Biological Criteria for Municipal Wastewater Effluent Monitoring Programs

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As part of the long-term strategy for addressing issues related to municipal wastewater effluents (MWWE), Environment Canada is developing environmental quality objectives (EQOs) for the aquatic receiving environment. Recommended biological monitoring components of the aquatic ecosystem include fish communities, benthic macroinvertebrate communities, sentinel fish species and primary producers (macrophytes, attached algae, phytoplankton). A set of criteria was developed for measurable attributes (indicators) of each of those components. Recommended numeric and narrative criteria could be used to determine when MWWE should be managed. Warning-level criteria for indices of benthic community composition are considered effects on indices of composition that deviate from the mean reference response by more than ±2 standard deviations. For sentinel fish population parameters, warning-level effects are considered >25% differences from reference in gonad or liver size, growth, or age, or a >10% change in condition factor. For primary producers, warning-level effects are considered those that coincide with anticipated changes in fish communities based on existing models. Where warning-level criteria are exceeded, it is recommended that monitoring be repeated at two- to three-year intervals. Where continued monitoring demonstrates an increase in the extent or magnitude of effects on indices of benthic community composition, or sentinel fish population parameters, it is recommended that effects be considered unacceptable and that the cause of effects be identified and managed. Losses of non-rare species or shifts in dominance are considered severe fish-community effects that should trigger management (i.e., identification and elimination of causative agents). Domination of the benthic community by one or a few tolerant taxa normally coincides with effects on fish communities, and should also be considered a severe effect that triggers management.

Key words: municipal wastewater, environmental effects monitoring, bioassessment, biocriteria

Introduction

Municipal wastewater is a mixture of liquid wastes, solids, debris and chemicals discharged from residential, institutional, commercial and industrial sources into sewer or wastewater collection systems. Effluents from wastewater collection and treatment systems are the largest source of pollution to Canadian waters (Environment Canada 2001b), and their management is complex, involving multiple jurisdictions. Environmental and human health impacts of wastewater effluent discharges have been clearly established in the scientific literature (see Chambers et al. 1997). Municipal wastewaters contain a number of compounds and chemicals such as heavy metals, nutrients, oxygen-depleting substances, suspended solids, chemicals that disrupt natural endocrine functions of aquatic organisms (i.e., EDCs; Jobling and Sumpter 1993) and pharmaceuticals (Daughton and Ternes 1999). These compounds can have direct harmful impacts on human health, the environment and the economy, including degradation of fish and wildlife populations, beach closures and other restrictions on recreational water use, restrictions on fish and shellfish harvesting and consumption, and restrictions on drinking water consumption. The effects of endocrine-disrupting compounds (EDCs), pharmaceuticals and personal care products are largely unknown (Chambers et al. 1997).

Environment Canada recognizes that addressing the risks associated with wastewater effluents is a complex issue that involves multiple jurisdictions and requires a long-term comprehensive strategy. In addition to pollution prevention measures, Environment Canada’s strategy involves a framework for integrating environmental quality objectives (EQOs; Kilgour et al. 2002) for the aquatic receiving environment, including biological monitoring (Kilgour et al. 2003). A healthy aquatic ecosystem was proposed as the vision within the EQO framework
Biological Criteria for Municipal Wastewater (Kilgour et al. 2002, 2003), with the major goals being unimpaired human uses (Goal 1) and a diverse and functioning aquatic ecosystem (Goal 2; Fig. 1). Criteria for assessing the status of human uses are available in government publications (CCME 1999). Objectives for functioning and diverse aquatic ecosystems included healthy birds and mammals, and healthy fish communities.

The use of higher trophic levels as ultimate objectives to be used in the management of ecosystems has been argued elsewhere. In the Great Lakes basin for example, the Great Lakes Fisheries Commission in part defines a healthy aquatic ecosystem as having naturally reproducing fish populations and self-regulating fish communities (IJC and GLFC 1992; GLFC 1997). State and provincial agencies responsible for the management of the Great Lakes ecosystems have developed and are managing towards fish community objectives for each of the Great Lakes (e.g., Ryan et al. 2003). Management of these systems towards community-based objectives was implemented around 1980 after species-by-species approaches were shown to be inadequate (GLFC 1997).

Fish and aquatic birds and mammals represent trophic levels that integrate the conditions of all other trophic levels (Karr 1981). If these higher trophic levels are protected, there is some expectation that at least the function (e.g., production, transfer of energy through food chains) of lower trophic levels (e.g., benthos, plants, algae, plankton, fungi, bacteria) is also protected (Karr 1981) even if composition and diversity of those lower trophic levels are not. Here, the fish community, as well as aquatic birds and mammals are proposed as ultimate “objectives” that are considered relevant to the goal of having functioning and diverse aquatic ecosystems. By focusing on the protection of these higher trophic levels, there is an admission that impacts to the species composition of other trophic levels are acceptable so long as they do not in themselves cause impacts on fish or aquatic birds or mammals (as per Kilgour and Barton 1999).

This paper describes recommended aquatic-environment biological components and their associated measurable attributes (indicators) for evaluating the objective of a healthy fish community. We first describe the recommended components, provide an overview of specific measurable indicators, and then provide an overview of recommended criteria for evaluating the individual indicators.

