# CALIBRATION OF THE BIOLOGICAL CONDITION GRADIENT FOR STREAMS OF MINNESOTA

**Prepared for:**
**Minnesota Pollution Control Agency**
**St. Paul, MN**

**Prepared by:**


Jeroen Gerritsen
Erik W. Leppo
Lei Zheng

Tetra Tech, Inc.
400 Red Brook Boulevard, Suite 200
Owings Mills, MD 21117

and

Chris O. Yoder
Midwest Biodiversity Institute & Center for Applied Bioassessment & Biocriteria
P.O. Box 21561
Columbus, OH 43221-0561


**June 30, 2012**

# EXECUTIVE SUMMARY

The objective of the Clean Water Act is to “restore and maintain physical, chemical, and biological integrity of the Nation’s waters.” To meet this goal, we need a uniform interpretation of biological condition and operational definitions that are independent of different assessment methodologies. These definitions must be specific, well-defined, and allow for waters of different natural quality and different desired uses. The USEPA has outlined a tiered system of aquatic life use designation, along a gradient (the Biological Condition Gradient, or BCG) that describes how ecological attributes change in response to increasing levels of human disturbance. The BCG is a conceptual model that describes changes in aquatic communities. It is consistent with ecological theory and has been verified by aquatic biologists throughout the United States.

Specifically, the BCG describes how 10 biological attributes of natural aquatic systems change in response to increasing pollution and disturbance. The 10 attributes are in principle measurable, although several are not commonly measured in monitoring programs. The attributes are:

I. Historically documented, sensitive, long-lived, or regionally endemic taxa
II. Sensitive and rare taxa
III. Sensitive but ubiquitous taxa
IV. Taxa of intermediate tolerance
V. Tolerant taxa
VI. Non-native taxa
VII. Organism condition
VIII. Ecosystem functions
IX. Spatial and temporal extent of detrimental effects
X. Ecosystem connectance

The gradient represented by the BCG has been divided into 6 BCG levels of condition that biologists think can be readily discerned in most areas of North America:

1. Natural or native condition
2. Minimal changes in structure of the biotic assemblage and minimal changes in ecosystem function
3. Evident changes in structure of the biotic assemblage and minimal changes in ecosystem function
4. Moderate changes in structure of the biotic assemblage with minimal changes in ecosystem function
5. Major changes in structure of the biotic assemblage and moderate changes in ecosystem function
6. Severe changes in structure of the biotic assemblage and major loss of ecosystem function

This report communicates the development of a quantitative BCG model, consistent with the conceptual model of the BCG of Davies and Jackson (2006). A panel of aquatic biologists in Minnesota applied and calibrated the general BCG model to Minnesota streams. Data from

Minnesota's monitoring program were examined to determine whether the data were adequate to apply to the BCG. The panel was able to assign taxa in the database to the first six attributes listed above, and the panel assigned a set of test sites to BCG levels 1 to 6 based on the sample data.

The panel assigned 728 samples to levels of the BCG—351 benthic macroinvertebrate samples, and 377 fish samples. For some samples, the panel's evaluation reflected some ambiguity between adjacent levels, such that a sample may have had characteristics intermediate between two levels. Level assignments were made across 9 stream types for both fish and benthic macroinvertebrates, including southern coldwater, and northern coldwater streams.

From the panelists' descriptions of their decision criteria for assessing sites and assigning levels, we developed a set of quantitative operational rules for assigning sites to levels. The rules capture the consensus professional judgment of the panel, and can ensure consistent decision-making. The panel's assessments, and the rules, were consistent but not identical across stream classes. The rules were incorporated into a multiple attribute decision model that makes use of mathematical fuzzy-set theory to account for discontinuities and to identify when BCG level assignments may be intermediate between adjacent levels. The purpose of the BCG model is to replicate panel decisions, using the panel-derived rules, so that stream assessments can be automated. The model was incorporated into a stand-alone Microsoft Access application, delivered separately to MPCA. The automated model exactly matched 81% of the fish panel decisions, and 88% of the benthic macroinvertebrate panel decisions. All mismatches were within a single BCG level, and several apparent mismatches were instances where the model, the panel, or both identified a tie between adjacent BCG levels.

The decision rules are documented, so that they have a degree of transparency not available in other index methods (e.g., arithmetic averaging of metrics, development of multivariate discriminant models to identify "true" reference). This also means that the decision rules can be formally changed by future panels as improved information becomes available. The BCG model is appropriate and consistent for use in Minnesota's Tiered Aquatic Life Use development, although we make the following recommendations for strengthening the index over time:

- Test rules with new (unassessed) sites to determine model and panel concordance. Expansion of the calibration dataset could be used to further refine the BCG models and can also help to identify stream reaches that do not fit into the current stream classification framework.
- The BCG rules were more troublesome to develop and readjust to the two headwaters categories: Northern Headwaters and Southern Headwaters. The final BCG models developed for these classes reasonably predicted panel decisions (77-88%), but we recommend that the fish BCG for the two headwater stream classes be reviewed further to demonstrate that the BCG models are consistent.

## ACKNOWLEDGMENTS

This report is the product of two workshops and several teleconferences hosted by the Minnesota Pollution Control Agency, between April 2009 and January 2010, in St. Paul, MN. Principal participants of the workshops were:

**Invertebrate Workgroup**

| | |
|---|---|
| Will Bouchard | Minnesota PCA |
| Joel Chirhart | Minnesota PCA |
| John Genet | Minnesota PCA |
| Jeroen Gerritsen (facilitator) | Tetra Tech, Inc. |
| Gary Montz | Minnesota DNR |
| Kevin Stroom | Minnesota PCA |

**Fish Workgroup**

| | |
|---|---|
| Brenda Asmus (reporter) | Minnesota PCA |
| Mike Feist | Minnesota PCA |
| Brett Nagle | Minnesota DNR |
| Scott Niemela | Minnesota PCA |
| John Sandberg | Minnesota PCA |
| Konrad Schmidt | Minnesota DNR |
| Chris Yoder (facilitator) | Midwest Biodiversity Institute |

We also thank Liejun Wu for developing the related MS-Access application to calculate the quantitative BCG model, and Clair Meehan for technical review and editing.

# TABLE OF CONTENTS

**Page**

**TABLE OF CONTENTS (CONTINUED)**

# LIST OF TABLES

**Page**

## LIST OF FIGURES

**Page**

# 1.0 INTRODUCTION

This report describes the calibration of the Biological Condition Gradient (BCG) to streams of Minnesota. This report translates the conceptual BCG framework into a BCG-based assessment index for use by Minnesota PCA. It can also be applied by sister agencies, and tribes in the ecoregions of Minnesota. The index is calibrated for biological assessment of warm, cold and cold-cool streams of Minnesota. The tool is calibrated for both macroinvertebrate and fish assemblages.

For over a decade, the Minnesota Pollution Control Agency (MPCA) has been using fish and benthic macroinvertebrate assemblage data to assess water resource quality. Until recently, biological indexes have been developed in Minnesota for individual drainage basins. Fish IBI's have been developed for streams in the Minnesota, Red, St. Croix, and Upper Mississippi River Basins (Niemela et al. 1998; Niemela and Feist 2000; 2002), and macroinvertebrate indexes have been developed for the St. Croix and Upper Mississippi basins (Chirhart 2003; Genet and Chirhart 2004). MPCA is currently developing a statewide fish IBI, following the approach in Whittier et al. (2007). The BCG calibration described here relies heavily on the knowledge and experience gained from the previous basin efforts, but it is now intended to be statewide, and addresses MPCA's objective to develop biological criteria for all streams within Minnesota.

The USEPA has supported efforts to develop uniform assessments of aquatic resource condition and to set more uniform aquatic life protection and restoration goals (Davies and Jackson, 2006). These efforts have led to a conceptual model—the BCG— that describes ecological changes, from pristine to completely degraded, that take place in flowing waters with increased anthropogenic degradation (Davies and Jackson, 2006). The BCG framework supports development of biological criteria in a state's water quality standards that can protect the best quality waters; that can be used as a tool to prevent or remediate cumulative, incremental degradation; and that can help to establish realistic management goals for impaired waters. The basis of the framework is recognition that biological condition of waterbodies responds to human-caused disturbance and stress, and that the biological condition can be measured reliably.

This report includes the results of two separate calibration efforts: one to calibrate the BCG for warmwater streams of Minnesota (this report), and the second to calibrate the BCG for cold and cool-water streams in Minnesota, Wisconsin, Michigan, and tribal lands of the region (Gerritsen and Stamp 2013. Results from the multistate calibration are also included here so that all BCG models for Minnesota are in one place.

## 1.1 What Is the BCG?

Over the past 40 years, states have independently developed technical approaches to assess biological condition and set designated ALUs for their waters. The BCG was designed to provide a means to map different indicators on a common scale of biological condition to facilitate comparisons between programs and across jurisdictional boundaries in context of the CWA. The BCG is a conceptual, narrative model that describes how biological attributes of aquatic ecosystems change along a gradient of increasing anthropogenic stress. It provides a framework for understanding current conditions relative to natural, undisturbed conditions (Figure 1).

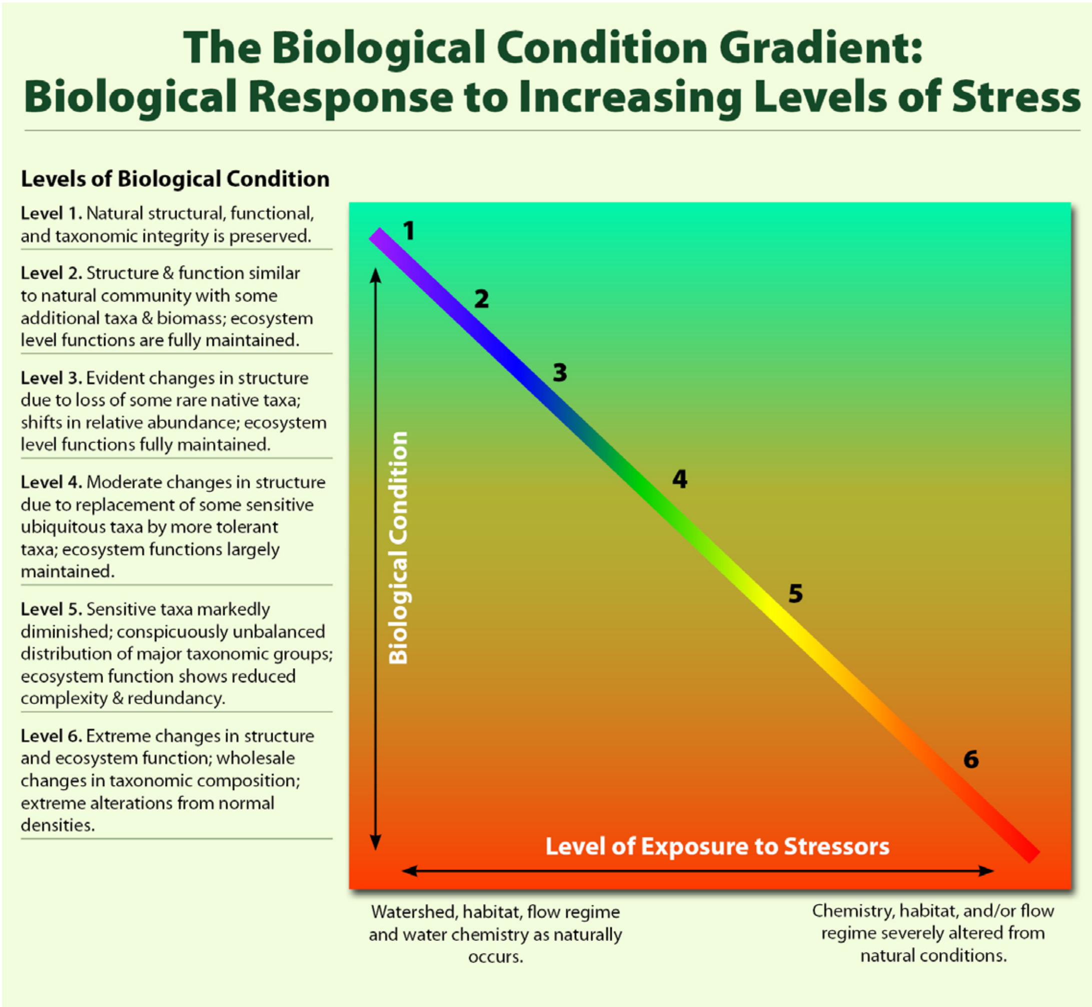


**Figure 1.** The Biological Condition Gradient (BCG). The BCG was developed to serve as a scientific framework to synthesize expert knowledge with empirical observations and develop testable hypotheses on the response of aquatic biota to increasing levels of stress. It is intended to help support more consistent interpretations of the response of aquatic biota to stressors and to clearly communicate this information to the public, and it is being evaluated and piloted in several regions and states.

*Source: Modified from Davies and Jackson 2006.

The BCG, as a conceptual model, is a universal framework that defines biologically recognizable categories of condition, and the framework is applicable for all states and broad regions. The BCG is not a management system, nor does it describe management goals. However, the reverse is true: management goals can be described in terms of the BCG, and biological information as measured by the BCG can tell us whether criteria are being met. Minnesota can thus identify management goals and levels of protection in terms of the BCG. The highest levels of the BCG could correspond to exceptional natural resource waters, as well as levels to be maintained under antidegradation policy. The interim goal of the Clean Water Act (CWA) (minimally fishable-swimmable) could correspond to the no-longer-pristine middle levels of the BCG, and lower levels would be nonattaining.

A BCG requires strong scientific knowledge on the response of aquatic biological assemblages to stressors, as well as the biota inhabiting a region. Using the scientific information to better assess and manage living aquatic resources also requires a legal foundation that permits the determination of scientifically defensible management goals (policies, designated uses, standards, criteria) in keeping with the goals of the CWA. Finally, developing a quantitative methodology for assessing waterbodies in relation to the BCG requires a scientifically sound biological monitoring program.

Under the CWA a state can identify use classes called designated uses, for its waterbodies. As biological condition can be divided into levels, so can designated aquatic life uses (ALUs) of waterbodies be divided into tiers corresponding to the biological expectation for the different uses. The relationship between ALU tiers and BCG levels must be addressed in the context of the state's programs and policies. BCG development may be required for each tier of ALU (where the ALU tier is defined by environmental classification), or BCG levels may coincide with ALU tiers (where the expected biological condition is the basis for the ALU tier). In this report, we focus on the BCG level development.

Biologists from across the United States developed the BCG model, agreeing that a similar sequence of biological alterations occurs in streams and rivers in response to increasing stress, even in different geographic and climatological areas (Davies and Jackson 2006). The model shows an ecologically-based relationship between the stressors affecting a waterbody (e.g., physical, chemical, biological impacts) and the response of the aquatic community (i.e., biological condition). The model is consistent with ecological theory and can be adapted or calibrated to reflect specific geographic regions and waterbody type (e.g., streams, rivers, wetlands, estuaries, lakes).

The BCG is divided into six levels of biological conditions along the stressor-response curve, ranging from observable biological conditions found at no or low levels of stress (Level 1) to those found at high levels of stress (level 6) (Figure 1). Table 1 provides a description of 10 attributes of aquatic ecosystems that change in response to increasing levels of stressors along the gradient, from level 1 to 6. The attributes include several aspects of community structure, organism condition, ecosystem function, spatial and temporal attributes of stream size, and connectivity. Levels of the condition gradient (Figure 1) are described in greater detail in the following text:

**Level 1: Natural or native condition.**
*Native structural, functional, and taxonomic integrity is preserved; ecosystem function is preserved within the range of natural variability.*

> Level 1 represents biological conditions as they existed (or still exist) in the absence of measurable effects of stressors. The Level 1 biological assemblages that occur in a given biogeophysical setting are the result of adaptive evolutionary processes and biogeography that selects in favor of survival of the observed species. For this reason, the expected Level 1 assemblage of a stream from the arid southwest will be very different from that of a stream in the northern temperate forest. The maintenance of native species populations and the expected natural diversity of species are essential for Levels 1 and 2. Non-native taxa (Attribute VI) may be present in Level 1 if they

cause no displacement of native taxa, although the practical uncertainties of this provision are acknowledged.

