reported total mercury concentrations in sediments above the provincial Severe Effect Level (SEL) (Persaud et al. 1993).

Reference areas selected outside Jellicoe Cove but still within the Peninsula Harbour AOC included one site located in Carden Cove (PH15; Figure 1). Remaining reference areas were selected along the northern shore of Lake Superior and south of Marathon in Prospect Cove

(Figure 1). These reference stations provided data on background mercury concentrations in sediment and invertebrates relevant to the AOC.

2.4 Experimental Design

2.4.1 Sampling design

Sampling stations were arrayed in a multiple gradient design supplemented with reference sites. Stations in Jellicoe Cove were positioned in seven radial arms, with three to four stations in each arm (Figure 2). In total, 38 stations – 13 reference + 25 test (i.e., potentially exposed to previous effluent loadings) – were sampled for sediment chemistry, overlying water variables and benthic invertebrate tissue 20-31 May 2002. A list of station co-ordinates is provided in Table 1. The locations of stations were selected on the basis of (a) representing the widest range of mercury concentrations in sediment, and encompassing a 'hot spot' identified by Burt and Fitchko (2002), (b) representing least contaminated/reference conditions in the area, and (c) overlapping locations of previous studies.

This mixed (multiple gradient + control/potential impact) sampling design allowed several types of comparisons for assessing the distribution of mercury in sediment and invertebrates. Using all sites, relationships between sediment [Hg] and invertebrate [Hg] concentrations were examined. In addition, Hg concentrations at locations in Jellicoe Cove were compared to Hg concentrations at reference locations. The grid-like array of the Jellicoe Cove sites also allowed a spatial analysis of Hg conditions, in which locations of elevated Hg in sediment, invertebrates and receptors (predicted from models) were identified.

2.4.2 Measurement endpoints

Invertebrates (amphipods and midges) and sediment for mercury analyses were collected from locations of sediment deposits potentially exposed to past discharges of mercury-containing effluent, as well as from unexposed reference locations. Sediment was obtained from the top 0 - 10 cm layer of lake bed. This layer includes the vertical home range of most benthic invertebrates. Two distinct invertebrate taxa were targeted for collection from each location. Midges and amphipods were obtained from all test and reference sites. Analyses of total and

methyl mercury were performed on samples composited from organisms within each of two taxa (i.e., taxa were analyzed separately). Invertebrates were not allowed time to clear sediment from their guts because predators consume whole organisms. Mercury associated with sediment, as well as that incorporated into tissues, is potentially available for transfer through the food chain.

2.4.3 Assumptions

For the prediction of Hg concentrations in the tissues of upper trophic level biota, bioaccumulation is considered to occur predominantly through dietary pathways. This is suggested by several experimental and modelling studies (Bodaly et al. 1997; Downs et al. 1998). In modelling the exposure to and uptake of Hg by receptors, several conservative (i.e., maximum potential exposure to Hg) assumptions have been made. These include:

- For fish receptor
  - Fish consume invertebrates only from the site.
  - Fish feed on the same invertebrate taxa as those collected in field sampling.
- For wildlife receptor
  - 100% of the diet is fish.
  - Fish are consumed only from the site in question.
  - Fish consume invertebrates only from the site.
  - Fish feed on the same invertebrate taxa as those collected in field sampling.

In addition, the flux of mercury between sediment, water and biota compartments were considered in equilibrium.

3 METHODS

3.1 Sample Collection and Handling

Prior to sediment collections, temperature, conductivity, pH and dissolved oxygen were measured in the water column approximately 0.5 m above the bottom using Hydrolab apparatus. A Ponar sampler was used to collect the sediment. At each site, a sample of the top 10 cm sediment was collected from each Ponar grab and set aside in a glass tray. The remaining top 10

cm of sediment was placed in a 68 L tub. When the tub was full, the sediment set aside in the glass tray was homogenized and distributed to containers for individual analyses. Sediment collected for determination of total and methyl mercury was dispensed in pre-cleaned polyethylene bottles. Variables measured at each tissue collection site are listed in Table 2. All samples were kept at 4°C, with the exception of the sediment mercury and invertebrates samples, which were frozen (-20°C).

Invertebrates were removed from the top 10 cm of sediment (in the 68 L tubs) by wet sieving with lake water using 12" stainless steel sieves (500-μm mesh). Biota collected on the sieve were sorted into separate taxa in glass trays using stainless steel instruments, rinsed with deionized water and placed in pre-weighed and pre-cleaned (10 % HCL) 5 mL scintillation vials, weighed, and frozen on site (-20°C). A layer of parafilm was placed between vial and cap. Invertebrate samples were later freeze-dried and reweighed. The wet:dry ratios were used in converting mercury concentrations in invertebrates from a dry weight to wet weight basis (see section 3.4.2.2).

Stainless steel sieves and instruments were detergent washed between stations. If persistent organic matter remained on the sieve after the detergent wash (on visual inspection), a more aggressive cleaning solution was implemented (caustic ethanol). Homogenizing and sorting trays and scoops were detergent washed, rinsed in 20% HCl, and rinsed with lake water.

3.2 Sample Analyses

Concentrations of total phosphorus, total nitrogen, total organic carbon, Fe and Mn in sediment were measured by Caduceon Environmental Laboratory (Ottawa, ON) following procedures outlined by USEPA/CE (1981). Particle size analysis (percents clay, silt, sand, gravel) was performed by the Sedimentology Laboratory, NWRI (Burlington, ON) following the procedure of Duncan and LaHaie (1979). Mercury (total and methyl) analyses of sediment and invertebrates were performed by Flett Research Ltd. (Winnipeg, MB). Procedures for mercury analyses, which are based on Bloom and Crecelius (1983), Horvat et al. (1993) and Liang et al. (1994), are summarized below.

3.2.1 Total mercury in sediment

Flett Research Laboratory: Between 100 and 1000 mg of thawed sediment sample (or spiked sediment, blanks or reference material) was digested overnight (16-18 hours) in 3 mL of 7:3 nitric/sulfuric acid at 150°C. After cooling, the sample was diluted to 25 mL with low-mercury deionized water, spiked with BrCl and allowed to react. The residual BrCl was then destroyed by addition of hydroxylamine hydrochloride. An aliquot of the sample (100 µL – 2 mL) was placed into a sparging vessel, to which was added stannous chloride. The elemental mercury produced was purged onto a gold trap with Hg-free nitrogen. The gold trap was heated with UHP argon carrier gas passing through it, and the mercury released was measured by a Brooks-Rand CVAFS model-2 detector. The detection limit was 1-5 ng /g.

Caduceon Laboratory: Total mercury was determined by methods described in USEPA/CE (1981). Freeze dried sediments (0.5 g) were digested with HNO_3:HCl for two hours. $SnCl_2$ was added to reduce Hg to volatile metallic form. If there was high organic material, $KMnO_4$ was added to the digestion solution to destroy organo-mercury bonds. Hydroxyl amine hydrochloride was then added to neutralize $KMnO_4$ excess so $SnCl_2$ could react with Hg in solution. Digestion was followed by measurement using a cold vapour atomic absorption spectrometer. The detection limit was 5 ng/g sediment.

3.2.2 Total mercury in invertebrates

The same procedure as described for analysis of total mercury in sediment by Flett Research was used for invertebrates, with the following differences in the sample digestion: up to 100 mg of thawed invertebrate sample (or spikes, blanks or reference material) was digested for 6 hours in 10 mL of 1:2.5 nitric/sulfuric acid at 250°C; after cooling, the sample was diluted to 25 mL with low mercury deionized water, spiked with BrCl and allowed to react.

3.2.3 Methyl mercury in sediment

Sediment was prepared for analysis by distilling 200-300 mg of homogenized sample (or spikes or blanks) in ~45 mL of low-mercury deionized water. Approximately 40 mL of distillate was

collected and acidified with KCl/H_2SO_4. (Note: Since methyl mercury results were ≤0.1% of the total mercury results, a methylene chloride extraction was carried out on some of the highest total mercury samples. No significant difference in methyl mercury concentrations was observed between results obtained by either method. Therefore, it is assumed that insignificant methyl mercury production was occurring in the distillation process and thus all samples were processed by distillation.) An aliquot of the prepared sample (1-2 mL, depending on observed interferences from the matrix) was ethylated in solution (final volume ~ 40 mL) using sodium tetraethyl borate. The solution was buffered to pH 5.5. The resulting ethylmethyl mercury was purged onto a Tenax trap with mercury-free nitrogen. The trap was heated, purged with UHP argon onto a GC column (for separation of the ethylmethyl mercury from Hg° and diethyl mercury), run through a pyrolizer (to reduce all mercury to Hg°), and then sent to a cold vapour atomic fluorescence analyser for detection. (GC oven: Perkin Elmer 8410 GC; column: chromasorb WAW-DMSC 60/80 mesh with 15% OV-3; detector: Brooks-Rand CVAFS model-2). The detection limit was 0.25 ng/g dw.

3.2.4 Methyl mercury in invertebrates

Freeze dried invertebrates (5-10 mg of homogenized sample, spike, blank or reference material) were digested overnight with ~500 μL of KOH/methanol at 75 °C. Sample aliquots (50-60 μL) were then treated and analysed as described above for the ethylation and subsequent steps in the determination of methyl mercury in sediment. The detection limit was 1.2 ng/g dw.

3.3 Biota-Sediment Accumulation Factors

A biota-sediment accumulation factor (BSAF) was calculated for each invertebrate taxa and site combination, for total and methyl mercury. The BSAF equation used was that defined by Thomann et al. (1995), and is the ratio of the metal concentration in the organism to that in the sediment:

$$BSAF = [Hg]_{inv}/[Hg]_{sed}$$

BSAFs assume that the concentration of contaminant in the organism is a linear function of the contaminant concentration in the sediment.

3.4 Data Analyses

3.4.1 Mercury distribution in sediment and invertebrates

Sites in which concentrations of Hg in invertebrates ($[Hg]_{inv}$) were significantly elevated above background levels for the study area were identified by comparing $[Hg]_{inv}$ for Jellicoe Cove sites to the upper 99th % percentile of the reference sites. (Because there were 13 reference sites, this corresponded to the maximum value.) This was done separately for MeHg and THg and for each invertebrate taxon.

Relationships between concentrations of Hg in sediment and invertebrates were determined using regression analysis, again separately for MeHg and THg and for each invertebrate taxon. The goal was to estimate the degree to which Hg in invertebrates is predictable from Hg in sediment, with and without environmental covariables. Simple linear regression (ordinary least squares) was used for the single predictor ($[Hg]_{sed}$) model. "Best subset" multiple linear regression (Draper and Smith 1998; Minitab 2000) was used for the fitting of multiple predictor models. The environmental variables expected to potentially influence uptake of Hg from sediment by biota (based on reviews such as Braga et al. 2000; Lawrence and Mason 2001), including sediment concentrations of total organic C, total P, total Kjeldahl N, Fe, and Mn; sediment particle size fractions of sand, silt and clay; overlying water dissolved O_2, pH, and conductivity; and site depth were included in the models. To increase normality of data distributions and linearity of relations between variables, some data were transformed: log(x) for THg and MeHg in sediment and invertebrates; log(x) for nutrients, Fe and Mn in sediment and site depth; and arcsine-square root(x) for the particle size fractions. Normality and linearity of the water column data were not generally improved by transformations, so these were analyzed untransformed.

All models fitted to the data included $[Hg]_{sed}$ as a free predictor (i.e., it was not forced to be in the model). The specific null hypothesis of interest was that "the effect of $[Hg]_{sed}$ on $[Hg]_{inv} = 0$, after accounting for effects of other predictors". For the best subset regressions, models were fitted for all combinations of predictors. Determination of the "best" model was based on several criteria (in roughly decreasing order of importance):

- maximum $R^2_{adjusted}$
- significance of partial F-tests (= t-tests) for predictors (especially $[Hg]_{sed}$)
- significance of F-test for regression
- variance inflation factors (VIFs) for predictors < 10
- homoscadastic and normally distributed residuals
- Mallow's C_p statistic not >> number of predictors

Lack-of-fit tests for curvature in response-predictor relationships and interactions between predictors were performed and examined for nonsignificance. Observations having large standardized residuals or large influence on the regression were also considered in model evaluations. The best model was identified based on the overall meeting of these criteria. Both single and multiple predictor models were then examined for the degree to which $[Hg]_{sed}$ predicts $[Hg]_{inv}$, as indicated by the significance of the t-test of the coefficient for $[Hg]_{sed}$.

3.4.2 Prediction of mercury concentrations in receptors

3.4.2.1 Review and selection of biomagnification factors

A review of information on BMFs was conducted using typical methods of electronic database and chain-of-citation searches as well as consultation with leading researchers in the field of mercury ecotoxicology and risk assessment. Details on the methods and the results of the review are described in Appendix A. A summary is provided below.

The search was focused on the period 1996-2002, as a thorough review of the literature was carried out in 1997 by USEPA (1997a,b,c). The information required to estimate mercury concentrations in receptors was obtained by reviewing published literature, unpublished reports, databases, web pages and any other sources of data on BMFs relevant to the benthic invertebrate taxa and receptors; assessing the quality of the BMF data, and; tabulating BMFs and estimates of their variability, together with information on the BMF determinations (e.g., location of study, organisms involved, proportion of receptor's diet that is invertebrates, effects of cofactors (if any), assumed ingestion rates and home ranges). The following criteria were applied to screen

literature to obtain either BMFs or candidate datasets for calculating BMFs, after Suedel et al. (1994) and Gobas and Morrison (2000):

- If organisms that were presented were not from a logical food chain, or no evidence was presented that the feeding relationship between predator and prey was a functional feeding relationship, the data were not used. One exception to this rule was made in selecting a study of mink fed diets of different proportions of contaminated and uncontaminated fish (Halbrook et al. 1997), since there was a reasonable likelihood that these fish species would have been part of their diet.
- Mean concentrations of total Hg or MeHg needed to be presented for both predator and prey, and in comparable units.
- BMFs involving Hg concentrations in feathers or fur of predators were excluded.
- Unless evidence of comparability could be found, studies from non-freshwater systems or with non-comparable species were not used. More information is presented below on the assessment of comparability of different systems and species.

There were few studies that quoted BMF estimates specifically for the receptor species and feeding relationships defined in Figure A1. Of the small number of studies that calculated BMFs which were directly comparable in part to the food chain model, most were from freshwater pelagic food webs. Some were also studies in different ecosystems (marine, temperate montane freshwater, tropic freshwater). Thus, it was necessary to use the most relevant studies to obtain BMFs and document the relative comparability of different species and ecosystems to those presented in the study design for this assessment. Information to support substitutions of receptor with comparable species from the literature (in applying BMF estimates) is presented in Tables A3 – A12. Species were considered the most qualitatively similar when they occupied similar habitats, had similar feeding habits and dietary composition, similar range, similar feeding substrate, and similar food ingestion:body weight ratio. Sources for this information were CCME (1999a), CWS (2002), Sample and Suter (1999), Scott and Crossman (1973), and USEPA (1997c). A breakdown of the number of BMFs obtained/calculated per feeding relationship and the range of corresponding BMF values is presented in Table A1.

3.4.2.2 Calculation of receptor tissue mercury concentrations

It is widely recognized that mercury is transferred through trophic levels primarily in the methyl form (USEPA 1997b). It is also accepted that mercury in the tissues of fishes and higher trophic level organisms is almost entirely in the organic (methyl) form. Environment Canada (2002) states that "total mercury" concentrations in piscivorous fishes are probably ~99% methyl mercury, and note that Bloom (1992) suggests that previous studies reporting methyl mercury fractions in fishes less than 95% were likely in error. Therefore, mercury concentration in receptors were predicted on a MeHg basis, using (a) MeHg measurements in invertebrates and (b) combined THg and MeHg BMF values (assuming that reported THg concentrations largely represent MeHg concentrations).

Concentrations of MeHg (≈ total Hg) in the tissues of receptors were predicted by multiplying measured body concentrations in the resident invertebrates by the food chain multiplier relevant for the receptor:

$$C_{rec} = FCM \times C_{inv}$$

where:

C_{rec} = mean contaminant concentration in the consumer (receptor) species

C_{inv} = mean contaminant concentration in invertebrates

FCM = food chain multiplier

The FCM represents the cumulative biomagnification of a substance from one trophic level to a higher trophic level (USEPA 1997c). Whereas a BMF applies to only one trophic level transfer, a FCM refers to one or more, and may be a multiple of more than one BMF. Thus, FCM = $BMF_1 \times BMF_2 \times BMF_3 \times \ldots \times BMF_n$, where 1, 2, 3,…, n are transfers of one trophic level. The BMFs used to obtain FCMs and calculate C_{rec} values are in Table A1, which shows the low, medium and high BMFs from the literature review for each transfer between trophic levels as shown in Figure A1. In Table 3, the FCM for transfer from benthic invertebrates to each receptor is estimated by multiplying the BMFs for the serial steps from Table A1. Low, medium and high FCM values are obtained from use of all minimum, all medium or all maximum estimates for each BMF. In instances where only a single BMF value is available for a particular

receptor, the low, medium and high FCM is the same. For the trout, heron and mink, it is recognized that they could be trophic level 3 as well as trophic level 4 predators. Therefore, FCMs were estimated for both food chain pathways.

Invertebrate methyl Hg concentrations used in the predictions of Hg in receptors also included two values, one for each taxon. These were used as minimum and maximum observed $[Hg]_{inv}$ for the taxa collected from the site. "Medium" $[Hg]_{inv}$ for the site was calculated as the mean of the two values. Since fish contaminant data are reported for the most part on a wet weight basis, and the guidelines used in this study are also based on wet weights, methyl Hg concentrations in invertebrates were converted to a wet weight basis. Midges and amphipods comprised on average 84.8% and 85.9% water, respectively. The ratio of wet to dry weight was determined for each individual sample submitted for analysis (rather than using an overall average ratio for each taxon). $[Hg]_{inv}$ on a wet weight basis was determined using the following conversion:

$[Hg]_{inv}$ (ng/g dry weight) / (ratio of wet: dry weight) = $[Hg]_{inv}$ (ng/g wet weight)

Total and methyl mercury concentrations in each taxon, converted to wet weights, are shown in Appendix C, Tables C1 and C2.

For each site, minimum, intermediate and maximum concentrations of MeHg for each receptor were predicted by:

$$[Hg]_{rec} = FCM \times [Hg]_{inv}$$

using corresponding low, medium and high $[Hg]_{inv}$ and FCMs. For the lake trout, heron and mink, FCMs for both food chain pathways were combined. From the available values, the lowest and the highest FCMs were used for the minimum and maximum predictions, and the mean of the two medium values was used for the intermediate prediction. The predicted MeHg concentrations in receptors are generic in that they are not specific to particular tissues.

3.4.2.3 Areal averaging of receptor exposure to mercury

Predictions of [Hg] in receptors are made on a per site basis. However, for fish and wildlife receptors, the appropriate spatial and temporal boundaries for assessing potential biomagnification are not the same as those for assessing sediment contaminant concentrations, sediment toxicity and benthic invertebrate communities. Activities of fishes, birds and mammals are not limited to individual sites to the same degree as contaminants and invertebrates. Whereas incorporating invertebrate contaminant bioaccumulation information into the framework works well on a site-by-site basis, fish and wildlife data require some form of spatial averaging or weighting to reflect realistic contaminant exposure conditions. On a per site basis, fish and wildlife biomagnification predictions remain "theoretical" or overly conservative.

One way of addressing the problem is to assess exposure to contaminants across areas of sediment comparable to the foraging areas of the receptors, as suggested by Freshman and Menzie (1996). Their "average concentration with area curve" exposure model involves determining the average concentration of a contaminant for a series of increasing areas of soil, starting with the most contaminated site up to and beyond the foraging area of the receptor of interest. The average contaminant concentration for a section of soil corresponding to the foraging area is then compared to appropriate benchmark adverse effect levels. Exceedence of the benchmark by the average contaminant concentration is considered a potential impact to the receptor individual.

The grid-like array of sampling sites in Jellicoe Cove allows the application of this graphical type of analysis to the study area. Rather than working with soil or sediment concentration, [MeHg] in invertebrates (averaged for midges and amphipods) was used because it is the source of Hg exposure to the receptors. Initially, the spatial boundaries (areas of sediment) represented by each site were defined by Thiessen polygons (Ammon 2000), a commonly used GIS method. Within each polygon, all points are closest to the site enclosed by the boundary. A 75-m "buffer" (radius around sites) was used in the computations to ensure that all space between sites was covered. Sites were then ordered from highest to lowest $[MeHg]_{inv}$, and a graph of mean $[MeHg]_{inv}$ vs. cumulative area was plotted. Mean $[MeHg]_{inv}$ was weighted by the areas of the site polygons. Receptors were conservatively assumed to feed preferentially in the most

contaminated sites. However, the more contiguous these sites are, the more realistic the assumption. It was also assumed (for simplicity) that the distribution of invertebrates across site areas is homogeneous, and that distributions of $[MeHg]_{inv}$ within areas are homogeneous.

Two other types of estimates were made for the analysis: foraging areas of the receptors, and critical (benchmark) concentrations of $[MeHg]_{inv}$. For the former, an allometric model for estimating home ranges of fishes from Minns et al. (1996) was used, where ln(area per fish) = $e^{-10.37}$ + 2.57 ln(length). Maximum lengths for Longnose Sucker, Yellow Perch and Lake Trout were obtained from Coker et al. (2001). Based on maximum lengths of 583, 533 and 1310 mm for sucker, perch and trout, respectively, areas of habitat use per individual were estimated as 428, 340 and 3459 m^2. Critical $[MeHg]_{inv}$ was determined as the concentration which would result in the predicted receptor [MeHg] equalling the tissue residue guideline using the calculation in Sec. 3.4.2.2 (i.e., Critical $[MeHg]_{inv}$ = TRG / FCM). For the fishes, these values were 26.82, 5.36 and 3.53 ng/g ww for sucker, perch and trout, respectively, with the intermediate exposure and uptake scenario and a TRG = 92 ng/g ww (see Sec. 4.5.1). The value for the sucker is close to the upper range of $[MeHg]_{inv}$ for the reference sites: 26.36 ng/g ww. Therefore, 26.82 was selected as a "realistic" critical value.

3.5 Quality Assurance/Quality Control

3.5.1 Field

Four randomly chosen sites (JC4C, JC6C, JC5D and PH14) were designated as QA/QC stations. At these stations, triplicate sediment and water samples were collected for determination of within-site and among-sample variability.

3.5.2 Laboratory

Flett Research Ltd. conducted determinations of total and methyl mercury in sediment and benthic invertebrates. QC evaluation for these procedures included analyses of sample duplicates, matrix spikes and certified reference materials, as well as evaluations of sample recoveries. For sediment, sample duplicates were analyzed at least once every 15 samples, and matrix spikes were performed on every tenth sediment sample to determine mercury recoveries. The NRC certified sediment reference material "MESS-2" was concurrently digested and

analysed for total mercury. For biota, duplicate "DORM-2" reference material, "MQAP fish check samples", and spiked matrix duplicates were analyzed for total and methyl mercury with each lot of 10 - 20 samples. Each of the two invertebrate taxa was represented in the analyses of sample duplicates and matrix spikes.

Caduceon Environmental Laboratory analyzed sediment for total mercury (on a subset of 10 sites), total phosphorus, total nitrogen, total organic carbon, Fe, and Mn. QA/QC procedures involved control charting of influences, standards, and blanks. Reference material was used in each analytical run. Calibration standards were run before and after each run. Run blanks and reference standards were run 1 in 20 samples, while duplicates were run 1 in 10 samples.

An interlaboratory comparison of analyses for total Hg was conducted based on results from Flett and Caduceon laboratories for sediment sub-sampled from the same sample (10 sites only). Data for the 10 sites were compared by regression analysis. The slope of the regression line is a measure of the overall agreement in [THg] determinations, whereas the scatter of points about the line should indicate joint laboratory measurement error.

4 RESULTS

4.1 Quality Assurance/Quality Control

4.1.1 Field

Variability among site triplicates in a measured analyte has three sources: natural within-site heterogeneity in the distribution of the analyte in sediment or water, differences in handling among samples, and laboratory measurement error. Among-triplicate variability indicates the overall "error" associated with quantifying conditions at a site based on a single sample. Variability is expressed as the coefficient of variation (CV = standard deviation / mean × 100). Results for particle size, TOC, TN, TP, Fe, Mn and Hg for the field-replicated stations (JC4C, JC6C, JC5D and PH14) are shown in Appendix D, Table D1. Differences in variability are seen among sites and among the parameters from the same site. Overall, variability among sediment samples is low, with CVs ranging from 1 to 29%, and is not highest at any one site. Variability

is highest for total mercury, with CVs ranging from 12 to 29%. The CVs for total Hg in sediment for this study are similar to those reported by Milani et al. (2002) for replicate ponars taken from the Jellicoe Cove in 2000 (CV range of 4 to 45%).

4.1.2 Laboratory

Data for Flett Research laboratory duplicates and repeat analyses for mercury in sediment and invertebrates are shown in Tables 4 to 6. There is good agreement between sample duplicates and repeats. Mean CVs for duplicate analyses are 8, 9, 16, and 9% for $[THg]_{sed}$, $[THg]_{inv}$, $[MeHg]_{sed}$ and $[MeHg]_{inv}$, respectively. These are lower than those reported for other studies using gas chromatography and cold-vapour atomic fluorescence spectroscopy (Paterson et al. 1998). Repeat analyses, performed for $[MeHg]_{inv}$, have a mean CV of 5%. Recoveries for analyses of sediment and invertebrates samples, matrix spikes and certified reference materials are shown in Tables D2 and D3. Mean recoveries range from 93.9 to 99.3% for the samples, 95.0 to 99.1% for the matrix spikes, and 93.6 to 100.1% for the reference materials. The overall range of spike recoveries (75.9 to113.3%) is comparable to that obtained by Lawrence and Mason (2001), who used similar analytical methods.

Duplicate measurements of sediment metals and nutrients, and corresponding analyses of reference materials for the Caduceon Laboratory are shown in Table D4. The mean relative percent difference between sample duplicate measurements is 3.1% (range: 0 to 14.2%). Recoveries for reference materials range from 90.0 to 103.3% (mean 97.7%).

The inter-laboratory comparison for analyses of total mercury in sediment is described in Appendix D. Results show a strong agreement between measurements: the slope of Flett $[Hg]_{sed}$ vs. Caduceon $[Hg]_{sed}$ is determined to be 1.2. The percent explained variability (r^2) is 87%.

4.2 Mercury Levels

4.2.1 Sediment

4.2.1.1 Total mercury

Flett laboratory

On a dry weight basis, the lowest THg concentrations are found in the reference sediments (range 8 - 169, median 47 ng/g), followed by sediments collected from Arm 1 (range 138 – 1152, median 791 ng/g) (Table 4, Figure 3). The remaining test sites, with the exception of JC2A and JC3A, contain high concentrations of THg, ranging from 2008 to 32160 ng/g. The highest THg concentrations are found in sediments collected from Arms 6 (median/mean 16757 ng/g) and 7 (median 16604 ng/g). In general, lowest concentrations of THg are present in the "A" series stations, while highest THg concentrations are evident in the "B" and "C" series stations (sites 2B,C – 7B,C), and then decrease further out in the Cove (at "D" series stations).

The LEL for THg (200 ng/g) is not exceeded at any of the reference stations, nor at stations 1B (Arm 1), 2A (Arm 2), and 3A (Arm 3), which are located closest to shore in their respective arms. The SEL (2000 ng/g) is exceeded at all remaining test stations with the exception of 1C and 1D. Highest [THg] is noted at 7B and 4B.

Caduceon laboratory

On a dry weight basis, total mercury concentrations in the subset of 10 sites are similar to those reported by Flett (Table 4). Higher Hg values are reported by Caduceon for the reference sites. The greatest difference for exposed sites is noted for 4B, where values are 28094 and 7874 ng/g Hg for Flett and Caduceon laboratory, respectively, a 3.5-fold difference.

4.2.1.2 Methyl mercury

Methyl mercury concentrations (Table 4, Figure 4) are lowest at reference sites, ranging from 0.013 to 0.602 ng/g dry wt (median 0.175 ng/g), followed by sediments collected from Arm 1 (range 0.859 – 4.950 ng/g, median 3.890 ng/g). Methyl mercury at remaining test sites range from 0.281 to 23.700 ng/g (median 9.440 ng/g). The highest concentrations occur at "B" to "D" series stations. The mean fraction of methyl mercury relative to total mercury is 0.29% (95% confidence interval of -0.06 – 0.64%), but at four outlying sites - reference sites PH2, PH11, PH18, and PH21 – the percent methyl mercury is 0.68, 0.71, 1.11, and 1.85%, respectively. Regression analysis on log(x) - transformed data showing the relationship between methyl mercury and total mercury in the sediment is shown in Figure 5. A significant positive

correlation ($r^2 = 0.89$, $P<0.001$) is found between the methyl and total mercury concentrations in the sediment.

4.2.1.3 Comparison of sediment mercury at reference sites to Jellicoe Cove sites

For total mercury (Figure 3), all test sites exceed the maximum reference site concentration, with the exception of 1B and 3A (2A is just slightly above and no data are available for site 6A). Almost all Jellicoe Cove sites are 1-2 orders of magnitude higher in [THg] than the maximum [THg] of the reference sites, with the median of the Jellicoe Cove sites 164× the median of the reference sites.

A similar pattern is observed for methyl mercury (Figure 4). All test sites except two (2A, 3A) exceed the upper maximum of the reference sites. The degree of exceedence is less than that for THg: the median [MeHg] of the Jellicoe Cove sites 52× the median of the reference sites. Site PH22 is markedly high in [MeHg] among the reference sites – almost 3× the next highest [MeHg].

4.2.2 Invertebrates

4.2.2.1 Total mercury

On a whole-body, uncleared-gut basis, midges (chironomids) show a greater range of total Hg concentration (42 – 5172 ng/g, median 1065 ng/g) compared to the amphipods (40 – 2075 ng/g; median 374 ng/g; Table 5). The midges accumulate more total Hg than amphipods at 89% of the sites. Concentrations of THg in amphipods and midges are strongly correlated ($r=0.892$, $P<0.001$).

