Contaminated Sediments: Restoration of Aquatic Environment
STP 1554, 2012
Available online at www.astm.org
DOI:10.1520/STP104257

Mélanie Desrosiers,[1] Louis Martel,[1] Lise Boudreau,[2] Mario Cormier,[3] Christian Gagnon,[4] Serge Lepage,[3] Stéphane Masson,[5] Pierre Michon,[6] Magella Pelletier,[4] Suzie Thibodeau,[3] Gaëlle Triffault-Bouchet,[1] and Marc P. Babut[7]

Ecological Risk Assessment (ERA) of Open-water Disposal of Sediment to Support the Management of Dredging Project in the St. Lawrence River

REFERENCE: Desrosiers, Mélanie, Martel, Louis, Boudreau, Lise, Cormier, Mario, Gagnon, Christian, Lepage, Serge, Masson, Stéphane, Michon, Pierre, Pelletier, Magella, Thibodeau, Suzie, Triffault-Bouchet, Gaëlle, and Babut, Marc P., "Ecological Risk Assessment (ERA) of Open-water Disposal of Sediment to Support the Management of Dredging Project in the St. Lawrence River," *Contaminated Sediments: Restoration of Aquatic Environment* on May 23–25, 2012 in Montreal, Quebec, Canada; STP 1554, C. N. Mulligan and S. S. Li, Editors, pp. 105–125, doi:10.1520/STP104257, ASTM International, West Conshohocken, PA 2012.

ABSTRACT: The St. Lawrence River is subject to various anthropological pressures that can entail negative consequences for the ecosystem. As a result of the third and fourth St. Lawrence Action Plans, the current vision of sustainable management of this river and its main functions emphasizes the need for sound risk-based assessment approaches to support management

Manuscript received August 3, 2011; accepted for publication February 28, 2012; published online October 23, 2012.

[1]Centre d'expertise en analyse environnementale du Québec – MDDEP, 2700 Einstein St., Québec, QC, G1P 3W8, Canada.

[2]DSEE – MDDEP, 675 René-Lévesque, Québec, QC, G1R 5V7, Canada.

[3]EPOD – Environment Canada, 105 McGill, Montréal, QC, H2Y 2E7, Canada.

[4]STB – Environment Canada, 105 McGill, Montréal, QC, H2Y 2E7, Canada.

[5]Aquarium du Québec, SÉPAQ, 1675 av. des Hôtels, Québec, QC, G1W 4S3, Canada.

[6]DEE – MDDEP, 675 René-Lévesque, Québec, QC, G1R 5V7, Canada.

[7]IRSTEA UR MALY, 3 bis quai Chauveau, 69336 Lyon, France.

decisions. More specifically, the sustainable navigation strategy, drawn up under St. Lawrence Action Plan III, explicitly identifies the need to develop sediment quality assessment tools, including those derived from ecotoxicological studies. The first management option addressed in this perspective was the open-water disposal of dredged sediments. In this context, an ecotoxicological risk assessment (ERA) approach using chemical characterization in Tier 1 and benthic organisms' toxicity tests in Tier 2 was elaborated based on physicochemical, toxicity testing, and benthic community structure data acquired from sediment samples collected in 59 sites along the St. Lawrence River. Hence this ERA approach will be used to determine whether the risk posed by the exposure of benthic organisms to dredged sediments at deposit sites and downstream is acceptable and compatible with open-water disposal.

KEYWORDS: sediment, dredging, open-water disposal, ecotoxicological risk assessment

Ecotoxicological Risk Assessment Implementation Background

Approximately 400 000 to 600 000 m^3 of sediment are dredged annually from the St. Lawrence system, which includes the river, the estuary, Baie des Chaleurs, and the area around the Magdalen Islands [1,2]. Essentially, dredging maintenance work is performed in order to keep ports and navigation channels open. It is recognized that dredging activities might, among other things, adversely affect wildlife habitats or cause changes in the hydrological regime. The inappropriate management of contaminated sediments might also entail significant environmental risk. Most dredging projects should therefore undergo an environmental assessment beforehand in order to protect the environment and optimize the management of dredged materials.

In Quebec, the sediment quality criteria document *Criteria for the Assessment of Sediment Quality in Quebec and Application Frameworks: Prevention, Dredging and Remediation* [3] is the primary tool for assessing the chemical quality of sediments. This document states that the open-water disposal of dredged sediment can be considered only when it does not contribute to the deterioration of the receiving environment. Thus, in the context of the management of dredged sediments, when the concentration of a chemical in sediment is higher than the occasional effect level (OEL) but lower than or equal to the frequent effect level (FEL), the probability of observing adverse biological effects is relatively high and increases with the concentration (Table 1). In such cases, open disposal can be considered a valid management option only when proper toxicity tests have demonstrated that dredged sediments will not adversely affect the receiving environment.

The use of ecotoxicological risk assessments (ERAs) as a decision-making tool for managing contaminated sediments is an internationally accepted practice. Most industrialized countries regulate and manage contaminated sediments and dredged materials in their waterways. Consequently, various ERA

TABLE 1—*Ranges of metal and organic chemical concentrations in sediment from sampling areas on the St. Lawrence River [16]. Sediment quality guideline (SQG) thresholds (occasional effect level [OEL] and frequent effect level [FEL]) that were developed for sediment dredging management in the province of Quebec (Canada) are also provided [3]. Concentrations are presented in mg/kg.*

	SQGs (Québec) [3]		St. Lawrence River (this study) [16]	Environmental Baseline in Fluvial Lakes [3]		
	OEL	FEL		Saint-François	Saint-Louis	Saint-Pierre
As	7.6	23	0.57–40	5.0	7.0	2.0
Cd	1.7	12	<DL–3	0.80	1.0	0.40
Cr	57	120	10–380	52	93	66
Cu	63	700	10–3600	27	41	24
Hg	0.25	0.87	<DL–9.9	0.15	0.19	0.044
Ni	52	…	10.8–310	28	20	26
Pb	52	150	6–190	25	38	19
Zn	170	770	31–550	120	220	100
PCB (total)	0.079	0.78	<DL–2.248	0.12	0.069	0.034
PAH high						
benzo(a)anthracene	0.12	0.76	<DL–4.3	0.039	<0.020	0.021
benzo(a)pyrene	0.15	3.2	<DL–5.1	0.040	<0.010	0.023
Chrysene	0.24	1.6	<DL–16	0.048	<0.020	0.026
Fluoranthene	0.45	4.9	<DL–9	0.069	<0.010	0.045
Pyrene	0.23	1.5	<DL–6.7	0.058	<0.010	0.037
PAH low						
Acenaphtene	0.021	0.94	<DL–1	<0.005	<0.020	<0.005
Acenaphtylene	0.030	0.34	<DL–0.35	0.0088	<0.020	0.0068
Anthracene	0.11	1.1	<DL–5.9	0.020	<0.020	0.010
Fluorene	0.061	1.2	<DL–2.6	0.009	<0.020	0.005
Naphthalene	0.12	1.2	<DL–0.35	<0.010	<0.040	0.010
Phenanthrene	0.13	1.1	<DL–9.7	0.029	<0.020	0.023

