GENOTOXICITY IN WATER AND SEDIMENT EXTRACTS FROM THE ST. LAWRENCE RIVER SYSTEM, USING THE SOS CHROMOTEST

by

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Abstract

Surface water and sediments from the St. Lawrence River system (Québec region) were analysed for genotoxicity using non-linear SOS Chromotest parameters, as well as for their chemical concentrations of polycyclic aromatic hydrocarbons and heavy metals. Additionally, sediments chlorobenzenes, polychlorinated biphenyls, organochlorinated pesticides, ammonia and nitrites concentrations were determined. Water and sediments sampled from twenty-five sites were initially partitioned into their aqueous and particulate phases by tangential flow filtration and centrifugation, respectively. Organic contaminants were extracted from the fractions with dichloromethane. For surface water, fifteen extracts of filtered water and seven of particulates, and for sediments, one extract of pore water and three of particulates proved to be weakly genotoxic. All but one of the genotoxic responses observed in the surface water were obtained from samples taken from the highly industrial portion of the St. Lawrence River system, with the strongest responses observed in Lake St-Louis. Surface water genotoxicants partitioning favors the particulate fraction. Bottom particulates genotoxicity was one thousand fold weaker than suspended particulates. Additionally, whole sediments were extracted with a 10 % dimethylsulfoxide-saline solution. Genotoxicity of hydrophilic contaminants was detected in all extracts. The observed distributions of genotoxicity values did not correlate with observed concentrations of demonstrated SOS

inducers, mutagens and/or carcinogens, nor with the presence of other toxic chemical.

Résumé

La génotoxicité des eaux et sédiments de surface provenant de vingt-cinq sites situés sur le réseau fluvial du Saint-Laurent a été déterminée à l'aide de paramètres non-linéaires reliés au SOS Chromotest. Les concentrations en hydrocarbures aromatiques polycycliques et en métaux lourds des eaux et sédiments ainsi que les concentrations en biphényles polychlorés, pesticides organochlorés, chlorobenzènes, ammoniac et nitrites des sédiments ont été mesurées. Les fractions aqueuse et particulaire des échantillons d'eau et de sédiments ont été obtenues par filtration à écoulement tangentiel et par centrifugation. Les contaminants organiques de chacune des fractions ont été extraits au dichlorométhane. Quinze extraits de fraction aqueuse et sept extraits de fraction particulaire des échantillons d'eau de surface se sont avérés génotoxiques. Pour ce qui est des sédiments, un extrait de fraction aqueuse et trois extraits de fraction particulaire se sont avérés génotoxiques. A l'exception d'un seul, tous les extraits génotoxiques proviennent d'échantillons prélevés dans la zone hautement industrielle du réseau fluvial du Saint-Laurent; les réponses les plus fortes étant associées aux échantillons d'eau de surface prélevés sur le lac Saint-Louis. La fraction particulaire de l'eau de surface est nettement plus génotoxique que la fraction aqueuse. Par ailleurs, la fraction particulaire des sédiments l'est mille fois moins que celle de l'eau de surface. Des génotoxines hydrophiles extraites à l'aide d'une solution saline contenant 10% de diméthylsulfoxide se sont avérées présentes dans tous les

échantillons de sédiments entiers. La génotoxicité des extraits n'est en aucun cas corrélée aux concentrations de substances génotoxiques, mutagènes et/ou cancérigènes reconnues, ou aux concentrations de toute autre substance toxique présente dans les échantillons d'eau et de sédiments.

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Preface

This thesis has been prepared in the format of one manuscript which has been submitted to scientific journals. The supervisors of the thesis, Dr. Joseph Rasmussen, Mr. Harm Sloterdijk and Dr. Christian Blaise will appear as the co-authors of the paper.

The originality of the research is first believed to lie in the use of the SOS Chromotest, a recently developed micro-bioassay, to determine the genotoxicity of non point-source contaminated environmental samples, more precisely southern Québec waterways surface waters and sediments. The study sheds a light on the partitioning of genotoxicants between the aqueous and particulates fractions of the St. Lawrence River system, as well as on the presence of hydrophobic and hydrophilic genotoxicants in that system. Finally, it introduces an alternative method for the estimation of the SOS Chromotest genotoxicity parameters, based on the non-linearity of the concentration-response curve.

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Introduction

In Canada, the St. Lawrence River drains one of the largest urban-industrial complexes of the world. During the last decades, urban-industrial activity has clearly been identified as a major source of contaminants for aquatic environments, via atmospheric deposition and wastewaters discharge (Rand and Petrocelli, 1985). It is now well established that many of these contaminants have the ability to induce genetic disorders (Nestmann, 1985; Pitts, 1983). In particular, DNA-damaging agents have been shown to induce inherited genetic defects and cancer (Brusick, 1987; Loprieno, 1982). Consequently, concern has been growing about potential adverse effects of genotoxicants on aquatic biota and public health through contamination of drinking water supplies, recreational waters or edible aquatic species (Loper, 1980; McGeorge *et al.*, 1985).

The use of biotesting has proved essential in investigating the presence of genotoxic activity in natural environments (Blaise *et al.*, 1988; USEPA, 1985). Bacteria have been widely used as test organisms to detect genotoxicants (Kibley *et al.*, 1984). The Salmonella/microsome assay is one of the best known and most studied systems (Ames *et al.*, 1975). The research by Ames and co-workers was important in establishing the association between DNA damage, mutagenicity and carcinogenicity (McCann *et al.*, 1975). Recently, a sensitive, rapid and practical assay, the SOS Chromotest, was developed (Quillardet *et al.*, 1982). This colorimetric assay is based on the induction of a gene which is controlled by the general

repressor of the SOS (DNA repair) system in *E. coli* (Little and Mont, 1982; Walker, 1984). Although limited, cross-referencing has been carried out between the Ames and the SOS tests, the results obtained thus far show 90-100 % agreement between the two tests (Vigerstad *et al.*, 1988).

Most biological responses to toxic agents display a threshold behaviour, that is, relationships between exposure level and response exhibited tend to be non-linear (Rand and Petrocelli, 1985). There exists a high concentration range where maximal response occurs and the system approaches zero order kinetics. In addition, a low concentration range with no response is sometimes present. The definition of the concentration-response relationship is usually centered around the responsive range of concentrations, with the simplest analytical approach being to fit a linear model in this range. Quillardet and Hofnung (1985) defined three parameters to quantitatively describe SOS Chromotest assay results: 1) the minimum detectable genotoxic concentration (MDC), 2) the SOS-inducing potency (SOSIP), the slope of the linear portion of the concentration-response curve, and 3) the maximum inducing level (MIL) (Fig. 1). Thus, Quillardet fits a linear model to the responsive range of the assay. However, the present study shows that the responsive range of the SOS Chromotest concentration-response is often better described by a hyperbola than by a linear model. In such instances, the choice of points making up the linear portion of the concentration-response curve and consequently the delineation of

Quillardet's MDC, SOSIP and MIL are highly subjective and the linear model produces a poor fit to data.

A concentration step is often necessary before genotoxicity testing because of low concentrations of genotoxicants in environmental samples. Concentration methods are primarily based on organic contaminants liquid-liquid, XAD resin and Soxhlet extraction, using ultrapure organic solvents (Janardan *et al.*, 1980; USEPA, 1985).

Toxic metals and many of the more commonly detected toxic organic chemicals are often closely associated with suspended particulates. Therefore, the settling of particulate matter on bottom sediments acts as one of the primary removal mechanisms from the water column for selected contaminants, including genotoxicants. At the same time, the settling of particulate matter plays a major role in determining the bioavailability of these contaminants at various levels of the aquatic food web, including humans (Allan, 1986).

This thesis reports the results of a study designed to evaluate the genotoxic activity in dichloromethane (DCM) extracts of the particulate and aqueous fractions of surface water and sediments from the St. Lawrence River system. Whole sediment (pore water and particulates) 10% dimethylsulfoxide (DMSO)-saline extracts were also tested for genotoxicity, in order to assess the contribution of hydrophilic compounds to environmental

genotoxicity. All extracts were analysed with the SOS Chromotest. A non-linear model of the SOS Chromotest concentration-response relationship was developed. The genotoxicity of the extracts was evaluated on the basis of parameters derived from this non-linear model and tested in terms of water and sediments observed chemical concentrations and sampling area industrial activity.

Materials and methods

Study area

The St. Lawrence River extends from the mouth of lake Ontario, where it forms the border between Canada and the United States, to the Gulf of St. Lawrence eastward. Its drainage basin includes the North American Great Lakes as well as southern Québec (Canada) and parts of the northeastern U.S. and supports intensive and diversified agricultural and urban-industrial activities. In Québec, more than half of the 12 000 industries are situated on the river's watershed and half the population of 6.8 million has settled on the river's shore (MENVIQ, 1988). South-east of Montréal, within the St. Lawrence River system, lie Lakes Champlain, Memphrémagog, Brome and Waterloo whose watersheds have suffered much less industrialisation (DEL, 1982; Janus and Vollenweider, 1981; USEPA, 1977) (Fig. 2 and Table 1).

Surface water

Surface water was collected from nineteen sites on the St. Lawrence River and tributaries, between Cornwall and Trois-Rivières, and from six sites on four southern Québec lakes: Champlain, Brome, Waterloo and Memphrémagog (Fig. 2), between June and October 1988. The samples were kept on ice and returned

within 24 hours to the laboratory, where they were kept in the dark at 4°C, for 48 hrs. Each 24 l water sample was then passed through 0.4 µm HVLP membranes (Millipore^{TM}) using a tangential flow filtration apparatus. The filtrate was then extracted with 200 ml of pesticide grade DCM at pH 2 and 11 on a large volume extractor, at a flow rate of 500 ml/min (Neilson *et al.*, 1988). Combined DCM extracts were dried with anhydrous sodium sulphate, reduced to 5 ml in a Kuderna-Danish evaporator, and to dryness under a stream of ultrapure nitrogen at room temperature. The residue was resuspended in 250 µl of pesticide grade DMSO, for a concentration factor of 9.6 X 10^4 with respect to the original water volume. The particulate fraction, which had been concentrated in a 200 ml water volume after tangential flow filtration, was recovered on 0.4 µm Nuclepore polyester membranes (Nuclepore^{TM}), under nitrogen pressure. Membranes and particulates were desiccated for 48 hours and extracted with 150 ml of DCM on a Soxhlet apparatus for 6 hours (USEPA, 1985). The extract was then concentrated as described for the filtered water extracts and resuspended in 500 µl of DMSO, for a concentration factor of 4.8 X 10^4.

