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Sediment Management: Ecological end points must direct actions

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Abstract

The need for guidance on the bioassessment and management of contaminated sediment has been articulated by Remedial Action Plan (RAP) practitioners, the International Joint Commission, and scientists and managers in many jurisdictions. Encouragingly, there is beginning to be a convergence of opinion on what constitutes a comprehensive sediment assessment. However, there continues to be a need for ecologically meaningful methods to interpret and integrate multiple pieces of information on sediment chemistry, biological information from field monitoring and laboratory sediment bioassessment.

Recognizing the current state of knowledge, we advocate that the development and application ecologically relevant techniques to interpretation sediment assessment data. We provide a recommended approach to comprehensive sediment bioassessment that is driven by the need to rehabilitate "beneficial uses" as described in the Great Lakes Water Quality Agreement. We highlight advances in data interpretation that are facilitating the development of sediment management strategies.

Besoin de critères d'évaluation écologiques pour orienter la gestion des sédiments

SOMMAIRE À L'INTENTION DE LA DIRECTION

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Résumé

Des chercheurs et des gestionnaires du Plan d'assainissement (PA), de la Commission mixte internationale et d'un grand nombre de gouvernements réclament des balises pour faciliter la bioévaluation et la gestion des sédiments contaminés. Il est encourageant de constater que l'on commence à s'entendre sur ce que devrait être une évaluation détaillée des sédiments. Cependant, on ne dispose pas encore de méthodes écologiques pour interpréter et intégrer les nombreux éléments d'information sur la chimie des sédiments, sur les aspects biologiques de la surveillance *in situ* et sur la bioévaluation des sédiments en laboratoire.

Compte tenu de l'état actuel des connaissances, nous préconisons le développement et l'application de techniques écologiques pour l'interprétation des données d'évaluation des sédiments. Nous présentons une approche recommandée pour la bioévaluation détaillée des sédiments, axée sur le rétablissement des « utilisations avantageuses », telles qu'elles sont définies dans l'Accord relatif à la qualité de l'eau des Grands Lacs. Nous soulignons les progrès réalisés dans l'interprétation des données , qui devraient faciliter le développement d'une stratégie de gestion des sédiments.

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Sediment Management: Ecological and Ecotoxicological Effects Must Direct Actions

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The need for guidance on the bioassessment and management of contaminated sediment has been articulated by Remedial Action Plan practitioners, the International Joint Commission, scientists, and managers in many jurisdictions. Encouragingly, a convergence of opinion, on what constitutes a comprehensive sediment assessment, is beginning. However, there continues to be a need for methods to interpret and integrate multiple pieces of information on sediment chemistry, biological information from field monitoring and laboratory sediment bioassessment in an ecologically meaningful way. This paper recommends an approach to comprehensive sediment bioassessment that is driven by the need to rehabilitate "beneficial uses" as described in the Great Lakes Water Quality Agreement. The paper also highlights advances in data interpretation that are facilitating he development of sediment management strategies.

Key words: **contaminated sediment management, integrated bioassessment**

Introduction

In its 1985 report, the Water Quality Board (WQB) of the International Joint Commission (IJC) identified 42 Areas of Concern (AOC) in the Great Lakes that exhibit various types of problems associated with impaired quality(GLWQB 1985). The concept of "impaired beneficial uses" was introduced to summarize these problems and was adopted by Canada and the U.S. in the 1987 revisions to the Great Lakes Water Quality Agreement (GLWQA) (United States and Canada 1987).

Through the course of RAP development, the presence of contaminants in sediment at levels greater than jurisdictional guidelines has been confirmed at all AOCs. It has become evident that if beneficial uses in Great Lakes Areas of Concern are to be revitalized, it is important to evaluate the degree to which contaminated sediment contributes to their impairment.

The WQB is comprised of senior program mangers from the eight states and two provinces that border the Laurentian Great Lakes. This board has advocated that sediment management decisions should be driven by the restoration of beneficial uses. This is a primary goal of both the GLWQA and the U.S. Clean Water Act. In its 1997–1999 Priorities Report,

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the WQB called for a step-wise and incremental approach to management of contaminated sediment and restoration of beneficial uses (IJC 1999). The WQB went on to state: "Sediment remediation, removal by dredging of a mass of contaminants, and reduction of risk are important indicators of incremental progress. The ultimate success of sediment management activities will be judged upon restoration of beneficial uses such as elimination of fish consumption advisories, restoration of fish and wildlife populations and restoration of benthos." (IJC 1999).