Note: "<DL" indicates that the minimum concentration was below the detection limit.

approaches have been developed [4–7]. In Canada, Environment Canada regulates ocean and estuarine dredging operations and open-water disposal under the 1999 Canadian Environmental Protection Act [8]. Environment Canada's Disposal at Sea program administers a permit system for sediment management at sea based on a multi-tier process [8,9]. Environment Canada and the Ontario Ministry of the Environment have also recently developed a risk assessment framework for evaluating contaminated sites [10]. This framework was primarily developed for the Laurentian Great Lakes and is mainly intended to provide guidance in making remediation decisions [10,11]

The ERA approach described in this document addresses the lack of information on sediment toxicity in the freshwater portion of the St. Lawrence River and therefore will enhance the review procedure for managing the open-water disposal of dredged sediments, as well as improve the overall decision-making process. The management question to be answered by the assessment may be stated as follows: *In the context of a specific dredging project, is open-water disposal of dredged sediments acceptable?* In other words, this ERA approach estimates whether the risk posed by the exposure of benthic organisms to dredged sediments, both at deposit sites and downstream, is acceptable and compatible with open-water disposal.

Development of the ERA Framework

Many ERA frameworks applicable to contaminated sediments have been published, for either dredging or remediation activities [6,10,11]. These ERA frameworks are generally based on tiered approaches that seek to optimize the resources invested based on the uncertainty of the available knowledge and data. From a decision-making standpoint, when the uncertainty is considered too great at a given tier, one should go on to the next tier, at which point more comprehensive investigations will be conducted. These are the principles that guided the development of the ERA approach discussed herein.

The development of the ERA framework required the collection of new field data, as well as the utilization of existing data on the St. Lawrence River obtained from the literature. To obtain chemical, toxicological, and biological data, two sampling campaigns were conducted: one in September and October 2004, and another during the same period in 2005. Areas of sedimentation (fluvial lakes, port area, river mouths of tributaries, etc.) were favored because it is recognized that higher levels of contaminants are often associated with fine particle accumulation. Sediments and macroinvertebrates were sampled at 59 stations located along the fluvial section of the St. Lawrence River (Fig. 1).

Surficial sediments and macroinvertebrates were sampled with a Shipek grab sampler (400 cm^2). At each station, 20 to 25 l of sediments were collected and placed in clear polyethylene bags. Samples were placed in a bucket with ice for 24 to 30 h until their arrival at the laboratory, where they were stored in a cold room (4°C). Sediments were then sieved through 2 mm mesh, manually homogenized, and subsampled for individual analyses within 24 to 48 h after sampling. Sediment porewater was extracted via two centrifugations, the first with whole sediment (3000 g, 20 min) and the second with retrieved porewater (10 000 g, 30 min) to remove suspended fine particles. Subsamples of interstitial water were kept for toxicity tests and measurements of dissolved organic carbon.

In order to reduce the sorting time, macroinvertebrate samples were preserved on site in a 10% formaldehyde solution stained with Rose Bengal in order to fix and colour macroinvertebrates. Sediment samples were rinsed with tap water at the laboratory, and macroinvertebrates were collected on a sieve with a 500 μm mesh size and sorted at the coarse taxonomic level. The

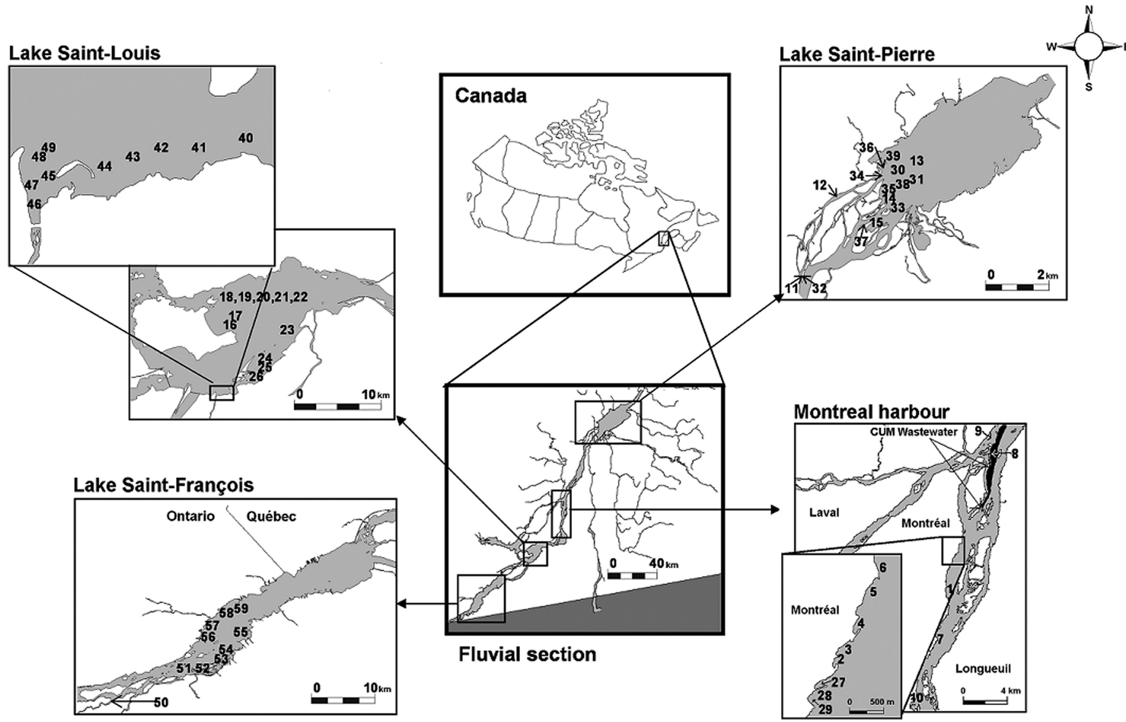

FIG. 1—*Study area of the 59 stations in the St. Lawrence River (Canada) located in three fluvial lakes (Saint-François, Saint-Louis, and Saint-Pierre) and the Montréal harbour area.*

organisms were then stored in 70% alcohol for later identification. The taxonomic analysis of macroinvertebrates was carried out by a private firm (Laboratoires SAB Inc.) at the family, genera, and species levels using several identification keys and methods [12–15].