Selecting Components and Indicators

The selection of components and indicators for assessment is in many ways largely philosophical. By identifying a healthy fish community as a major objective, indicators should be selected that provide an “indication” of the condition of the fish community. The composition of fish communities should, therefore, be evaluated where it is possible to do so. Measured indicators of sentinel fish populations (on species such as white sucker, sculpins and shellfish, etc.), benthic macroinvertebrates and plants (macrophytes, macroalgae, phytoplankton)
can be used as indications of the condition of fish community composition where fish communities are difficult to sample. These biological monitoring components (quantified by specific measurement endpoints) can provide an early warning of impending effects on fish communities, and/or can be diagnostic as to potential causes of altered fish communities. The recommended suite of biological components (i.e., fish community, sentinel fish species, benthos, plants) is not exhaustive but is considered to be representative of some of the more common components available with recognized and/or standardized methods for measurement.

Criteria

For the selected components and typical indicators, three recommended sets of criteria that lead to management action are provided. “Warning-level” criteria are those numeric or narrative conditions that indicate that the composition of the fish community may be impaired. Management of effluent quality is not triggered by a warning-level exceedance because changes in the fish community do not necessarily occur upon such an exceedance. Second, “unacceptable effects” are cases when a measurable indicator is already at a condition that is in excess of a warning level, and that is also “trending” over time (i.e., deviations from reference are getting larger) towards a severe effect. Where there is an unacceptable trend, it is recommended that there be some consideration for identifying causative agents and elimination (i.e., management). A “severe effect” occurs when the fish community is impaired (as defined below), or when another measurable indicator has a condition that implies that fish communities are now, or will be, impaired in the future in the absence of improvement in environmental conditions. As with unacceptable trends, it is recommended that some consideration be given to identifying and managing the cause(s) of severe effects. Specific numeric or narrative criteria are provided below for measurable indicators of each of the recommended components.

Fish communities. Given that it is the fish community that has been proposed as the major objective in determining if further management action is needed to control MWWE, some consideration to characterizing fish communities (through measurement of standing stock biomass or abundance, and/or other measures of richness, diversity or composition) should be given. Fish community surveys have a long history of use in Canada, the U.S. and worldwide. In Ontario and elsewhere, fish community surveys were used extensively in the 1950s and 1960s to demonstrate MWWE impacts on streams (Wichert 1994). Those studies were evidence enough of the effects of MWWE, and were the cause of secondary treatment being implemented at many locations.

A critical evaluation of the suitability of fish community surveys was carried out during the development of the Metal Mining Environmental Effects Monitoring Program (EVS 1997). Indices of fish community composition were considered about as sensitive to mining as population parameters of sentinel fish species, but the costs of characterizing fish communities were considered to be a little higher than for collecting sentinel fish (Table 1). EVS (1997) considered fish community data to be a more relevant and direct assessment of effects, and recommended that fish community surveys be carried out whenever the costs are low. In small systems that have received liquid effluents for some time, assessment of fish communities is the most direct way to determine whether communities are impaired. Fish communities, however, can be difficult to characterize in large systems (e.g., Gibbons et al. 1995), so the detection of subtle community-level impacts may not always be easy.

There are, however, additional conceptual challenges with using fish community surveys. First, some programs have intentionally avoided assessing fish communities because effects on fish communities are only detectable after they occur. Monitoring fish communities, therefore, provides no early warning of impending future impacts. If impacts to the community are very significant (i.e., the irreversible loss of keystone species), then there may be no way to recover the lost resource. Monitoring of the fish community would not detect the loss of a keystone species until after it had occurred.

Second, if large-scale effects (i.e., the loss of an abundant species) occur, the causes of effects are more difficult to diagnose or relate to specific stressors the higher up in the food chain the component is, or the more complex is the level of organization (i.e., community) (Munkittrick et al. 2000a). It can be difficult, for example, to determine why species are absent. Species may be absent now because they were: (1) never present, (2) were extirpated by a previous discharge or other event, or (3) have been recently extirpated by the discharge under study or other actions or events. Where fish community surveys demonstrate effects, other components and their measurable indicators can be used to develop the burden of proof of the cause of effects. Assessments of fish community trophic guilds (Karr 1981), temperature tolerances (Wichert 1994), etc., can assist in diagnosis, as can assessments with other tools including population responses of sentinel fish species (Munkittrick and Dixon 1989a), benthic macroinvertebrates (Rooke and Mackie 1982) and plants and algae. Thus, although assessments of fish communities in isolation may not logically lead to appropriate management actions, the use of other indicators should enhance our ability to make proper inferences of cause-effect.

Third, abundances and biomass of fish are considered highly variable spatially, temporally and among types of gear (e.g., electrofishers, variable mesh size gill
Biological Criteria for Municipal Wastewater

Variability in catches is, however, an issue in an assessment of any community including benthic macroinvertebrates and plants. As with those other monitoring components, variability can be reduced by standardizing equipment, habitat and timing (season) among sampling areas (see for example, Environment Canada [2001a] for detailed guidance on designing studies to minimize extraneous variation). Further, assessment of a community’s condition at a test site is usually relative to conditions at reference sites. Variability in catches is inherent in any survey, and a necessary part of the assessment (Kilgour et al. 1998).

Because it is the fish community that is the ultimate objective in aquatic environments, fish communities should be assessed directly where possible (as per EVS 1997), and especially where effluents have been discharged for some time. Fish communities should be assessed indirectly with other biological components in the following situations: (1) when fish communities are difficult to sample or there is an expectation that it will be difficult to adequately characterize the community (as perhaps in large rivers and lakes), or (2) where severe effects are not likely to have occurred (i.e., a new high-quality or low-volume discharge) and there is a desire to have early warning of impending effects on the fish community.