4.2.2.2 Methyl mercury

The midges also show a greater range of methyl Hg concentration (13 – 533 ng/g, median 47 ng/g) compared to the amphipods (20 – 359 ng/g, median 112 ng/g; Table 6). The amphipods, however, accumulate more methyl Hg than midges at 66% of the sites. The correlation between midges and amphipods for $[MeHg]_{inv}$ is significant ($r=0.688$, $P<0.001$). Relative to other reference sites, markedly high $[MeHg]_{inv}$ is observed at PH15. Concentrations in midges (255

ng/g) and amphipods (130 ng/g) at PH15 are 5.4× and 2.3×, respectively, the next highest reference site $[MeHg]_{inv}$.

4.2.2.3 Comparison of mercury in invertebrates at reference sites to Jellicoe Cove sites

Figures 6 – 9 compare the concentrations of total and methyl mercury in midges and amphipods at Jellicoe Cove sites to concentrations at the reference sites. The 99% percentile values (= maximum value in the present case) for the reference sites are indicated.

Midges – Total Hg 15 of the 25 test sites exceed the maximum reference site concentration (Figure 6). Overall, the lowest total Hg concentration in midges occurs in Arm 1, while the greatest concentration occurs in Arms 5, 6 and 7. Total Hg concentrations in midges from exposed sites range from 0.2 × to 4.0 × the reference site maximum.

Midges – Methyl Hg 4 sites (5A, 6A, 7A and 7B) exceed the maximum reference site concentration (Figure 7). Excluding the outlier site PH15 from the reference group, 17 of the Jellicoe Cove sites exceed the reference maximum. In Jellicoe Cove, the lowest methyl mercury concentration in midges occurs in Arm 2, and the greatest concentration is seen in the "A" sites of Arms 3 – 7 as well as 7B. Methyl Hg concentrations in midges from exposed sites range from 0.08× to 2.1× the reference site maximum.

Amphipods – Total Hg 23 of the 25 test sites exceed the maximum reference site concentration (Figure 8). The lowest total mercury concentration in Jellicoe Cove amphipods occurs in Arm 1, and the greatest concentration is seen in Arms 5, 6 and 7. Total Hg concentrations in amphipods from exposed sites range from 0.9× to 9.7× the reference site maximum.

Amphipods – Methyl Hg 14 of the 25 test sites exceed the maximum reference site (PH15) concentration; without PH15, 24 Jellicoe Cove sites have higher amphipod [MeHg] than the remaining 12 reference sites (Figure 9). Among test sites, the lowest methyl mercury concentration occurs in Arm 1 and 7C. The greatest concentration is seen in amphipods collected from Arms 5, 6 and 7 (same as for total Hg). Methyl Hg concentrations in amphipods from exposed sites range from 0.2× 2.8× the reference site maximum.

4.2.3 Biota-sediment accumulation factors

The BSAFs for total and methyl mercury are shown by area for each taxon in Figure 10. For midges, [THg] at 11 of the 13 reference sites and at 6 test sites, located in Arms 1 (1B, 1D), 2 (2A, 2B), 3 (3A), and 5 (5A), are greater in the tissues than in the sediment. For amphipods, [THg] at 11 reference sites and three test sites, located in Arms 1 (1B), 2 (2A), and 3 (3A), are greater in the tissues than in the sediment. Reference sites have the highest BSAFs for both taxa. In general, the sites that show a BSAF >1 are those with the lowest total mercury concentrations. Methyl mercury accumulates in both taxa to much higher concentrations than that found in sediment at all sites. The greatest accumulation (relative to sediment concentration) occurs at reference sites and at sites in Arms 1 (1B), 2 (2A), and 3 (3A) for both taxa (similar to that observed for total Hg).

4.3 Supplementary Physico-Chemical Conditions of Sediment and Overlying Water

4.3.1 Sediment nutrients

Total phosphorus (TP), total nitrogen (TN), and total organic carbon (TOC) in sediments are shown in Table E1 (Appendix E). Total OC at reference sites range from 0.1 to 2.1% (median 0.7%) and from 0.3 to 10.0% at exposed sites (median 3.8%). Highest TOC is noted at 7C. Total nitrogen ranges from 127 to 2251 μg/g at reference sites (median 634 μg/g) and from 73 to 1316 μg/g at the exposed sites (median 746 μg/g), and TP ranges from 330 to 1084 μg/g at reference sites (median 652 μg/g) and from 283 to 691 μg/g at exposed sites (median 521 μg/g). Whereas reference and Jellicoe Cove sites show similar distributions in TN and TP concentrations, TOC is generally higher and much more variable in Jellicoe Cove than in reference locations (Appendix E, Figure E1).

4.3.2 Sediment particle size

Particle size data for Jellicoe Cove and reference sediments are shown in Table E1 (Appendix E). Sediment in the study area consists mainly of silt (ranging from 1.2 to 73.3%; median 41.6%) and sand (ranging from 6.9 to 92.5%; median 38.1%). Percent clay at exposed sites ranges from 0 to 74.1%, median 12.8%). At reference sites, the median percentage silt (45.8%) and sand (33.1%), is close to that observed at test sites, and the median percentage clay at reference sites

(19.0%) is slightly higher than at test sites. Six of the 25 exposed stations (4A, 7A, 1B, 1C, 2C and 1D) contain gravel (ranging from 0.1 to 14.5%), and three reference sites (PH13, 15, and 26) contain gravel, ranging from 0.7 to 1.4%. Overall, Jellicoe Cove sites contain lower proportions of clay than the reference sites. Sand and silt fractions range over the same values in both groups of sites (Appendix E, Figure E1).

4.3.3 Iron and manganese

Concentrations of iron and manganese and the corresponding provincial LELs and SELs are shown in Table E2 (Appendix E). Iron and Mn are less than LEL at all exposed sites in the study area except for 2A, which is slightly above the LEL for each metal. At the reference sites, the LEL is exceeded at five stations for Fe and four stations for Mn. The SEL is exceeded slightly for Mn at one reference site (PH17). Comparing Fe and Mn concentrations at reference sites and test sites, percent iron is slightly higher at the reference sites, ranging from 0.8 to 3.5% (median 1.4%), and ranging from 1.1 to 2.4% (median 1.3%) at test sites (Appendix E, Figure E1). Manganese concentrations at most reference sites (range 114 to 1160; median 276 μg/g) are higher than that at test sites (range 133 to 488; median 155 μg/g).

4.3.4 Overlying water chemistry

Conditions (pH and conductivity) of overlying water 0.5 m above the sediment (Table E2, Figure E1) are similar at reference and test sites, with overlapping ranges and similar medians for each variable. The ranges of dissolved oxygen, pH, and conductivity are fairly low (2 mg/L, 0.8 pH units and 32 μS/cm, respectively). Dissolved oxygen is ≥12.4 mg/L at all sites.

4.3.5 Site depth/Temperature

The reference sites are deeper than test sites with median depths of 26.9 and 10.8 m, respectively. Depth at exposed sites in Jellicoe Cove range from 4.8 to 16.9 m, and range from 1.2 to 64.8 m at reference sites (Table 1, Figure E1). There is a greater range in temperatures at the reference sites (2.9 to 10°C) compared to test sites (3.4 to 4.2°C), although median temperatures are similar at 3.9 and 3.7°C, respectively.

4.3.6 Total PCBs

Levels of total PCBs in longnose suckers, collected historically from Peninsula Harbour, show levels elevated above the consumption restriction guideline of 500 µg/kg (MOE 2002). From 1978 to 1990, there was a decrease in PCB levels (from 10902 to 1493 µg/kg) in 45 cm longnose suckers collected from Peninsula Harbour. From 1990 to 2002, however, there have been no further reductions, with levels at between 1500-2500 µg/kg. Levels of PCBs in longnose suckers collected from other areas in Lake Superior are a magnitude lower than that observed in Peninsula Harbour, with the most recent levels from each area ranging from 44 to 352 µg/kg (MOE 2002). As a result of these findings and the possible ongoing sources of PCBs to Peninsula Harbour, PCBs were measured in the sediment samples collected from Jellicoe Cove, with results are shown in Appendix E, Table E3.

Aroclor 1260 is the only aroclor detected with certainty in all samples, with concentrations ranging from 0.055 to 0.62 µg/g (median 0.30 µg/g, mean 0.33 µg/g). Generally, higher levels are seen in "C" and "D" series sites with the highest concentration observed at JC5D. All sites, with the exception of JC2B and JC7B are a magnitude above the LEL (0.07 µg/g). The SEL (normalized to % TOC for each site) is not exceeded at any site.

Standard QA/QC procedures included matrix spikes and duplicates (with three aroclors that were also measured in the sediment samples), matrix spikes using surrogate PCBs, and method blanks. Percent recoveries from matrix spikes (performed on samples 4A and 7A) range from 34 to 110 % (mean 75%) (Appendix E. Table E3). Matrix spikes using surrogate compounds (compounds that are similar to the ones that were analyzed) were performed on each sample. Overall percent recoveries range from 43 to 114% (mean 88.6%). Method blanks were all below detection limits.

4.4 Relationships between Mercury Concentrations in Invertebrates and Sediment

4.4.1 Total mercury

Concentrations of total Hg in each invertebrate taxon vs total Hg in sediment are plotted in Figure 11, with fitted regression lines using sediment [THg] alone as the predictor. For both

taxa, the slopes are highly significant ($P \leq 0.001$) and the adjusted r^2 values are 0.716 (midges) and 0.858 (amphipods). Prediction of $[THg]_{inv}$ is moderately improved for both taxa by either Mn and % sand (midges) or TKN and Mn (amphipods) as additional predictors in the model (Table 7). These brought the R^2_{adj} values up to 0.797 and 0.906 for the midges and amphipods, respectively. For both taxa, $[THg]_{sed}$ is the strongest predictor ($P \leq 0.001$). Coefficients for all predictors are positive except for TKN.

4.4.2 Methyl mercury

The relationships between MeHg in invertebrates and MeHg in sediment (Figure 12, Table 7) are weaker than those for total Hg. With $[MeHg]_{sed}$ alone as the predictor, regressions are significant for both taxa ($P=0.026$ and $P<0.001$ for the midges and amphipods, respectively). The r^2_{adj} values are 0.109 (midges) and 0.526 (amphipods). With additional predictors, the regressions account for more variability in $[MeHg]_{inv}$, with R^2_{adj} increasing to 0.342, and 0.713 for the midges and amphipods, respectively. As with $[THg]_{sed}$, $[MeHg]_{sed}$ is the most important predictor of $[MeHg]_{inv}$ in the multiple linear regressions, with $P<0.001$ for both taxa. For the midges, the significant environmental predictors are % sand and % clay; for the amphipods these are TKN, pH and % clay. Coefficients are positive for % sand and % clay, and negative for TKN and pH. Thus, invertebrate MeHg concentrations are influenced by sediment MeHg concentrations, but to a lower extent than $[THg]_{inv}$ is by $[THg]_{sed}$. However, the fact that (a) the models that best predict $[MeHg]_{inv}$ include $[MeHg]_{sed}$ as the most significant term and that (b) the magnitudes and directions of the regression coefficients are more or less stable across various models, suggest real relationships between $[MeHg]_{inv}$ and $[MeHg]_{sed}$. Relationships between $[MeHg]_{inv}$ and $[THg]_{sed}$ were also examined and found to be slightly stronger than the $[MeHg]_{inv}$ - $[MeHg]_{sed}$ ones. With $[THg]_{sed}$ alone as the predictor, regressions are significant for the midges ($P=0.013$) and amphipods ($P<0.001$), with R^2_{adj} values = 0.139 and 0.597, respectively.

4.5 Predictions of Methyl Mercury Concentrations in Receptors

4.5.1 Presentation of model outcomes

Predicted concentrations of methyl mercury in each receptor species at each sampling site, calculated by multiplying observed methyl mercury concentrations in invertebrates (wet weight values from Appendix C, Tables C1 and C2) by the appropriate FCMs (from Table 3), are shown in Table 8 and Figures 13 to 15. Receptor MeHg concentrations are presented separately for "minimum", "intermediate" and "maximum" levels of mercury exposure and uptake scenarios. In each of three series of subfigures, predicted $[Hg]_{rec}$ for five receptors are presented in (a) bar charts to compare reference and Jellicoe Cove sites, and (b) simplified maps to show spatial patterns of $[Hg]_{rec}$ for Jellicoe Cove sites. In the bar charts, which have the same logarithmic scales in all figures and subfigures, two criteria concentrations are marked: (1) the maximum of the predicted $[Hg]_{rec}$ for the reference sites, and (2) tissue residue guideline (TRG) for the fishes. Exceedences of criteria are summarized in Table 9. In the maps, the areas of the solid circles denoting Jellicoe Cove site locations are proportional to the predicted $[Hg]_{rec}$. The legend next to the Lake Trout map scales circle sizes to $[Hg]_{rec}$ and applies to all five maps within the series. Scaling in the legends differ among series. Site circles are also coloured to indicate exceedences of criteria: blue = $[Hg]_{rec}$ < maximum for ref. sites *and* $[Hg]_{rec}$ < TRG; green = TRG < $[Hg]_{rec}$ < maximum for ref. sites; dark yellow = maximum for ref. sites < $[Hg]_{rec}$ <TRG; red = maximum for ref. sites < $[Hg]_{rec}$ *and* TRG < $[Hg]_{rec}$. For the heron and mink, only green ($[Hg]_{rec}$ < maximum for ref. sites) and red (maximum for ref. sites < $[Hg]_{rec}$) categories are used.

The tissue residue guideline applies only to the fish receptors. It refers to the concentration of MeHg in the diets of wildlife that consume aquatic biota. The TRG used for MeHg is the lowest of the reference concentrations derived by Environment Canada (2002) for the protection of wildlife receptors in the AOC that consume aquatic biota: 92 ng/g ww. This pertains to the American mink (table 12 of Environment Canada 2002). The recommended TRG for the protection of *all* wildlife species —33 ng/g ww — is not considered appropriate because it is based on the reference concentration for Wilson's Storm Petrel, which is not native to the Peninsula Harbour area.

4.5.2 Exceedences of criteria

Methyl Hg – minimum The low predictions of $[MeHg]_{rec}$ in all receptors result in 9 of 25 Jellicoe Cove sites exceeding those for the reference sites (Figure 13). Of the exposed site predictions, the number of sites at which the predicted $[MeHg]_{rec}$ exceeds the TRG is 4 for the sucker, 20 for the perch, and 4 for the trout. In comparison, only 2 exceedences of the TRG (for perch) are predicted for receptors at reference sites.

Methyl Hg – intermediate The intermediate predictions of $[MeHg]_{rec}$ in all receptors result in 7 of 25 Jellicoe Cove sites exceeding those for the reference sites (Figure 14). Of the exposed site predictions, the number of sites at which the predicted $[MeHg]_{rec}$ exceeds the TRG is 7 for the sucker, and 25 for both the perch and trout. In comparison, reference site exceedences of the TRG are predicted at 0 sites for the sucker, 3 sites for the perch and 7 sites for the trout.

Methyl Hg – maximum The maximum predictions of $[MeHg]_{rec}$ in all receptors result in 6 of 25 Jellicoe Cove sites exceeding those for the reference sites (Figure 15). Of the Jellicoe Cove predictions, the number of sites at which the predicted $[MeHg]_{rec}$ exceeds the TRG is 10 for the sucker and 25 for both the perch and trout. In comparison, reference site exceedences of the TRG are predicted at 1 site for the sucker, 4 sites for the perch and all 13 sites for the trout.

4.5.3 Overall patterns

Beyond the comparisons of predicted $[MeHg]_{rec}$ for exposed sites to reference sites and to the TRG, patterns are evident in the differences in predicted $[MeHg]_{rec}$ among the five receptors, and among the three exposure and uptake scenarios.

Among receptors Predicted $[MeHg]_{rec}$ generally increases with the trophic level of the receptor, with differences of 4 – 50× between sucker and heron or mink predictions (Table 8, Figures 13 – 15). Consequently, the number of sites at which $[MeHg]_{rec}$ exceeds the TRG, and the amount by which the TRG is exceeded, increases with the trophic level of the receptor. However, the number of exposed sites at which predicted $[MeHg]_{rec}$ exceeds the maximum of reference site concentrations is the same among receptors. This is because within a series (i.e., any of the minimum/ intermediate/ maximum groups), $[MeHg]_{rec}$ all derive from the same

$[MeHg]_{inv}$ values. Differences among predicted $[MeHg]_{rec}$ values reflect differences among uptake pathways in the FCMs from Table 3. The pattern of variability among sites is the same for all receptors within a scenario (i.e., the $[MeHg]_{rec}$ values are fully correlated among receptors).

Among exposure and uptake scenarios Looking at differences between the minimum, intermediate and maximum exposure and effect scenarios for the same receptor, predicted $[MeHg]_{rec}$ ranges 2-67×. The number of Jellicoe Cove sites for which $[MeHg]_{rec}$ values exceed the TRG increases from minimum to maximum scenario. In the minimum predictions, only a few Jellicoe Cove and 2 reference site $[MeHg]_{rec}$ values exceed the TRG, except for the perch, for which 20 Jellicoe Cove sites exceed the TRG. In the intermediate scenario, 7 sites based on sucker, and 25 of 25 sites based on perch and trout have $[MeHg]_{rec}$ greater than the TRG. The reference sites exceedences are 0 for sucker, 3 for perch and 7 sites for the trout. In the maximum scenario, 10 sites based on sucker, and 25 of 25 sites based on perch and trout have $[MeHg]_{rec}$ greater than the TRG, while the reference sites exceedences are 1 for sucker, 4 for perch and 13 sites for the trout (Table 8).

4.5.4 Areal averaging of receptor exposure to mercury

Boundaries of Jellicoe Cove sites, as defined by Thiessen polygons, are shown in Figure 16. The "average concentration with area" curve in Figure 17 shows how the average invertebrate [MeHg] to which a receptor would be exposed declines as it forages through an increasingly greater number of sites, starting from the most (site 7B) to the least (site 1D) contaminated. Initially, the mean $[MeHg]_{inv}$ drops from over ~ 60 ng/g ww for the 3 most contaminated sites, to < 45 ng/g for the 5 most contaminated sites. After that, the decline to ~ 20 ng/g ww is less steep and relatively even as additional sites are included in the averaging. For comparison, the sites with the lowest mean $[MeHg]_{inv}$ (1D, 7C, 3D and 2D) ranged from 7.7 to 10.1 ng/g ww (on a per site basis; Table C2).

The estimated areas of habitat use by the three fish receptors are much smaller than the sampling area, and smaller than nearly all sites areas. The maximum individual foraging area of Lake Trout (0.35 ha) was greater than only three Jellicoe Cove sites. If a receptor foraged

preferentially in the most contaminated sites, as is conservatively assumed for the "average concentration with area" curve (Figure 17), it would have to feed over an area greater than 9.2 ha to be exposed to a mean $[MeHg]_{inv}$ less than the critical concentration of 26.8 ng/g ww. Because sucker, perch and trout are expected to feed over much smaller areas, "dilution" of MeHg from the most contaminated sites is minimal and the potential exposure to MeHg from invertebrates could be high.

DISCUSSION

5.1 Mercury Concentrations in Jellicoe Cove Sites relative to Reference Sites

5.1.1 Sediment

Concentrations of total Hg in the upper 10 cm layer of sediment sampled in 2002 from all Jellicoe Cove sites are much greater than [THg] in sediment from references sites, with the exception of JC1B, JC2A and JC3A (Figure 3). The maximum $[THg]_{sed}$ observed in exposed sites is 32160 ng/g dry weight, and most concentrations are ≥ 2000 ng/g (=SEL), compared to 8 – 170 ng/g for the reference sites. The reference concentrations compare to background concentrations of 10 – 700 ng/g for the Great Lakes, and Jellicoe Cove concentrations are higher than concentrations of up to 3200, 15000 and 5568 ng/g for contaminated sites in the Niagara River (Ontario), St. Clair River (Ontario), and St. Lawrence River (at Cornwall, Ontario), respectively (Environment Canada 1997; Grapentine et al. 2003). The CCME (1999b) freshwater sediment quality guideline (Probable Effect Level) for THg is 486 ng/g. In the Jellicoe Cove sampling area, contamination is lowest closest to shore (Arm 1 and "A" sites in Arms 2 – 7, and highest at the "B" and/or "C" sites in Arms 2 – 7. $[THg]_{sed}$ then decreases at the "D" sites farthest from shore (but not to less than that seen closest to shore). At sites 1B, 2A, and 3A, $[THg]_{sed}$ is similar to the higher reference site values. For MeHg, the same general pattern is observed (Figure 4) as for THg. $[MeHg]_{sed}$ is strongly related to sediment $[THg]_{sed}$ (Figure 5), with [MeHg] making up an average of 0.29% of the [THg]. The [THg] in the 0 – 10 cm layer of sediment in Jellicoe Cove sediments from the 2000 surveys (range < 15 to 32000 ng/g dw), are similar to that seen in the present study. The spatial pattern of these results is strong evidence for a local (as opposed to regional) source of Hg to the Cove.

5.1.2 Benthic invertebrates

Both THg and MeHg are taken up by the two invertebrate taxa assessed. Biota-sediment accumulation factors (based on whole-body, uncleared-gut concentrations) are >1 for 11 of 13 reference sites and for sites located in Arms 1, 2, 3, and 5 for THg, and for all 38 sites for MeHg. The BSAFs range up to ~ 12 for THg and to ~ 1500 for MeHg (excluding outliers, Figure 10). Midges have slightly higher BSAFs and [Hg] than amphipods. Tremblay et al. (1996b), in a study of two reservoirs and a natural lake in Quebec, reported BSAFs for detritivorous insects to be 1.9 – 2.8 for THg (similar to the current study) and 5.2 – 22.6 for MeHg (much lower than the current study).

Gut contents were included in the mercury analyses of the invertebrates, which could obscure true BSAFs. As the amount of sediment in the gut increases, the measured BSAF will converge to 1. A true BSAF < 1 will be overestimated because the concentration in the sediment is greater than the tissue concentration, whereas a true BSAF >1 will be underestimated because sediment concentrations are lower than that found in the tissue (Bechtel Jacobs 1998).

In general, $[Hg]_{inv}$ for the Jellicoe Cove sites are several fold the $[Hg]_{inv}$ for the reference sites: the Jellicoe Cove-to-reference site ratios of median values are 9.9 – 16× for THg and 2.7 – 4.8× for MeHg. Fewer exceedences by individual Jellicoe Cove sites of the maximum (=99th percentile) of the reference sites are observed for MeHg (4, 14 sites) than for THg (15, 23 sites) due to an outlier reference site (Section 4.2.2.2, Figures 7 and 9). At this reference site (PH15, in Carden Cove near the town of Marathon), both midges and amphipods accumulate more MeHg than at other reference sites although sediment [MeHg] and [THg] are not unusually high. Among reference sites, PH15 is distinct in several of the physico-chemical conditions measured in sediment and overlying water samples. The site is lowest in TOC, TKN and TP concentrations and second highest in % sand in sediment. In the multiple regression models for predicting $[MeHg]_{inv}$, % sand and TKN are highly significant ($P \leq 0.002$) predictors: % sand is positively correlated with [MeHg] in midges; $[TKN]_{sed}$ is negatively correlated with [MeHg] in amphipods (Table 7). Thus, low nutrient and sandy sediments may account for the unusually high $[MeHg]_{inv}$ at PH15, and unless a water-borne source of Hg can be identified in the Carden Cove area the site appears to indicate an upper end of MeHg bioaccumulation under natural

conditions along the north shore of Lake Superior. Evaluation of QA/QC information and the fact that the high $[MeHg]_{inv}$ was determined in both taxa suggest that the values are not artefacts. A similar situation was observed in Clear Lake, CA by Suchanek et al. (2000), where [MeHg] was anomalously high in invertebrates at a site distant (~17 km) from the source of inorganic Hg. The authors suggested this was due to either (1) high *in situ* production of MeHg at the site (which was low in inorganic Hg concentrations) or (2) transfer to the site by wind-driven currents of MeHg produced in an area of high inorganic mercury levels.

5.2 Effects of Mercury in Sediment on Mercury in Invertebrates

Mercury concentrations in midges and amphipods from Jellicoe Cove and reference sites are significantly influenced by Hg in sediment (Table 7, Figures 11 and 12). The relationship is stronger for THg than for MeHg. In the single predictor models, $[THg]_{sed}$ accounts for 72 and 86% of the variability in $[THg]_{inv}$, whereas $[MeHg]_{sed}$ accounts for 11 and 53% of the variability in $[MeHg]_{inv}$. For both forms of Hg, the amphipod regressions are tighter than those for the midges. In the multiple predictor models, the amount of variance explained increases, but in all cases $[Hg]_{sed}$ is the most significant predictor of $[Hg]_{inv}$. These results clearly suggest that Hg in sediment is an important source of Hg to the invertebrates.

Concentrations of Hg in the benthic invertebrates were measured without clearing their guts. Thus, a fraction of the observed $[Hg]_{inv}$ could include sediment-bound Hg in the gut. While this is relevant for assessing uptake of Hg by predators of invertebrates, which consume whole organisms, it also contributes to the strong $[THg]_{sed}$ to $[THg]_{inv}$ relationship. Concentrations of THg in sediment are generally 2 – 3 orders of magnitude greater than those for MeHg, and they vary more among sites. Therefore, it is not surprising that the $[THg]_{sed}$ - $[THg]_{inv}$ relationship is stronger than the $[MeHg]_{sed}$ - $[MeHg]_{inv}$ relationship.

Several other studies report similarly significant relationships between [Hg] in sediment and [Hg] in benthic invertebrates. Bechtel Jacobs (1998) reviewed data from 15 studies of [Hg] in freshwater benthic invertebrates and sediment. In 13 of these, invertebrate guts were not cleared. Slopes of $\log[THg]_{inv}$ vs. $\log[THg]_{sed}$ regressions were 0.327 ± 0.246 (mean ± S.E.), and the

mean r^2 was 0.12. Slopes for the Peninsula Harbour sites are 0.431 and 0.376. Tremblay et al. (1996b) found a correlation between [MeHg] in midges and $[MeHg]_{sed}$ of r=0.78 (P<0.005, n=18) for a series of Quebec lakes, compared to r=0.11 (P=0.026, n=38) for midges in the present study. Sediments of Tremblay et al. (1996b) and Bechtel Jacobs (1998) were much less contaminated with Hg (≤ 350 ng/g dw THg; ≤ 1.6 ng/g dw MeHg) than the Jellicoe Cove sites, however. In an assessment of bioaccumulation by midges and amphipods from Hg-contaminated and reference sediments in the St. Lawrence River (at Cornwall) (Grapentine et al. 2003) using the same methods as the current study, agreement between studies for $\log[Hg]_{inv}$ vs. $\log[Hg]_{sed}$ regressions is strong. The corresponding slope coefficients (Cornwall / Peninsula Harbour) are:

- THg in midges = 0.570 / 0.431,
- THg in amphipods = 0.284 / 0.376,
- MeHg in midges = 0.160 / 0.163,
- MeHg in amphipods = 0.334 / 0.300.

In multiple linear regressions, there are also consistencies between studies in the signs of the physico-chemical co-predictors and their relative significance. Overall, the Cornwall models explain less variation in $[Hg]_{inv}$ than those for Peninsula Harbour; however, sediments in the latter AOC are higher in [Hg] than the former.

5.3 Predicted Mercury Concentrations in Receptor Species

5.3.1 Integration of prediction outcomes

Models involving a range of biomagnification conditions were used to predict potential [MeHg] in receptors. Five receptor species were considered to encompass the trophic levels linking sediments to the top predators, where biomagnification is expected to be greatest. Three levels of dietary exposure and trophic transfer of Hg were assumed: minimum and maximum scenarios to bracket the range of potential outcomes and an intermediate scenario to characterize "average" conditions. Conclusions determined from overall evaluations of the model outcomes should consider:

- $[MeHg]_{rec}$ for exposed sites compared to $[MeHg]_{rec}$ for references sites;

- $[MeHg]_{rec}$ relative to the TRG;
- How many receptors are predicted to exceed the criteria at each site;
- How many of the exposure and uptake scenarios result in exceedences.

On the whole, about a third (6 – 9) of the Jellicoe Cove sites are predicted to have $[MeHg]_{rec}$ higher than the maximum reference site $[MeHg]_{rec}$ (Figures 13 – 15). However, this proportion would be a majority if the outlyingly high prediction for reference site PH15 was discounted. Exceedences of TRGs are the rule rather than the exception for Jellicoe Cove sites. Whereas minimum predictions are mostly below TRGs (perch being the exception), intermediate and maximum predictions for $[MeHg]_{rec}$ are almost all elevated above the TRG. [MeHg] in sucker is predicted as elevated above the TRG for up to 10 sites.

The TRG applies to concentrations of MeHg in fishes, and are for the protection of wildlife consumers of fishes. Some data are available for direct evaluation of the predicted tissue mercury levels for heron and mink. Wolfe et al. (1998) reviewed THg and MeHg toxicity and tissue residue data associated with adverse effects for birds and mammals. (As noted above, nearly all mercury in fishes and higher trophic level animals should be in the methyl form.) For white heron, liver concentrations > ~6000 ng/g ww THg correlated with chronic adverse effects. A conservative residue threshold for major toxic effects in water birds was concluded to be 5000 ng THg/g ww in liver. For mink, a similar criterion of 5000 ng/g ww MeHg in muscle or brain was suggested. This value of 5000 ng/g corresponds to 3.7 on the log-scales in Figures 13 to 15. Based on the maximum exposure and uptake scenario, this benchmark is exceeded at 3 Jellicoe Cove sites in for the great blue heron, and 8 Jellicoe Cove and 1 reference site for the mink (Table 8).

The more critical outcome of the evaluation is whether or not the predicted $[MeHg]_{rec}$ values for exposed sites exceed the appropriate TRG *and* exceed the reference site maximum $[MeHg]_{rec}$. For the sucker, 4 – 7 exposed sites are predicted to result in such "hits", depending on the exposure and uptake scenario. Perch $[MeHg]_{rec}$ predictions result in 6 – 9 hits, while trout $[MeHg]_{rec}$ predictions result in 4 – 7 hits. Among all predictions, a group of sites in the southeastern section of Jellicoe Cove is consistently indicated to exceed both reference site

conditions and TRGs (coded as red site symbols in Figures 13-15): the inner "A" sites of Arms 3, 5, 6 and 7; and sites 7B, 6B and 6C. (See Figure 2 for site labels.)