Toxicity tests were performed on whole sediments with two benthic organisms (a chironomid, *Chironomus riparius*, and an amphipod, *Hyallela azteca*) and on the pore water with two pelagic organisms (a rotifer, *Brachionus calyciflorus*, and an alga, *Pseudokirchneriella subcapitata*) [16]. *H. azteca* and *C. riparius* were cultured in the Centre d'expertise en analyse environnementale du Québec laboratory according to standard methods [17–19], and whole-sediment toxicity tests were conducted according to standard procedures [17–19]. *B. calyciflorus* test organisms were two-hour-old females hatched from cysts obtained from Microbiotests Inc. (Nazareth, Belgium) according to Association Française de Normalisation (AFNOR) procedures [20]. Toxicity tests were conducted according to AFNOR procedures and a procedure described by Snell and Moffat [21]. The impact on the growth of the unicellular alga *Pseudokirchneriella subcapitata* (formerly *Selenastrum capricornutum*) was assessed using two protocols, in one vial (96 h without ethylenediamine tetra-acetic acid [EDTA] [22]) and in microplates (72 h with EDTA [23]).

All of the chemical analysis and toxicity testing was conducted in the laboratories of the Centre d'expertise en analyse environnementale du Québec according to standardized methods and with the required quality controls [16,24,25].

The Conceptual Model

A generic conceptual model was developed to cover the activities of open-water disposal of dredged sediment (Fig. 2). The sources of exposure, as well as targets and effects to consider during the ERA process, are described.

Analysis of the Source of Stress: Description of the Impacts of the Open-water Disposal of Dredged Sediment—The behavior of sediment in open-water deposition can be described in terms of the following phases: convective descent, dynamics collapse, the formation of deposits, and dispersion after resuspension (Fig. 2) [26]. Convection is characterized by the rapid descent of the mass of sediments under the influence of gravity. Passive diffusion is the detachment of particles from the mass of sediment during convection and dispersion by currents. Collapse dynamics involve the impact of the mass of sediment on the bottom and horizontal spread. A density gradient is formed radially around the point of impact and depends on the size of the particles. Deposit formation is the formation phase of a mound that is more or less eroded by the hydrodynamic forces present. Finally, the impact of these hydrodynamic forces on the deposit causes the resuspension of sediments in the

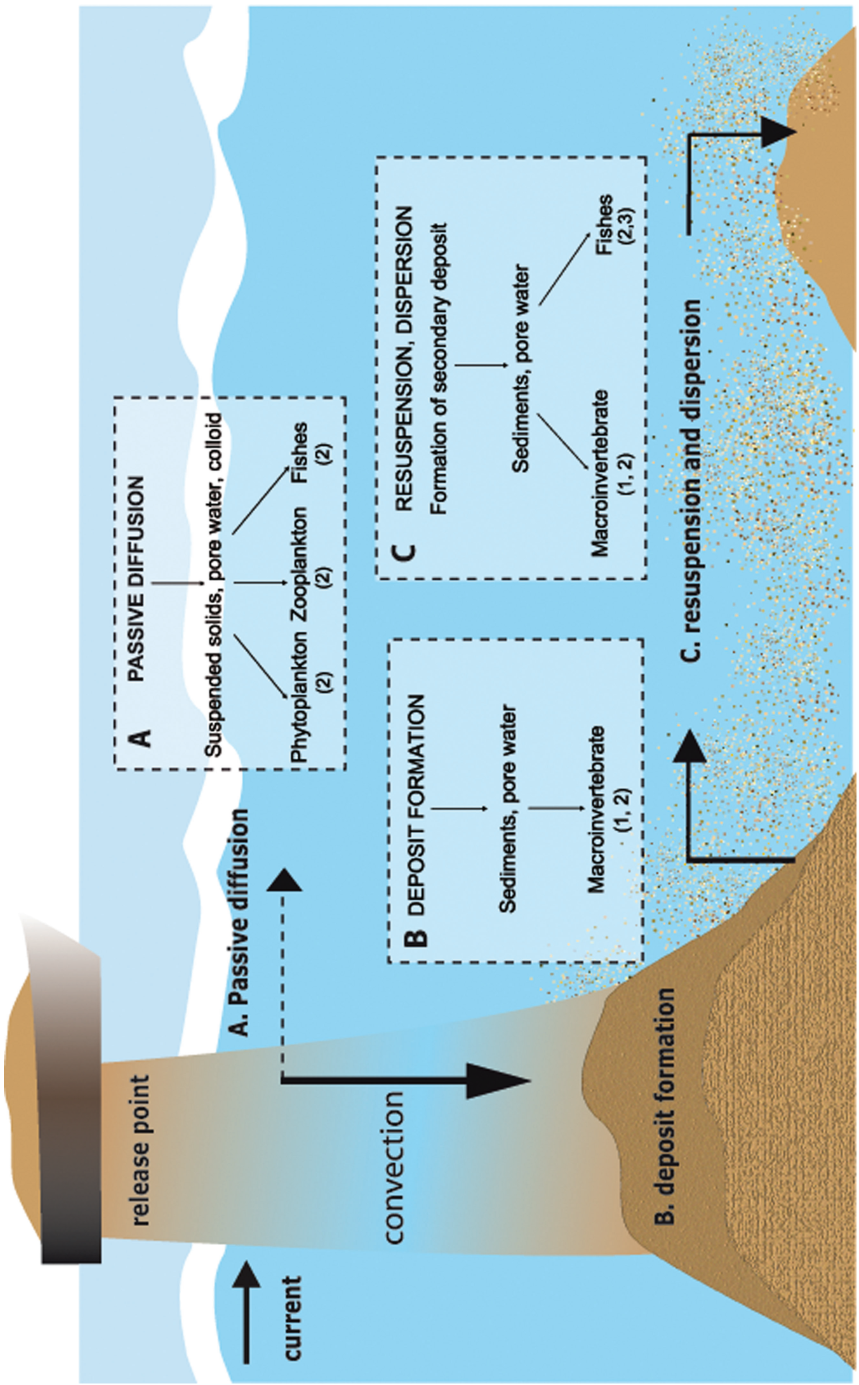

FIG. 2—*Conceptual model for open-water disposal of dredged sediment.*

longer term and the transport of material particles or resuspension over varying distances.

In order to determine whether open-water disposal is ecotoxicologically acceptable, analysis of various chemicals must be performed, and the results must be compared with the appropriate contamination level thresholds (OEL and FEL) developed for the assessment of sediment quality in Quebec. These thresholds define three classes of contamination [3] (Table 1).

The impact of open-water disposal must be assessed in the short, medium, and long term with regard to the potential for the resuspension and transport of sediment on the bottom over time. Firstly, to determine whether an open-water discharge poses a risk in terms of ecotoxicology, analysis of various chemical parameters should be performed, and the results should be compared to sediment quality criteria [3]. Based on the results, risk assessment procedures using toxicity tests are complementary tools with which to qualify criteria that might be required.