Surficial sediments

Surficial sediments (2 cm depth) were collected at each surface water sampling site, with a 12" X 12" X 12" Eckman dredge. They were immediately homogenised and kept on ice, in the dark until returned to the laboratory. Each sample was centrifuged for 20

min at 1000 G, in order to separate the particulate fraction from pore water. A 25 ml aliquot of homogenised pore water (supernatant) was extracted with 25 ml of DCM at pH 2 and 11 (USEPA, 1985). The extract was reduced to dryness as described previously and resuspended in 100 µl of DMSO, for a 250 fold concentration. A 25 g aliquot of homogenised particulates was dehydrated with anhydrous magnesium sulfate and extracted with 150 ml of DCM for 6 hours in a Soxhlet apparatus. The extract was reduced to dryness and resuspended in 1 ml of DMSO, for a final concentration factor of 25, with respect to original sediments weight. Additionally, for twenty-three sediments samples, 40 g of whole sediments (pore water and particulates) were extracted with 40 ml of a 10 % DMSO-saline solution (0.85 % NaCl in demineralized water), in a teflon centrifuge tube. The tube was stoppered and vigorously shaken by hand for 3 min. The mixture was then centrifuged for 20 min at 1000 G and the supernatant recovered (Xu *et al.*, 1987). In order to complete the sampling program within the short summer period and due to limited manpower, water and sediments extracts were kept in the dark at 4°C for a period of one to three months, before biological testing could take place. Effects of prolonged storage on extract genotoxicity have not been assessed in the present study and are generally not known. However, sample extraction is used to preserve water and sediments samples (Plumb, 1981).

SOS Chromotest

The SOS Chromotest makes use of a specially constructed strain of *Escherichia coli* (PQ37: F^- *thr leu his-4 pyrD thi galK or galT lacΔU169 slr300* :: Tn*10 rpoB rpsL uvrA rfa trp* :: Mu*c* + *sulA* :: Mu*d* (Ap *lac*) cts Pho^C), in which the *sulA* gene, involved in the bacterial DNA repair SOS regulatory network, is fused with the *lacZ* gene, responsible for β-galactosidase production (Wood and Sedgwick, 1986). Thus, β-galactosidase is produced whenever the SOS response is induced as a result of DNA damage. Since the normal and independent bacterial *lacZ* gene has been deleted from the tester strain, β-galactosidase production becomes strictly dependent on *sulA* expression. The activity of the constitutive enzyme alkaline phosphatase (AP) is monitored as an indirect measure of cell viability (Quillardet *et al.*, 1982).

The genotoxicity of each extract was tested with the miniaturized version of the SOS Chromotest according to the protocol described by Orgenics Ltd. (1986). All extracts were tested in the presence and absence of the S9 activation mix (Microbiological Assossiates), a crude rat liver enzymes extract, induced with Aroclor 1254 on Sprague-Dawley male rats. The S9 mix simulates the mammalian detoxification system. Mammalian liver enzymes can, in fact, under oxidizing conditions convert some non-genotoxic materials to active genotoxic entities and vice-versa (Fish *et al.*, 1985).

For the experimental undertaking of the SOS Chromotest, 8 wells (one column) of a 96-well microplate were dedicated to the preparation of two-fold serial dilutions for each tested extract. SOS Chromotest bacteria were inoculated into each well. Other columns of the microplate included a negative control (8 wells of bacteria and growth medium), a positive control without activation (8 two-fold serial dilutions of 4-nitro-quinoline-oxide, bacteria, and growth medium), or a positive control with activation (8 two-fold serial dilutions of 2-amino-anthracene, bacteria, and growth medium). After two hours of incubation at 37°C, a mixture of the two chromogenic substrates 5-bromo-4-chloro-3-indolyl-β-D-galactosidase and p-nitrophenyl-phosphate were added to the wells, allowing the activity of β-galactosidase and alkaline-phosphatase to be expressed as a blue and a yellow color respectively. The plate was further incubated for 75 min. β–galactosidase and alkaline phosphatase activity of test and control wells were measured spectrophotometrically at 620 (blue) and 405 (yellow) nm, and corrected for pre-incubation optical density (initial color of the extracts).

Induction of the *sulA* gene at sample concentration C is expressed as the ratio R(C) of β-galactosidase and alkaline phosphatase activities. To correct for the contribution of the spontaneous background induction of the *sulA* gene, a normalised induction factor I(C)=R(C)/R(0) is used, where R(0) represents the ratio of the two enzyme activities, averaged over the eight negative control wells. The induction factor I(C) of the negative control is

therefore equal to 1. I(C) is regarded as a statistically significant indication of genotoxic activity when R(C) exceeds R(0) by two standard errors.

Normalised induction factors I(C) were plotted against concentrations C (equivalent volume or weight of original sample) to produce an hyperbolic concentration-response curve (Fig. 3). The curve has been defined in term of the hyperbolic equation I(C) - 1 = (MIF - 1) * (C - XT)/(KC + (C - XT)), where MIF is the maximum induction factor possible, i.e. the asymptote of the curve, XT is the highest concentration of the test substance that results in an induction factor equal to the negative control or 1, i.e. the X-intercept of the curve and KC is the sample concentration above XT which results in an I(C) equal to (MIF - 1)/2. White *et al.* (1991) have demonstrated that, in terms of both statistical precision and bias, the hyperbolic model provides a superior fit to the concentration-response data than the linear approach. The three parameters defining the curve were estimated by non-linear regression, via an iterative maximum likelihood method using SYSTAT (Wilkinson, 1987). In the majority of cases, all data points were included in the nonlinear regression. In a few cases low concentrations which did not elicit a statistically significant response were removed prior to fitting the curve. In addition, the highest concentrations tested occasionally elicited sub-maximal responses. Such observations were removed when they were significant outliers, as determined by analysis of studentized residuals (Wilkinson, 1987). Since the SOS Chromotest monitors

alkaline phosphatase activity to provide a means of correcting for test substance toxicity, such sub-maximal responses at high test concentrations are uncommon, but do occur when toxicity is too high. Normally the induction factor, corrected for test substance toxicity, levels off to a plateau (Quillardet and Hofnung, 1985). Sample genotoxicity was determined from the curve parameters estimates in terms of: 1) a minimum detectable genotoxic concentration (MDGC), by solving the non-linear equation for C when I(C) is systematically equal to the negative control induction factor plus two standard errors; 2) an SOS response inducing potency (SRIP), equal to the slope of the initial portion of the curve or (MIF - 1)/2/KC; and 3) a maximum induction factor (MIF).

Where the range of tested genotoxic concentrations was not sufficient to produce a full hyperbola, SRIP was taken as the slope of the line passing through the statistically significant portion of the incomplete concentration-response curve, MDGC was taken as the sample concentration associated with the intersection point between that line and the background induction level plus two standard errors, and MIF as the maximum induction factor I(C) reached within the range of tested concentrations.

Physico-chemical parameters

Surface water and sediments were analysed for polycyclic aromatic hydrocarbons (PAH) and for heavy metals. Additionally, sediments were analysed for chlorobenzenes, organochlorinated pesticides, polychlorinated biphenyls (PCB), ammonia and nitrites. Analyses of organic and metallic compounds were performed by Environment Canada laboratories in Burlington, Ontario, while sediments ammonia and nitrites contents were determined by Analex Laboratories Inc., Montréal, Québec (Environment Canada, 1988) (Table 2).

Results and discussion

Surface water

Results of the SOS Chromotest applied to the aqueous and particulate fractions of surface water are presented in Tables 3 and 4, respectively. The highest concentration tested corresponds to 200 ml of water and 0.6 mg of suspended particulates per microplate well. The final absorbance values of three particulate matter extracts for which initial color showed to be markedly different from control were corrected as described in the methods section Genotoxic activity was detected in fourteen aqueous fractions out of twenty-five, in absence of metabolic activation (MIF: 1.17-2.22; SRIP: 0.002-0.049 IF per ml of filtered water; MDGC: 5.6-43.5 ml) and in eleven of these when S9 mix was used (MIF: 1.16-1.65; SRIP: 0.001-0.010 IF per ml of filtered water; MDGC: 18.8-104.5 ml). Genotoxic activity was also expressed in seven of the particulate matter extracts, when tested without metabolic activation (MIF: 1.11-1.21; SRIP: 5 140-37 150 IF per g of dry particulates; MDGC: 5.5-15.6 µg).

Genotoxicity is shown to be highly correlated with the highly urban-industrially impacted sites of the St. Lawrence River and tributaries as opposed to headwater lake sites (14/19 St. Lawrence River or tributary sites were positive compared to 1/6 headwater sites, T=3.19, P=0.004) (Fig. 2).

Although showing different inducibilities, genotoxic extracts appear to be weak inducers of the *E. coli* SOS system. These results are in agreement with previous findings concerning the low level of mutagenic activity of urban-industrially impacted waters, detected by means of the Ames test (Kreijl and Slooff, 1985; Maruoka *et al.*, 1986). In comparison, pure compounds such as 4-nitro-quinoline-oxide (MIF: 17.76; SRIP: 13.96 IF per ng; MDGC: 0.001 ng) and 2-amino-anthracene (MIF: 2.85; SRIP: 1.23 IF per ng; MDGC: 0.138 ng), both used as positive controls in the SOS Chromotest, prove to be extremely potent. Highest responses are found in Lakes St-François, Des Deux Montagnes and more particularly in Lake St-Louis (filtered water MIF at site 3: 2.22, SRIP at site 1: 0.049 IF per ml and MDGC at site 1: 5.6 ml). Lake St-Louis is known as one of the most contaminated waterbodies in Québec (Germain et Janson, 1984). Apart from receiving western Montréal and Beauharnois region domestic and industrial wastewaters (Champoux et Sloterdijk, 1988), Lake St-Louis supplies potable water to these areas. In this respect, it might prove a potential source of carcinogens for humans.