Attributes I and II (e.g., historically documented and highly sensitive taxa) can be used to help assess the status of native taxa and could be a surrogate measure to identify threatened or endangered species when classifying a site or assessing its condition.

**Level 2: Minimal changes in structure of the biotic community and minimal changes in ecosystem function.**
*Virtually all native taxa are maintained with some changes in biomass and/or abundance; ecosystem functions are fully maintained within the range of natural variability.*

Level 2 represents the earliest changes in densities, species composition, and biomass that occur as a result of slight elevation in stressors (such as increased temperature regime or nutrient enrichment). There may be some reduction of a small fraction of highly sensitive or specialized taxa (Attribute II) or loss of endemic or rare taxa (Attribute I) as a result. Condition level 2 can be characterized as the first change in condition from natural and it may be manifested in nutrient enriched waters as slightly *increased* richness and density of intermediate sensitive taxa and taxa of intermediate tolerance (Attributes III and IV).

**Level 3: Evident changes in structure of the biotic community and minimal changes in ecosystem function.**
*Evident changes in structure due to loss of some highly sensitive native taxa; shifts in relative abundance of taxa but sensitive-ubiquitous taxa are common and abundant; ecosystem functions are fully maintained through redundant attributes of the system.*

Level 3 represents readily observable changes that, for example, can occur in response to organic enrichment or increased temperature. The “evident” change in structure for Level 3 is interpreted to be perceptible and detectable decreases in highly sensitive taxa (Attribute II) and increases in opportunist, intermediate tolerant organisms (Attribute IV). Attribute IV taxa (intermediate tolerants) may increase in abundance as an opportunistic response to nutrient inputs.

**Level 4: Moderate changes in structure of the biotic community with minimal changes in ecosystem function.**
*Moderate changes in structure due to replacement of some intermediate-sensitive taxa by more tolerant taxa, but reproducing populations of some sensitive taxa are maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant attributes.*

Moderate changes of structure occur as stressor effects increase in Level 4. A substantial reduction of the two sensitive attribute groups (II and III) and replacement by more tolerant taxa (Attributes IV and V) may be observed. A key consideration is that some Attribute III sensitive taxa are maintained at a reduced level but are still an important functional part of the system (function maintained).

**Level 5: Major changes in structure of the biotic community and moderate changes in ecosystem function.**
*Sensitive taxa are markedly diminished; conspicuously unbalanced distribution of major groups from those expected; organism condition shows signs of physiological stress; ecosystem function shows reduced complexity and redundancy; increased build-up or export of unused materials.*

Changes in ecosystem function (as indicated by marked changes in food-web structure and guilds) are critical in distinguishing between Levels 4 and 5. This could include the loss of functionally important sensitive taxa and keystone taxa (Attribute I, II and III taxa) such that they are no longer important players in the system, though a few individuals may be present. Keystone taxa control species composition and trophic interactions, and are often, but not always, top predators. Additionally, tolerant non-native taxa (Attribute VI) may dominate some assemblages and changes in organism condition (Attribute VII) may include significantly increased mortality, depressed fecundity, and/or increased frequency of lesions, tumors and deformities.

**Level 6: Severe changes in structure of the biotic community and major loss of ecosystem function.**
*Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities and distributions; organism condition is often poor; ecosystem functions are severely altered.*

Level 6 systems are taxonomically depauperate (low diversity and/or reduced number of organisms) compared to the other levels. For example, extremely high or low densities of organisms caused by excessive organic enrichment or severe toxicity may characterize Level 6 systems.

In practice, the BCG is used to first identify the critical attributes of an aquatic community (Table 1-1) and then to describe how each attribute changes in response to stress. Practitioners can use the BCG to interpret biological condition along a standardized gradient, regardless of assessment method, and apply that information to different state or tribal programs.

The BCG model provides a framework to help water quality managers do the following:

- Decide what environmental conditions are desired (goal-setting)—The BCG can provide a framework for organizing data and information and for setting achievable goals for waterbodies relative to “natural” conditions (e.g., condition comparable or close to undisturbed or minimally disturbed condition).
- Interpret the environmental conditions that exist (monitoring and assessment)—Practitioners can get a more accurate picture of current waterbody conditions.
- Plan for how to achieve the desired conditions and measure effectiveness of restoration—The BCG framework offers water program managers a way to help evaluate the effects of stressors on a waterbody, select management measures by which to alleviate those stresses, and measure the effectiveness of management actions.
- Communicate with stakeholders—When biological and stress information is presented in this framework, it is easier for the public to understand the status of the aquatic resources relative to what high-quality places exist and what might have been lost.

**Table 1.** Attributes used to characterize the BCG.

| Attribute | Description |
|---|---|
| I. Historically documented, sensitive, long-lived, or regionally endemic taxa | Taxa known to have been supported according to historical, museum, or archeological records, or taxa with restricted distribution (occurring only in a locale as opposed to a region), often due to unique life history requirements (e.g., sturgeon, American eel, pupfish, unionid mussel species). |
| II. Highly sensitive (typically uncommon) taxa | Taxa that are highly sensitive to pollution or anthropogenic disturbance. Tend to occur in low numbers, and many taxa are specialists for habitats and food type. These are the first to disappear with disturbance or pollution (e.g., most stoneflies, brook trout [in the east], brook lamprey). |
| III. Intermediate sensitive and common taxa | Common taxa that are ubiquitous and abundant in relatively undisturbed conditions but are sensitive to anthropogenic disturbance/pollution. They have a broader range of tolerance than attribute II taxa and can be found at reduced density and richness in moderately disturbed sites (e.g., many mayflies, many darter fish species). |
| IV. Taxa of intermediate tolerance | Ubiquitous and common taxa that can be found under almost any conditions, from undisturbed to highly stressed sites. They are broadly tolerant but often decline under extreme conditions (e.g., filter-feeding caddisflies, many midges, many minnow species). |
| V. Highly tolerant taxa | Taxa that typically are uncommon and of low abundance in undisturbed conditions but that increase in abundance in disturbed sites. Opportunistic species able to exploit resources in disturbed sites. These are the last survivors (e.g., tubificid worms, black bullhead). |
| VI. Nonnative or intentionally introduced species | Any species not native to the ecosystem (e.g., Asiatic clam, zebra mussel, carp, European brown trout). Additionally, there are many fish native to one part of North America that have been introduced elsewhere. |
| VII. Organism condition | Anomalies of the organisms; indicators of individual health (e.g., deformities, lesions, tumors). |
| VIII. Ecosystem function | Processes performed by ecosystems, including primary and secondary production; respiration; nutrient cycling; decomposition; their proportion/dominance; and what components of the system carry the dominant functions. For example, shift of lakes and estuaries to phytoplankton production and microbial decomposition under disturbance and eutrophication. |
| IX. Spatial and temporal extent of detrimental effects | The spatial and temporal extent of cumulative adverse effects of stressors; for example, groundwater pumping in Kansas resulting in change in fish composition from fluvial dependent to sunfish. |
| X. Ecosystem connectance | Access or linkage (in space/time) to materials, locations, and conditions required for maintenance of interacting populations of aquatic life; the opposite of fragmentation. For example, levees restrict connections between flowing water and floodplain nutrient sinks (disrupt function); dams impede fish migration, spawning. |

*Source: Modified from Davies and Jackson 2006.

# 2.0 METHODS AND DATA

## 2.1 Developing and Calibrating a Quantitative BCG Model

The BCG defines the response of aquatic biota to increasing levels of stress in a specific region. Although the BCG was developed primarily using forested stream ecosystems, the model can be applied to any region or waterbody by calibrating it to local conditions using specific expertise and local data. To date, many states and tribes are calibrating BCG-based indexes using the first seven attributes (Table 1) that characterize the biotic community primarily tolerance to stressors, presence/absence of native and nonnative species, and organism condition.

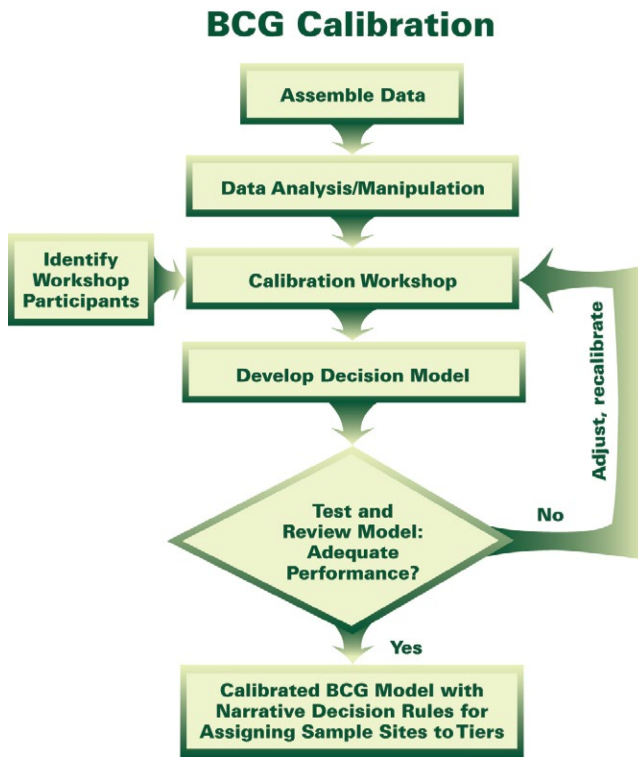


**Figure 2.** Steps in a BCG calibration.

Calibrating a BCG model to local conditions (Figure 2) is a multistep process. The process is followed to describe the native aquatic assemblages under natural conditions; identify the predominant regional stressors; and describe the BCG, including the theoretical foundation and observed assemblage response to stressors. Index calibration begins with the assembly and analysis of biological monitoring data. A calibration workshop is held at which experts familiar with local conditions use the data to define the ecological attributes and set narrative statements. For example, the experts determine narrative decision rules for assigning sites to a BCG level on the basis of the biological information collected at sites. Documentation of expert opinion in assigning sites to tiers is a critical part of the process. A decision model is then developed that encompasses those rules and is tested with independent data sets. A decision model based on the tested decision rules is a transparent, formal, and testable method for documenting and validating expert knowledge. A quantitative data analysis program can then be developed using those rules.

### 2.1.1 Assigning Sites to BCG Levels

Aquatic biologists familiar with Minnesota streams met as a workgroup to develop both the ecological attributes and rules for assigning sites to levels in the gradient. Their expertise included aquatic ecology, benthic macroinvertebrate sampling and monitoring, water quality, and fisheries biology. This development of the gradient included systematic application to both benthic macroinvertebrates and fish, collected by the methods used in Minnesota's monitoring program. As in other applications, we developed the BCG using only attributes I–VI, because the monitoring program does not collect information on the other attributes.

After reviewing EPA's conceptual model of the BCG, the group reviewed the list of taxa identified in the Minnesota ambient monitoring program to assign taxa to attribute groups I–VI. Appendix A includes the taxa list and assigned attribute groups. The group then considered data from selected monitoring sites, and assigned the sites to levels of the BCG based on the taxa present in the sample.

The conceptual model of the BCG is universal (Davies and Jackson 2006; USEPA 2005), but descriptions of communities, species, and their responses to the stressor gradient are specific to the conditions and communities found in the sample region. The expert panel described the biological condition levels that can be discerned within Minnesota. The description of natural conditions requires biological knowledge of the region, a natural classification of the assemblages, and, if available, historical descriptions of the habitats and assemblages. Working from the description of undisturbed communities and species composition data from example sites, the panel then assigned sites to the levels of the BCG. These site assignments were used to describe changes in the aquatic communities for lower levels of biological condition, leading to a complete descriptive model of the BCG for the region. Throughout this process, the panel made use of the prepared data, examining species composition and abundance data from sites with different levels of cumulative stress, from least stressed to severely stressed. Samples were selected by data analysts; the panel was initially unaware of the stressor status of individual sites. The panel worked with data tables showing the species and attributes for each site. In developing assessments, the panel worked "blind", that is, no stressor information was included in the data table. Only non-anthropogenic classification variables were shown. Panel members discussed the species composition and what they expected to see for each level of the BCG, for example, "I expect to see more stonefly taxa in a BCG level 2 site."

### 2.1.2 Quantitative Description

Level descriptions in the conceptual model tend to be rather general (e.g., "reduced richness"). To allow for consistent assignments of sites to levels, it is necessary to formalize the expert knowledge by codifying level descriptions into a set of rules (e.g., Droesen 1996). If formalized properly, any person (with data) can follow the rules to obtain the same level assignments as the group of experts. This makes the actual decision criteria transparent to stakeholders.

Rules are logic statements that experts use to make their decisions; for example, "If taxon richness is high, then biological condition is high." Rules on attributes can be combined, for example: "If the number of highly sensitive taxa (attribute II) is high, and the number of tolerant individuals (attribute V) is low, then assignment is level 2." In questioning individuals on how decisions are made in assigning sites to levels, people generally do not use inflexible, "crisp" rules, for example, the following rule is unlikely to be adopted:

"Level 2 always has 10 or more attribute II taxa; 9 attribute II taxa is always level 3."

Rather, people use strength of evidence in allowing some deviation from their ideal for any individual attributes, as long as most attributes are in or near the desired range. Clearly, the definitions of "high," "moderate," "low," etc., are fuzzy. These rules preserve the collective professional judgment of the expert group and set the stage for the development of models that reliably assign sites to levels without having to reconvene the same group. In essence, the rules and the models capture the panel's collective decision criteria.

As the panel assigned example sites to BCG levels, the members were polled on the critical information and criteria they used to make their decisions. These formed preliminary, narrative rules that explained how panel members made decisions. For example, "For BCG level 2, sensitive taxa must make up half or more of all taxa in a sample." The decision rule for a single level of the BCG does not always rest on a single attribute (e.g., highly sensitive taxa) but may include other attributes as well (intermediate sensitive taxa, tolerant taxa, indicator species), so these are termed "Multiple Attribute Decision Rules." With data from the sites, the rules can be checked and quantified. Quantification of rules allows users to consistently assess sites according to the same rules used by the expert panel, and allows a computer algorithm, or other persons, to obtain the same level assignments as the panel.

Rule development requires discussion and documentation of BCG level assignment decisions and the reasoning behind the decisions. During this discussion, we recorded:

- Each participant's decision ("vote") for the site
- The critical or most important information for the decision—for example, the number of taxa of a certain attribute, the abundance of an attribute, the presence of indicator taxa, etc.
- Any confounding or conflicting information and how this was resolved for the eventual decision

Following the initial site assignment and rule development, we developed descriptive statistics of the attributes and other biological indicators for each BCG level determined by the panel. These descriptions assisted in review of the rules and their iteration for testing and refinement.

Rule development is iterative, and may require several panel sessions. Following the initial development phase, the draft rules were tested by the panel with new data to ensure that new sites are assessed in the same way. The new test sites were not used in the initial rule development and also should span the range of anthropogenic stress. Any remaining ambiguities and inconsistencies from the first iterations were also resolved.

### 2.1.3 Decision Criteria Models

Consensus professional judgment used to describe the BCG levels can take into account nonlinear responses, uncommon stressors, masking of responses, and unequal weighting of attributes. This is in contrast to the commonly used biological indexes, which are typically unweighted sums of attributes (e.g., multimetric indexes; Barbour et al. 1999; Karr and Chu 1999), or a single attribute, such as observed to expected taxa (e.g., Simpson and Norris 2000; Wright 2000). Consensus assessments built from the professional judgment of many experts result in a high degree of confidence in the assessments, but the assessments are labor-intensive (several experts must rate each site). It is also not practical to reconvene the same group of experts for every site that is monitored in the long term. Since experts may be replaced on a panel over time, assessments may in turn "drift" due to individual differences of new panelists.

Management and regulation, however, require clear and consistent methods and rules for assessment, which do not change unless deliberately reset.

Use of the BCG in routine monitoring and assessment thus requires a way to automate the consensus expert judgment so that the assessments are consistent. We codified the decision criteria into a decision model, which has the advantage that the criteria are visible and transparent.