Even when the sediments are not contaminated, it is important to limit the spread of suspended solids (SS) at the time of dredging or during open-water disposal. The goal is to prevent high concentrations of SS and limit impacts that could include clogging the gills of fish or fish habitats due to sediment accumulation in spawning areas downstream. Therefore, when monitoring is performed during dredging activities, one must pay attention to the extent of sediment resuspension and, if necessary, take further action to limit the increase of SS concentrations in the water column. In this regard, guidelines are being developed for the management of SS associated with dredging and sediment disposal in open water. These tags include specific management criteria for SS during dredging. These are adapted in part from the quality criteria for surface water based on the analysis of background levels of SS in the St. Lawrence and concentrations measured during dredging activities. Whereas the Canadian Council of Ministers of the Environment quality criteria for surface water are mainly used for the management of effluent discharges, management criteria that are adapted for dredging activities are developed to ensure that appropriate measures will be taken to minimize the impacts of such activity on aquatic biota. When the monitoring of SS for a dredging project is required, SS concentrations must be measured prior to the work in order to establish the initial concentration range. Subsequently, environmental monitoring during dredging is used to verify the achievement of objectives set in advance and to adapt implementation measures, if necessary, in order to minimize impacts.

The assessment of potential physical impacts associated with the dispersion of SS, the erosion of dredged sediment disposal areas, and deposits is important in determining the risk of damage to the receiving environment, particularly in sensitive areas. The evaluation of such physical disturbances is not part of the ERA process but should be further included for the selection of acceptable areas of sediment deposition. The choice of disposal site might be influenced by the presence of sensitive natural or human environments nearby.

Analysis of the Receiving Ecosystem: Identification of Biological Receptors and Apprehended Responses—The receiving ecosystem is populated by several biological receptors, from species that live in the water column, including organisms from phytoplankton to fishes, to those living on sediment, such as periphyton and macroinvertebrates. Some birds and mammals also depend on aquatic environments for food or habitats and may also be considered as part of the receiving ecosystem.

At the time of the open-water disposal, the conceptual model would consider the short-term effects on the survival of organisms in the water column (phytoplankton, zooplankton, fish; process A, Fig. 2). Subsequently there obviously would be some destruction or partial loss of benthic communities following the formation of the dredged sediment deposit on the bottom (process B, Fig. 2). This effect can occur over an area extending beyond the boundaries of the release point because, firstly, the mass of sediment is spread horizontally upon impact on the bottom and, secondly, the erosion caused by hydrodynamic forces provokes the long-term spread of the deposit (process C, Fig. 2). However, this effect could be offset by recolonization of the site by adjacent benthic communities if conditions are favorable to their implementation.

Ecotoxicological Impact Hypotheses for Open-water Disposal of Dredged Sediments—The disposal site can accommodate a benthic community and therefore serve as a feeding area for fishes (especially juvenile fish) and birds. Open-water disposal might thus indirectly affect fishes and birds by leading to a loss of their feeding areas. In addition, if a high percentage of fine particles are driven downstream, clogging might also occur in spawning areas. Thus even uncontaminated sediments might have a significant physical effect on the functioning of spawning and feeding areas for fish. In addition, in the presence of contaminated sediments, the downstream deposition of eroded sediment could also have a significant effect on the survival, growth, and reproduction of fishes from these sites.

Although they are relevant to the process of assessing the impacts of the open-water disposal of dredged sediment, several biological targets or anticipated effects are not included in the ERA process, as they are already taken into account elsewhere.

- An assessment of the physical impact of dredged material on spawning areas is not included in the process of ERA, but such impacts must be considered when selecting the disposal site.
- Even when sediment contamination is not an issue, it is important to limit the spread of suspended solids at the time of dredging or stockpiling in order to prevent any impact on aquatic organisms.

In addition, during the descent of sediment in the water column, the risks to fish communities, zooplankton, and algae are considered negligible compared to the risks to benthic communities. Indeed, ecotoxicological risks to receptors in the water column are considered relatively low when taking into account the very short exposure time, the small amount of sediment that usually is dispersed from the total mass, and the potential avoidance and/or colonization rates of pelagic species. In addition, the relatively high flow rate in the St. Lawrence River allows the rapid dispersal of suspended solids in the water column.

Therefore, the ERA framework presented in this paper focuses on the assessment of risks posed by contaminants in dredged material to the recolonization of benthic communities at an open-water disposal site in the St. Lawrence River.

Tier 1: Detecting the Level of Sediment Contamination

In developing the ERA approach for the application framework for the open-water disposal of dredging sediment, it was decided that Tier 1 would involve a comparison of chemical concentrations in sediments using the criteria for the assessment of sediment quality in Quebec [3].

In this context, the predictive ability of decision thresholds must be verified using standardized toxicity tests performed in conjunction with chemical analyses [6,27]. The application of these thresholds can be difficult because there is seldom only one contaminant in the natural environment, and it is often necessary to consider contaminants' bioavailability and cumulative effect [27] and the influence of other environmental factors, such as the physical and chemical properties of the sediment or the physical geography of the sites sampled. It is therefore recommended that sediment quality criteria not be used in an ERA approach without their predictive capability having been verified first [28,29].

Initially, we classified sediments based on quality criteria and according to the most critical factor. This means that the chemical with the worst ranking conferred its quality rating to the sediment under study. In addition, the risk can be calculated by taking into account all chemicals measured. Each contaminant can be represented by a quotient obtained by calculating the ratio between the concentration of the contaminant measured in the environment and a threshold effect concentration. Most clustering methods assume that risk is additive, and this is generally considered acceptable in the literature [28,30–32]. Contaminants can also be grouped by chemical family (e.g., metals, pesticides) [33], and this can be an interesting alternative. Various methods of assigning a quality grade were assessed for this purpose. A scientific publication provided a detailed description of the scientific reasoning used to validate the proposed thresholds and the key findings that led to the development of Tier 1 of the ERA approach [16].

After using these different methods for assigning quality classes, we demonstrated that type II errors or false negatives in class 1 sediments amounted to nearly 50 %, i.e., samples with contamination levels below the OEL tested positive for significant toxicity. It is important to note that despite the observed toxicity, some class 1 sediments might have contamination levels below the lowest criteria, threshold effect level, or rare effect level, depending on the chemical parameters [16]. In addition, benthic organisms found in these stations also had (structural and functional) community structures that in many cases were similar to those of class 3 stations located outside the Port of Montreal area [25,34]. These laboratory and field observations suggested that a factor other than the contaminants covered by the quality criteria affected the toxicity and structure of the benthic communities that we observed.