Genotoxicity is generally higher in absence of activation enzymes (S9 mix). This may indicate the predominance of direct-acting genotoxicants in water. It may also be caused by a poor stabilization of the mammalian enzymes in liquid medium (Quillardet *et al.*, 1982), by the detoxification of genotoxicants by the S9 mix (Harwood *et al.*, 1989) or by the non-specific adsorption of the direct-acting genotoxicants present by the proteinaceous components of the S9 mix.

Five sites, producing a full hyperbolic concentration-response curve, showed to be genotoxic for both their aqueous and particulate fractions, when tested without metabolic activation (Table 4, omitting Cornwall 2 and Lake St-François 2). Aqueous and particulates fractions MDGC (expressed as ml of whole surface water) ratios show that the volume of whole surface water required to induce a minimum genotoxic response from filtered water alone is equal to or more than 2.2 times the volume required to induce a minimum genotoxic response from particulates alone. Additionally, surface water genotoxic activity partition coefficients, based on the aqueous and particulate fractions MDGC (nL of filtered water/µg of particulates) show that genotoxicants will favor the particulate fraction by six orders of magnitude. These results support previous findings showing that highly hydrophobic organic contaminants have a high affinity for suspended particulates (Allan, 1986; Karickhoff *et al.*, 1979). No conclusion can be reached regarding the partitioning of genotoxicants for those sites for which one or both fractions showed to be below sensitivity level of the SOS Chromotest.

Results of the chemical analysis of water samples for those compounds which have been detected and recognized as demonstrated SOS inducers, mutagens and/or carcinogens (IARC, 1972, 1976, 1980a, 1983; Quillardet *et al.*, 1985; Vigerstad, 1988) are presented in Table 5. Of the individual compounds detected and measured in our study, only pyrene, which occured frequently, is a known SOS inducer. We tested for another SOS inducer, benzo(a)pyrene, but did

not detect it at any of our sites The PAHs fluoranthene and phenanthrene are known mutagens, that occurred at many of our sites and have yet to be tested for SOS activity. Arsenic, cadmium, chromium, nickel and lead which are known mutagens/carcinogens, were present in some or all of the samples. Linear regression analyses were used to link genotoxic response parameters (SRIP, MDGC and MIF) to the concentrations of each individual chemical measured, including pyrene (our only known SOS inducer), total genotoxicants/mutagens/carcinogens, total mutagenic/carcinogenic metals, and total PAHs. None of the chemical compounds or groups tested were found to be significant predictors of genotoxicity parameters, either individually or in multiple regressions. Thus, we cannot account for any of the observed SOS activity, with our measurements of known SOS inducers or mutagens/carcinogens. It is not, however, obvious that we should have expected to see a clear relationship between genotoxicity parameters and the chemical profile. Synergistic and/or antagonistic interactions between the various contaminants present in a complex chemical mixture are possible and would greatly alter the relationship between genotoxic responses and the chemical profile.

Surficial sediments

Results of the SOS Chromotest applied to the aqueous and particulate fractions of surficial sediments are presented in Table 6 The highest test concentration corresponds to 8 ml of pore water

or 30 mg of bottom particulates per microplate well. The final absorbance values of two particulates extracts for which initial color showed to be markedly different from control values were corrected as described in the methods section. Genotoxic activity was detected in Lake Waterloo pore water extract (MIF: 1.27; SRIP: 1.60 IF per ml of pore water; MDGC: 69.6 µl) and in the three Lake St-François particulates extracts (MIF: 1.25-1.41; SRIP: 5.52-27.06 IF per g of dry bottom particulates; MDGC: 9.0-22.1 mg), when using metabolic activation.

In terms of MDGC, genotoxic bottom particulates will yield a thousand fold larger values, and thus a weaker genotoxic activity, than genotoxic suspended solids (Tables 4 and 6). This may indicate that bottom sediments have more non-genotoxic material per unit weight than does the suspended solids. However, gravel and sand content of genotoxic bottom particulates can not account for such a difference, since it is always less than 10 %. Substance(s) responsible for genotoxic activity in bottom sediments could be microbially degradable, as many organic substances are known to be (Richards and Shieh, 1986; Voll *et al.*, 1977). Neff (1979) has shown that microbial degradation is a major avenue for loss of PAHs. Sediments which showed not to be genotoxic in the present study should be further investigated. Previous studies from Sato *et al.* (1983) and Suzuki *et al.* (1982) have shown that the genotoxic activity of similarly industrially-impacted bottom sediments become detectable only when volumes ten to hundred fold larger than the ones tested in this study are used.

Results of the SOS Chromotest applied to twenty-three 10% DMSO-saline extracts of whole sediments are presented in Table 7. The highest test concentration corresponds to 25 mg of whole sediments per microplate well. The final absorbance values of fourteen extracts for which initial color showed to be markedly different from control values were corrected as described in the methods section. Genotoxic activity was detected in all extracts, when metabolic activation was used (MIF: 1.58-1.97; SRIP: 33.15-670.21 IF per g of wet sediments; MDGC: 0.1-1.5 mg). Results compare well with previous findings reported for Prince Edward Island (PEI) ponds and Southern Ontario lake and river genotoxic sediments in terms of MIF and SRIP equivalents (MIL and SOSIP), although PEI and Southern Ontario sediments also proved to be genotoxic without liver enzymes activation (Dutka *et al.*, 1987; Xu *et al.*, 1987).

Due to the nature of the solvent (10% DMSO-saline) used in the extraction, the observed genotoxic activity should be attributed to relatively hydrophilic compounds (Suzuki *et al.*, 1982). Such compounds appear to be present at all sites, even those remote from urban-industrial effects (17/17 St. Lawrence River or tributary sites were positive compared to 6/6 headwater lake sites, T=1.00, P=0.33). Although the identification of the hydrophilic compounds was not possible, these might prove to be natural substances. In fact, common hydrophilic biological degradation products, such as hydroxylamine, have been shown to be mutagenic and/or carcinogenic (Goodenough, 1978). Others, such as nitrite, nitrate and amines will,

under specific conditions, lead to the formation of various highly mutagenic and/or carcinogenic nitrosamines and N-Nitroso compounds (IARC, 1980b and 1984). Attempts to correlate sediments ammonia (nitrite precursor) and nitrite contents to SRIP and MDGC values proved unsuccessful. Interestingly, between-lakes SRIP variability is larger than within-lake variability ($F=6.494$, $P=0.0106$, $N=14$). Lake or watershed related variables, such as area and/or particulates loading rate, might play an important role in determining the amount of hypothetical natural genotoxicants reaching bottom sediments.

Results of the chemical analysis of sediments for those compounds which have been detected and recognised as demonstrated SOS inducers, carcinogens and/or mutagens are presented in Table 8. Fluoranthene, phenanthrene, pyrene and polychlorinated biphenyls (mutagens/carcinogens) were the only organic contaminants of that type to be detected. Arsenic, chromium, lead and nickel were present in all samples, while cadmium was found in only five. Linear regression analyses were used to link genotoxic response parameters (SRIP, MDGC and MIF) to the concentrations of each individual chemical measured, total genotoxicants/ mutagens/carcinogens, total mutagenic/carcinogenic metals, and total PAHs. None of the chemical compounds or groups tested were found to be significant predictors of genotoxicity parameters, either individually or in multiple regressions.

Conclusions

The present work reveals the presence of a weak but statistically significant genotoxic activity in southern Québec waterways. All genotoxic responses were observed at sample concentrations for which bacteria alkaline phosphatase activity levels was comparable to controls. Thus, the presence of positive genotoxicity in our samples does not result from factors that might decrease AP activity levels in the absence of cytotoxicity or general inhibition of protein synthesis. The SOS protocol is sufficiently sensitive to reliably detect weak genotoxicity in environmental samples where low concentrations are present.

In particular, surface water organic genotoxicity appears to be strongly correlated with the urban-industrially impacted St. Lawrence River and tributaries and predominates in the particulates fraction. Bottom sediments are shown to be less genotoxic than suspended solids, on a per unit mass basis. Hydrophilic genotoxicants (DMSO extracts) are ubiquitous in bottom sediments and their presence appears to be dependent upon lake and/or watershed characteristics.

The absence of correlation between genotoxicity parameters and chemical concentrations of demonstrated SOS inducers, mutagens and/or carcinogens or of other contaminants may indicate that the substances analyzed are different than the ones responsible for sample genotoxicity or that they can not alone explain

genotoxicity. Contaminants for which samples have been analysed most probably represent only a fraction of the genotoxicants present in the environmental mixtures. Common biological degradation products, which have not been analysed, have been shown to be or to lead to the formation of mutagens. Various processes such as volatilization, heat transformation, photo and chemical oxidation and microbial degradation might take place *in situ*, during sample extraction or extract storage and testing and ultimately account for the presence of genotoxicants which add to or differ from the ones measured. Moreover, chemical analysis techniques do not always allow for the measurement of the active or bioavailable forms of contaminants, which may be highly dependent upon the physico-chemical characteristics of the sample and contaminant (McCarthy and Black, 1988; Tessier and Campbell, 1987). Finally, synergistic and/or antagonistic interactions between compounds are likely to play an important role in determining the global genotoxicity of environmental mixtures (Berenbaum, 1985; Bingham *et al.*, 1976). While most of these questions remain unclear, they confirm the essential need for bioassays in assessing the potential risk to biota resulting from multiple genotoxic exposures.

We know virtually nothing about the impact of prolonged exposure to low levels of genotoxicants on aquatic biota and human health. In the present study, genotoxic activity is detected in as little as a few milliliters of water or a few micrograms of particulate matter. Considering the ability of aquatic organisms to ingest far greater quantities of material over time and to

bioconcentrate a wide spectrum of contaminants, it becomes apparent that, under certain conditions, unacceptable consequences might result.

Clearly, further studies investigating the formation, transformation, interactions and fate of genotoxicants in the aquatic environment are to be encouraged. More efforts should be devoted to the identification of synthetic and natural genotoxicants, which find their way into the aquatic ecosystem. Effects of manipulations such as extraction and storage on environmental samples chemical constituents should be assessed. Potential short and long-term impacts of genotoxic stresses on aquatic populations and communities, including humans, should be further investigated. Finally, more ecologically relevant genotoxicity, mutagenicity and/or carcinogenicity bioassays should be developed and results compared to short-term microbial bioassays data.

