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Determining degradation and restoration of benthic conditions for Great Lakes Areas of Concern

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ABSTRACT

"Degradation of benthos" is one of the most common beneficial use impairments identified in Great Lakes Areas of Concern (AOCs). Management of AOCs towards recovery from impairment can benefit from a consolidation of quantitative methods for describing benthic conditions, determining impairment and its probable cause, and detecting recovery that are linked to targets for restoring beneficial use. Benthic conditions are effectively characterized by multiple descriptors, such as physicochemical conditions of sediment, toxicity of sediment, benthic macroinvertebrate community structure, bioaccumulation of contaminants in benthic invertebrates, and substrate stability. Degradation is quantifiable in terms of the degree to which conditions in AOCs differ from reference conditions and exceed environmental quality criteria or other empirically derived benchmarks that are associated with adverse effects. Inferring causality of adverse effects by association with putative stressors is important for the development of management actions to promote restoration. Recovery of benthic conditions after elimination of exposure to the stressor (s) of concern can be identified as the reversal of degradation or, due to effects of interacting environmental factors, a restabilization at a state different from predisturbance conditions. It is recommended that delisting criteria, which define targets for restoration of the beneficial use, be based on the benthic descriptors and conditions used to identify degradation and recovery, with the recognition that the remedial action plan process allows the criteria to be modified to accommodate impacts from other nonmanaged stressors and additional nonecological considerations.

Introduction

In the 1970s, over 40 locations in the Great Lakes where the aquatic environment was severely degraded were identified as "problem areas" by the International Joint Commission (IJC). In all of these locations (Fig. 1), later termed Areas of Concern (AOCs), sediments were considered to be contaminated based on the application of chemical guidelines (SedPAC 1999). Among the 14 beneficial use impairments (BUIs) in AOCs identified in the Great Lakes Water Quality Agreement, the restoration of 11 beneficial uses was determined to be potentially impeded by contaminated sediments (SedPAC 1997).

"Degradation of benthos" is one of the most widespread of the impairments: 84% of the AOCs in Canada and the United States have exhibited the BUI (Table 1). Understood as a deleterious alteration in the structure or function of the benthic invertebrate community, this BUI is also one of the most direct and causally linked ecological effects of contaminated sediment. Benthic communities can also be impacted by industrial and municipal discharges of organic material and nutrients (Carter et al. 2006). The assessment of benthic invertebrates and related benthic conditions is well established as a meaningful and practical indicator of not only sediment quality, but also the potential health of the wider aquatic food web, including fish populations (Burton and Scott 1992; Rosenberg and Resh 1993; USEPA 2002a). It is, therefore, important that the degradation of benthos BUI be appropriately addressed by AOC managers.

After recommendations from the IJC's Great Lakes Water Quality Board in 1985, Remedial Action Plans (RAPs) were developed and implemented for each of the AOCs (Hartig and Zarull 1992). The RAP approach and process is described in the Protocol to the Great Lakes Water Quality Agreement (Canada and the United States 1987). The goal is to restore the "beneficial uses" of the aquatic ecosystem, through a "systematic and comprehensive ecosystem approach" that includes assessment and analyses of ecological conditions, development and implementation of restorative measures, and follow-up assessment and analyses of ecological conditions.

Addressing the degradation of benthos BUI as part of a RAP involves (1) measurements of relevant and practical attributes for describing "benthos", (2) quantifying "degradation", (3) determining likely causes of degradation, and (4) identifying recovery of benthic conditions following implementation of management action, after which the beneficial use can be considered restored and "delisted". A consolidation of effective and broadly applicable procedures for addressing these objectives could assist assessors, managers and