For many AOCs, the data, needed to make the connections between contaminants in sediment and at least some of the beneficial use impairments, have been collected. Sediment contaminant concentrations, benthic community structure and composition, laboratory toxicity, contaminant bioaccumulation/ biomagnification, and the physical and chemical stability of the sediment have been assessed. However, converting these data into information on the environmental significance of the assessment results has remained problematic. This is particularly the case when univariate statistics are used, and differences between test and reference materials are reported according to $p<0.05$. Does this level of significance impart an understanding of the ecological consequence of the test results (i.e., does it provide sufficient protection for the aquatic ecosystem)? Probably not. Therefore, it is important that an ecotoxicological/ecological approach be used.

The degree to which contaminants in sediment are contributing to the observed impairments represents information that is critical to managing the problem. Remedial strategies should be directed towards the appropriate management action that will lead to the recovery of beneficial uses — the recovery of ecosystem structure and function. If contaminated sediment is not causing or contributing to any use impairments, and the site is stable, from a physical and chemical perspective, then regardless of sediment chemistry, no sediment management actions may be needed beyond routine monitoring (and pollution prevention). The chemical and physical site stability is a fundamentally important consideration. The present status needs to be known and the potential for change in the future needs to be assessed. If the contaminated sediment is linked to one or more use impairments, and/or site stability cannot be ensured, then it is recommended that the relationship between contaminated sediment and use impairments be established and the appropriate remedial actions initiated.

In 1995, the IJC concluded that sediment remediation in the AOCs was not progressing at an acceptable rate and instructed its WQB to examine the magnitude of the situation and make recommendations on how to improve sediment management. The WQB established the Sediment Priority Action Committee (SedPAC) with experts from state, provincial and federal agencies, including members from the IJC's Science Advisory Board and Council of Research Managers. SedPAC's first report concluded that one of the major obstacles to sediment management was the lack of decision-making tools that enabled clear ecological interpretations of the bioassessment data (SedPAC 1997). In 1999, SedPAC synthesized a series of data interpretation tools to assist RAP practitioners in reaching a conclusion regarding the ecological implications of contaminant in sediment (SedPAC 1999). The key features are summarized here and the reader is directed to the original publications for further detail.

Bioassessment and Deciding on a Management Strategy

Currently, exceeding chemical criteria is normally the most common trigger that initiates a biological assessment. For example, in Ontario, chemical guidelines identify the lowest effect level (LEL) as the level of contamination at which there is a 5% chance of an effect on the benthos and requires further biological testing to determine the need for a management plan. The severe effect level (SEL) is considered heavily polluted and has a 95% chance of affecting the health of benthic organisms (Persaud et al. 1992). Even these latter values are not in and of themselves cleanup criteria, but when they are exceeded, biological testing is required to determine, on a site-specific basis, whether the sediment elicits lethal or sublethal responses to biota (Persaud and Jaagumagi 1996). However, decisions to remediate should be based on the assessment of biological effects of contaminants, and to ensure that real effects are not missed, the biological assessments should be done at the same time.

A battery of different biological tests is usually employed to indicate whether the study area under consideration presents a ecological or human health risk. The use of a battery of tests, with multiple endpoints and different test organisms is highly desirable to reduce the chance of missing an effect. However, results from these tests can generate complexity for making a clear decision. First, the interpretation of individual tests is not always straightforward. Since the tests are often designed to provide a minimum of redundant data, the integration of information from multiple tests can be confusing. Aside from extreme responses, for example, acute lethality or absence of benthos, linked to sediment contamination, the identification of an unacceptable biological effect is somewhat subjective. For example, would a highly significant reduction in the growth test result in a sample failure and direct remediation or would some combination of test results be necessary for a sample failure? Therefore, some pre-assigned, subjective level of unacceptable effect and the necessary weighting factors are required to aid the final interpretation of the results (Krantzberg et al. 2000).

Management goals or targets are based on site-specific expectations and attributes for the location in question. As a first principal in seeking the ecological ramifications from the assessment data, it is important to note that there is a normal variance associated with biological responses or endpoints in regions remote from contamination. Unacceptable impacts could be defined as those that exceed the normal variation observed in reference locations. The greater the departure from the normal variance, the more certainty that the test site is in fact different from the reference locations. Calling such sites stressed or extremely stressed requires that the nature of the departure excludes confounding factors not associated with in-place pollutants, such as navigational scour or the influence of exotic species.

Over the past 15 years, methods developed in the United Kingdom (Wright et al. 1984; Moss et al. 1987; Armitage et al. 1987; Ormerod and Edwards 1987) and elsewhere (Corkum and Currie 1987; Johnson and Wiederholm 1989) have demonstrated the ability to predict the community structure of benthic invertebrates in clean (or "uncontaminated" sites using simple habitat and water quality descriptors.

This approach allows appropriate site-specific biological objectives to be set for ecosystems from measured habitat characteristics and also provides an appropriate reference for determining when degradation is occurring at a site due to anthropogenic contamination. The acceptance by regulatory agencies of biological water quality and sediment quality objectives has been slow but is now being given serious consideration in Canada, the U.S., United Kingdom and in Australia (Wright et al. 2000, 1984; Reynoldson and Zarull 1993; Reynoldson et al. 1995; Hunsaker and Carpenter 1990).

The determination of the reference condition is based on the premise that sites least affected by human activity will exhibit biological conditions most similar to those at natural, pristine, locations. The reference approach compares biological attributes of a test sediment to the predicted condition, which is determined using a model based on abiotic site attributes.

The community structure or bioassay endpoints of a test site can be compared to appropriate reference sites and the divergence resulting from environmental disturbance can be assessed. As responses will represent a continuum from good to poor quality, methods are being developed to establish the significance and severity of deviation from normal (Reynoldson and Day 1998; Reynoldson et al. 2000). Deviations from normal enable the analyst to evaluate the likelihood that the observed data are within the range of natural variation, or have a high probability of being driven by contaminant stressors.

This is just one illustration of ecologically relevant interpretation of sediment bioassessment data. The data interpretation tools presented in Table 1 and the checklist in Table 2 have been developed to help make a decision regarding whether the scientific evidence necessitates action beyond source control.

Once the sediment assessment elements have been evaluated in the context of ecological risk, interpretation of the different lines of evidence is the next step. As recognized above, the battery of tests is selected to provide non-redundant information. As a consequence, not all pieces of information will show a positive or negative influence related to contaminants in sediment. Table 3 illustrates this point and offers a sample of the range of interpretations that are tenable. Discussions of the integration of laboratory toxicity endpoints into a single conclusion (+ or —), and alter-

Table 1. A matrix of data interpretation tools and references to be used in making a sediment management decision beyond source control in order to restore beneficial uses as defined in the Great Lakes Water Quality Agreement[1]

Use impairment	Assessment element	Data interpretation tools
Restrictions on fish and wildlife consumption	Bioaccumulation	Equilibrium partitioning, comparison to guidelines
Degradation of fish and wildlife populations	Community structure, bioaccumulation	Food web model, weight of evidence
Fish tumours or other deformities	Bioaccumulation, chemistry	Reference frequencies
Bird of animal deformities or reproduction problems	Bioaccumulation, community structure	Food web model, comparison to reference conditions, weight of evidence
Degradation of benthos	Community structure, toxicity (bioassays)	Comparison to reference conditions
Restrictions on dredging activities	Chemistry, toxicity (bioassays), stability[2]	Comparison to guidelines and/or reference conditions
Eutrophication or undesirable algae	Chemistry, stability	Modelling
Degradation of aesthetics	Chemistry, stability	Comparison to reference conditions
Added costs to agriculture or industry	Chemistry, stability	Comparison to reference conditions
Degraded phytoplankton and zooplankton populations	Bioaccumulation, chemistry, stability	Comparison to reference conditions, target nutrient loads
Loss of fish and wildlife habitat	Chemistry, bioaccumulation, toxicity, benthos, stability	Comparison to reference conditions, weight of evidence

[1] Modified from SedPAC 1999 and Krantzberg et al. 2000

[2] Physical sediment characteristics, knowledge of consolidation, resuspension energetics, etc.

Table 2. A checklist of key elements to consider in making a sediment management decision beyond source control

Assessment element
Characterization of the nature and extent of chemical contamination
Measurement of toxicity endpoints (lethal and sublethal chronic effects)
Assessment of bioaccumulation/biomagnification potential
Characterization of benthic communities
Evaluation of the nature, extent and cause of fish tumours and abnormalities
Assessment of human health risk from contaminants in sediment
Assessment of wildlife health risk from contaminants in sediment
Assessment of fish and other aquatic life health risk from contaminants in sediment
Evaluation of the physical stability of contaminated sediment deposits (e.g., would a storm resuspend the sediment, resulting in a pulsed loading of contaminants downstream?)
Determination of contaminant control at source (i.e., have upstream sources of contamination also been controlled/ terminated?)

native methods for assigning an ecologically relevant positive or negative outcome to sediment assessment data can be found in SedPAC (1999) and Wright et al. (2000).

It is beyond the scope of this paper to address how decisions are tempered by factors other than the science-based tools discussed above. Once a decision has been made to intervene, however, the following additional elements will likely require attention.

The size of the area. A real extent for which remediation has been determined to be required needs to be clearly defined since it will have a significant bearing on the remedial option chosen from both a cost and technology perspective.

Depth of cleanup. To ensure that the full vertical extent of the problem has been adequately defined and avoid potential for sediment removal revealing deeper layers of higher contamination.

Engineering factors. Technical feasibility, contaminant reduction potential, permanence of remedial options like capping, in situ treatment, dredging and disposal, etc.

Economic factors. Cost-effectiveness, economic benefits, benefits forecasting.

Long-term monitoring considerations. Measure the effectiveness of the management action.

Table 3. Information provided by comparisons of chemical, laboratory, field and bioaccumulation results (modified from Chapman 1990)1

Contaminants above the LEL	Laboratory toxicity	Benthic community impairment	Bioaccumulation	Possible conclusions
+	+	+	+	Conclusive evidence for pollution-induced degradation.
+	—	+	+	Strong evidence for pollution-induced degradation, possible laboratory false negative due to sediment handling and change in contaminant bioavailability
+	+	+	—	Conclusive evidence for pollution-induced degradation, unlikely due to persistent bioaccumulative substances.
+	—	—	—	Contaminants are not bioavailable.
—	+	—	—	Laboratory false positive due to change in contaminant bioavailability; or less likely, due to an unknown chemical.
—	—	+	—	Impairment not due to toxic chemicals, possible water column effect or physical disturbance of substrate.
—	—	—	+	Low concentrations of highly bioavailable chemical or analytical error.
+	+	—	—	Toxic chemicals may be stressing the system; local benthos may have developed tolerance.
—	+	+	—	Unmeasured chemicals could be causing degradation;
—	—	+	+	Contaminants bioavailable, food web concerns. Impairment likely due to contaminants.
+	—	+	—	Inconclusive, impairment may or may not be due to contaminant; other stressors may be active.
+	—	—	+	Although bioavailable, contaminants are not affecting the system; potential food web effects

The plus sign (+) indicates an adverse response to contaminated sediment (or exceeding a sediment standard); the dash (—) indicates no ecologically significant outcome of the assessment element.

Social factors. Public acceptance, partners' opinions, adherence to public use goals, conflicting actions.

Existing and planned uses of the area and the potential to impact adjoining areas through the movement of contaminated sediment. Uses may include protection of fish, wildlife, benthic communities, fish consumption, etc.; there is a need to consider both the toxic and bioaccumulation potential of contaminants.

A human health perspective. Compounds that are persistent and pose a threat to water supplies or fish and wildlife will be weighted differently from compounds that do not pose similar threats, thereby influencing decisions on management actions.

The physical environment. The potential for resuspension of contaminated sediment, with resultant contamination of adjacent or downstream areas will be an important factor in developing a remediation plan.

Recovery potential. The time required, given a known rate of contaminant degradation or sedimentation, for the contaminant concentrations to be reduced below levels that pose an ecological risk.

Conclusions

Most sediment management decisions continue to be made based on chemical criteria, reduction of risk and/or available resources through settlements and negotiations. A fundamental shift needs to occur, from sediment management decisions based on chemical criteria, reduction of risk, and/or available resources through settlements and negotiations, to sediment management decisions being made based on restoration of uses. Quantitative use restoration targets must be established first to set clear direction and to be able to predict and measure the degree of use restoration achieved as a result of sediment management actions.

A step-wise approach that addresses the most severely stressed zones, followed by additional actions for areas of lower environmental concern, is also strongly advised. Sediment management initiatives should be driven initially by science, with socio-economic constraints tempering the final actions.

In all cases, source control is the fundamental action at contaminated locations. Monitoring the recovery of sediment quality and beneficial uses is an integral component of the sediment management strategy. The ability to verify the response of the ecosystem to management actions through post-project monitoring will afford us the intelligence to select management actions in the future that are knowledge-based, cost-effective and result in measurable, positive ecological improvements.

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