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Table 1. Study area watersheds surface area and population[1]

Waterbody	Watershed	
	Surface area (km^2)	Population[2] (inhabitants)
St. Lawrence R.	1 183 324	40 000 000
L. Champlain	19 881	500 000
L. Memphremagog	1764	3000
L. Brome	200	5000
L. Waterloo	33	5000

[1] MPE (1978), USEPA (1977), DEL (1982), Janus and Vollenweider (1981)
[2] Population rounded off to nearest 1000

Table 2. Environmental variables and detection limits measured at each site in the St. Lawrence River system.

Compound	Sediments	Compound	Water	Sediments
Chlorobenzenes	(ng/g dry)	**Polycyclic Aromatic Hydrocarbons**	(ng/l)	(ng/g dry)
Hexachlorobenzene	6.3			
Alphabenzenehexachloride	2.3	Benzo(b)fluoranthene	30.0	30.0
Gammabenzenehexachloride	2.9	Benzo(k)fluoranthene	30.0	30.0
1,3 Dichlorobenzene	11.1	Indene	10.0	10.0
1,4 Dichlorobenzene	11.7	1,2,3,4 Tetrahydro-naphtalene	10.0	10.0
1,2 Dichlorobenzene	14.7	Fluoranthene	15.0	15.0
1,3,5 Trichlorobenzene	1.8	2 Methylnaphtalene	10.0	10.0
1,2,4 Trichlorobenzene	3.6	1 Methylnaphtalene	10.0	10.0
1,2,3 Trichlorobenzene	1.9	B-Chloronaphtalene	10.0	10.0
1,2,3,4 Tetrachlorobenzene	2.7	Acenaphtylene	10.0	10.0
Pentachlorobenzene	3.7	Fluorene	15.0	15.0
		Phenanthrene	15.0	15.0
Organochlorinated Pesticides	(ng/g dry)	Pyrene	15.0	15.0
		Benzo(a)pyrene	30.0	30.0
Aldrin	1.6	Indenopyrene	30.0	30.0
Heptachlorepoxide	1.9	Benzoperylene	30.0	30.0
Gammachlordane	1.5			
Alphachlordane	2.3	**Heavy Metals**	(mg/l)	(mg/kg dry)
Alphaendosulfan	1.4			
PP/DDE	5.6	Aluminum	2E-03	100.00
Dieldrin	3.2	Chromium	2E-04	1.00
Endrin	2.9	Iron	4E-04	5.00
OP/DDT	7.0	Manganese	1E-04	1.00
PP/TDE	6.0	Zinc	2E-04	1.00
PP/DDT	7.5	Cadmium	1E-04	1.00
Betaendosulfan	2.9	Copper	2E-04	1.00
Mirex	4.3	Nickel	2E-04	3.00
PP/Metoxychlor	18.0	Lead	2E-04	5.00
Heptachlor	1.4	Arsenic	1E-04	0.20
PCB	77.0	Selenium	1E-04	0.20
		Mercury	1E-05	0.01
Nitrogenous cpds	(mg N/kg dry)	Vanadium	1E-04	
		Barium	2E-04	
Nitrites	0.01	Beryllium	5E-04	
Ammomium	5.0	Cobalt	1E-04	
		Lithium	1E-04	
		Molybdenum	1E-04	
		Strontium	1E-04	
		Calcium		500.00

Table 3. Results[1] of the SOS Chromotest on DCM extracts of the aqueous fraction of surface water[2]

sample	w/o activation			with activation[3]		
	MIF	SRIP (IF per ml)	MDGC (ml)	MIF	SRIP (IF per ml)	MDGC (ml)
Cornwall 1	1.53	0.027	17.6	1.36	0.004	38.1
Cornwall 2	1.28	0.009	43.5	*[4]1.21	*0.001	*103.3
L. St-François 1	1.55	0.026	8.9		ng[5]	
L. St-François 2		ng			ng	
L. 2-Montagnes 1	1.47	0.007	33.7		ng	
L. 2-Montagnes 2	1.42	0.019	20.5	1.20	0.001	85.2
L. 2-Montagnes 3		ng			ng	
L. St-Louis 1	1.87	0.049	5.6	1.27	0.010	18.8
L. St-Louis 2	1.24	0.014	38.6	1.28	0.005	31.5
L. St-Louis 3	2.22	0.012	21.0	*1.65	*0.004	*43.1
Laprairie	1.21	0.007	13.2		ng	
Assomption R.		ng			ng	
Contrecoeur 1	1.36	0.002	43.3	*1.24	*0.001	*90.2
Contrecoeur 2	1.17	0.006	39.2	*1.18	*0.001	*104.5
L. St-Pierre 1		ng			ng	
L. St-Pierre 2		ng			ng	
L. St-Pierre 3	1.19	0.010	22.6		ng	
St-François R.	1.34	0.005	37.1	*1.34	*0.002	*77.0
Yamaska R.	2.13	0.007	11.2	1.20	0.003	55.0
L. Champlain 1		ng			ng	
L. Champlain 2		ng			ng	
L. Memphrémagog 1		ng			ng	
L. Memphrémagog 2		ng			ng	
L. Brome		ng			ng	
L. Waterloo		ng		1.28	0.001	69.7

[1] Maximum induction factor (MIF) is the ratio of maximum β–galactosidase enzyme activity caused by the test material over background induction. Potency (SRIP) is the induction factor per unit of test material. Minimum detectable genotoxic concentration (MDGC) is the amount of test material at which the response is equal to the mean plus twice the standard error of background induction in unexposed bacteria

[2] Results are given in terms of the original volume of water from which chemicals were extracted

[3] Activation refers to the additon of rat liver enzymes to the test mixture

[4] A genotoxicity parameter calculated from an incomplete dose-response curve is denoted by * (see Materials and Methods)

[5] Not genotoxic (ng)

Table 4. Results[1] of the SOS Chromotest on DCM extracts of the particulate fraction of surface water[2] and partitioning of surface water genotoxicity
(MIF: maximum induction; SRIP: genotoxic potential)
(MDGC: minimum sample required to detect genotoxicity)

	Surface water					
	Particulates genotoxicity			Genotoxicity partitioning		
sample	MIF	w/o activation[3] SRIP (IF per g)	MDGC (µg)	Particles conc. in water (µg/ml)	MDGC[4] ratio (water/particles)	Kp[5]
Cornwall 1	1.11	37150	15.6	2	2.2	1.1 X 10^6
Cornwall 2	*[6]1.13	*4150	*18.3	na[7]	na	na
L. St-François 2	1.13	26517	6.0	na	na	na
L. 2-Montagnes 1	1.13	15352	6.1	3	16.9	5.5 X 10^6
L. 2-Montagnes 2	1.21	5140	14.2	6	8.6	1.4 X 10^6
L. St-Louis 2	1.13	25198	6.7	1	5.7	5.8 X 10^6
L. St-Louis 3	1.15	24831	5.5	1	3.8	3.8 X 10^6

[1] See footnote "1" in Table 3

[2] Results are given for genotoxic samples only, in terms of the original dry weight of particutate matter; for a complete list of sampling sites, see Table 3

[3] See footnote "3" in Table 3; No extract showed to be genotoxic when tested with the addition of rat liver enzymes

[4] MDGC ratio (MDGC water/MDGC particles) = MDGC water (amount of filtered water required for minimum genotoxic response)/MDGC particles (amount of water containing sufficient particles for minimum genotoxic response = MDGC particles (µg)/particles conc. in water (µg/ml))

[5] Kp or particle/water partition coefficient = (MDGC particle (µg)/MDGC water (µg=nL))

[6] See footnote "4" in Table 3

[7] Not applicable: for Cornwall 2, the data didn't permit the fitting of the hyperbolic response model; for L. St-François 2, the surface water aqueous fraction was not genotoxic

Table 5. Concentrations[1] of demonstrated SOS inducers, mutagens and/or carcinogens[2] in surface water

	PAH (ng l^{-1})			Heavy metals (µg l^{-1})				
sample	Fl	Ph	Py	As	Cd	Cr	Ni	Pb
Cornwall 1		29.1		0.7		0.6	0.7	0.5
Cornwall 2				0.7		0.5	0.5	0.9
L. St-François 1				0.7		0.4	0.3	0.5
L. St-François 2				0.7		0.3	0.5	
L. 2-Montagnes 1				0.4		0.6	0.6	0.3
L. 2-Montagnes 2				0.4		0.8	0.9	1.1
L. 2-Montagnes 3				0.4		0.7	0.7	
L. St-Louis 1		24.4	26.1	0.6		0.6	0.2	
L. St-Louis 2				0.4		0.5	0.6	
L. St-Louis 3				0.5		0.5	0.3	0.9
Laprairie	22.5	31.3	20.3	0.8		0.4	0.4	0.8
Assomption R.	23.0	23.6	15.7	0.1		1.2	1.3	1.2
Contrecoeur 1		29.1		0.5		2.6	0.7	0.7
Contrecoeur 2				0.7		1.4	0.9	1.6
L. St-Pierre 1	26.6	36.0	23.4	0.6		0.5	0.4	0.3
L. St-Pierre 2		24.1		0.6		0.5	0.6	0.6
L. St-Pierre 3				0.7	0.1	2.0	2.2	1.6
St-François R.			20.9	1.2		1.0	2.3	1.1
Yamaska R.		16.2		0.9	0.2	3.1	2.3	2.0
L. Champlain 1				0.4		0.3	0.8	
L. Champlain 2				0.5	0.1	0.8	1.3	0.6
L. Memphrémagog 1				0.5		0.2	0.9	
L. Memphrémagog 2				1.1		0.3	1.0	0.3
L. Brome				0.3		0.2	0.6	
L. Waterloo				0.3		0.2	0.4	0.5

[1] Below detection limit concentrations are represented by a blank space

[2] Fl: fluoranthene, Ph: phenanthrene, Py: pyrene, As: arsenic, Cd: cadmium, Cr: chromium, Ni: nickel, Pb: lead

Table 6. Results[1] of the SOS Chromotest on DCM extracts of pore water and the particulate fraction of bottom sediments[2]

(MIF: maximum induction; SRIP: genotoxic potential)

(MDGC: minimum sample required to detect genotoxicity)

Sample	w/o activation			with activation[3]		
	MIF	SRIP	MDGC	MIF	SRIP	MDGC
(pore water)		(IF per ml)	(µl)		(IF per ml)	(µl)
L. Waterloo		ng[4]		1.27	1.6	69.6
(bottom particulates)		(IF per g)	(mg)		(IF per g)	(mg)
Cornwall 1		ng		1.33	5.5	22.05
Cornwall 2		ng		1.25	27.1	9.04
L. St-François 1		ng		1.41	10.3	10.33

[1] See footnote "1" in Table 3

[2] Results are given for genotoxic samples only, in terms of the original volume of pore water or the original dry weight of bottom particulates

[3] See footnote "3" in Table 3

[4] See footnote "5" in Table 3

Table 7. Results[1] of the SOS Chromotest on 10% DMSO-saline extracts of whole sediments[2]

(MIF: maximum induction; SRIP: genotoxic potential)

(MDGC: minimum sample required to detect genotoxicity)

sample	w/o activation			with activation[3]		
	MIF	SRIP (IF per g)	MDGC (mg)	MIF	SRIP (IF per g)	MDGC (mg)
Cornwall 1		ng[4]		1.78	61.7	0.7
Cornwall 2		ng		1.76	59.0	0.9
L. St-François 1		ng		1.66	130.9	0.5
L. St-François 2		ng		1.67	124.5	0.4
L. 2-Montagnes 1		ng		1.73	462.0	0.1
L. 2-Montagnes 2		ng		1.77	195.4	0.2
L. 2-Montagnes 3		ng		1.61	564.8	0.1
L. St-Louis 1		ng		1.64	209.2	0.5
L. St-Louis 2		ng		1.66	196.3	0.2
L. St-Louis 3		ng		1.63	240.4	0.3
Laprairie		ng		1.72	110.7	0.4
Contrecoeur 1		ng		1.74	63.9	1.3
Contrecoeur 2		ng		1.97	33.2	1.5
L. St-Pierre 1		ng		1.89	116.2	0.4
L. St-Pierre 2		ng		1.69	100.6	0.6
St-François R.		ng		1.76	242.0	0.1
Yamaska R.		ng		1.82	179.8	0.2
L. Champlain 1		ng		1.58	432.8	0.1
L. Champlain 2		ng		1.61	379.7	0.2
L. Memphrémagog 1		ng		1.71	493.1	0.2
L. Memphrémagog 2		ng		1.63	670.2	0.1
L. Brome		ng		1.68	207.3	0.1
L. Waterloo		ng		1.63	72.6	0.2

[1] See footnote "1" in Table 3

[2] Results are given in terms of the original wet weight of sediments

[3] See footnote "3" in Table 3

[4] See footnote "5" in Table 3

Table 8. Concentrations[1,2] of demonstrated SOS inducers, mutagens and/or carcinogens[3] in bottom sediments

	PAH ($ng\ g^{-1}$)			PCB ($ng\ g^{-1}$)	Heavy metals ($\mu g\ g^{-1}$)				
sample	Fl	Ph	Py		As	Cd	Cr	Ni	Pb
Cornwall 1	66.9	20.4	56.1	1273	4.3		34.3	11.7	28.4
Cornwall 2	242.0	195.0	297.0	85	5.5		47.5	20.7	38.6
L. St-François 1	31.5				2.9		31.6	16.5	20.3
L. St-François 2	61.9			360	3.2		41.9	20 4	28.0
L. 2-Montagnes 1	28.4		28.2		8.3		78.0	41.4	58.0
L. 2-Montagnes 2	45.0	19.0	41.1		3.8		67.0	30 7	31 4
L. 2-Montagnes 3	60.8	48.6	44.8		1.7		29 6	11.2	13.2
L. St-Louis 1	38.8	17.4	44.1	193	3.8		44 6	15.9	21.0
L. St-Louis 2					20.2		59.5	30.9	39.7
L. St-Louis 3	35.4	17.7	41.6	148	5.5	1.2	76.3	36.9	43.9
Laprairie	167.0	65.5	106.0	892	6.6		61.7	32 2	74.5
Assomption R.	29.9		33.4		1.0		22.2	8.3	10.0
Contrecoeur 1					5.8		87.7	24 2	12.2
Contrecoeur 2	28.4	23.9	54.3		2.0	9.2	28.3	10.9	12.8
L. St-Pierre 1	196.0	138.0	139.0	191	6.7	1.5	93.3	45.0	62.1
L. St-Pierre 2	86.7	60.3	84.4		3.2		66.2	27.9	35 1
L. St-Pierre 3					2.2		26.1	11.1	13.0
St-François R.	25.2	15.1	40.0		5.8		44.7	23 6	11.5
Yamaska R.					2.4		64 4	28.5	18.2
L. Champlain 1	32.7				5.9		51.2	33.2	42.6
L. Champlain 2					5.9		62.2	36 2	24.6
L. Memphrémagog 1	22.3		20.5		38.8		154.0	164.0	75.7
L. Memphrémagog 2					13.2		60.1	25.9	14.9
L. Brome	48.1		35.1		8.6	1.0	59.9	37.1	100.0
L. Waterloo	162.0	29.1	60.0		10.6	1.1	48.0	30.5	103.0

[1] Per gr dry weight
[2] See footnote "1" in Table 5
[3] See footnote "2" in Table 5; PCB: polychlorinated biphenyls

Figure 1. SOS Chromotest concentration-response curve and genotoxicity parameters used with the linear method of analysis, as described by Quillardet and Hofnung (1985). The SOSIP, the SOS inducing potency, is equal to the slope of the linear region of the concentration-response curve. The MIL, the maximum inducing level, is the maximum response or induction factor I(C) observed in a particular experiment. The MDC, the minimum detectable concentration, is the lowest concentration of test substance that elicits an I(C) significantly above control.

Figure 1

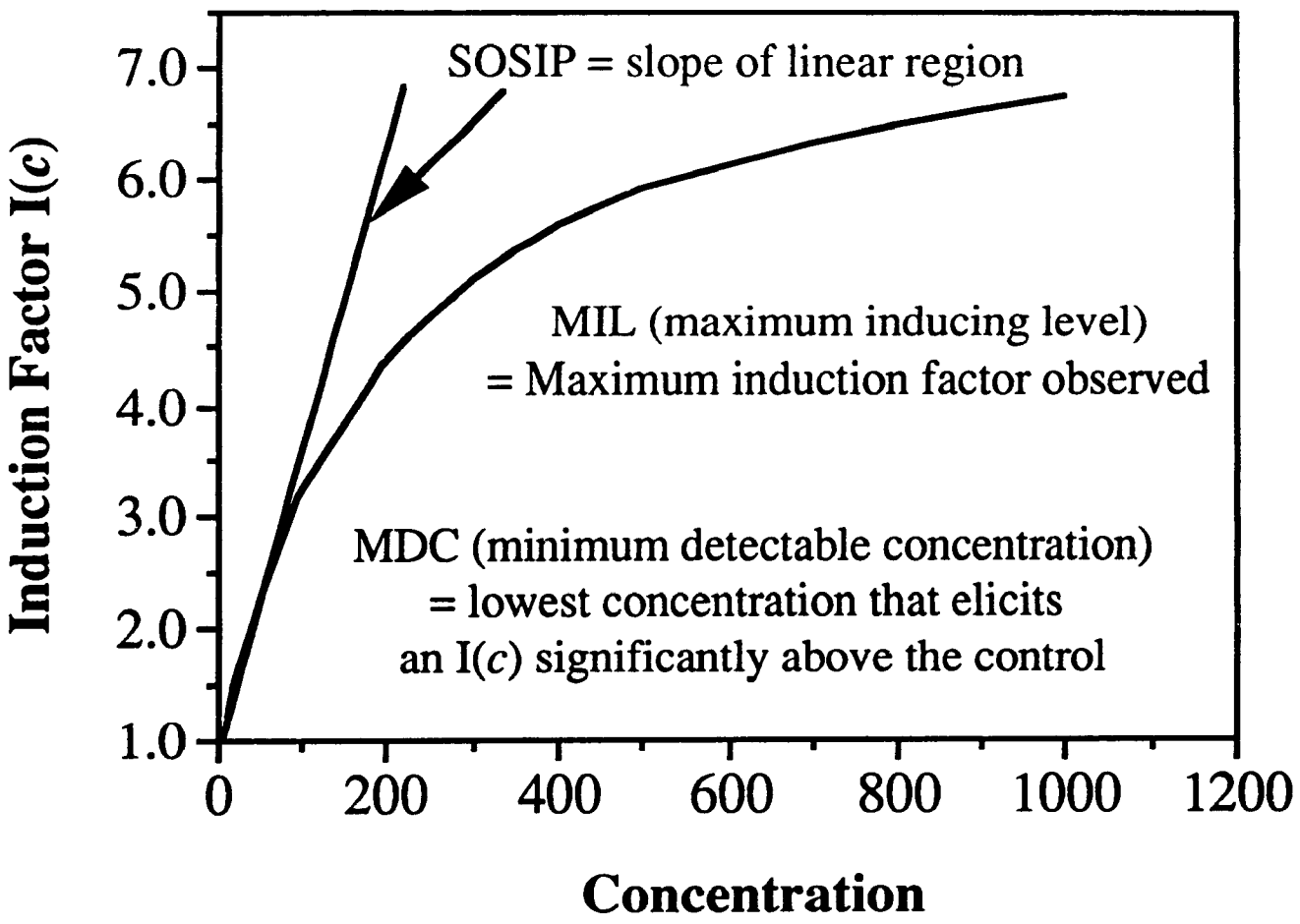

SOSIP = slope of linear region
MIL (maximum inducing level)
= Maximum induction factor observed
MDC (minimum detectable concentration)
= lowest concentration that elicits
an I(c) significantly above the control
Induction Factor I(c)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
200
400
600
800
1000
1200
Concentration

Figure 2. Location of the study area and sampling sites on the St. Lawrence River, tributaries and neighbouring lakes. A sampling site characterised by the presence of genotoxic activity in the surface water aqueous and/or particulates fractions is denoted by ▲, while a site characterised by the absence of genotoxic activity in surface water is denoted by △.

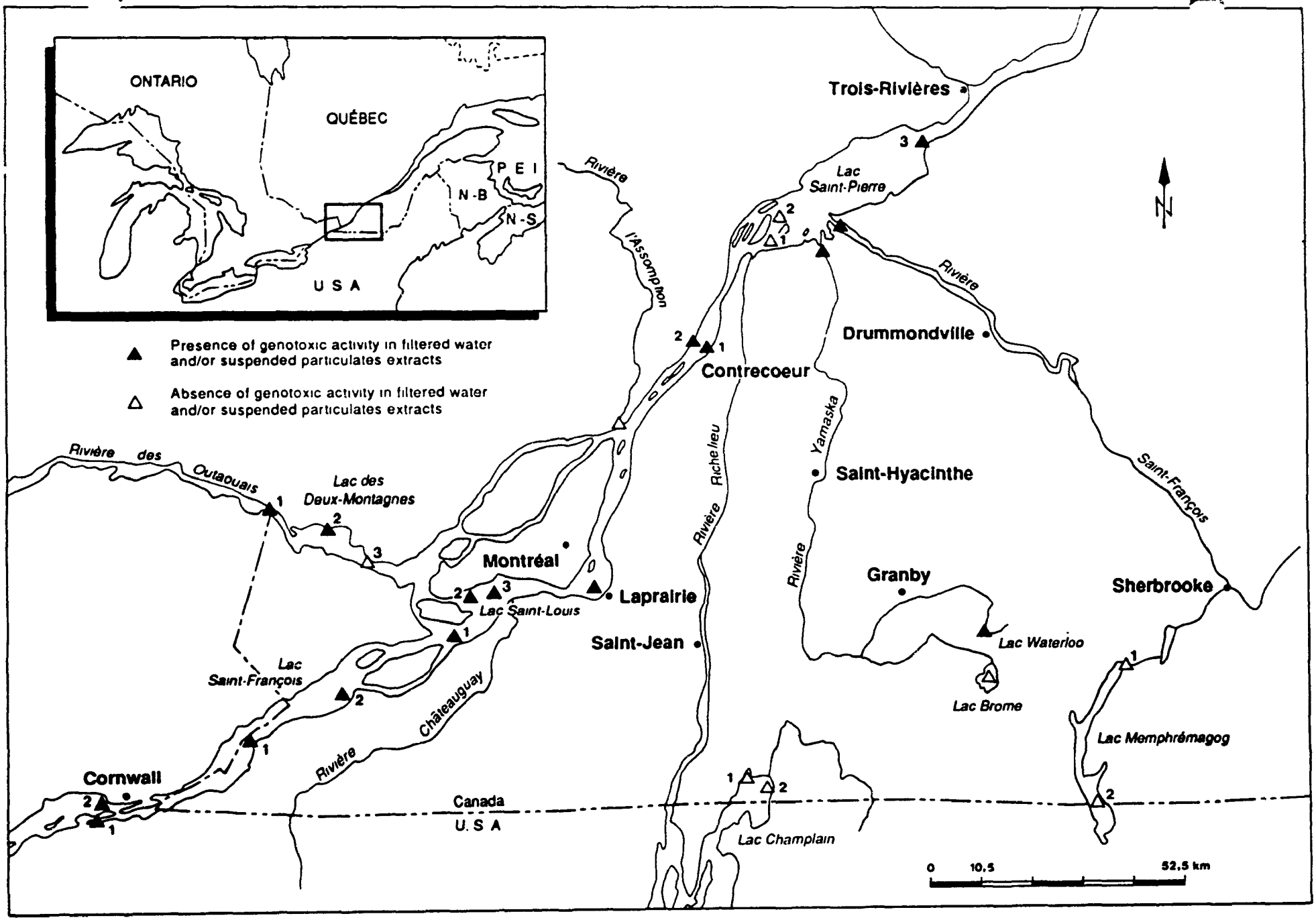
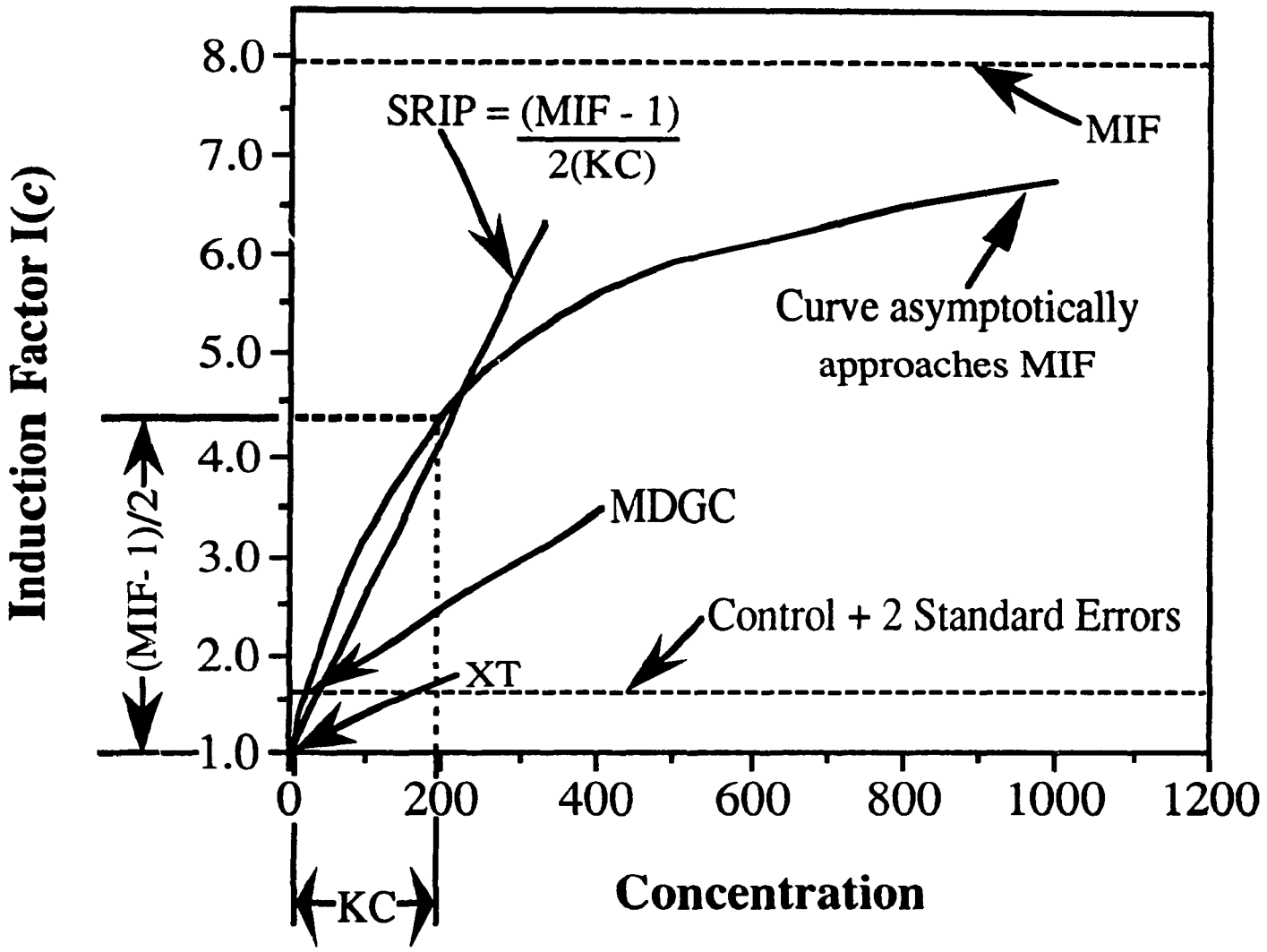

ONTARIO
QUÉBEC
P E I
N-B
N-S
U S A
▲ Presence of genotoxic activity in filtered water and/or suspended particulates extracts
△ Absence of genotoxic activity in filtered water and/or suspended particulates extracts
Trois-Rivières
Lac Saint-Pierre
Rivière l'Assomption
Rivière
Drummondville
Contrecoeur
Rivière Richelieu
Yamaska
Saint-Hyacinthe
Rivière
Saint-François
Granby
Sherbrooke
Lac Waterloo
Lac Brome
Lac Memphrémagog
Rivière des Outaouais
Lac des Deux-Montagnes
Montréal
Laprairie
Lac Saint-Louis
Saint-Jean
Lac Saint-François
Châteauguay
Rivière
Cornwall
Canada
U.S.A
Lac Champlain
0 10,5 52,5 km

Figure 3. SOS Chromotest concentration-response curve and genotoxicity parameters used with the non-linear method of analysis. The MIF is the maximum induction factor I(C) possible, i.e. the asymptote of the curve. XT is the highest concentration which produces a response equal to the control, i.e. the X-intercept. KC is the increase in concentration above XT, which results in an increase in induction factor of (MIF - 1)/2. SRIP, the SOS response inducing potency, is equal to (MIF - 1)/2/KC, i. e. the slope of the initial portion of the concentration-response curve. MDGC, the minimum detectable genotoxic concentration, is calculated by solving the non-linear equation for C when I(C) equals the control plus two standard errors.

Figure 3


Induction Factor I(c)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(MIF- 1)/2
SRIP = (MIF - 1) / 2(KC)
MIF
Curve asymptotically approaches MIF
MDGC
Control + 2 Standard Errors
XT
0
200
400
600
800
1000
1200
KC
Concentration

Appendix 1. Description of abbreviations and symbols used in the thesis.

AP: Alkaline phosphotase.

C: Sample concentration.

DCM: Dichloromethane.

DMSO: Dimethylsulfoxide.

I(C): Genotoxicity induction factor at concentration C of the sample.

KC: Sample concentration above XT, which results in an induction factor equal to (MIF-1)/2.

MDC: Minimum detectable genotoxic concentration, obtained from the linear model of the genotoxicity concentration-response curve.

MDGC: Minimum detectable genotoxic concentration, obtained from the non-linear model of the genotoxicity concentration-response curve.

MIF: Maximum induction factor, obtained from the non-linear model of the genotoxicity concentration-response curve.

MIL: Maximum genotoxicity inducing level, obtained from the linear model of the genotoxicity concentration-response curve.

PAH: Polycyclic aromatic hydrocarbon.

PCB: Polychlorinated biphenyl.

R(C): Ratio of β-galactosidase and alkaline phosphatase activities induced at concentration C of the sample.

R(0): Ratio of β-galactosidase and alkaline phosphatase activities induced by the negative control.

SOSIP: SOS response inducing potency, obtained from the linear model of the genotoxicity concentration-response curve.

SRIP: SOS response inducing potency, obtained from the non-linear model of the genotoxicity concentration-response curve.

S(9): Crude rat liver enzymes extract which simulates the mammalian detoxification system.

XT: Highest sample concentration resulting in an induction factor equal to the negative control.

Appendix 2. Chemical concentrations of elements found in water and sediments samples from the St. Lawrence River System.

Abbreviations of chemical elements listed in Appendix 2.

Compound		Compound	
Chlorobenzenes		**Polycyclic Aromatic Hydrocarbons**	
1,2 Dichlorobenzene	1,2 CB		
1,2,3 Trichlorobenzene	1,2,3 CB	Phenanthrene	Ph
1,2,4 Trichlorobenzene	1,2,4 CB	Benzo(k)fluoranthene	Bkf
1,3,5 Trichlorobenzene	1,3,5 CB	Pyrene	Py
		Fluoranthe	Fl
		2 Methylnaphtalene	2 Mnp
		1 Methylnaphtale	1 Mnp
		Acenaphtylene	Anp
		Fluorene	Fle
Organochlorinated Pesticides			
Endrin	end		
PP/DDE	dde		
Gammachlordane	gam	**Heavy Metals**	
Alphachlordane	alc		
PP/TDE	tde	Aluminum	Al
PCB	pcb	Chromium	Cr
		Iron	Fe
		Manganese	Mn
		Zinc	Zn
		Cadmium	Cd
		Copper	Cu
		Nickel	Ni
		Lead	Pb
		Arsenic	As
		Selenium	Se
		Mercury	Hg
		Vanadium	Va
Nitrogenous cpds		Barium	Ba
		Calcium	Ca
Nitrites	no2-	Cobalt	Co
Ammomium	nh4+	Lithium	Li
		Molybdenum	Mo
		Strontium	Sr

WATER - POLYCYCLIC AROMATIC HYDROCARBONS
(NG/L)

Station	Ph	Py	Fl
Cornwall 1	15.5		15.2
Cornwall 2			
L. St-François 1			
L. St-François 2			
L 2-Montagnes 1			
L. 2-Montagnes 2			
L. 2-Montagnes 3			
L. St-Louis 1	24.4	26 1	
L. St-Louis 2			
L. St-Louis 3			
Laprairie	31.3	20 3	22.5
Assomption R.	23 6	15 7	23
Contrecoeur 1	29 1		
Contrecoeur 2			
L. St-Pierre 1	36	23 4	26 6
L. St-Pierre 2	24 1		
L. St-Pierre 3			
St-François R.		20 9	
Yamaska R	16 2		
L. Champlain 1			
L. Champlain 2			
L. Memphremagog 1			
L. Memphremagog 2			
L. Brome			
L. Waterloo			

WATER - Station	HEAVY METALS (MG/L) Hg	Al	Cr	Fe	Mn
Cornwall 1	0 14	0.059	0 0006	0 0624	0 0058
Cornwall 2	0 15	0 035	0 0005	0 023	0 003
L. St-François 1	0 15	0.045	0 0004	0 0437	0 0043
L. St-François 2	0 16	0 012	0 0003	0 0107	0 0029
L. 2-Montagnes 1	0 16	0 16	0 0006	0 252	0 0191
L. 2-Montagnes 2	0 16	0 263	0 0008	0 363	0 0165
L. 2-Montagnes 3	0 16	0 232	0 0007	0 321	0 0212
L. St-Louis 1	0 15	0 123	0 0006	0 119	0 0084
L. St-Louis 2	0 17	0 136	0 0005	0 2	0 0145
L. St-Louis 3	0 15	0 119	0 0005	0 121	0 0212
Laprairie	0 15	0 115	0 0004	0 189	0 0274
Assomption R	0 16	0 342	0 0012	0 339	0 0317
Contrecoeur 1	0 13	0 275	0 0026	0 428	0 0134
Contrecoeur 2	0 15	0 411	0 0014	0 56	0 0202
L St-Pierre 1	0 15	0 153	0 0005	0 166	0 0131
L. St-Pierre 2	0 16	0 058	0 0005	0 075	0 012
L. St-Pierre 3	0 14	0 565	0 002	0 814	0 0462
St-François R	0 15	0 327	0 001	0 519	0 0758
Yamaska R.	0 16	1 41	0 0031	1 5	0 0825
L. Champlain 1		0 091	0 0003	0 115	0 0175
L. Champlain 2		0 406	0 0008	0 596	0 0395
L. Memphremagog 1	0 01	0 011	0 0002	0 016	0 0047
L. Memphremagog 2	0 01	0 007	0 0003	0 0315	0 0192
L. Brome		0 051	0 0002	0 0922	0 0232
L. Waterloo		0 068	0 0002	0 289	0 0924

	Cd	Co	Ni	Pb	As
Cornwall 1			0 0007	0 0005	0 0007
Cornwall 2		0.0001	0 0005	0 009	0 0007
L. St-François 1		0 0001	0 0003	0 005	0 0007
L. St-François 2			0.0005		0 0007
L. 2-Montagnes 1			0 0006	0 0003	0 0004
L. 2-Montagnes 2		0 0001	0 0009	0 0011	0 0004
L. 2-Montagnes 3			0 0007		0 0004
L. St-Louis 1		0 0003	0 0002		0 0006
L. St-Louis 2			0 0006		0 0004
L. St-Louis 3		0 0002	0 0003	0 0009	0 0005
Laprairie		0 0002	0 0004	0 0008	0 0008
Assomption R.		0.0003	0 0013	0 0012	0 0001
Contrecoeur 1		0.0004	0 0007	0 0007	0 0005
Contrecoeur 2		0 0003	0.0009	0 0016	0 0007
L. St-Pierre 1			0 0004	0 0003	0 0006
L. St-Pierre 2			0 0006	0 0006	0 0006
L. St-Pierre 3	0.0001	0.0006	0 0022	0 0016	0 0007
St-François R.		0 0003	0 0023	0 0011	0 0012
Yamaska R.	0 0002	0.001	0 0023	0 002	0 0009
L. Champlain 1		0 0002	0 0008		0 0004
L. Champlain 2	0 0001	0.0003	0 0013	0 0006	0 0005
L. Memphremagog 1			0 0009		0 0005
L. Memphremagog 2			0 001	0 0003	0 0011
L. Brome			0 0006		0 0003
L. Waterloo			0 0004	0 0005	0 0003

WATER - HEAVY METALS (MG/l)

Station	Zn	Cu	Se	Va
Cornwall 1	0.0022	0.001	0.0003	0.0005
Cornwall 2	0.0032	0 0009	0.0003	0 0004
L. St-François 1	0.0029	0 0009	0.0004	0.0004
L. St-François 2	0.0007	0.0007	0.0002	0.0107
L. 2-Montagnes 1	0 0015	0 0013	0 0002	0 0006
L. 2-Montagnes 2	0 0022	0 0015	0 0002	0.0009
L. 2-Montagnes 3	0 0017	0 0013	0 0001	0 0008
L. St-Louis 1	0 0022	0 0008	0 0002	0 0004
L St-Louis 2	0 0018	0 0015	0 0002	0 0007
L. St-Louis 3	0 0013	0 0011	0 0003	0 0006
Laprairie	0 0029	0 0009	0 0004	0 0007
Assomption R	0.0045	0 0015	0 0002	0 001
Contrecoeur 1	0 0038	0 0012	0 0001	0 0071
Contrecoeur 2	0 0046	0.0023	0.0002	0 0011
L St-Pierre 1	0 0032	0 0011	0.0004	0 0006
L St-Pierre 2	0 0017	0 0013	0 0002	0 0007
L St-Pierre 3	0 004	0 0024	0 0001	0 0049
St-François R	0 0058	0 0029	0.0001	0 0009
Yamaska R.	0 0119	0 004	0 0002	0 005
L. Champlain 1	0 0007	0 001	0 0002	0 0005
L. Champlain 2	0 0026	0 0014	0 0002	0 001
L Memphremagog 1	0 0011	0.0007	0 0001	0.0002
L. Memphrémagog 2	0 0009	0 0009	0 0002	0 0003
L. Brome	0.0007	0 0004	0.0002	0.0002
L. Waterloo	0 0012	0.0006	0.0002	0 0002

	Ba	Li	Mo	Sr
Cornwall 1	0.0223	0.0026	0 0011	164
Cornwall 2	0 0219	0.0024	0 0011	166
L. St-François 1	0 0231	0 0021	0.0009	169
L. St-François 2	0 0219	0 0022	0 0011	169
L. 2-Montagnes 1	0 0159	0.0005		0 0444
L. 2-Montagnes 2	0.0166	0 0006		0 0456
L. 2-Montagnes 3	0 017	0.0006		0 0502
L. St-Louis 1	0.0225	0.0023	0.001	0 165
L. St-Louis 2	0.016	0.0007	0.0003	0.065
L. St-Louis 3	0 0172	0.0015	0.0005	0 0885
Laprairie	0.0242	0.0026	0.0009	0 197
Assomption R.	0.0172	0.0015	0.0004	0 0867
Contrecoeur 1	0 024	0.0024	0.0009	0 17
Contrecoeur 2	0 0224	0.0018	0.0008	0 117
L. St-Pierre 1	0 0215	0.0019	0.0007	0 148
L. St-Pierre 2	0 0194	0.0022	0 0009	0 15
L. St-Pierre 3	0 0202	0.0023	0.0007	0 157
St-François R.	0 0142	0 0015	0.0002	0.122
Yamaska R.	0 0469	0.0057	0.0006	0.349
L. Champlain 1	0 0144	0 0007	0.0001	0 102
L. Champlain 2	0 0178	0.0011	0.0001	0 116
L. Memphremagog 1	0 0039	0.0007		0 0945
L. Memphreamgog 2	0.0033	0.0007	0.0001	0 0995
L. Brome	0 0059	0.0003		0 0746
L. Waterloo	0 0177	0.0001		0 0732

SEDIMENTS - CHLOROBENZENES (NG/G DRY)

Station	1,2,4CB	1,3,5CB	1,2CB	1,2,3CB
Cornwall 1			30.6	
Cornwall 2			32 8	
L. St-François 1				
L. St-François 2				
L. 2-Montagnes 1				
L. 2-Montagnes 2				
L. 2-Montagnes 3				
L. St-Louis 1		2 38	40	
L. St-Louis 2				
L. St-Louis 3			28	
Laprairie	53 8		28	6 32
Assomption R.			69 4	
Contrecoeur 1			32	
Contrecoeur 2	4 2		26 8	
L. St-Pierre 1			42 4	
L. St-Pierre 2	3 78		36 6	
L. St-Pierre 3			47 2	
St-François R.			28.4	
Yamaska R	4 24		67 2	
L. Champlain 1				
L. Champlain 2				
L. Memphremagog 1				
L. Memphremagog 2				
L. Brome				
L. Waterloo				

SEDIMENTS - ORGANOCHLORINATED PESTICIDES (NG/G DRY)

Station	end	dde	gam	alc	tde	pcb
Cornwall 1		11.1				1273
Cornwall 2		9 38				85 4
L. St-François 1						
L. St-François 2						360
L. 2-Montagnes 1						
L. 2-Montagnes 2						
L. 2-Montagnes 3						
L. St-Louis 1						193
L. St-Louis 2						
L. St-Louis 3						148
Laprairie	3.12	5 6	6 5	5 04	8 14	892
Assomption R.						
Contrecoeur 1						
Contrecoeur 2		7.14				
L. St-Pierre 1		5.76	2 3		6 22	191
L. St-Pierre 2						
L. St-Pierre 3						
St-François R.						
Yamaska R.						
L. Champlain 1						
L. Champlain 2						
L. Memphremagog 1		45 6				
L. Memphrémagog 2						
L. Brome						
L. Waterloo						

SEDIMENTS - NITROGENOUS CPDS. (MG N/KG DRY)

Station	nh4+	no2-
Cornwall 1	82	0.1
Cornwall 2	220	0 14
L. St-François 1	220	0.04
L. St-François 2	290	0.06
L. 2-Montagnes 1	270	0.12
L. 2-Montagnes 2	200	0 08
L. 2-Montagnes 3	91	0 04
L. St-Louis 1	81	0 11
L St-Louis 2	52	0 08
L. St-Louis 3	140	0 14
Laprairie	130	0 02
Assomption R		
Contrecoeur 1	38	0.04
Contrecoeur 2	22	0 04
L. St-Pierre 1	400	0.06
L. St-Pierre 2	92	0.04
L. St-Pierre 3	26	0.02
St-François R	33	0.06
Yamaska R.	42	0.06
L. Champlain 1	150	0.07
L. Champlain 2	120	0.07
L. Memphremagog 1	300	0.09
L. Memphrémagog 2	19	0.07
L. Brome	320	0.13
L. Waterloo	680	0.23

SEDIMENTS - WATER (%)

Station	
Cornwall 1	58.8
Cornwall 2	71.6
L. St-François 1	68
L. St-François 2	70 6
L. 2-Montagnes 1	90.7
L. 2-Montagnes 2	77
L. 2-Montagnes 3	48.2
L. St-Louis 1	53.6
L. St-Louis 2	39.3
L. St-Louis 3	71
Laprairie	43.2
Assomption R.	24.3
Contrecoeur 1	42.9
Contrecoeur 2	26.5
L. St-Pierre 1	72.4
L. St-Pierre 2	55.1
L. St-Pierre 3	21.2
St-François R.	33.2
Yamaska R.	46.6
L. Champlain 1	74
L. Champlain 2	62.4
L. Memphrémagog 1	85.2
L. Memphrémagog 2	40.9
L. Brome	87.3
L. Waterloo	92.4

SEDIMENTS - POLYCYCLIC AROMATIC HYDROCARBONS (NG/G DRY)

Station	Ph	Py	Fl	2 Mnp
Cornwall 1	20.4	56 1	66 9	
Cornwall 2	195	297	242	72 4
L. St-François 1			31 5	
L. St-François 2			61 9	
L. 2-Montagnes 1		28.2	28.4	
L. 2-Montagnes 2	19	41.1	45	
L. 2-Montagnes 3	48 6	44 8	60.8	
L St-Louis 1	17.4	44.1	38.8	
L. St-Louis 2				
L. St-Louis 3	17 7	41 6	35 4	
Laprairie	65 5	106	167	16 9
Assomption R		33.4	29.9	
Contrecoeur 1				
Contrecoeur 2	23 9	54 3	28 4	
L. St-Pierre 1	138	139	196	25 3
L. St-Pierre 2	60.3	84.4	86 7	
L. St-Pierre 3				
St-François R	15 1	40	25 2	
Yamaska R				
L. Champlain 1			32 7	
L. Champlain 2				
L. Memphremagog 1		20.5	22 3	
L. Memphrémagog 2				
L. Brome		35.1	48 1	
L. Waterloo	29.1	60	162	

	1 Mnp	Anp	Fle	Bkf
Cornwall 1				
Cornwall 2	39.9	18.6	19 9	
L. St-François 1				
L. St-François 2				44 5
L. 2-Montagnes 1				
L. 2-Montagnes 2				
L. 2-Montagnes 3				
L. St-Louis 1				
L. St-Louis 2				
L. St-Louis 3				
Laprairie				
Assomption R.				
Contrecoeur 1				
Contrecoeur 2				
L. St-Pierre 1	15	19		
L. St-Pierre 2				
L. St-Pierre 3				
St-François R.				
Yamaska R.				
L. Champlain 1			32 7	
L. Champlain 2				
L. Memphremagog 1				
L. Memphrémagog 2				
L. Brome				
L. Waterloo				

SEDIMENTS	HEAVY METALS (MG/KG DRY)						
Station	Hg	Al	Cr	Fe	Mn	Zn	Ca
Cornwall 1	0.14	54200	56.8	22900	605	122	32700
Cornwall 2	0.63	57700	49.4	26900	529	262	45200
L. St-François 1	0.1	50700	50.5	21900	589	108	33800
L. St-François 2	0.2	54600	50 4	21900	594	153	31300
L. 2-Montagnes 1	0 14	76000	83.7	55600	2390	213	14600
L. 2-Montagnes 2	0.4	74600	79.7	44900	1170	195	16800
L. 2-Montagnes 3	0 06	64600	33.6	18300	650	67.3	14900
L. St-Louis 1	0 38	54300	71.5	22700	793	112	30800
L St-Louis 2	0 11	63200	75.3	87100	2060	298	13100
L St-Louis 3	0.4	70100	94.9	40000	1140	343	19100
Laprairie	0 2	67200	49.5	33000	573	312	17000
Assomption R	0 03	56200	18.8	13200	268	67 9	9900
Contrecoeur 1	0 04	62400	119	50900	980	129	17300
Contrecoeur 2	0 05	58700	39 1	15900	278	70 6	8720
L. St-Pierre 1	0 32	65000	91	42500	752	372	21500
L St-Pierre 2	0 2	64000	73 9	33100	678	211	21700
L St-Pierre 3	0 01	62100	32	20600	494	49 2	13000
St-François R	0 05	46100	58 7	21800	607	85.4	5920
Yamaska R	0 05	59800	71.1	24400	582	78 9	10600
L Champlain 1	0 11	66300	43.7	30100	1180	108	9570
L. Champlain 2	0.12	52000	69.2	40300	1170	131	8860
L. Memphremagog 1	0 15	60200	175	46900	2230	144	7410
L Memphremagog 2	0 03	38500	64.1	15800	1560	36.4	6240
L. Brome	0 22	54600	67.9	49500	1900	193	6190
L. Waterloo	0 34	39800	60.5	29200	1210	238	6610

	Cd	Cu	Ni	Pb	As	Se
Cornwall 1		25	11.7	28.4	4.3	0.9
Cornwall 2		39.1	20.7	38 6	5.5	1 9
L. St-François 1		17 5	16.5	20 3	2.9	0.7
L. St-François 2		28.1	20.4	28	3.2	1 3
L. 2-Montagnes 1		35.1	41.4	58	8 3	0 6
L. 2-Montagnes 2		35.1	30.7	31.4	3.8	0 6
L. 2-Montagnes 3		6.12	11.2	13.2	1.7	
L St-Louis 1		22.2	15.9	21	3 8	0 6
L. St-Louis 2		9 93	30.9	39 7	20 2	0 4
L. St-Louis 3	1.21	43.1	36.9	43.9	5 5	1 8
Laprairie		44.7	32.3	74.5	6 6	1
Assomption R.		6.94	8 31	10	1	
Contrecoeur 1		22.3	24.2	12.2	5 9	0 2
Contrecoeur 2	9.29	7.2	10.9	12.8	2	
L. St-Pierre 1	1.56	123	45	62.1	6 7	2.5
L. St-Pierre 2		54 9	27.9	35.1	3 2	2.2
L. St-Pierre 3		7.86	11.1	13	2 2	
St-François R.		13.8	23.6	11.5	5.8	
Yamaska R		33.1	28.5	18.2	2 4	0.3
L. Champlain 1		18 3	33.2	42.6	5.9	0 6
L. Champlain 2		25.2	36.2	24.6	5 9	0 6
L. Memphremagog 1		23.9	164	75.7	38 8	1 5
L. Memphrémagog 2		4.71	25.9	14.9	13 2	
L Brome	1 07	44.7	37.1	100	8 6	2 2
L. Waterloo	1.13	39 3	30.5	103	10 6	1.7