*Codification of Decision Criteria*

The expert rules can be automated in Multiple Attribute Decision Models. These models replicate the decision criteria of the expert panel by assembling the decision rules using logic and set theory, in the same way the experts used the rules. Instead of a statistical prediction of expert judgment, this approach directly and transparently converts the expert consensus to automated site assessment. The method uses modern mathematical set theory and logic (called "fuzzy set theory") applied to rules developed by the group of experts. Fuzzy set theory is directly applicable to environmental assessment, and has been used extensively in engineering applications worldwide (e.g., Demicco and Klir 2004) and environmental applications have been explored in Europe and Asia (e.g., Castella and Speight 1996; Ibelings et al. 2003).

Mathematical fuzzy set theory allows degrees of membership in sets, and degrees of truth in logic, compared to all-or-nothing in classical set theory and logic. Membership of an object in a set is defined by its membership function, a function that varies between 0 and 1. To illustrate, we compare how classical set theory and fuzzy set theory treat the common classification of sediment, where sand is defined as particles less than or equal to 2.0 mm diameter, and gravel is greater than 2.0 mm (Demicco and Klir 2004). In classical "crisp" set theory, a particle with diameter of 1.999 mm is classified as "sand", and one with 2.001 mm diameter is classified as "gravel." In fuzzy set theory, both particles have nearly equal membership (approximately 0.5) in both classes (Demicco 2004). Very small measurement error in particle diameter greatly increases the uncertainty of classification in classical set theory, but not in fuzzy set theory (Demicco and Klir 2004). Demicco and Klir (2004) proposed four reasons why fuzzy sets and fuzzy logic enhance scientific methodology:

- Fuzzy set theory has greater capability to deal with "irreducible measurement uncertainty," as in the sand/gravel example above.
- Fuzzy set theory captures vagueness of linguistic terms, such as "many," "large" or "few."
- Fuzzy set theory and logic can be used to manage complexity and computational costs of control and decision systems.
- Fuzzy set theory enhances the ability to model human reasoning and decision-making, which is critically important for defining thresholds and decision levels for environmental management.

*Development of the BCG*

In order to develop the fuzzy inference model, each linguistic variable (e.g., "high taxon richness") must be defined quantitatively as a fuzzy set (e.g., Klir 2004). A fuzzy set has a membership function; example membership functions of different classes of taxon richness are shown in Figure 3. In this example (Figure 3), piecewise linear functions (functions consisting of line segments) are used to assign membership of a sample to the fuzzy sets. Numbers below a lower threshold have membership of 0, and numbers above an upper threshold have membership of 1, and membership is a straight line between the lower and upper thresholds. For example, in Figure 3, a sample with 20 taxa would have a membership of approximately 0.5 in the set "low to moderate Taxa" and a membership of 0.5 in the set "Moderate Taxa."

How are inferences made? Suppose there are two rules for determining if a waterbody is BCG Level 3 (using definitions of Figure 2-2):

- The number of total taxa is high

The number of sensitive taxa is low to moderate

In crisp set theory, these rules translate to:

- Total taxa > 27
- Sensitive taxa > 10

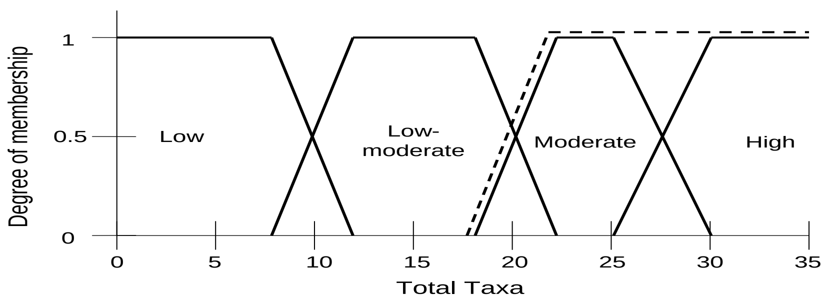


**Figure 3.** Fuzzy set membership functions assigning linguistic values of Total Taxa to defined quantitative ranges. Heavy dashed line shows membership of fuzzy set defined by "Total taxa are moderate to high."

If the two rules are combined with an "AND" operator, that is, both must be true, then under crisp set theory, if total taxa = 28 and sensitive taxa = 10, the sample would be judged not to be in the set of BCG level 3. This is because sensitive taxa is 1 short of being greater than 10.

In fuzzy set theory, an AND operator is equivalent to the minimum membership given by each rule: level 3 = MIN (total taxa is high, sensitive taxa is low to moderate)

Fuzzy membership in "total taxa is high" = 0.6 (Figure 2-2), and fuzzy membership in "sensitive taxa is low to moderate" = 0.5 (Figure 2-2). Membership of Level 3 is then 0.5

If the two rules are combined with an "OR" operator, then either can be true for a site to meet BCG level 3, and both conditions are not necessary. Crisp set theory now yields a value of "true" if total taxa = 28 and sensitive taxa = 10 (total taxa > 27, therefore it is true). Fuzzy set theory yields a membership of 0.6 (maximum of 0.5. and 0.6). Using the fuzzy set theory model, finding an additional taxon in a sample does not cause the assessment to flip to another class, unlike crisp decision criteria.

## 2.2 Data—Minnesota's Water Monitoring Program

Consistent, high quality biological monitoring information is necessary for developing a quantitative assessment system within a BCG framework. MPCA operates a sizable ambient monitoring program throughout the state; as of 2011, MPCA had recorded more than 5000 fish sampling events and nearly 3000 macroinvertebrate sampling events in its database.

Sites may be selected for assessment for a number of reasons including: 1) sites randomly selected for condition monitoring as part of the Environmental Monitoring and Assessment Program (EMAP), 2) sites selected for the development and calibration of biological criteria, and 3) sites selected to evaluate a suspected source of pollution.

### 2.2.1 Fish sampling

Fish collection Standard Operating Procedures (SOPs) were extracted from MPCA (2009), *Fish Community Sampling Protocol for Stream Monitoring Sites*,[1] and are summarized below:

A fish sampling reach is defined as 35 times the mean stream width, and is based on the distance necessary to capture a representative and repeatable sample of the fish assemblage within a stream segment (Lyons 1992; cited in MPCA 2009). Sampling is conducted during daylight hours within the summer index period of mid-June through mid-September. Sampling should occur when streams are at or near base-flow because flood or drought events can have a profound effect on fish assemblage structure and sampling efficiency.

Fish are collected before the physical habitat assessment so as not to disturb the fish assemblage prior to sampling. All habitat types within the sampling reach are sampled in the approximate proportion that they occur. An effort is made to collect all fish observed, but fish < 25 mm in total length are not counted as part of the catch. Fish are collected with electrofishing, using one of 4 methods: backpack shocker in small headwater streams; towed stream shocker in larger wadeable streams; mini-boom shocker (2-person jonboat) in small, non-wadeable streams, and a larger boom shocker (boat mounted) in larger streams and rivers.

### 2.2.2 Macroinvertebrate sampling

Macroinvertebrate collection SOPs were extracted from MPCA (undated), *Invertebrate Sampling Procedures*, EMAP-SOP4, Rev. 0.[2]

---

[1] http://www.pca.state.mn.us/index.php/water/water-monitoring-and-reporting/biological-monitoring/stream-monitoring/stream-monitoring-fish.html

[2] http://www.pca.state.mn.us/index.php/water/water-monitoring-and-reporting/biological-monitoring/stream-monitoring/stream-monitoring-aquatic-invertebrates.html

The multihabitat method entails collecting a composite sample from up to five different habitat types to get a sample representative of the invertebrate assemblage of a particular sampling reach. The habitats were chosen to represent broad categories rather than microhabitats. Every broad category includes numerous microhabitats, some of which will not be sampled. Habitats are sampled to reflect the most common microhabitat of any given broad habitat category. The habitats to be sampled include:

- *Hard bottom (riffle/cobble/boulder)*—All hard, rocky substrates, not just riffles. Runs and wadeable pools often have suitable "hard" substrates, and should not be excluded from sampling. Unproductive surfaces of large boulders and areas of flat, exposed bedrock are avoided unless they are productive.

- *Aquatic Macrophytes (submerged/emergent vegetation)*—Any vegetation found at or below the water surface. Emergent vegetation is included because all emergent plants have stems that extend below the water surface, serving as suitable substrate for macroinvertebrates.

- *Undercut Banks (undercut banks/overhanging vegetation)*—This category is meant to cover in-bank or near-bank habitats, shaded areas away from the main channel that typically are buffered from high water velocities.

- *Snags (snags/rootwads)*—Snags include any piece of large woody debris found in the stream channel, and include, rootwads, logs, tree trunks, entire trees, tree branches, large pieces of bark, and dense accumulations of twigs.

- *Leaf Packs*—Leaf packs are dense accumulations of leaves typically present in the early spring and late fall. They are found in deposition zones, generally near stream banks, around logjams, or in current breaks behind large boulders.

Sampling consists of dividing 20 sampling efforts equally among the dominant, productive habitats present in the reach. If 2 habitats are present, each habitat receives 10 sampling efforts. If 3 habitats are present, the two most dominant habitats should receive 7 jabs, the third should receive 6 jabs. If a productive habitat is present in a reach but not in great enough abundance to receive an equal proportion of sampling efforts, it is thoroughly sampled and the remaining samples should be divided among the remaining habitat types present.

A sample effort is defined as taking a single dip or sweep in a common habitat. A sweep is taken by placing the D-net on the substrate and disturbing the area directly in front of the net opening equal to the net width, ca. 1ft$^2$. The net is swept several times over the same area to ensure that an adequate sample is collected; each sweep covers approximately .09 m$^2$ of substrate. Total area sampled is ca. 1.8 m$^2$.

### 2.2.3 Data Management

Currently, all of MPCA's fish and benthic data and associated metadata are entered into a Microsoft Access database, where metrics and summary information are generated through queries. MPCA provided Tetra Tech with an extract of the database that included more than 5000 valid fish samples and sites and approximately 3000 benthic macroinvertebrate samples for use in the calibration exercise.

## 2.3 Identifying Attributes

### 2.3.1 Preliminary Disturbance Gradient

MPCA has developed a disturbance index, based on watershed land use, stream alteration, riparian condition, and known permitted discharges. Disturbance index score can range from 1, representing completely altered and heavily stressed streams, to 81, representing nearly pristine watersheds.

### 2.3.2 Assignment of taxa to attributes

Biologists have long observed that taxa differ in their sensitivity to pollution and disturbance. While biologists largely agree on the relative sensitivity of taxa, there may be subtle differences among stream types (high vs. low gradient) or among geographic regions. We applied several statistical models to estimate tolerance of fish and macroinvertebrates to stressors, in this case MPCA's disturbance gradient. The workgroup participants examined the empirical information derived from the models, as well as using their collective experience and judgment to assign sensitivities of the organisms to the disturbance gradient.

*Quantitative tolerance models*
Prior to the workshops, we examined tolerances of the fish and macroinvertebrate taxa to the stressor gradient. While optima or tolerance values can be estimated from a variety of models, scatterplots of individual taxa on the disturbance gradient, and a maximum likelihood model of the probability of observing a taxon at a particular disturbance score were deemed the most useful for assigning taxa to the tolerance attributes.

*Maximum likelihood estimates (GLM model)*—The probability of observing a particular taxon can be modeled as:

$$\ln\left[\frac{p}{1-p}\right] = b_0 + b_1 x + b_2 x^2$$

Where p is the probability of observing the taxon and x is the disturbance gradient score. The optimum of the model (maximum probability) yields the tolerance value. To assist experts in assigning taxa to attributes, we plotted the probability over the range of the disturbance gradient (See Figure 3-1).

Prior to calibrating BCG levels, the two workgroups (fish and benthic macroinvertebrates) assigned Minnesota taxa to the taxonomic attribute groups (attributes I to VI; Section 1.1.1). Assignments of taxa to attributes relied on a combination of empirical examination of taxon occurrences at sites in the different stress classes, as well as professional experience of field biologists who had sampled the streams of Minnesota. The empirical analyses and professional opinions tended to agree, but in cases of disagreement, the group relied on consensus professional opinion, unless contradicted by an overwhelming response in the data analysis. As a group, participants discussed each taxon in the calibration data set, and developed a consensus assignment (Appendix A).

## 2.4 Classification

Experience has shown that a robust biological classification is necessary to calibrate a BCG-based index, because the natural biological class indicates the species expected to be found in undisturbed, high-quality sites. As an example, low-gradient prairie or wetland-influenced streams typically contain species that are adapted to slow-moving water and often to hypoxic conditions. These same species found in a high-gradient, forest stream could indicate habitat degradation and organic enrichment.

MPCA had previously developed classification systems for both the fish and the benthic macroinvertebrate communities, with 11 fish classes and 12 macroinvertebrate classes for streams. These classes were based on distributions of species among Minnesota's ecoregions (forest, prairies), a north-south gradient, stream size for fish samples (headwater, wadeable, and river), and stream gradient for macroinvertebrate samples (Riffle-run and Glide-pool).

The first BCG calibration exercise was done on 19 of the above stream classes (excluding 4 coldwater classes), but after the workshop MPCA re-examined the classifications to see if some of the classes could be recombined to reduce the total number of classes. The objective was to reduce the complexity of the assessment system, as well as to ensure a more complete stress/disturbance gradient for each stream class. A revised set of stream classes was developed by MPCA from further data analysis and examination of results from the calibration exercises (Table 2). The final classification identified 7 warmwater stream classes for both fish and benthic macroinvertebrates, and 2 cold and coolwater classes (Table 2-1), for a total of 18 classes, 9 each for fish and invertebrates.

**Table 2.** Final MPCA classification of stream types for fish and macroinvertebrates, and number of samples with valid data in each (through September 2011).

| Fish | | | Benthic macroinvertebrates | | |
|---|---|---|---|---|---|
| **MPCA no.** | **Name** | **N** | **MPCA no.** | **Name** | **N** |
| **1** | Prairie Rivers | 525 | **1** | Northern Forest River | 125 |
| **2** | Southern Wadeable Streams | 665 | **2** | Prairie Rivers (north and south) | 155 |
| **3** | Southern Headwaters | 638 | **3** | Northern Forest Riffle-run | 271 |
| **4** | Northern Forest Rivers | 358 | **4** | Northern Forest Glide-pool | 425 |
| **5** | Northern Wadeable Streams | 523 | **5** | Southern Riffle-run | 445 |
| **6** | Northern Headwaters | 706 | **6** | Southern Hardwood Glide-pool | 396 |
| **7** | Wetland-lacustrine Streams | 313 | **7** | Prairie Glide-pool | 617 |
| **10** | Southern Coldwater | 288 | **8** | Northern Coolwater | 166 |
| **11** | Northern Coolwater | 628 | **9** | Southern Coldwater | 245 |

## 3.0 DESCRIPTIVE RESULTS

MPCA hosted workshops and webinars to develop the rules and models for warmwater streams. USEPA hosted additional workshops and webinars for cold- and coolwater streams, for the 3 states and several tribes in northern-most EPA Region 5 (Gerritsen and Stamp 2012). Following the coldwater BCG development, MPCA subsequently refined the cold and coolwater BCG models to obtain better fits to MPCA data.

In the final webinars for both warmwater and coldwater calibration, the panels assessed sites that were not used in the calibration of the BCG model, to serve as independent tests of model performance. Several of these sites were used for MPCA's final refinement of the index models, so they can no longer be considered independent test sites for the current configuration of the models.

In this process, panelists first assigned BCG attributes to fish and macroinvertebrate taxa (See section 3.1). Next they examined biological data from individual sites and assigned those samples to Levels 1 to 6 of the BCG. The intent was to achieve consensus and to identify rules that experts were using to make their assignments. Panelists operated on the assumption that sites had been classified correctly into the stream types identified in Table 2.

The data that the experts examined when making BCG level assignments were provided in worksheets. The worksheets contained lists of taxa, taxa abundances, BCG attribute levels assigned to the taxa, BCG attribute metrics and limited site information (e.g., such as watershed area), size class (i.e., headwater), and stream gradient. Participants were not allowed to view Station IDs or waterbody names when making BCG level assignments, as this might bias their assignments. Fish and macroinvertebrate worksheets can be found in Appendix D.