From the standpoint of the sustainable management of dredged sediment in the St. Lawrence River, the presence of class 1 sediment significantly toxic to benthic communities was a major problem that we attempted to understand. Firstly, the research focused on toxic substances not covered by the list of quality criteria (petroleum hydrocarbons, organotins, etc.), and secondly, we studied the influence of confounding factors that could, for example, change the availability of the contaminants (particle size, total organic carbon, etc.). This part of the study demonstrated that for class 1 sediments, the toxic response was somewhat mitigated by certain sediment properties, primarily the presence of sulfur, a substance not covered by the quality criteria, which explained a significant percentage of the observed toxicity [16], as well as the structure of the benthic communities [25,34].

The toxicity observed in class 1 sediments might have led to changes in Tier 1 of the risk assessment such as introducing toxicity tests from the outset. However, this screening step proved effective for distinguishing class 2 and 3 sediments with 69% and 75% observed toxicity, respectively. In addition, the statistical analysis results presented by Desrosiers et al. [16] demonstrate that for the subset of class 1 stations, the total sulfur concentrations were associated with this unexpected toxicity. Thus, a total sulfur concentration in excess of 1400 mg/kg in uncontaminated sediments appears to be indicative of a potential risk to benthic organisms. Adding this parameter to our ERA framework significantly reduced the percentage of type II error in class 1 sediments: the initial type II error rates were nearly 50% for *H. azteca* and *C. riparius* mortality, and these decreased to 10% and 20%, respectively [16].

Tier 2: Assessing Sediment Toxicity

Introducing toxicity tests in Tier 2 enabled us to focus more specifically on exposure routes and the impact that all toxic substances in a sediment have on biological organisms. Several issues were also studied in detail during the toxicity test selection process for the proposed ERA approach to assessing dredged materials. The following summary report presents only the main findings that dictated the choice of tests [35].

Four standardized toxicity tests were assessed during this study: two whole sediment tests and two pore water tests. Whole sediment toxicity tests were conducted with young amphipods *Hyalella azteca* [36,37], epibenthic organisms living in the water–sediment interface, and benthic Chironomidae larvae (*Chironomus riparius*) [38,39]. The pore water toxicity tests were performed on organisms representing two trophic levels: the algae *Pseudokirchneriella subcapitata* [23], representing the primary producers, and the rotifers *Brachionus calyciflorus* [20], representing the primary consumers.

The effect thresholds for the four toxicity tests were determined by considering the presence or absence of a significant difference (*t*-test; $p < 0.05$) between the test sample and the control sample, and by considering the variability observed in the controls. This is how we determined that the sediment was detrimental to the survival or growth of *C. riparius* and *H. azteca* organisms (mortality and growth) when the response was ≥20% relative to the control results. The pore water test results for both tests with *P. subcapitata* were 15 %, and 40% for the reproduction of *B. calyciflorus*.

The major issue that was reviewed involved the choice of the battery of tests to be performed and the complementarity of the tests. The relationships observed between sediment contamination and toxicity test response varied with species. *H. azteca* mortality increased significantly in the presence of As, Cd, Cu, Pb, and Zn, whereas *C. riparius* mortality increased in the presence of Cd, Cu, Zn, and butyltin. *H. azteca* and *C. riparius* growth was not very sensitive to the presence of contaminants. Growth was more sensitive to the presence of nutrients in the sediment.

The *B. calyciflorus* test was a reproduction test. Reproduction was a more sensitive parameter than mortality, and the test appeared to demonstrate the influence of metals (Cd, Pb, and Zn), as well that of organic contaminants (polychlorinated biphenyls [PCBs], polycyclic aromatic hydrocarbons [PAHs], and butyltin. This was a real advantage. However, the test results could be difficult to interpret. For example, the stimulation of reproduction could be observed in the presence of endocrine disruptors such as we observed in our study of a site significantly impacted by agricultural operations. In addition, the variability of the controls also seemed high, which resulted in an increase in the toxicity threshold (≈40 % for the "reproduction" parameter) relative to those of other tests. The results of this test could therefore be difficult to interpret, and the test could not be used alone.

Algae tests quite often showed growth stimulation of *P. subcapitata* and did not seem appropriate for detecting toxicity in sediments. They could, however, be useful if the assessment parameter in a particular case study included a risk of eutrophication.

The pore water toxicity test results (*P. subcapitata* and *B. calyciflorus*) were correlated to one of the two whole sediment tests (*C. riparius* and *H. azteca*; Table 2). Performing these two tests did not appear to produce additional information that would justify extracting pore water in order to perform additional toxicity tests.

Because of the observed correlations with whole sediment tests and the difficulty of interpreting the results when the tests were performed on pore water, not to mention the need to extract this water, requesting these types of tests in the ERA approach to sediment from dredging activities did not appear to provide any real benefits. Also, as mentioned in the conceptual model, significant dilution occurs in the river during open-water disposal, making it difficult to assess the short-term effects on organisms potentially exposed to pore water.

Implementing the Ecotoxicological Risk Assessment Framework

In order to support the management of dredged sediments in the St. Lawrence River, the ERA approach proposed in this document incorporates quality criteria early in the assessment process in Tier 1, and performing the toxicity tests in Tier 2 provides successive tiers for assessing the ecotoxicological risk associated with the open-water disposal of dredged sediments (Fig. 3). The objective of the ERA approach is to determine whether the open-water disposal of sediments is acceptable from an ecotoxicological standpoint.

In Tier 1 of the process, the chemical analysis results are compared with criteria for the assessment of sediment quality developed in Quebec (Fig. 3). Two levels of contamination define three sediment classes and situations used in dredged sediment management: OEL and FEL [3].

The parameters to be analyzed at each dredging are particle size, metals (arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc), PCBs, PAHs, total organic carbon, petroleum hydrocarbons (C_{10}–C_{50}), and total sulfur. There are sediment quality criteria for metals, PCBs, and PAHs [3]. Other parameters can be added to this list based on the specific nature of each dredging operation.

TABLE 2—*Significant correlations observed among the results of the four toxicity tests performed on samples collected in 2004–2005.*

	C. riparius Mortality	*C. riparius* Growth	*H. azteca* Mortality	*H. azteca* Growth	*P. subcapitata* Growth
C. riparius growth	**	…			
H. azteca mortality	**	*	…		
H. azteca growth		*		…	
P. subcapitata growth	*	**	**		…
B. calyciflorus reproduction		**			

Notes: Significant Spearman correlations; *$p < 0.05$, **$p < 0.01$.

Situation 1

In situation 1, the concentration of all contaminants is less than the OEL, the concentration at which the probability of observing adverse biological effects is relatively low, and the sediment sample is defined as class 1. If a sediment belongs to class 1 but the total sulfur concentration exceeds 1400 mg/kg, the sample might be toxic to benthic organisms. It is therefore necessary to continue the assessment and proceed to Tier 2 (Fig. 3).