5.3.2 Uncertainty in the prediction of mercury concentrations in receptors

The prediction of the potential transfer of mercury from benthic invertebrates to the trophically linked receptor species involves several simplifying assumptions, each of which is associated with some degree of uncertainty in its relevance to conditions in Jellicoe Cove. While it is beyond the scope of this study to quantify these uncertainties, those considered most important are identified here.

Assumptions regarding the modelling of Hg biomagnification include those dealing with the exposure of the receptors to Hg, and those dealing with the effects of Hg on the receptors. Regarding the latter category, some of the sources of uncertainty discussed by USEPA (1997c) could apply to the present study:

- validity of the biomagnification model,
- variability of the calculated BMFs and FCMs,
- selection of the receptors of concern,
- trophic levels at which receptors feed,
- limitations of the toxicity database (with respect to the determination of TRGs), and
- effects of environmental cofactors and multiple stressors.

Among these sources, the greatest contributor to uncertainty in predicting the trophic transfer of mercury could be the large range in the selected BMF and FCM values. These range over 1 – 1.5 orders of magnitude between lowest and highest, and include all BMFs judged to be potentially applicable to the Peninsula Harbour AOC. Further validation of their relevance would require field studies beyond the scope of this assessment. Owing to limitations of the available data and the desire to minimize assumptions about the distributions of the data, a probabilistic approach was not applied to predict receptor mercury concentrations. Rather, low, medium and high FCMs were used to define the range of possible outcomes and intermediate values that "balance" the minimum and maximum rates of biomagnification. Another problem

inherent in the literature-derived BMF data is the difficulty in assigning prey and predator species to discrete trophic levels due to omnivory. When omnivory is integrated with a continuous measurement of trophic position (e.g., using stable isotope methods), estimates of BMFs will generally be higher for each discrete trophic level (Vander Zanden and Rasmussen 1996). Correct determination of trophic levels is also limited by how well the composition of a predator's diet is quantified. Often the information necessary to clearly establish this is not available in the published studies.

Another potentially large source of uncertainty in predictions of $[MeHg]_{rec}$ relates the exposure of receptors to Hg. These assumptions (listed in Section 2.4.3) are recognized as being conservative and limited in their representation of natural conditions. Spatial (and perhaps temporal) heterogeneity in the distribution of THg and MeHg throughout the study area, and aspects of receptor ecology challenge the maximum exposure scenario. A particularly important source of uncertainty could be the assumption of 100% residency of all consumers in the food chain on each site. The degree to which this assumption is unrealistic is proportional to the size of the foraging areas of the receptor species relative to the area of contaminated sediment. Given that the sampling sites could be on the order of 10 × 10 m to 100 × 100 m (= 0.01 to 1.0 ha), the 100% residency assumption is likely unrealistic, at least for the heron and mink. According to data compiled in the Wildlife Exposure Factors Handbook (USEPA 1993), feeding territory sizes for great blue heron range from 0.6 ha to 0.98 km^2, and distances they travel from heronry to foraging grounds range from 1.8 to 8 km. Home range sizes of mink are reported as 7.8 to1626 ha, and 1.85 to 5.9 km of stream/river. These foraging/home range areas substantially exceed the site boundaries of this study. If areas outside of Jellicoe Cove are not equally Hg-contaminated, the actual $[MeHg]_{rec}$ would be lower than those predicted by the models.

The application of tissue Hg residue data that are associated with adverse effects in other studies to evaluate potential risks to the receptors in the present study carries some uncertainty. The data come from different tissues, species, environmental conditions and study types (e.g., field vs. lab). In addition, Hg detoxification and a possible ameliorative effect of dietary selenium may contribute further uncertainty in the extrapolation of results from one set of conditions to another (USEPA 1997c). The TRGs also typically include uncertainty factors. For example, the MeHg

reference concentration (92 ng/g wet wt) incorporates an uncertainty factor of 5 (Environment Canada 2002). Considering these uncertainties and the generally conservative ("worst case") assumption of the trophic transfer model, quantifying the probability that mercury from sediments in Jellicoe Cove could cause adverse effects to specific receptors is difficult. However, even assuming minimum invertebrate Hg burdens and minimum BMFs does not rule out potential risk at some sites.

5.3.3 Observed mercury levels in receptors from Peninsula Harbour

Comparisons with observed [Hg] in fishes, heron and mink from the Peninsula Harbour AOC are potential means of validating the predicted $[MeHg]_{rec}$. Although fish and wildlife receptors may not feed as assumed by the prediction model (i.e., focus on single sites), and exposure histories can be difficult to determine, sources of mercury from beyond Jellicoe Cove should be low and contribute little to receptor mercury burdens, because expected foraging areas (at least for the fishes) are substantially smaller than the Jellicoe Cove area (Sec. 4.5.4). Measured [Hg] in recently sampled receptors indicate actual, as opposed to potential, biomagnification.

The most recent surveys of sport fish contaminant levels include collections of Longnose Sucker and Lake Trout from the Peninsula Harbour AOC in 1997 and 2002 (MOE 2002). Concentrations of THg in suckers adjusted for 45 cm length are reported as 630 and 640 ng/g ww for 1997 and 2002, respectively. Concentrations of THg in trout adjusted for 50 cm from the AOC are reported as 140 and 220 ng/g ww for 1997 and 2002, respectively. The measured sucker [THg]s substantially exceed the highest maximum-scenario prediction of 257 ng/g ww (site 6A), while the observed trout values correspond to the higher minimum-scenario and lower intermediate scenario predicted [THg]. Higher Hg levels in sucker than in trout could result from the fact that suckers are more associated with sediments in diet and habit than the trout (Scott and Crossman 1973), and likely have more restricted habitat use areas (Minns et al. 1996).

Observations of [MeHg] in receptor species residing in the Peninsula Harbour AOC suggest that mercury does accumulate in tissues of higher trophic level members of aquatic food webs. It is also evident that the receptor MeHg concentrations predicted from the screening level approach of this assessment are not overshooting actual tissue levels for sucker and trout.

5.4 Potential Risk of Adverse Effects of Mercury due to Biomagnification from Sediment

Concluding that mercury originating from contaminated sediment could concentrate in the food web at levels that can cause adverse effects depends on establishing that:

(1) mercury in invertebrates from sites potentially exposed in the past to industrial effluents is elevated relative to concentrations in invertebrates from reference sites;

(2) mercury in invertebrates is related to mercury in sediment; and

(3) predicted levels of mercury in receptors at exposed sites that exceed levels in receptors at reference sites also exceed the TRG.

Results show that at most of the Jellicoe Cove sites THg and, to a lesser degree (especially for the midges), MeHg in both invertebrate taxa are significantly higher than concentrations for the reference sites (Figures 6-9). Measured mercury concentration in invertebrates is related to mercury concentration in sediment for both THg and, importantly, the more biologically available MeHg (Figures 11-12, Table 7). While $[MeHg]_{sed}$ is statistically predictive of $[MeHg]_{inv}$ for both taxa, the effect is not large for the midges. Alone, $[MeHg]_{sed}$ shows a relationship to $[MeHg]_{inv}$ for both taxa; however, the addition of other predictors (sediment and overlying water) improves the relationship (Table 7). This it noteworthy because MeHg is the form important to the biomagnification process. Regarding the trophic transfer modelling, *all* Hg-exposure scenarios predict $[Hg]_{rec}$ for a group of at least six sites in Jellicoe Cove to exceed TRGs and the maximum $[Hg]_{rec}$ for the reference sites. In some of the modelling scenarios, this group involves nine sites (Figures 13-15). These sites can therefore be considered potentially at risk to adverse effects of mercury due to biomagnification from sediment.

5.5 Risk Reduction

The potential for adverse effects to receptors of Hg due to biomagnification from sediment would be eliminated if Hg levels in invertebrates were reduced to concentrations below which feeding fishes do not accumulate Hg to levels greater than the TRG. For an assumed benchmark concentration of MeHg in invertebrates = 26.8 ng/g ww (Sec. 3.4.2.3), six sites (7B, 6A, 5A, 7A,

6C and 3A) have $[MeHg]_{inv}$ higher than the benchmark, and are thus candidates for remediation. Because individual receptor fishes are expected to forage within a site, averaging across sites should not give a better estimate of exposure to Hg. However, bird and mammal receptors could be expected to feed on fishes from multiple sites. Therefore, application of the "average concentration with area" analysis is warranted to assess exposure to Hg. Assuming the same critical $[MeHg]_{inv}$ (26.8 ng/g ww) for fish-eating birds and mammals, how many sites would need to be Hg-reduced to bring down the average $[MeHg]_{inv}$ below the benchmark? If the sediment of a site could be remediated so that the $[MeHg]_{inv}$ was lowered to a background level of 10 ng/g ww (which is greater than the all reference site values [except that for PH15] and lower than almost all Jellicoe Cove site values), the effect on the "average concentration with area" curve of serially remediating the 10 most contaminated sites is shown in Figure 18. It is apparent that if the $[MeHg]_{inv}$ in the 6 most contaminated sites is reduced to 10 ng/g ww, all areal mean $[MeHg]_{inv}$ to which a receptor could be exposed would be less than the critical value of 26.8 ng/g ww.

6 CONCLUSIONS

The purpose of the study was to determine if mercury could potentially be transferred from sediments through benthic invertebrates to fish or wildlife in Jellicoe Cove, Peninsula Harbour. This was addressed by:

A. Determining if THg and MeHg are bioaccumulated by benthic invertebrates to higher concentrations in Jellicoe Cove sites than in unexposed reference sites;
B. Testing if concentrations of THg and MeHg in invertebrates are related to concentrations in sediment; and
C. Predicting if concentrations of MeHg in consumers of benthic invertebrates and their predators (i.e., trophically linked receptor species) reach levels associated with adverse effects.

The main findings of the study are:

A. Total and methyl mercury concentrations in sediment at the majority of sites exposed to historical industrial discharges are substantially higher than those at reference sites. The maximum $[THg]_{sed}$ observed in Jellicoe Cove sites is 32160 ng/g dw, and most concentrations are ≥ 2000 ng/g, compared to 8 – 170 ng/g for the reference sites. Methyl mercury levels range up to 21.7 ng/g dw in Jellicoe Cove, and up to 0.60 ng/g dw at reference sites. **The spatial pattern of these results is strong evidence for a local (as opposed to regional) source of Hg to the Cove.**

B. Total mercury concentrations in invertebrates (midges, amphipods including gut contents) are higher at the majority (15 – 23 out of 25) of Jellicoe Cove sites relative to the reference sites. Methyl mercury concentrations in amphipods are higher in 14 Jellicoe Cove sites, whereas midge [MeHg] exceeds the maximum for reference sites at 4 of 25 Jellicoe Cove sites. **This indicates that Hg is bioaccumulated by benthic invertebrates in Jellicoe Cove to a greater degree than in uncontaminated reference sites.**

C. Concentrations of total mercury in sediment are strongly predictive of concentrations in amphipods and midges. **This suggests that sediment [THg] affects invertebrate [THg].** Methyl mercury in sediment is significantly predictive of methyl mercury in amphipods and midges, but less so than in the total mercury relationship. **This suggests that sediment [MeHg] affects invertebrate [MeHg].**

D. In Jellicoe Cove, the proportion of sites predicted to have $[MeHg]_{rec}$ higher than the maximum reference site $[MeHg]_{rec}$ is about a third (6-9 sites). Almost all sites potentially have receptor [MeHg] elevated above the TRG for the protection fish-consuming wildlife for one or two of the three fish receptors. **Among all predictions, $[MeHg]_{rec}$ for a group of seven nearly contiguous sites in the southeastern section of Jellicoe Cove is consistently indicated to exceed both reference site conditions and TRGs.**

A group of seven sites are potentially at risk of adverse effects of mercury due to biomagnification from sediment. However, the likelihood of realizing the degree of mercury biomagnification predicted for the receptor species is not clear, due to uncertainties associated

with predicting receptor [MeHg] values and conservative assumptions of the assessment. Reducing uncertainty in the predictions of mercury biomagnification in Jellicoe Cove would be best achieved by identifying a more narrow range of appropriate BMFs, and by quantifying the actual exposures of receptors to dietary mercury. Reduction of Hg in invertebrates from the six most contaminated sites to local background concentrations would reduce overall exposure of dietary Hg to receptors from Jellicoe Cove to below levels predicted to result in biomagnification above the TRG.

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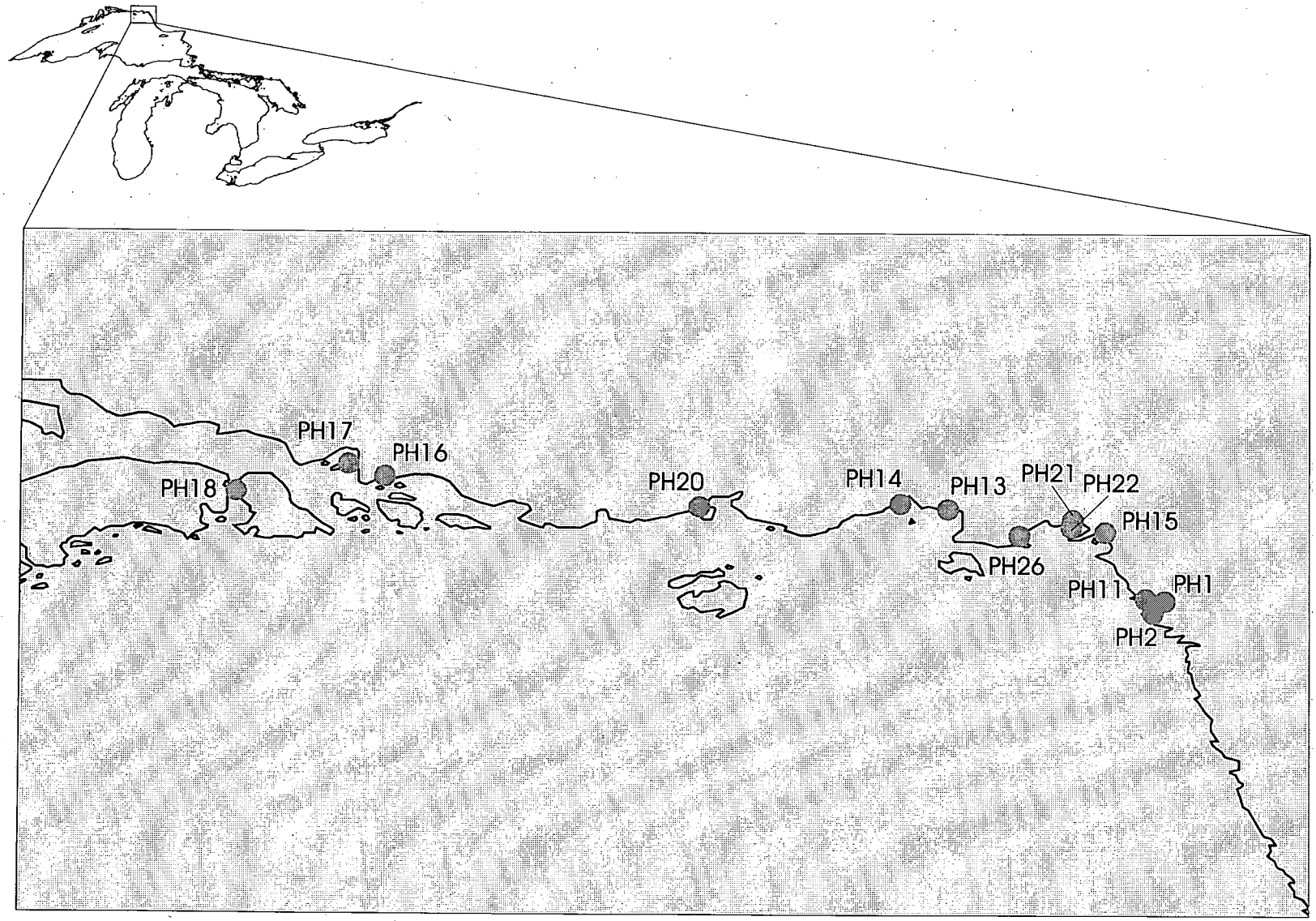

Figure 1. Reference invertebrate and sediment sampling locations.

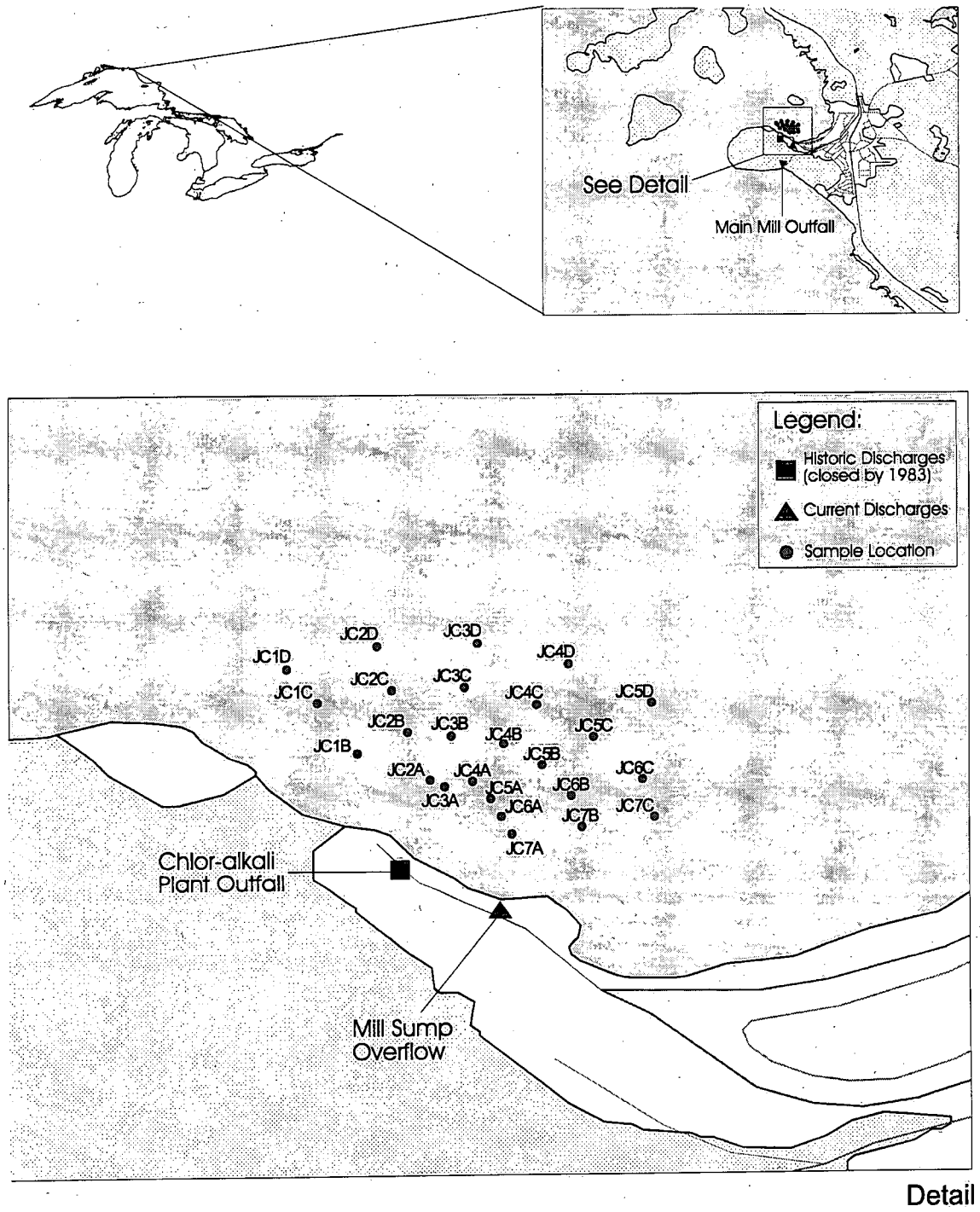

Figure 2. Invertebrate and sediment sampling locations in Jellicoe Cove, Peninsula Harbour.

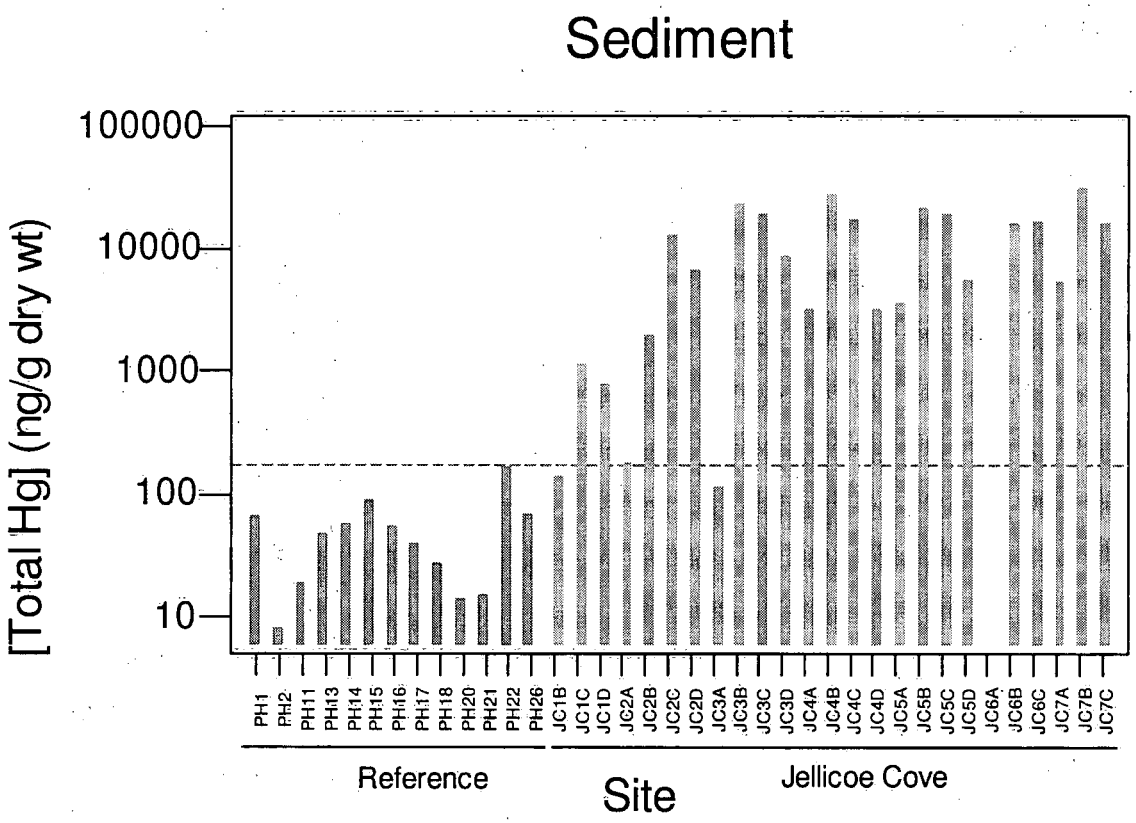

Figure 3. Total mercury concentration in sediment (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

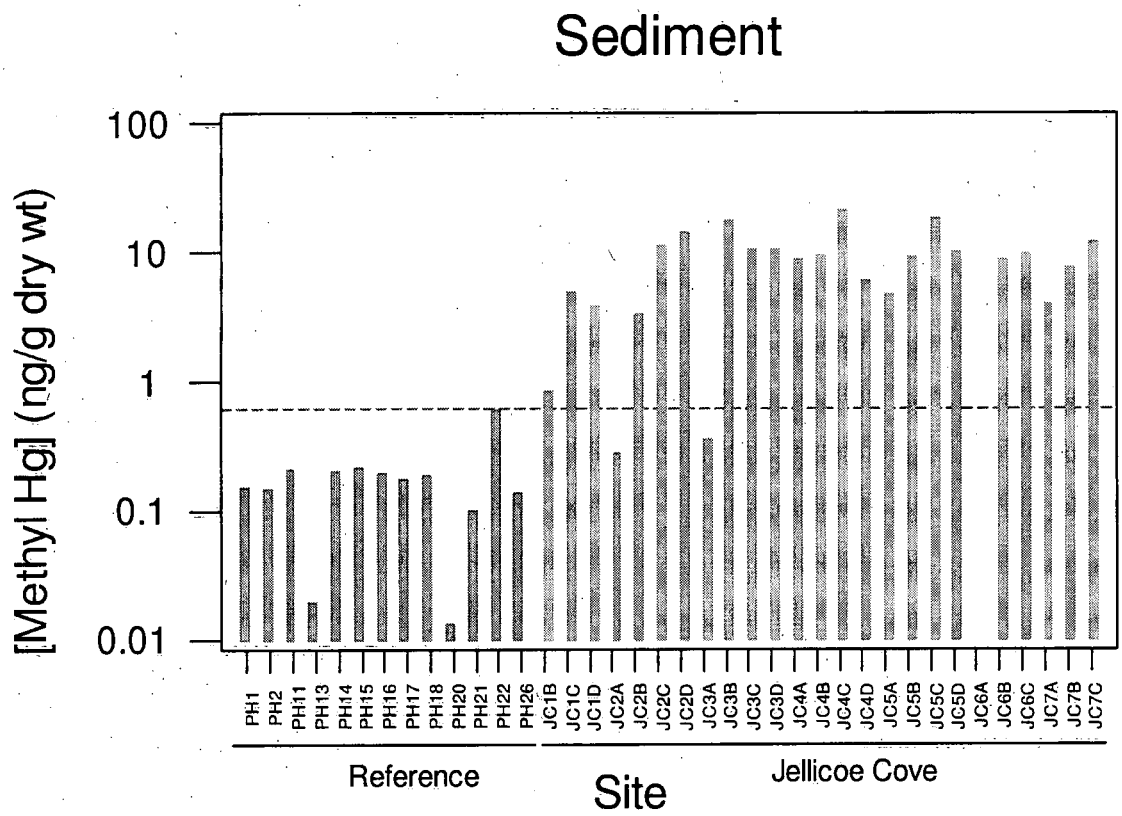

Figure 4. Methyl mercury concentration in sediment (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

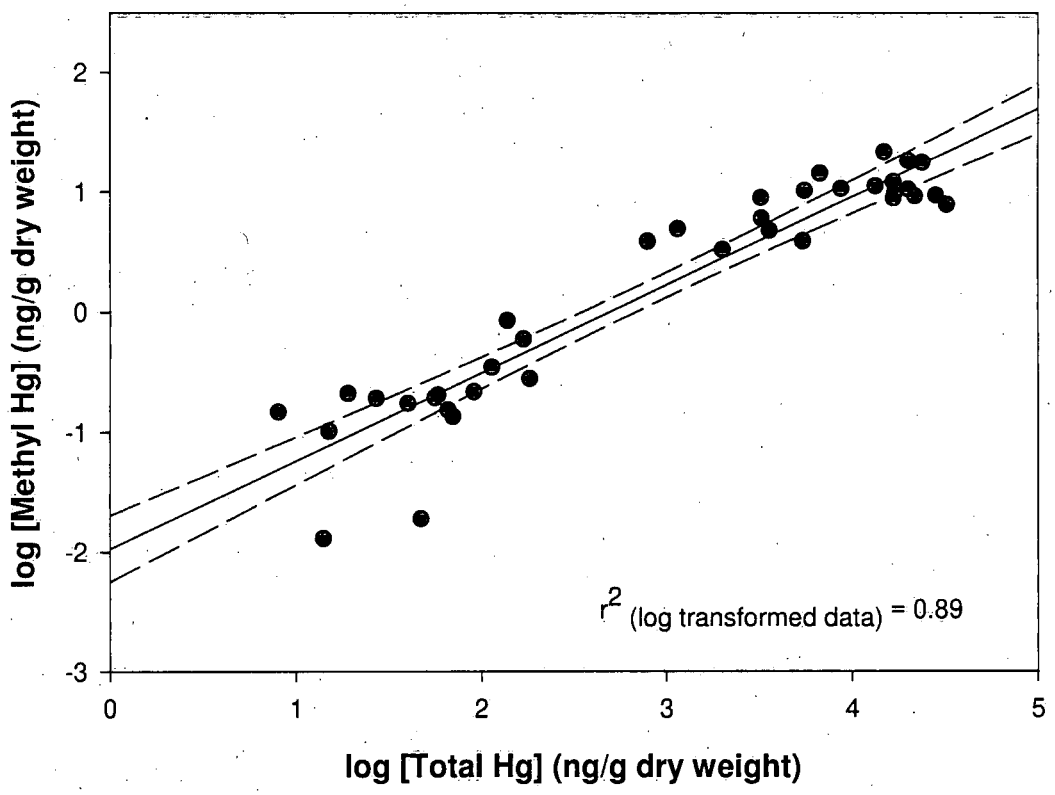

Figure 5. Log scatter plot of methyl mercury versus total mercury in sediment. The 95% confidence interval for the regression equation is shown by the dashed lines.