Preliminary sets of decision rules were developed based on these calibration worksheets. The rules were automated in Excel spreadsheets and BCG level assignments were calculated for each sample. The model-assigned BCG level assignments were then compared to the BCG level assignments that had been made by the panelists to evaluate model performance. A second workshop and several webinars were held to reconsider samples that had the greatest differences between the BCG level assignments based on the model versus the panelists. Decision rules were adjusted based on group consensus. After the decision rules were finalized, Tetra Tech also developed an application in MS-Access for automated calculation of BCG level for new sample data.

### 3.1 BCG Taxa Attributes

Scatterplots of abundance of individual taxa on the disturbance gradient, which also showed the maximum likelihood model, was deemed to be the most useful for identifying attribute groups (Figure 4). Scatterplots were plotted for all taxa with more than 20 occurrences in the data set (Appendix B). Figures 4-7 show examples of the scatterplots and maximum likelihood models for taxa assigned to attributes II through V. Undisturbed sites score high on the Minnesota disturbance gradient (maximum score = 81). The scatterplots of relative abundance (points shown in Figs. 4-7) may be misleading because the distribution of the disturbance scores is not uniform: there are many more sites in the database with scores above 40 than scores below 40. An apparent reduction in point density at low disturbance scores reflects the fact that few sites in the database had such low scores, and not necessarily the response of the taxa. The capture probability curve shows better which taxa are most tolerant to, or indeed thrive in, disturbed conditions (Figure 4).

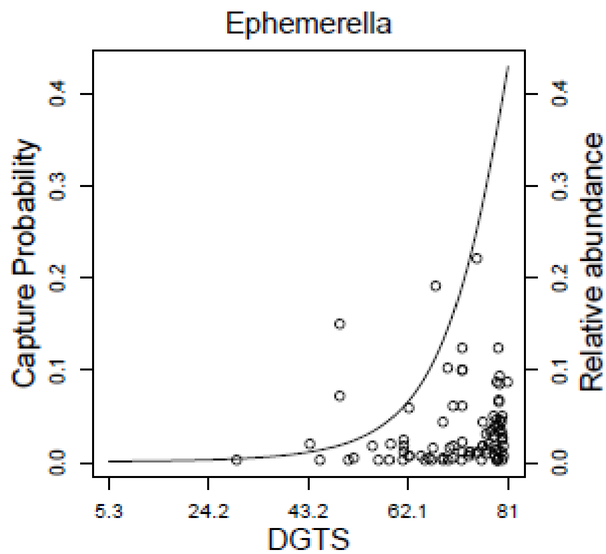


**Figure 4.** Disturbance score and Ephemerella occurrence in stream samples. Circles show observations and relative abundance of Ephemerella (right axis); line shows probability of occurrence (left axis; maximum likelihood). Ephemerella was assigned to attribute II (highly sensitive taxa), as shown by its high abundance and high probability of occurrence in minimally-disturbed sites (disturbance score 81).

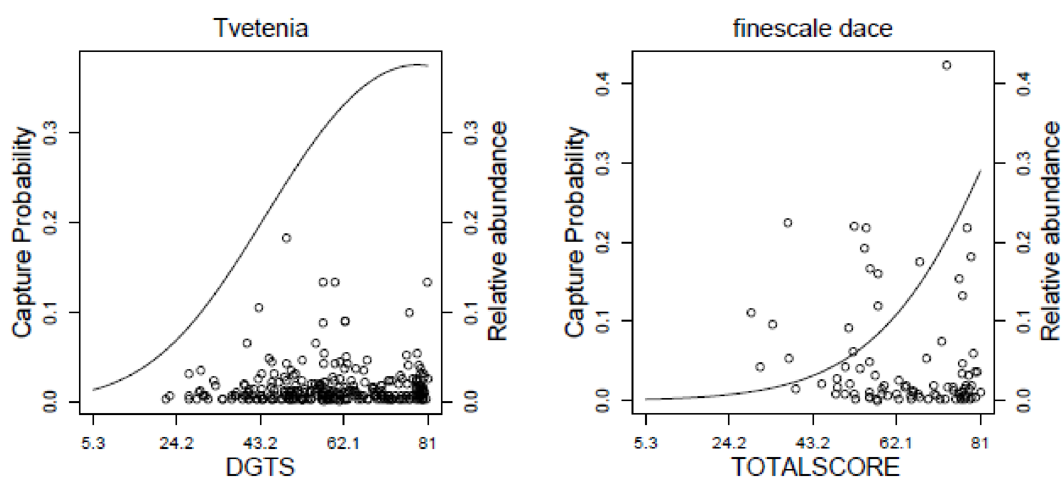


**Figure 5.** Examples of attribute III taxa, *Tvetenia* and finescale dace. These species occur throughout the disturbance gradient, but with higher probability in better sites. Final attribute assignment was based not only on these plots, but also on professional judgment of the panel.

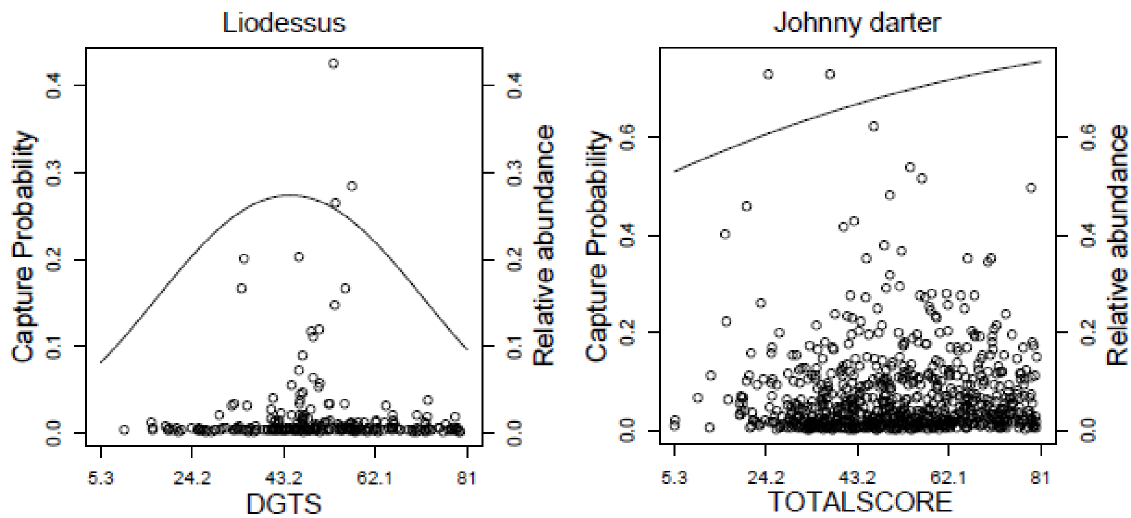


**Figure 6.** Examples of intermediate tolerant, attribute IV taxa, *Liodessus* and johnny darter. These species occur throughout the disturbance gradient, but with roughly equal probability throughout, or with a peak in the middle of the disturbance range.

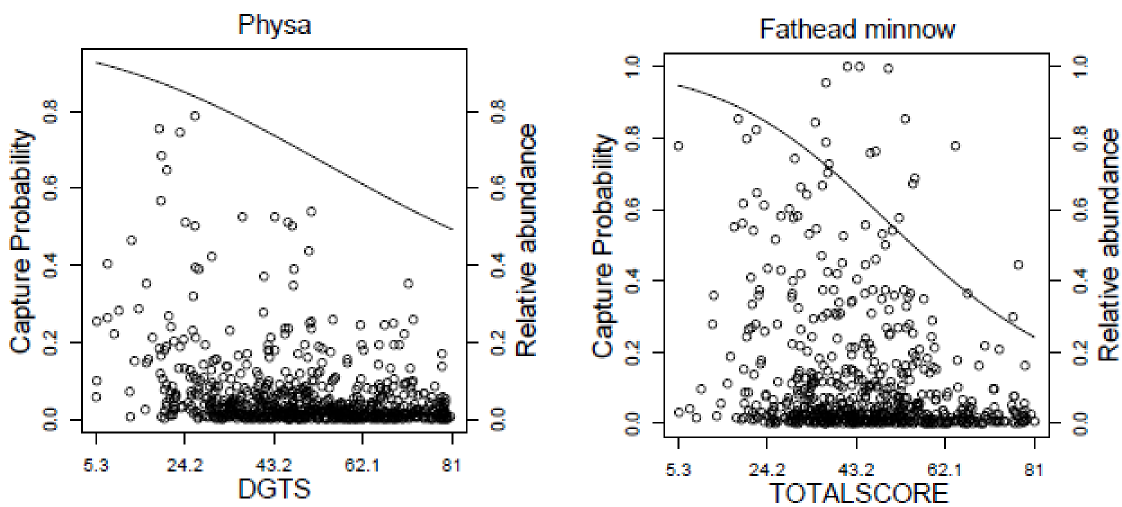


**Figure 7.** Examples of tolerant (or highly tolerant) attribute V taxa, *Physa* and fathead minnow (Va; highly tolerant). These species occur throughout the disturbance gradient, but with higher probability of occurrence, and higher abundances, in more stressed sites.

Fish species were assigned to attributes separately for each of the 9 fish stream classes, and macroinvertebrates were assigned separately to 4 classes: glide-pool, riffle-run, coolwater, and coldwater. One or more taxa differed in attribute assignment in each of the stream classes, although the majority of taxa were in the same attribute among most classes where they occurred.

To illustrate different tolerance among the stream classes, we show the tolerance graphics for creek chub, compared in the wadeable streams and Headwaters classes (Figure 8). Based on the graphics, creek chub appears to be more tolerant in the wadeable streams than in headwaters.

Other species (e.g., fathead minnow, attribute V) appeared the same in both wadeable and headwaters. Attribute assignments for all taxa among the stream classes are given in Appendix A.

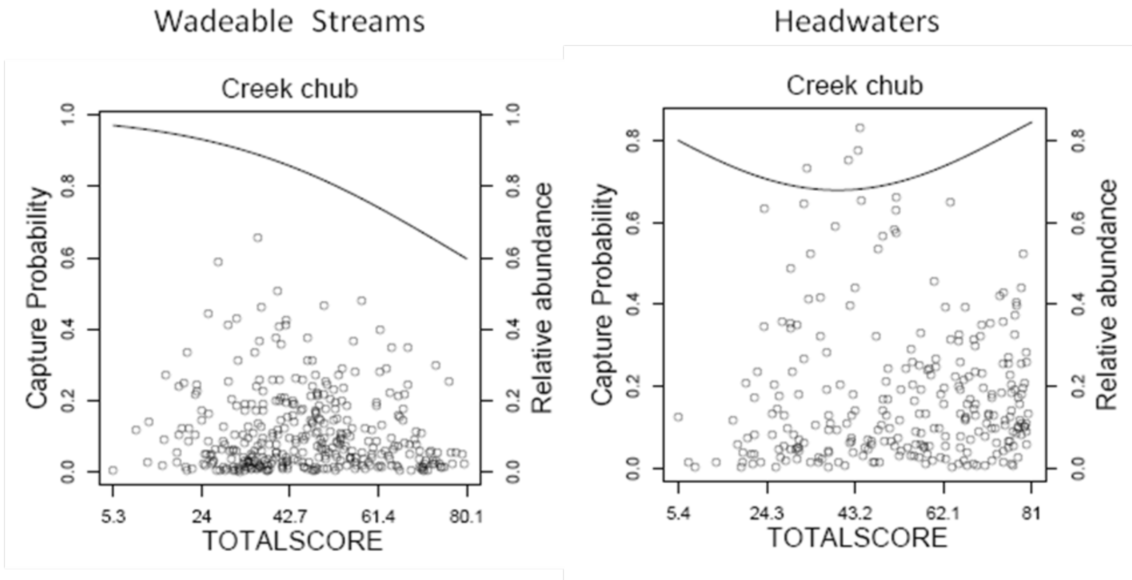


**Figure 8.** Tolerance graphics for creek chub in wadeable streams (left) and headwaters (right). In wadeable streams, creek chub is tolerant, an attribute V species. In headwaters, Creek chub appears equally likely to occur in the nearly all sites, making it a species of intermediate tolerance (attribute IV).

Fish experts identified two additional attributes of highly tolerant taxa, the most tolerant fishes (attribute V-a; the last survivors in the most highly stressed sites, and further divided the nonnative into moderately sensitive nonnative salmonids (Attribute VI; including brown trout and rainbow trout); and highly tolerant non-salmonid, nonnative species (attribute VI-a, including ruffe, sea lamprey, carp).  The distinction separating the highly tolerant attribute V-a fish from the merely tolerant attribute V was based on the collective professional experience and judgment of the fish panel. The panel was of the opinion that identifying the highly tolerant V-a and VI-a attributes would improve discrimination of BCG levels.

A summary breakdown of taxa by attribute group is shown in Tables 3 and 4. The Minnesota taxa lists and final attribute assignments are given in Appendix A. More than 100 invertebrate taxa were left unassigned because participants felt there was insufficient information on the taxa, or they were relatively unusual in the data set. Only 2 fish were left unclassified; both hybrids.

**Table 3.** Examples of macroinvertebrate taxa by attribute group. Assignment to attribute varied for some taxa among habitat (glide-pool and riffle-run), and stream temperature class (warmwater and cold-cool).

| Ecological Attribute | Number of genera* | Example Taxa |
|---|---|---|
| **I Endemic, rare** | 1-2 | *Goera, Apatania* (cold and cool only) |
| **II Highly Sensitive** | 29-41 | *Stempellina, Heleniella, Ephemerella, Paraleuctra, Ophiogomphus, Parapsyche, Diplectrona, Lepidostoma, Dolophilodes, Rhyacophila* |
| **III Intermediate Sensitive** | 107-148 | *Diamesa, Tvetenia, Hexatoma, Plauditus, Parapoynx, Isoperla, Boyeria, Amphinemura, Pycnopsyche, Brachycentrus, Limnephilus* |
| **IV Intermediate Tolerant** | 201-231 | Dytiscidae, Ceratopogonidae, *Polypedilum, Limonia, Perlesta, Heptagenia, Libellula, Hydropsyche, Sphaerium, Planorbella* |
| **V Tolerant** | 25-41 | Erpobdellidae*, Cricotopus, Pseudocloeon*, Corixidae, *Enallagma, Caecidotea,* Physidae |
| **VI Nonnative** | 1 | *Corbicula* |
| **x Unassigned** | 33 | Family identifications or unusual taxa; *Chaoborus, Zavrelia, Didymops*, Nemata |

* range of number of genera assigned to attribute group among 4 groups

**Table 4.** Examples of fish taxa by attribute group.

| Ecological Attribute | Number of species* | Example Species |
|---|---|---|
| **I Endemic, rare** | 1 - 9 | blue sucker, crystal darter, gilt darter, greater redhorse, lake sturgeon, pugnose shiner, river redhorse, shovelnose sturgeon, Topeka shiner |
| **II Highly Sensitive** | 6 - 17 | American brook lamprey, blackchin shiner, brook trout, southern brook lamprey, western sand darter |
| **III Intermediate Sensitive** | 15 - 35 | blacknose shiner, burbot, golden redhorse, hornyhead chub, shorthead redhorse, smallmouth bass |
| **IV Intermediate Tolerant** | 26 - 43 | common shiner, gizzard shad, johnny darter, northern pike, spotfin shiner, white sucker[1] |
| **V Tolerant** | 5 - 18 | creek chub, brassy minnow, brook stickleback, central stoneroller, sand shiner |
| **V-a Highly tolerant** | 7 - 8 | bigmouth shiner, bluntnose minnow, fathead minnow, green sunfish |
| **VI Sensitive Nonnative** | 3 | brown trout, rainbow trout, chinook salmon |
| **VI-a Tolerant nonnative** | 4 | common carp, goldfish, ruffe, threespine stickleback |
| **x unassigned** | | Unidentified fish, hybrids |

*Range of numbers of species assigned to attribute among 9 stream types.
[1] White sucker is classed “tolerant” (attribute V) in wadeable streams only

## 3.2 Site Assignments to BCG Levels

The workgroup examined macroinvertebrate data from 351 samples (9 stream classes), and fish data from 377 samples (9 stream classes). The group was able to reach a majority opinion on the BCG level assignments for all sites reviewed. Data files used in the workshops are in Appendix D, and are summarized in Appendix C. In some cases, there was discussion and some disagreement on which of two adjacent BCG levels a site should be assigned to. These sites were apparently intermediate, with characteristics of both of the adjacent BCG levels.