In the case in which all contaminants are below the OEL and the total sulfur concentration is less than 1400 mg/kg, the ERA may be considered complete (Fig. 3). Sediments may be discharged into open water or used for other purposes, provided such disposal does not adversely affect the receiving environment. Although compliance with chemical quality criteria is usually indicative of good sediment quality, ecosystems might still be disrupted. As mentioned in the conceptual model, dredged sediment deposition and large increases in the concentration of suspended solids that accompany the deposits can alter aquatic ecosystems or cause habitat loss, even if no toxic substances are present. Considerations concerning the health of the receiving ecosystem, in terms of both aquatic life and human health; the presence of a specific use or a threatened or vulnerable species; or the presence of spawning areas might require specific mitigation measures or additional interventions. The meeting of quality criteria must never be deemed as implicit approval for degrading sites until the selected threshold values are attained [3].

Situation 2

In situation 2, the concentration of at least one contaminant is between the OEL and the FEL, and the sediment sample is defined as class 2. Between these two concentrations, the probability of observing adverse biological effects is relatively high and increases with concentration. The probability of detecting adverse effects on benthic organisms is relatively high. In our study, classification based on the most critical parameter predicted toxicity in 69% of the class 2 stations. The open-water disposal of class 2 sediments can be considered a valid option only if toxicity tests demonstrate that the sediments will not adversely affect the receiving environment. As a result, and in accordance with what is suggested in the sediment quality assessment document [3], a battery of toxicity tests will be performed on these sediments, and it will have to be demonstrated at Tier 2 that the sediments will not have toxic effects on the aquatic organisms. It will then be possible to release the sediments into the aquatic environment if they do not have any adverse effects (Fig. 3).

Open-water disposal can be considered a valid option only if none of the toxicity tests demonstrate a significant toxic response (Fig. 3). Sediments are considered harmful to the health of benthic organisms and open-water disposal is prohibited when at least one of the tests shows a significant toxic response.

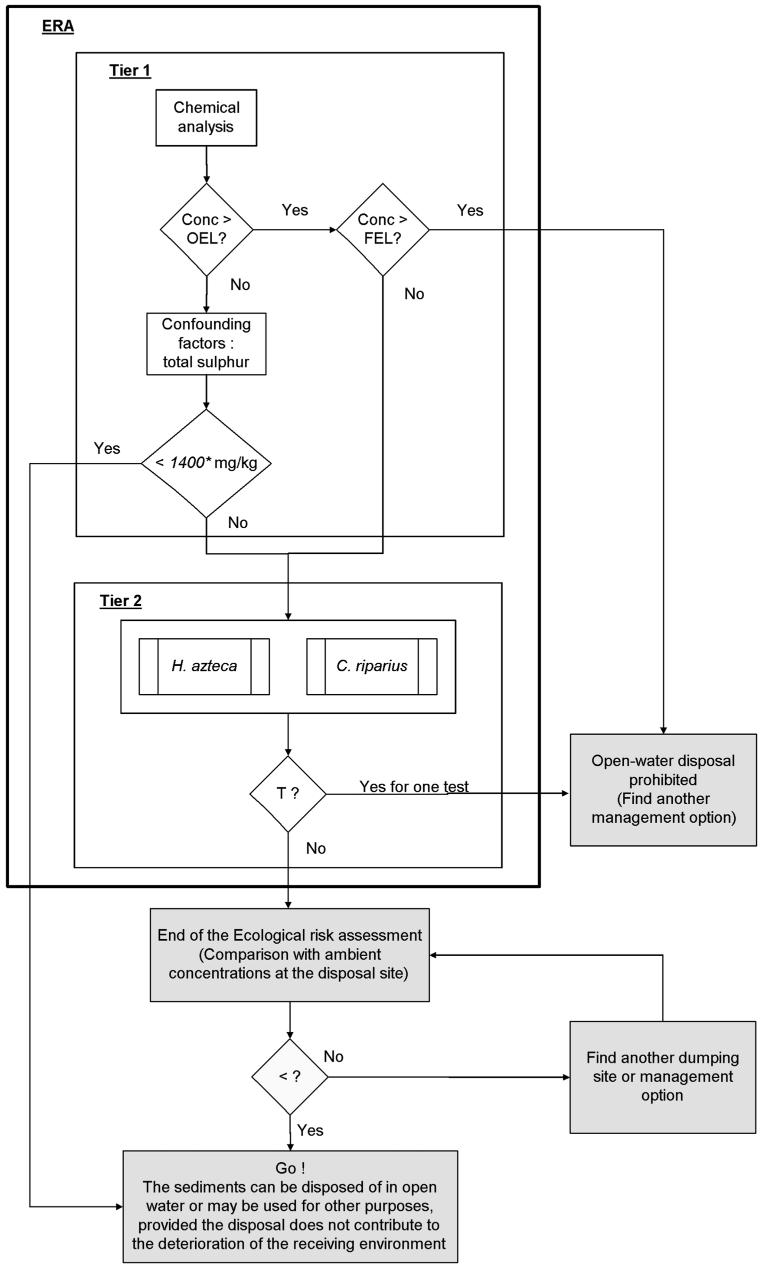

FIG. 3—*Ecotoxicological risk assessment framework to support the management of the open-water disposal of dredged sediments in the St. Lawrence River.*

However, even in the absence of toxicity, an adequate characterization of the disposal site is required before disposal can occur. Dredged sediment concentrations are less than or equal to the levels measured in sediment samples taken from the disposal site. This comparison of sediment quality should be made according the respective class (1, 2, or 3) of each of the substances targeted by the quality criteria. This procedure ensures that non-toxic class 2 sediments are not deposited on class 1 sediments or on class 2 sediments that do not have a similar contamination baseline for each of the target substances. This should ensure that the deposit area of dredged sediment limits the negative impacts on the environment and the activities connected to it. It is also appropriate to ensure that the site selected for disposal of the dredged materials minimizes adverse effects on the environment and activities related to the site. However, we may exceptionally ask to carry out bioaccumulation testing in the presence of substances that are highly bioaccumulative but potentially non-toxic to benthos.

Situation 3

In situation 3, the concentration of at least one contaminant is greater than the FEL, the concentration at which the probability of observing adverse biological effects is very high, and the sediment sample is defined as class 3. Our study showed that sediments in which at least one contaminant exceeded the FEL (class 3) were predominantly toxic (75 %). Although the other sediments were non-toxic to the organisms tested, they contained high levels of Hg, a contaminant that poses a high risk of bioaccumulation and trophic transfer. These observations were consistent with the high probability of detecting adverse biological effects as expected in class 3 sediments. As a result, the open-water disposal of class 3 sediments is prohibited as specified in the document describing the revised sediment quality criteria [3] (Fig. 3). As such, class 3 sediments must be treated or adequately contained.