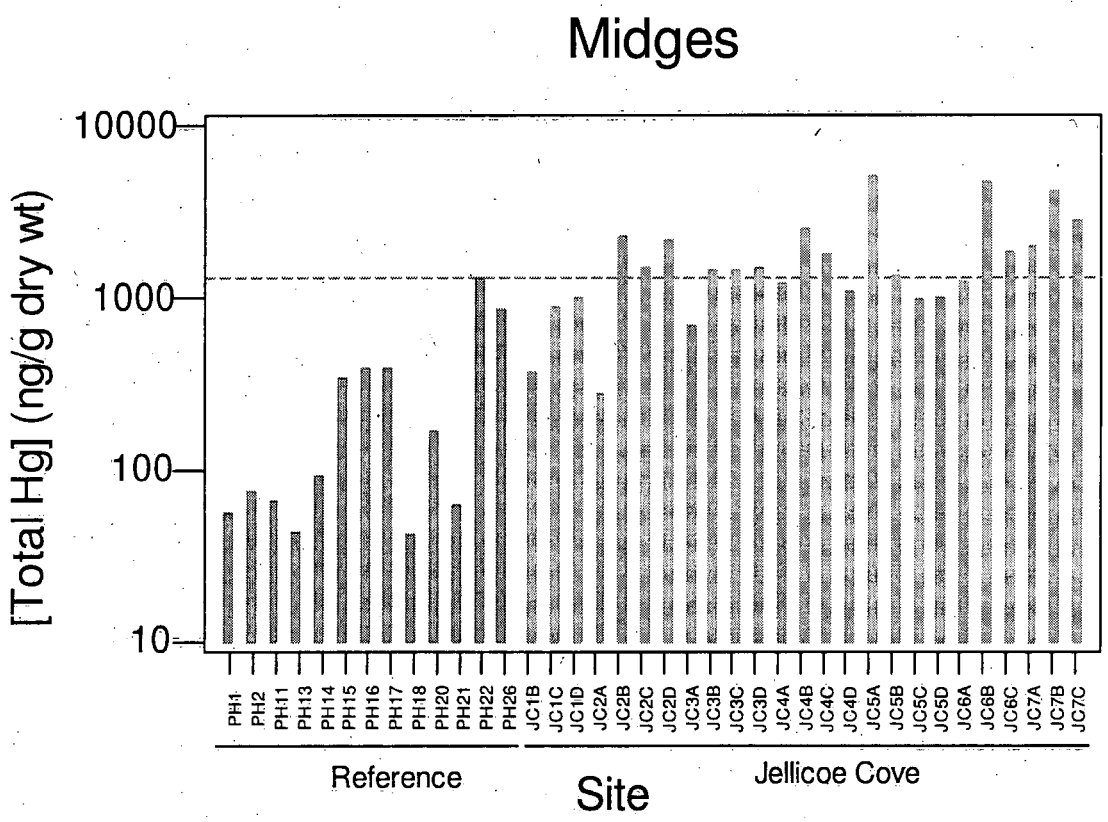

Figure 6. Total mercury concentration in midges (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

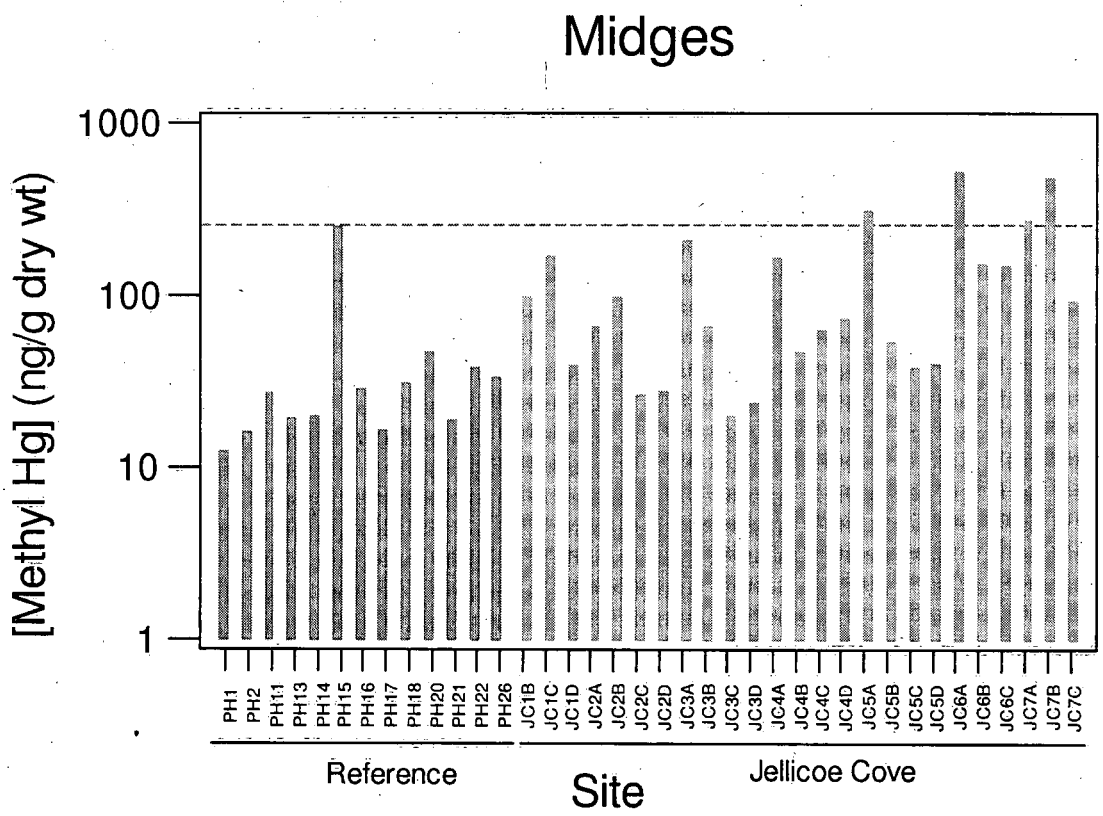

Figure 7. Methyl mercury concentration in midges (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

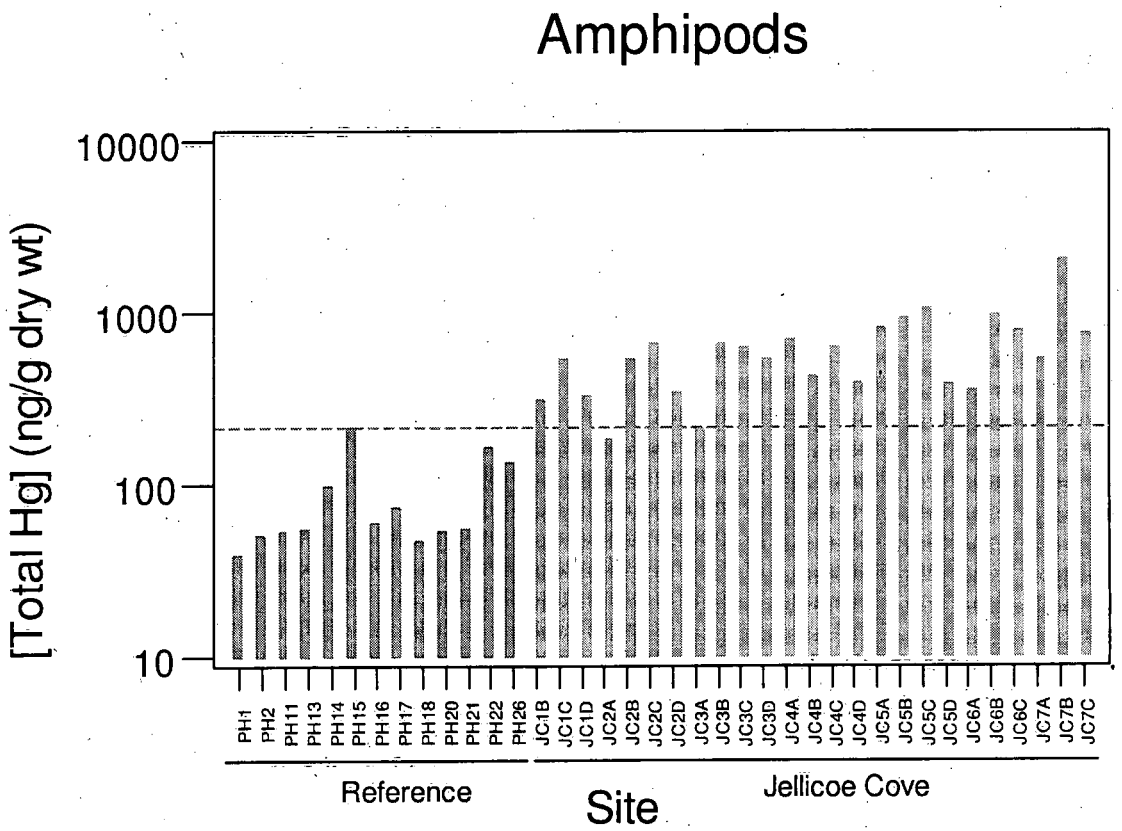

Figure 8. Total Hg concentration in amphipods (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

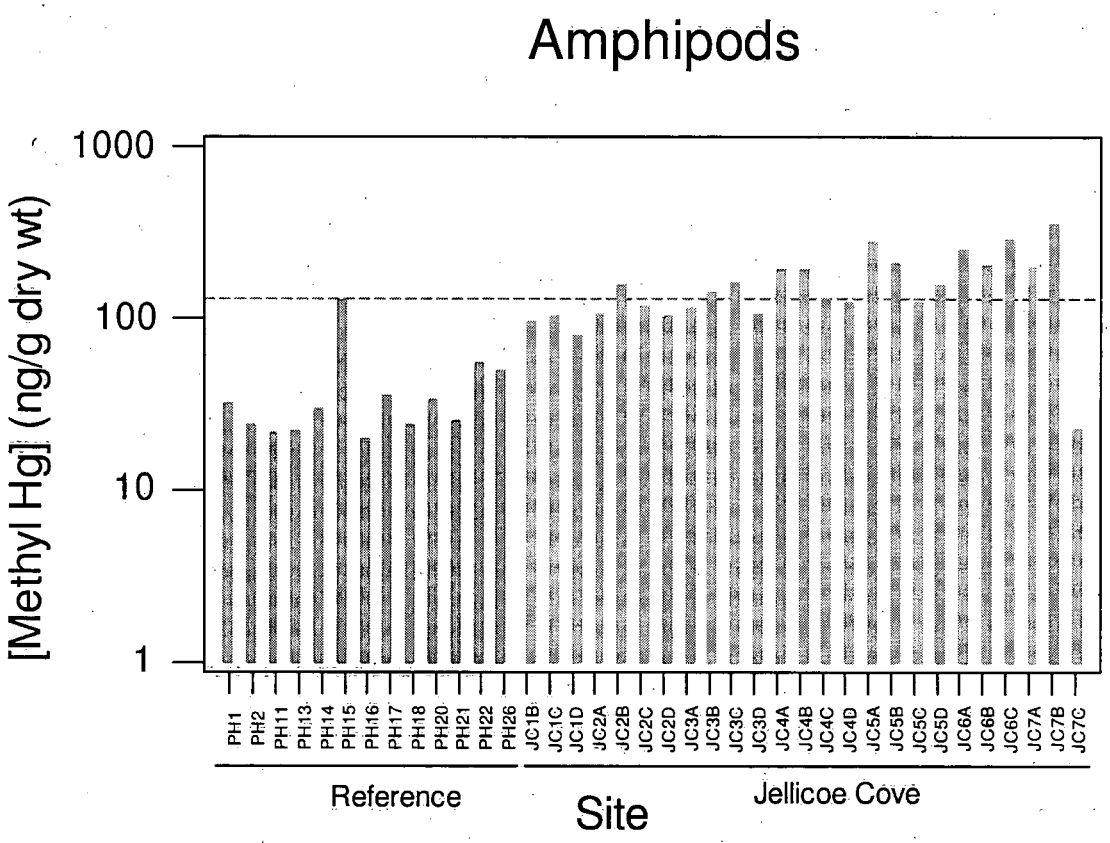

Figure 9. Methyl Hg concentration in amphipods (ng/g dw) collected from Jellicoe Cove and reference sites. The dotted line indicates the 99th percentile for reference sites.

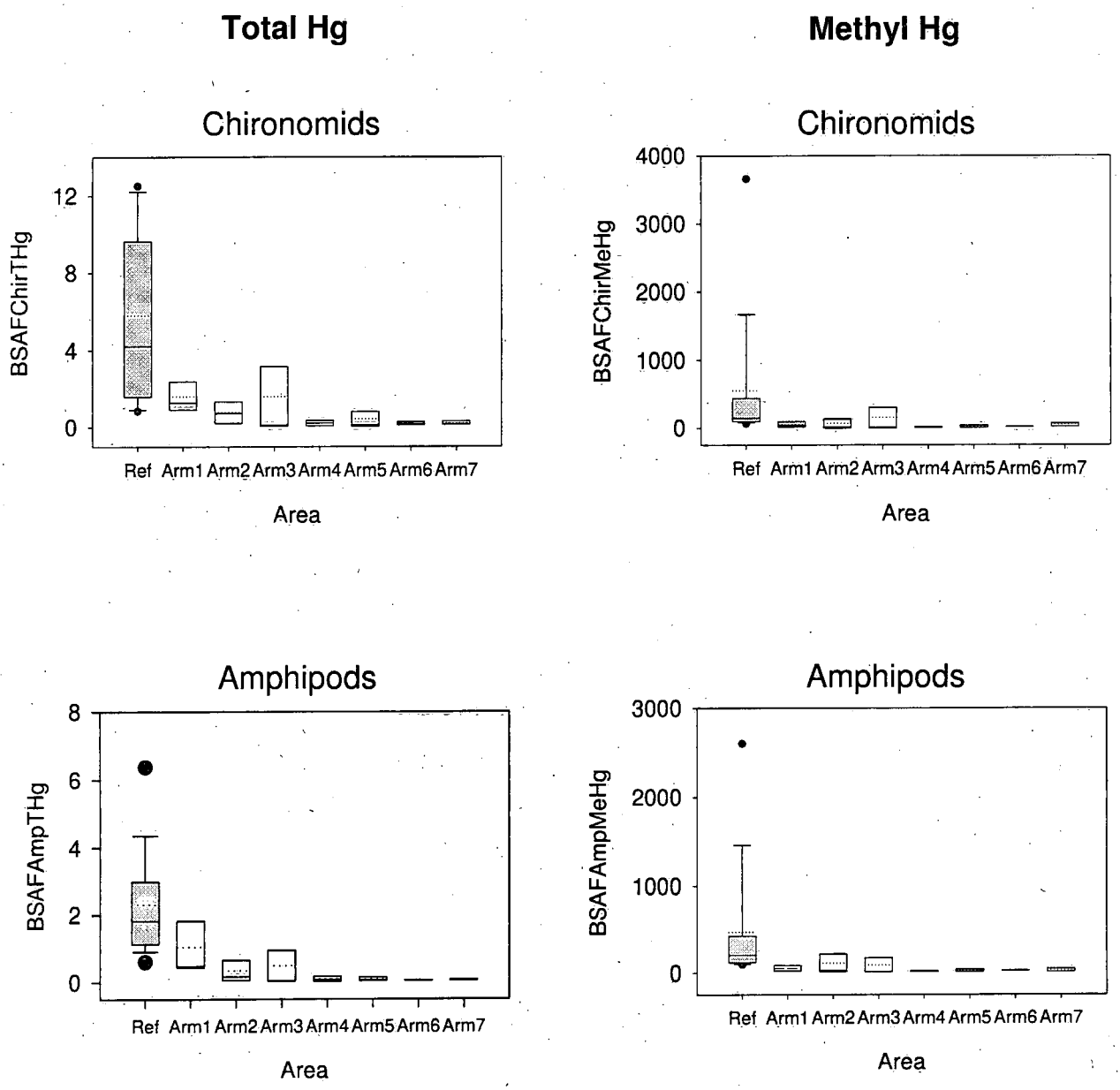

Figure 10. Biota-sediment accumulation factors for invertebrate taxa from Jellicoe Cove and reference sites. Boxplots of BSAFs (=$[Hg]_{inv}$ / $[Hg]_{sed}$) for each taxon within areas show 90th and 10th percentile (whiskers above and below boxes), inter-quartile ranges (box boundaries closest and farthest from zero), median (solid horizontal line within boxes) and mean (dotted line).

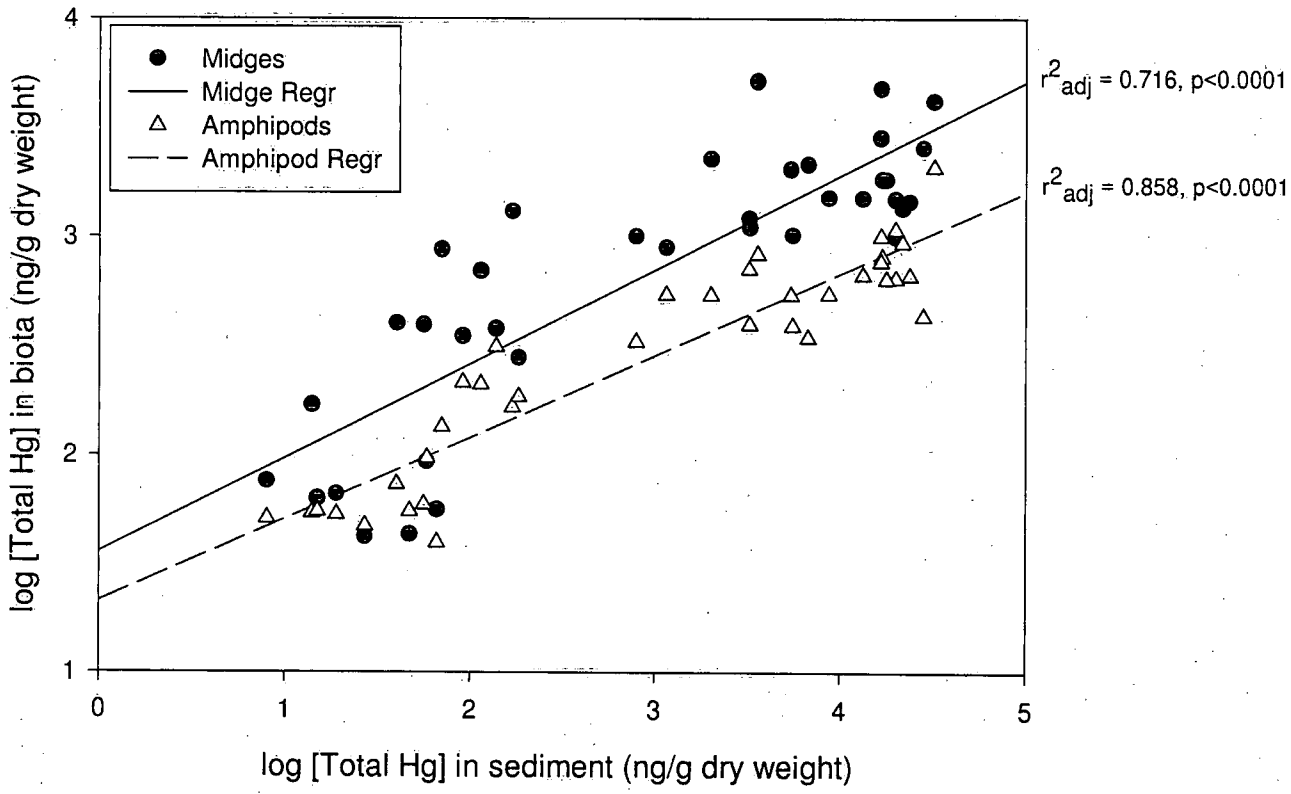

Figure 11. Relationships between total mercury in midges and amphipods versus total mercury in sediment. Separate regression lines are shown for each taxon.

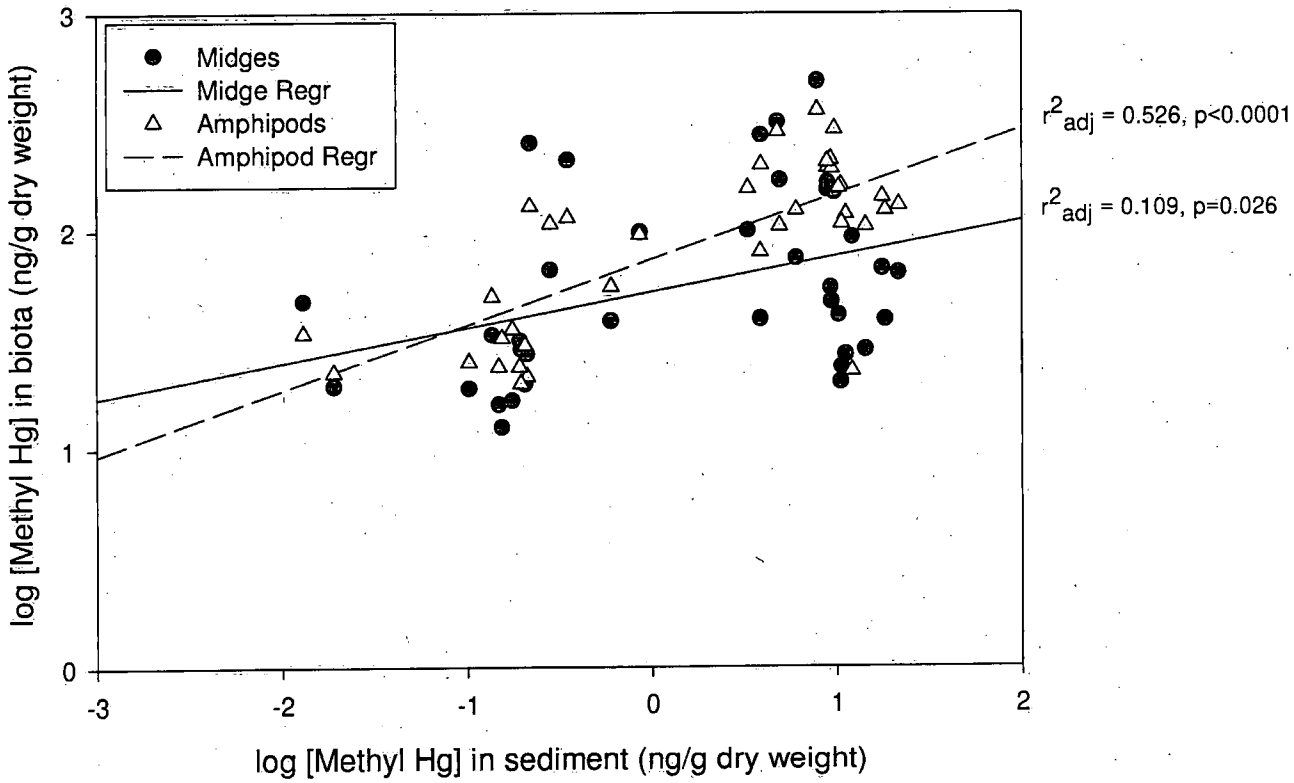

Figure 12. Relationships between methyl mercury in midges and amphipods versus methyl mercury in sediment. Separate regression lines are shown for each taxon.

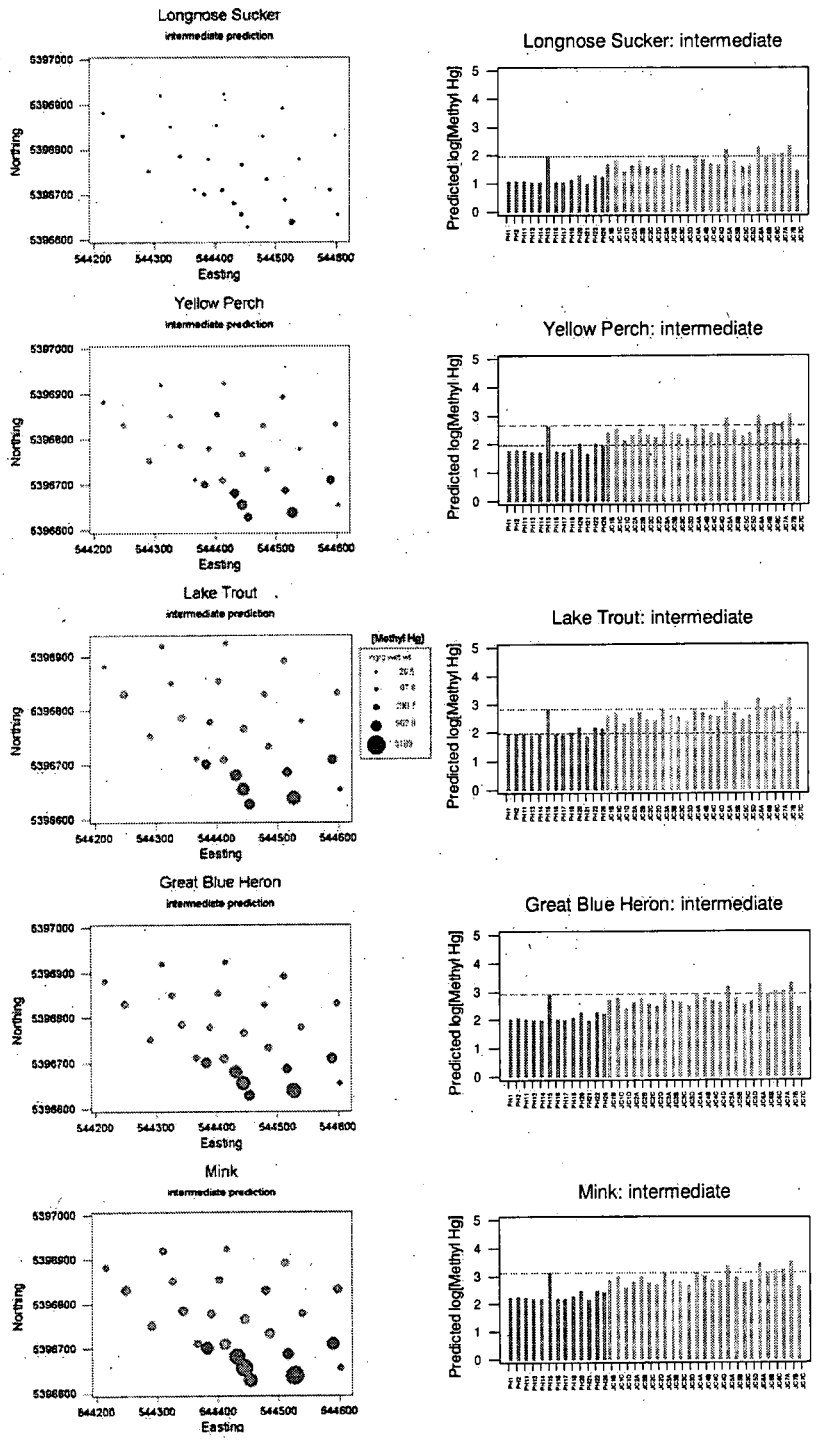

Figure 14. "Intermediate" predictions of methyl mercury concentrations (ng/g wet weight) in 5 receptor species for Jellicoe Cove and reference sites. These are from calculations using mean $[MeHg]_{inv}$ and medium BMFs. Maps on the left show geophaphic patterns of predicted receptor [MeHg] for Jellicoe Cove sites. Site symbol area is proportional to the for the $[MeHg]_{rec}$ site. Symbol colour indicates relation to reference sites predictions and the applicable tissue residue guideline: ● =$[MeHg]_{rec}$ < max. for ref. sites, < TRG; ● = $[MeHg]_{rec}$ < max. for ref. sites, > TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, <TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, > TRG. Charts on the right compare predicted [MeHg] among receptors and between reference (green bars) and Jellicoe Cove (gray bars) sites. Highest predicted [MeHg] for references sites is indicated by green dashed line. The tissue residue guideline (92 ng/g ww, Environment Canada 2002; CCME 2000), where applicable, is shown by a red dotted line.

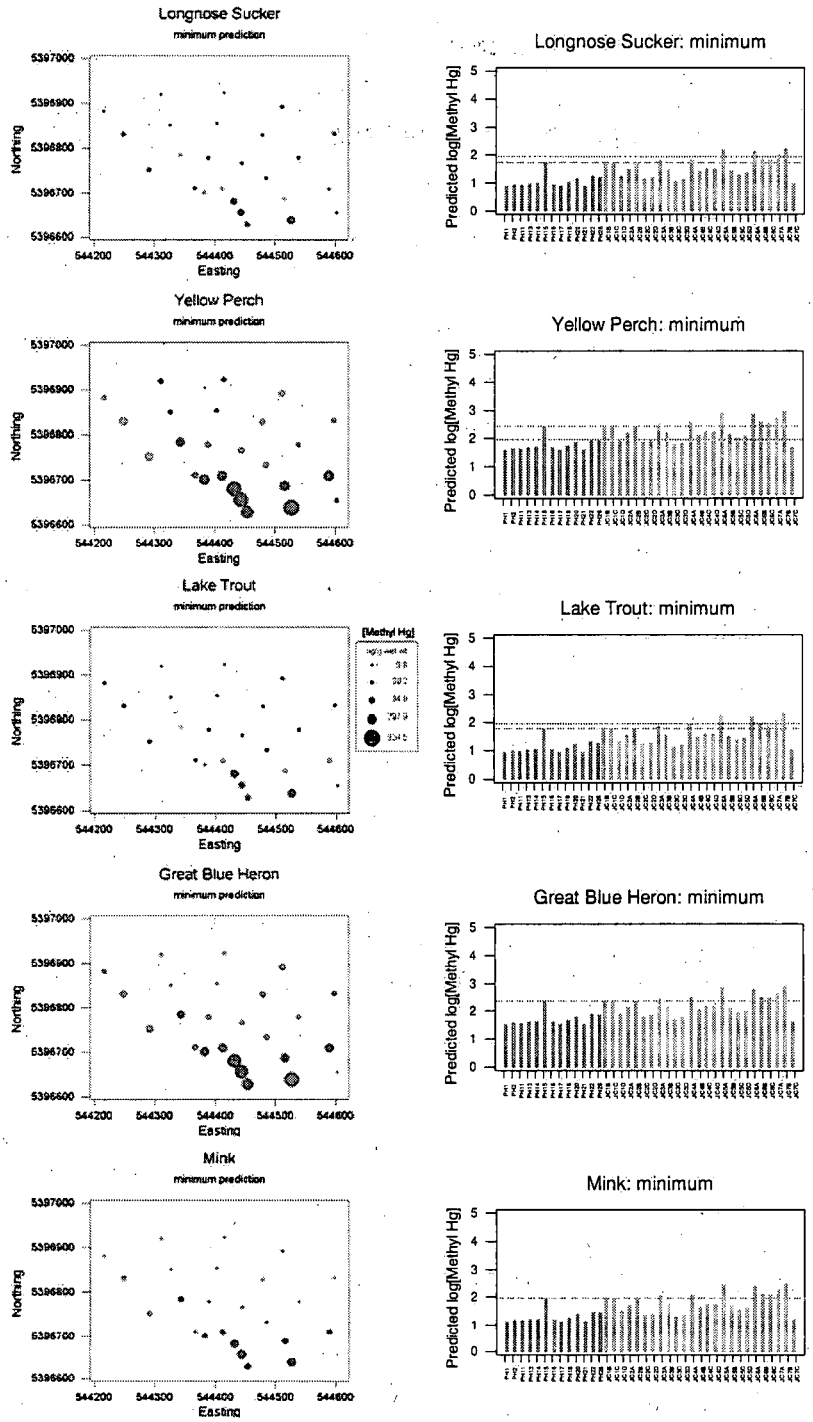

Figure 13. "Minimum" predictions of methyl mercury concentrations (ng/g wet weight) in 5 receptor species for Jellicoe Cove and reference sites. These are from calculations using minimum $[MeHg]_{inv}$ and minimum BMFs. Maps on the left show geophaphic patterns of predicted receptor [MeHg] for Jellicoe Cove sites. Site symbol area is proportional to the $[MeHg]_{rec}$ for the site. Symbol colour indicates relation to reference sites predictions and the applicable tissue residue guideline: ● =$[MeHg]_{rec}$ < max. for ref. sites, < TRG; ● = $[MeHg]_{rec}$ < max. for ref. sites, > TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, <TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, > TRG. Charts on the right compare predicted [MeHg] among receptors and between reference (green bars) and Jellicoe Cove (gray bars) sites. Highest predicted [MeHg] for references sites is indicated by green dashed line. The tissue residue guideline (92 ng/g ww, Environment Canada 2002; CCME 2000), where applicable, is shown by a red dotted line.