The panels were able to distinguish 6 separate BCG levels (BCG Levels 1-6), although both levels 1 (nearly pristine) and 6 (extreme degradation) were rare. Nine level 1 samples were identified by the fish group (Appendix C, D), but none were identified by the macroinvertebrate group. In general, macroinvertebrate experts felt that Level 1 and Level 2 sites are not distinguishable using macroinvertebrate data only, in part because rare and endemic taxa are poorly identified, their historic distributions are very poorly known, and finally, the macroinvertebrate sampling methodology is extremely inefficient at finding rare and endemic species. Further examination may be necessary to determine if these sites meet criteria for “minimally disturbed” (Stoddard et al., 2006). Nine level 6 samples were identified by the macroinvertebrate group, and eight by the fish group.

### 3.3 Attributes and BCG Levels

Examinations of taxonomic attributes among the BCG levels determined by the panels showed that several of the attributes are useful in distinguishing levels, and indeed, were used by the biologists for decision criteria. We derived metrics relating to the attributes (taxa richness, percent of taxa, percent of individuals, dominance, etc.). Metric values, by BCG level, are graphically presented as box and whisker plots in Figures 9-16, and statistical summaries of each metric and BCG level are given in Appendix C.

Several generalizations can be made from the panel’s assignments:

Warmwater invertebrates (Figures 9-11):

- Total taxa richness declines from BCG level 2 to poorer BCG levels, but there is much overlap between adjacent BCG Levels.
- Attribute I and II taxa occur in BCG level 2, but decline markedly in Level 3, and are generally absent in levels 4-6
- All sensitive taxa (attributes I, II, and III combined) are common and abundant in Level 2 and decline markedly and almost disappear from levels 5 and 6.
- Intermediate taxa (Attribute IV) increase to high relative richness and relative abundance at BCG Level 4, but decline in Levels 5 and 6.
- Tolerant taxa (attribute V) increase in abundance and dominance at BCG levels 4 to 6, although they are represented at all levels.

Cold and coolwater invertebrates (Figure 12) - Least-disturbed coldwater streams have somewhat lower taxa richness than warmwater streams, and total taxa richness increases somewhat at BCG Level 3. Other attributes and metrics are similar between cold and warm water.

Warmwater fish (Figures 13-15):

- Taxa richness declines from BCG Level 1 to Level 6. All Level 1 sites were large waterbodies (rivers), and so may be more influenced by size than by condition

- Attribute I  taxa were characteristic of BCG Level 1 (but all Level 1 sites were large rivers), and are generally absent in levels 3-6
- All sensitive taxa (attributes I, II, and III combined) are common and abundant in Levels 1 and 2 and decline markedly and almost disappear from levels 5 and 6.
- Intermediate taxa (Attribute IV) are nearly constant throughout the gradient, but decline in Level 6.
- Highly Tolerant taxa (attribute V-a) increase in abundance, dominance and variability at BCG levels 4 to 6, although they are represented at all levels.

High variability of the fish attribute metrics in Figures 13-15 is partly the result of a mix of streams from headwaters to large rivers being represented in the figures. This variability was reduced somewhat when considering single stream types.

Cold and cool water fish (Figure 16) – taxa richness of high-quality coldwater streams is low, consisting typically of brook trout and at most one or two other species. With increasing stress, other species (some warmwater) enter the community.  The number of fish species increases from coldwater to coolwater to warmwater streams. In cold- and coolwater streams, taxa richness increases from BCG levels 2 to 3, but then declines in BCG level 5. Sensitivity and tolerance attributes and metrics of cold and cool streams behave similarly to warmwater streams.

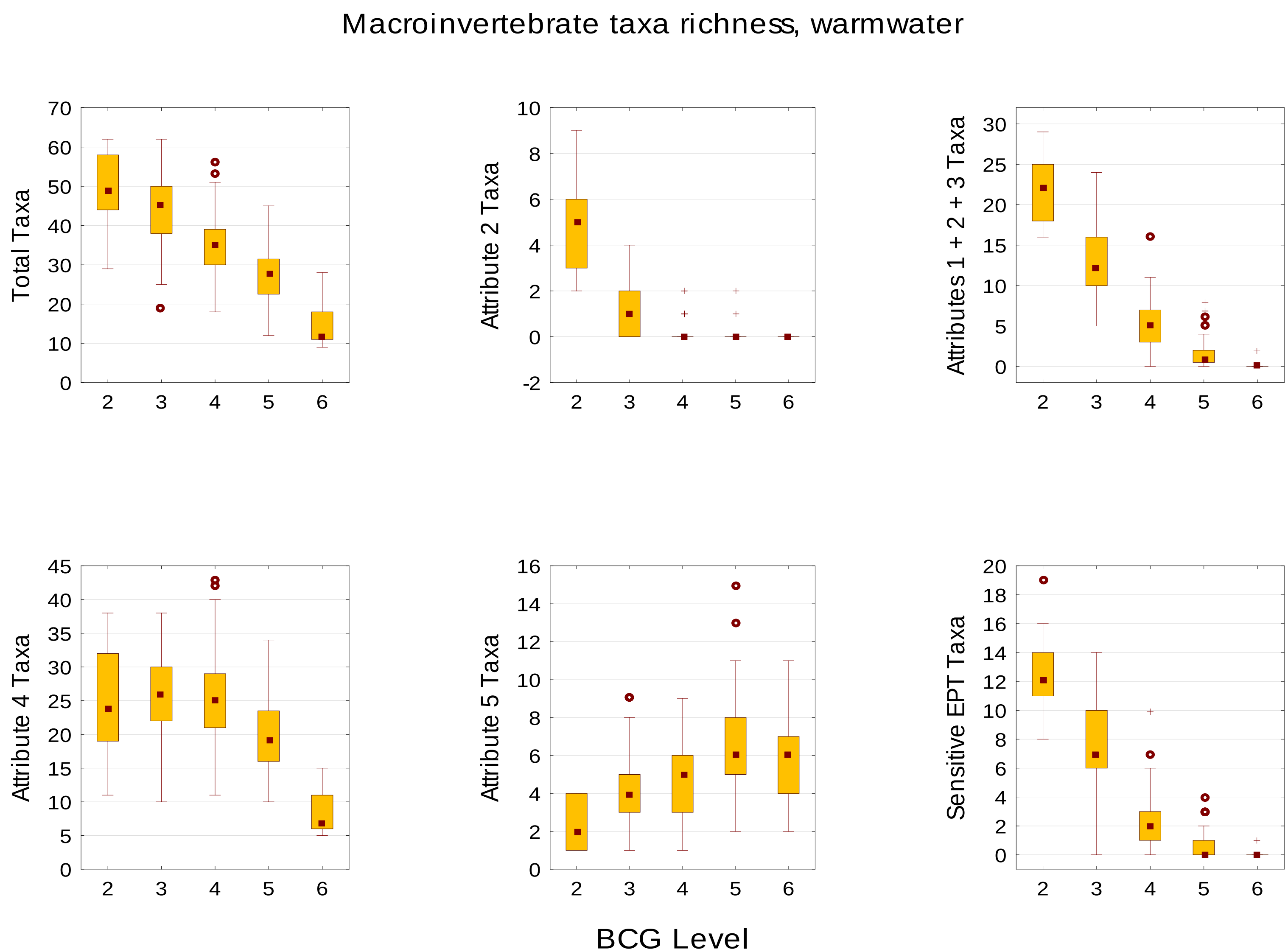


**Figure 9.** Benthic macroinvertebrate attribute taxa richness metrics, by BCG level (all rated warmwater sites).

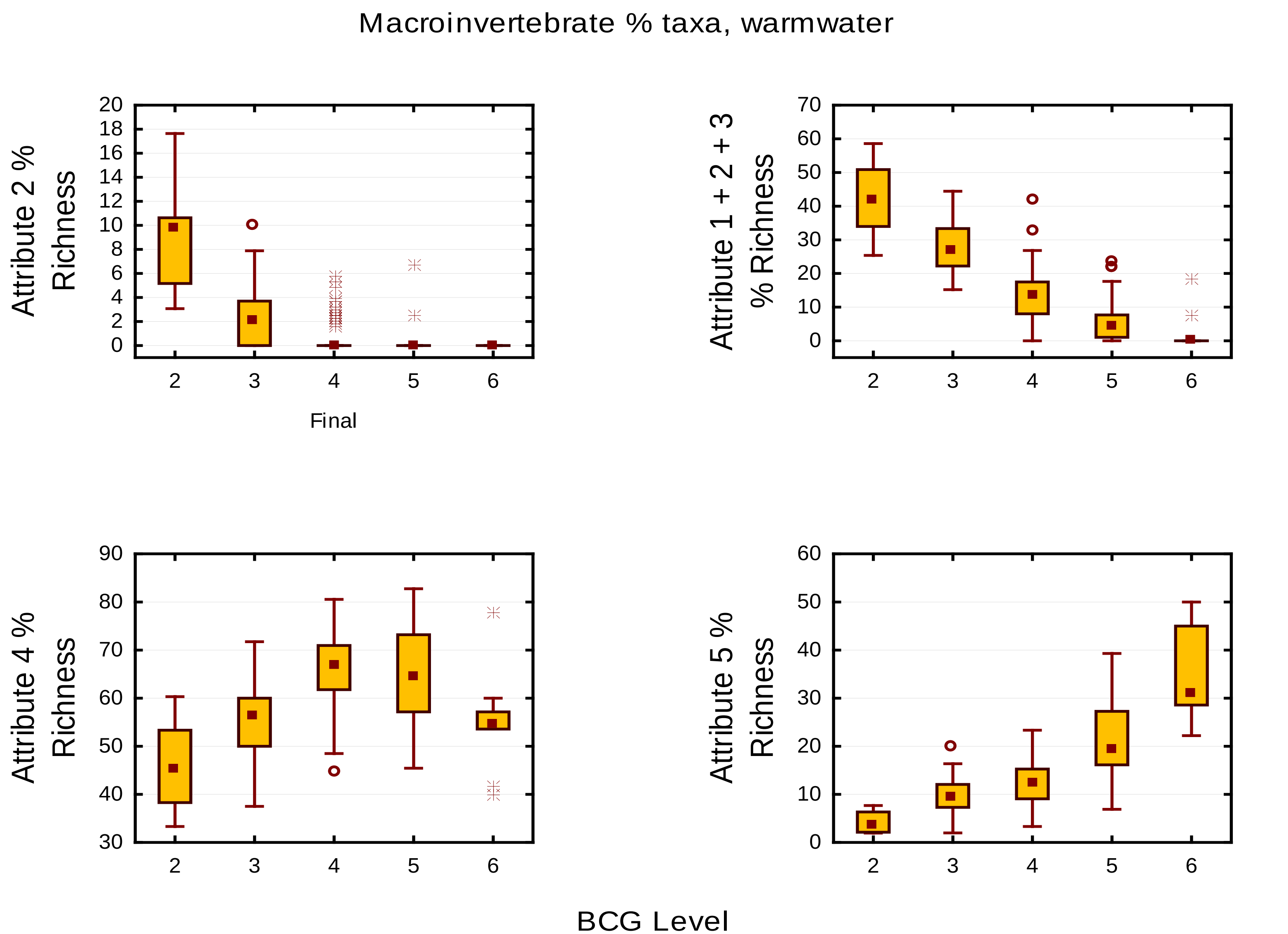


**Figure 10.** Benthic macroinvertebrate attribute relative richness metrics, by BCG level (all rated warmwater sites).

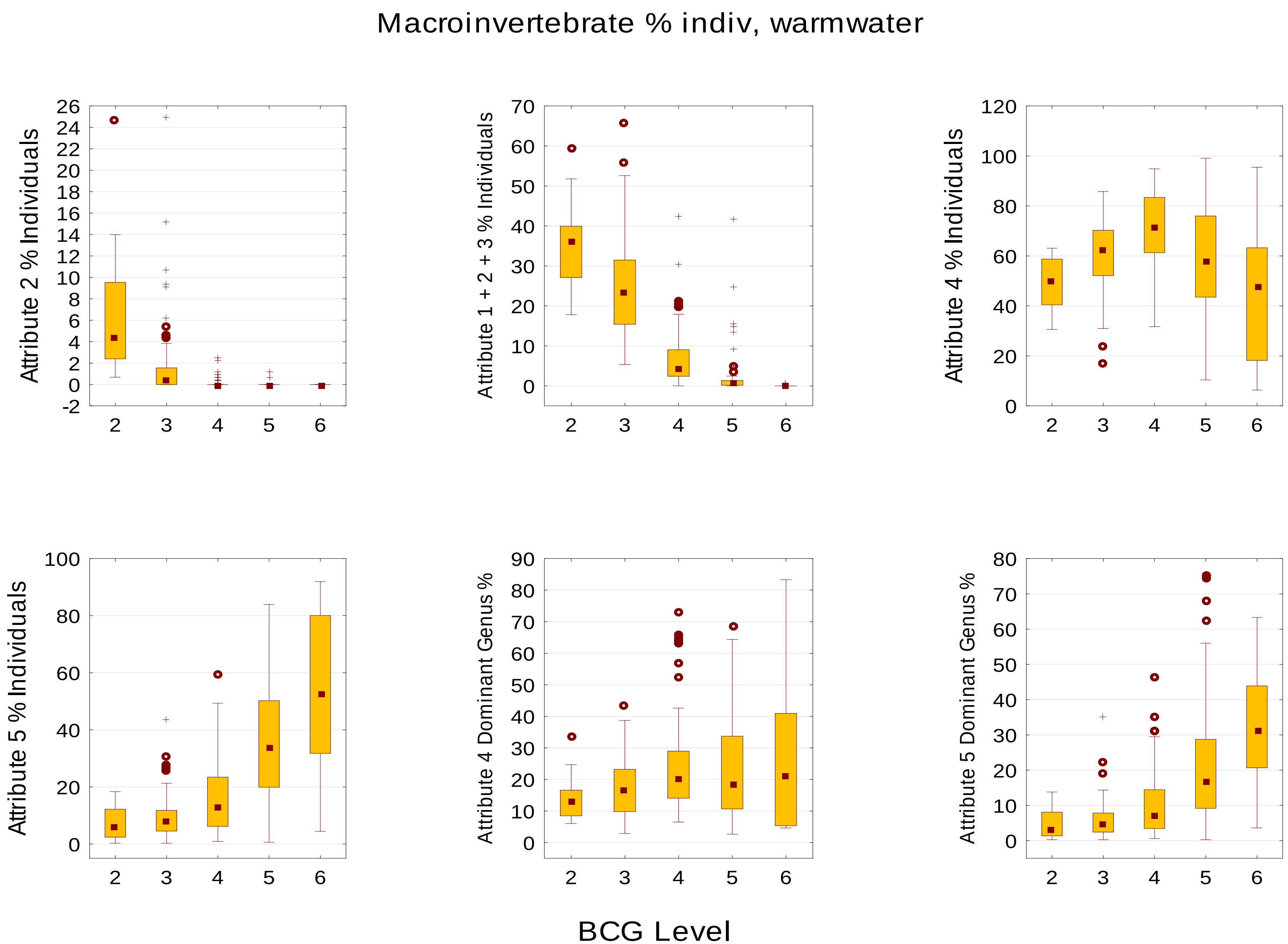


**Figure 11.** Benthic macroinvertebrate attribute proportional abundance and dominance metrics, by BCG level (all rated warmwater sites).

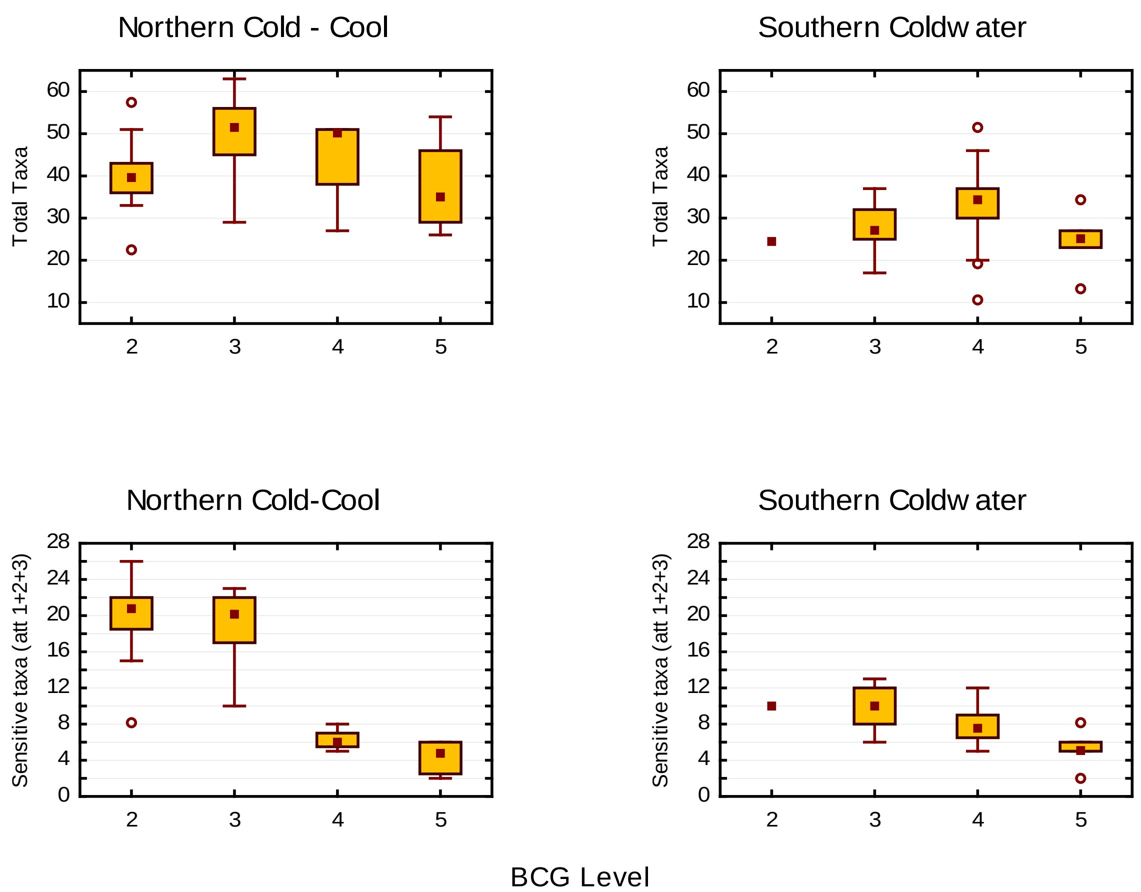


**Figure 12.** Selected cold and coolwater benthic macroinvertebrate metrics, by BCG level (all rated cold and coolwater sites in Minnesota).

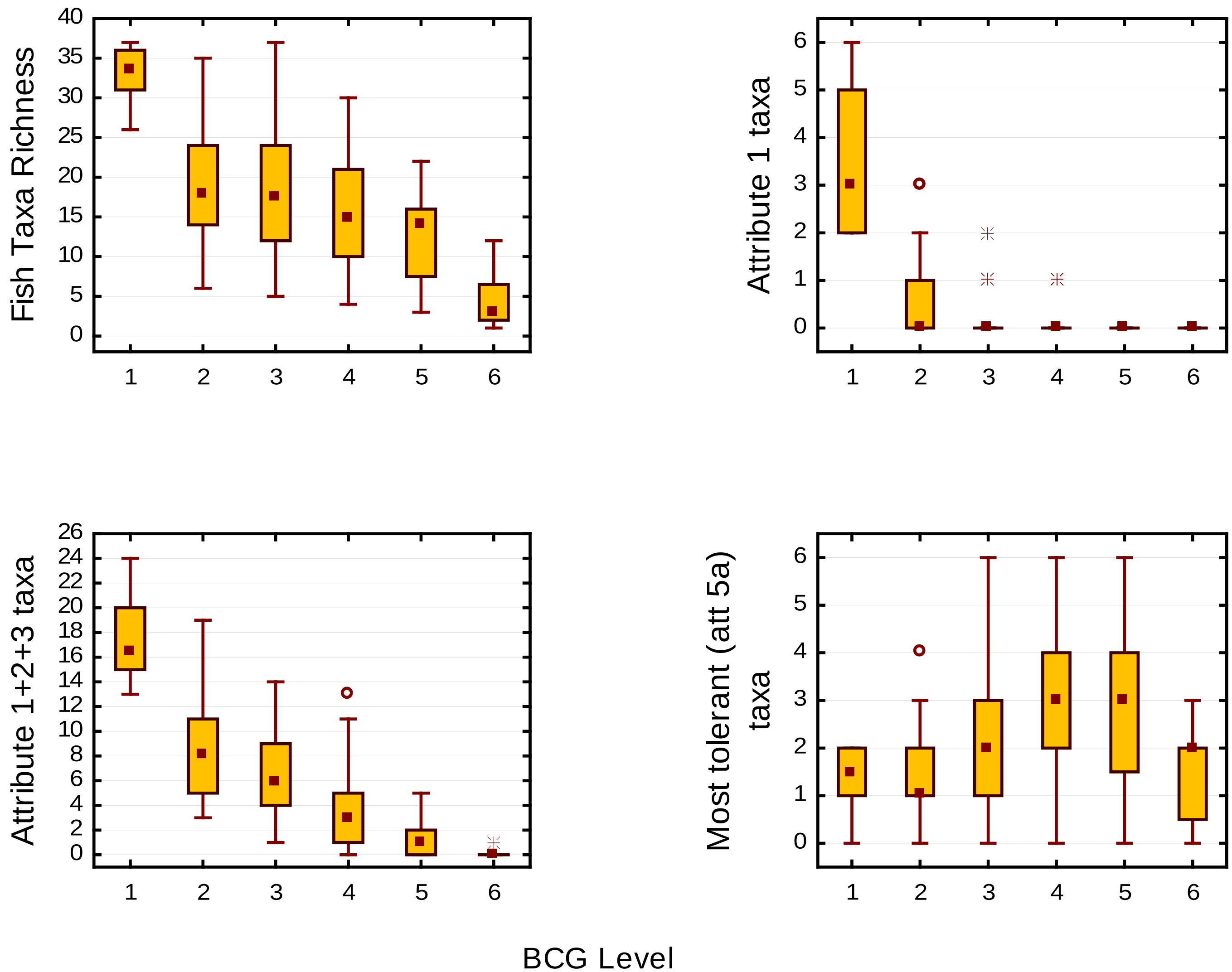


**Figure 13.** Fish attribute taxa richness metrics, by BCG level (all rated warmwater sites).

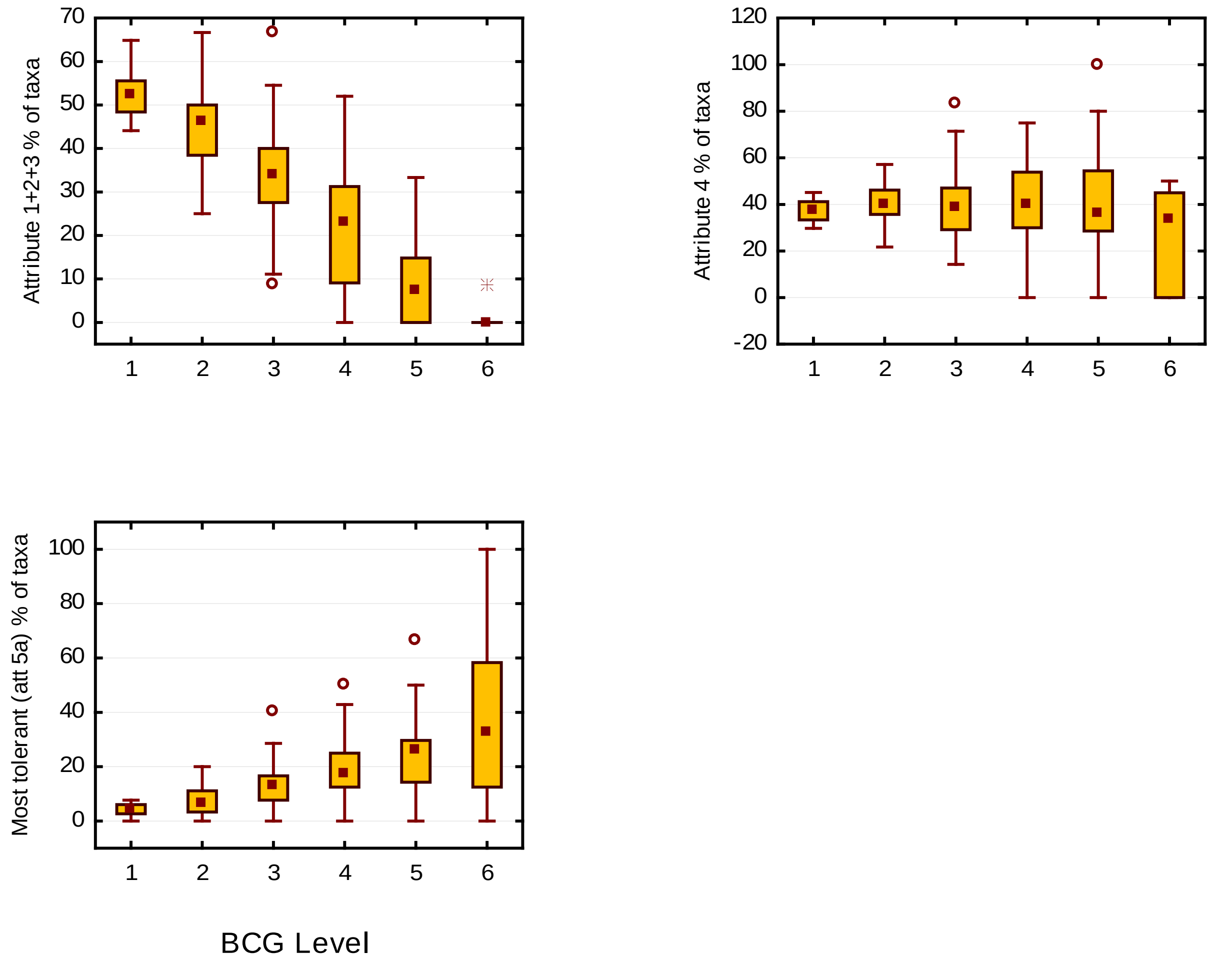


**Figure 14.** Fish attribute relative richness metrics, by BCG level (all rated warmwater sites).

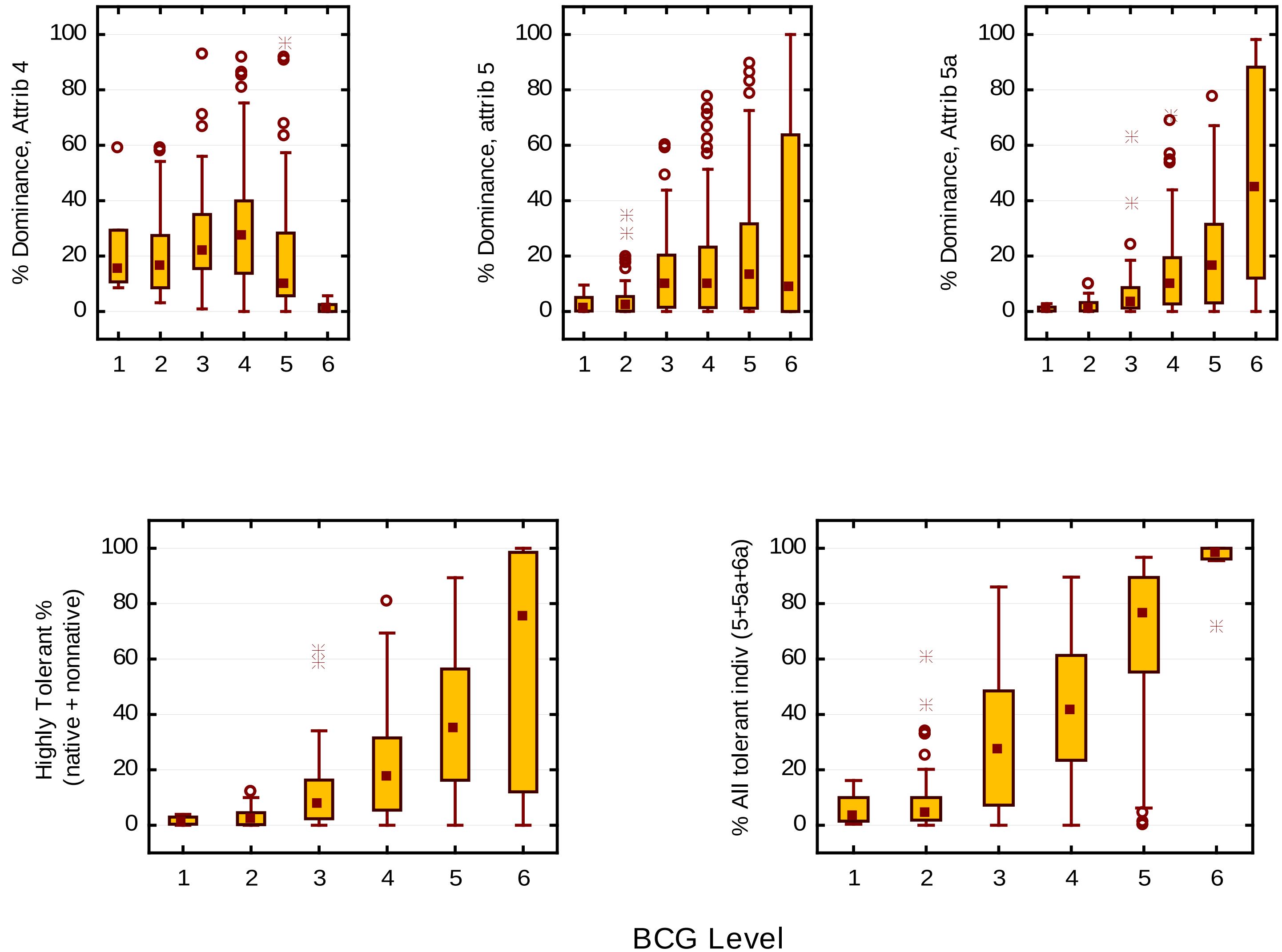


**Figure 15.** Fish attribute proportional abundance and dominance metrics, by BCG level (all rated warmwater sites).

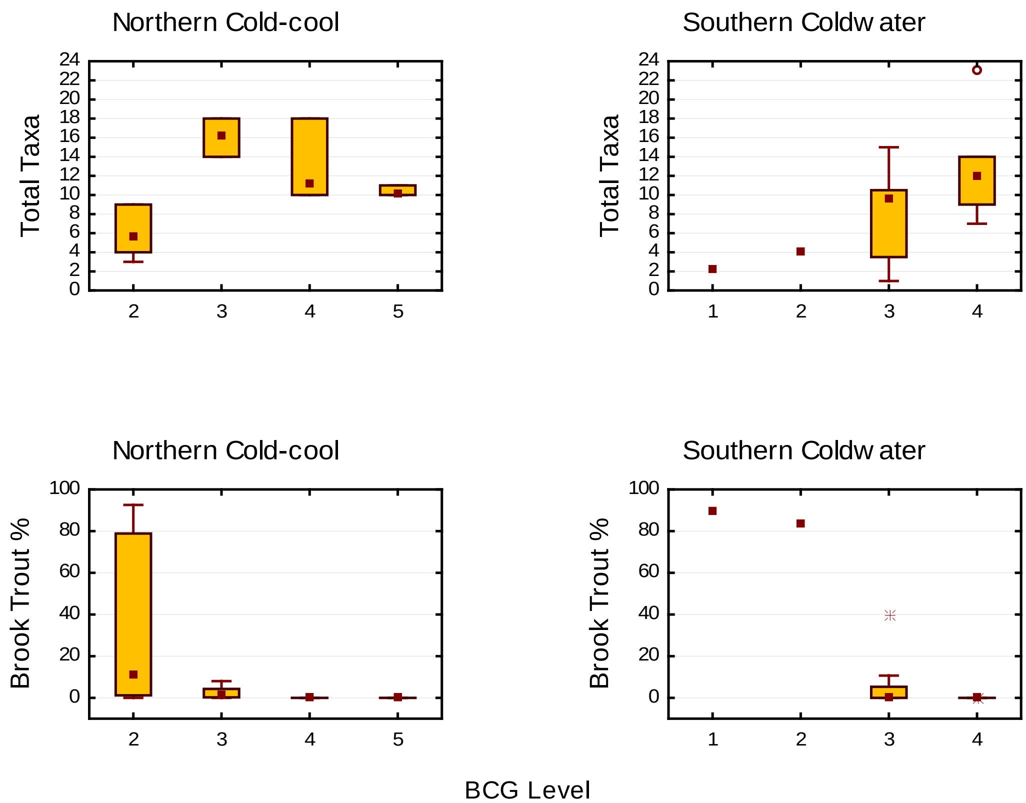


**Figure 16.** Selected cold and coolwater fish metrics, by BCG level (all rated cold and coolwater sites in Minnesota).

# 4.0 MINNESOTA BCG

## 4.1 BCG Rule Development

Panelists followed the descriptions of the BCG levels given in Chapter 1, and gave their reasoning during the deliberations for assigning sites to given levels. These resulted in statements such as, “This sample represents Level 4 because sensitive taxa are severely reduced but still present;” or “attribute IV and V individuals greatly outnumber sensitive individuals.” When panelists agreed on such statements they were used as preliminary rules. Initial quantitative boundaries on the rules were taken from the distributions of attribute metrics in the assigned BCG levels (Figures 9-16; Appendix C). In subsequent sessions the rules were refined by examining more samples and by re-examining samples where the panel and the candidate rules had not resulted in the same outcome. Final rules for all 18 assessed stream classes are shown in tables 5-13. The cold- and coolwater rules have been modified from Gerritsen and Stamp (2012).