The fish community, of the components identified here, is perhaps the most difficult to characterize. Given “noisy” catches, etc., subtle effects will be difficult to detect and even more difficult to attribute to a stressor. Here, we define a severe effect on the community as loss of any non-rare fish species. Losses of non-rare species are the most likely to be detected (Table 2), and are thus the specific criterion provided here as indicating a severe effect. There is no recognized guidance on how to interpret fish community data for assessment purposes in Canada. There are, however, a number of documents in the U.S., including several outlined in Simon (1999). Rochet and Trenkel (2003) also provide suggestions for marine fish communities. As above, it is envisioned that surveys of fish communities will be generally qualitative. Though we have defined a severe effect on the community as a loss of non-rare species, any change in the composition of the fish community that can be demonstrated with due diligence should be taken as a severe effect. Rigorous inventories are not to be discouraged, nor is the use of indices of composition or more conservative criteria.

**TABLE 1.** Evaluation of organism (and higher) level methods for assessing effects of mining effluents on fishes in monitoring programs (revised from EVS 1997)

<table>
<thead>
<tr>
<th>Level of biological organization, indicator</th>
<th>Ecological relevance</th>
<th>Sensitivity to stressors</th>
<th>Response time</th>
<th>Cost of collection</th>
<th>Cost of processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth</td>
<td>1</td>
<td>1</td>
<td>Slow</td>
<td>Med.</td>
<td>Low-med.</td>
</tr>
<tr>
<td>Reproduction</td>
<td>1</td>
<td>1</td>
<td>Int.</td>
<td>Med.</td>
<td>Low-med.</td>
</tr>
<tr>
<td>Condition</td>
<td>2</td>
<td>2?</td>
<td>Int.-fast</td>
<td>Med.</td>
<td>Low</td>
</tr>
<tr>
<td>Population</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct (CPUE)</td>
<td>1</td>
<td>1–2</td>
<td>Slow</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Indirect (adult fish surveys)</td>
<td>1</td>
<td>1</td>
<td>Int.-slow</td>
<td>Med.</td>
<td>Med.</td>
</tr>
<tr>
<td>Community</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish community surveys</td>
<td>1</td>
<td>1</td>
<td>Slow</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

| Note: Relevance (ecological): 1 = highly relevant; 2 = somewhat relevant. |
| Sensitivity: 1 = very sensitive; 2 = somewhat sensitive. |
| Response time: Fast = within days or weeks; Int. = within months or a year. |
| Cost of field collection: Med. = >20 fish/site, few sites; High = >20 fish/site, multiple sites. |
| Cost of processing (in field and lab): Low = a few simple measurements, mostly in the field, required; Med. = some simple lab measurements or processing required. |
| Int.; Intermediate. |
| Med.; Medium. |
| CPUE; Catch-per-unit-effort. |

**Benthic macroinvertebrates.** The composition of benthic macroinvertebrate communities is typically monitored as an integrating measure of the condition of fish habitat. Where indices of benthic community composition (e.g., abundance, richness, evenness, various biotic indices) are shown to be impaired, fish habitat is considered to be impaired. Benthic community composition relates to the condition of fish communities both directly and indirectly. Because most fish eat benthic organisms during at least part of their lifecycle, benthic production influences fish production through bottom-up effects. Waters (1988) and others have demonstrated relationships between benthic and fish production for streams, while similar relationships have been developed for lake (Matuszek 1978; Boisclair and Leggett 1989) and marine systems (MacKinnon 1973). In contrast, fish can influence the composition of the benthic community through top-down feeding effects (Elliott 1986; Morgan and
Finally, there are numerous studies showing relationships between the composition of benthic communities and the composition of fish communities (Berkman et al. 1986; Kilgour and Barton 1999). There is, therefore, considerable justification for using indices of benthic community composition as surrogate measures of the potential for effects on the fish community when fish communities cannot be adequately monitored.

Three levels of criteria are recommended for interpreting benthic community data. Warning-level effects include deviations in indices of composition in excess of ±2 SDs from the mean response of the reference community (Table 2). Unacceptable effects are those where indices of composition or the abundances of tolerant species indicate increases in magnitude and/or extent. Severe effects are deviations from a reference condition that can be confidently associated with a predicted deviation in composition of the fish community.

Environment Canada (2001a) recommends sampling approaches, and the following indices of composition for interpretation: (1) total abundance, (2) number of taxa, (3) diversity (Simpson’s), and (4) Bray-Curtis distance from the median reference community. Environment Canada (2001a) provides specific guidance on how to calculate those indices, and how to use them in hypothesis testing. It is recommended that those indices be considered the minimum, while the use of other indices that make sense is encouraged. Other indices may be highly suited to characterizing MWWE effects in specific environments. Hilsenhoff’s (1988) family biotic index (FBI), for example, was specifically designed to detect (relate to) nutrient enrichment in lotic environments. Some may find the review of multimetric indices and their derivation by Gerritsen (1995) useful. Multivariate ordination methods are often superior to the detection of effects when compared to univariate indices (Reynoldson et al. 1997; Kilgour et al. 2004). Ordination procedures should, therefore, be considered in any assessment of benthic community composition. Methods for sampling benthic communities, and approaches for analyzing community data, are described in a variety of texts for stream (Davis and Simon 1995; U.S. EPA 1999), lake (Rosenberg and Resh 1993; U.S. EPA 1998) and marine (Rhoads and Germano 1986; Diaz 1992) environments.

Here, it is recommended that effects exceeding the normal range of variation for site-specific reference sites be considered evidence of potential (warning-level) effects (Table 2). The normal range is here defined as the mean ±2 SD (as per Lowell 1997; Kilgour et al. 1998; Environment Canada 2001a). For some variables such as the Bray-Curtis distance measure, the normal range region should be $X \pm 2$ SD, not $\pm 2$ SD because only a larger number can infer impairment. Other indices may be logically treated in the same manner. Exceedances of these warning levels would not imply a severe effect in the fish community, but should be used to justify routine follow-up monitoring at 2- to 3-year intervals. Degradation over time of the benthic community could be used as evidence of an unacceptable effect for which the follow-up action might justifiably be identification and elimination of the cause of effects.

<table>
<thead>
<tr>
<th>Conclusion</th>
<th>Action</th>
<th>Fish Adult fish community (FC)</th>
<th>Benthos</th>
<th>Adult fish surveys (AFS)</th>
<th>Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td>Identify cause and manage</td>
<td>Loss of any dominant or non-rare species</td>
<td>Changes that correspond with FC change, when fish community survey not reliable (e.g., <em>Chironomus</em>, <em>Tubifex</em> or <em>Limnodrilus</em> dominant in freshwater, <em>Capitella</em> dominant in salt water)</td>
<td>Degrading (increase in magnitude or extent)</td>
<td>Stress-related response patterns Increasing age</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>Identify cause and manage</td>
<td>Degrading (increase in magnitude or extent)</td>
<td>Degrading (increase in magnitude or extent)</td>
<td>Stress-related response patterns Increasing age</td>
<td></td>
</tr>
<tr>
<td>Warning</td>
<td>Monitor</td>
<td>&gt;2 SD difference in composition from reference</td>
<td>&gt;25–30% difference from reference in GSI, LSI, growth, age &gt;10% difference from reference in condition (K)</td>
<td>Various (see Table 4) Degrading (increase in magnitude or extent)</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2.** Proposed biological criteria and potential management actions
and Kilgour et al. (1998). Fish communities generally produce statistically larger effects than benthos (Kilgour and Stanfield In press), so any effect in benthos exceeding ±2 SDs from a reference condition will generally coincide with effects on fish communities of the same or greater magnitude. The Capital Regional District of Victoria, British Columbia (CRD 2000), is using the ±2 SD rule in assessments of marine benthos in British Columbia to identify situations requiring management.

There are some benthic communities that indicate severe impairment and that have been associated with severe impairment of the fish community (as defined in Table 2). Where freshwater benthic communities are dominated by one or a few stress-tolerant species such as the chironomid Chironomus, or the worms Tubifex and Limnodrilus, or where there are no benthic animals, severe effects in the fish community are highly likely. For example, excessive nutrient enrichment resulting in anoxia can cause benthic communities to disappear or be dominated by a few tolerant species (oligochaetes, chironomids), and to have similar impacts on fish communities. This has occurred, for example, in the Moose River basin downstream of the pulp mill at Kapuskasing (in the 1970s and earlier) when dissolved oxygen concentrations were near zero. Impacts on the benthic community corresponded with an absence of game fish (walleye, pike) downstream of the mill. Later, a recovery in the benthic community (increase in species richness, reduced abundance) coincided with a recovery in the game fish community (B.A.R. Environmental Inc. 1993). Similarly, in marine environments, severe effects on fish communities are highly likely when the benthic community is dominated by one or a few species (e.g., Capitella capitata). Therefore, those kinds of benthic communities (and others where applicable) should be considered to be evidence of severe impairment. In those cases, the cause of effects should be identified and managed.

Sentinel fish populations. Population responses of sentinel fish species have been used extensively in Canada to evaluate point-source discharge effects on receiving aquatic environments. For example, the Environmental Effects Monitoring (EEM) Programs for the pulp and paper and mining sectors have incorporated sentinel fish studies into regulations under the Fisheries Act. Sentinel fish studies have also been used extensively in the U.S. (e.g., Adams et al. 1996) and Scandinavia (e.g., Larsson et al. 2000).

There is a wide variety of population-level responses (i.e., specific measurements) that can be monitored, ranging from changes in abundance to average individual-level responses such as measures of survival, growth, reproduction and energy storage. These are thought to be the principal measures that integrate the performance of the fish associated with their environmental conditions. These approaches have been under development for more than a decade (Munkittrick and Dixon 1989a,b; Munkittrick 1992; Gibbons and Munkittrick 1994; Munkittrick et al. 2000b) and guidance documents have been prepared for the application of these techniques for EEM purposes (Environment Canada 1994; DFO and EC 1995a; Courtenay et al. 1998; Environment Canada 1997; 1998, 2001a, 2002). Environment Canada (2002) and Dubé et al. (2002) provide guidance on conducting mesocosm studies, which are an alternative to classic field studies.

Population responses of sentinel fish species relate reasonably well to community-level effects. In a review of older literature, Munkittrick and Dixon (1989a,b) demonstrated that mean age, energy storage (condition) and energy use (growth, gonad development) are variously affected in a variety of species (brook trout, wall-eye, lake trout, arctic char) when the fish community is altered through overfishing, stocking programs or invasive species. In more recent work, Adams et al. (1996) demonstrated that green sunfish grew faster downstream of a bleached kraft pulp mill on the Pigeon River (western North Carolina and Tennessee), where the fish community was severely impaired (substantial reductions in number of native species). In southern Ontario, Fitzgerald et al. (1999) demonstrated that assessments based on creek chub provided similar resolution to assessments with the fish community, but creek chub responses had more potential for interpreting causes of effects.

Monitoring at the population level reduces the time lag for individual-level effects of effluents (e.g., physiological) to be detected, but allows detection of effluent-related effects before they compound to community-level consequences (Munkittrick and Dixon 1989a). Population-level responses, therefore, offer a compromise between the ecological relevance of community-level changes and the sensitivity of individual-level responses. Changes in growth, reproduction and survival of individuals are directly relevant to the performance of the population, respond relatively quickly to changes in ambient conditions (weeks to months), and are linked closely to physiological measures so that there is some ability to trace cause-effect relationships (Munkittrick et al. 2000b). Fish population characteristics are known to be responsive to the major constituents of MWWE including nutrients, low dissolved oxygen levels, synthetic hormones, etc. (Munkittrick and Dixon 1989a), and are anticipated to provide evidence of a response prior to changes resulting in the loss of a species.

Two levels of criteria are recommended for interpreting population responses of sentinel species (Table 2). Warning-level effects include ≥±10% differences in body condition from the mean of reference populations, or ≥±25% differences in gonad size, liver size, growth and age, between reference and exposure populations. Unacceptable effects include an increase in the magnitude or extent of effects on body condition, gonad size, liver
size, growth and age over time, or a “stress”-related response (Table 3), or an increase in mean age in the exposure area over time relative to what is observed in reference populations.

There are several Canadian documents providing guidance on interpreting population characteristics of sentinel fish species including those developed for the Pulp and Paper (DFO and EC 1995a) and Metal Mining (Environment Canada 2001a) Environmental Effects Monitoring Programs. Much of the federal guidance is based on a series of papers by Munkittrick and colleagues (Munkittrick and Dixon 1989a, b; Gibbons and Munkittrick 1994; Munkittrick et al. 2000b).

The definition of important effect sizes is a critical step in the use of sentinel fish surveys as a part of the strategy for evaluating and managing MWWE effects in aquatic receiving environments. Preliminary evidence suggests that differences of 25% between reference and exposure populations for liver size, gonad size and weight at age, and 10% differences in condition factor may be appropriate (Munkittrick et al. 2002; Lowell et al. 2003), and are thus recommended here as warning-level criteria. Sentinel populations may be unsustainable in the exposure area where differences in liver size, gonad size, weight at age and condition factor between reference and exposure areas get larger over time, and when the sentinel population is getting older. Sentinel species are chosen in part because they are abundant, but also because their responses are anticipated to be reflective of responses by other species. The presence of significant responses in sentinel species should be taken as a warning sign that there are chronic, subtle impacts present that need to be further evaluated. Potential extirpation of the sentinel species should be taken as evidence of a potentially severe effect on the fish community. If fish community surveys have been done, and significant changes have not been observed, it can be assumed that the presence of any observed subtle population-level responses are sustainable (if the discharge has been present for a significant period of time). If these responses were to worsen over time, in terms of extent or magnitude, the level of concern about the sustainability of the situation would increase.

There is a variety of responses that could occur with sewage effluents that would not affect the sustainability of the system (Table 3). For example, eutrophication would be expected to increase food resources, and ultimately increase reproductive effort, reducing the mean age of fish populations in the affected area. This condition does not threaten the existence of that specific species. In fact, patterns that do potentially affect the sustainability of the population (recruitment failure, food limitation, metabolic disruption) all affect the mean age of the population by making the average fish older (Gibbons and Munkittrick 1994; Munkittrick et al. 2000b). For this reason, it is assumed that an “unacceptable” effect would be the presence of effects greater than the critical effect size, and cyclical monitoring data demonstrating that the responses are increasing in extent or magnitude, and fish populations are significantly older in the affected site.

**Primary producers.** Primary producers are an integral component of the littoral zones of lake and river systems, forming the basis of food chains, providing cover for fish, and substrate for many kinds of invertebrates. Aquatic plants (macrophytes), macroalgae, periphyton (attached algae) and phytoplankton (suspended algae) are included in this trophic group. Macrophytes are important in structuring habitat in lake, river and estuarine environments (U.S. EPA 1998, 1999, 2000a, b). Macroalgae are important in providing habitat structure for fish in estuarine and coastal environments (U.S. EPA 2001). The absence of large aquatic plants and macroalgae in aquatic habitats can significantly limit the production of fish populations and communities (Crowder and Painter 1991). An excess of primary producers can lead to oxygen depressions at night, under ice, and in

<table>
<thead>
<tr>
<th>Generalized stress-related pattern</th>
<th>Age distribution</th>
<th>Energy utilization</th>
<th>Energy storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploitation/eutrophication</td>
<td>Shift to younger</td>
<td>Increased</td>
<td>Increased</td>
</tr>
<tr>
<td>Recruitment failure</td>
<td>Shift to older</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>Multiple stressors</td>
<td>Shift to older</td>
<td>Decreased</td>
<td>Decreased</td>
</tr>
<tr>
<td>Food limitation</td>
<td>No change</td>
<td>Decreased</td>
<td>Decreased</td>
</tr>
<tr>
<td>Niche shift</td>
<td>No change</td>
<td>Decreased</td>
<td>No change</td>
</tr>
<tr>
<td>Metabolic redistribution</td>
<td>Shift to younger</td>
<td>Mixed</td>
<td>Mixed</td>
</tr>
<tr>
<td>Chronic recruitment failure</td>
<td>Shift to older</td>
<td>Increased</td>
<td>Increased or decreased</td>
</tr>
<tr>
<td>Null response</td>
<td>No change</td>
<td>No change</td>
<td>No change</td>
</tr>
</tbody>
</table>

*The stressors could be chemical or habitat-related, and the surviving populations integrate the conditions in the receiving environment (both chemical and habitat). A shift in age distribution can be indicated by mean age or larger samples for ages of the population. Energy utilization can be reflected in growth rate, reproductive rates or age at maturity. Energy storage can be reflected in condition factors, liver size or in lipid storage levels.*

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**TABLE 3.** Generalized response patterns of fish populations to changes in populations (modified from Munkittrick et al. [2002]).
hypolimnia, and can result in significant changes in fish communities (Dillon and Rigler 1975).

Macrophytes, periphyton and macroalgae are considered an important biological monitoring component with respect to MWWE because of the obvious relationship between nutrient additions and primary production. Numerous studies have demonstrated the impacts of MWWE on macrophytes, periphyton, macroalgae and phytoplankton in marine (Kindig and Littler 1980), subtidal (Whigham et al. 1980), lake (Ozimek 1978) and river systems (Chambers 1993). It is not anticipated that surveys of primary producers will demonstrate effects associated with some of the more unusual chemicals found in MWWE like pharmaceuticals and antibiotics.

As with benthic invertebrates and the fish community survey, the specific methods used to characterize measurable indicators of primary producers should be selected on the basis of local conditions (Winter Unpublished manuscript). It is recommended that the data provided by any survey be semi-quantitative measurements of community composition taking into account areal abundance and/or biomass. That level of detail is considered adequate for detecting effects that correspond with impacts on the fish community.

Macrophytes are the recommended monitoring tools for shallow, standing and slow-moving freshwater (i.e., lake and river littoral zones). It is further recommended that the areal cover by macrophytes be considered the main measured indicator because cover tends to relate well with the condition of fish communities and populations. In shallow river and creek environments, cover of the bottom by macroalgae (i.e., Cladophora) is often a good indicator of the health of the system and the kinds of fish that are to be found (U.S. EPA 1999, 2000b). In deeper lakes, Secchi depth transparencies (or other more rigorous measures of primary production—e.g., chlorophyll a) are the recommended monitoring tool because they are simple and inexpensive to measure, and because of the strong obvious relationship to primary production, night-time and under-ice oxygen depressions and fish community composition (U.S. EPA 2000a). Eutrophic lakes can either be macrophyte dominated or phytoplankton dominated (Scheffer et al. 1992). It may, therefore, be necessary to consider assessing both phytoplankton and macrophytes in lakes. In coastal environments, areal cover by macrophytes is the recommended monitoring tool, again because of the relationship to productivity and fish community composition.

When differences in areal coverage of plants or macroalgae, or in Secchi disc depth, have been demonstrated to be due to the effluent discharge, then some consideration for criteria such as those provided in Table 4 should be made. The absence of differences between reference and exposure areas in measures of primary production indicates no effluent-related effects. Warning-level criteria are provided for primary producers only (Table 2, 4). Warning-level criteria include: (1) growths of attached macroalgae (Cladophora) where areal coverage is ≥70% (in rivers), (2) macrophyte cover ≥40% in lakes, (3) change in Secchi disc depths coinciding with predicted changes in fish community composition (in lakes as in Table 4), and (4) macro algal cover ≥40% (in coastal environments).

There are various sources that provide criteria for primary producers in freshwater and marine environments. Biggs (2000) suggests that trout habitats are impaired when filamentous algae cover more than 30% of the stream. The New Mexico Environment Department (NMED 2002) considers aerial coverage by filamentous algae or macrophytes in excess of 70% to be excessive from an aesthetic and fish habitat perspective. Here, any areal coverage in excess of 70% that can be argued to be due to the effluent discharge should be taken as evidence of a potential warning-level effect on the fish community. Those effects would in part justify routine monitoring at 1- to 2-year intervals of primary producers, benthos and population responses of sentinel fish species.

Generic recommendations on excessive coverage of lake littoral areas by macrophytes are not available, but there are extensive recommendations on how to interpret Secchi disc depth transparencies. Table 4 summarizes the suggestions from Dillon and Rigler (1975) and U.S. EPA (2000a). Where average summer Secchi depths exceed 5 m, there is good potential for cold-water fisheries to be maintained. Hypolimnetic waters are not likely to go anoxic during summer. In lakes with Secchi disc depths between 2 and 5 m, there is some potential for hypolimnetic oxygen depletions, and concomitant changes in the fish community (loss of salmonids). The likelihood of oxygen depletions in the hypolimnion and epilimnion are increased with shallower Secchi depths, with subsequent shifts in the fish community to more tolerant species. As Secchi disc depths get shallower, the use of lake waters for recreation (body contact) also declines (Dillon and Rigler 1975). In these lake environments, any reduction in Secchi disc depth that results in a re-classification of the lake should be taken as evidence of potential warning-level effects on the fish community (Table 2). These criteria could be augmented with data on more rigorous measurable endpoints where resources allow it.