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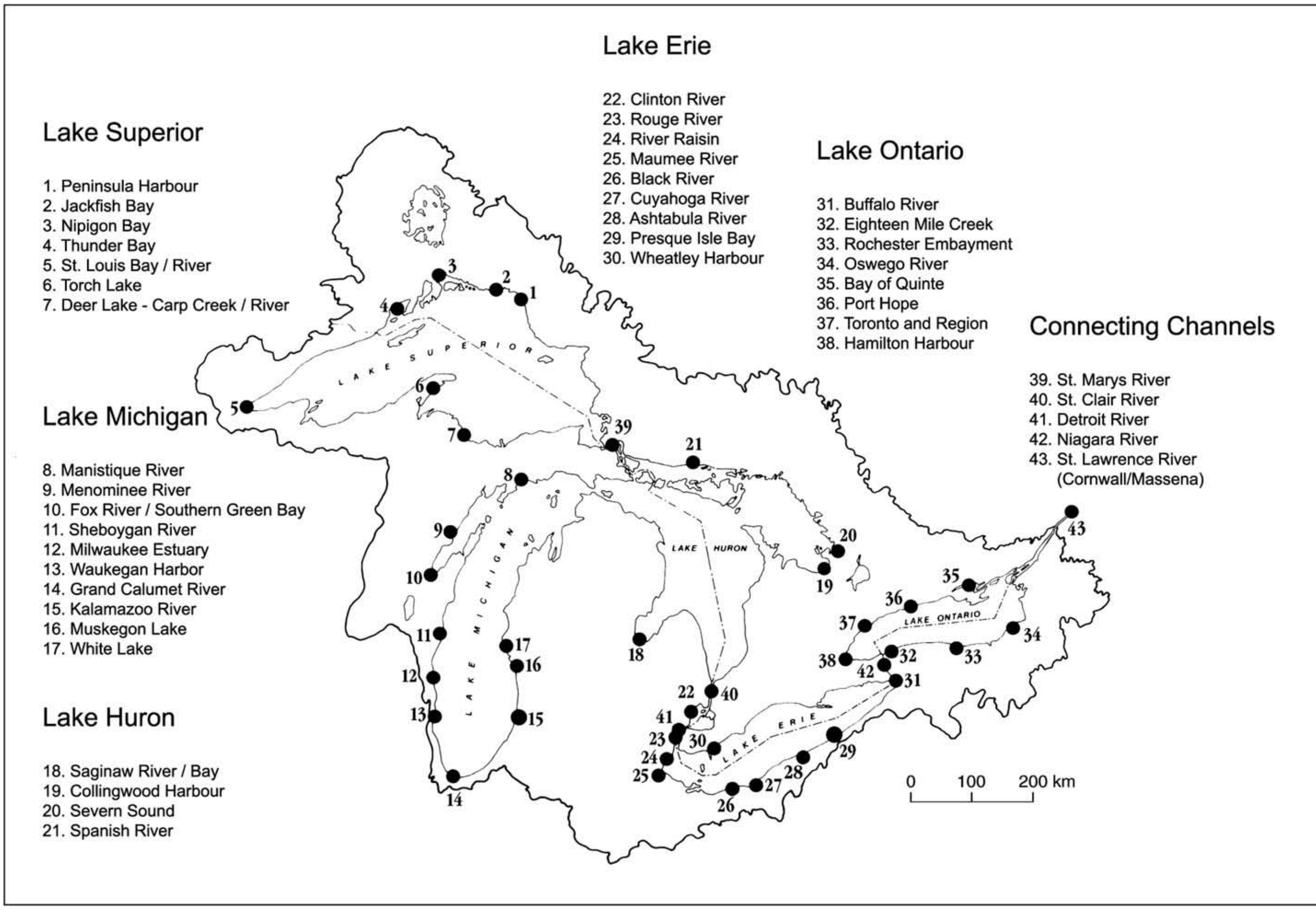

Fig. 1. Locations of 43 Areas of Concern in the Laurentian Great Lakes drainage basin (after Zarull et al. 1999).

other stakeholders involved in determining BUI delisting targets, developing monitoring programs to assess progress towards delisting, and evaluating actions aimed at restoring benthic conditions in AOCs. The purpose of this paper is to (a) describe and offer effective approaches and methods for achieving these objectives (including the selection of reference conditions and benchmarks for quantifying degradation, and determining its potential cause), and (b) discuss the development of delisting criteria for the degradation of benthos BUI.

Measurement of benthic conditions

"Degradation of benthos" initially related to the benthic invertebrate communities and toxicity of sediments in AOCs (IJC 1991). Assessments for this BUI, however, usually examine the broader benthic environment, including attributes for characterizing exposure to stressors and important habitat factors. In most AOCs, depositional areas are the dominant benthic habitat, as well as being the locations where contaminated sediments and organic matter accumulate.

Assessment methodologies applicable to freshwater sediments are well developed. These include the Sediment Quality Triad (e.g., Chapman et al. 1992, Crane et al. 2005), the Assessment and Remediation of Contaminated Sediments (ARCS) program (USEPA 1994), the Benthic Assessment of Sediment (BEAST) approach (Reynoldson et al. 1995), multimetric indices (Barbour et al. 1996), and the USEPA's Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater Ecosystems (USEPA 2002a, b,c). Common to these methodologies is the collection of information on multiple components of the benthic environment. Comprehensive assessments involve multiple lines of evidence because that allows characterization of exposure to stressors, estimation of putative biological responses, accounting for effects of interacting factors (natural and anthropogenic), and indication of potential or probable causal relationships between stressors and benthos.

Some consensus has been reached on the key components of a comprehensive sediment assessment (Krantzberg et al. 2000, Chapman and Anderson 2005). These include information about sediment physicochemistry and grain size, benthic invertebrate community structure, sediment toxicity, contaminant bioaccumulation, and substrate stability.

Concomitantly collected data for these components from an array of locations throughout the study area provide both unique and confirmatory information on various attributes of benthic conditions. Data on physicochemistry and grain size of sediments quantify the degree to which sites are contaminated or enriched with organic matter and nutrients, indicate potential or probable exposure pathways of contaminants to organisms, and provide supplemental information useful for interpretation of observed biological conditions. Benthic invertebrate community structure data can show whether natural faunal assemblages in an AOC differ from those in undisturbed reference locations. As residents of the AOC, these organisms experience the most ecologically relevant exposures to AOC stressors and other site-specific conditions. Sediment toxicity information, especially from tests involving several types of benthic organisms, link biological responses to sediments in ways benthic community data alone cannot. Measurements of contaminant concentrations in tissues of resident benthic fauna or toxicity test organisms provide evidence of bioavailability and causality of observed toxic effects (Borgmann et al. 2001, Rainbow 2002). In addition, for substances liable to biomag-

Table 1
Beneficial use impairments identified for 43 Areas of Concern in the Great Lakes

Area of Concern	Beneficial use Impairment[a]													
	Restrictions on fish and wildlife consumption	Tainting of fish and wildlife flavour	Degradation of fish and wildlife populations	Fish tumours or other deformities	Bird or animal deformities or reproduction problems	Degradation of benthos	Restrictions on dredging activities	Eutrophication or undesirable algae	Restrictions on drinking water consumption or taste and odour	Beach closings	Degradation of aesthetics	Added costs to agriculture or industry	Degradation of phytoplankton or zooplankton populations	Loss of fish and wildlife habitat
Peninsula Harbour	X		X			X	X			X	X		X	X
Jackfish Bay			X	X		X								X
Nipigon Bay			X			X		X			X			X
Thunder Bay	X		X	X		X	X			X	X		X	X
St. Louis River/Bay	X		X	X		X	X	X		X	X			X
Torch Lake	X					X								
Deer Lake	X				X			X						
Manistique River	X						X			X				X
Menominee River	X		X			X	X			X				X
Fox River/Lower Green Bay	X		X		X	X	X	X	X	X	X		X	
Sheboygan River	X		X	X	X	X	X	X					X	X
Milwaukee Estuary	X		X	X	X	X	X	X		X	X		X	X
Waukegan Harbor	X					X	X			X			X	X
Grand Calumet River	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Kalamazoo River	X		X		X	X	X			X	X			X
Muskegon Lake	X		X			X	X	X	X	X	X			X
White Lake	X		X			X	X	X	X		X			X
Saginaw River/Bay	X	X	X		X	X	X	X	X	X	X		X	X
Collingwood Harbour	X						X	X			X			
Severn Sound	X		X			X	X	X		X	X		X	X
Spanish Harbour	X					X	X							
Clinton River	X		X			X	X	X		X	X			X
Rouge River	X		X	X		X	X	X		X	X			X
River Raisin	X		X		X	X	X	X		X	X			X
Maumee River	X		X	X		X	X	X	X	X	X			X
Black River	X		X	X		X	X	X	X	X	X			X
Cuyahoga River	X		X	X		X	X			X	X			X
Ashtabula River	X		X	X		X	X							X
Presque Isle Bay				X										
Wheatley Harbour	X		X				X	X						X
Buffalo River	X			X		X	X				X			X
Eighteen Mile Creek	X					X	X							
Rochester Embayment	X		X		X	X	X	X	X	X	X	X	X	X
Oswego River	X		X											X
Bay of Quinte	X		X			X	X	X	X	X	X		X	X
Port Hope							X							
Toronto and Region	X		X			X	X	X		X	X			X
Hamilton Harbour	X		X	X		X	X	X		X	X			X
St. Marys River	X		X	X	X[b]	X	X	X		X	X			X
St. Clair River	X	X[b]			X[b]	X	X		X[b]	X	X	X[b]		X
Detroit River	X	X	X[b]	X	X[b]	X	X		X	X	X			X
Niagara River	X		X[c]	X[b]	X[c]	X	X[b]	X[c]		X[c]				X
St. Lawrence River (Cornwall/Massena)	X		X[c]			X[c]	X[c]	X[c]		X[c]				X

[a] Sources: SSRAPT (1993), Krantzberg and Houghton (1996), Environment Canada (2005, 2008), USEPA (2008). Beneficial use impairments for Collingwood Harbour and Severn Sound apply to period before restoration.
[b] Area of Concern in both the U.S. and Canada. Beneficial use considered impaired by USEPA.
[c] Area of Concern in both the U.S. and Canada. Beneficial use considered impaired by Environment Canada. U.S. and Canadian assessment areas may be partially or completely nonoverlapping.

nification, tissue residues can be used to assess the risk of adverse affects to higher trophic level organisms (i.e., consumers of benthic invertebrates and their predators). Assessments of the physical stability of sediments, and their likelihood of disturbance by natural processes (e.g., storm events, ice scouring, changes in flow regime) or human activity, address the risks of mobilization of buried contaminants over time and redistribution of surficial contaminants across distances.

In some assessments, information on additional components of the benthic environment, such as the physicochemistry and toxicity of overlying water, surficial sediment porewater, and subsurface sediment (USEPA 2002c); the condition of particular invertebrate populations or taxonomic groups (e.g., incidence of chironomid deformities (Diggins and Stewart 1993)); and demersal fish health (McMaster et al. 1991) have been valuable for further characterizing sediment quality and biological impacts.

Arriving at a conclusion about the overall benthic condition requires analyses, integration, and interpretation of information from both within each of the assessment components and among all components. Within assessment components, this usually involves the reduction of multivariate data to binary states (e.g., pass/fail) or ordinal ranks (e.g., not/possibly/probably/very probably degraded) for each site. Several methods for achieving data reduction are possible (Reynoldson et al. 1995; Canfield et al. 1996; Barbour et al. 1999; Grapentine et al. 2002; Bowman and Somers 2006). These tend to involve either multivariate procedures, or the weighting, ranking and adding of multiple indices and other metrics. Reynoldson et al. (1997) provide a comparison of these two groups of methods. Statistical ordination, in which data for multiple observed variables are transformed into 2 or 3 composite descriptors, is advantageous as an objective and efficient means of accommodating information redundancy and interactions among variables. The composite descriptors of sediment quality, which can be adjusted for effects of nonstressor factors, are then used for comparison of the AOC (test) conditions with reference conditions. Multivariate procedures are typically more sensitive than indices and other metrics for detecting differences between test and reference sites, especially when the impacting stressor is not known (Kilgour et al. 2004). However, indices and other metrics are of use in understanding impacts in terms of individual or subgroups of variables.

For combining information among assessment components, a rule-based, weight-of-evidence approach (Krantzberg et al. 2000; Grapentine et al. 2002; USEPA 2002c; Chapman and Anderson 2005), developed from the Sediment Quality Triad, provides interpretations for various combinations of within-component outcomes in a contingency table format. In reaching final conclusions about sediment conditions, many currently applied frameworks are effects-based in their interpretations. Elevated concentrations of contaminants or nutrients in sediments alone are not indications of ecological degradation. Rather, it is the biological responses to these that are the concern. These include adverse effects on (a) biota resident in the sediment, and (b) other organisms (e.g., fishes, wildlife, humans) affected by physical, chemical or biological relocation of contaminants from the sediment. Determination of the latter effects requires examination of additional assessment components, such as was conducted by MacDonald et al. (2002) for an assessment of injury to fish and wildlife resources in the Grand Calumet River and Indiana Harbour AOC, and by Henning et al. (2007) for an ecological risk assessment for fish and wildlife in the Peninsula Harbour (Lake Superior) AOC.

To evaluate benthic conditions for the whole AOC conclusions must be integrated across sampling sites. Procedures for this step could include:

- mapping the spatial extent of degradation,
- consideration of the degree of degradation at each site,
- conducting ecological risk assessment, and
- evaluation by expert and stakeholder groups (USEPA 2002c; Chapman and Anderson 2005).

Reaching conclusions about the spatial extent of degradation in the AOC is necessary for making decisions about management action, delisting the BUI, and comparing to conditions in other AOCs.

Quantification of degradation

The IJC defined degradation of benthos as either a divergence from unimpacted control sites in the benthic macroinvertebrate community structure, or an exceedence of control tests in the toxicity of sediment-associated contaminants (IJC 1991). In terms of the broader characterization of benthic conditions, degradation can be considered as a significant difference between an AOC site and the *reference condition* for the individual assessment component. Degradation is thus defined by what constitutes both “reference condition” and “significant difference”.

Reference conditions

Reference conditions are the conditions representative of the natural, background, or hypothetically expected state of a descriptor of benthic conditions in the absence of the stressor(s) of concern. Reference sites are matched to the AOC sites to be as similar as possible in all respects except exposure to the stressor(s) of concern. The term “reference” is more accurate than “control” because in observational field studies commonly conducted for AOC assessments, sites are subject to effects of various uncontrolled factors in addition to the stressor(s) of concern, and are not controls in the traditional experimental sense. In environmental assessments, the sampling of *multiple* reference sites is required to quantify not only average or median conditions, but also the variability of conditions at the appropriate spatial scale (Reynoldson et al. 1997). Variability among reference sites is the yardstick by which differences in benthic conditions of test sites are gauged.

Several types of reference conditions are of use in field assessments: (1) natural sites that are completely undisturbed by anthropogenic stressors; (2) minimally disturbed sites not exposed to the stressor(s) of concern that represent local background conditions; and (3) hypothetical undegraded conditions, defined by environmental quality guidelines or ecotoxicological modelling. Unlike the first two types, the third type of reference condition is not based on direct observations from reference sites. In optimal situations, the first type provides the best characterization of reference conditions. Ideally, temporal references (predisturbance data from the AOC) would be included with spatial references. Commonly, though, predisturbance data are lacking, and assessments must be based solely on spatial references that are assumed to represent predisturbance conditions. In many regions, particularly in the lower Great Lakes, few reference sites appropriately matched by habitat attributes exist that are not affected by human impacts, especially cultural eutrophication and nonpoint source contamination for lake areas, and “urban stream syndrome” (Walsh et al. 2005) for lotic systems. Urban stream syndrome includes a flashier hydrology, elevated nutrient and contaminant concentrations, altered channel morphology, and discharges of stormwater and wastewater. With this minimally disturbed/background reference condition, effects of human activities excluding the stressor(s) of concern add to the noise or “nuisance” variability among sites against which degradation must be detected. The third type of reference condition is the least optimal situation, and is used when the amount of background nuisance variability among potential reference sites is expected to be too great to allow detection of the desired degree of degradation. Or, the AOC may be in a habitat unique for the region, such as geomorphically altered harbours and other waterways, for which there are no

Table 2
Expected performances of different types of reference conditions used for assessing degradation of benthos

Reference condition	Advantages	Disadvantages
Undisturbed, natural areas	• Most ecologically relevant • High power	• Highest cost • Potential unavailability of sites
Minimally disturbed, local background	• Best accommodation of area-specific conditions • Moderate-high power	• Limits on site selection • Moderate ecological relevance
Hypothetical undegraded condition	• Lowest cost • Widest application	• Lowest ecological relevance • Possibly low power

See text for discussion.

suitable reference sites. In these cases, the reference conditions are set *a priori*, or predicted from derived relationships between the benthic condition descriptor and the stressor(s) (e.g., Chessman and Royal 2004; Ciborowski et al. 2005). The type of reference condition selected for an assessment represents a trade-off between statistical power and ecological relevance on the one hand, and what is experimentally valid and possible under area-specific conditions on the other (Table 2). Power (i.e., the likelihood of detecting existing degradation) is expected to decrease as the level of disturbance of the reference condition increases, and the difference from test (AOC) condition decreases. Lesser power also results with fewer sample replicates and higher variability in the assessment endpoint. For the hypothetical undegraded condition, the sample replication does not apply, and endpoint variability is either undefined or predicted based on a model. Power could therefore appear high or low.

Difference from reference conditions

Degradation is determined by the degree to which individual test sites differ from the reference conditions. These differences should be ecologically, as well as statistically, significant to be environmentally meaningful (Mapstone 1996). Whereas various standard procedures exist for establishing statistical significance, procedures for establishing ecological significance are less widely accepted, especially for community-level descriptors. Ecological significance is determined by the magnitude (i.e., the effect size) and the direction (adverse effect or not) of the difference from reference conditions.

While various definitions exist for ecologically important effect sizes, an objective and increasingly accepted one is a difference that exceeds the normal range of variation among reference sites (Reynoldson et al. 1997; Kilgour et al. 1998; Barbour et al. 1999). This range is typically defined as that enclosing 95% or 99% of the population of reference values, and can be in terms of standard deviations, percentiles, or generalized distances depending on the nature of the data (normally/non-normally distributed; univariate/multivariate). A site outside of the normal range of reference conditions is unusual and considered likely to be altered.

Sensitivity of the analysis for difference between a test site and the reference condition can be enhanced by adjusting descriptors of benthic conditions for effects of habitat or other environmental covariables (Reynoldson et al. 1997; Bailey et al. 1998). This involves partitioning out variability due to natural/nuisance factors (e.g., organic carbon content and grain size distribution for sediment contaminant concentrations and sediment toxicity; habitat attributes for benthic community structure; organism size/age and lipid content for tissue contaminant bioaccumulation). The range of reference conditions is thereby constrained to provide a more appropriate comparison with test site conditions.

Degradation implies adverse conditions. For many descriptors of benthic conditions, the direction of difference from reference conditions associated with adverse effects is clear. For example, high contaminant concentrations in sediment and tissues, high toxicity, and low overall invertebrate abundance and diversity are typically adverse. An exception is benthic community composition. The ecological importance of the replacement of one set of taxa by another is not always known. For this descriptor, alterations can be evaluated based on the densities of individual taxa and their ecological traits (e.g., Charvet et al. 2000). Degradation can be concluded based on the loss of taxa that perform key ecological functions and have important relationships to other members of the food web (Clements and Newman 2002).

Benchmarks of adverse effects

The range of reference conditions is one of several methods of defining a benchmark or environmental criterion that distinguishes between degraded and undegraded conditions. While the strength of this method is its use of information on *in situ* conditions from a large number of appropriately matched sites in the region of the assessment, it is arguable that "different from reference" does not imply impairment or degradation. This issue can be important in management of AOCs when the need to consider remedial action arises.

The case for concluding degradation is improved by additionally comparing test site conditions to environmental quality criteria/guidelines or other empirically derived benchmarks that are associated with adverse effects. The comparison of test site conditions to benchmarks of adverse effects in addition to reference conditions is included in some assessment frameworks (e.g., USEPA 2002c; Chapman and Anderson 2005). Table 3 proposes benchmarks applicable for each benthic assessment component from above, excluding site stability. Comparison to the normal range of reference conditions is conducted for all components. For efficiency, multiple variables within assessments components can be transformed to multivariate descriptors (e.g., by ordination) before comparison.

Contaminant concentrations in sediment and invertebrate tissue can be compared to sediment quality and tissue residue guidelines,

Table 3
Proposed criteria for indicating degradation in assessments of benthic conditions

Assessment component	Degradation benchmark	
	Reference condition	Benchmark associated with adverse effect
Contaminants/nutrients in sediment	Test site concentration >upper 95 or 99% prediction bound for reference site concentrations	Test site concentration >sediment quality guideline
Sediment toxicity	Acute or chronic endpoints for test sites more toxic than upper 95 or 99% prediction bound for reference site toxicity	Test site toxicity >20% different from mean/median reference site toxicity[a]
Benthic macro-invertebrate community	Test site descriptors beyond 95 or 99% prediction bounds for reference site descriptors	Test site exceeds or fails to meet *a priori* selected biocriterion
Contaminants in invertebrate tissue	Test site concentration >upper 95 or 99% prediction bound for reference site concentrations	Test site concentration >tissue residue guideline

[a] Chapman and Anderson (2005).

respectively, if available. Sediment quality guidelines (SQGs) exist for a wide range of contaminants and nutrients (MacDonald et al. 2000), and have been applied as targets for the protection of benthic communities in some AOCs (e.g., Crane and MacDonald 2003). Although the use of SQGs in sediment assessments has been much debated (Wenning et al. 2005), it is generally accepted that nonexceedence of a SQG is a good predictor of a lack of toxicity due to the chemical concerned. It is also recognized that exceedence of a SQG only indicates a potential for adverse biological effects, with the likelihood dependent on how the SQG was derived, the magnitude of the exceedence, and various site-specific environmental conditions. Tissue residue guidelines are not widely available for many benthic invertebrate taxa, but benchmarks can be obtained from studies associating tissue residues with adverse effects (e.g., Jarvinen and Ankley 1999; Meador 2006), or by back-calculating invertebrate tissue concentrations predicted to be protective of trophically-linked fishes and wildlife receptors using risk-based ecological modelling (USEPA 2002c).

For sediment toxicity, it has been argued that small differences between test and reference sites are not ecologically relevant, even if the test site falls outside the normal range of reference conditions. Chapman and Anderson (2005) recommend a >20% difference in toxicity between test and reference sediments as a benchmark of degradation in a framework for contaminated sediment decision-making in the Great Lakes.

Assessments of benthic communities have applied a wide variety of biocriteria to determine impacts. Beyond the normal range of reference site conditions, there is little agreement on a generally applicable benchmark (USEPA 2002c). However, for specific stressors various statistics, indices or other metrics could be relevant indicators of ecologically significant degradation (reviewed in Barbour et al. 1999). Previously selected and theoretically justified criteria (e.g., the absence of taxa sensitive to the stressor of concern) could serve as adverse effects benchmarks for the benthic community assessment. Taxon-specific tolerance information that has long existed for nutrient/organic matter enrichment and sedimentation stressors has more recently become available and applied in benthic assessments for contaminants such as metals (Clements et al. 2000; Pollard and Yuan 2006).

Determination of causality

Determining the likely causes of degradation of benthos is the step in the RAP process that informs development of management actions to restore the BUI (Hartig and Zarull 1992). Identification of the stressor(s) of potential concern is one of the early steps in assessments of benthic conditions. In fact, the AOCs were established largely on the basis of known stressors. Linking the stressor(s) to observed degradation is important for confirming causality, and for quantifying the strength of the relationship. How much degradation is accountable by exposure to the stressor(s) bears directly not only on the consideration of remediation, but also on development of delisting criteria. If the degradation is determined to be due (at least in part) to natural causes or factors external to the AOC, expectations of recovery could differ from the situation in which the stressor(s) accounting for degradation is managed (see below).

Suter et al. (2002) describe a framework for inferring the causes of observed impairments in aquatic ecosystems, involving three potential methods: eliminating alternatives, using diagnostic protocols, and comparing the strength of evidence supporting each candidate cause. A fundamental form of evidence, especially in the context of the type of benthic assessment described here, is an association between measurements of exposure to the candidate stressor and observed effects. The type of association can be spatial co-occurrence, spatial gradient, temporal relationship (effects observed after initial stressor exposure), and temporal gradient (Suter at al. 2002). Examples of the application of such association analyses in AOCs include an assessment of the St. Louis River AOC by Crane et al. (2005) that examined spatial patterns to identify physical habitat attributes, rather than contaminated sediments, as the likely cause of benthic community alteration in most of the sampled sites; and an evaluation of studies of the Muskegon Lake AOC by Carter et al. (2006) that examined spatial and temporal patterns to find nutrient/organic inputs accounted for more benthic community variation than toxic contaminants or zebra mussel densities.

Among diagnostic methods (i.e., examining the symptoms of exposed organisms), one of the most important applicable for sediment assessment is the examination of contaminant bioaccumulation patterns. Measurements of contaminants in tissues of resident benthic fauna provide evidence of bioavailability, and that the contaminants may be responsible for observed effects on the organisms (Borgmann et al. 2001). Causes of sediment toxicity can be identified from sediment and porewater toxicity evaluation procedures (Ankley and Schubauer-Berigan 1995). Examination of alterations in benthic community composition based on the ecological traits and tolerances to stressors of individual taxa (e.g., Poff 1997; Liess and Von der Ohe 2005; Weiss and Reice 2005; Poff et al. 2006) is another potential diagnostic tool. Benthic invertebrate assemblages have been viewed as the responses of colonizing species from a regional pool of taxa to various habitat selective forces, which act as "environmental filters" at multiple spatial and temporal scales (Poff 1997). Taxa present at a site are those possessing suitable functional attributes (species traits) to persist under the local physicochemical and biotic conditions. If information is available on the typical responses of resident invertebrates to a stressor of concern, it may be possible to account for differences in benthic community composition between reference and test sites as due to effects of that specific stressor.

Identification of recovery

Reversal of degradation

Delisting criteria are targets for environmental conditions that define the restoration of a beneficial use. When a beneficial use has been restored, that particular impairment is dropped from the list of environmental problems for the AOC (United States Policy Committee 2001). Restoration, in its simplest interpretation, is recovery from degradation. If the stressors responsible for degradation are eliminated, and the biological communities are fully resilient, recovery can be considered the reverse of degradation. In such cases, the criteria of Table 3 can be reversed and applied as indicators of recovery for the degradation of benthos BUI.

"Reversal of degradation" has been adopted by the IJC as the generic or default delisting criterion for degradation of benthos; i.e., restoration exists "when the benthic macroinvertebrate community structure does not significantly diverge from unimpacted control sites" and "in the absence of community structure data, … when toxicity of sediment associated contaminants is not significantly higher than controls" (United States Policy Committee 2001). However, these criteria do not address the other two benthic assessment components: contaminant concentrations in sediment and contaminant bioaccumulation. Because elevated levels of contaminants or nutrients in sediments, in and of themselves, are not biological effects, delisting criteria directed specifically to sediment contaminant levels are only as effective as the strength of their relationships to adverse biological effects. To avoid the pitfall of being over- or underprotective, it is recommended that targets for recovery from adverse effects of sediment contaminants or nutrients include sediment toxicity and benthic community endpoints, or information from assessments of other BUIs that are demonstrated to be linked to sediment conditions, such as (a) fish tumours or other deformities, (b) bird or animal deformities or reproductive problems, (c) degradation of fish and wildlife populations, or (d) restrictions on fish and wildlife consumption. Elevated contaminant concentrations in invertebrate tissues are also relevant. Although not necessarily adverse effects in and of themselves, contaminants in tissues indicates a more serious risk to the aquatic food web than contaminants in sediments, especially for substances liable to biomagnify (USEPA 2002c; Meador 2006).

Alternate recovery states

In some cases, recovery may not be the reversal of degradation. After cessation of exposure to the stressors(s) of concern, the benthic environment, particularly the macroinvertebrate community component, could restabilize at a state different from the predisturbance conditions (Paine et al. 1998). This can occur for several reasons: temporal changes in the natural habitat selective forces that shape biotic assemblages; compounded effects of multiple stressors; taxonomic turnover in the regional pool of species from which colonizers of the local sites come (Poff 1997); and adaptation of the resident community, such as the replacement of taxa sensitive to the stressor(s) of concern by taxa that are tolerant (e.g., pollution-induced community tolerance; Blanck and Wangberg 1988; Clements 1999). Consideration of these factors is relevant for benthic communities in the Great Lakes that have been subject to alteration by (a) numerous invasive species, which have caused well documented ecological effects (IAGLR 2002), or (b) multiple stressors, which are particularly extant in certain AOCs.

The effect that these factors have on detecting restoration and determining delisting criteria will depend on the type of reference conditions used in the assessment, and the spatial and temporal scales of the effects of the factors. If available, predisturbance or other temporally replicated data from AOC and reference sites allow examination of time trends in benthic conditions that could distinguish effects of the stressor(s) of concern from effects of other factors. The data could also possibly indicate restabilization of a community. Clements and Newman (2002) note that disturbed communities generally show greater temporal variability than undisturbed ones, and suggest the use of reduced temporal variability as an indicator of recovery.

Comparison of AOC conditions to the normal range of spatial reference conditions will be effective for identifying recovery from degradation if the impacts of altered habitat selective forces, multiple stressors, or taxonomic turnover extend to the reference as well as the AOC sites. If the reference and AOC site conditions are changing along the same trajectories through time, restoration could be detected as return to reference conditions even though the AOC sites do not recover to predisturbance conditions. This could be the case for factors impacting on a lake-wide or regional scale. Knowledge of the potential for this type of impact before conducting the benthic assessment would be important for selecting appropriate reference sites.

Permanent effects of disturbance

It has been suggested that disturbed communities are unlikely to ever return to their predisturbance states, because the effects of most environmental events persist for long periods. The community conditioning hypothesis (Landis et al. 1996; Matthews et al. 1996) states that communities tend to “retain information about events in their history”, and as dynamic, nonequilibrium systems, individual communities are products of their unique history of responses to disturbances. The development of community tolerance to contaminants is an example of community conditioning. The hypothesis was developed to explain results of laboratory multispecies toxicity tests and, as Clements and Newman (2002) point out, requires further testing in other ecological systems, including natural (*in situ*) ones. But if the hypothesis is generally applicable, it is argued that concepts of community “health”, “stability”, and “recovery” would not be meaningful, and that assessments of anthropogenic impacts should abandon the idea of a “baseline of normality” against which recovery can be measured (Matthews et al. 1996). This seems somewhat extreme, because references conditions can be defined in terms that recognize that no two communities are the same (thus, a *range* of reference conditions), and that communities are dynamic and not necessarily drawn towards equilibria (thus, trajectories through time).

Development of delisting criteria

Progress towards beneficial use restoration for benthic conditions cannot be tracked without consistent, unambiguous definitions of delisting criteria (Zarull et al. 1999). A compilation of delisting targets from 2004 for U.S. and U.S.-Canada shared AOCs (Great Lakes Commission 2004) suggests that definitions are variable and still in development for many of the AOCs. Among Canadian AOCs, the situation appears similar (George and Boyd 2007). Recently, general restoration or delisting criteria have been defined for Ohio's 4 AOCs (Ohio EPA 2005) and Michigan's 14 AOCs (Michigan Department of Environmental Quality 2006). Development of workable delisting criteria for the remaining AOCs should be straight forward because, in contrast to most other BUIs, degradation of benthos is highly amenable to quantitative characterization and monitoring (George and Boyd 2007). Workable delisting criteria are essential for monitoring programs required to support management plans (United States Policy Committee 2001).

Restoration as recovery

The default for achieving restoration, thereby allowing delisting of the degradation of benthos BUI, can be the recovery of benthic conditions to the predisturbance state (i.e., the reversal of degradation) or to an alternative equivalent-to-reference state, as described above. Although this is the most straight-forward situation for developing measurable indicators of restoration, specific definitions and targets (e.g., definition of reference conditions, degree to which AOC sites are to be similar to reference conditions) require determination by a technical experts under the management process.

Delisting without recovery

The IJC and various federal, state, and provincial agencies responsible for the implementation of RAPs recognize that beneficial uses may not become fully restored even if all remedial actions are untaken (United States Policy Committee 2001). Under a set of guidelines and principles adopted for the development of general delisting criteria, exceptional circumstances were identified that would allow removal of a BUI designation in the absence of complete recovery. These include situations where the:

- BUI is due to natural rather than human causes;
- BUI is not limited to the AOC, but rather is typical of lakewide, region-wide, or area-wide conditions; and
- Impairment is caused by sources (stressors) outside the AOC.

Decisions on delisting BUIs without meeting the initial restoration targets are expected to be justified by clear rationale and supporting scientific evidence. In order to delist where impairment is caused by sources outside the AOC, responsibility for management may be transferred from the RAP to another party or program (e.g., Lakewide Management Plan; Great Lakes Binational Toxics Strategy; other national, binational, and international initiatives).

Some of these exceptional circumstances could be relevant for delisting degradation of benthos in certain AOCs. For example, climate change is expected to affect physical and biological conditions in the Great Lakes, such as mixed layer dynamics, bottom temperatures, and algal biomass (Lehman 2002), which may in turn impact benthic communities. Zebra and quagga mussel invasions, which extend to whole areas of the lower Great Lakes, appear to have altered benthic communities on soft, as well as hard, substrates (e.g., Lozano et al. 2001). Benthic impairment in the Muskegon Lake AOC was attributed in part to the deposition of externally sourced organic matter from the Muskegon River (Carter et al. 2006). In situations such as these, the criteria for recovery may have to incorporate effects of a non-local stressor that is not targeted for management by the RAP (United States Policy Committee 2001, p. 4).

Nonecological considerations

While a requirements of an ecosystem approach to restoring AOCs is that delisting criteria be relevant to maintaining ecological health or integrity (Canada and the United States 1987), it is also recognized that AOC management may also consider economic and societal issues (IJC 1991). Hartig and Zarull (1992) point out that RAPs are ultimately the result of a collaborative effort involving regulators, industry, public advisory groups, and others, besides scientists. Issues beyond ecological relevance can influence the development of delisting criteria for individual AOCs. These include:

- Limits to management actions (e.g., where certain stressors, such as disturbance from shipping and navigational dredging, are unlikely to be eliminated);
- Local usage goals and environmental objectives determined by public and other stakeholder interests; and
- Applicable federal, provincial, or state regulations and policies (United States Policy Committee 2001).

Although the guidelines and principles for the development and evaluation of delisting criteria recommended by the United States Policy Committee (2001) allow for “flexibility”, “common sense”, and “realistic” expectations of restoration in adapting delisting criteria to site-specific conditions, the challenge is to balance these with a consistently applied framework that accurately identifies recovery of benthic conditions.

Summary and conclusions

In the late 1990s, one of the obstacles to the management of contaminated sediment was identified as a lack of a scientific framework for evaluating the ecological significance of contaminants in sediment (Zarull et al. 1999). Recent research and assessment experience can now offer the following guidance for addressing key issues related to determining degradation and restoration of benthic conditions and the development of delisting criteria for the degradation of benthos BUI in AOCs of the Great Lakes:

- Measure benthic conditions by assessing multiple ecological components, including sediment physicochemistry and grain size, benthic invertebrate community structure, sediment toxicity, contaminant bioaccumulation, and substrate stability.
- Quantify degradation by comparing effects-based (i.e., biological) conditions in AOCs to (a) the most ecologically relevant reference conditions available, and (b) benchmarks associated with adverse effects.
- Determine the probable cause(s) of degradation to confirm relationships between biological impacts and putative anthropogenic stressors, and to inform potential management evaluation.
- Identify recovery of benthic conditions after exposure to the causal stressor(s) as either a reversal of degradation to reference conditions, or stabilization at an alternative state defined by effects of inherent ecological processes.
- Develop delisting criteria that define restoration of the beneficial use based on the measurable benthic descriptors and conditions used to quantify degradation and recovery, with the recognition that the RAP process allows the definition of restoration to be modified to accommodate impacts from other nonmanaged stressors or economic and sociological factors.

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