In the decision model, rules work as a logical cascade from BCG level 1 to level 6. A sample is first tested against the level 1 rules; if a single rule fails, then the level fails, and the assessment moves down to level 2, and so on (Figure 17). All required rules must be true for a site to be assigned to a level. Level 6 is not listed, because failure at level 5 results in a level 6 assessment.

As described in Section 2.1, membership functions had to be defined for metrics used in the quantitative models. Membership functions are defined in the rules tables as piecewise linear functions (line segments; Figure 3), and they tend to be inequalities (“number of taxa greater than 20”). Rules in Tables 5-13 are expressed as an inequality and a range, e.g., “> 15 - 25,” where the range describes the linear segment as it increases from 0 to 1 for “>” and decreases from 1 to 0 for “<”. So, for a rule expressed as “> 15 - 25 %”, the given membership is 0 at a metric value <=15%; rises linearly to 1 at a metric value of 25%; and remains 1 for values > 25%.

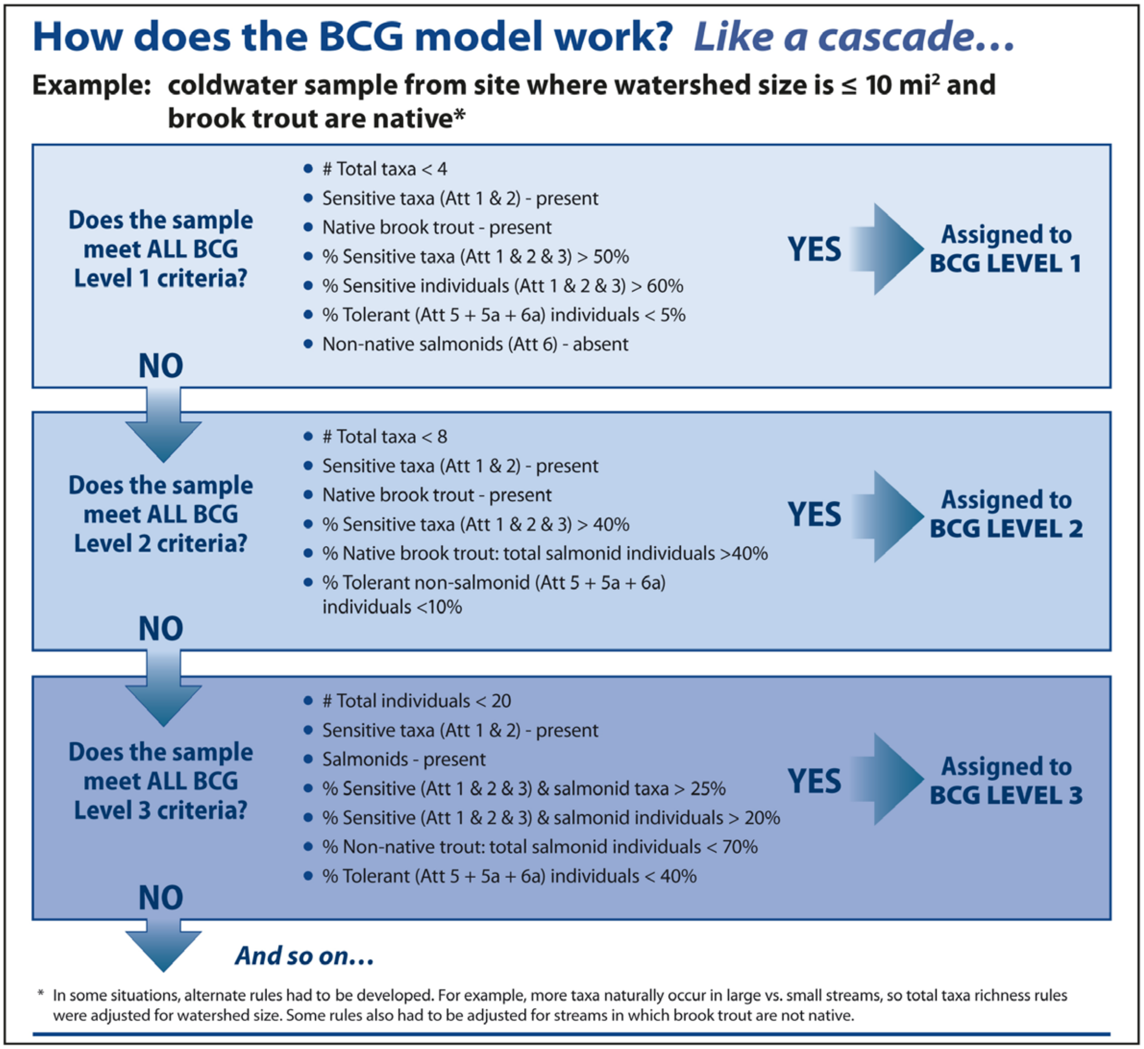


**Figure 17.** Flow chart depicting how rules work as a logical cascade in the BCG model. Illustration taken from Gerritsen and Stamp (2011 draft); is not identical to coldwater model in Table 8.

Some rule sets include alternatives, that is, there may be two or three alternative rules for a certain BCG level (e.g., Table 5). In this case, at least one of the alternatives must be true for the site to be assigned to that level. Alternatives usually reflected a trade-off specified by the panel: for example, a high number of total taxa could offset a low proportion of sensitive taxa, and vice-versa, to be considered (say) BCG Level 3.

In general, panelists preferred to use taxa richness within the sensitive attributes as the most important criteria for determining site BCG level assignments. Thus, the number of sensitive taxa was most often used to distinguish between BCG level 2 and level 3 sites. BCG level 2 should have several highly sensitive taxa (attribute II), but their richness may be reduced in level 3. All of the Level 1 fish samples had 2 or more Attribute I taxa (rare or endemic taxa).

The higher BCG levels all required some minimum quantities or relative richness of sensitive taxa (attributes I, II and III). These included number of taxa, percent of taxa, or percent of individuals. Additionally, for a site to be considered in Level 1 to Level 3, participants often also placed upper limits on the abundance and richness of tolerant taxa, especially abundance and dominance of attribute V. In summary, to be rated in Levels 1 to 3, sites require a minimum richness and sometimes minimum relative abundance (“floor”) of sensitive taxa (attributes I to III), and a maximum abundance and sometimes maximum richness (“ceiling”) of tolerant taxa (attribute V).

There was consistency of attribute metric values, and hence of the rules among the macroinvertebrate stream classes (Tables 10-13). The exceptions to the overall consistency were the glide-pool habitat at BCG level 2, where a greater abundance of tolerant taxa were allowed, and the coldwater streams, which have generally lower expectations of total richness in BCG levels 2 and 3 (Table 13).

Attribute values and the rules were less consistent among the fish stream types. This was in part because overall fish taxa richness is lower than invertebrate richness, and also because richness is strongly dependent on stream size. Headwater streams and wetland-lacustrine streams were relatively depauperate, which results in poorer precision and discriminatory ability of any index or assessment method that uses the fish assemblage data in these habitats.

**Table 5.** Decision rules for fish assemblages in rivers. Rules show the ranges of fuzzy membership functions (see Fig. 9). N shows the number of sites at the indicated BCG level and stream class in the calibration data set.

| Metric | Prairie Rivers (1) | Northern Forest Rivers (4) | | Wetland-Lacustrine (7) | |
|---|---|---|---|---|---|
| **BCG Level 1** | N=2 | N=3 | | N=0[1] | |
| Total taxa | > 25 - 35 | > 16 - 24 | | > 25 - 35 | |
| Endemic taxa (Att 1) | Present | Present | | Present | |
| Att 1+2 taxa | > 2 - 5 | > 1 - 2 | | > 2 - 5 | |
| Att 1+2+3 % taxa | > 45 - 55% | > 35 - 45% | | > 45 - 55% | |
| Att 1+2+3 % ind | > 25 - 35% | > 45 - 55% | | > 25 - 35% | |
| Att 5a or 6a Dominance | | < 7 - 13% | | | |
| Tolerant % ind (5 + 5a + 6a) | < 3 - 7% | | | < 3 - 7% | |
| Highly tol % ind (5a + 6a) | | < 7 - 13% | | | |
| **BCG Level 2** | N=6 | N=15 | | N=7 | |
| | | | | **Alt 1** | **Alt 2** |
| Total taxa | > 16 - 24 | > 6 - 10 | | > 6 - 10 | > 11 - 16 |
| Att 1+2 taxa | Present | | | Present | n/a |
| Att 1+2+3 % taxa | > 35 - 45% | > 25 - 35% | | > 25 - 35% | = alt 1[2] |
| Att 1+2+3 % Ind | > 15 - 25% | > 25 - 35% | | > 30 - 40% | = alt 1[2] |
| Att 5a or 6a Dominance | | < 7 - 13% | | | |
| Highly tol % ind (5a + 6a) | < 7 - 13% | < 7 - 13% | | < 7 - 13% | = alt 1[2] |
| **BCG Level 3** | N=25 | N=11 | | N=7 | |
| | | | | **Alt 1** | **Alt 2** |
| Total taxa | > 11 - 16 | > 6 - 10 | | > 1 - 5 | > 6 - 10 |
| Att 1+2+3 % taxa | > 15 - 25% | > 15 - 25% | | > 10 - 20% | > 20 - 30% |
| Att 1+2+3 % Ind | > 7 - 13% | > 7 - 13% | | > 10 - 20% | > 20 - 30% |
| Tol % ind (5 + 5a + 6a) | | < 25 - 35% | | | |
| Att 5a or 6a Dominance | < 7 - 13% | < 10 - 20% | | | |
| Highly tol % ind (5a + 6a) | <25 - 35% | | | < 7 - 13% | <35 - 45% |
| **BCG Level 4** | N=31 | N=16 | | N=11 | |
| | | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** |
| Total taxa | > 11 - 16 | > 6 - 10 | = alt 1[2] | > 1 - 5 | > 6 - 10 |
| Att 1+2+3 % taxa | 10 - 20% | > 15 - 25% | > 7 - 13% | present | > 7 - 13% |
| Att 1+ 2+3 % Ind | 0 - 1% | > 3 - 7% | present | n/a | > 7 - 13% |
| 1+2+3+4 % Ind | | | | > 45 - 55% | n/a |
| Att 5a or 6a Dominance | <35 - 45% | < 25 - 35% | = alt 1[2] | < 35 - 45% | <45 - 55% |
| Tol % ind (5 + 5a + 6a) | | n/a | < 30 - 40% | | |
| Highly Tol % ind (5a + 6a) | <45 - 55% | < 35 - 45% | = alt 1[2] | | |
| **BCG Level 5** | N=12 | N=2 | | N=6 | |
| Total taxa | > 11 - 16 | 6 - 10 | | >0 - 4 | |
| Att 1+2+3+4 % Taxa | | | | present | |
| Att 5a or 6a Dominance | <65 - 75% | <35 - 45% | | <55 - 65% | |
| Highly tol % ind (5a + 6a) | | <55 - 65% | | | |
| **BCG Level 6** (no rules) | N=1 | N=0 | | N=2 | |

[1]**BCG Level 1 for Wetland-lacustrine (shaded) set to same criteria as Prairie Rivers.**

[2] "= alt 1" the rule is the same as given under Alt 1 for this metric

**Table 6.** Decision rules for fish assemblages in wadeable streams, as in Table 5.

| Metric | Southern Wadeable Streams (2) | | | Northern Wadeable Streams (5) | |
|---|---|---|---|---|---|
| **BCG Level 1** | N=0[1] | | | N=0[1] | |
| total taxa | > 25 - 35 | | | > 25 - 35 | |
| 1 Endemic taxa | present | | | present | |
| Att 1+2 taxa | >2 - 5 | | | >2 - 5 | |
| att 1+2+3 % taxa | > 45 - 55% | | | > 45 - 55% | |
| att 1+2+3 % Ind | > 25 - 35% | | | > 25 - 35% | |
| Tol % ind (5 + 5a + 6a) | < 3 - 7% | | | < 3 - 7% | |
| **BCG Level 2** | N=1 | | | N=8 | |
| total taxa | > 16 - 24 | | | >11 - 16 | |
| att 1+2+3 total taxa | > 6 - 10 | | | | |
| att 1+2+3 % taxa | > 35 - 45% | | | > 25 - 35% | |
| att 1+2+3 % Ind | > 7 - 13% | | | > 7 - 13% | |
| att 5a or 6a dom | | | | < 7 - 13% | |
| Tol % ind (5 + 5a + 6a) | | | | < 30 - 40% | |
| Highly tol % ind (5a + 6a) | < 15 - 25% | | | | |
| **BCG Level 3** | N=4 | | | N=10 | |
| total taxa | >11 - 16 | | | > 11 - 16 | |
| att 1+2+3 % taxa | > 7 - 13% | | | > 20 - 30% | |
| att 1+2+3 % Ind | > 3 - 7% | | | > 3 - 7% | |
| att 5a or 6a dom | < 15 - 25% | | | < 7 - 13% | |
| Highly tol % ind (5a + 6a) | < 35 - 45% | | | < 15 - 25% | |
| **BCG Level 4** | N=10 | | | N=15 | |
| | **Alt 1** | **Alt 2** | | **Alt 1** | **Alt 2** |
| total taxa | > 6 - 10 | > 16 - 24 | | > 6 - 10 | = alt 1[2] |
| att 1+2+3 % taxa | 0 - 1% | n/a | | > 3 - 7% | n/a |
| att 1+ 2+3 % Ind | 0 - 1% | n/a | | present | n/a |
| 1+2+3+4 % Ind | | | | n/a | > 65 - 75% |
| att 1+2+3+4 % taxa | | | | n/a | > 45 - 55% |
| att 5a or 6a dom | < 45 - 55% | = alt 1[2] | | < 25 - 35% | < 15 - 25% |
| Tol % ind (5 + 5a + 6a) | <65 - 75% | = alt 1[2] | | | |
| Highly tol % ind (5a + 6a) | <55 - 65% | = alt 1[2] | | <55 - 65% | n/a |
| **BCG Level 5** | N=18 | | | N=4 | |
| | **Alt 1** | **Alt 2** | **Alt 3** | | |
| total taxa | > 3 - 7 | > 11 - 16 | > 16 - 24 | >1 - 5 | |
| att 1+2+3 % Taxa | n/a | present | n/a | | |
| att 1+2+3+4 % Taxa | > 7 - 13% | n/a | > 15 - 25% | > 10 - 20% | |
| att 5a or 6a dom | < 45 - 55% | n/a | n/a | < 65 - 75% | |
| Highly tol % ind (5a + 6a) | < 65 - 75% | n/a | n/a | | |
| **BCG Level 6** (no rules) | N=2 | | | N=0 | |

[1]**BCG Level 1 (shaded) set to same criteria as Prairie Rivers, Table 4-1.**
[2] "= alt 1" the rule is the same as given under Alt 1 for this metric

**Table 7.** Decision rules for fish assemblages in headwater streams, as in Table 5.

| **Metric** | **Southern Headwaters (3)** | | **Northern Headwaters (6)** | | |
|---|---|---|---|---|---|
| **BCG Level 1** | N=0[1] | | N=0[1] | | |
| total taxa | > 25 - 35 | | > 25 - 35 | | |
| 1 Endemic taxa | present | | present | | |
| Att 1+2 taxa | >2 - 5 | | >2 - 5 | | |
| att 1+2+3 % taxa | > 45 - 55% | | > 45 - 55% | | |
| att 1+2+3 % Ind | > 25 - 35% | | > 25 - 35% | | |
| Tol % ind (5 + 5a + 6a) | < 3 - 7% | | < 3 - 7% | | |
| **BCG Level 2** | N=0 | | N=4 | | |
| total taxa | > 6 - 10 | | > 6 - 10 | | |
| att 1+2+3 total taxa | > 0 - 4 | | > 1 - 4 | | |
| att 1+2+3 % taxa | >15 - 25% | | >15 - 25% | | |
| att 1+2+3 % Ind | > 15 - 25% | | > 15 - 25% | | |
| att 5a or 6a dom | < 3 - 7% | | < 3 - 7% | | |
| Highly tol % ind (5a + 6a) | < 7 - 13% | | < 7 - 13% | | |
| **BCG Level 3** | N=3 | | N=9 | | |
| total taxa | > 5 - 9 | | > 3 - 7 | | |
| att 1+2+3 % taxa | present | | > 10 - 20% | | |
| att 1+2+3 % Ind | | | > 7 - 13% | | |
| att 1+2+3+4 % taxa | 15 - 25% | | | | |
| att 5a or 6a dom | < 3 - 7% | | < 25 - 35% | | |
| Highly tol % ind (5a + 6a) | < 7 - 13% | | < 25 - 35% | | |
| **BCG Level 4** | N=22 | | N=10 | | |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** | **Alt 3** |
| total taxa | > 4 - 8 | = alt 1[2] | > 6 - 10 | > 2 - 5 | present |
| att 1+2+3 % taxa | n/a | present | > 7 - 13% | = alt 1[2] | = alt 1[2] |
| att 1+ 2+3 % Ind | | | > 3 - 7% | = alt 1[2] | = alt 1[2] |
| att 1+2+3+4 % taxa | > 7 - 13% | = alt 1[2] | | | |
| att 5a or 6a dom | < 45 - 55% | n/a | < 35 - 45% | <25 - 35% | absent |
| Highly tol % ind (5a + 6a) | | | | | |
| **BCG Level 5** | N=4 | | N=8 | | |
| total taxa | > 1 - 5 | | > 0 - 4 | | |
| att 1+2+3+4 % Taxa | | | > 7 - 13% | | |
| att 5a or 6a dom | < 65 - 75% | | | | |
| **BCG Level 6** (no rules) | N=3 | | N=0 | | |

**[1]BCG Level 1 for Wetland-lacustrine (shaded) set to same criteria as Prairie Rivers.**
**[2] "= alt 1" the rule is the same as given under Alt 1 for this metric**

**Table 8.** Decision rules for fish assemblages in southern coldwater streams (Driftless area in MN). Modified from Gerritsen and Stamp (2013). Numbers (N) include sites in Wisconsin and Michigan.

| **Metric** | **Southern Coldwater (10)** | | | |
|---|---|---|---|---|
| **BCG Level 1** | N=4 | | | |
| | **Brook Trout native** | | **Brook trout not native** | |
| Total taxa | < 2 - 5 | | = alt 1[1] | |
| Brook trout | present | | absent | |
| Att 1+2 taxa | 0 - 1 | | = alt 1[1] | |
| Att 1+2+3 % taxa | > 45 - 55% | | = alt 1[1] | |
| Att 1+2+3 % Ind | > 55 - 65% | | = alt 1[1] | |
| Other Salmonidae (nonnative) | absent | | = alt 1[1] | |
| Tolerant% ind (5 + 5a + 6a) | < 3 - 7% | | = alt 1[1] | |
| **BCG Level 2** | N=9 | | | |
| | **Brook Trout native** | | **Brook trout not native** | |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** |
| Total taxa (by area) | if area < 10, ( < 6-10), else ( > 2-5 AND < 11-16) | | | |
| Brook trout % ind | present | = alt 1[1] | n/a | n/a |
| Att 1+2+3 % taxa | > 35 - 45% | > 15 - 25% | n/a | > 15 - 25% |
| Att 1+2+3+6 % Ind | n/a | n/a | > 65 - 75% | n/a |
| BT % of total Salmonidae | > 35 - 45% | = alt 1[1] | n/a | n/a |
| Tolerant% ind (5 + 5a + 6a) | < 7 - 13% | < 0 - 1% | n/a | < 7 - 13% |
| **BCG Level 3** | N=17; BT status not relevant for Levels 3 - 6 | | | |
| | **Alt 1** | | **Alt 2** | |
| Number individuals (by area) | | | | |
| Att 1+2 taxa | n/a | | 0 - 1 | |
| sensitive + Salmonidae % taxa | 20 - 30% | | = alt 1[1] | |
| sensitive + Salmonidae % Ind | 15 - 25% | | = alt 1[1] | |
| BT + Att 6 % ind (all trout) | 0 - 1% | | = alt 1[1] | |
| Att 4-5 dom | < 45 - 55% | | = alt 1[1] | |
| Tolerant% ind (5 + 5a + 6a) | < 7 - 13% | | < 35 - 45% | |
| **BCG Level 4** | N=9 | | | |
| Att 1+2+3+6 % taxa | 3 - 7% | | | |
| Att 1+2+3+6 % Ind | 3 - 7% | | | |
| % Taxa (5 + 5a + 6a) | < 40 - 50% | | | |
| Highly Tolerant % ind (5a + 6a) | < 7 - 13% | | | |
| **BCG Level 5** | N=8 | | | |
| Total taxa | > 1 - 4 | | | |
| Att 1+2+3+4 % Taxa | > 7 - 13% | | | |
| **BCG Level 6** (no rules) | N=0 | | | |

[1] **"= alt 1": the rule is the same as given under Alt 1 for this metric**

**Table 9.** Decision rules for fish assemblages in northern cold-cool water streams. Modified from Gerritsen and Stamp (2011). Numbers (N) include sites in Wisconsin and Michigan.

| **Metric** | **Northern Cold-cool (11)** | |
|---|---|---|
| | N=0 | |
| **BCG Level 1** | **Brook Trout native** | **Brook trout not native** |
| Total taxa | > 2 - 5 and < 11 - 16 | = alt 1[1] |
| Brook trout | present | absent |
| Att 1+2 taxa | 0 - 1 | = alt 1[1] |
| Att 1+2+3 % taxa | > 35 - 45% | = alt 1[1] |
| Att 1+2+3 % Ind | > 35 - 45% | = alt 1[1] |
| Other Salmonidae (nonnative) | absent | = alt 1[1] |
| Tolerant % ind (5 + 5a + 6a) | < 3 - 7% | = alt 1[1] |
| **BCG Level 2** | N=14 | |
| total taxa (by area) | < 16 - 24 | = alt 1[1] |
| Brook trout % ind | present | n/a |
| Att 1+2 taxa | 0 - 1 | n/a |
| Att 1+2+3 % taxa | > 25 - 35% | = alt 1[1] |
| Att 1+2+3 % Ind | > 17 - 27% | = alt 1[1] |
| BT % of total Salmonidae | > 35 - 45% | n/a |
| Tolerant % ind (5 + 5a + 6a) | <15 - 25% | = alt 1[1] |
| | N=13; BT status not relevant for Levels 3 - 6 | |
| **BCG Level 3** | **Alt 1** | **Alt 2** |
| Number individuals (by area) | | |
| Total taxa | <16 - 24 | = alt 1[1] |
| Sensitive + Salmonidae % taxa | Sensitive + Salmonidae % taxa > tolerant % taxa (Att 5, 5a, 6a) | n/a |
| Sensitive + Salmonidae % Ind | n/a | Sensitive + Salmonidae % ind > tolerant % ind (Att 5, 5a, 6a) |
| Att 4-5 dom | IF area > 5, THEN < 60 - 70 | = alt 1[1] |
| Tolerant% ind (5 + 5a + 6a) | | |
| Highly tolerant % ind (5a + 6a) | <3 - 7% | = alt 1[1] |
| **BCG Level 4** | N=9 | |
| Att 1+2+3+6 % taxa | > 3 - 7% | |
| Highly Tolerant % ind (5a + 6a) | < 15 - 25% | |
| **BCG Level 5** | N=6 | |
| Total taxa | > 1 - 4 | |
| Att 1+2+3+4 % Taxa | > 7 - 13% | |
| **BCG Level 6** (no rules) | N=0 | |

[2] **“= alt 1” the rule is the same as given under Alt 1 for this metric**

**Table 10.** Decision rules for macroinvertebrate assemblages in rivers, as in Table 5.

| **Metric** | **Prairie Rivers (2)** | **Northern Forest Rivers (1)** | |
|---|---|---|---|
| **BCG Level 2** | N=0 | N=7 | |
| Total taxa | > 35 - 45 | > 35 - 45 | |
| Att 1+2 taxa | > 2 - 5 | > 1 - 4 | |
| Att 1+2+3 % taxa | > 20 - 30% | > 20 - 30% | |
| Att 1+2+3 % Ind | > 10 - 20% | > 10 - 20% | |
| Att 5 % Ind | < 7 - 13% | < 7 - 13% | |
| Sensitive EPT taxa | > 6 - 10 | > 6 - 10 | |
| **BCG Level 3** | N=6 | N=15 | |
| | | **Alt 1** | **Alt 2** |
| Total taxa | > 25 - 35 | > 20 - 30 | > 40 - 50 |
| Att 1+2+3 % taxa | > 10 - 20% | > 15 - 25% | > 7 - 13% |
| Att 1+2+3 % Ind | > 3 - 7% | > 7 - 13% | > 3 - 7% |
| Att 5 % Ind | < 15 - 25% | < 35 - 45% | = alt 1[1] |
| Att 5 Dom | < 10 - 20% | < 25 - 35% | = alt 1[1] |
| Sensitive EPT taxa | > 2 - 5 | > 2 - 5 | = alt 1[1] |
| **BCG Level 4** | N=19 | N=6 | |
| Total taxa | > 16 - 24 | > 16 - 24 | |
| Att 1+2+3 % taxa | > 3 - 7% | > 7 - 13% | |
| Att 1+2+3 % Ind | present | > 3 - 7% | |
| Att 5 % Ind | < 45 - 55% | < 45 - 55% | |
| Att 5 Dom | < 35 - 45% | < 35 - 45% | |
| Sensitive EPT taxa | present | present | |
| **BCG Level 5** | N=4 | N=0 | |
| Total taxa | > 16 - 24 | > 16 - 24 | |
| Att 5 % taxa | < 35 - 45% | < 35 - 45% | |
| Att 5 Dom | < 65 - 75 | < 65 - 75 | |
| **BCG Level 6** (no rules) | N=0 | N=0 | |

[2] "= alt 1" the rule is the same as given under Alt 1 for this metric

**Table 11.** Decision rules for macroinvertebrate assemblages in riffle-run habitat, as in Table 5.

| **Metric** | **5 Southern riffle-run** | | **3 Northern forest riffle-run** | |
|---|---|---|---|---|
| **BCG Level 2** | N=0 | | N=2 | |
| Total taxa | > 35 - 45 | | > 35 - 45 | |
| Att 1+2 taxa | > 2 - 5 | | > 2 - 5 | |
| Att 1+2+3 % taxa | > 45 - 55% | | > 45 - 55% | |
| Att 1+2+3 % Ind | > 25 - 35% | | > 25 - 35% | |
| Att 5 % Ind | < 3 - 7% | | < 7 - 13% | |
| Sensitive EPT taxa | > 11-16 | | > 9 - 14 | |
| **BCG Level 3** | N=8 | | N=17 | |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** |
| Total taxa | > 25 - 35 | > 40 - 50 | > 25 - 35 | > 40 - 50 |
| Att 1+2+3 % taxa | > 15 - 25% | > 7 - 13% | > 15 - 25% | > 10 - 20% |
| Att 1+2+3 % Ind | > 10 - 20% | > 3 - 7% | > 7 - 13% | > 3 - 7% |
| Att 4 Dom | | | < 20 - 30% | = alt 1[1] |
| Att 5 % Ind | < 15 - 25% | = alt 1[1] | | |
| Att 5 Dom | < 7 - 13% | = alt 1[1] | < 30 - 40% | = alt 1[1] |
| Sensitive EPT taxa | > 2 - 5 | = alt 1[1] | > 2 - 5 | = alt 1[1] |
| **BCG Level 4** | N=19 | | N=9 | |
| | **Alt 1** | **Alt 2** | | |
| Total taxa | > 16 - 24 | > 25 - 35 | > 16 - 24 | |
| Att 1+2+3 % taxa | > 3 - 7% | present | > 7 - 13% | |
| Att 1+2+3 % Ind | > 3 - 7% | present | present | |
| Att 5 % Ind | < 30 - 40% | < 35 - 45% | < 30 - 40% | |
| Att 5 Dom | < 15 - 25% | = alt 1[1] | < 20 - 30% | |
| Sensitive EPT | present | = alt 1[1] | present | |
| **BCG Level 5** | N=20 | | N=2 | |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** |
| Total taxa | > 11 - 16 | > 16 - 24 | > 11 - 16 | > 16 - 24 |
| Att 2+3+4 % taxa | n/a | > 45 - 55% | | |
| Att 5 % taxa | < 35 - 45% | n/a | < 35 - 45% | < 45 - 55% |
| Att 5 Dom | < 55 - 65% | n/a | < 55 - 65% | = alt 1[1] |
| **BCG Level 6** (no rules) | N=0 | | N=0 | |

[2] **“= alt 1” the rule is the same as given under Alt 1 for this metric**

**Table 12.** Decision rules for macroinvertebrate assemblages in glide-pool habitat, as in Table 5.

| Metric | 7 Prairie glide-pool | | 6 Southern forest glide-pool | | 4 Northern Forest glide-Pool |
|---|---|---|---|---|---|
| **BCG Level 2** | N=0 | | N=0 | | N=5 |
| Total taxa | > 25 - 35 | | > 25 - 35 | | > 20 - 30 |
| Att 1+2 taxa | present | | present | | present |
| Att 1+2+3 % taxa | > 25 - 35% | | > 25 - 35% | | > 25 - 35% |
| Att 1+2+3 % Ind | > 15 - 25% | | > 15 - 25% | | > 15 - 25% |
| Att 4 Dom | < 10 - 20% | | < 10 - 20% | | < 10 - 20% |
| Att 5 % Ind | < 15 - 25% | | < 15 - 25% | | < 15 - 25% |
| Sensitive EPT taxa | > 6-10 | | > 6-10 | | > 6-10 |
| **BCG Level 3** | N=3 | | N=5 | | N=13 |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** | |
| Total taxa | > 25 - 35 | > 40 - 50 | > 14 - 22 | > 25 - 35 | > 16 - 24 |
| Att 1+2+3 % taxa | > 10 - 20% | = alt 1[1] | > 10 - 20% | > 7 - 13% | > 10 - 20% |
| Att 1+2+3 % