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# CHAPITRE I

## INTRODUCTION

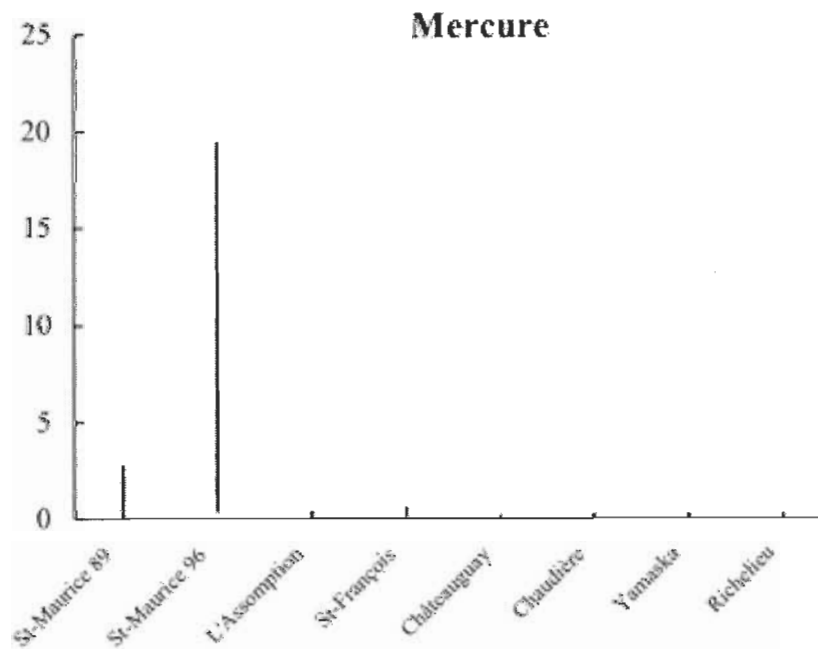
### 1.1 Mise en contexte

L'économie régionale de la Mauricie a bénéficié pendant plusieurs années d'une industrie de pâtes et papiers florissante basée sur l'exploitation forestière du bassin versant (16 700 km<sup>2</sup>) de la rivière Saint-Maurice (RSM), recouvert à 85 % d'une dense forêt de conifères. Prenant source dans le réservoir Gouin et se déversant dans le fleuve Saint-Laurent (FSL), la RSM a longtemps été utilisée comme voie de flottaison du bois destiné aux moulins à papier situés dans la portion sud de la région. Les activités de drave ont ainsi favorisé l'accumulation d'une grande quantité de matières organiques au fond de la rivière. De plus, diverses substances toxiques, induites par différentes activités industrielles, sont encore présentes dans les sédiments de la rivière et affectent les organismes présents dans la RSM depuis leurs émissions (Dumas et Rivard, 1996).

Au total, 53 espèces de poissons ont historiquement été recensées dans la rivière. Cependant, 32 d'entre elles ont été répertoriées en aval du barrage de la Gabelle, obstacle considéré comme infranchissable pour les poissons (Dumas et Rivard, 1996). Cette section de rivière, longue de 20 kilomètres, est composée de zones d'eaux vives et turbulentes, de marais et marécages, d'îles et de rapides. Certaines de ces zones sont utilisées comme frayères par plusieurs espèces de poissons provenant du fleuve (Houde, 2007). Effectivement en 1999, l'aménagement d'une frayère à esturgeon a été réalisé en aval du barrage de la Gabelle sur un site de frais connu et le site aménagé est désormais fréquenté par plusieurs espèces (GDG, 2001).

Bien que les concentrations de mercure (Hg) naturellement présentes dans l'environnement sont modulées par les conditions chimiques, physiques ou biologiques du milieu, elles peuvent être altérées et amplifiées par diverses activités anthropiques

(Celo *et al.*, 2006; Gabriel et Williamson, 2004; Ward *et al.*, 2010b). En 1993, on retrouvait des concentrations en Hg plus élevées que la directive gouvernementale de  $0,05 \text{ mgkg}^{-1}$  chez les poissons capturés en amont du barrage de la Gabelle (Lapierre, 1995). En 1996, des mousses aquatiques (*Fontinalis dalecarlica*) ont été disposées dans la RSM de La Tuque à Trois-Rivières afin de déterminer le nombre, la nature et les concentrations des toxines susceptibles d'être présentes dans cette rivière. La méthode employée a révélé que les concentrations en Hg retrouvées dans la RSM étaient plus élevées que les concentrations retrouvées dans le FSL et ses autres tributaires (Figure 1.1; Berryman *et al.*, 2002). En 1998, les teneurs en Hg dissous dans l'eau excédaient le critère de prévention de la contamination de l'eau et des organismes aquatiques ( $1,8 \text{ ng/l}$ ) avec des valeurs 1,1 à 1,7 fois plus élevées ( $1,94$  à  $2,64 \text{ ng/l}$ ) que la norme provinciale du ministère de l'Environnement et de la Faune (Lapierre, 2002). Depuis 2007, la région de la Mauricie (Québec, Canada) est considérée comme l'un des endroits en Amérique du Nord où l'on retrouve les concentrations en Hg organique les plus élevées (Evers *et al.*, 2007).



**Figure 1.1** Concentration ( $\text{mgkg}^{-1}$ ) de Hg dans des mousses aquatiques placées dans plusieurs tributaires du fleuve Saint-Laurent (concentration moyenne par station; Berryman *et al.*, 1996).

### 1.1.1 Mercure

Le Hg, métal inorganique, se retrouve dans la nature sous trois formes :  $\text{Hg}^0$ ,  $\text{Hg}_2^{2+}$  et  $\text{Hg}^{2+}$ . Sa forme prédominante est influencée par le pH, la force ionique, le potentiel d'oxydoréduction, les concentrations de matières organiques dissoutes, l'oxygène dissous, les sulfures et les particules solides en suspension (Gabriel et Williamson, 2004; Jackson, 1991; Langley, 1973). Une grande portion du Hg assimilé par les organismes aquatiques est d'origine anthropique et se retrouve dans l'environnement par dépôts atmosphériques (Boennin, 2000; Ward *et al.*, 2010b). Dans certaines régions industrielles du monde, 60 à 90 % des émissions totales de Hg sont reliées directement aux activités industrielles (Hissler et Probst, 2006). La présence de forêts de conifères favorise la formation des dépôts locaux de Hg, car les conifères sont d'excellents capteurs du Hg atmosphérique (Kolka *et al.*, 1999). Cependant, suite à une coupe, les dépôts de végétaux laissés au sol occasionnent un intrant important de carbone organique dissous (COD) et de Hg (Rudd, 1995). Le COD contribue à l'augmentation du Hg dans un milieu en favorisant la production de méthylmercure et son exportation vers les milieux humides (Miskimmin *et al.*, 1992).

Le Hg inorganique retrouvé dans les sédiments est transformé en méthylmercure par la méthylation microbienne (biotique) et la méthylation chimique (abiotique), qui le rendent biodisponible dans la chaîne trophique (Celo *et al.*, 2006; Gabriel et Williamson, 2004; Rosenberg *et al.*, 1997; Rudd, 1995). La production de méthylmercure semble être favorisée suite à la mise en fonction d'un réservoir (Kelly *et al.*, 1997; Rosenberg *et al.*, 1997). En effet, la mise en eau d'un réservoir provoque généralement l'inondation d'habitat terrestre riche en matières organiques. La décomposition de cette matière organique contribue à la création de conditions anoxiques favorisant la présence de bactéries sulfato-réductrices, principale source de méthylation du Hg dans les sédiments anoxiques (Brinkmann et Rasmussen, 2012).

L'accumulation du Hg dans un poisson dépend de l'âge, de la taille, du poids, du sexe, du taux de croissance, de l'alimentation et du temps d'exposition du poisson (Jackson, 1991). Le Hg est majoritairement emmagasiné dans les matrices de protéines

présentes dans les tissus musculaires et son taux d'excrétion est très lent (Dorea *et al.*, 2006; Trudel et Rasmussen, 1997). La concentration en Hg retrouvée dans un individu peut être influencée par sa position trophique, puisque le Hg est bioamplifié par la chaîne trophique. La bioamplification se définit comme l'augmentation de la concentration d'une substance dans la chaîne trophique, allant des organismes positions trophiques inférieures vers des organismes niveaux trophiques supérieurs (Watras *et al.* 1998).

Par conséquent, pour une même espèce dans un même milieu, des spécimens de petite dimension devraient avoir des concentrations moins élevées que les gros individus (Trudel et Rasmussen, 2006). De plus, les concentrations de Hg dans les poissons prédateurs peuvent aussi être reliées à la structure et la longueur de la chaîne trophique (Herendeen et Hill, 2004).

La consommation de poissons est la principale voie d'absorption du Hg chez l'homme (Mergler *et al.*, 2007). À de fortes concentrations, ce métal peut avoir un impact important sur la santé et affecter les systèmes nerveux, cardiovasculaire, reproducteur et immunitaire. Une fois assimilé, il s'accumule dans le cerveau et le système nerveux pouvant causer des troubles sensoriels, une diminution du champ de vision, de la dysarthrie (trouble de l'articulation de la parole et du système nerveux), des troubles auditifs et des tremblements (Mergler *et al.*, 2007). Chez les nouveau-nés et les enfants, une forte accumulation de Hg peut causer un retard mental, une ataxie cérébelleuse, des réflexes primitifs, une dysarthrie ou encore une hyperkinésie.

### **1.1.2 Exposition et exportation des contaminants**

Au cours de leur ontogénie, les organismes vivants sont exposés à un large éventail de contaminants de sources naturelles et anthropiques. Bien que les contaminants se retrouvent généralement à une échelle locale et peuvent être exportés par le biais de facteurs environnementaux tels le vent ou l'écoulement naturel de l'eau, certains organismes (les biovecteurs) ont la capacité de transporter un contaminant par

des comportements migratoires. Le déplacement de contaminants par les biovecteurs passe par trois étapes cruciales : la bioaccumulation de contaminant; le transport et la focalisation du contaminant; et le dépôt, la libération ou le transfert de contaminants à un site récepteur (Blais *et al.*, 2007). Dans plusieurs cas, une exposition passant par l'alimentation favorise la bioamplification de ces composés dans les chaînes trophiques (Cabana et Rasmussen, 1994; Kiriluk *et al.*, 1995). Par exemple, les poissons exposés à de l'eau et de la nourriture contaminée par le Hg accumulent 1 000 fois plus rapidement le Hg que les poissons exposés seulement à une eau contaminée (Hill *et al.*, 1996; McKim *et al.*, 1976; Trudel et Rasmussen, 2001).

Les concentrations en polluants retrouvées dans les poissons varient dans l'espace et dépendent de la niche alimentaire exploitée. Chez les achigans à grande bouche (*Micropterus salmoides*) récoltés à l'intérieur d'un même lac, les individus habitant les zones littorales composés de milieux humides étaient deux fois plus contaminés au Hg que ceux capturés en zone pélagique (Chumchal *et al.*, 2008). Des différences similaires en concentration en Hg ont aussi été retrouvées dans des organismes occupant des positions trophiques inférieures. Les fortes concentrations en Hg retrouvées dans les achigans littoraux étaient dues aux concentrations élevées de Hg retrouvées dans la chaîne alimentaire littorale.

Les concentrations en contaminants retrouvées dans des poissons peu mobiles provenant d'un milieu peu contaminé peuvent être influencées par des biovecteurs (proies ou prédateurs) qui effectuent des migrations uniques ou multiples afin d'accomplir leur cycle ontogénique (Baker *et al.*, 2009; Blais *et al.*, 2007). Par exemple, la migration du saumon rouge (*Oncorhynchus nerka*) peut agir comme vecteur de transport des biphényles polychlorés (BPC) (Krümmel *et al.*, 2003). Après la fraie, une majorité de saumons meurent aux abords des sites de fraie. Les charges en BPC accumulées en mer se retrouvent donc libérées et contribuent à faire augmenter de sept fois la concentration en BPC retrouvée naturellement dans les sédiments des lacs (Krümmel *et al.*, 2003; Nagorski *et al.*, 2014). Également, l'anguille migratrice agit comme vecteur de transport du Mirex dans le système hydrologique Grands Lacs -

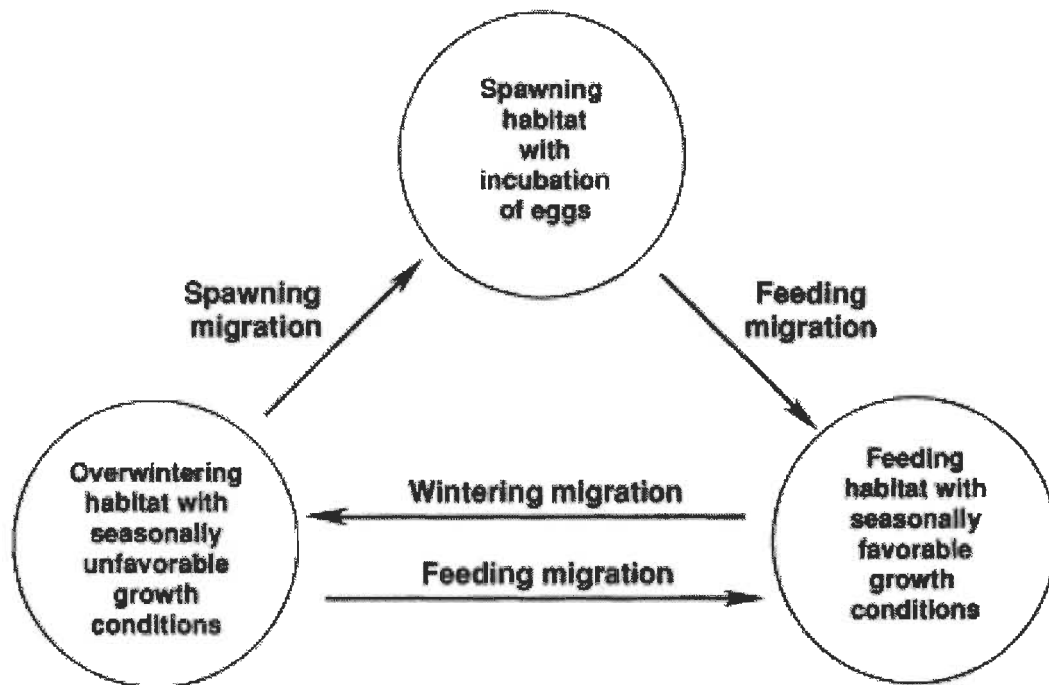


fleuve Saint-Laurent, un contaminant, dont les deux seules sources connues étaient situées dans deux tributaires du lac Ontario (Lum *et al.*, 1987). En effet, de fortes charges de ce contaminant ont été retrouvées dans les bélugas qui consommaient des anguilles en migration dans l'estuaire du Saint-Laurent.

### 1.1.3 Connectivité et systèmes aquatiques ouverts

Les cours d'eau sont généralement décrits comme étant des écosystèmes dynamiques de tailles variables caractérisés par le transfert de matière, d'énergie et d'organismes. La connectivité entre cours d'eau varie rapidement dans le temps et l'espace (Taylor et Warren, 2001). Les mouvements de dispersion ou de migration entre cours d'eau permettent aux poissons d'échapper aux conditions locales défavorables d'un milieu et d'avoir accès à des ressources associées aux besoins ontogéniques (Figure 1.2; Campbell *et al.*, 2007). Cependant, l'habilité des poissons à occuper un réseau de cours d'eau est limitée par leurs capacités de dispersion.

Le type de migrations (alimentation, reproduction) joue un rôle important dans l'acquisition et l'accumulation des contaminants. Par exemple, un poisson qui effectue fréquemment des migrations afin de s'alimenter dans un cours d'eau fortement contaminé devrait accumuler une plus grande concentration en contaminant qu'un poisson qui migre qu'une seule fois pour s'y reproduire sur une courte période. Cependant, peu d'études se sont intéressées aux mouvements de contaminants en système ouvert.



**Figure 1.2** Le cycle de vie des poissons de rivière et leurs modes d'utilisation de l'habitat (Schlosser, 1991).

#### 1.1.4 Isotopes stables

Les isotopes stables sont couramment utilisés afin d'étudier et de décrire les flux de matières organiques dans les réseaux trophiques, de suivre les migrations d'animaux et de montrer les variations dans les différentes stratégies alimentaires des individus (DeNiro et Epstein, 1978; Fry, 1999). L'approche isotopique se base sur l'hypothèse que les valeurs isotopiques des animaux sont en équilibre avec les valeurs isotopiques de leur régime alimentaire (Post, 2002). Effectivement, l'équilibre isotopique dépend du taux de renouvellement isotopique et du régime alimentaire de l'organisme étudié (Buchheister et Latour, 2010).

Les ratios isotopiques du carbone ( $^{13}\text{C}/^{12}\text{C}$ ) dépendent initialement des sources de carbone inorganique dissous (CID) provenant de sources d'eaux minérales, de l'atmosphère et de la décomposition de la matière organique (Peterson et Fry, 1987). Le  $\delta^{13}\text{C}$ , mesure intégrative de la chaîne trophique, est généralement utilisé afin

d'évaluer le flux de carbone passant par l'alimentation d'individus et ainsi d'identifier l'origine spatiale des sources de nourriture utilisées. Cette mesure est particulièrement utilisée, car l'on retrouve peu de fractionnement isotopique ( $1,1 \text{ ‰} \pm 0,3 \text{ ‰}$ ) entre les différents niveaux trophiques (Hecky et Hesslein, 1995; McCutchan *et al.*, 2003; Vander Zanden *et al.*, 2001). Le fractionnement isotopique correspond à l'enrichissement d'un isotope par rapport à un autre dans un processus chimique ou physique.

Les ratios isotopiques de l'azote ( $^{15}\text{N}/^{14}\text{N}$ ) sont influencés par les dépôts atmosphériques, mais les fertilisants, les sols et l'eau contribuent à faire fluctuer les concentrations finales retrouvées dans l'environnement. Le  $\delta^{15}\text{N}$  est utilisé afin de déterminer le niveau trophique des individus (Cabana et Rasmussen, 1996). Ce ratio dépend initialement du type de ressources alimentaires utilisées (végétaux, invertébrés, poissons) et le fractionnement isotopique retrouvé entre les différents niveaux trophiques est approximativement  $3,3 \text{ ‰}$  ( $\pm 0,26 \text{ ‰}$ ; Cabana *et al.*, 1994; McCutchan *et al.*, 2003).

## 1.2 Problématique

La connectivité des cours d'eau favorise les échanges entre les communautés ichthyennes, mais peut cependant contribuer à l'exportation de contaminants présents dans l'environnement. Plusieurs études ont décrit les mouvements des contaminants à grande échelle chez des espèces anadromes et catadromes ainsi que les transferts de contaminants dans la chaîne trophique dans des systèmes aquatiques fermés. (Chumchal *et al.*, 2008; Lum *et al.*, 1987; Krümmel *et al.*, 2003; Nagorski *et al.*, 2014). Cependant, peu se sont intéressées aux transferts de contaminants entre un fleuve et l'un de ses confluents.

La confluence entre la rivière Saint-Maurice et le fleuve Saint-Laurent permet la libre circulation des poissons entre les deux cours d'eau et favorise un échange entre les communautés de ces deux systèmes (Dumas et Rivard, 1996). Lors de migrations vers la RSM, les poissons provenant du FSL se retrouvent exposés à de fortes concentrations en Hg (Laliberté, 2003). On ne connaît pas en détail les patrons de migration des espèces

utilisant la RSM, il est donc difficile de déterminer quelles espèces jouent le rôle de biovecteur ou accumulent du Hg lors de leurs déplacements. Afin d'évaluer les déplacements spatio-temporels des poissons, quatre campagnes d'échantillonnage ont été réalisées dans l'axe hydrologique RSM-FSL afin de couvrir un cycle annuel. Cet échantillonnage a permis d'analyser le Hg total et les signatures isotopiques du carbone ( $\delta^{13}\text{C}$ ) et de l'azote ( $\delta^{15}\text{N}$ ) dans le muscle de 316 poissons.

### 1.3 Objectifs

#### 1.3.1 Objectif général

L'objectif général de ce projet était d'évaluer si des poissons avaient une dépendance trophique à un affluent contaminé au Hg à l'aide du  $\delta^{13}\text{C}$ .

#### 1.3.2 Objectifs spécifiques

Le premier objectif spécifique était de réaliser une description isotopique des deux cours d'eau étudiés afin d'y caractériser les variations isotopiques à l'aide d'organismes (invertébrés aquatiques) retrouvés à la base de la chaîne alimentaire.

Le second objectif spécifique était de décrire à l'aide des isotopes stables du carbone les patrons spatio-temporels d'utilisation de la RSM, par le meunier rouge (*Catostomus catostomus*) et le chevalier rouge (*Moxostoma macrolepidotum*), deux espèces benthivores, l'achigan à petite bouche (*Micropterus dolomieu*) et la barbie de rivière (*Ictalurus punctatus*), deux espèces omnivores, et le doré jaune (*Sander vitreus*), une espèce prédatrice. Les isotopes stables de l'azote ont été utilisés afin de déterminer les positions trophiques des poissons étudiés (Cabana et Rasmussen 1994).

Le troisième objectif spécifique était de décrire, sur un cycle annuel, les variations inter- et intra cours d'eau des concentrations en Hg chez les cinq espèces de poissons étudiées et de les relier à leur dépendance trophique à la RSM à l'aide des isotopes stables du carbone.

## CHAPITRE II

### TRACKING MERCURY CONCENTRATION IN FISH IN A LARGE RIVER ECOSYSTEM WITH CARBON STABLE ISOTOPES

Manuscrit en attente de soumission à la revue scientifique

*Ecological Applications*

Simon **Boisvert**<sup>1</sup>, Luc **Farly**<sup>1</sup>, Marco A. **Rodríguez**<sup>1</sup>, Philippe **Brodeur**<sup>2</sup>,  
and Gilbert **Cabana**<sup>1\*</sup>

<sup>1</sup> Centre de recherche sur les interactions bassins versants - écosystèmes aquatiques (RIVE) and Groupe de recherche interuniversitaire en limnologie et en environnement aquatique (GRIL), Université du Québec à Trois-Rivières, C.P. 500, Trois-Rivières, Québec G9A 5H7, Canada

<sup>2</sup> Direction régionale Mauricie et Centre du Québec, Secteur de la faune et des parcs, Ministère des Forêts, de la Faune et des Parcs, 100 rue Laviolette, Bureau 207, Trois-Rivières, Québec G9A 5S9, Canada

\* Corresponding author:

e-mail: gilbert.cabana@uqtr.ca

Tel: 819 376-5011, ext. 3366

## Abstract

Hydrological connectivity in large river ecosystems plays a key role in the life cycle of many species of fish. River areas or tributaries may also constitute important sources of contaminants that can be biomagnified and transported by fish throughout the river network. We used a biogeochemical approach, based on carbon stable isotopes, to investigate how Hg biomagnification in longnose sucker (*Catostomus catostomus*), shorthead redhorse (*Moxostoma macrolepidotum*), channel catfish (*Ictalurus punctatus*), smallmouth bass (*Micropterus dolomieu*) and walleye (*Sander vitreus*) is influenced by patterns of migration between a contaminated tributary and the main stem of the St. Lawrence River (SLR), Canada. We first developed a two end-member mixing model based on large differences observed between the  $\delta^{13}\text{C}$  of sessile organisms collected in the SLR ( $\delta^{13}\text{C} \approx -20\text{‰}$ ) and the Saint-Maurice River (SMR;  $\delta^{13}\text{C} \approx -30\text{‰}$ ), a tributary where Hg in biota has been observed to be greater than in the SLR. Regression models including trophic linkage ( $\delta^{13}\text{C}$ ) to alternate habitats and fish size (weight) as independent variables predicted a large part of the total Hg. These results clearly show how carbon stable isotopes can reveal the effect of extended trophic exposure to the highly contaminated SMR; high Hg levels were observed in species or individuals that were resident of the SMR. Tracking the spatial origin of fish will help wildlife managers to have better understanding of mercury concentrations in fish in large river ecosystems.

**Key words:** connectivity, contaminant, food web, mercury, migration, stable isotopes

## Introduction

Globally dispersed biomagnifying contaminants such as mercury (Hg) and several persistent organic products have been increasing in aquatic ecosystems over the past decades (Schwarzenbach *et al.*, 2006). These substances can have the potential to be atmospherically or hydrologically transported over long ranges to locations hundreds or even thousands of kilometers away from their source. They represent an ecological risk for high trophic level consumers, including humans (Christensen *et al.*, 2005; Clarkson,

1998; Doréa, 2008; Gochfeld, 2003; Hightower and Moore, 2003; Mergler *et al.*, 2007) as they can then be locally biomagnified to variable degrees. For example, using isolated lakes as comparative units, several studies have elucidated the role of local ecological factors such as lake biogeochemistry, food chain length, use of alternate food sources, and bioenergetics in explaining patterns in fish biomagnification. In contrast with lakes, rivers are more open connected systems, allowing not only downstream movement of particulate and dissolved substances, but also upstream/downstream migration of fish and other consumers. River connectivity, which plays a key role in the completion of the natural cycle of several species, can also have important consequences for the spatial distribution of biomagnifying contaminants (Blais *et al.*, 2007). For example, Krümmel *et al.* (2003) showed that during spawning migrations, sockeye salmon (*Oncorhynchus nerka*) were transport vectors of poly-chlorinated biphenyls (PCBs) assimilated in the ocean and imported back to their natal lakes. Following the death of returning fish, PCBs were released and increased by sevenfold in lake sediments. Baker *et al.* (2009) and Nagorski *et al.* (2013) showed similar effects of transport via salmon migrations for Hg. In the Great Lakes - St. Lawrence hydrologic system, migratory eels assimilated high loads of lipophilic contaminants in two tributaries of Lake Ontario. The catadromous eels then transported these contaminants, such as mirex, which could be traced into beluga populations located more than 1000 kms downstream in the St. Lawrence Estuary (Lum *et al.*, 1987).

At smaller spatial scales, habitat-specific differences in contaminant concentration can lead to spatial variation of contamination in top predators. Chumchal *et al.* (2008) showed that the higher concentration of Hg in largemouth bass (*Micropterus salmoides*) from littoral habitat (wetland) compared to the individuals inhabiting the pelagic zone was due to elevated Hg concentrations in the wetland food web. Using carbon stable isotopes ( $\delta^{13}\text{C}$ ) to analyse the food web of a single lake, Eagles-Smith *et al.* (2008) reported elevated Hg levels in the benthic food chain compared to the pelagic food chain. The opposite result was observed by Power *et al.* (2002) in a sub-arctic lake where pelagic consumers, identified by more negative  $\delta^{13}\text{C}$ , showed higher Hg concentrations than members of the benthic food chain. These results suggest that

foraging in different habitats can have important implications for Hg bioaccumulation. Connectivity between streams and rivers can provide access to alternate foraging resources to fish and as these ecosystems can differ in contaminant loads (e.g. Ward *et al.*, 2010), movement between tributaries and river mainstem could contribute to increase fish exposition to contaminants. Feeding vs no-feeding during fish migration and exposure time related to movement patterns then may be factors explaining variation in contaminant levels in fish inhabiting highly connected river systems.

The St. Maurice River (SMR), a tributary of the St. Lawrence River (SLR), is a hotspot for contamination by organic Hg in north-eastern North America (Evers *et al.*, 2007; Lapierre, 1995; Quémerais *et al.*, 1999). In the 20<sup>th</sup> century, industrial activities contributed to contamination of SMR sediments by Hg (Dumas and Rivard, 1996). Hg contamination has been amplified by the biogeochemical characteristics of the SMR river (high dissolved organic carbon concentrations), extensive wetlands located in the watershed, and construction of hydroelectric reservoirs (Dumas and Rivard, 1996; Houde, 2007; Lapierre, 1995; St. Louis *et al.*, 1996; Porvari, 2003). As a result, fish from the SMR have Hg body concentrations greater than in any other tributary of the SLR (Lapierre, 2002; Laliberté, 2003) and exceed the threshold specified by Environment Canada (0.5 mg/kg). Stable carbon isotope ratios ( $\delta^{13}\text{C}$ ) of dissolved inorganic carbon (DIC) are lower (by about 10 permil) in the SMR compared to the carbonate-rich mainstem SLR (Yang *et al.*, 1996). Thus, important spatial variation in baseline  $\delta^{13}\text{C}$  is likely to be easily detectable in the SMR-SLR connected food web and could potentially provide time-integrated information on consumer movements between the tributary and the river mainstem (DeNiro and Epstein, 1978; Fry, 1999; Hobson, 1999; Rounick and Winterbourn, 1986). For exemple, Robillard *et al.* (2011) have used  $\delta^{13}\text{C}$  for investigate diversity of habitats used and trophic ecology of brook trout (*Salvelinus fontinalis*) in Lake Superior and his tributary streams.

In the present study, a biogeochemical approach based on carbon stable isotopes was used to identify patterns in spatial and trophic use of the SMR/SLR ecosystem by five fish species. Our main objective was to examine if fish trophic reliance on



this contaminated tributary, measured with  $\delta^{13}\text{C}$ , could explain variation in Hg concentrations both within and between these species. We first developed a two end-member mixing model based on large differences observed between the  $\delta^{13}\text{C}$  of sessile organisms collected in the SLR ( $\delta^{13}\text{C} \approx -20\%$ ) and the SMR ( $\delta^{13}\text{C} \approx -30\%$ ). Trophic linkage ( $\delta^{13}\text{C}$ ) to alternate habitats and fish size, an important well-known biological factor influencing Hg, were then included as independent variables in regression models to explain variation in Hg concentrations both within and between these five fish species.

## Methods

### *Study site*

The SMR River, which drains a 45,000 km<sup>2</sup> watershed dominated by coniferous forest, is an acidic river characterized by high concentration of dissolved organic carbon (Gobeil *et al.*, 2005; Quémerais *et al.*, 1999; Yang *et al.*, 1996). Nine hydroelectric dams regulate the SMR's hydrologic regime. The most downstream hydroelectric dam, La Gabelle is located approximately 20 kilometers upstream from the confluence of the SMR and the SLR (18T 673575.35E 5146395.38N) and represents an impassable upstream barrier for fish (Fig. 1). The SMR discharges into the SLR near the city of Trois-Rivières and can contribute up to 15% of the SLR's total flow during high-water periods (Dumas and Rivard, 1996). The SLR drains a 1,609,845 km<sup>2</sup> watershed. Land use on the SLR floodplain is dominated by agricultural, industrial, and municipal activities. The SLR is composed of many heterogeneous water masses (Frenette *et al.*, 2012) but 80% of the SLR discharge after the spring flood period originates from the Laurentian Great Lakes (Hélie *et al.*, 2002).

### *Sample collections*

Invertebrates were sampled from September to October 2012 and from June to July 2013 using kick nets, small seines, and a benthic sled. In the SMR, two sampling

stations were located upstream and five sampling stations were located downstream of La Gabelle Dam (Fig. 1). In the SLR, eight sampling stations were located in shallow areas along the shoreline (fringing floodplain waters) and seven were at a depth of 2 m (Great Lakes waters). Water conductivity, a conservative tracer of water origin in the SLR (Yang *et al.*, 1996), was used to distinguish fringing floodplain waters from waters from the Great Lakes, which dominate the SLR. SLR sampling areas were separated in two sectors to evaluate if water from tributaries found in the fringing floodplain had depleted invertebrates  $\delta^{13}\text{C}$  compared to those inhabiting Great Lakes waters. Invertebrates were placed in a cooler with ice until they were transported back to the laboratory at the University of Quebec at Trois-Rivières (UQTR).

Fish were collected in August, September, and November 2012, and April, May and August 2013 with experimental gillnets and seines (Fig. 1). In the SMR, three stations were located upstream and seven stations were located downstream of La Gabelle Dam. In the SLR, six sampling stations were located along a stretch running from 15 km upstream SLR-SMR confluence near Lake Saint Pierre, a fluvial lake on the main stem of the SLR, to approximately 30 km downstream of the SLR-SMR confluence. Species were selected on the basis of their presence in both rivers as well as their trophic diversity. Trophic groups were assigned following Scott and Crossman (1973). We collected benthivorous longnose sucker (*Catostomus catostomus*), shorthead redhorse (*Moxostoma macrolepidotum*), omnivorous channel catfish (*Ictalurus punctatus*), smallmouth bass (*Micropterus dolomieu*) and piscivorous walleye (*Sander vitreus*). Fish < 10 cm total length were euthanized in a eugenol solution. Larger specimens were anesthetized in a solution of eugenol and then euthanized by cervical dislocation. Specimens were placed in a cooler with ice and brought back to the laboratory.

A non-lethal sampling technique was used to spare walleye during their breeding period, from April to May of 2013. Following anesthesia with a eugenol solution (2 ml/50 L water), a biopsy (True-Cut, 6 mm, Robbins Instruments) of the dorsal muscle tissue was taken below the dorsal fin of each fish. The wound was then coated with

surgical glue (Nexaband) to reduce infection after manipulation. Total length (TL, mm) and weight (g) were recorded in the field. All fish were put in a plastic holding tank for recuperation before being returned to water.

At the laboratory, invertebrates were identified to family (Merritt and Cummins, 1996; Moisan, 2010). Invertebrate functional groups (grazer, filterer, predator) were determined following Merritt and Cummins (1996). Only invertebrates classified as grazers or filterers were kept. Fish were identified to species, measured (TL;  $\pm 1$  mm), weighed ( $\pm 1$  g), sexed, and assessed for maturity state (Nikolsky, 1963; Scott and Crossman, 1974). For fish  $> 10$  cm TL, a scalpel was used to collect a minimum of one gram of dorsal muscle tissue. Fish  $< 10$  cm TL were frozen whole. Invertebrates, fish muscle tissue, and complete small fish were frozen at  $-20$  °C.

#### *Stable isotope analyses*

Primary consumer invertebrates reflect baseline stable isotope signatures specific to each river (Anderson and Cabana, 2006). Fish muscle tissues and whole invertebrates were dried for at least 48 hours at  $60$  °C, ground with a mortar and pestle to a homogeneous powder and kept in tightly sealed glass vials ( $19 \times 51$  mm, 2 drams; Fisherbrand). An aliquot (0.9 to 1.2 mg) of each sample was introduced into a tin capsule ( $8 \times 5$  mm; Bn 202723; ISOMASS). Samples were analyzed at the Laboratory for Analyses in Aquatic Ecology and Sedimentology, UQTR, using an isotope ratio mass spectrometer (Delta V Plus; Thermo Scientific). Carbon and nitrogen isotope ratios were expressed in the delta ( $\delta$ ) notation, defined as the deviation from an international standard materials (Vienna Pee Dee Belemite and air nitrogen) in parts per thousand (‰). The working standard was USGS40 (L-glutamic acid:  $\delta^{13}\text{C}$   $-26.389 \pm 0.09$ ‰;  $\delta^{15}\text{N}$   $-4.21 \pm 0.12$ ‰) from the International Atomic Energy Agency (IAEA). Two internal references from dorsal muscle tissues of two specimens of brook trout (*Salvelinus fontinalis*) were used to monitor the accuracy and precision of carbon (average standard deviation of several runs:  $\text{sd} = 0.08$ ‰;  $\text{sd} = 0.14$ ‰) and nitrogen ( $\text{sd} = 0.09$ ‰;  $\text{sd} = 0.13$ ‰) values in each analysis run. Muscle tissue  $\delta^{13}\text{C}$  values were

corrected by the C/N ratio method to account for the effect of lipids (Perga and Gerdeaux, 2005; Post *et al.*, 2007). The C:N ratio of all muscle tissues was low (average 3.59) and lipid corrections resulted in very small shifts in carbon isotopic ratios (averaged shift = 0.26‰, sd = 0.26).

### *Trophic position*

Primary consumers (filterers and grazers) were used to estimate baseline carbon and nitrogen isotopic values (Cabana and Rasmussen, 1994; Post, 2002) in both rivers. We used Post's (2002) linear interpolation model to estimate baseline  $\delta^{15}\text{N}$  from  $\delta^{13}\text{C}$  using the grand means of primary consumers from each river as end-members because both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  differed between the two rivers. The two end-member mixing model allows for the estimation of the proportion of carbon obtained from each source ( $\alpha$ ), such as the SLR and SMR food webs:

$$\alpha = (\delta^{13}\text{C}_{\text{secondary consumers}} - \delta^{13}\text{C}_{\text{base 1}}) / (\delta^{13}\text{C}_{\text{base 1}} - \delta^{13}\text{C}_{\text{Base 2}})$$

where base 1 and base 2 represent grand means of primary consumers from respectively each river (SLR and SMR). Trophic position was calculated as:

$$\text{Trophic position} = [(\text{Fish } \delta^{15}\text{N} - \text{estimated baseline } \delta^{15}\text{N}) / 3.4] + 2$$

where 3.4 represents the  $\delta^{15}\text{N}$  discrimination between trophic steps. (Cabana and Rasmussen, 1994; Post 2002).

### *Mercury*

Concentration of total Hg in muscle tissues of fish (dry weight;  $\text{ngg}^{-1}$ ) was measured with a direct Hg analyser (DMA-80 Express Mercury Analyser; Milestone Inc.). Analyses were standardized with certified reference materials (fish protein: Dorm-2, Dorm-3) (CV of replicates = 3.4% and 2.3%) and lobster hepatopancreas

reference material (Tort-2) for trace metals (CV = 3.0%). Twenty-four fish muscle replicates were analyzed to evaluate the precision of results (CV = 1.8%).

### *Statistical analyses*

Fish size is a well-known covariate of Hg concentration in fish, reflecting the effect of fish age and, in some cases, increases in trophic position with size (Mendez *et al.*, 2001; Rivers *et al.*, 1972). To remove the effect of individual fish size on the within-species relationships between Hg and  $\delta^{13}\text{C}$  we used the following model:

$$\log_{10}(\text{Hg}_i) = b_0 + b_1\delta^{13}\text{C}_i + b_2\log_{10}(W_i) + e_i$$

where  $W$  stands for fish weight (g),  $\delta^{13}\text{C}$  stand for stable carbon isotope ratio, and  $e_i$  is a normally distributed error term. Variation in invertebrate  $\delta^{13}\text{C}$  and fish trophic position among sampling stations were investigated using ANOVA.

## **Results**

### *Isotopic baseline indicators*

Mean isotopic ratios for 12 invertebrate families in the SMR and 17 invertebrate families in the SLR were used to calculate overall means for baseline  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  for each river. Mean  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values for invertebrates were higher in the SLR than in the SMR (Fig. 2 and Table 1). In the SMR, isotopic means of invertebrates captured upstream and downstream of the dam were similar and varied little over the 20 km reach studied (Table 1). ANOVA showed no significant differences among invertebrate SMR (upstream dam and connected) sampling stations for  $\delta^{13}\text{C}$  [ $F(4,18) = 1.3$ ,  $p = 0.31$ ] and  $\delta^{15}\text{N}$  [ $F(4,18) = 1.2$ ,  $p = 0.35$ ]. Isotopic ratios of primary consumers used in the calculations of fish trophic positions were less negative in the SLR (mean  $\delta^{13}\text{C} = -21.72\text{‰}$ ,  $sd = 3.77$ ,  $n = 19$ ; means  $\delta^{15}\text{N} = 9.34\text{‰}$ ,  $sd = 1.35$ ,  $n = 19$ ) than in the SMR (mean  $\delta^{13}\text{C} = -29.12\text{‰}$ ,  $sd = 1.74$ ,  $n = 19$ ; mean  $\delta^{15}\text{N} = 4.76\text{‰}$ ,  $sd = 1.72$ ,  $n = 19$ ).

### *Fish isotopic ratios and trophic linkage*

In total, 316 fish were sampled, of which 15% were captured upstream of La Gabelle Dam, 55% downstream of the dam in the SMR where fish had free access to the SLR (hereafter “the connected SMR”), and 30% in the SLR. No shorthead redhorse or channel catfish were captured upstream of La Gabelle Dam. Most of the fish were caught in August-September 2012 (38%) or April-May 2013 (42%, Fig. 3). Fish captured upstream of La Gabelle Dam showed little  $\delta^{13}\text{C}$  variability (-30‰ to -28‰) and were more negative than fish from SLR. This contrasted with fish captured in the SLR which had  $\delta^{13}\text{C}$  signatures ranging from -22‰ to -20‰. Thus, fish isolated by the dam from the SLR differed from the SLR fish by about 8‰ for  $\delta^{13}\text{C}$  (Table 1). In the connected SMR, fish  $\delta^{13}\text{C}$  was much more variable than in the two others study areas spanning the whole range of  $\delta^{13}\text{C}$  values observed in the SLR and the section upstream of La Gabelle Dam combined (Fig. 4). However, greater variability in the connected SMR was not observed in all species (Fig. 4). Channel catfish from the connected SMR showed the greatest variability in  $\delta^{13}\text{C}$  of all species, spanning the entire isotopic gradient found between the two rivers.

### *Fish trophic position*

In each sampled area, fish with the greatest  $\delta^{15}\text{N}$  were top predators (walleye, channel catfish, smallmouth bass) followed by benthivorous species (longnose sucker, shorthead redhorse). For all species,  $\delta^{15}\text{N}$  values were positively associated with  $\delta^{13}\text{C}$  (Fig. 5) and were more variable in the connected SMR than elsewhere (Table 1). Most of the fish fell between trophic levels 3 and 4, corresponding to benthivory and piscivory, respectively (Fig. 5). ANOVA showed no significant difference between trophic position smallmouth bass [ $F(1,16) = 0.02$ ,  $p = 0.88$ ] caught upstream of La Gabelle Dam and in the SLR but showed a significant difference for longnose sucker [ $F(1,26) = 12.45$ ,  $p = 0.0016$ ] and walleye [ $F(1,53) = 4.039$ ,  $p = 0.05$ ]. Longnose sucker had the greatest variation in trophic position, and had a higher trophic position in the SMR section compared to the connected SMR and the SLR.

### *Mercury*

Fish weight was related to Hg concentration in all species but shorthead redhorse (Table 2). For the three species found upstream of the dam, regression showed that Hg concentration in fish was not only related to weight but to  $\delta^{13}\text{C}$  as well (Fig. 6; Table 2). Downstream of the dam and in SLR, only channel catfish did not have a significant relationship between  $\delta^{13}\text{C}$  and mercury.

### **Discussion**

We used  $\delta^{13}\text{C}$  as a tracer to identify intra- and interspecific patterns in fish migration between a mainstem lowland river (SLR) and a Hg-contaminated tributary (SMR). Intraspecific variation in  $\delta^{13}\text{C}$  of fish caught in the connected 22-km tributary section ranged from apparent equilibrium with local food sources to equilibrium with the  $\delta^{13}\text{C}$  signature of the main stem river (SLR) invertebrates. Hg concentrations in fish were strongly related to fish isotopic signatures with high Hg associated with individuals having the most negative  $\delta^{13}\text{C}$ , typical of the SMR above the dam. In several species, individuals with intermediate  $\delta^{13}\text{C}$  and Hg values were observed in the connected tributary, suggesting feeding during migration. Variation in trophic position within species was not significantly different between the SM and SLR and was not related to variation in Hg in fish. Thus the important variation in Hg in the SMR/SLR system is related to the relative contaminant of each habitat and not differences in trophic position between them.

### *Migratory strategies*

Our isotopic and Hg data suggest that fish living in the SMR tributary connected to the main river can be classified into three functional groups: populations dominated by sedentary individuals, partially migratory populations with little trophic use of the tributary, and partially migratory populations with trophic use of the tributary. Sedentary smallmouth bass and shorthead redhorse showed little within-site variation in Hg

and  $\delta^{13}\text{C}$ . The close matching of  $\delta^{13}\text{C}$  of fish and invertebrates caught upstream and downstream of La Gabelle dam and the lack of temporal variability in  $\delta^{13}\text{C}$  strongly suggest that these two species residing in the connected SMR accomplished all their life cycle within the connected SMR. Correlations observed between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  for those species, which are coherent with a two-source mixing model between the SLR and SMR, further supported this interpretation. These two sedentary species also clearly showed matching higher Hg concentrations in the connected SMR compared to the SLR. Robillard *et al.* (2011) observed a similar pattern in an inshore brook trout population of Lake Superior, where sedentarity was inferred from a close matching of fish and primary consumer isotopic ratios.

This pattern contrasted with the higher intraspecific variation in  $\delta^{13}\text{C}$  observed in walleye, longnose sucker, and channel catfish in the tributary suggesting a partial migration strategy (Chapman *et al.*, 2011; Jonsson and Jonsson, 1993; Kerr *et al.*, 2009). Our results suggest that a partial migration strategy can be further analysed in terms of feeding vs no feeding during migration. For example, strong isotopic disequilibrium shown by walleye and longnose sucker individuals in the spring in the SMR suggests partial migration with little or no feeding activity. Furthermore, no individuals were found to have  $\delta^{13}\text{C}$  values intermediate between the SMR and SLR end-members later in the summer-fall period. This strategy has been observed in percids where mainstream-tributary movements are characterized by temporary occupation, with fish returning to the river from which they originate without feeding (Collette *et al.*, 1977; Koster *et al.*, 2014).

In contrast with non-feeding migrants, some fish species move between, feed and accumulate biomass in alternate habitats (Schlosser, 1991). For example, channel catfish have been observed on other studies to not only use tributaries for reproduction but also to stay on site during the summer to feed and only return to the main river at the end of summer to overwinter (Butler and Wahl, 2011; Pellett *et al.*, 1998). Depending on assimilation rates and the duration of feeding in alternate habitats (Carleton *et al.*, 2008), fish using this strategy would be unlikely to reach complete isotopic equilibrium with



local food sources. Here, channel catfish captured in the connected tributary in spring and at the end of summer showed highly variable  $\delta^{13}\text{C}$  (Fig. 3). MacAvoy *et al.* (2001) reported field-based estimates for channel catfish for muscle  $\delta^{13}\text{C}$  turnover rate of 0.015‰ per day. Thus, it may take 90 days to see a 1.5‰ change in isotopic signal. This suggests that fish need to come back many years to the SMR, with little feeding during overwintering in the SLR, to achieve depleted  $\delta^{13}\text{C}$  observed in the SMR for this species. Altogether our results confirm recent studies suggesting that patterns of fish movements are heterogenous with partial migration being the norm rather than the exception (Chapman *et al.*, 2011; Chapman *et al.*, 2012; Radinger and Wolter, 2014; Rodríguez 2002).

#### *Contaminants and fish migration*

Understanding the spatial origin and population migratory behavior of fish is crucial for monitoring of fish contamination and understanding the redistribution of biomagnifying contaminants in hydrologically connected systems (Blais *et al.*, 2007). For example, individual striped bass (*Morone saxatilis*) classified as freshwater residents in the Hudson River had greater levels of PCBs than those spending variable time in higher salinity habitats where exposure to PCBs was less severe (Zlokovitz and Secor, 1999). Male burbot (*Lota lota*) feeding near the mouths of rivers with sediments contaminated with PCBs in Lake Erie had higher PCBs concentrations than females which fed elsewhere in the lake (Stapanian *et al.*, 2013). Here, SMR resident fish, identified by their more negative  $\delta^{13}\text{C}$  signature, accumulated higher Hg levels than feeding migrants and non-feeding migrants because they were always in contact with highly contaminated prey. Non-feeding migrants showed the lowest Hg levels, followed by and feeding the SLR g migrants were fish with intermediated Hg level. It is also possible that some fish also move from the SMR to the SLR. However, no single specimen in the SLR was captured with the very negative isotopic signature of the SMR.

*$\delta^{13}\text{C}$  as an integrated tool in the monitoring of Hg in aquatic ecosystems*

In the SMR/SLR ecosystem fish with depleted  $\delta^{13}\text{C}$  had higher Hg concentrations than fish with more positive  $\delta^{13}\text{C}$ . A similar relationship was observed by Power *et al.* (2002) in the fish community of a sub-Arctic lake. Walleye and smallmouth bass Hg strongly covaried with  $\delta^{13}\text{C}$  of dissolved inorganic carbon in our comparative analysis of the whole SLR/tributaries systems). The slopes of these relationships were remarkably close to those obtained for the Hg/fish muscle data in the present study. Several biogeochemical factors may contribute to generate these Hg- $\delta^{13}\text{C}$  relationships by acting in parallel to stimulate Hg methylation and bioaccumulation and promote carbon recycling via respiration and methanotrophy.

Dissolved organic matter (DOC) acts like a vector of Hg within watershed and facilitates its exportation and accumulation in aquatic systems. Co-transport may be an important source of inorganic and organic Hg to lakes and rivers in cases in which Hg is primarily derived from wetlands and soils (Lee *et al.*, 2000; Wallschlager *et al.*, 1996). In the Rio Negro, a large acidic black-water river, DOC appears to play a key role in controlling the geographical pattern of Hg contamination (Silva-Forsberg *et al.*, 1999). DOC is a substrate for microbial activity using organic matter as energy source. DOC can stimulate microbial growth and enhance the bacterial transformation of inorganic Hg in methylmercury (MeHg) (Amon and Benner 1996; McArthur *et al.* 1985; Watras *et al.* 1995b). For example, Garcia *et al.* (2006) showed that the pattern of distribution of MeHg in zooplankton from boreal lakes paralleled that of DOC.

Moreover, high bacterial production associated with high DOC in stream can lead to an increased production of  $\text{CO}_2$  by bacterial respiration (Hessen, 1992; Hope *et al.*, 1996; Riera *et al.*, 1999).  $\text{CO}_2$  derived from microbial respiration can lead to depleted  $\delta^{13}\text{C}$ -DIC (Finlay, 2003; Yang, 1996). Lennon *et al.* (2006) showed that high DOC were correlated with high epilimnetic  $\text{CO}_2$ , and  $\delta^{13}\text{C}$  of  $\text{CO}_2$  were negatively correlated with DOC. DIC uptake by primary producers would then lead to  $^{13}\text{C}$ -depleted food chains reflecting low  $\delta^{13}\text{C}$ -DIC sources (Lennon *et al.*, 2006). Carbonic acids ( $\text{HCO}_3^- + \text{CO}_3^{2-}$ )

also have an effect on  $\delta^{13}\text{C}$ - DIC (Zhang *et al.*, 1995) and lower pH in humic streams can lead to a relatively depleted  $\delta^{13}\text{C}$  signature of DIC.

Although eating fish provides omega-3 fatty acids, which help reduce the risk of neurological and psychological disorders (Calon and Cole, 2007; Daviglius *et al.*, 2002), it can also result in bioaccumulation of contaminants, posing a potential health risk to fish consumers (Gochfeld, 2003; Hightower and Moore, 2003). The primary source of Hg for humans is through the consumption of fish (Holmes *et al.*, 2009; Mergler *et al.*, 2007), which can become a public health problem not only in hotspots with industrial legacies of contamination, but also in near-pristine ecosystems prone to increased Hg methylation (e.g., Ward *et al.*, 2010). Our results showed that fish  $\delta^{13}\text{C}$  is a simple time-integrated measure of trophic linkage to Hg-rich environments in a hydrologically connected large river system. Similarly, Hg in two species of fish was predictable from  $\delta^{13}\text{C}_{\text{DIC}}$  in water in 19 tributary and main stem sites along the St. Lawrence River. Monitoring of Hg in fish for human consumption generally does not take into account the effects of fish movements on Hg accumulation in open systems such as large rivers. Adding a low-cost isotopic marker ( $\delta^{13}\text{C}$ ) to track the spatial origin of fish and its potential linkage to high Hg tributaries could help wildlife managers to have better understanding of Hg concentrations in fish.

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## Tables

**Table 1.** Mean, standard deviation (sd) and size (n) for  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and trophic position (Tp) of primary consumers and fish species captured upstream and downstream of La Gabelle Dam in the St. Maurice River (SMR) and the St. Lawrence River (SLR).

Species	Isotope ratio or Trophic position	SMR				SLR	
		Upstream of dam		Downstream of dam		Mean (sd)	n
		Mean (sd)	N	Mean (sd)	n		
Primary consumers	$\delta^{13}\text{C}$	-28.2 (2.22)	17	-28.9 (2.22)	24	-24.7 (4.02)	66
	$\delta^{15}\text{N}$	4.9 (0.93)	10	4.6 (2.20)	13	8.4 (1.80)	55
Longnose sucker	$\delta^{13}\text{C}$	-29.4 (0.80)	10	-22.9 (4.01)	19	-20.6 (1.30)	18
	$\delta^{15}\text{N}$	8.7 (0.34)	10	12.0 (1.53)	19	12.9 (0.63)	18
	Tp	3.20 (0.14)	10	3.02 (0.38)	19	2.86 (0.28)	18
Shorthead redhorse	$\delta^{13}\text{C}$			-30.1 (2.35)	15	-21.7 (1.00)	12
	$\delta^{15}\text{N}$			9.0 (1.13)	15	13.2 (0.58)	12
	Tp			3.59 (0.14)	15	3.15 (0.20)	12
Walleye	$\delta^{13}\text{C}$	-28.7 (0.81)	28	-21.2 (3.68)	36	-20 (2.25)	29
	$\delta^{15}\text{N}$	10.6 (0.70)	28	14.8 (1.45)	36	15.6 (0.72)	29
	Tp	3.65 (0.29)	28	3.58 (0.28)	36	3.50 (0.26)	29
Smallmouth bass	$\delta^{13}\text{C}$	-28.2 (0.51)	7	-28 (1.95)	40	-20.5 (1.64)	12
	$\delta^{15}\text{N}$	10.7 (0.68)	7	11.1 (1.13)	40	15.5 (0.37)	12
	Tp	3.58 (0.21)	7	3.69 (0.24)	40	3.60 (0.23)	12
Channel catfish	$\delta^{13}\text{C}$			-24.6 (3.11)	66	-21.5 (1.24)	24
	$\delta^{15}\text{N}$			11.9 (1.50)	66	13.4 (0.98)	24
	Tp			3.31 (0.31)	66	3.16 (0.26)	24

**Table 2.** Coefficients (95% confidence interval) of regression models for  $\log_{10}$ -transformed Hg concentration in fish captured in the St. Maurice and St. Lawrence Rivers, by species.

Species	Intercept	$\log_{10}(W)$	$\delta^{13}C$	$R^2$	N
Smallmouth bass	0.77 (0.26, 1.29)	0.52 (0.40, 0.63)	-0.04 (-0.06, -0.03)	0.63	59
Shorthead redhorse	1.30 (0.06, 2.53)	0.27 (-0.18, 0.73)	-0.04 (-0.07, -0.02)	0.38	27
Longnose sucker	-0.68 (-1.59, 0.23)	0.97 (0.62, 1.32)	-0.05 (-0.06, -0.03)	0.66	47
Walleye	0.84 (0.57, 1.11)	0.49 (0.42, 0.55)	-0.05 (-0.06, -0.04)	0.80	93
Channel catfish	1.25 (0.64, 1.87)	0.46 (0.31, 0.60)	-0.02 (-0.04, 0.01)	0.32	90

### Figure captions

**Fig. 1.** Study area showing the sampling stations for invertebrates and fish along the St. Lawrence and St. Maurice Rivers, Québec, Canada. Sampling gear are indicated by different symbols.

**Fig. 2.** Box plots of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  for families invertebrate primary consumers caught in the St. Maurice (A, C) and the St. Lawrence Rivers (B, D). For each family, the median shown by the thick horizontal placed between the horizontal lines represents the first and third quartiles. Circles represent outliers outside and solid lines represent the observations inside the 1.5 gap interquartiles. The horizontal line spanning all the families represents the overall means for all families plus or minus one standard deviation.

**Fig. 3.** Seasonal variation in intra-specific  $\delta^{13}\text{C}$  signatures of fish captured from the St. Maurice River upstream (x) and downstream (solid circles) of La Gabelle Dam, and from the St. Lawrence River (open squares). The shaded areas represent the spawning periods (see Methods).

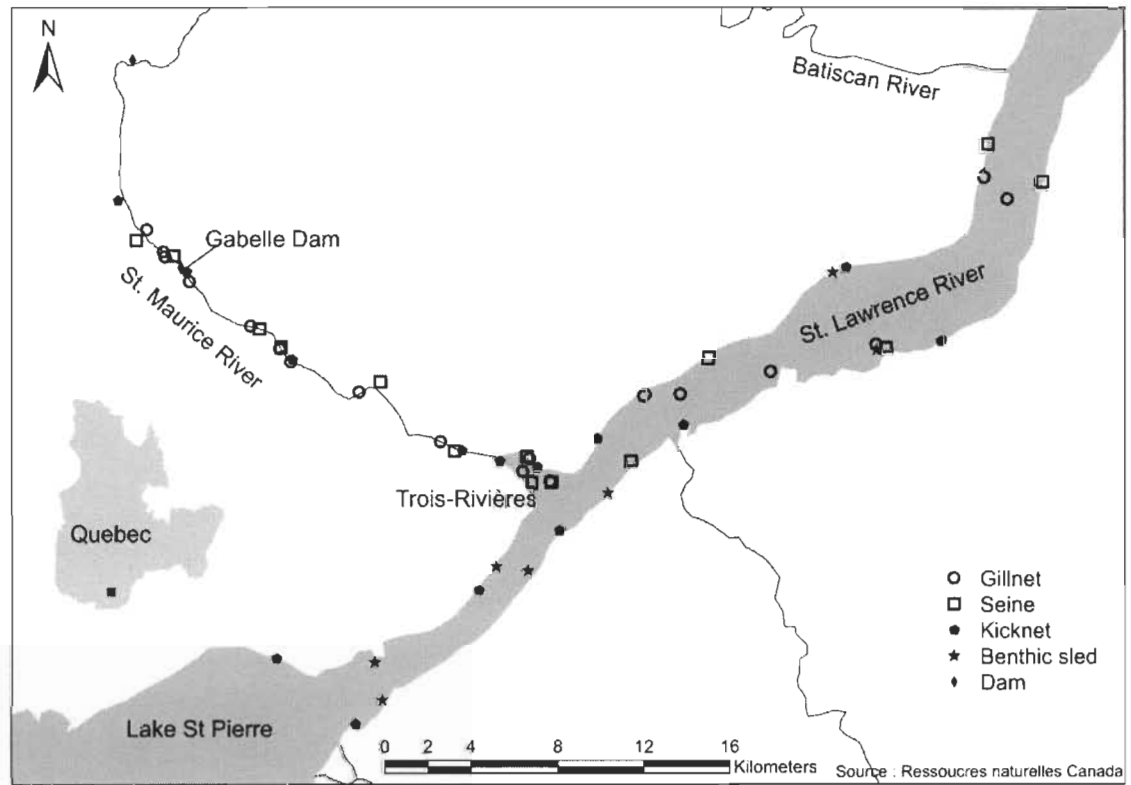
**Fig. 4.** Comparison of  $\delta^{13}\text{C}$  (mean  $\pm$  2 s.d.) in the SMR and SLR for: A) smallmouth bass, B) shorthead redhorse, C) walleye, D) longnose sucker and E) channel catfish. The black line represents the 1:1 relationship. Crosses correspond to twice the standard deviation.

**Fig. 5.** Intra-specific relationship between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  for fish from the St. Maurice River upstream (x) and downstream (solid circles) of La Gabelle Dam, and the St. Lawrence River (open squares). Solid black line: baseline stable isotope values (trophic level two; see Methods); dashed line: trophic level three; dotted line: trophic level four. Trophic position of each fish is determined by its position relative to the trophic level lines.

**Fig. 6.** Intra-specific relationship between mercury concentration  $\text{ngg}^{-1}$  dry mass,  $\log_{10}$  scale) and  $\delta^{13}\text{C}$  for fish from the St. Maurice River upstream (x) and downstream (solid circles) of La Gabelle Dam, and the St. Lawrence River (open squares).

**Figures**

Fig. 1.





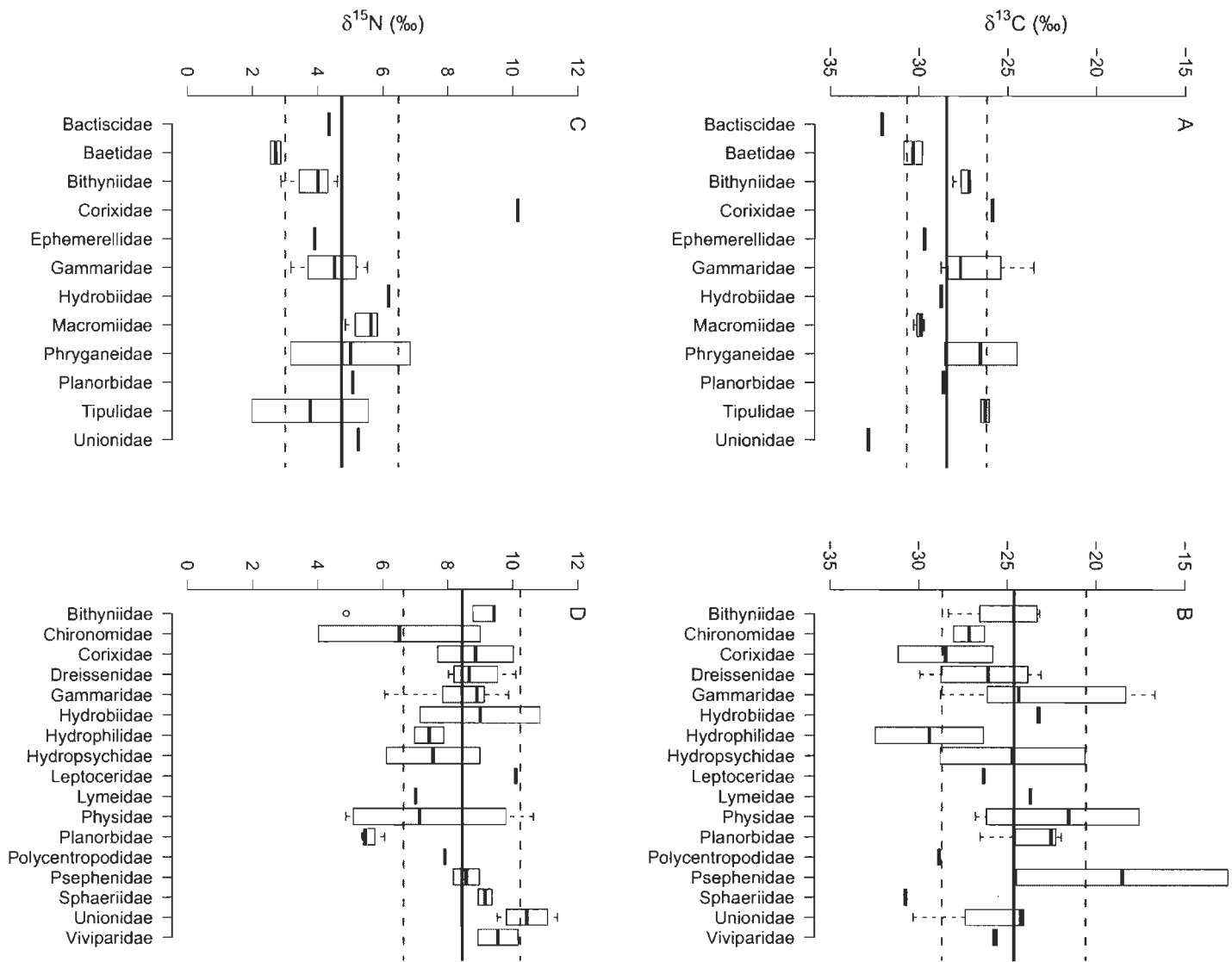


Fig. 2.

Fig. 3.

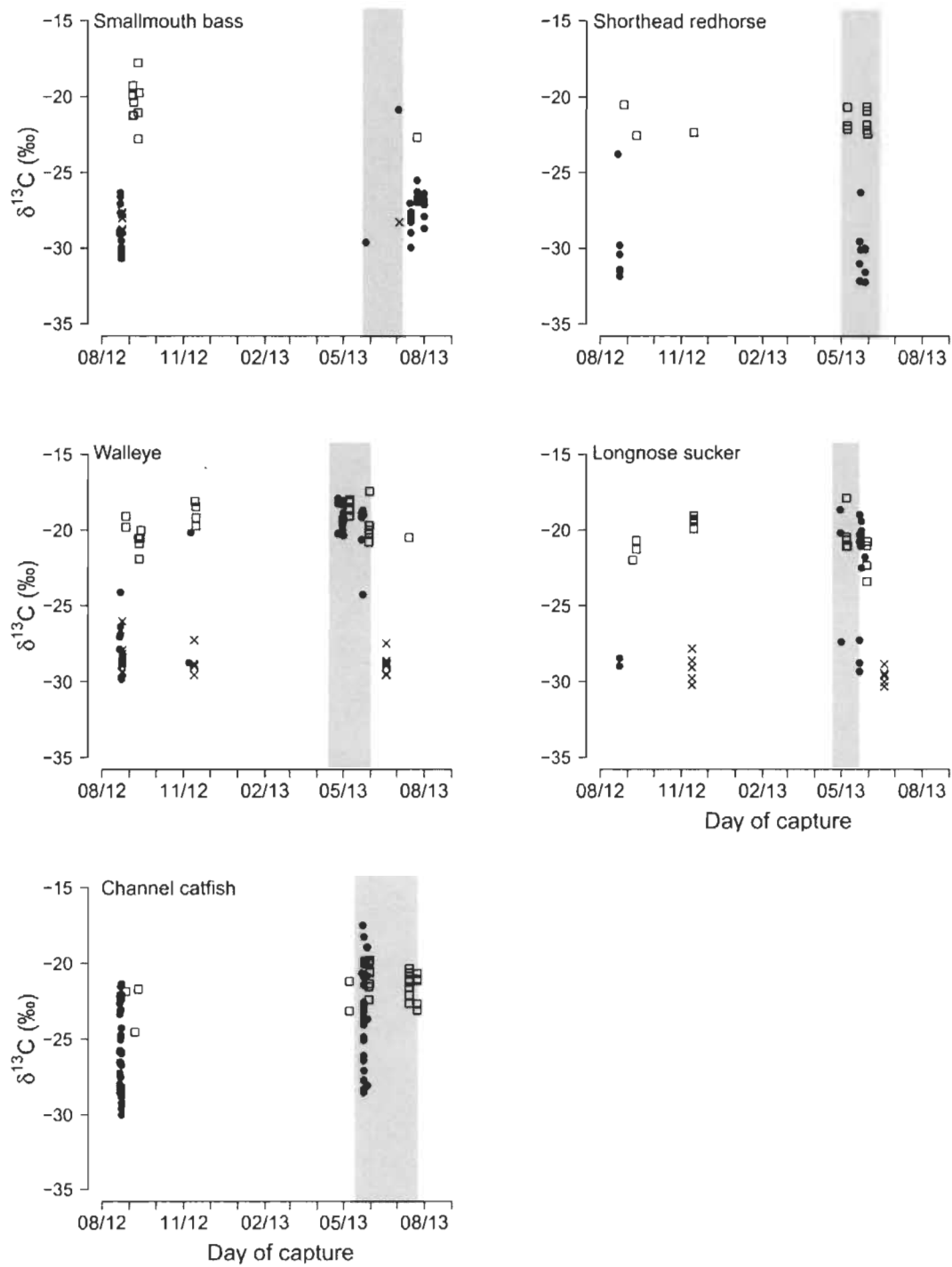


Fig. 4.

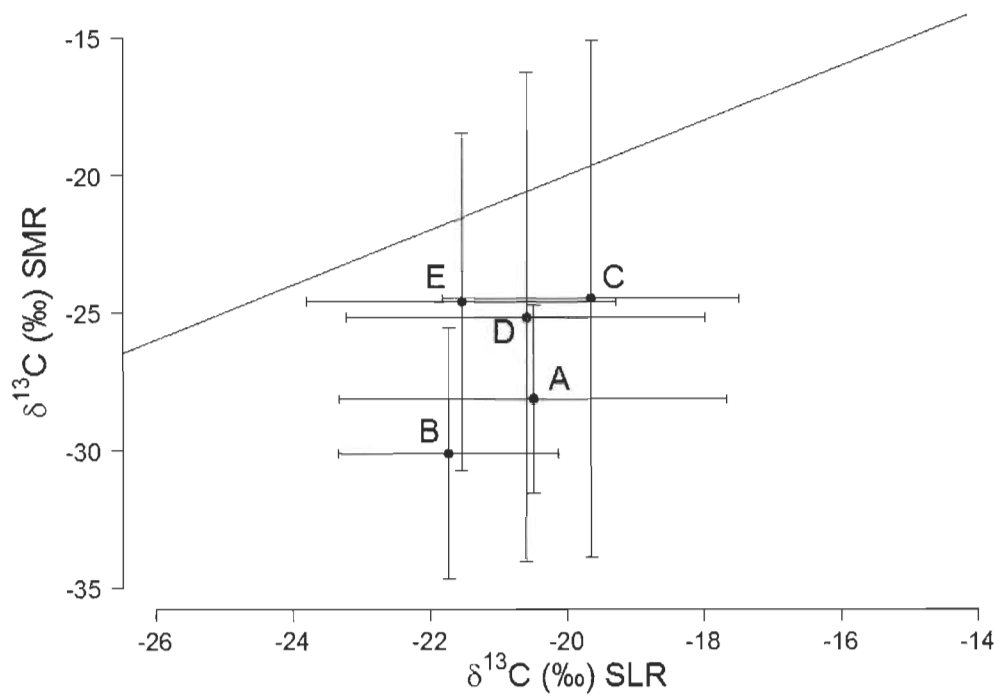


Fig. 5.

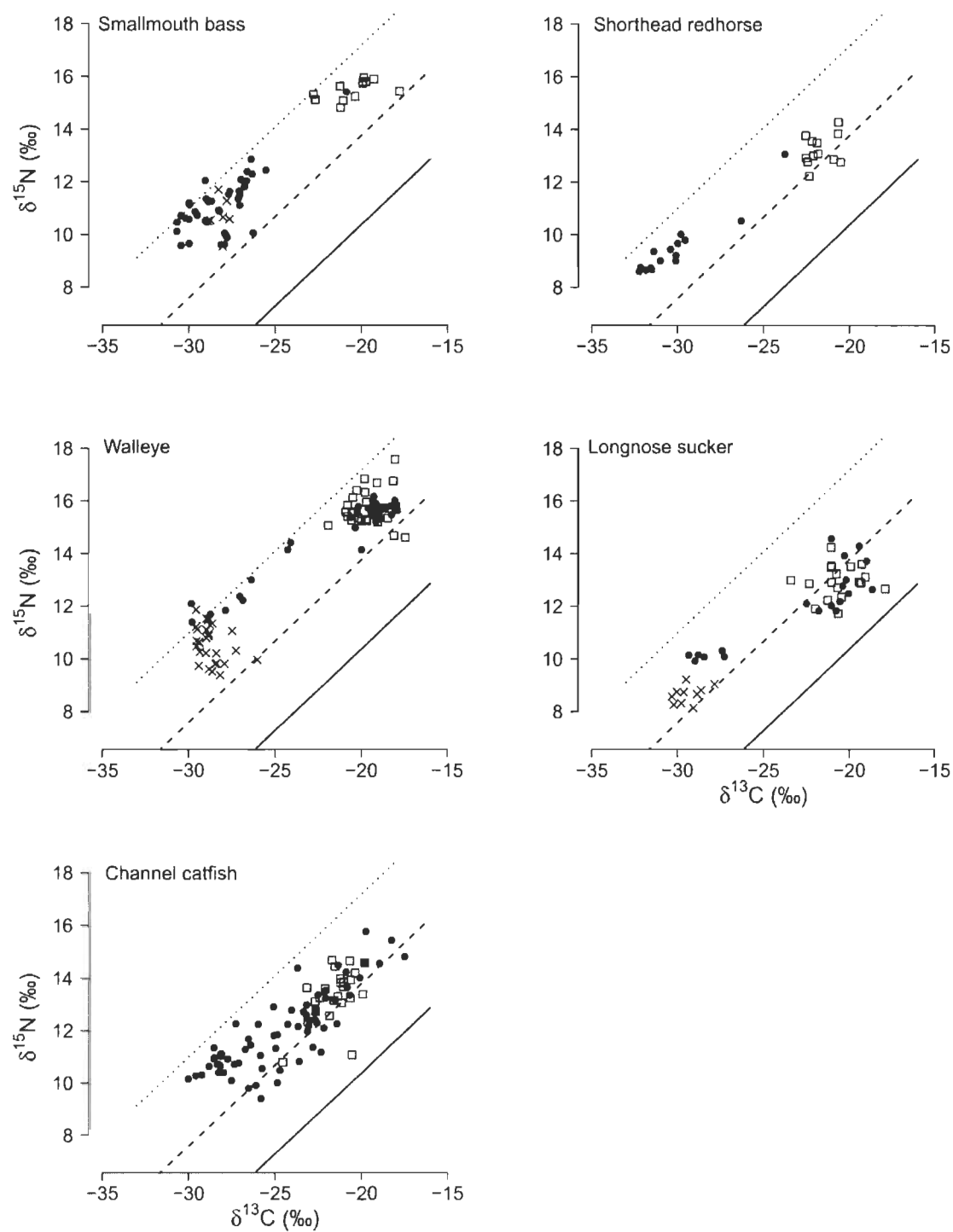
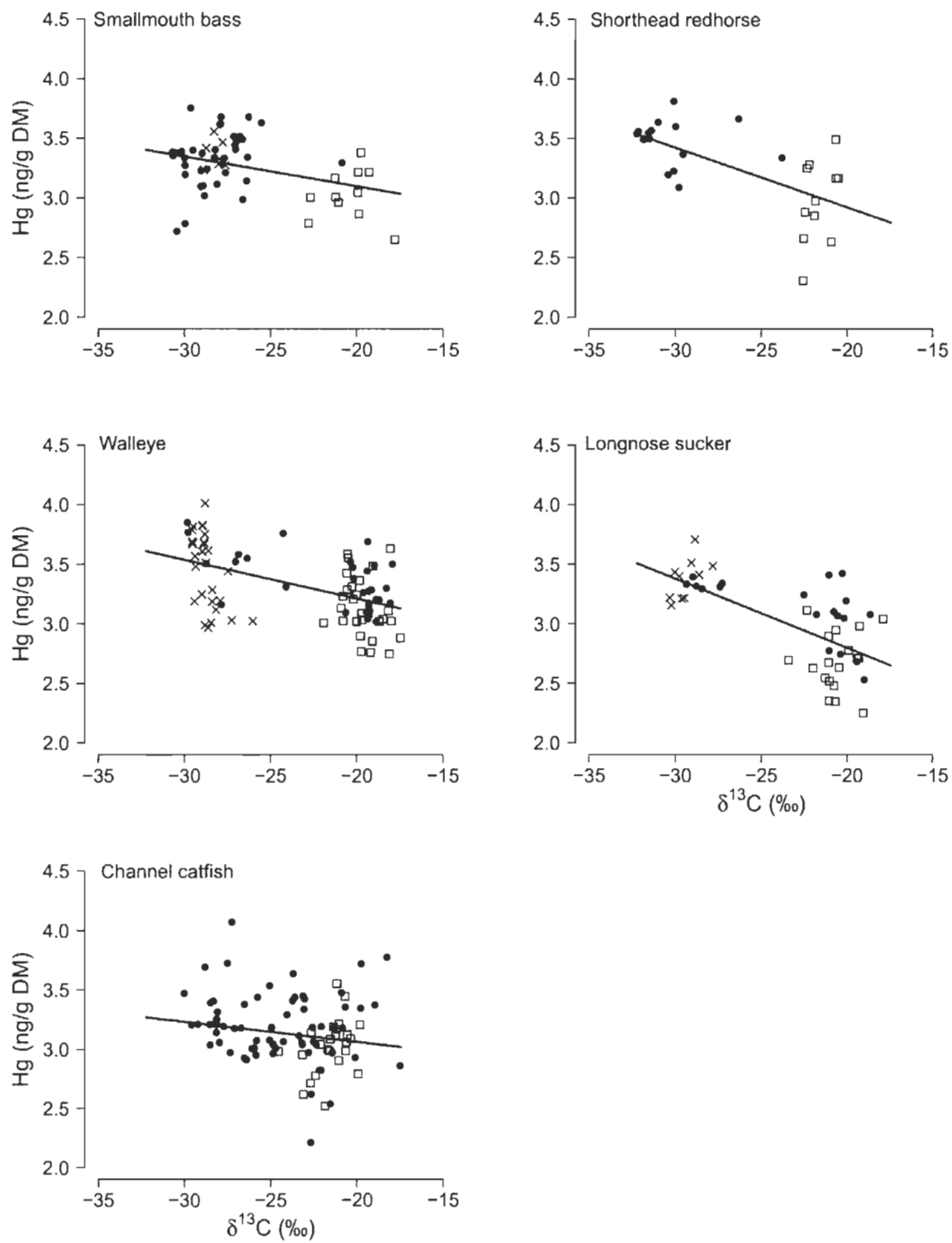


Fig. 6.



## CHAPITRE III

### CONCLUSION GÉNÉRALE

#### 3.1 Contextualisation

À l'intérieur de systèmes hydrologiques, les poissons peuvent entreprendre des migrations afin d'échapper à des conditions locales défavorables et ainsi avoir accès à des ressources éloignées et isolées (Jungwirth *et al.*, 1998; Hohausova *et al.*, 2003; Campbell *et al.*, 2007). La confluence entre la rivière Saint-Maurice (RSM) et le fleuve Saint-Laurent (FSL) permet cet échange entre les diverses communautés de poissons résident dans ces deux cours d'eau (Dumas et Rivard, 1996). Lapiere (1996) a montré que les concentrations de mercure (Hg) retrouvées dans des poissons de la SMR étaient en général nettement supérieures à celles retrouvées dans ceux du SLR. Cependant, l'impact des migrations sur les concentrations de Hg retrouvées dans les poissons fréquentant ce système hydrologique complexe était difficile à décrire compte tenu du manque de connaissances des patrons de migration de ces poissons.

L'objectif général de ce projet de maîtrise était d'évaluer si des poissons avaient une dépendance trophique à un affluent contaminé au Hg. Cette évaluation a été faite à l'aide d'une mesure stable et intégrative de la chaîne trophique ( $\delta^{13}\text{C}$ ) qui pourrait expliquer les variations intra et interspécifiques de Hg chez les poissons.

#### 3.2 Principaux résultats

Les analyses effectuées sur les invertébrés recueillis dans les deux cours d'eau ont montré que les signatures isotopiques ( $\delta^{13}\text{C}$ ) de ceux capturés dans la SMR (-30) étaient plus négatives que ceux provenant du SLR (-20). Les  $\delta^{13}\text{C}$  étaient peu variables tout au long du 20 km de la RSM (Table 1, Fig. 2, Chapitre II).

Les différences isotopiques entre les invertébrés capturés dans les systèmes à l'étude se retrouvaient aussi chez les poissons. Tous ceux capturés en amont du barrage de la Gabelle (RSM) avaient des  $\delta^{13}\text{C}$  se retrouvant entre -30 ‰ et -28 ‰ tandis que ceux capturés dans le FSL entre -22 ‰ et -20 ‰. Les  $\delta^{13}\text{C}$  des poissons capturés en aval du barrage de la Gabelle étaient plus variables que dans les deux autres secteurs à l'étude (-30 ‰ à -20 ‰; Table 1, Fig. 3, Fig. 4, Chapitre II).

Dans la RSM, les  $\delta^{13}\text{C}$  des achigans à petite bouche capturés en amont et en aval du barrage variaient peu. Chez les dorés jaunes et les meuniers rouges, les  $\delta^{13}\text{C}$  étaient plus variables en aval du barrage qu'en amont. En aval du barrage, plusieurs individus avaient des  $\delta^{13}\text{C}$  similaires aux  $\delta^{13}\text{C}$  pouvant être retrouvés dans les poissons capturés dans le FSL. Les barbues de rivières capturées en aval du barrage avaient des  $\delta^{13}\text{C}$  très variables qui correspondaient aux signatures de poissons provenant de la RSM ou du FSL. De plus, certains d'entre eux avaient des signatures intermédiaires aux RSM et FSL. Contrairement aux trois dernières espèces, les  $\delta^{13}\text{C}$  des chevaliers rouges variaient peu en aval du barrage.

Toutes zones d'échantillonnage confondues, le  $\delta^{15}\text{N}$  était positivement corrélé au  $\delta^{13}\text{C}$  pour l'ensemble des poissons (Table 1, Fig. 5, Chapitre II). Le doré jaune, l'achigan à petite bouche et la barbu de rivière occupaient les positions tropiques les plus élevées suivies respectivement du chevalier rouge et du meunier rouge.

Les concentrations en Hg des poissons capturés en amont du barrage de la Gabelle étaient plus élevées que celles retrouvées dans les poissons du FSL. Le Hg dans les poissons était positivement corrélé à leur poids et négativement corrélé au  $\delta^{13}\text{C}$  de leurs muscles. Outre la barbu de rivière, les pentes de  $\delta^{13}\text{C}$  du modèle de régression variaient peu entre les espèces (Table 2, Fig. 6, Chapitre II).

Les concentrations moyennes en Hg présentes dans le doré jaune et l'achigan à petite bouche (données tirées du site internet MDDELCC) étaient corrélées aux  $\delta^{13}\text{C}$  du

carbone inorganique dissous (DIC) de l'eau mesurés par Yang *et al.* (1996) dans plusieurs tributaires du FSL (Fig. 7, Chapitre II).

### 3.3 Conclusion

Déterminer les patrons de distribution, l'origine spatiale, le type d'utilisation et les comportements migratoires des poissons demeure crucial dans un contexte de surveillance et de suivi des contaminants présents dans les poissons. L'acquisition de ces connaissances demeure particulièrement importante dans des systèmes hydrologiques ouverts présentant une structure spatiale de distribution des contaminants. Les méthodes actuelles de suivi ne considèrent pas l'origine spatiale des poissons et l'échantillonnage sporadique dans le temps ne permet pas un suivi adéquat d'un contaminant comme le Hg dans l'environnement. L'ajout d'un marqueur isotopique comme le  $\delta^{13}\text{C}$  permettrait aux gestionnaires de la faune d'identifier comment les charges en Hg sont spatialement distribuées en fonction des mouvements des poissons. En outre, la bonification du système d'informations publique aiderait les décideurs à mieux informer les consommateurs sur la qualité et le niveau de contamination présent dans les poissons potentiellement consommés.

Mieux comprendre les schémas de migrations et les temps de résidence permettrait d'acquérir plus d'informations sur le type et le temps d'exposition qui peuvent favoriser la bioamplification d'un contaminant. Aussi, dans de futures études, il serait à envisager de déterminer les contingents de migration avec précision afin de bien identifier les patrons de résidence de chacune des espèces étudiées. Enfin, des suivis à long terme favoriseraient l'acquisition de connaissances sur la distribution des vecteurs de contaminants dans les systèmes aquatiques ouverts, permettant ainsi de prédire et de suivre les déplacements des contaminants dans l'environnement.



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## ANNEXE A

### ESPÈCES DE POISSONS CAPTURÉS DANS LA RIVIÈRE SAINT-MAURICE ET LE FLEUVE SAINT-LAURENT

**Tableau A.1**

Liste des espèces de poissons capturés dans la rivière Saint-Maurice et  
le fleuve Saint-Laurent en 2012 et 2013

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Walleye	2012-08-24	SMRupstream	14	-29.38	9.968	2.98	1056
Walleye	2012-08-24	SMRupstream	64	-28.38	9.838	3.37	1540
Walleye	2012-08-24	SMRupstream	70	-28.39	10.222	3.48	1934
Walleye	2012-08-24	SMRupstream	62	-28.17	9.391	3.20	1315
Walleye	2012-08-24	SMRupstream	59	-27.92	9.821	3.28	1570
Walleye	2012-08-24	SMRupstream	170	-29.38	10.645	3.79	3701
Walleye	2012-08-24	SMRupstream	88	-29.42	9.749	3.53	1549
Walleye	2012-08-24	SMRupstream	222	-29.34	10.267	3.67	3031
Walleye	2012-08-24	SMRupstream	18	-28.62	9.534	3.32	932
Walleye	2012-08-24	SMRupstream	19	-28.81	9.619	3.38	974
Walleye	2012-08-24	SMRupstream	11	-28.46	9.814	3.38	1024
Walleye	2012-08-24	SMRupstream	417	-28.97	10.799	3.76	4041
Longnose sucker	2012-11-13	SMRupstream	604	-30.22	8.26	3.24	1431
Walleye	2012-11-13	SMRupstream	465	-28.95	11.537	3.97	6731
Longnose sucker	2012-11-13	SMRupstream	746	-29.77	8.321	3.18	2505
Walleye	2012-11-13	SMRupstream	538	-28.81	11.522	3.94	10292
Walleye	2012-11-13	SMRupstream	657	-29.56	11.867	4.18	6147
Walleye	2012-11-13	SMRupstream	52	-28.99	10.226	3.59	1772
Walleye	2012-11-13	SMRupstream	44	-27.25	10.325	3.31	1077
Longnose sucker	2012-11-13	SMRupstream	889	-28.62	8.81	3.11	2577

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Longnose sucker	2012-11-13	SMRupstream	824	-27.83	9.052	3.04	3036
Longnose sucker	2012-11-13	SMRupstream	632	-29.07	8.137	2.99	3250
Walleye	2013-06-19	SMRupstream	205.27	-28.62	11.344	3.85	4128
Walleye	2013-06-19	SMRupstream	148.34	-28.75	11.287	3.86	3250
Walleye	2013-06-19	SMRupstream	365.65	-29.56	11.225	3.99	4893
Walleye	2013-06-19	SMRupstream		-28.84	10.875	3.76	4692
Walleye	2013-06-19	SMRupstream	346.47	-28.96	11.105	3.85	6615
Walleye	2013-06-19	SMRupstream	519.47	-28.82	10.952	3.78	5646
Walleye	2013-06-19	SMRupstream	199.9	-27.47	11.066	3.56	2765
Walleye	2013-06-19	SMRupstream	408.75	-29.49	11.121	3.95	6580
Walleye	2013-06-19	SMRupstream	164.22	-29.53	10.683	3.83	4671
Longnose sucker	2013-06-19	SMRupstream	964.38	-28.86	8.669	3.11	5117
Longnose sucker	2013-06-19	SMRupstream	443.62	-29.63	8.744	3.28	1627
Longnose sucker	2013-06-19	SMRupstream	508.88	-29.48	9.22	3.39	1642
Longnose sucker	2013-06-19	SMRupstream	856.29	-30.03	8.757	3.35	2713
Longnose sucker	2013-06-19	SMRupstream	551.6	-30.32	8.576	3.35	1659
Walleye	2013-06-19	SMRupstream	601.61	-29.52	10.49	3.77	4782
Walleye	2013-06-19	SMRupstream	873.29	-28.88	11.471	3.94	4797
Smallmouth bass	2013-07-04	SMRupstream	233.81	-28.28	11.702	3.90	3606
Smallmouth bass	2012-08-24	SMRupstream	229	-28.87	10.509	3.66	1714
Smallmouth bass	2012-08-24	SMRupstream	180	-28.00	10.654	3.54	2121
Smallmouth bass	2012-08-24	SMRupstream	243	-27.64	10.58	3.45	1871
Smallmouth bass	2012-08-24	SMRupstream	377	-28.74	10.542	3.64	2616
Smallmouth bass	2012-08-24	SMRupstream	249	-28.02	9.543	3.22	1916
Smallmouth bass	2012-08-24	SMRupstream	719	-27.79	11.28	3.68	2931
Walleye	2012-09-14	SLR	470.4	-20.01	15.307	3.45	1742
Longnose sucker	2012-11-15	SLR	207.29	-19.06	13.114	2.63	178
Longnose sucker	2012-11-15	SLR	550.44	-19.27	13.606	2.82	952
Longnose sucker	2012-11-15	SLR	807.59	-19.92	13.51	2.91	600
Longnose sucker	2012-11-15	SLR	518.13	-19.32	12.894	2.61	517

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Longnose sucker	2012-11-15	SLR	504.74	-19.43	12.926	2.64	514
Walleye	2012-11-15	SLR	76.91	-19.73	15.301	3.40	587
Walleye	2012-11-15	SLR	53.87	-19.19	15.522	3.36	575
Walleye	2012-11-15	SLR	515.72	-18.48	15.343	3.18	1097
Walleye	2012-11-14	SLR	56.22	-18.10	14.687	2.92	560
Walleye	2013-05-08	SLR	1110.11	-18.05	17.573	3.76	4273
Walleye	2013-05-08	SLR	511.26	-18.68	15.728	3.33	1051
Walleye	2013-05-08	SLR	1248.3	-19.06	15.2	3.25	3054
Channel catfish	2013-05-08	SLR	859.76	-23.16	13.636	3.53	903
Channel catfish	2013-05-08	SLR	1521.05	-21.19	13.819	3.23	1481
Longnose sucker	2013-05-08	SLR	270.72	-21.08	13.494	3.11	788
Walleye	2013-05-08	SLR	309.51	-18.16	16.754	3.54	1289
Walleye	2013-05-08	SLR	420.48	-18.00	15.798	3.23	1056
Longnose sucker	2013-05-07	SLR	583.05	-20.66	11.729	2.52	888
Longnose sucker	2013-05-07	SLR	740.38	-20.46	12.349	2.66	430
Longnose sucker	2013-05-07	SLR	360.1	-21.08	14.242	3.33	473
Longnose sucker	2013-05-07	SLR	794.74	-17.90	12.669	2.29	1098
Longnose sucker	2013-05-07	SLR	346.3	-21.05	12.914	2.94	225
Channel catfish	2013-05-30	SLR	126.62	-19.91	13.378	2.87	623
Walleye	2013-05-30	SLR	453.42	-19.69	15.243	3.37	1082
Walleye	2013-05-30	SLR	288.71	-20.79	15.403	3.62	1058
Walleye	2013-05-30	SLR	322.81	-20.80	15.836	3.75	1704
Walleye	2013-05-30	SLR	377.07	-20.19	15.344	3.50	1616
Longnose sucker	2013-05-30	SLR	185.57	-21.04	13.54	3.12	330
Channel catfish	2013-05-30	SLR	328.69	-22.40	13.237	3.28	602
Channel catfish	2013-05-30	SLR	954.33	-21.54	14.442	3.48	1220
Longnose sucker	2013-05-30	SLR	352.32	-22.34	12.854	3.15	1304
Walleye	2013-05-30	SLR	535.54	-20.00	15.231	3.43	1048
Walleye	2013-05-30	SLR	629.24	-20.27	16.4	3.82	2055
Longnose sucker	2013-05-30	SLR	168.71	-23.41	12.996	3.39	495

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Walleye	2013-05-31	SLR	285.17	-19.70	15.948	3.58	1229
Walleye	2013-05-31	SLR	126.31	-17.45	14.614	2.78	762
Longnose sucker	2013-05-31	SLR	542.65	-20.76	13.236	2.98	301
Channel catfish	2013-05-31	SLR	773.05	-21.36	13.294	3.10	1552
Channel catfish	2013-05-31	SLR	1120.76	-19.81	14.58	3.20	1606
Channel catfish	2013-05-31	SLR	755.15	-20.61	13.927	3.15	1152
Walleye	2013-07-15	SLR	632.7	-20.50	16.129	3.78	3583
Channel catfish	2013-07-15	SLR	252.32	-20.35	14.19	3.19	1233
Channel catfish	2013-07-15	SLR	172.72	-21.59	13.142	3.10	971
Channel catfish	2013-07-15	SLR	60.61	-22.65	12.732	3.18	1380
Channel catfish	2013-07-15	SLR	525.08	-21.05	13.673	3.16	805
Channel catfish	2013-07-15	SLR	1158.36	-21.23	13.973	3.28	1315
Channel catfish	2013-07-15	SLR	594.31	-22.10	13.592	3.33	1101
Channel catfish	2013-07-15	SLR	259.56	-20.64	13.232	2.96	970
Smallmouth bass	2013-07-24	SLR	279.95	-22.69	15.119	3.88	1005
Channel catfish	2013-07-24	SLR	1026.01	-21.14	13.054	3.00	3582
Channel catfish	2013-07-24	SLR	189.62	-22.69	13.099	3.29	520
Channel catfish	2013-07-24	SLR	2071.3	-20.68	14.653	3.38	2786
Channel catfish	2013-07-24	SLR	191.37	-23.10	12.336	3.14	418
Channel catfish	2013-07-24	SLR	1445.7	-21.04	13.847	3.21	1632
Channel catfish	2012-08-28	SLR	111.4	-21.85	12.565	2.98	332
Shorthead redhorse	2012-08-28	SLR	76.5	-20.52	12.758	2.79	1468
Walleye	2012-08-28	SLR	1173.7	-19.82	16.834	3.87	2314
Walleye	2012-08-28	SLR	523	-19.10	16.684	3.69	716
Walleye	2012-08-28	SLR	330.7	-19.78	16.322	3.71	790
Channel catfish	2012-09-07	SLR	574.6	-24.55	10.792	2.95	960
Longnose sucker	2012-09-07	SLR	262.1	-21.99	11.911	2.81	424
Longnose sucker	2012-09-11	SLR	416.2	-20.69	12.711	2.81	222
Smallmouth bass	2012-09-11	SLR	42.6	-17.79	15.44	3.09	446
Smallmouth bass	2012-09-11	SLR	353.3	-22.79	15.321	3.96	612



Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Walleye	2012-09-11	SLR	416.3	-20.56	15.538	3.62	1932
Smallmouth bass	2012-09-11	SLR	446.7	-21.06	15.079	3.58	916
Channel catfish	2012-09-11	SLR	1202.2	-21.70	14.674	3.57	1001
Shorthead redhorse	2012-09-11	SLR	497.4	-22.55	12.92	3.21	456
Shorthead redhorse	2012-09-11	SLR	965.3	-22.57	13.77	3.47	202
Smallmouth bass	2012-09-05	SLR	571.8	-19.94	15.741	3.57	1108
Smallmouth bass	2012-09-05	SLR	1072.5	-21.25	15.628	3.77	1469
Smallmouth bass	2012-09-05	SLR	720.9	-19.86	15.952	3.61	731
Smallmouth bass	2012-09-05	SLR	1366.9	-19.28	15.899	3.49	1639
Smallmouth bass	2012-09-05	SLR	1315.5	-19.92	15.805	3.58	1644
Smallmouth bass	2012-09-06	SLR	130	-20.37	15.246	3.50	
Smallmouth bass	2012-09-06	SLR	458.8	-21.22	14.818	3.53	1012
Smallmouth bass	2012-09-12	SLR	2218	-19.75	15.803	3.55	2392
Walleye	2012-09-12	SLR	355.9	-21.92	15.07	3.73	1016
Walleye	2012-09-12	SLR	316	-20.90	15.581	3.69	1358
Longnose sucker	2012-09-11	SLR	264.7	-21.28	12.232	2.78	351
Walleye	2012-09-13	SLR	1283.5	-20.57	15.264	3.54	2656
Walleye	2012-09-13	SLR	1043.9	-20.54	15.599	3.63	3841
Walleye	2012-09-14	SLR	470.4	-20.01	15.307	3.45	
Shorthead redhorse	2012-11-15	SLR	861.2	-22.35	12.224	2.97	1780
Shorthead redhorse	2013-05-08	SLR	637.7	-21.90	13.499	3.26	708
Shorthead redhorse	2013-05-08	SLR	1019.88	-20.68	13.843	3.14	3101
Shorthead redhorse	2013-05-30	SLR	921.86	-22.20	13.561	3.34	1908
Shorthead redhorse	2013-05-30	SLR	287.07	-20.93	12.865	2.90	429
Shorthead redhorse	2013-05-30	SLR	586.26	-21.85	13.074	3.13	945
Shorthead redhorse	2013-05-30	SLR	1311.1	-20.66	14.281	3.27	1476
Shorthead redhorse	2013-05-31	SLR	619.32	-22.45	12.773	3.15	760
Shorthead redhorse	2013-05-08	SLR	378.45	-22.12	12.998	3.16	
Walleye	2013-06-25	SLR	1.435	-29.88	14.168	4.91	
Channel catfish	2013-05-31	SLR	769.15	-20.55	11.072	2.30	1330

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Walleye	2012-08-22	SMR	557	-26.36	13.008	3.93	3551
Walleye	2012-08-22	SMR	162	-24.10	14.419	3.94	2053
Smallmouth bass	2012-08-22	SMR	240	-26.61	12.389	3.80	965
Channel catfish	2012-08-22	SMR	152	-21.54	13.159	3.10	346
Channel catfish	2012-08-22	SMR	1572	-24.87	10.006	2.78	1111
Channel catfish	2012-08-22	SMR	2341	-25.05	11.814	3.34	3420
Channel catfish	2012-08-22	SMR	1245	-23.03	12.378	3.14	2662
Channel catfish	2012-08-22	SMR	1222	-26.53	11.679	3.57	2379
Channel catfish	2012-08-22	SMR	1417	-27.51	10.09	3.28	5314
Walleye	2012-08-22	SMR	535	-26.86	12.232	3.80	3818
Smallmouth bass	2012-08-22	SMR	281	-27.68	11.534	3.74	2152
Smallmouth bass	2012-08-22	SMR	295	-26.34	12.297	3.72	2194
Smallmouth bass	2012-08-22	SMR	264	-27.07	11.644	3.66	2780
Channel catfish	2012-08-22	SMR	2453	-23.13	11.966	3.04	2812
Smallmouth bass	2012-08-22	SMR	40	-28.93	10.464	3.65	1260
Channel catfish	2012-08-22	SMR	1699	-24.72	10.487	2.89	1022
Walleye	2012-08-21	SMR	395	-27.04	12.381	3.87	3327
Walleye	2012-08-21	SMR	189	-27.87	11.838	3.86	1454
Smallmouth bass	2012-08-21	SMR	189	-29.05	12.045	4.14	1245
Channel catfish	2012-08-21	SMR	571	-27.34	10.721	3.44	939
Channel catfish	2012-08-21	SMR	721	-26.53	9.8	3.02	849
Channel catfish	2012-08-21	SMR	500	-27.98	10.4	3.46	1146
Channel catfish	2012-08-21	SMR	380	-22.65	12.741	3.18	419
Channel catfish	2012-08-21	SMR	680	-28.52	11.337	3.83	1092
Channel catfish	2012-08-21	SMR	389	-28.15	10.664	3.57	1391
Channel catfish	2012-08-21	SMR	840	-22.17	12.096	2.90	669
Channel catfish	2012-08-21	SMR	753	-23.35	12.723	3.30	1298
Channel catfish	2012-08-21	SMR	688	-28.25	10.407	3.51	1627
Channel catfish	2012-08-21	SMR	411	-23.19	12.595	3.23	1136
Channel catfish	2012-08-21	SMR	3025	-27.25	12.251	3.87	11794

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Smallmouth bass	2012-08-21	SMR	137	-28.85	11.243	3.87	1040
Channel catfish	2012-08-21	SMR	636	-22.08	13.234	3.22	669
Channel catfish	2012-08-21	SMR	913	-22.51	13.363	3.34	1162
Channel catfish	2012-08-21	SMR	1144	-25.75	10.554	3.10	2749
Channel catfish	2012-08-21	SMR	1557	-25.82	9.405	2.77	1190
Channel catfish	2012-08-23	SMR	591	-26.71	11.284	3.49	1515
Channel catfish	2012-08-23	SMR	669	-25.95	12.248	3.63	1029
Channel catfish	2012-08-23	SMR	1693	-21.35	14.491	3.45	1518
Channel catfish	2012-08-23	SMR	835	-28.50	10.961	3.72	2468
Channel catfish	2012-08-23	SMR	1178	-30.01	10.153	3.76	2974
Channel catfish	2012-08-23	SMR	888	-28.14	11.021	3.67	1621
Channel catfish	2012-08-23	SMR	802	-25.85	11.05	3.26	894
Longnose sucker	2012-08-23	SMR	555	-28.98	9.926	3.50	2468
Channel catfish	2012-08-23	SMR	346	-29.58	10.283	3.72	1612
Smallmouth bass	2012-08-23	SMR	450	-30.66	10.466	3.97	2268
Smallmouth bass	2012-08-23	SMR	394	-29.99	10.569	3.88	2161
Longnose sucker	2012-08-23	SMR	596	-28.45	10.077	3.45	1966
Channel catfish	2012-08-23	SMR	1044	-28.82	10.645	3.69	4907
Channel catfish	2012-08-23	SMR	999	-22.35	11.176	2.66	1096
Channel catfish	2012-08-23	SMR	931	-22.06	13.524	3.30	1558
Smallmouth bass	2012-08-23	SMR	48	-30.43	9.583	3.67	524
Smallmouth bass	2012-08-23	SMR	354	-30.69	10.119	3.87	2423
Smallmouth bass	2012-08-23	SMR	548	-29.50	10.73	3.84	2515
Smallmouth bass	2012-08-23	SMR	437	-29.96	11.204	4.06	1876
Smallmouth bass	2012-08-23	SMR	514	-30.44	10.718	4.00	2387
Walleye	2012-08-23	SMR	1353	-29.83	12.103	4.30	7079
Smallmouth bass	2012-08-20	SMR	323	-28.22	10.878	3.64	2528
Channel catfish	2012-08-23	SMR	665	-28.13	11.105	3.70	1799
Walleye	2012-08-23	SMR	1112	-29.79	11.403	4.09	5845
Channel catfish	2012-08-23	SMR	534	-29.23	10.314	3.66	1628

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Smallmouth bass	2012-08-23	SMR	622	-30.17	10.615	3.92	2455
Smallmouth bass	2012-08-23	SMR	38	-29.96	9.656	3.60	607
Channel catfish	2012-08-23	SMR	1161	-24.26	12.245	3.33	1172
Smallmouth bass	2012-08-23	SMR	164	-29.04	10.513	3.69	1691
Walleye	2012-11-09	SMR	821	-20.18	15.775	3.62	2399
Walleye	2012-11-07	SMR	204	-28.74	11.695	3.98	3210
Walleye	2013-04-30	SMR	1570	-19.32	15.606	3.41	
Walleye	2013-04-30	SMR	506	-19.42	15.543	3.41	1256
Walleye	2013-04-30	SMR	900	-19.14	15.89	3.46	1933
Walleye	2013-04-30	SMR	550	-19.61	15.726	3.50	1834
Walleye	2013-04-30	SMR	533.4	-20.00	14.145	3.11	
Walleye	2013-04-30	SMR	408.61	-19.28	15.827	3.47	1486
Walleye	2013-04-30	SMR	425.59	-19.29	15.438	3.36	1411
Walleye	2013-04-30	SMR	501.08	-19.36	15.693	3.45	1101
Walleye	2013-04-30	SMR	547.23	-18.31	15.798	3.29	
Longnose sucker	2013-04-30	SMR	798.44	-20.19	13.011	2.81	1117
Longnose sucker	2013-04-30	SMR	1069.77	-18.65	12.638	2.42	1192
Longnose sucker	2013-05-01	SMR	583.07	-27.40	10.319	3.33	2049
Walleye	2013-05-01	SMR	500.1	-18.88	15.314	3.25	1043
Walleye	2013-05-01	SMR	463.87	-19.28	16.168	3.57	1178
Walleye	2013-05-01	SMR	2712.7	-19.36	16.009	3.54	4902
Walleye	2013-04-25	SMR	1470	-20.24	15.551	3.56	2977
Walleye	2013-04-25	SMR	1040	-18.26	15.473	3.18	1992
Walleye	2013-04-25	SMR	1535	-17.92	15.628	3.16	3167
Walleye	2013-04-25	SMR	998	-17.97	15.823	3.23	
Longnose sucker	2013-05-23	SMR	373.48	-20.56	12.186	2.63	1168
Longnose sucker	2013-05-23	SMR	360.22	-21.06	12.032	2.68	598
Walleye	2013-05-23	SMR	1047.72	-24.27	14.147	3.89	5725
Longnose sucker	2013-05-23	SMR	450.58	-20.38	12.778	2.77	556
Channel catfish	2013-05-23	SMR	1777.5	-17.50	14.811	2.85	732

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Walleye	2013-05-23	SMR	573.44	-18.70	15.762	3.35	1586
Channel catfish	2013-05-24	SMR	385.68	-27.73	10.907	3.56	1562
Longnose sucker	2013-05-24	SMR	499.02	-22.51	12.108	2.97	1762
Longnose sucker	2013-05-24	SMR	810.87	-21.06	14.58	3.43	2573
Channel catfish	2013-05-24	SMR	1148.36	-28.32	10.71	3.61	2548
Channel catfish	2013-05-24	SMR	1968.1	-20.88	14.231	3.29	3001
Channel catfish	2013-05-24	SMR	1127.42	-22.81	11.372	2.80	942
Channel catfish	2013-05-24	SMR	551.06	-26.41	11.448	3.48	820
Channel catfish	2013-05-24	SMR	999.25	-26.10	9.914	2.97	1012
Channel catfish	2013-05-24	SMR	3174.8	-18.25	15.44	3.17	5958
Channel catfish	2013-05-24	SMR	2914.3	-23.06	12.172	3.08	2177
Channel catfish	2013-05-24	SMR	1812.7	-24.05	12.774	3.44	1970
Channel catfish	2013-05-24	SMR	2916.8	-23.17	12.973	3.34	1102
Channel catfish	2013-05-24	SMR	1173.76	-27.10	10.768	3.41	1502
Channel catfish	2013-05-24	SMR	2197.08	-22.68	12.415	3.09	163
Channel catfish	2013-05-24	SMR	3128.2	-21.43	12.253	2.81	938
Channel catfish	2013-05-24	SMR	584.36	-25.06	12.895	3.66	1196
Channel catfish	2013-05-24	SMR	648.4	-28.53	10.916	3.71	1621
Channel catfish	2013-05-24	SMR	849.73	-20.08	14.005	3.08	856
Channel catfish	2013-05-24	SMR	2221.2	-19.78	14.602	3.20	2214
Channel catfish	2013-05-24	SMR	3044.6	-23.70	14.378	3.85	2571
Longnose sucker	2013-05-24	SMR	408.77	-19.42	14.294	3.05	481
Channel catfish	2013-05-24	SMR	784.69	-24.86	11.842	3.32	922
Channel catfish	2013-05-24	SMR	2094.2	-22.57	12.289	3.03	1531
Channel catfish	2013-05-24	SMR	1363.5	-24.95	11.313	3.18	1530
Longnose sucker	2013-05-24	SMR	586.24	-20.06	12.484	2.63	1553
Walleye	2013-05-24	SMR	648.3	-18.98	15.46	3.31	3075
Channel catfish	2013-05-28	SMR	797.6	-28.08	11.107	3.69	2068
Longnose sucker	2013-05-28	SMR	559.78	-21.79	11.828	2.75	1192
Channel catfish	2013-05-28	SMR	1311.4	-20.82	13.649	3.11	1512

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Channel catfish	2013-05-28	SMR	2915.1	-19.76	15.773	3.54	5250
Channel catfish	2013-05-28	SMR	2172.4	-18.94	14.556	3.04	2372
Longnose sucker	2013-05-22	SMR	561.03	-20.29	13.919	3.09	2653
Walleye	2013-05-22	SMR	426.35	-19.16	15.209	3.27	
Longnose sucker	2013-05-22	SMR	362.3	-18.99	13.72	2.80	339
Walleye	2013-05-22	SMR	421.2	-18.88	15.651	3.35	1600
Longnose sucker	2013-05-22	SMR	494.4	-20.78	11.83	2.57	1264
Longnose sucker	2013-05-22	SMR	597	-28.79	10.157	3.54	2069
Channel catfish	2013-05-22	SMR	3054.2	-20.67	13.348	2.99	2276
Longnose sucker	2013-05-22	SMR	657.17	-27.28	10.093	3.24	2193
Longnose sucker	2013-05-22	SMR	542.56	-29.35	10.154	3.64	2153
Walleye	2013-05-22	SMR	330.61	-20.63	15.373	3.58	1247
Channel catfish	2013-05-28	SMR	1773.3	-23.68	12.158	3.19	4331
Smallmouth bass	2013-05-27	SMR	817.9	-29.63	10.865	3.90	5661
Smallmouth bass	2013-07-03	SMR	1136.61	-20.86	15.416	3.64	1974
Smallmouth bass	2013-07-16	SMR	512.21	-27.04	11.509	3.61	3150
Smallmouth bass	2013-07-17	SMR	274.21	-27.62	11.633	3.76	1624
Smallmouth bass	2013-07-17	SMR	464.07	-27.77	9.887	3.27	1903
Smallmouth bass	2013-07-17	SMR	548.51	-27.93	9.62	3.22	4127
Smallmouth bass	2013-07-17	SMR	684.41	-27.87	9.991	3.32	4787
Smallmouth bass	2013-07-17	SMR	185.96	-28.12	9.609	3.25	1300
Smallmouth bass	2013-07-17	SMR	255.55	-29.95	11.129	4.04	1569
Smallmouth bass	2013-07-17	SMR	299.32	-28.98	11.355	3.92	2367
Smallmouth bass	2013-07-17	SMR	201.3	-28.26	10.92	3.67	2169
Smallmouth bass	2013-07-24	SMR	486.62	-26.64	12.027	3.70	3107
Smallmouth bass	2013-07-24	SMR	821.55	-26.27	10.064	3.05	4779
Smallmouth bass	2013-07-24	SMR	761.98	-25.52	12.436	3.61	4248
Smallmouth bass	2013-07-24	SMR	611.04	-26.98	12.086	3.77	3005
Smallmouth bass	2013-08-01	SMR	628.2	-27.13	11.359	3.59	3283
Smallmouth bass	2013-08-01	SMR	664.53	-27.92	10.044	3.34	4205

Species	Date	Site	Weight (g)	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Trophic position	Mercury (ng/g)
Smallmouth bass	2013-08-01	SMR	361.75	-27.04	11.111	3.50	2551
Smallmouth bass	2013-08-01	SMR	242.76	-28.68	11.269	3.84	1746
Smallmouth bass	2013-08-01	SMR	509.15	-26.77	11.808	3.65	3271
Smallmouth bass	2013-08-01	SMR	127.33	-26.37	12.85	3.89	1386
Walleye	2013-05-01	SMR		-18.06	16.013	3.30	1493
Walleye	2013-05-01	SMR		-19.31	15.902	3.50	1886
Walleye	2013-05-01	SMR		-19.25	15.654	3.41	1285
Walleye	2013-05-01	SMR		-19.40	15.656	3.44	2774
Walleye	2013-05-01	SMR		-20.36	14.98	3.42	3311
Shorthead redhorse	2012-08-21	SMR	2378	-23.78	13.056	3.48	2177
Shorthead redhorse	2012-08-23	SMR	1021	-31.40	9.366	3.78	3685
Shorthead redhorse	2012-08-23	SMR	1042	-31.85	8.653	3.65	3107
Shorthead redhorse	2012-08-23	SMR	649	-30.41	9.443	3.62	1569
Shorthead redhorse	2012-08-23	SMR	780	-29.80	10.02	3.68	1232
Shorthead redhorse	2012-08-23	SMR	1183	-31.51	8.676	3.60	3143
Shorthead redhorse	2013-05-22	SMR	851.79	-29.56	9.794	3.57	2330
Shorthead redhorse	2013-05-22	SMR	1136.31	-32.15	8.759	3.74	3632
Shorthead redhorse	2013-05-22	SMR	1041.76	-31.00	9.001	3.60	4292
Shorthead redhorse	2013-05-23	SLR	1980.1	-30.10	9.006	3.44	6515
Shorthead redhorse	2013-05-23	SLR	804.14	-26.31	10.532	3.20	4629
Shorthead redhorse	2013-05-28	SMR	776.26	-30.09	9.214	3.50	1682
Shorthead redhorse	2013-05-28	SMR	904.36	-29.99	9.67	3.61	3974
Shorthead redhorse	2013-05-28	SMR	945.45	-31.56	8.733	3.62	3529
Shorthead redhorse	2013-05-28	SMR	1075.63	-32.23	8.605	3.71	3476
Smallmouth bass	2012-09-18	SMR	2.605	-24.06	9.462	2.47	
Channel catfish	2013-05-24	SMR	1241.6	-23.61	10.833	2.79	2758

## ANNEXE B

### INVERTÉBRÉS AQUATIQUES CAPTURÉS DANS LA RIVIÈRE SAINT-AURICE ET LE FLEUVE SAINT-LAURENT

**Tableau B.1**

Liste des invertébrés aquatiques capturés dans la rivière Saint-Maurice et  
le fleuve Saint-Laurent en 2012 et 2013

<b>Family</b>	<b>Date</b>	<b>Localisation</b>	<b>Number</b>	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$
Macromiidae	2013-06-13	SMR	11	-29.704	5.459
Gammaridae	2013-06-13	SMR	10	-28.762	4.817
Hydrobiidae	2013-06-13	SMR	8	-28.74	6.178
Planorbidae	2013-06-13	SMR	8	-28.626	5.079
Bithyniidae	2013-06-13	SMR	11	-28.092	4.606
Gammaridae	2012-09-18	SMR	1	-23.547	4.222
Macromiidae	2013-06-19	SMR	1	-29.919	4.854
Macromiidae	2013-06-19	SMR	3	-29.924	5.859
Unionidae	2013-06-19	SMR	4	-32.847	5.248
Bithyniidae	2013-06-19	SMR	2	-27.109	2.867
Chironomidae	2013-07-13	SLR	7	-26.265	9.005
Gammaridae	2013-07-13	SLR	12	-24.634	9.295
Leptoceridae	2013-07-13	SLR	2	-26.318	10.094
Viviparidae	2013-07-12	SLR	2	-25.539	8.925
Bithyniidae	2013-07-12	SLR	1	-23.173	9.416
Hydrobiidae	2013-07-12	SLR	9	-23.345	10.847
Gammaridae	2013-07-12	SLR	14	-24.16	8.897
Gammaridae	2013-07-12	SLR	32	-23.958	8.984
Gammaridae	2013-07-12	SLR	37	-24.208	7.034
Polycentropodidae	2013-07-12	SLR	8	-28.829	7.912



Family	Date	Localisation	Number	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$
Hydropsychidae	2013-07-12	SLR	13	-28.791	6.114
Viviparidae	2013-07-12	SLR	7	-25.765	10.168
Bithyniidae	2013-07-12	SLR	4	-23.33	8.772
Sphaeriidae	2013-07-12	SLR	12	-30.656	9.36
Gammaridae	2013-07-12	SLR	19	-25.522	8.765
Hydrobiidae	2013-07-12	SLR	1	-23.147	7.151
Gammaridae	2013-06-14	SLR	20	-25.388	7.855
Corixidae	2013-06-14	SLR	3	-25.808	7.691
Gammaridae	2013-06-25	SLR	5	-26.735	8.501
Corixidae	2013-06-25	SLR	7	-31.168	10.026
Psephenidae	2013-06-25	SLR	5	-24.471	8.182
Hydrophilidae	2013-06-25	SLR	1	-32.44	6.971
Gammaridae	2013-06-25	SLR	23	-27.288	8.923
Bithyniidae	2013-06-25	SLR	1	-24.637	13.067
Lymeidae	2013-06-25	SLR	2	-23.687	7.006
Bithyniidae	2013-06-28	SLR	15	-26.537	9.458
Physidae	2013-06-28	SLR	3	-25.536	4.863
Hydrophilidae	2013-06-28	SLR	1	-26.332	7.885
Gammaridae	2013-06-25	SLR	26	-26.796	8.898
Physidae	2013-06-25	SLR	3	-26.785	8.952
Gammaridae	2013-06-14	SLR	8	-28.762	7.85
Gammaridae	2013-06-14	SLR	2	-24.51	6.057
Gammaridae	2012-09-27	SLR	24	-16.686	9.26
Gammaridae	2012-10-23	SLR	106	-16.889	9.73
Gammaridae	2012-10-23	SLR	8	-18.239	7.088
Planorbidae	2012-09-18	SLR	4	-22.539	6.051
Physidae	2012-09-18	SLR	1	-17.566	5.315
Gammaridae	2012-10-23	SLR	35	-18.359	9.882
Physidae	2012-10-23	SLR	1	-17.55	10.642
Dreissenidae	2012-10-23	SLR	1	-23.09	10.098

<b>Family</b>	<b>Date</b>	<b>Localisation</b>	<b>Number</b>	<b><math>\delta^{13}\text{C}</math></b>	<b><math>\delta^{15}\text{N}</math></b>
Gammaridae	2012-10-09	SLR	9	-17.995	8.949
Hydropsychidae	2012-10-09	SLR	2	-20.63	8.986
Psephenidae	2012-10-09	SLR	6	-12.542	8.979
Unionidae	2012-11-15	SLR	1	-24.364	10.091
Dreissenidae	2012-11-15	SLR	3	-24.594	8.032
Unionidae	2013-07-13	SLR	1	-24.086	11.385
Unionidae	2013-07-12	SLR	1	-24.052	10.78
Dreissenidae	2013-07-12	SLR	1	-27.556	8.357
Dreissenidae	2013-07-12	SLR	6	-29.938	8.97
Unionidae	2013-07-12	SLR	1	-30.307	9.531
Planorbidae	2012-10-23	SLR	4	-21.942	5.455
Bithyniidae	2012-10-23	SLR	s1	-28.326	4.875
Planorbidae	2012-10-23	SLR	1	-26.513	5.356
Chironomidae	2012-10-23	SLR	22	-28.026	4.027
Sphaeriidae	2013-07-12	SLR	1	-30.814	8.938
Bithyniidae	2013-06-13	SMR	5	-27.174	4.006
Phryganeidae	2013-06-13	SMR	1	-24.473	6.842
Corixidae	2013-06-13	SMR	2	-25.863	10.153
Gammaridae	2013-06-13	SMR	1	-27.234	3.177
Macromiidae	2013-06-13	SMR	1	-30.306	5.801
Baetidae	2013-06-13	SMR	1	-30.859	2.548
Bactiscidae	2013-06-13	SMR	4	-32.085	4.347
Baetidae	2013-06-13	SMR	3	-29.83	2.86
Ephemerellidae	2013-06-13	SMR	2	-29.7	3.9
Gammaridae	2013-06-13	SMR	1	-28.081	5.526
Phryganeidae	2013-06-13	SMR	1	-28.548	3.173
Tipulidae	2012-09-18	SMR	2	-26.494	5.56
Tipulidae	2012-09-18	SMR	1	-26.029	1.978