Conclusion and Perspectives

This approach to the ecological risk assessment (ERA) of the open-water disposal of sediment in support of the management of dredging projects has been developed based on data collected from the freshwater portion of the St. Lawrence River. Consequently, this approach applies ERA only for the open-water disposal of dredged sediments included in the freshwater portion of the St. Lawrence River extending from Cornwall to the east of Île d'Orléans and in Lakes St. François, St. Louis, and St. Pierre. When planning work in salt water, one should refer to the procedures and toxicity tests proposed in the framework of the Environment Canada Disposal at Sea program. Regarding the area of brackish water, a project that will be developed in the fifth Plan Saint-Laurent will establish the tolerance limits of toxicity testing based on proposed toxicity testing conditions found in brackish rivers. The second management option, which will be developed in future works, is the remediation of contaminated sediment sites. This second ERA will estimate the risk posed by in-place sediment contamination and thus will assist in determining whether site remediation is a desirable and sustainable option.

Acknowledgments

This study is a part of a larger collaborative program funded by the third and fourth phases of the St. Lawrence Plan for Sustainable Development with the active participation of Environment Canada (Environmental Protection Operations Division and Science and Technology Branch), the Ministère du Développement durable, de l'Environnement et des Parcs du Québec (Centre d'expertise en analyse environnementale du Québec; Direction des evaluations environnementales; Direction du suivi de l'état de l'environnement), and IRSTEA from Lyon (France). The project was also associated with the Sustainable Navigation Strategy for the St. Lawrence River, which includes aspects such as sustainable dredging management, contaminated site restoration, and sediment quality guideline revision for contaminated sediment. The writers acknowledge the Commission Permanente de Cooperation Franco-Québecoise for travel funding during this collaborative project. The writers also acknowledge all fieldwork participants, particularly M. Arseneault, P. Turcotte, A. Lajeunesse, and G. Brault, who helped over the two sampling years, and all persons connected to the laboratories of chemistry and biology of the Centre d'expertise en analyse environnementale du Québec.

References

[1] Environment Canada, "Sediment Quality and Dredging Activities in the St. Lawrence River," St. Lawrence Centre, Technology Development Section, Environmental Protection Branch, Montreal, QC, Canada, 1993.

[2] Ministère des Transports du Québec, "Portrait des activités de dragage sur le Saint-Laurent: Les aspects opérationnels et environnementaux," Direction du transport maritime aérien et ferroviaire, Québec, Canada, 2003.

[3] Environment Canada, Ministère du Développement durable, de l'Environnement et des Parcs, "Criteria for the Assessment of Sediment Quality in Quebec and Application Frameworks: Prevention, Dredging and Remediation," Environment Canada, Ministère du Développement durable, de l'Environnement et des Parcs, Québec, Canada, 2007.

[4] Alvarez-Guerra, M., Viguri, J. R., Casado-Martinez, M. C., and DelValls, T. A., "Sediment Quality Assessment and Dredged Material Management in Spain: Part I, Application of Sediment Quality Guidelines in the Bay of

Santander," *Integrated Environmental Assessment and Management*, Vol. 3, 2007, pp. 529–538.

[5] Apitz, S. E., Barbanti, A., Bocci, M., Carlin, A., Montobbio, L., and Bernstein, A. G., "The Sediments of the Venice Lagoon (Italy) Evaluated in a Screening Risk Assessment Approach: Part I—Application of International Sediment Quality Guidelines," *Integrated Environmental Assessment and Management*, Vol. 3, 2007, pp. 394–414.

[6] Babut, M. P., Delmas, H., Bray, M., Durrieu, C., Perrodin, Y., and Garric, J., "Characterizing the Risks to Aquatic Ecosystems: A Tentative Approach in the Context of Freshwater Dredged Material Disposal," *Integrated Environmental Assessment and Management*, Vol. 2, 2006, pp. 330–343.

[7] Babut, M. P., Ahlf, W., Batley, G. E., Camusso, M., De Deckere, E., and Den Besten, P. J., "International Overview of Sediment Quality Guidelines and Their Uses," *Use of Sediment Quality Guidelines and Related Tools for the Assessment of Contaminated Sediments*, R. J. Wenning, G. E. Batley, C. G. Ingersoll, and D. W. Moore, Eds., Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, FL, 2005, pp. 345–382.

[8] CEPA, 1999, "Statutes of Canada, Chapter 33, Schedule 6," Federal Government of Canada, Ottawa, ON, Canada, www.ec.gc.ca/CEPARegistry/the_act/Schedules_6.cfm (Last accessed April 2, 2007).

[9] Agius, S. J. and Porebski, L., "Towards the Assessment and Management of Contaminated Dredged Materials," *Integrated Environmental Assessment and Management*, Vol. 4, 2008, pp. 255–266.

[10] Environment Canada, Ontario Ministry of the Environment, "Canada-Ontario Decision-making Framework: For Assessment of Great Lakes Contaminated Sediment," Environment Canada, Ontario Ministry of the Environment, 2007.

[11] Chapman, P. M., and Anderson, J., "A Decision-making Framework for Sediment Contamination," *Integrated Environmental Assessment and Management*, Vol. 1, 2005, pp. 163–173.

[12] Klemm, D. J., Lewis, P. A., Fulk, F., and Lazorchak, J. M., 1990, "Macroinvertebrate Field and Laboratory Methods for Evaluating the Biological Integrity of Surface Waters," U.S Environmental Protection Agency, Office of Research and Development of the Environmental Monitoring Systems Laboratory, Cincinnati, OH.

[13] Merritt, R. W., and Cummins, K. W., *An Introduction to the Aquatic Insects of North America*, 3rd ed., Kendall/Hunt Publishing Company, Dubuque, IA, 1996, p. 442.

[14] Bartlett, A. J., Borgmann, U., George, D., Batchelor, S. P., and Maguire, R. J., "Toxicity and Bioaccumulation of Tributyltin in *Hyalella azteca* from Freshwater Harbour Sediments in the Great Lakes Basin, Canada," *Can. J. Fish. Aquat. Sci.*, Vol. 62, 2005, pp. 1243–1253.

[15] Thorp, J. H. and Covich, A. P., *Ecology and Classification of North American Freshwater Invertebrates*, 2nd ed., Academic Press, San Diego, 2001, p. 1038.
[16] Desrosiers, M., Babut, M. P., Pelletier, M., Bélanger, C., Thibodeau, S., and Martel, L., "Efficiency of Sediment Quality Guidelines for Predicting Toxicity: The Case of the St. Lawrence River," *Integrated Environmental Assessment and Management*, Vol. 6, 2010, pp. 225–239.
[17] Environment Canada, "Biological Test Method: Test for Survival and Growth in Sediment Using the Freshwater Amphipod *Hyalella azteca*," Technical Report EPS 1/RM/33, Ottawa, ON, Canada, 1997, p. 141.
[18] AFNOR, "Qualité de l'Eau—Détermination de la Toxicité des Sédiments d'Eau Douce vis-à-vis de *Hyalella azteca*," *XP T 90-338-1*, Paris, France, 2003.
[19] AFNOR, "Qualité de l'Eau—Détermination de la Toxicité des Sédiments d'Eau Douce vis-à-vis de *Chironomus riparius*," Technical Report *XP T 90-339-1*, Paris, France, 2004.
[20] AFNOR, "Qualité de l'Eau—Détermination de la Toxicité Chronique vis-à-vis de *Brachionus calyciflorus* en 48 h," Technical Report *NF T 90-377*, AFNOR, Paris, France, 2000.
[21] Snell, T. W. and Moffat, B. D., "A 2-d Life Cycle Test with the Rotifer *Brachionus calyciflorus*," *Envir. Toxicol. Chem.*, Vol. 11, 1992, pp. 1249–1257.
[22] Centre d'Expertise en Analyse Environnementale du Québec, "Détermination de la toxicité: Inhibition de la croissance chez l'algue *Pseudokirchneriella subcapitata* MA 500 - P. sub 1.0," Ministère du développement durable, de l'environnement et des Parcs du Québec, 2005.
[23] Environment Canada, "Biological Test Method: Growth Inhibition Test Using the Freshwater Alga *Selenestrum capricornutum*," *EPS 1/RM/25*, Environmental Protection Publications, Ottawa, ON, Canada, 1992.
[24] Desrosiers, M., Gagnon, C., Masson, S., Martel, L., and Babut, M. P., "Relationships among Total Recoverable and Reactive Metals and Metalloid in the St. Lawrence River Sediment: Bioaccumulation by Chironomids and Implication for Ecological Risk Assessment," *Sci. Total Environ.*, Vol. 389, 2008, pp. 101–114.
[25] Masson, S., Desrosiers, M., Pinel-Alloul, B., and Martel, L., "Relating Macroinvertebrate Community Structure to Environmental Characteristics and Sediment Contamination at the Scale of the St. Lawrence River," *Hydrobiologia*, Vol. 647, 2010, pp. 35–50.
[26] Truitt, C. L., "Dredged Material Behavior during Open-Water Disposal," *J. Coastal Res.*, Vol. 4, 1988, pp. 489–497.
[27] MacDonald, D. D., Ingersoll, C. G., and Berger, T. A., "Development and Evaluation of Consensus-based Sediment Quality Guidelines for

Freshwater Ecosystems," *Arch. Environ. Contam. Toxicol.*, Vol. 39, 2000, pp. 20–31.

[28] Fairey, R., Long, E. R., Roberts, C. A., Anderson, B. S., Phillips, B. M., Hunt, J. W., Puckett, H. R., and Wilson, C. J., "An Evaluation of Methods for Calculating Mean Sediment Quality Guideline Quotients as Indicators of Contamination and Acute Toxicity to Amphipods by Chemical Mixtures," *Envir. Toxicol. Chem.*, Vol. 20, 2001, pp. 2276–2286.

[29] Batley, G. E., Stahl, R. G., Babut, M. P., Bott, T. L., Clark, J. R., Field, L. J., Ho, K. T., Mount, D. R., Swartz, R. C., and Tessier, A., "Scientific Underpinnings of Sediment Quality Guidelines," *Use of Sediment Quality Guidelines and Related Tools for Assessment of Contaminated Sediments*, R. J. Wenning, G. E. Batley, C. G. Ingersoll, and D. W. Moore, Eds., Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, FL, 2005, pp. 39–120.

[30] Ingersoll, C. G., Ivey, C. D., Brunson, E. L., Hardesty, D. K., and Kemble, N. E., "Evaluation of Toxicity: Whole-sediment versus Overlying-water Exposures with Amphipod *Hyalella azteca*," *Envir. Toxicol. Chem.*, Vol. 19, 2000, pp. 2906–2910.

[31] MacDonald, D. D., Dipinto, L. M., Field, J., Ingersoll, C. G., Long, E. R., and Swartz, R. C., "Development and Evaluation of Consensus-based Sediment Effect Concentration for Polychlorinated Biphenyls," *Envir. Toxicol. Chem.*, Vol. 19, 2000, pp. 1403–1413.

[32] Long, E. R., Field, L. J., and MacDonald, D. D., "Predicting Toxicity in Marine Sediments with Numerical Sediment Quality Guidelines," *Envir. Toxicol. Chem.*, Vol. 17, 1998, pp. 714–727.

[33] Ingersoll, C. G., MacDonald, D. D., Wang, N., Crane, J. L., Field, L. J., Haverland, P. S., Kemble, N. E., Lindskoog, R. A., Severn, C., and Smorong, D. E., "Prediction of Sediment Toxicity Using Consensus-based Freshwater Sediment Quality Guidelines," *Arch. Environ. Contam. Toxicol.*, Vol. 41, 2001, pp. 8–21.

[34] Desrosiers, M., Usseglio-Polatera, P., Archaimbault, V., Pinel-Alloul, B., and Méthot, G., "Using Macroinvertebrate Functional Traits for Assessing Sediment Quality in the St. Lawrence River" (unpublished).

[35] Desrosiers, M., Triffault-Bouchet, G., Masson, S., Martel, L., and Babut, M. P., "Relationships between Sediment Toxicity and Chemical Mixed Contamination in the St. Lawrence River (Canada)," *Sci. Total Environ.* (unpublished).

[36] Environment Canada, "Biological Test Method: Test for Survival and Growth in Sediment Using the Freshwater Amphipod *Hyalella azteca*," *Technical Report SPE 1/RM/33*, Ottawa, Ontario, Canada, 1997.

[37] AFNOR, "Qualité de l'eau—Détermination de la toxicité des sédiments d'eaux douces vis-à-vis de *Hyalella azteca*," *Technical Report XP T 90-338-1*, AFNOR, Paris, France, 2003.

[38] AFNOR, “Détermination de la toxicité des sédiments d’eau douce vis-à-vis de *Chironomus riparius*,” *Technical Report XP T90-339-1*, AFNOR, Paris, France, 2004.
[39] Environnement Canada, *Méthode d’essai biologique: Essai de survie et de croissance des larves dulcicoles de chironomes (Chironomus tentans ou Chironomus riparius) dans les sediments*, Environnement Canada, Ottawa, Ontario, 1997.