There is an apparent lack of guidance on acceptable macrophyte or macro algal coverages for lake or coastal environments. In the absence of such guidance, it is recommended here that any coverage in excess of 40%, and where the cover has been shown to increase relative to baseline or reference conditions, be considered indicative of a potential warning-level effect on fish communities. Cover of about this magnitude is considered potentially degraded in lotic systems (Table 2), and may be relevant to lentic systems.
Applying Criteria in a Biological Monitoring and Assessment Framework

The criteria recommended in Table 2 can be integrated into a comprehensive decision framework for evaluating MWWE discharges (Fig. 2). The process involves screening facilities on the likelihood that they may have biological effects. Historical information is reviewed or new biological data are developed for facilities that are considered likely to cause effects. Where warning-level effects are exceeded (from Table 2), then surveillance is carried out, whereby effects are monitored at two- to three-year intervals. Where deviations from a reference condition are getting larger over time, or where effects exceed severe-effect thresholds, it is recommended that causes be identified and managed.

**Initial biological assessment (screening).** There are over 3000 facilities that discharge MWWE to aquatic receiving environments in Canada. Although all are expected to be discharging EDCs, pharmaceuticals and personal care products, not all are expected to be causing impacts. In the short term, the assessment of biological effects at those 3000+ facilities is infeasible. In the interim, biological effects at facilities that discharge <5000 m³/d or where effluent volumes are <10% of flow volumes in the receiver is acceptable. That notion may change after more knowledge of the impacts of MWWE on aquatic environments is accumulated. Thus it is anticipated that screening criteria will be revised over time, and that facilities will repeat the screening process periodically (say every 1 to 2 years).

**Review existing data.** Existing site-specific data should be collected and reviewed to determine if there are effects on the fish community, and/or to assist in the design of reconnaissance and detailed surveys. Historical data on the receiving environment may be obtainable from local municipal, provincial and federal agencies. Information that is of value in designing detailed studies includes: (a) the locations of any point-source discharges (e.g., combined sewer overflows) that may confound or modify the responses of measured indicators, (2) requiring the preparation and implementation of pollution prevention plans for inorganic chloramines and chlorinated wastewater effluents”) or if effluent volumes are ≥10% of the flow of the receiving environment. It is anticipated that these criteria will capture the largest 5 to 10% of facilities (i.e., 150 to 300) with the biggest potential for significant impacts. Over time it is also anticipated that studies on these 5 to 10% of facilities will be useful for refining the criteria used to select facilities for further evaluation/assessment.

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### Table 4. Potential criteria for interpreting the significance of responses by primary producers

<table>
<thead>
<tr>
<th>Primary producer</th>
<th>Criterion</th>
<th>Effect</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rivers</strong></td>
<td>% Cover by macroalgae</td>
<td>&gt;40</td>
<td>Nuisance growth</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>Maximum cover before trout habitat is impaired</td>
<td>Biggs (2000)</td>
</tr>
<tr>
<td></td>
<td>&gt;2 cm long</td>
<td>Nuisance growth</td>
<td>Biggs (2000)</td>
</tr>
<tr>
<td></td>
<td>&gt;30</td>
<td>May indicate excessive nutrient enrichment</td>
<td>NMED (2002)</td>
</tr>
<tr>
<td><strong>Lakes</strong></td>
<td>Macrophyte cover (%)</td>
<td>≥40%</td>
<td>High cold-water fishery potential (i.e., salmonids)</td>
</tr>
<tr>
<td></td>
<td>Secchi depth (m)</td>
<td>2–5</td>
<td>Hypolimnetic anoxia may result in loss of salmonids. Walleye may predominate.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1–2</td>
<td>Hypolimnetic oxygen depletions very likely. Warm-water fishery likely (e.g., bass, pike).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;1.5</td>
<td>Warm-water fishery only. Under-ice fish kills very likely.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5–1</td>
<td>Algal scums and macrophyte problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;0.25</td>
<td>Algal scums, few macrophytes. Rough fish dominate. Summer fish kills possible.</td>
</tr>
<tr>
<td><strong>Coastal</strong></td>
<td>Macrophyte biomass (g/m²)</td>
<td>&gt;40%</td>
<td></td>
</tr>
</tbody>
</table>

requiring the preparation and implementation of pollution prevention plans for inorganic chloramines and chlorinated wastewater effluents”), or if effluent volumes are ≥10% of the flow of the receiving environment. It is anticipated that these criteria will capture the largest 5 to 10% of facilities (i.e., 150 to 300) with the biggest potential for significant impacts. Over time it is also anticipated that studies on these 5 to 10% of facilities will be useful for refining the criteria used to select facilities for further evaluation/assessment.

It is assumed, in the interim, that biological effects at facilities that discharge <5000 m³/d or where effluent volumes are <10% of flow volumes in the receiver is acceptable. That notion may change after more knowledge of the impacts of MWWE on aquatic environments is accumulated. Thus it is anticipated that screening criteria will be revised over time, and that facilities will repeat the screening process periodically (say every 1 to 2 years).
resource use (e.g., angling, commercial harvest), (3) fish species present in the system (i.e., knowledge gained through inventory by other agencies or groups), and (4) habitat mapping (if available).

Where there is appropriate and sufficient existing data, they can be used to assess whether there are existing receiving-environment effects (severe, unacceptable, warning). Where effects are severe, and there is evidence that the effects were caused recently and related to present-day effluent quality, then identification and management of the cause of effects would be justified. In the absence of adequate data, new data would be required, and could be obtained through reconnaissance and/or through a detailed study. If effects were caused by historical conditions it would be necessary to evaluate the potential effects of the current effluent quality in order to determine if management is required.

Reconnaissance. New field biological data will be required to make an assessment in the absence of adequate existing data. Reconnaissance is the first step in the design of an adequate sampling program, and typically involves: (1) delineation of the effluent mixing zone, (2) habitat characterization and mapping, and (3) preliminary sampling of fish and other potential biological components. Environment Canada (1998, 2001a) provides guidance on conducting reconnaissance-level surveys. Preliminary sampling of fish should determine whether

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Fig. 2. Recommended sequence for carrying out biological assessment of effects of municipal wastewater effluents.
fish community surveys can be conducted, and to identify potential sentinel species. Crews may use different sampling methods in a variety of habitats to identify possible combinations that could be used in more rigorous sampling episodes. Preliminary sampling of benthic macroinvertebrates may also be carried out to identify samplers for specific habitats. Visual surveys of macrophyte/macroalgae algal growths (or Secchi depths where relevant, or other measures) should be part of the reconnaissance survey. Data from reconnaissance surveys may demonstrate severe effects in fish communities, benthic communities and primary producers (i.e., from Table 2). Where effects are evident (and it is understood that at the reconnaissance level effects would have to be very severe to be detected) some form of immediate management action may be warranted, especially if it is clear that effects are related to present-day operations and effluent quality. It is not anticipated that reconnaissance-level surveys will provide the kinds of rigorous data that would be needed to identify warning-level effects.

Design and carry out study. Assuming that reconnaissance does not detect severe effects, a more detailed and rigorous field study should be designed incorporating fish communities (if possible), one or two sentinel fish species and benthic macroinvertebrate communities. Fish community surveys may not be rigorous, but it is envisioned that basic inventories capable of detecting severe effects will be possible in many circumstances. It is anticipated that specimens for sentinel species evaluations could also be obtained as part of the fish community evaluation. An evaluation of primary producers is not envisioned at this level. Reconnaissance-level fish community surveys should be conducted in case the fish community has deteriorated. Surveys of sentinel fish studies should be conducted because they are most able to provide early warning of effects caused by unusual chemicals. Surveys of benthic communities should be conducted because they are most likely to provide early warning of effects caused by conventional pollutants (e.g., nutrients, suspended solids) and physical habitat alterations. Field studies should be designed following recognized guidance. Manuals and documents produced by Environment Canada (1998, 2001a, 2002) for the Pulp and Paper and Metal Mining Environmental Effects Monitoring Programs provide as much guidance as should be required, though experience in conducting and evaluating field programs is an asset.

Interpretation of observed effects for each of the components should be relative to the criteria proposed in Table 2. Where any measured indicator demonstrates a warning-level effect, monitoring of all elements should be continued or repeated as part of ongoing surveillance. Surveillance monitoring studies should be designed to determine if the extent of effects is increasing over time, and that may require the addition of new stations at increasing distances from the point of discharge. It may also be possible to incorporate additional indicators or new stations into surveillance monitoring to assist in determining whether effects are recent and effluent-related, and to identify the cause of effects. The recommended frequency of surveillance monitoring is once every two to three years.

Unacceptable effects (i.e., an increase in magnitude or geographic extent of effects that exceed warning-level criteria) over time in any indicator would be indicative of an unacceptable effect that if allowed to continue could lead to severe effects. Where effects increase in magnitude in near-field locations, it is also likely that the geographic extent of effects increase. It is recommended that degrading conditions trigger identification and management of the cause of effects.

It is recommended that indicators that demonstrate a severe effect or effects that degrade over time should trigger identification and management of the cause of effects. Where there are no warning-level biological effects, it is recommended that desktop screenings be revisited whenever there are significant changes in effluent quality or quantity.

Identify cause and manage. Where effects are unacceptable or severe, it is recommended that the cause of effects be determined and then managed. Ideally, management would involve the elimination of causative chemicals or physical factors. Management may, however, involve other actions (e.g., addition of binding agents, etc.) that reduce effects in the receiving environment. Hewitt et al. (2005) fully describe a process that can be used for identifying causative chemicals.

Summary

As part of its strategy to reduce risks associated with municipal wastewater effluent, Environment Canada is committed to ensuring environmental quality is the driver for management action. The proposed environmental objectives framework incorporating biological monitoring and assessment can be used to assess the receiving environmental quality and the need for management action. Assessment of biological tools requires the consideration of the magnitude and nature of effects worth preventing or otherwise managing. We have, here, recommended the use of a series of biological components (fish and benthic communities, sentinel fish populations, primary producers) and their associated measurable indicators for monitoring MWWE, and have provided a combination of narrative and numeric criteria against which to judge the severity of effects in measurable indicators of those components. We have recommended simpler tools and more general criteria to assess large effects that justify management action, and more detailed tools and more conservative criteria for justifying continued
monitoring. The tools and approaches recommended here have been derived from programs from other sectors (e.g., pulp and paper, mining, oil and gas), and should be applicable in assessments of the aquatic receiving environment impacts of any anthropogenic activities.

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