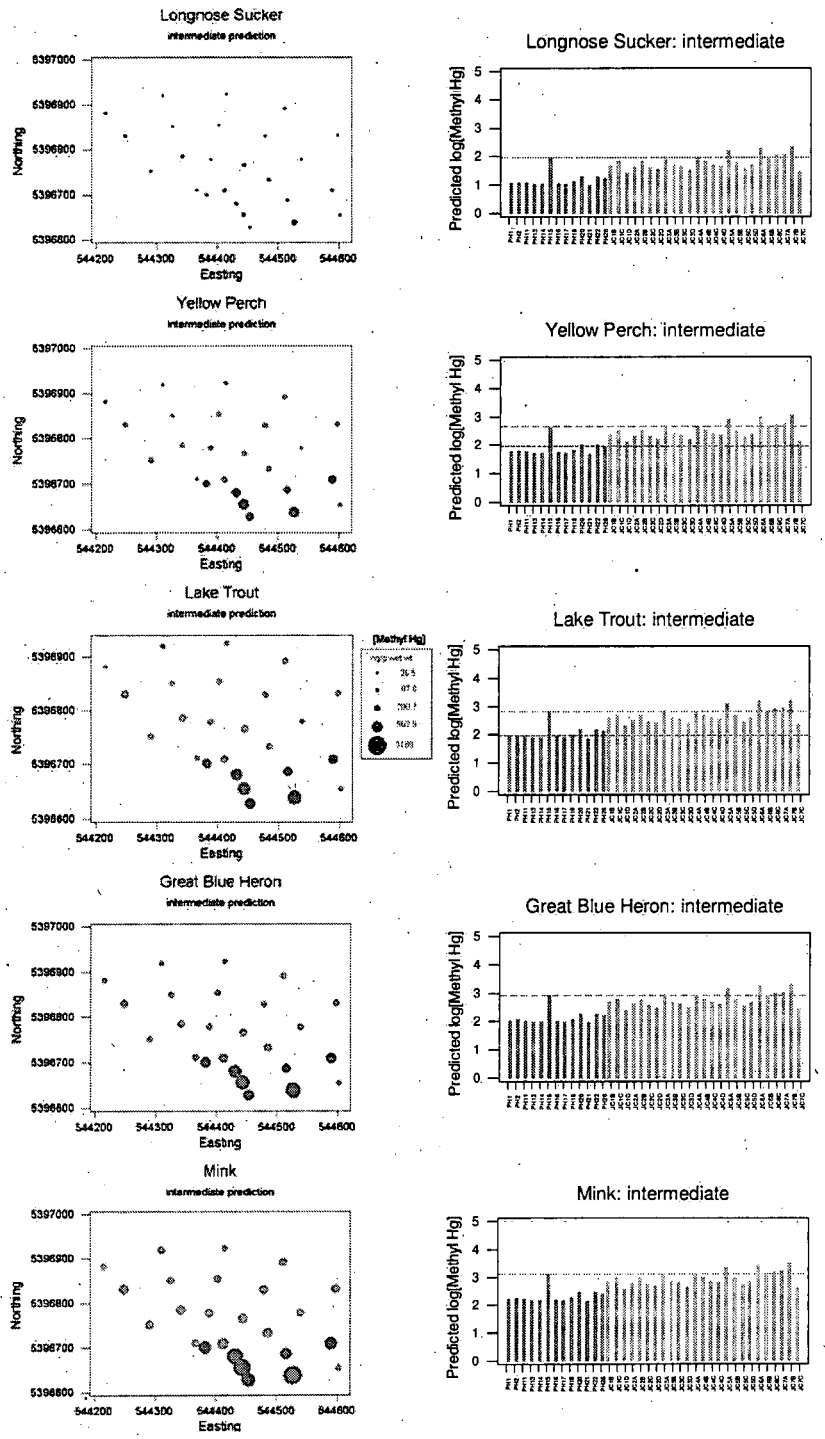

Figure 14. "Intermediate" predictions of methyl mercury concentrations (ng/g wet weight) in 5 receptor species for Jellicoe Cove and reference sites. These are from calculations using mean $[MeHg]_{inv}$ and medium BMFs. Maps on the left show geophaphic patterns of predicted receptor [MeHg] for Jellicoe Cove sites. Site symbol area is proportional to the for the $[MeHg]_{rec}$ site. Symbol colour indicates relation to reference sites predictions and the applicable tissue residue guideline: ● =$[MeHg]_{rec}$ < max. for ref. sites, < TRG; ● = $[MeHg]_{rec}$ < max. for ref. sites, > TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, <TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, > TRG. Charts on the right compare predicted [MeHg] among receptors and between reference (green bars) and Jellicoe Cove (gray bars) sites. Highest predicted [MeHg] for references sites is indicated by green dashed line. The tissue residue guideline (92 ng/g ww, Environment Canada 2002; CCME 2000), where applicable, is shown by a red dotted line.

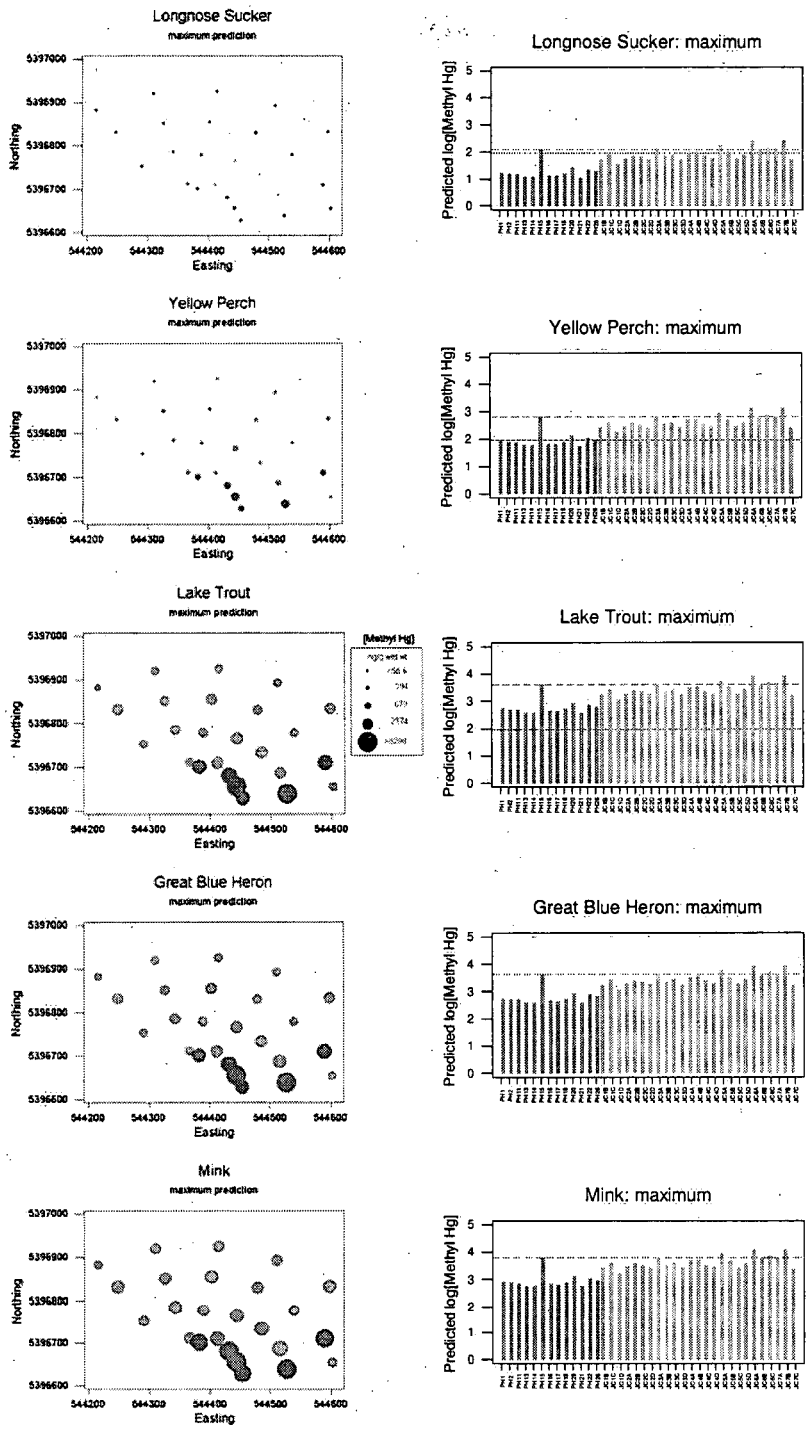

Figure 15. "Maximum" predictions of methyl mercury concentrations (ng/g wet weight) in 5 receptor species for Jellicoe Cove and reference sites. These are from calculations using maximum $[MeHg]_{inv}$ and maximum BMFs. Maps on the left show geophaphic patterns of predicted receptor [MeHg] for Jellicoe Cove sites. Site symbol area is proportional to the for the $[MeHg]_{rec}$ site. Symbol colour indicates relation to reference sites predictions and the applicable tissue residue guideline: ● =$[MeHg]_{rec}$ < max. for ref. sites, < TRG; ● = $[MeHg]_{rec}$ < max. for ref. sites, > TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, <TRG; ● = $[MeHg]_{rec}$ > max. for ref. sites, > TRG. Charts on the right compare predicted [MeHg] among receptors and between reference (green bars) and Jellicoe Cove (gray bars) sites. Highest predicted [MeHg] for references sites is indicated by green dashed line. The tissue residue guideline (92 ng/g ww, Environment Canada 2002; CCME 2000), where applicable, is shown by a red dotted line.

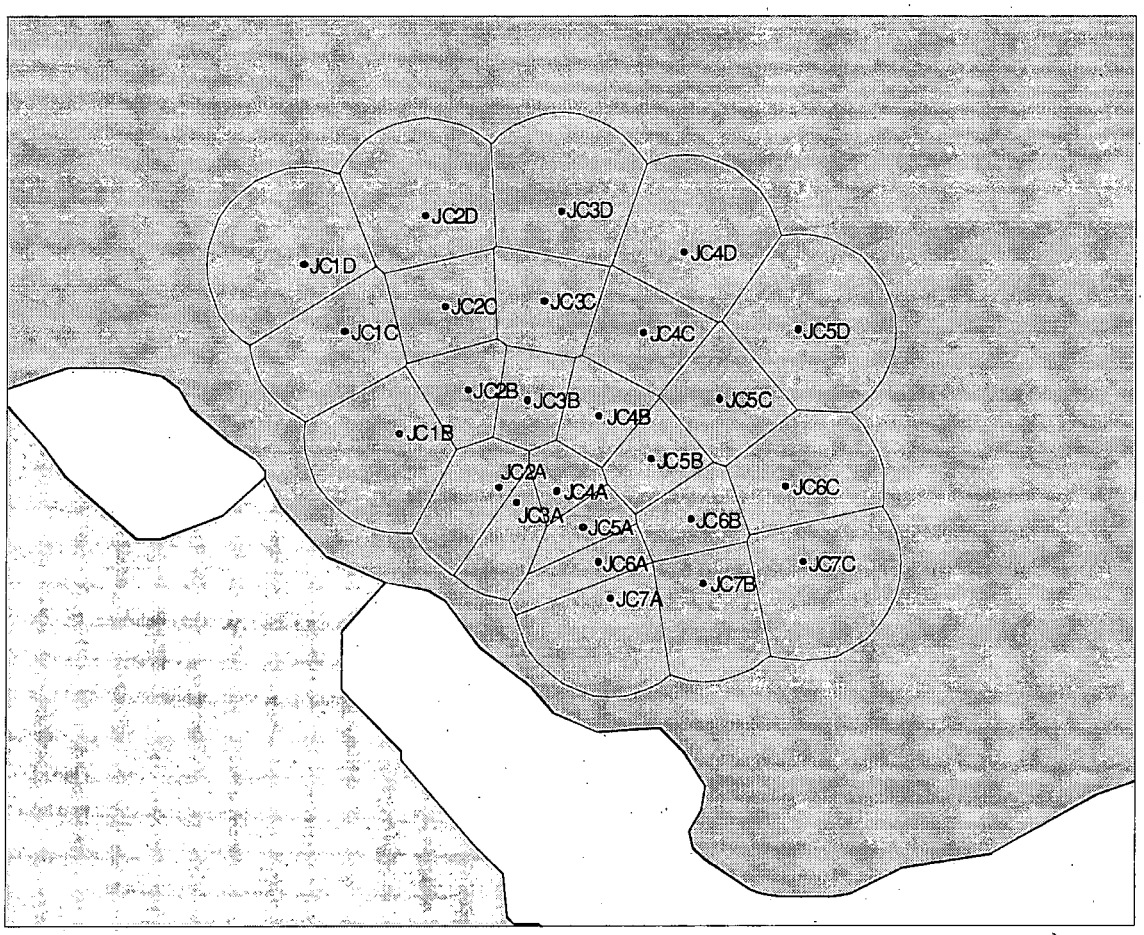

Figure 16. Spatial boundaries of invertebrate and sediment sampling sites as defined by Thiessen polygons with 75-m buffers. All points within each polygon are closer to the enclosed site than to any other site.

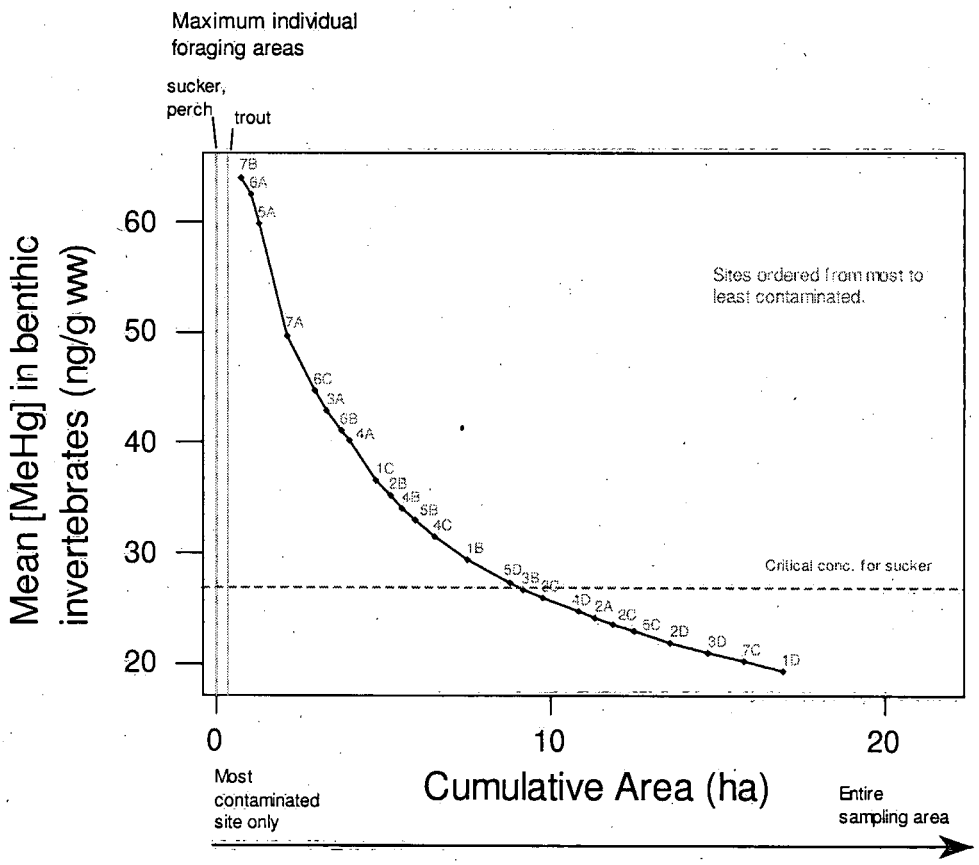

Figure 17. "Average concentration with area curve" for Jellicoe Cove sites. Points represent the mean $[MeHg]_{inv}$ and summed areas of all sites labelled at, and to the left of, the point. Vertical solid lines show estimated foraging areas for 3 fish receptors. (Longnose sucker and yellow perch areas are too similar to be distinctly shown.) The horizonal dashed line is the estimated critical $[MeHg]_{inv}$ for sucker bioaccumulation (i.e., the $[MeHg]_{inv}$ at which the predicted [MeHg] in sucker would equal the tissue residue guideline).

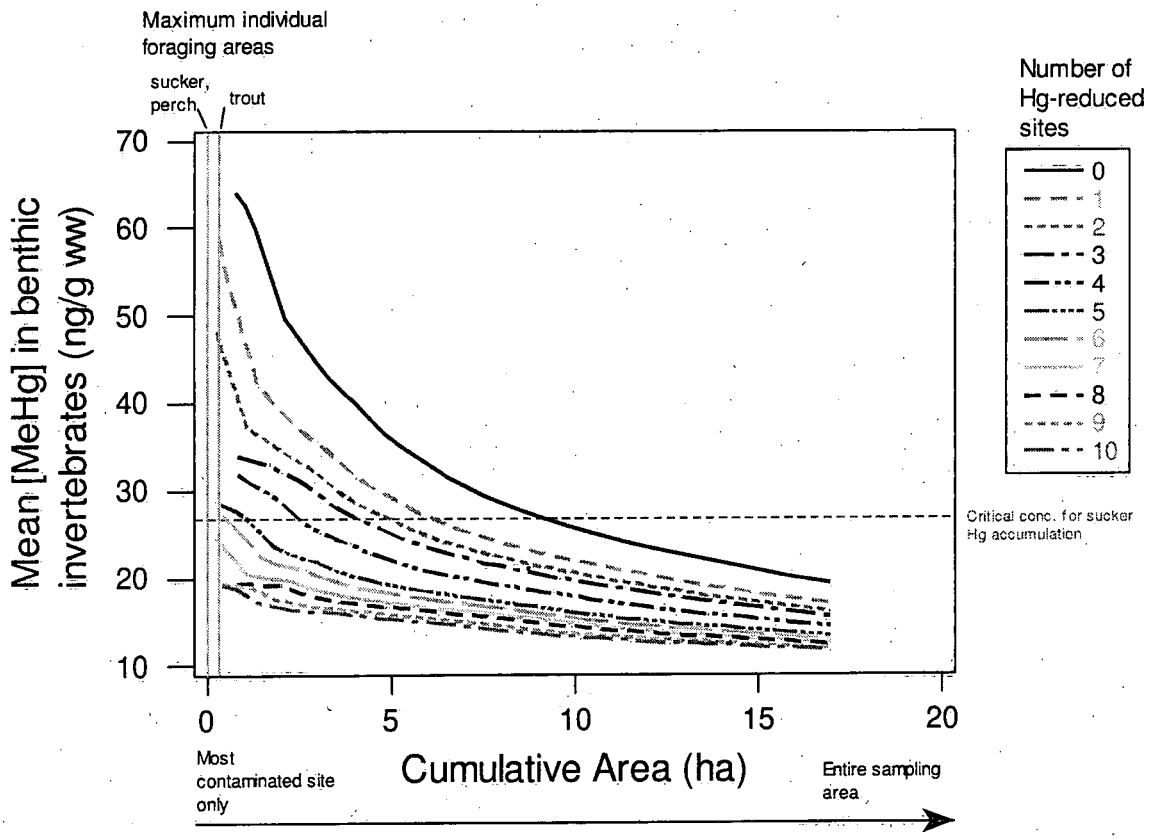

Figure 18. Effects on the "average concentration with area curve" of reducing methyl mercury concentrations in the 10 most contaminated sites of Jellicoe Cove. Assumed $[MeHg]_{inv}$ reductions were to 10 ng/g ww, which is assumed to be the approximate background concentration for the area.

Table 1. Tissue and sediment sampling site co-ordinates (UTM NAD 83) and site depth for Jellicoe Cove and reference sites.

Site	Depth (m)	Northing	Easting
Reference			
PH1	2.7	5385705	548946
PH2	1.2	5385168	549731
PH11	26.9	5387649	548785
PH13	13.2	5402907	526305
PH14	43.6	5403841	520730
PH15	8.4	5399005	544152
PH16	27.4	5408595	461938
PH17	41.0	5410755	457816
PH18	23.3	5406082	444807
PH20	26.2	5403155	498041
PH21	29.4	5401241	540354
PH22	64.8	5400026	540285
PH26	38.4	5398319	534292
Jellicoe Cove			
JC2A	7.5	5396712.0	544366.8
JC3A	7.7	5396701.6	544382.0
JC4A	10.6	5396710.1	544411.9
JC5A	7.5	5396681.4	544431.8
JC6A	6.9	5396656.1	544443.0
JC7A	6.8	5396628.3	544453.6
JC1B	9.0	5396753.1	544291.0
JC2B	12.2	5396786.6	544342.9
JC3B	-[b]	5396779.7	544389.0
JC4B	12.0	5396767.4	544444.8
JC5B	11.0	5396734.4	544484.9
JC6B	7.5	5396687.6	544515.5
JC7B	4.8	5396639.5	544526.5
JC1C	10.0	5396831.5	544248.0
JC2C	15.0	5396851.1	544325.5
JC3C	13.6	5396855.0	544402.5
JC4C	12.6	5396830.4	544478.4
JC5C	11.2	5396780.4	544538.6
JC6C	8.0	5396710.5	544590.1
JC7C	5.3	5396655.3	544603.1
JC1D	15.0	5396883.0	544215.9
JC2D	16.9	5396920.8	544310.1
JC3D	14.6	5396925.1	544414.7
JC4D	13.5	5396892.6	544511.1
JC5D	11.8	5396832.8	544598.5

Table 2. List of environmental variables measured at each site.

Geographical	Water	Sediment	Biota
Northing	Temperature	Total Mercury	Total Mercury
Easting	Conductivity	Methyl Mercury	Methyl Mercury
Site Depth	pH	Total Phosphorus	
	Dissolved Oxygen	Total Nitrogen	
		Total Organic Carbon	
		Fe, Mn	
		% Clay, Silt, Sand, & Gravel	

Table 3. Literature derived biomagnification factors (BMFs) for the receptors of concern. For each receptor, the number of trophic levels removed from benthic invertebrates (Level 1) is indicated. For each transfer between trophic levels, the lowest, medium and highest estimated BMFs (from Table A1) are used in calculating the food chain multipliers (FCMs). Where receptors have only one BMF value, the same value is used for the low, medium, and high FCM calculations. See text for further details.

Receptor	Predator Type	Trophic levels of transfer	BMFs (low | med | high) of transfer	Food chain multipiers (low | med | high)
Longnose Sucker	benthivorous / planktivorous fish	1 - 2	3.43	3.43
Yellow Perch	small piscivorous fish	1 - 2 - 3	3.43 x 5	17.15
Adult Lake Trout	large piscivorous fish	1 - 2 - 3	3.43 x (1.12 | 3.20 | 32.40)	3.84 | 10.98 | 111.1
		1 - 2 - 3 - 4	3.43 x 5 x 2.40	41.16
Great Blue Heron	piscivorous bird	1 - 2 - 3	3.43 x 6.80	23.32
		1 - 2 - 3 - 4	3.43 x 5 x (0.85 | 2.37 | 6.80)	14.58 | 40.65 | 116.6
Mink	piscivorous mammal	1 - 2 - 3	3.43 x (1.70 | 5.20 | 22.64)	5.83 | 17.84 | 77.66
		1 - 2 - 3 - 4	3.43 x 5 x (1.70 | 4.70 | 10.00)	29.16 | 80.61 | 171.5

Table 4. Total and methyl mercury in sediment (ng/g wet and dry weight –recovery corrected) collected from Jellicoe Cove and reference sites. Within-site replicates for the four randomly selected quality assurance/quality control sites are denoted by a "-" + replicate number. For data analyses, means of replicates are used. (F) = Flett results, (C) = Caduceon results (subset of sites).

Area	Site	Total Hg (F) (ng/g) wet wt	Total Hg (F) (ng/g) dry wt	Total Hg (C) (ng/g) dry wt	Methyl Hg (F) (ng/g) wet wt	Methyl Hg (F) (ng/g) dry wt
Reference	PH1	40	66	-	0.093	0.154
	PH2	6	8	54	0.109	0.148
	PH11	12	19	98	0.116 (0.155)[a]	0.181 (0.241)[a]
	PH13	34	47	-	0.013	0.019
	PH14-1	43	69	-	0.133	0.213
	PH14-2	37	63	-	0.130	0.220
	PH14-3	26	43	-	0.091 (0.129)[a]	0.152 (0.215)[a]
	PH15	71	91	-	0.169	0.218
	PH16	18 (22)[a]	51 (61)[a]	-	0.070	0.195
	PH17	15	40	-	0.066	0.175
	PH18	9	27	-	0.066	0.192
	PH20	9	14	-	0.008	0.013
	PH21	10	15	-	0.075 (0.060)[a]	0.113 (0.091)[a]
	PH22	82	169	-	0.293	0.602
	PH26	41	70	-	0.080	0.136
Jellicoe Cove	JC2A	120 (109)[a]	191 (174)[a]	39	0.172 (0.180)[a]	0.275 (0.287)[a]
	JC3A	76	114	315	0.413 (0.183)[a] (0.060)[b] (0.148)[bc]	0.618 (0.273)[a] (0.090)[b] (0.221)[bc]
	JC4A	2015	3229	-	5.61	8.99
	JC5A	2186	3595	4622	2.77 (3.07)[a]	4.56 (5.04)[a]
	JC6A	-[d]	-[d]	-	-[d]	-[d]
	JC7A	3863	5442	-	3.06 (2.51)[c]	4.30 (3.53)[c]
	JC1B	102	138	-	0.179 (0.430)[a] (1.29)[b]	0.243 (0.584)[a] (1.75)[b]
	JC2B	1317	2008	2867	2.18	3.32
	JC3B	12754 (13460)[a]	23118 (24397)[a]	-	9.76	17.7
	JC4B	13822	28094	7874	4.60	9.44
	JC5B	10514	21711	-	4.51	9.32
	JC6B	9599	16647	-	4.98 (5.31)[a]	8.63 (9.21)[a]
	JC7B	20998	32160	-	5.14	7.87
	JC1C	748	1152	-	3.22	4.95
	JC2C	7595	13289	-	6.57 (6.30)[a]	11.5 (11.0)[a]
	JC3C	11299	19963	14545	6.01	10.6
	JC4C-1	12738 (11307)[a]	25130 (22306)[a]	20149	11.3	22.3
	JC4C-2	7696	14007	-	10.5	19.2
	JC4C-3	8182	15661	-	12.4	23.7
	JC5C	9721 (12095)[a]	17768 (22107)[a]	-	10.3 (9.86)[a]	18.8 (18.0)[a]
	JC6C-1	8738	16498	-	4.95 (4.85)[a]	9.35 (9.15)[a]
	JC6C-2	11287 (11041)[a]	20414 (19969)[a]	-	5.33	9.63
	JC6C-3	7482	13909	-	5.60 (5.58)[c]	10.4 (10.4)[c]
	JC7C	8808	16604	-	6.47	12.2
	JC1D	534	791	-	2.63	3.89
	JC2D	3965	6728	-	8.50	14.4
	JC3D	4951	8714	-	6.08	10.7
	JC4D	1295	3255	5733	2.42	6.08
	JC5D-1	2746	5722	-	4.87	10.2
	JC5D-2	2746	6115	-	4.02	8.96
	JC5D-3	2178	4810	-	5.33	11.8

[a] laboratory duplicate, [b] lab triplicate, [c] repeat analysis, [d] data not available

Table 5. Total mercury (ng/g dry weight) in benthic invertebrates collected from Jellicoe Cove and reference sites. For data analyses, means of replicates are used.

Area	Site	BIOTA – Total Hg	
		Midge	Amphipod
Reference	PH1	56	43 (36)[a]
	PH2	76	51
	PH11	66	53
	PH13	43	53 (57)[a]
	PH14	93	89 (105)[a]
	PH15	350	215
	PH16	394	59
	PH17	400	73
	PH18	42	47
	PH20	170	54
	PH21	63	55
	PH22	1388 (1230)[a]	166
	PH26	875	135
Jellicoe Cove	JC2A	279	185
	JC3A	700	211
	JC4A	1218	710
	JC5A	5457 (4887)[a]	833
	JC6A	1251	358
	JC7A	2038	539
	JC1B	379	313
	JC2B	2286	540
	JC3B	1456	661
	JC4B	2558	430
	JC5B	1356	936
	JC6B	4268 (5328)[a]	1001
	JC7B	4193	2075
	JC1C	894	543
	JC2C	1504	692 (640)[a]
	JC3C	1487	642
	JC4C	1835	637
	JC5C	1003	1074
	JC6C	1842	806
	JC7C	2852	743 (792)[a]
	JC1D	1007	330
	JC2D	2157	343
	JC3D	1514	544
	JC4D	1108	395
	JC5D	1080 (962)[a]	389

[a] laboratory duplicate

Table 6. Methyl mercury (ng/g dry weight) in benthic invertebrates collected from Jellicoe Cove and reference sites.

Area	Site	BIOTA – Methyl Hg	
		Midge	Amphipod
Reference	PH1	12.6	32.2
	PH2	16.0	23.8
	PH11	27.0 (27.6)[a]	22.9 (20.1)[a]
	PH13	19.4	22.3
	PH14	19.9	29.9
	PH15	255	130
	PH16	30.0 (27.4)[b]	19.0 (20.9)[b]
	PH17	16.7	35.5
	PH18	31.4	24.3 (23.3)[b]
	PH20	47.5	33.8 (33.9)[b]
	PH21	18.2 (19.7)[b]	22.7 (27.4)[b]
	PH22	38.6	55.4
	PH26	33.4	50.0
Jellicoe Cove	JC 2A	65.7 (66.6)[b]	108
	JC 3A	212	115
	JC 4A	167	200 (193)[b]
	JC 5A	316	306 (268)[a]
	JC 6A	533	258
	JC 7A	276	202
	JC 1B	102 (98.9)[b] (96.1)[a]	96.1
	JC 2B	100	157
	JC 3B	66.8	143
	JC 4B	47.2	194
	JC 5B	54.4	228 (198)[a]
	JC 6B	155	186 (231)[a]
	JC 7B	486	359
	JC 1C	171	105
	JC 2C	26.9	119
	JC 3C	20.2	162
	JC 4C	63.8	131
	JC 5C	39.0	124
	JC 6C	150	294
	JC 7C	93.1	22.7
	JC 1D	36.5 (44.0)[a] (40.9)[ab]	79.9
	JC 2D	28.4	105
	JC 3D	23.7	108
	JC 4D	74.6	124
	JC 5D	40.8	158

[a] lab duplicate, [b] repeat analysis

Table 7. Results of regressions of whole body concentrations of mercury in benthic invertebrates vs sediment mercury concentration alone ("A" models), and sediment mercury concentration + other sediment and overlying water physico-chemical variables ("B" models).The groups of multiple predictors listed are from the models that best predicted $[Hg]_{inv}$. All sediment variables in the models were transformed: arcsine-square root (x) for the "%" variables; log(x) for the others. Water variables were not transformed.

Response ($[Hg]_{inv}$)	Model	Predictor ([X])	Coefficient	P (predictor)	R^2_{adj}	P (regression)
Total Hg Midges	A	total Hg	0.431	<0.001	0.716	< 0.001
	B	total Hg	0.545	< 0.001	0.797	< 0.001
		% sand	0.481	0.012		
		Mn	1.101	< 0.001		
Total Hg Amphipods	A	total Hg	0.376	<0.001	0.858	< 0.001
	B	total Hg	0.438	< 0.001	0.906	< 0.001
		Mn	0.305	0.038		
		TKN	-0.430	< 0.001		
Methyl Hg Midges	A	methyl Hg	0.163	0.026	0.109	0.026
	B	methyl Hg	0.256	< 0.001	0.342	0.001
		% sand	1.216	< 0.001		
		% clay	1.392	0.007		
Methyl Hg Amphipods	A	methyl Hg	0.300	< 0.001	0.526	< 0.001
	B	methyl Hg	0.425	< 0.001	0.713	<0.001
		% clay	0.412	0.045		
		TKN	-0.469	0.002		
		pH	-0.764	0.003		

Table 8. Predicted methyl mercury concentrations (ng/g wet weight) in receptor species for Jellicoe Cove, Peninsula Harbour and reference sites. Highlighted values exceed the Environment Canada (2002) tissue residue guideline (92 ng/g ww) applicable for fishes.

		Longnose Sucker			Yellow Perch			Lake Trout			Great Blue Heron			Mink		
Area	Site	min	med	max	min	med	max	min	med	max	min	med	max	min	med	max
Reference	PH1	7.89	12.18	16.46	39.45	60.88	82.32	8.83	92.55	533.28	33.53	113.56	559.68	13.41	174.77	823.20
Reference	PH2	9.33	12.38	15.44	46.65	61.91	77.17	10.45	94.11	499.95	39.66	115.48	524.70	15.86	177.72	771.80
Reference	PH11	8.75	11.77	14.78	43.73	58.82	73.92	9.79	89.42	478.84	37.18	109.73	502.55	14.87	168.86	739.20
Reference	PH13	9.67	10.58	11.49	48.36	52.91	57.45	10.83	80.43	372.19	41.12	98.69	390.61	16.44	151.87	574.50
Reference	PH14	9.95	10.75	11.56	49.74	53.77	57.80	11.14	81.73	374.41	42.28	100.29	392.94	16.91	154.34	578.00
Reference	PH15	54.95	90.42	125.88	274.74	452.07	629.40	61.52	687.21	4077.37	233.57	843.26	4279.22	93.40	1297.70	6294.10
Reference	PH16	9.40	11.37	13.34	46.99	56.85	66.71	10.52	86.42	432.18	39.95	106.05	453.57	15.97	163.20	667.10
Reference	PH17	7.99	10.51	13.03	39.96	52.56	65.17	8.95	79.90	422.18	33.97	98.05	443.08	13.58	150.89	651.70
Reference	PH18	11.15	13.34	15.54	55.74	66.71	77.69	12.48	101.41	503.28	47.39	124.44	528.20	18.95	191.50	776.90
Reference	PH20	15.06	20.37	25.69	75.29	101.87	128.45	16.86	154.86	832.14	64.01	190.02	873.33	25.59	292.43	1284.50
Reference	PH21	8.30	9.81	11.32	41.50	49.05	56.59	9.29	74.56	366.63	35.28	91.49	384.78	14.11	140.80	565.90
Reference	PH22	18.56	20.34	22.12	92.78	101.70	110.62	20.77	154.60	716.60	78.88	189.70	752.07	31.54	291.93	1106.20
Reference	PH26	17.18	17.87	18.56	85.92	89.35	92.78	19.24	135.82	601.05	73.05	166.67	630.81	29.21	256.49	927.80
Arm 1	JC1B	51.31	51.43	51.55	256.56	257.16	257.76	57.45	390.92	1669.83	218.12	479.69	1752.50	87.22	738.20	2577.60
Arm 1	JC1C	52.93	65.96	78.99	264.62	329.79	394.96	59.25	501.33	2558.63	224.97	615.17	2685.30	89.96	946.69	3949.60
Arm 1	JC1D	18.83	26.46	34.09	94.15	132.31	170.47	21.08	201.13	1104.33	80.04	246.80	1159.00	32.01	379.81	1704.70
Arm 2	JC2A	31.83	43.90	55.98	159.15	219.52	279.89	35.64	333.70	1813.15	135.30	409.47	1902.91	54.10	630.14	2798.90
Arm 2	JC2B	56.73	65.96	75.19	283.66	329.79	375.93	63.51	501.33	2435.31	241.15	615.17	2555.87	96.43	946.69	3759.30
Arm 2	JC2C	14.92	40.44	65.96	74.60	202.20	329.79	16.70	307.37	2136.45	63.42	377.16	2242.22	25.36	580.42	3297.90
Arm 2	JC2D	16.36	34.75	53.13	81.81	173.73	265.65	18.32	264.09	1720.94	69.55	324.06	1806.13	27.81	498.70	2656.50
Arm 3	JC3A	67.98	97.29	126.60	339.91	486.46	633.01	76.11	739.48	4100.70	288.98	907.40	4303.71	115.55	1396.41	6330.10
Arm 3	JC3B	33.34	50.95	68.57	166.70	254.76	342.83	37.33	387.27	2220.89	141.72	475.21	2330.83	56.67	731.31	3428.30
Arm 3	JC3C	12.28	45.50	78.72	61.40	227.49	393.59	13.75	345.82	2549.74	52.20	424.35	2675.97	20.87	653.04	3935.90
Arm 3	JC3D	14.03	33.03	52.03	70.14	165.15	260.17	15.71	251.05	1685.39	59.63	308.06	1768.82	23.85	474.08	2601.70
Arm 4	JC4A	72.92	84.36	95.80	364.61	421.80	479.00	81.64	641.19	3103.02	309.97	786.79	3256.64	123.95	1210.81	4790.00
Arm 4	JC4B	27.30	65.31	103.31	136.51	326.54	516.56	30.57	496.37	3346.33	116.06	609.09	3511.99	46.41	937.34	5165.60
Arm 4	JC4C	34.23	51.74	69.25	171.16	258.71	346.26	38.32	393.27	2243.11	145.51	482.57	2354.15	58.18	742.63	3462.60
Arm 4	JC4D	34.13	45.38	56.63	170.64	226.89	283.15	38.21	344.91	1834.26	145.07	423.23	1925.07	58.01	651.31	2831.50
Arm 5	JC5A	162.62	165.57	168.52	813.08	827.83	842.58	182.05	1258.40	5458.34	691.24	1544.16	5728.56	276.40	2376.33	8425.80
Arm 5	JC5B	29.40	63.11	96.83	146.98	315.56	484.14	32.91	479.69	3136.35	124.95	588.62	3291.62	49.96	905.83	4841.40
Arm 5	JC5C	20.96	38.21	55.46	104.79	191.05	277.32	23.46	290.42	1796.49	89.08	356.37	1885.42	35.62	548.42	2773.20
Arm 5	JC5D	24.70	51.26	77.83	123.48	256.31	389.13	27.65	389.62	2520.86	104.98	478.09	2645.65	41.98	735.74	3891.30
Arm 6	JC6A	145.78	201.60	257.42	728.88	1007.99	1287.11	163.20	1532.26	8338.05	619.65	1880.21	8750.83	247.78	2893.49	12871.10
Arm 6	JC6B	74.98	92.95	110.93	374.90	464.76	554.63	83.94	706.50	3592.97	318.72	866.93	3770.84	127.44	1334.13	5546.30
Arm 6	JC6C	71.48	109.19	146.91	357.41	545.97	734.53	80.03	829.94	4758.41	303.85	1018.40	4993.98	121.50	1567.24	7345.30
Arm 7	JC7A	104.34	116.62	128.90	521.70	583.10	644.50	116.81	886.38	4175.14	443.52	1087.66	4381.83	177.35	1673.82	6445.00
Arm 7	JC7B	186.90	220.09	253.27	934.50	1100.43	1266.36	209.24	1672.78	8203.62	794.46	2052.64	8609.74	317.68	3158.84	12663.60
Arm 7	JC7C	9.64	29.40	49.15	48.19	146.98	245.76	10.79	223.42	1592.06	40.97	274.15	1670.88	16.38	421.90	2457.60

Table 9. Exceedences of criteria for predicted methyl mercury concentrations in receptors based on three exposure and uptake scenarios for the Peninsula Harbour study. The tissue residue guideline (TRG) for MeHg is 92 ng/g ww. n = 25 for Jellicoe Cove (J-Cove) sites; n = 13 for reference sites.

Receptor	Scenario	# Sites in J-Cove where $[Hg]_{rec}$ > maximum $[Hg]_{rec}$ for Reference Sites	# Sites in J-Cove where $[Hg]_{rec}$ > TRG	# Reference Sites where $[Hg]_{rec}$ > TRG
Sucker	minimum	9	4	0
Perch	minimum	9	20	2
Trout	minimum	9	4	0
Heron	minimum	9	-	-
Mink	minimum	9	-	-
Sucker	intermediate	7	7	0
Perch	intermediate	7	25	3
Trout	intermediate	7	25	7
Heron	intermediate	7	-	-
Mink	intermediate	7	-	-
Sucker	maximum	6	10	1
Perch	maximum	6	25	4
Trout	maximum	6	25	13
Heron	maximum	6	-	-
Mink	maximum	6	-	-

APPENDIX A. *Literature review of biomagnification factors (BMFs) for total and methyl mercury*

1.0 Introduction

This literature review was carried out to provide supporting information for the assessment of risk of biomagnification of mercury from contaminated sediments in Cornwall, Ontario. Biomagnification factors (BMFs), predator-prey factors (PPFs), and trophic transfer coefficients (TTCs) were obtained or derived from the literature for the calculation of total mercury and methylmercury concentrations in different trophic levels of a simple benthic freshwater food chain model (Figure A1).

1.1 Terminology

Biomagnification is the process at by which the chemical concentration in an organism exceeds that in the organism's diet, due to dietary absorption (Gobas and Morrison 2000). The biomagnification factor (BMF) is an empirically-derived measure of the rate of contaminant transfer between the organism's diet and the organism, and is expressed as the ratio of chemical concentration in the organism to the concentration in its diet (Gobas and Morrison 2000). The synonymous terms predator-prey factor (PPF) and trophic transfer coefficient (TTC) are also found in the literature (USEPA 1997a; Suedel et al. 1994). A food chain multiplier (FCM) is used to quantify the increase in contaminant body burden through uptake from the food chain, but is defined as the factor by which a substance at higher trophic levels exceeds the bioconcentration factor (BCF) at trophic level 1 (NCASI 1999; USEPA 1997a). Therefore, it does not necessarily apply to a specific trophic transfer, and may be a multiple of more than one BMF. BMFs, TTCs, and PPFs are unitless, and the concentrations used to derive them are usually expressed in units of mass of chemical per kg of the organism, and mass of chemical per kg of food, respectively (Gobas and Morrison 2000). These concentrations can be expressed on a wet weight or dry weight basis (Gobas and Morrison 2000). BMFs, TTCs, and PPFs can be applied to specific trophic levels, as well as individual species in a food chain (USEPA 1997b). The term BMF will be used in this document in reference to biomagnification factors, predator-prey factors, and trophic transfer coefficients acquired from the literature.

2.0 Methods

2.1 Literature Search

The literature search was done using typical methods of electronic database and chain-of-citation searches as well as consultation with leading researchers in the field of mercury ecotoxicology and risk assessment. The following electronic databases were used to search primary literature, secondary literature, grey literature, and internet resources:

- ISI Current Contents Connect
- CSA Aquatic Sciences and Fisheries Abstracts (ASFA)
- CSA TOXLINE
- MEDLINE
- National Research Council of Canada (NRC) Research Press database
- US Environmental Protection Agency (USEPA)- various databases of government publications
- US Army Corp. of Engineers (USACE)- various databases of government publications
- Integrated Risk Information System (IRIS)
- Environmental Fate Database (EFDB)
- Oak Ridge National Laboratory (ORNL) publications

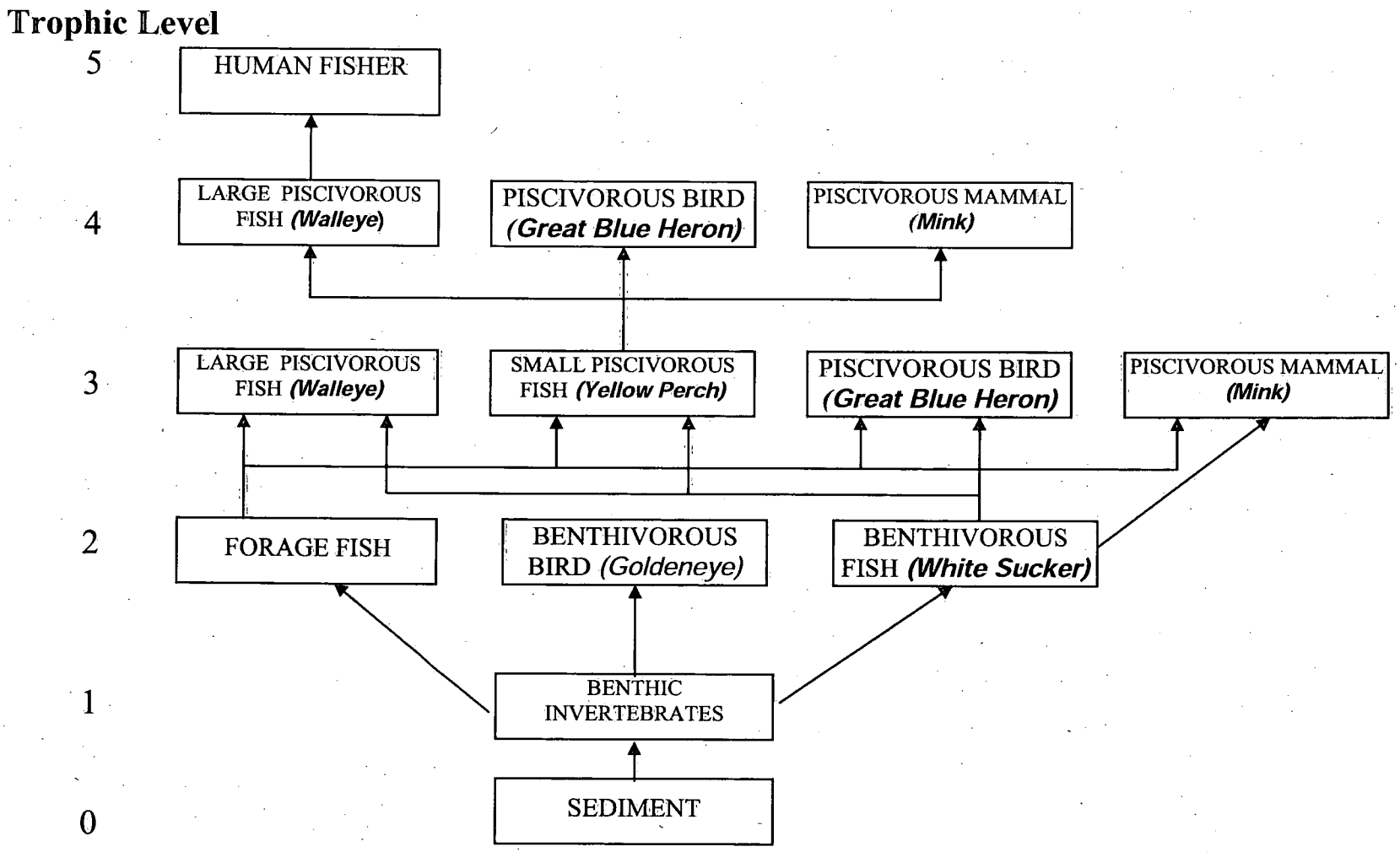

Figure A1. Generalized foodweb model for the assignment of trophic level to biomagnification factor estimates

In addition, the following journals were individually searched for recent and upcoming articles:

- *Archives of Environmental Contamination and Toxicology*
- *Archives of Environmental Health*
- *Bulletin of Environmental Contamination and Toxicology*
- *Canadian Journal of Fisheries and Aquatic Sciences*
- *Chemosphere*
- *Environmental Pollution*
- *Environmental Research*
- *Hydrobiologia*
- *Journal of Great Lakes Research*
- *Science of the Total Environment*
- *Water, Air, and Soil Pollution*
- *Water Research*

Several researchers active in mercury bioaccumulation studies were also contacted as part of the literature search.

The search was focused on the period 1996-2002, as a thorough review of the literature was carried out in a 1997 USEPA document entitled "Mercury Study Report to Congress" document (USEPA 1997a,b,c).

2.2 Assigning Trophic Levels to Receptor Species

Discrete trophic levels were applied using the food chain model (Figure A1). This was done to allow comparison of BMFs from different systems/foodwebs, as well as to conceptualize the transfer and magnification of mercury in the Cornwall scenario. However, the use of discrete trophic levels may lead to lower estimates of BMFs. An excellent discussion about the effects of omnivory on trophic position is found in Vander Zanden and Rasmussen (1996). In short, omnivory is common in aquatic communities (for example, up to 50% in pelagic food webs), and the use of discrete variables to represent trophic position will not adequately account for omnivory. When omnivory is integrated with the use of a continuous measurement of trophic position (ie- using stable isotope methods), estimates of BMFs will generally be higher for each discrete trophic level (Vander Zanden and Rasmussen 1996). Unfortunately, this literature survey did not yield any stable isotope studies on benthic freshwater food webs, and therefore system-specific BMFs based on continuous trophic position could not be obtained for lower trophic levels. Two such estimates for trophic levels 3 and 4 respectively, were obtained from pelagic foodweb studies.

2.3 Selecting Biomagnification Factor Estimates or Candidate Datasets from the Literature

The following criteria were applied to screen literature to obtain either BMFs or candidate datasets for calculating BMFs, after Suedel et al. (1994) and Gobas and Morrison (2000):

- If organisms that were presented were not from a logical food chain, or no evidence was presented that the feeding relationship between predator and prey was a functional feeding relationship, the paper was not used. One exception to this rule was made in selecting a study of mink fed diets of different proportions of contaminated and uncontaminated fish (Halbrook et al. 1997), since there was a reasonable likelihood that these fish species would have been part of their diet.
- Mean concentrations of total Hg or MeHg needed to be presented for both predator and prey, and in comparable units.
- Unless evidence of comparability could be found, studies from non-freshwater systems or with non-comparable species were not used. More information is presented below on the assessment of comparability of different systems and species.

2.4 Calculation of Biomagnification Factors from Candidate Datasets

Biomagnification factors were calculated from mean concentrations of total mercury and/or methylmercury from the literature using the equation (Gobas and Morrison 2000):

$$BMF = C_B/C_D$$

where:
C_B= mean contaminant concentration in the consumer (receptor) species
C_D= mean contaminant concentration in the diet of the organism

In all cases where BMFs were calculated from mean concentrations, the calculation was for the mean concentrations from two trophic levels with a functional feeding relationship, which was defined and demonstrated in the study. Where results were presented for a number of different locations (i.e., several different lakes), BMFs were calculated for each location and then averaged, as opposed to averaging the mean concentrations from all locations to calculate a BMF. In three cases (Hughes et al. 1997; Neumann and Ward 1999; Suedel et al. 1994), a mean BMF was calculated by averaging several reported BMFs. Summaries of these calculations are presented in Tables A3 - A12.

2.5 Comparability of Species and Systems

There were very few studies that quoted BMF estimates for the receptor species and feeding relationships defined in Figure A1. Of the small number of studies which calculated BMFs that were directly comparable in part to the food chain model, most were from freshwater pelagic foodwebs. Some were also studies in quite different ecosystems (marine, temperate montane freshwater, tropic freshwater). Thus, it was important to document the relative comparability of different species and ecosystems to those presented in the study design for this assessment. Information to support substitutions of receptor species for comparable species from the literature (in applying BMF estimates) is presented in Table A13. Species were considered the most qualitatively similar when they occupied similar habitats, had similar feeding habits and dietary composition, similar range, similar feeding substrate, and similar food ingestion:body weight ratio. Sources for this information were CCME (1999a,b), CWS (2002), Sample and Suter (1999), Scott and Crossman (1973), and USEPA (1997c).

Applying BMFs calculated from one system to another is controversial, since rates of trophic transfer of mercury are thought to vary due to abiotic and biotic factors (USEPA 2001). The USEPA, in developing national bioaccumulation factors to assess the risk to human health of mercury exposure, indicated that these factors are poorly understood and are likely to be system and site-specific (USEPA 1997b; USEPA 2001). Abiotic factors which may influence the chemistry of mercury include pH, temperature, and dissolved organic carbon in the waterbody, and these are usually determined by watershed characteristics which in turn affect inputs, bioavailability, speciation, and methylation of mercury in the sediments and water column (Downs et al. 1998; Greenfield et al. 2001; Meyer 1998; Mason et al. 2000; USEPA 2001; Watras et al. 1998). Biotic factors include food chain length, horizontal food web structure, feeding mechanisms of organisms at lower trophic levels, and the age/size/weight or metabolic rates of individuals in the sample used to calculate a given BMF (Environment Canada 1997; Power et al. 2002; USEPA 2000). However, no single factor has been correlated with extent of bioaccumulation in all cases examined (USEPA 2001).

It was also suggested (as discussed above) that much of the uncertainty around applying BMFs from different systems may be due to an oversimplification of predator-prey relationships by using discrete trophic levels (Vander Zanden and Rasmussen 1996). One stable isotope study was found from Papua, New Guinea whose results indicated similar magnitude of biomagnification to temperate and arctic foodwebs (Bowles et al. 2001). Another stable isotope study from an arctic foodweb indicated that age did not affect bioaccumulation of mercury in the muscle of ringed seals or clams (Atwell et al. 1998). A third from a subarctic lake found a higher rate of biomagnification (BMF=5.4 versus 3.0) than for a comparable freshwater temperate system (Power et al. 2002).

Unless the relative comparability to temperate freshwater systems was demonstrated, studies from marine, arctic marine, and tropic freshwater were not used to select or derive BMFs.

3.0 Results

A total of 80 references were examined in detail to yield BMFs, datasets to calculate BMFs, or to provide supporting information in applying BMFs. Results are broken down as follows:

- Primary literature- 61 references
- Secondary literature- 5 references
- Grey literature- 14 references

Of those 80, only 11 yielded appropriate BMFs or datasets, following guidelines set out in section 2 above. However, a number of the references (Cantox Environmental Inc. 2001; Suedel et al. 1994; USEPA 1997a) were reviews that synthesized BMFs from several sources. Along with BMF estimates, the following supporting information was gathered:

- Range, standard deviation, or standard error of BMF estimates
- Trophic level of predator/receptor
- Type of study (field, laboratory, modeling, review)
- Prey species
- Predator species
- Mercury parameter (total Hg or MeHg)
- Scope of study (ie- number of lakes sampled)
- Location of study
- Biological medium sampled
- Relative age/size of organisms sampled
- Reference from which BMF or dataset came from
- Comments

These results are reported in Table A2.

A breakdown of the number of BMFs obtained/calculated per feeding relationship, and the range of corresponding BMF values is presented in Table A1.

Table A1- Breakdown of results of literature review for each hypothetical feeding relationship

Feeding Relationship	Trophic levels of transfer	# of Estimates	Total and Methyl Hg BMFs			Comments
			Low	Medium *	High	
Benthic invertebrates to forage or benthivorous fish	1 - 2	1	3.43	3.43	3.43	High BMF calculated from benthos [THg] values which are below DL excluded.
Benthivorous or forage fish to small piscivorous fish	2 - 3	1	5	5	5	
Benthivorous or forage fish to large piscivorous fish	2 - 3	8	1.12	3.20	32.4	
Benthivorous or forage fish to piscivorous bird	2 - 3	1	6.80	6.80	6.80	High THg value from heron with ambiguous feeding relationship dropped.
Benthivorous or forage fish to piscivorous mammal	2 - 3	10	1.70	5.20	22.64	High THg value from fur/hair excluded. Hg form given as total and methyl for most values.
Small piscivorous fish to large piscivorous fish	3 - 4	1	2.40	2.40	2.40	
Small piscivorous fish to piscivorous bird	3 - 4	6	0.85	2.37	6.80	High THg values from plumage excluded.
Small piscivorous fish to piscivorous mammal	3 - 4	9	1.70	4.7	10.00	Hg form given as total and methyl for most values.

* "Medium" = datum if n = 1, median if n > 2

Table A2- Summary of Literature-Derived Biomagnification Factors by Trophic Level

Value	Range	Trophic Level	Type of Study	Prey Species	Predator Species	Hg Parameter	Scope	Location	Sample Medium	Age/Size of Sample	Reference	Comments
2.14	0.3-7	2	Review	"Primary consumers" (aquatic)	"Secondary consumers" (aquatic)	Total Hg					Suedel et al., 1994	Values reported as TTCs
3.43	0.5-10.5	2	Review	"Primary consumers" (aquatic)	"Secondary consumers" (aquatic)	MeHg					Suedel et al., 1994	Values reported as TTCs
17.13	Not calculated	2	Field	Benthos	Carp and bullhead	Total Hg	One estuary	Old Woman Creek, Lake Erie	Skinless fillets (carp), whole body (bullhead)	>30 cm in length	Francis et al., 1998	BMFs calculated from mean concentrations and feeding relationships reported in paper.
1.12	0.2-1.9	3	Review	"Secondary consumers" (aquatic)	"Top predators" (aquatic)	Total Hg					Suedel et al., 1994	Values reported as TTCs
1.51	Not calculated	3	Field	Lake chubsucker	Redfin pickerel	Total Hg	Nine wetlands	Savannah River Site, South Carolina	Whole body	Chubsucker mean length/weight=79 mm/4g Pickerel mean length/weight= 106 mm/3g	Snodgrass et al., 2000	Mean BMF calculated from individual wetland BMFs, which were calculated from geometric mean concentrations in each species for each wetland. Feeding relationship implied by results cited from other studies from that area.
1.55	1.2-1.8	3	Field	Groove-snouted catfish (omnivore) and seven-spotted archerfish (insectivore)	Barramundi, giant freshwater anchovy, Sepik garpike	MeHg	One lake	Papua, New Guinea	Whole body		Bowles et al., 2001	Stable isotope ($\delta^{15}N$) study. Results suggest that the biomagnification power of the food web is similar to that of temperate-lake and arctic-marine systems. Range of BMFs based on BMFs calculated from +/- 1 SD from mean MeHg concentrations.
1.70	Not reported	3	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	Pooled results of twelve studies.	Ontario (3 studies), Georgia (3), Louisiana (1), Manitoba (2), Wisconsin (2), Norway (1)	Muscle	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1986. BMF calculated by Cantox Environmental Inc.
2.40	1-4	3	Field	Bluegill, black crappie, yellow perch	Chain pickerel, largemouth bass	Total Hg	Two lakes	Connecticut	Axial muscle (whole fillets)	Fish aged 2-5 years	Neumann and Ward, 1999	
2.70	Not reported	3	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Georgia	Muscle	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
3.00	Not reported	3	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	One lake, N=20 for fish sample, N=4 for otter sample	Tadenac Lake, Muskoka, Ontario	Muscle	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1983. BMF calculated by Cantox Environmental Inc.
3.40	Not reported	3	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
4.00	Not reported	3	Modelling	Pelagic forage fish (smelt, ciscoes, coregonids, alewife, ninespine stickleback)	Lake trout	Total Hg	96 lakes, >10 individuals/species; period 1975-84 (source= MOE sportfish contaminants monitoring)	Canadian Shield lakes, Ontario	Whole skinless fillets (smaller fish), axial muscle (larger fish)	Pooled results	Vander Zanden and Rasmussen, 1996	BMF corrected by authors for omnivory from original value of 2.0 defined by Cabana et al., 1994. Correction based on results of $\delta^{15}N$ stable isotope study of trophic position and effects of omnivory on trophic position. Sampling details from Cabana et al.
4.70	Not reported	3	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	Pooled results of twelve studies.	Ontario (3 studies), Georgia (3), Louisiana (1), Manitoba (2), Wisconsin (2), Norway (1)	Liver	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1986. BMF calculated by Cantox Environmental Inc.
5.00	Geometric SD=1.47	3	Review	"Forage fish"	"Piscivorous fish"	MeHg	14 studies	Michigan (2 studies), Ontario (5), Manitoba (1), Wisconsin (1), New York (1), Norway (1), Sweden (2), Brazil (1)	Various	Various	USEPA, 1997	BMF is geometric mean of values from literature review. Selected values from the literature used in the calculation of the average BMF are presented in attached "USEPA, 1997" worksheet.
5.40	Not reported	3	Field	Forage fish (burbot, cisco, northern lake chub, round whitefish, threespine stickleback) and benthivores (longnose sucker, slimy sculpin)	Lake trout	Total Hg	One lake	Stewart Lake, northern Labrador	Dorsal muscle	All age classes	Power et al., 2002	BMF reported in study. Stable isotope study of a subarctic freshwater lacustrine system.
5.70	Not reported	3	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Georgia	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
6.80	Not reported	3	Review	Bluntnose minnow, rainbow smelt	Common loon	Total Hg	One lake, N=20 for fish sample; N=1 for loon sample	Tadenac Lake, Muskoka, Ontario	Whole skinless fillet (fish), breast muscle (birds)	Pooled sample of fish from beach seining (fish). Loon= 5 kg	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1983. BMF calculated by Cantox Environmental Inc.
10.00	Not reported	3	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Not reported	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
10.00	Not reported	3	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
14.29	Not calculated	3	Field	Carp, bullhead, catfish (<30 cm length)	Bowfin, catfish (>30 cm length)	Total Hg	One estuary	Old Woman Creek, Lake Erie	Skinless fillets (carp, bowfin, catfish), whole body (bullhead)	Piscivores= >30 cm in length, benthivores= <30 cm length	Francis et al., 1998	BMFs calculated from mean concentrations and feeding relationships reported in paper.
32.40	0.1-141	3	Review	"Secondary consumers" (aquatic)	"Top predators" (aquatic)	MeHg					Suedel et al., 1994	Values reported as TTCs
86.56	Not calculated	3	Field	Carp, bullhead, catfish (<30 cm length); gizzard shad, black crappie	Great blue heron	Total Hg	One estuary	Old Woman Creek, Lake Erie	Skinless fillets (carp, catfish, crappie), whole body (bullhead, gizzard shad)	Benthivores= <30 cm length, heron (N=1) size not reported	Francis et al., 1998	BMFs calculated from mean concentrations and feeding relationships reported in paper.
87.81	82-96	3	Field	Freshwater and intertidal fishes	Otter	Total Hg	One coastal creek and estuary (N= 32 otters)	Prince William Sound, Alaska	Fur	Juveniles to old adults (four age categories)	Ben-David et al., 2001	BMF calculated from mean concentrations and standard errors presented in paper. The feeding relationship with freshwater fishes was supported by stable isotope measurements.
Liver- 13.92 Kidney- 22.64 Hair- 108.23	Liver- 12-17 Kidney- 20-25 Hair- 87-149	3	Controlled field	Benthivores	American mink	Total Hg	50 female farmed mink	Oak Ridge National Laboratory, Tennessee	Liver, kidney, and fur	Female adults	Halbrook et al., 1997	BMFs calculated from mean concentrations in different tissues and different specific dietary mixes of contaminated and uncontaminated fish.

Table A2- Summary of Literature-Derived Biomagnification Factors by Trophic Level (continued)

Value	Range	Trophic Level	Type of Study	Prey Species	Predator Species	Hg Parameter	Scope	Location	Sample Medium	Age/Size of Sample	Reference	Comments
1.70	Not reported	4	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	Pooled results of twelve studies.	Ontario (3 studies), Georgia (3), Louisiana (1), Manitoba (2), Wisconsin (2), Norway (1)	Muscle	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1986. BMF calculated by Cantox Environmental Inc.
1.93	1-4	4	Field	Yellow perch	Osprey	Total Hg (osprey), MeHg (yellow perch)	Five osprey nesting areas	St. Mary's R., Georgian Bay, Kawartha Lakes, New Jersey	Eggs	Freshly laid and addled eggs	Hughes, 1997	
2.40	1-4	3	Field	Bluegill, black crappie, yellow perch	Chain pickerel, largemouth bass	Total Hg	Two lakes	Connecticut	Axial muscle (whole fillets)	Fish aged 2-5 years	Neumann and Ward, 1999	
2.70	Not reported	4	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Georgia	Muscle	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
3.00	Not reported	4	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	One lake, N=20 for fish sample, N=4 for otter sample	Tadenac Lake, Muskoka, Ontario	Muscle	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1983. BMF calculated by Cantox Environmental Inc.
3.40	Not reported	4	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
4.70	Not reported	4	Review	Only reported as "concentration of MeHg in diet"	Otter	Total Hg and MeHg	Pooled results of twelve studies.	Ontario (3 studies), Georgia (3), Louisiana (1), Manitoba (2), Wisconsin (2), Norway (1)	Liver	Not reported	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1986. BMF calculated by Cantox Environmental Inc.
5.70	Not reported	4	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Georgia	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
6.90	Not reported	4	Review	Smallmouth bass, northern pike, lake trout	Common loon	Total Hg	One lake, N=20 for fish sample, N=1 for loon sample	Tadenac Lake, Muskoka, Ontario	Dorso-lateral muscle (fish), breast muscle (birds)	Pooled sample of fish from gill netting (fish). Loon= 5 kg	Cantox Environmental Inc., 2001	Sampling details from Wren et al., 1983. BMF calculated by Cantox Environmental Inc.
10.00	Not reported	4	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Not reported	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
10.00	Not reported	4	Review	Fish (species not reported)	Otter	Total Hg and MeHg	Not reported	Not reported	Liver	Not reported	Cantox Environmental Inc., 2001	BMF calculated by Cantox Environmental Inc.
10.00		4	Review	Predatory fishes	American mink	MeHg	Not reported	Not reported	Not reported	Not reported	USEPA, 2000	
14.50	12-16	4	Field	Yellow perch	Osprey	Total Hg (osprey), MeHg (yellow perch)	Five osprey nesting areas	St. Mary's R., Georgian Bay, Kawartha Lakes, New Jersey	Feathers- wing/mantle/tail	Pooled sample from chicks and adults	Hughes, 1997	
Liver-2.61 Kidney- 3.81 Brain- 0.85 Muscle- 1.40 Feathers- 55.7	Not calculated	4	Field	Northern pike, coregonids, walleye, suckers	Osprey	Total Hg	130 nests in three major watersheds in areas impacted and not impacted by hydroelectric development	James Bay/Hudson Bay areas, Quebec	Liver, kidney, brain, breast muscle, and feathers of osprey	Chicks and adults	Des Granges et al., 1998	BMFs calculated from mean concentrations in different tissues and weighted mean concentrations in main fish species consumed in the diet. Evidence for feeding relationship established in the paper.

Table A3- Data summary and calculations from Hughes (1997).

Location	Feather/YP (4-5)	Feathers/YP (20)	Eggs/YP (4-5)	Eggs/YP (20)
St. Mary's River	12.33	15.74	1.07	1.36
Georgian Bay	12.00	21.71	2.05	3.71
Kawartha Lakes	13.58	11.64	1.83	1.57
Mean BMF	**14.50**		**1.93**	

Notes- YP=yellow perch. (4-5)=yellow perch aged 4-5 years, (20)= 20 cm yellow perch. Data presented are unitless BMFs. Mean BMFs are for mercury in feathers and eggs, averaged for both groups of prey each. Mercury concentrations used to derive BMFs were ug/g dry weight total Hg.

Table A4- Data summary and calculations from Neumann and Ward (1999).

		BMF @ age				
Lake	Species	Age 2	3	4	5	Lake Average BMF
Pickerel	Black crappie->TP	3.7	3.1	2.7	2.2	2.88
	Bluegill->TP	2.4	2.6	2.9	3.4	
Lillinonah	Yellow perch->TP	1.4	1.4	1.3	1.2	1.93
	Bluegill->TP	1.9	2.3	2.7	3.2	
					Mean	**2.40**

Notes- TP=top predators- largemouth bass, smallmouth bass, and chain pickerel. Mercury concentration values used to derive BMFs were expressed in ug/g dry weight total Hg.

Table A5- Data summary and calculations from Suedel et al. (1994).

Parameter	Trophic Level 2	Trophic Level 3
BMF Total Hg	0.3	0.2
	0.3	0.4
	1.6	1
	1.7	1.4
	6.8	1.8
		1.9
Mean	**2.14**	**1.12**
BMF MeHg	0.5	0.1
	0.7	0.2
	2	0.3
	10.5	0.7
		4.5
		80
		141
Mean	**3.425**	**32.4**

Note- data from literature used to derive BMFs (reported as trophic transfer coefficients (TTCs)) were exp
comparable units measured in organisms which were part of functional food chains/feeding

Table A6- Data summary and calculations from Bowles et al. (2001).

Species	Trophic Level	Mean [MeHg]	+1SD	-1SD
Arius berneyi	2	0.18	0.33	0.03
Toxotes chatareus	2	0.29	0.44	0.14
Mean [MeHg] TL2		0.24	0.38	0.09
Strongylura kreffti	3	0.38	0.63	0.14
Thryssa scratchleyi	3	0.34	0.66	0.02
Lates calcarifer	3	0.46	0.76	0.16
Mean [MeHg] TL3		0.39	0.68	0.10
BMFs	**2 --> 3**	**1.67**	**1.78**	**1.20**
Mean BMF		**1.55**		

Note- *A. bernyi*=groove-snouted catfish *T. chatareus*=seven-spotted archerfish *S. kreffti*=Sepik garpike, *T.scratchleyi*=giant freshwater anchov *L. calcarifer*=barramundi. All concentrations used to derive BMFs were expressed as ug/g wet weight MeHg.

Table A7- Summary of BMFs used in USEPA's (1997) PPF calculation

BMF	Predator	Prey	Location
2.75	lake trout	bloater	L. Michigan
3.5	northern pike, largemouth bass	yellow perch, white sucker	35 lake aggregate, upper michigan
3.6	northern pike, largemouth bass	rainbow smelt, whitefish	L. Tyrifjorden, Norway
4	northern pike, walleye	specific weighted diets	L. Simcoe
5	lake trout (60 cm)	rainbow smelt (15 cm)	9 lake aggregate, Ontario
5.06	northern pike, walleye	white sucker, cisco	average of 6 Canadian Shield lakes
5.22	walleye (age 5)	yellow perch (age 2)	10 lake aggregate, Wisconsin
5.63	smallmouth bass, walleye	gizzard shad, bluegill	Onandaga Lake, New York
6.8	northern pike	yellow perch	43 lake aggregate, Sweden
7.1	largemouth bass	silversides	Clear L., California
7.4	northern pike	yellow perch	25 lake aggregate, Sweden
9.8	northern pike	spottail shiner, yellow perch	4 lake average, Manitoba

Table A8- Data summary and calculations from Ben-David et al. (2001).

Trophic Transfer	Mean [total Hg]	+1 SE	-1 SE	Comments
Jackpot Bay freshwater fishes	0.12	0.14	0.1	Dolly Varden, coastrange sculpin, sticklebacks
Jackpot Bay intertidal fishes	0.085	0.092	0.07	Rockfish, kelp greenling, crescent gunnels, intertidal sculpins,
Mean Jackpot Bay fishes	0.1025	0.116	0.085	
Jackpot Bay otters	9	9.5	8.2	River otter
BMF	**87.80**	**81.90**	**96.47**	

Note- all mercury concentrations used to calculate BMFs were expressed as mg/kg dry weight total Hg. Standard errors used were those reported in the study. Both intertidal and freshwater fish Hg concentrations were used due to stable isotope dietary analysis which indicated a significant portion of intertidal fish in diet.

Table A9- Data summary and calculations for Des Granges et al. (1998).

Type of Habitat	mean [Fish]	mean [Liver]	mean [Kidney]	mean [Brain]	mean [Muscle]	mean [Feathers]
Developed	1.420	3.610	5.280	1.010	1.790	58.090
Natural	0.234	0.720	0.910	0.230	0.360	16.470

BMF per Habitat	Liver	Kidney	Brain	Muscle	Feathers
BMF Developed	2.542	3.718	0.711	1.261	40.908
BMF Natural	3.080	3.893	0.984	1.540	70.460
Mean BMF	**2.811**	**3.806**	**0.848**	**1.400**	**55.684**

Note- concentrations are expressed in mg/kg dry weight total Hg. "Developed" areas are nesting sites on hydroelectric reservoirs.

Table A10- Data summary and calculations from Halbrook et al. (1997).

Diet	mean [Diet]	mean [Liver]	mean [Kidney]	mean [Hair]
B	0.05	0.61	1.25	7.43
D	0.15	1.93	3.47	13.44
E	0.22	3.67	4.35	19.03

Diet	BMF Liver	BMF Kidney	BMF Hair
B	12.20	25.00	148.60
D	12.87	23.13	89.60
E	16.68	19.77	86.50
Mean BMF	13.92	22.64	108.23
Range	12-17	20-25	87-149

Table A11- Data summary and calculations for Snodgrass et al. (2000).

Wetland	Gmean[total Hg] benthivore	Gmean[total Hg] top predator
40	0.18	0.26
41	0.32	0.49
42	0.19	0.32
77	0.63	1.05
97	0.27	0.24
136	0.33	0.68
139	0.28	0.35
142	0.2	0.31
Mean		

Note- benthivore= lake chubsucker, top predator= redfin pickerel, Gmean=geometric mean. All concentrations are expressed in ug/g dry weight total Hg.

Table A12- Data summary and calculations from Francis et al. (1998).

Receptor	Mean [Total Hg]	Mean [MeHg]	Cutoff
Benthos	0.003		
Carp Sm	0.019	0.015	<30 cm
Carp Lg.	0.100	0.101	>30 cm
Catfish Sm.	0.066	0.064	<30 cm
Catfish Lg.	0.199	0.199	>30 cm
Bullhead	0.003	0.003	
Bowfin	0.636	0.613	
Great Blue Heron	1.620		
Crappie	0.003	0.001	
Gizzard Shad	0.004	0.002	

Trophic Transfer	Trophic Level	BMF	Details
Benthos-Benthivores	2	17.128	mean[large carp+bullhead]/[benthos]
Benthivores-Large Piscivores	3	14.294	mean[bowfin+large catfish]/mean[small carp+bullhead+small catfish]
Benthivores-Piscivorous Birds	4	85.563	[heron]/mean[small carp+bullhead+small catfish+crappie+gizzard shad]

Note- Benthos= oligochaetes, larval Chironomids, Ceratopogonidae, Chaoboridae. Carp and catfish were grouped into small and large size classes to reflect their variable trophic level with size. Functional feeding relationships were defined in the study. BMFs were only derived for total Hg. Mercury concentrations were expressed as ug/g wet weight of total Hg and MeHg.

Table A13- Summary information to compare alternate species to receptor species

Trophic Level	Latin Name	Common Name	Receptor Species Comparison	Habitat	Range Include Cornwall?	Food Type	Food Substrate	Feeding Technique	Food Ingestion: Body Weight Ratio	Food Size Class	Source	Other
2	*Bucephala clangula*	Common goldeneye	Common goldeneye	Lakes/ponds/rivers	Yes	Omnivore	Freshwater benthic	Bottom forager	0.3		CCME, 1999; CWS, 2002	
2	*Bucephala albeola*	Bufflehead	Common goldeneye	Lakes/ponds/rivers	No, but in Great Lakes	Omnivore	Freshwater benthic	Gleaner	0.36		CCME, 1999; CWS, 2002	
2	*Aythya valisineria*	Canvasback	Common goldeneye	Marshes	Yes	Omnivore	Freshwater benthic	Bottom forager			CWS, 2002	Regionally very rare.
2	*Melanitta fusca*	White-winged scoter	Common goldeneye	Lakes/ponds/rivers	No, but in Great Lakes	Molluscovore/ crustaceovore	Freshwater benthic	Gleaner			CWS, 2002	Regionally rare.
2	*Aythya affinis*	Lesser scaup	Common goldeneye	Lakes/ponds/rivers	Yes	Omnivore	Freshwater benthic	Bottom forager	0.31		CCME, 1999; CWS, 2002	
2	*Catastomous commersoni*	White sucker	White sucker	Warmer, shallow lakes or warm, shallow bays, and tributary rivers of larger lakes. Generally found at depths <30 feet.	Yes	Insectivore/molluscovore	Freshwater benthic				Scott and Crossman, 1973	
2	*Erimyzon sucetta*	Lake chubsucker	White sucker	Small, shallow, warm, weedy ponds.	No, northern extreme of range is Lake Erie and Lake St. Clair	Insectivore	Freshwater benthic				Scott and Crossman, 1973	
2	*Cyprinus carpio*	Common carp	White sucker	Warm, turbid waters.	Yes	Herbivore/Insectivore/ Mutioscovore	Freshwater benthic				Scott and Crossman, 1973	
3	*Coregonus artedii*	Cisco	Forage fish	Deeper waters of lakes.	Yes	Omnivore	Freshwater pelagic				Scott and Crossman, 1973	
3	*Couesius plumbeus*	Northern lake chub	Forage fish	Deeper waters of lakes and large rivers.	Yes	Omnivore	Freshwater pelagic				Scott and Crossman, 1973	
3	*Amia calva*	Bowfin	Walleye	Swampy, vegetated bays of warm lakes and rivers.	Yes	Piscivore	Freshwater benthic				Scott and Crossman, 1973	
3	*Catastomous catastomous*	Longnose sucker	White sucker	Lakes/ponds/rivers (almost everywhere in clear, cold water)	Yes	Invertebrates	Freshwater benthic				Scott and Crossman, 1973	
3	*Cottus cognatus*	Slimy sculpin	White sucker	Deeper waters of lakes and cooler streams on rocky or gravelly substrate	Yes	Insectivore	Freshwater benthic				Scott and Crossman, 1973	
3	*Prosopium cylindraceum*	Round whitefish	White sucker	Lakes at depths less than 150 feet	Yes	Omnivore	Freshwater benthic				Scott and Crossman, 1973	
2 and 3	*Lepomis macrochirus*	Bluegill	Forage fish	Shallow, weedy, warm water of large and small lakes, ponds, and heavily vegetated, slowly flowing areas of small rivers and large creeks. Shallow water, < 20 feet deep.	Yes	Insectivore/omnivore	Freshwater benthic				Scott and Crossman, 1973	
2 and 3	*Coregonus clupeaformis*	Lake whitefish	Forage fish	Cool water of lakes, spawns in shallower water. Depth range of 60 to 174 feet.	Yes	Omnivore	Freshwater benthic				Scott and Crossman, 1973	
2 and 3	*Ictalurus punctatus*	Channel catfish	Walleye/white sucker	Cool, clear, deeper waters of large lakes and rivers	Yes	Omnivore	Freshwater benthic				Scott and Crossman, 1973	
2 and 3	*Perca flavescens*	Yellow perch	Yellow perch	Warm to cool water habitats of all types. Prefer clear water and abundant vegetation. Shallow water <30 feet deep.	Yes	Omnivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	
2 and 3	*Pomoxis nigromaculatus*	Black crappie	Yellow perch	Clear, quiet, warm water of large ponds, small lakes, bays and shallower areas of larger lakes, and areas of low flow of larger rivers.	Yes	Omnivore	Freshwater benthic				Scott and Crossman, 1973	
2 and 3	*Ictalurus nebulosus*	Brown bullhead	Yellow perch/white sucker	Shallow, warm-water areas of ponds/lakes/rivers. Depths of <40 feet.	Yes	Omnivore	Freshwater benthic				Scott and Crossman, 1973	
3 and 4	*Lutra canadensis*	River otter	American mink	Lakes/ponds/rivers	Yes	Piscivore	Freshwater pelagic and benthic		0.10-0.17	>30 cm	Sample and Suter, 1999; CCME, 1999; USEPA, 1997	100% of diet is fish
3 and 4	*Mustela vison*	American mink	American mink	Lakes/ponds/rivers	Yes	Omnivore	Freshwater pelagic and benthic		0.14-0.24	0-20 cm	Sample and Suter, 1999; CCME, 1999; USEPA, 1997	33-90% of diet is fish or aquatic prey (mean=55%)
3 and 4	*Gavia immer*	Common loon	Great blue heron	Lakes/ponds/rivers (primary habitat)	Yes	Piscivore	Freshwater pelagic	Diver	0.18		CWS, 2002; CCME, 1999	
3 and 4	*Pandion haliaetus*	Osprey	Great blue heron	Lakes/ponds/rivers (teritary habitat)	Yes	Piscivore	Freshwater pelagic	Foot plunger	0.2	0-40 cm	CWS, 2002; CCME, 1999; Sample and Suter, 1999	
3 and 4	*Ardea herodias*	Great blue heron	Great blue heron	Lakes/ponds/rivers (teritary habitat)	Yes	Piscivore	Freshwater pelagic	Ambusher	0.21	0-30 cm	CWS, 2002; CCME, 1999; Sample and Suter, 1999	
3 and 4	*Stizostedion vitreum*	Walleye	Walleye	Shallow, turbid lakes; large streams or rivers	Yes	Piscivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	
3 and 4	*Esox lucius*	Northern pike	Walleye	Heavily vegetated slow-moving rivers or weedy bays of lakes	Yes	Piscivore/Omnivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	
3 and 4	*Micropterus salmoides*	Largemouth bass	Walleye	Shallow bays of larger lakes, more rarely large, slow-moving rivers	Yes	Omnivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	Adult diet is 50-90% small fishes
3 and 4	*Esox niger*	Chain pickerel	Walleye	Sluggish streams and heavily vegetated lakes and ponds; water < 10 feet deep	Yes	Piscivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	
3 and 4	*Esox americanus americanus*	Redfin pickerel	Walleye	Sluggish, heavily vegetated acidic streams; less frequently in ponds and weedy backwaters/quiet bays of larger lakes/rivers	Yes	Piscivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	
3 and 4	*Salvelinus namaycush*	Lake trout	Walleye	Deep lakes; less frequently in northern half of range in shallow lakes and in rivers	Yes	Omnivore	Freshwater pelagic				Scott and Crossman, 1973	
3 and 4	*Lota lota* (Linnaeus)	Burbot	Walleye	In central/southern Canada, the deep waters of lakes and rivers. Restricted to below hypolimnion in summer.	Yes	Omnivore	Freshwater pelagic and benthic				Scott and Crossman, 1973	

APPENDIX B. *Mercury in sediment and biological effects from 2000 surveys*

Table B1. Mean total and methyl mercury levels in sediments from Jellicoe Cove 2000 surveys (concomitant sites). Biological effects from BEAST analysis.

	Total Hg in Sediment (ug/g)		Methyl Hg in Sediment (ng/g)		Biological Effects[a]	
Location/Site	2000[a]	2000[b]	2000[a]	2000[b]	Community	Toxicity
A1	0.04	< 0.015	0.00	-	Different	Toxic
A2	0.24	< 0.015	2.45	-	Very Different	Non-toxic
A5	2.26	5.0	9.53	-	Poss. Different	Non-toxic
B5	5.46	6.7	9.38	-	Different	Non-toxic
C3	0.65	6.1	9.64	-	Very Different	Non-toxic
6958/C5	10.10	4.0	7.16	-	Poss. Different	Non-toxic
C6	0.40	4.8	2.28	-	Very Different	Non-toxic
D1	1.90	0.36	10.0	-	Very Different	Non-toxic
D4	5.06	5.9	17.8	-	Different	Non-toxic
D5	8.13	13.8	15.2	-	Very Different	Non-toxic
E3	1.33	1.3	19.4	-	Very Different	Non-toxic
E5	12.50	24.0	16.5	15.7	Very Different	Non-toxic
F2	0.83	0.40	10.9	-	Very Different	Non-toxic
F4	11.10	7.4	20.4	-	Different	Non-toxic
G3	3.46	-	20.5	-	Different	Non-toxic
G5	7.59	31.0	18.3	-	Very Different	Non-toxic
G6	4.13	17.0	12.9	-	Very Different	Non-toxic
H3	3.93	3.8	14.3	-	Different	Non-toxic
H5	19.50	32.0	22.6	-	Very Different	Non-toxic
I5	2.30	4.6	8.76	-	Very Different	Non-toxic
6957/J5	0.94	0.55	2.50	-	Very Different	Non-toxic

[a] Milani et al. 2002.
[b] Burt and Fitchko 2002. Value represents the average Hg concentration of 0-5 cm and 5-10 cm core samples.

APPENDIX C. *Conversion of total and methyl mercury concentration (dry weight) in benthic invertebrates to wet weight concentrations*

Table C1. Total mercury in biota (***converted to ng/g wet weight***), collected from Jellicoe Cove, Peninsula Harbour, and from reference sites.

Area	Site	BIOTA – Total Hg (ng/g ww)	
		Midge	Amphipod
Reference	PH1	10.20	5.88
	PH2	12.92	9.65
	PH11	10.41	6.29
	PH13	6.25	8.25
	PH14	13.57	10.92
	PH15	50.38	26.49
	PH16	53.46	8.11
	PH17	55.85	7.82
	PH18	6.06	6.29
	PH20	26.80	7.01
	PH21	8.06	7.24
	PH22	218.86	16.20
	PH26	131.23	14.61
Jellicoe Cove	JC 2A	39.43	27.95
	JC 3A	121.88	36.37
	JC 4A	155.09	100.92
	JC 5A	804.15	137.62
	JC 6A	176.16	58.98
	JC 7A	277.51	81.17
	JC 1B	57.25	48.95
	JC 2B	378.21	75.38
	JC 3B	211.93	92.40
	JC 4B	431.60	66.76
	JC 5B	213.64	124.07
	JC 6B	676.79	155.26
	JC 7B	637.07	314.97
	JC 1C	120.42	79.81
	JC 2C	243.47	107.62
	JC 3C	263.71	90.93
	JC 4C	287.18	98.19
	JC 5C	157.13	140.06
	JC 6C	255.93	117.41
	JC 7C	439.13	95.01
	JC 1D	136.55	41.04
	JC 2D	362.47	50.60
	JC 3D	261.42	76.42
	JC 4D	147.77	52.60
	JC 5D	180.11	55.87

[a] lab duplicate, [b] lab replicate

Table C2. Methyl mercury in biota (***converted to ng/g wet weight***), collected from Jellicoe Cove, Peninsula Harbour, and from reference sites.

Area	Site	BIOTA – Methyl Hg (ng/g ww)	
		Midge	Amphipod
Reference	PH1	2.30	4.80
	PH2	2.72	4.50
	PH11	4.31	2.55
	PH13	2.82	3.35
	PH14	2.90	3.37
	PH15	36.70	16.02
	PH16	3.89	2.74
	PH17	2.33	3.80
	PH18	4.53	3.25
	PH20	7.49	4.39
	PH21	2.42	3.30
	PH22	6.45	5.41
	PH26	5.01	5.41
Jellicoe Cove	JC 2A	9.28	16.32
	JC 3A	36.91	19.82
	JC 4A	21.26	27.93
	JC 5A	49.13	47.41
	JC 6A	75.05	42.50
	JC 7A	37.58	30.42
	JC 1B	14.96	15.03
	JC 2B	16.54	21.92
	JC 3B	9.72	19.99
	JC 4B	7.96	30.12
	JC 5B	8.57	28.23
	JC 6B	21.86	32.34
	JC 7B	73.84	54.49
	JC 1C	23.03	15.43
	JC 2C	4.35	19.23
	JC 3C	3.58	22.95
	JC 4C	9.98	20.19
	JC 5C	6.11	16.17
	JC 6C	20.84	42.83
	JC 7C	14.33	2.81
	JC 1D	5.49	9.94
	JC 2D	4.77	15.49
	JC 3D	4.09	15.17
	JC 4D	9.95	16.51
	JC 5D	7.20	22.69

[a] lab duplicate, [b] lab replicate

APPENDIX D. *QA/QC results*

Table D1. Sediment nutrient concentrations, metals, and particle size fractions for field replicate samples.

Site		TOC	TKN	TP	% silt	% sand	% clay	Fe	Mn	Total Hg	Methyl Hg
PH14	Mean	1.20	773.67	603.00	19.93	57.71	22.36	1.31	276.00	58.33	0.21
	SD	0.12	49.60	16.46	1.83	2.53	2.69	0.14	18.25	13.61	0.02
	CV	9.61	6.41	2.73	9.17	4.38	12.03	10.34	6.61	23.34	9.43
JC4C	Mean	4.08	837.33	574.67	31.40	56.03	12.57	1.27	143.33	17795.33	21.73
	SD	0.13	70.19	62.17	0.86	1.47	2.26	0.04	5.86	5195.42	2.30
	CV	3.26	8.38	10.82	2.74	2.62	17.98	3.17	4.09	29.20	10.60
JC6C	Mean	5.36	956.67	535.33	23.67	63.82	12.51	1.30	143.33	16866.17	9.76
	SD	0.37	138.78	16.17	2.12	1.38	2.03	0.02	1.53	3157.39	0.59
	CV	6.90	14.51	3.02	8.97	2.17	16.24	1.54	1.07	18.72	6.00
JC5D	Mean	5.46	1096.67	509.00	15.02	70.93	14.05	1.24	153.33	5549.00	10.32
	SD	0.36	200.40	21.66	2.82	1.65	1.18	0.02	1.53	669.48	1.42
	CV	6.68	18.27	4.25	18.75	2.33	8.41	1.23	1.00	12.06	13.80

Table D2. Laboratory QA/QC data for sediment total and methyl mercury from Flett Research Ltd.

SEDIMENT: TOTAL MERCURY

Sample Recovery

Site	Comments	% Hg Recovery
PH1		98.7
PH2		103.0
PH11		103.0
PH13		98.7
PH1400		103.0
PH1401		103.0
PH1402		103.0
PH15		98.7
PH16		103.0
PH16	duplicate	103.0
PH17		103.0
PH18		103.0
PH20		103.0
PH21		103.0
PH22		103.0
PH26		103.0
JC2A		98.7
JC2A	duplicate	98.7
JC3A		95.1
JC4A		95.1
JC5A		103.0
JC6A		-
JC7A		98.7
JC1B		95.1
JC2B		95.1
JC3B		95.1
JC3B	duplicate	95.1
JC4B		95.1
JC5B		95.1
JC6B		95.1
JC7B		103.0
JC1C		98.7
JC2C		95.1
JC3C		95.1
JC4C-1		98.3
JC4C-2		95.1
JC4C-3		103.0
JC5C		95.1
JC5C	duplicate	95.1
JC6C-1		95.1
JC6C-2		103.0
JC6C-2	duplicate	103.0
JC6C-3		103.0
JC7C		103.0
JC1D		98.7
JC2D		103.0
JC3D		95.1
JC4D		103.0
JC5D-1		95.1
JC5D-2		98.7
JC5D-3		95.1
	Mean	**99.29**
	Range	**95.1 - 103.0**

Matrix Spike recovery

Site	% Recovery
JC3B	103.7
JC5C	86.6
PH16	103.3
JC6C	103.0
JC2A	98.7
Mean	**99.06**
Range	**86.6 - 103.7**

Reference Sediment

Marine sediment standard (MESS - 2: 92 ng/g)

Run	THg	Mean %Recovery
1	88.4	
2	96.6	100.6
3	88.9	
4	88.9	96.7
5	95.6	
6	93.8	103.0
Mean	**92.03**	**100.10**

SEDIMENT: METHYL MERCURY

Sample Recovery

Site	Comments	% Recovery
PH1		87.4
PH2		98.6
PH11		99.2
PH11	duplicate	99.2
PH13		87.4
PH14-1		99.2
PH14-2		87.4
PH14-3		87.4
PH14-3	duplicate	87.4
PH15		87.4
PH16		98.6
PH17		87.4
PH18		87.4
PH20		99.2
PH21		75.9
PH21	repeat	75.9
PH22		99.2
PH26		99.2
JC2A		96.7
JC2A	duplicate	96.7
JC3A		98.6
JC3A	duplicate	98.7
JC3A	triplicate	106.2
JC3A	trip-repeat	106.2
JC4A		94.4
JC5A		100.8
JC5A	duplicate	100.8
JC6A		-
JC7A		106.2
JC7A	repeat	106.2
JC1B		99.2
JC1B	duplicate	96.7
JC1B	triplicate	106.2
JC2B		98.6
JC3B		94.4
JC4B		96.7
JC5B		94.4
JC6B		98.6
JC6B	duplicate	98.6
JC7B		100.8
JC1C		96.7
JC2C		106.2
JC2C	duplicate	106.2
JC3C		94.4
JC4C-1		98.6
JC4C-2		98.6
JC4C-3		100.8
JC5C		94.4
JC5C	duplicate	94.4
JC6C-1		106.2
JC6C-1	duplicate	106.2
JC6C-2		101.8
JC6C-3		100.8
JC6C-3	repeat	100.8
JC7C		100.8
JC1D		96.7
JC2D		100.8
JC3D		106.2
JC4D		100.8
JC5D-1		94.4
JC5D-2		96.7
JC5D-3		94.4
	Mean	**97.3**
	Range	**75.9 - 106.2**

Matrix Spike Recovery

Site	Comments	% Recovery
JC3D		99.0
JC7A		113.3
PH21		75.9
PH1		89.6
PH13		85.1
JC1D		89.4
JC4B		104.0
JC6C-3		94.5
JC2D		107.1
JC4C-2		103.3
PH2		93.8
PH22		99.2
JC1B		99.2
PH22	repeat	104.7
JC1B	repeat	98.9
JC5D-1		94.3
JC3B		94.4
	Mean	**96.8**
	Range	**75.9 - 113.3**

Table D3. Laboratory QA/QC data for total and methyl mercury from Flett Research Ltd. (cont.)

BIOTA: TOTAL MERCURY

Reference Material (DORM 2, DFO MQAP FISH SAMPLES)

Run	Standard	THg	Expected THg	% Recovery	Mean
1	DFO Bag 296	476	449	106	100
	DFO Bag 296	420	449	94	
	DFO Bag 297	212	205	104	106
	DFO Bag 297	224	205	109	
	N.R.C. (Dorm2)	4278	4640	92	92
	N.R.C. (Dorm2)	4302	4640	93	
2	DFO Bag 296	461	449	103	100
	DFO Bag 296	442	449	98	
	DFO Bag 297	204	205	99	101
	DFO Bag 297	211	205	103	
	N.R.C. (Dorm2)	4327	4640	93	94
	N.R.C. (Dorm2)	4386	4640	95	
3	DFO Bag 296	366	449	81	88
	DFO Bag 296	425	449	95	
	DFO Bag 297	199	205	97	98
	DFO Bag 297	204	205	100	
	N.R.C. (Dorm2)	4029	4640	87	89
	N.R.C. (Dorm2)	4275	4640	92	
4	DFO Bag 296	473	449	105	103
	DFO Bag 296	451	449	100	
	DFO Bag 297	211	205	103	105
	DFO Bag 297	221	205	108	
	N.R.C. (Dorm2)	4348	4640	94	93
	N.R.C. (Dorm2)	4260	4640	92	
5	DFO Bag 296	442	449	98	100
	DFO Bag 296	453	449	101	
	DFO Bag 297	204	205	100	102
	DFO Bag 297	213	205	104	
	N.R.C. (Dorm2)	4219	4640	91	90
	N.R.C. (Dorm2)	4178	4640	90	
				Overall Mean	97.4

Sample Recovery

Site	Chironomid	Amphipod
PH1	99.3	100.3 (98.3)a
PH2	99.3	100.3
PH11	91.6	97.3
PH13	91.6	98.3 (98.3)a
PH14	91.6	98.3 (98.3)a
PH15	91.6	97.3
PH16	91.6	100.3
PH17	91.6	97.3
PH18	98.3	97.3
PH20	91.6	97.3
PH21	91.6	97.3
PH22	91.6 (91.6)a	97.3
PH26	91.6	97.3
JC2A	91.6	97.3
JC3A	91.6	97.3
JC4A	91.6	97.3
JC5A	91.6 (91.6)a	97.3
JC6A	91.6	97.3
JC7A	91.6	97.3
JC1B	91.6	97.3
JC2B	91.6	97.3
JC3B	99.3	100.3
JC4B	99.3	98.3
JC5B	99.3	100.3
JC6B	99.3 (99.3)a	100.3
JC7B	98.3	100.3
JC1C	99.3	100.3
JC2C	98.3	100.3 (100.3)a
JC3C	99.3	100.3
JC4C	98.3	100.3
JC5C	99.3	100.3
JC6C	99.3	100.3
JC7C	99.3	98.3 (98.3)a
JC1D	99.3	100.3
JC2D	99.3	100.3
JC3D	99.3	98.3
JC4D	99.3	100.3
JC5D	99.3 (99.3)a	100.3
a = duplicate		
Mean	95.5	98.7
Range	91.6 - 99.3	97.3 - 100.3

Matrix Spike Recovery

Sample	Taxa	% Recovery
JC6B	chironomid	98.2
JC5D	chironomid	95.3
PH14	amphipod	97.8
PH13	amphipod	97.5
JC7C	amphipod	92.1
PH22	chironomid	94.2
JC5A	chironomid	90.5
JC2C	amphipod	94.1
	Mean	95.0
	Range	90.5 - 98.2

BIOTA - METHYL MERCURY

Sample Recovery

Site	Chironomid	Amphipod
PH1	93.9	93.8
PH2	93.9	96.0
PH11	94.6 (95.7)a	88.0 (96.9)a
PH13	94.6	91.6
PH14	94.6	91.6
PH15	95.7	96.9
PH16	94.6 (94.6)b	91.6 (88.0)b
PH17	94.6	88.0
PH18	93.9	88.0 (88.0)b
PH20	93.9	91.6 (88.0)b
PH21	94.6 (94.6)b	88.0 (88.0)b
PH22	94.6	88.0
PH26	94.6	88.0
JC2A	95.7 (95.7)b	96.9
JC3A	95.7	96.9
JC4A	95.7	96.9 (96.9)b
JC5A	95.7	96.9 (96.0)a
JC6A	95.7	96.9
JC7A	95.7	96.9
JC1B	(91.6)a (95.7)b	96.9
JC2B	95.7	96.9
JC3B	94.6	96.9
JC4B	91.6	96.0
JC5B	91.6	96.0 (93.8)a
JC6B	93.9	93.8 (94.6)a
JC7B	91.6	96.0
JC1C	91.6	96.0
JC2C	91.6	96.0
JC3C	91.6	96.0
JC4C	91.6	96.0
JC5C	91.6	96.0
JC6C	93.9	93.8
JC7C	91.6	93.8
JC1D	91.6 (93.9)a (93.9)b	93.8
JC2D	93.9	93.8
JC3D	93.9	93.8
JC4D	93.9	93.8
JC5D	93.9	93.8
a = duplicate; b=repeat analysis		
Mean	93.9	94.0
Range	91.6 - 95.7	88.0 - 96.9

Reference Material (DORM- 2: 4470 +/- 340 ng/g)

Run	MeHg	Mean % Recovery
1	4348	93.9
	4051	
2	4260	91.6
	3932	
3	4406	95.7
	4146	
4	4175	94.6
	4265	
5	4083	93.8
	4299	
6	4206	96.0
	4380	
7	4367	96.9
	4295	
8	3927	88.0
	3943	
9	4094	91.6
Mean	4188	93.6
SD	161	

Matrix Spike recovery

Sample	Taxa	% Recovery
PH2	chironomid	100.7
JC7B	chironomid	90.2
JC6A	chironomid	87.1
PH14	chironomid	107.2
JC1D	amphipod	91.1
JC4B	amphipod	96.0
JC3B	amphipod	101.8
PH17	amphipod	103.8
PH14	amphipod	101.0
	Mean	97.7
	Range	87.1 - 107.2

Table D4. Laboratory QA/QC data from Caduceon Environmental Laboratory.

			Laboratory Duplicate - Relative % Difference							Reference Material - % Recovery			
Analyte	Units	Det limit	JC2A	PH26	JC4A	JC6C-3	JC1D	PH20	Blank	STSD-4	QC-1	QC-2	QC-3
Fe	pct	0.01	4.41	4.28		0			< 0.01	90			
Mn	µg/g	1	0.21	8.25		0			< 1	96			
Mercury	µg/g	0.005	14.2						< 0.001		93.5	103.3	
TOC	pct	0.02			0.33		1.26		< 0.002		100.2	97.9	99.3
TKN	µg/g	12.5						0.5	< 12.5		99		
TP	µg/g	2.5						0.4	< 2.5		100		
							Mean	**3.1%**				**Mean**	**97.7%**

Relative Percent Difference = $\frac{(x_1 - x_2)}{(x_1 + X_2/2)} \times 100$

Inter-Laboratory Comparison of Analyses of Total Hg in Sediment from Jellicoe Cove, Peninsula Harbour

Analyses for concentrations of total mercury (THg) in sediment were performed by 2 laboratories: Flett research Ltd., which was selected to measure THg and methyl mercury in sediment and biological samples, and Caduceon Environmental Laboratory, which conducted THg analyses on a subset of sites (10). Each lab received a sediment subsample from the same homogenized sample collected at each site. Those submitted to Flett were sent frozen, and those submitted to Caduceon were first freeze-dried. Figure E1 shows how the site measurements compare graphically.

Overall agreement between labs for the determinations of THg in sediment is indicated by the slope of a regression involving the two variables. As recommended by McArdle (1988) and Draper and Smith (1998), the regression was estimated by the geometric mean (GM, aka reduced major axis) method instead of the ordinary least squares (OLS) method. The OLS method assumes negligible error in the X variable, and can result in biased slope estimates when applied to data in which both X and Y variables are subject to errors of the same magnitude, a situation which clearly applies here. Rather than minimizing the sum of the squares of the deviations of observed Y values from the regression line, as in the OLS method, the GM method minimizes the sum of the areas of the triangles formed by the data point, the point on the line corresponding to the X value, and the point on the line corresponding to the Y value. Geometric Mean slope, b_{GM}, was estimated by

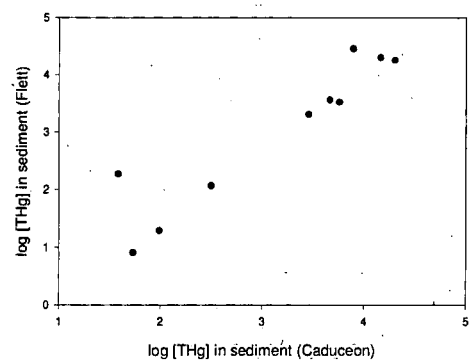

Figure D1. Comparison of total Hg measuremetns between labs.

$b_{GM} = s_y / s_x$ (Legendre and Legendre 1998)

where s_y = standard deviation of Y - values, and s_x = standard deviation of X - values. The b_{GM} estimate is also the geometric mean of the OLS slope of Y on X and the reciprocal of the slope of X on Y. (Note that when the purpose of the analysis is not to estimate functional parameters such as the slope, but only to predict values of Y for given X's, OLS regression is suitable (Legendre and Legendre 1998). For this reason, the GM method was not used for the invertebrate Hg – sediment Hg regressions.)

Geometric mean regression slope for $\log[THg]_{Flett}$ vs $\log[THg]_{Caduc}$:

Standard deviation of $\log[THg]_{Flett} = 1.2827 = s_y$
Standard deviation of $\log[THg]_{Caduc} = 1.0461 = s_x$

$b_{GM} = s_y / s_x = 1.5992/1.5737 = \mathbf{1.2262}$

OLS regression of Y vs X: $\log[THg]_{Flett} = -0.5640 + 1.1436 \log[THg]_{Caduc}$
OLS regression of X vs Y: $\log[THg]_{Caduc} = 0.8332 + 0.7606 \log[THg]_{Flett}$

For both regressions $P<0.001$ and $r^2 = 87.0\%$.

As a check, using the alternate slope estimation method: $b_{GM} = (1.1436 \times [1 / 0.7606])^{1/2} = 1.2262$

The overall agreement in measurements of THg in sediment is fairly good because the slope estimate is close to 1. This suggests that either (a) the analyses of the labs are accurate or (b) analyses are biased in identical ways. The unexplained 13.0% of the variation of the regression should be attributed to laboratory measurement error.

APPENDIX E. *Supplementary physico-chemical environmental data*

Table E1. Grain size and nutrient concentrations in sediment collected from Jellicoe Cove, Peninsula Harbour and reference sites.

Site	Sand %	Silt %	Clay %	Gravel %	TOC %	Total N µg/g	Total P µg/g
PH1	35.74	49.80	14.46	0	1.42	921	377
PH2	56.31	34.22	9.46	0	0.58	551	407
PH11	14.86	70.03	15.11	0	0.65	634	517
PH13	90.44	4.99	3.17	1.4	0.13	173	934
PH14[a]	19.93	57.71	22.36	0	1.20	773.7	603
PH15	66.87	13.36	19.03	0.74	0.10	127	330
PH16	11.42	52.26	36.32	0	2.13	2251	706
PH17	5.27	45.80	48.93	0	1.54	1723	1007
PH18	7.58	52.94	39.48	0	1.51	1626	652
PH20	33.05	14.00	52.95	0	0.37	411	1084
PH21	39.31	45.00	15.69	0	0.40	310	412
PH22	6.88	67.33	25.79	0	0.94	951	906
PH26	52.67	30.59	16.07	0.67	0.67	605	918
JC2A	6.90	19.03	74.07	0	0.27	474	603
JC3A	18.38	35.06	46.55	0	0.35	250	417
JC4A	61.70	26.45	11.75	0.11	6.10	739	398
JC5A	54.20	32.84	12.96	0	2.09	564	475
JC6A	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
JC7A	92.50	5.91	0	1.59	2.46	476	470
JC1B	84.36	1.16	0	14.48	1.35	73	283
JC2B	63.42	24.75	11.83	0	1.83	501	431
JC3B	55.09	31.40	13.51	0	3.16	645	466
JC4B	37.12	52.40	10.48	0	5.11	1058	554
JC5B	26.44	59.64	13.92	0	7.35	1316	567
JC6B	39.06	46.66	14.28	0	5.14	953	588
JC7B	74.60	17.36	8.04	0	3.65	414	660
JC1C	92.36	3.54	0	4.10	0.38	436	536
JC2C	44.10	41.60	13.99	0.30	3.96	752	475
JC3C	35.32	52.42	12.26	0	3.94	727	492
JC4C[a]	31.40	56.03	12.57	0	4.08	837	575
JC5C	21.59	65.37	13.03	0	4.30	779	649
JC6C[a]	23.67	63.82	12.51	0	5.36	956.7	535
JC7C	35.80	49.20	15.00	0	10.00	1065	532
JC1D	89.87	4.63	0	5.50	3.19	832	436
JC2D	46.11	41.67	12.23	0	2.07	594	588
JC3D	27.73	58.71	13.56	0	3.11	765	691
JC4D	12.39	73.32	14.29	0	6.63	1000	429
JC5D[a]	15.02	70.93	14.05	0	5.46	1097	509

[a] QA/QC site. Values represent the mean of three field replicates, [b] data not available

Table E2. Physico-chemical conditions of overlying water and iron and manganese concentrations in sediment collected from Jellicoe Cove, Peninsula Harbour and reference sites.

Site	pH	Conductivity	Temp	DO	Fe	Mn
Units		µS/cm	°C	mg/L	pct	ug/g
PH1	7.63	104	4.0	13.68	0.78	114
PH2	7.95	102	10.0	13.18	1.36	205
PH11	7.88	112	3.8	12.61	0.90	226
PH13	7.74	112	3.1	12.87	0.93	137
PH14[a]	7.83	111	3.0	12.98	1.31	276
PH15	7.69	111	3.9	12.47	1.09	170
PH16	7.84	116	4.5	12.82	2.43	338
PH17	7.46	111	4.6	12.54	3.49	1160
PH18	-[b]	134	4.6	13.31	3.20	571
PH20	7.85	111	2.9	12.79	2.36	379
PH21	7.86	113	4.2	12.42	0.90	209
PH22	7.75	124	3.2	13.58	2.07	897
PH26	7.65	111	3.6	12.97	1.83	488
JC2A	7.73	105	3.7	13.81	2.38	488
JC3A	7.63	104	3.7	13.81	1.42	329
JC4A	7.65	104	3.7	13.67	1.26	158
JC5A	7.67	104	3.6	13.35	1.14	157
JC6A	7.80	112	3.8	13.52	-[b]	-[b]
JC7A	-[b]	-[b]	3.7	13.30	1.30	157
JC1B	7.65	109	3.6	12.91	1.50	166
JC2B	7.82	105	3.4	13.55	1.29	167
JC3B	7.84	106	3.5	13.29	1.27	159
JC4B	7.76	106	3.7	13.52	1.42	153
JC5B	7.73	108	3.5	13.45	1.37	158
JC6B	7.83	113	3.5	13.71	1.33	144
JC7B	7.83	113	4.1	13.68	1.29	133
JC1C	7.78	104	3.6	14.35	1.28	147
JC2C	7.81	107	4.0	13.37	1.40	173
JC3C	7.83	113	3.6	13.26	1.35	156
JC4C[a]	8.03	104	3.6	12.89	1.27	143
JC5C	8.03	106	3.8	13.77	1.21	133
JC6C[a]	7.99	109	3.8	13.61	1.3	143
JC7C	8.09	108	4.1	13.56	1.28	146
JC1D	8.02	105	4.0	13.57	1.22	161
JC2D	8.00	104	4.2	13.56	1.28	148
JC3D	8.27	105	4.0	13.54	1.28	142
JC4D	7.77	107	4.0	12.37	1.15	145
JC5D[a]	7.76	103	4.0	13.33	1.24	153
LEL	-	-	-	-	2%	460
SEL	-	-	-	-	4%	1100

[a] QA/QC site. Values represent the mean of three field replicates for Fe and Mn, [b] data not available.

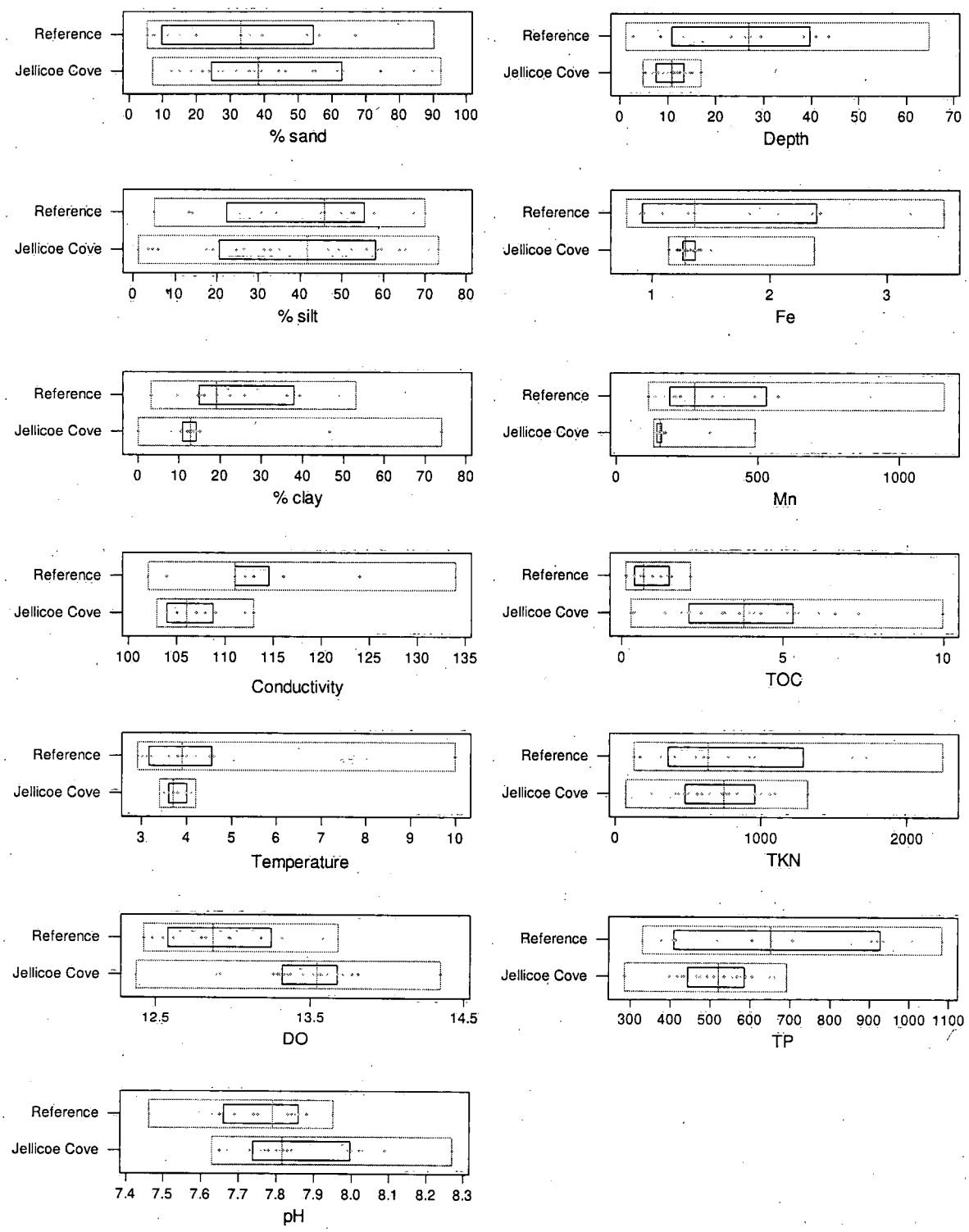

Figure E1. Comparison of sediment and overlying water physico-chemical conditions and site depths between reference and Jellicoe Cove sites of the Peninsula Harbour 2002 assessment. Inner boxes indicate 1st, 2nd (median) and 3rd quartiles; outer boxes enclose ranges of data. Individual data are shown by solid gray circles. See Tables E1 and E2 for units.

Table E3. Total PCBs (sum of 9 aroclors) in Jellicoe Cove sediments. QA/QC data is included

			Method								
	Site ID:		**Blank**	**JC1B**	**JC1C**	**JC1D**	**JC2A**	**JC2B**	**JC2C**	**JC2D**	**JC3A**
Component	MDL	Units									
Aroclor-1016	0.038	ug/gm	<	<	<	<	<	<	<	<0.039	<
Aroclor-1221	0.015	"	<	<	<	<	<	<	<	<	<
Aroclor-1232	0.038	"	<	<	<	<	<	<	<	<0.039	<
Aroclor-1242	0.038	"	<	<	<	<	<	<	<	<0.039	<
Aroclor-1248	0.021	"	<	<	<	<	<	<	<	<	<
Aroclor-1254	0.059	"	<	<	<	<	<	<	<	<0.060	<
Aroclor-1260	0.031	"	<	<	<	<	<	0.055	0.43	0.32	<
Aroclor-1262	0.031	"	<	<	<	<	<	<	<	<	<
Aroclor-1268	0.031	"	<	<	<	<	<	<	<	<	<
Total PCB	0.059	"	<	<	<	<	<	**0.055**	**0.43**	**0.32**	<
Surrogate Recoveries		%									
4,4'-Dibromooctaflourobiphenyl			78	99	80	84	85	105	96	84	92
Decachlorobiphenyl			91	98	83	88	90	106	105	98	91
	Site ID:		**JC3B**	**JC3C**	**JC3D**	**JC4A**	**JC4A**	**JC4A**	**JC4A**	**JC4A**	
Component	MDL	Units					**M. Spike**	**MS % Rec.**	**MS Dup**	**MSD % Rec.**	
Aroclor-1016	0.038	ug/gm	<0.041	<0.041	<0.053	<	-	-	-	-	
Aroclor-1221	0.015	"	<0.016	<0.016	<0.021	<	0.14	34	0.17	39	
Aroclor-1232	0.038	"	<0.041	<0.041	<0.053	<	-	-	-	-	
Aroclor-1242	0.038	"	<0.041	<0.041	<0.053	<	-	-	-	-	
Aroclor-1248	0.021	"	<0.023	<0.022	<0.029	<	0.35	83	0.36	85	
Aroclor-1254	0.059	"	<0.064	<0.063	<0.082	<	-	-	-	-	
Aroclor-1260	0.031	"	0.26	0.30	0.30	0.28	-	-	-	-	
Aroclor-1262	0.031	"	<0.033	<0.033	<0.043	<	-	-	-	-	
Aroclor-1268	0.031	"	<0.033	<0.033	<0.043	<	0.33	79	0.36	84	
Total PCB	0.059	"	**0.26**	**0.30**	**0.30**	**0.28**	**0.83**	**65**	**0.88**	**70**	
Surrogate Recoveries		%									
4,4'-Dibromooctaflourobiphenyl			114	85	90	94	80	80	107	107	
Decachlorobiphenyl			101	90	85	91	98	98	114	114	

Table E3 Continued.

	Site ID:		**JC4B**	**JC4C01**	**JC4C02**	**JC4D**	**JC5A**	**JC5B**	**JC5C**	**JC5D01**	**JC5D02**	**JC6B**
Component	MDL	Units										
Aroclor-1016	0.038	ug/gm	<0.046	<0.044	<0.045	<0.060	<0.046	<0.043	<0.045	<0.051	<0.048	<0.043
Aroclor-1221	0.015	"	<0.018	<0.017	<0.018	<0.024	<0.018	<0.017	<0.018	<0.020	<0.019	<0.017
Aroclor-1232	0.038	"	<0.046	<0.044	<0.045	<0.060	<0.046	<0.043	<0.045	<0.051	<0.048	<0.043
Aroclor-1242	0.038	"	<0.046	<0.044	<0.045	<0.060	<0.046	<0.043	<0.045	<0.051	<0.048	<0.043
Aroclor-1248	0.021	"	<0.025	<0.024	<0.025	<0.033	<0.026	<0.024	<0.025	<0.028	<0.026	<0.024
Aroclor-1254	0.059	"	<0.071	<0.069	<0.070	<0.093	<0.072	<0.066	<0.070	<0.079	<0.074	<0.067
Aroclor-1260	0.031	"	0.18	0.38	0.55	0.55	0.27	0.18	0.57	0.35	0.57	0.19
Aroclor-1262	0.031	"	<0.037	<0.036	<0.037	<0.049	<0.038	<0.035	<0.037	<0.042	<0.039	<0.035
Aroclor-1268	0.031	"	<0.037	<0.036	<0.037	<0.049	<0.038	<0.035	<0.037	<0.042	<0.039	<0.035
Total PCB	0.059	"	**0.18**	**0.38**	**0.55**	**0.55**	**0.27**	**0.18**	**0.57**	**0.35**	**0.57**	**0.19**
Surrogate Recoveries		%										
4,4'-Dibromooctaflourobiphenyl			76	106	117	103	82	93	104	63	86	99
Decachlorobiphenyl			82	89	93	105	88	97	88	68	87	99

	Site ID:		**JC6C01**	**JC7A**	**JC7A**	**JC7A**	**JC7A**	**JC7A**	**JC7B**	**JC7C**	**JC4C03**	**JC5D03**
Component	MDL	Units			**M. Spike**	**MS % Rec.**	**MS Dup**	**MSD % Rec.**				
Aroclor-1016	0.038	ug/gm	<0.043	<0.041	-	-	-	-	<	<0.042	<0.045	<0.058
Aroclor-1221	0.015	"	<0.017	<0.016	0.29	67	0.21	47	<	<0.017	<0.018	<0.023
Aroclor-1232	0.038	"	<0.043	<0.041	-	-	-	-	<	<0.042	<0.045	<0.058
Aroclor-1242	0.038	"	<0.043	<0.041	-	-	-	-	<	<0.042	<0.045	<0.058
Aroclor-1248	0.021	"	<0.024	<0.022	0.38	88	0.42	95	<	<0.023	<0.025	<0.032
Aroclor-1254	0.059	"	<0.067	<0.063	-	-	-	-	<	<0.065	<0.069	<0.090
Aroclor-1260	0.031	"	0.19	0.089	-	-	-	-	0.057	0.51	0.40	0.62
Aroclor-1262	0.031	"	<0.035	<0.033	-	-	-	-	<	<0.034	<0.036	<0.047
Aroclor-1268	0.031	"	<0.035	<0.033	0.46	110	0.41	94	<	<0.034	<0.036	<0.047
Total PCB	0.059	"	**0.19**	**0.089**	**1.1**	**87**	**1.0**	**79**	**0.057**	**0.51**	**0.40**	**0.62**
Surrogate Recoveries		%										
4,4'-Dibromooctaflourobiphenyl			55	75	95	95	95	95	62	64	43	76
Decachlorobiphenyl			56	75	110	110	110	110	75	82	73	84

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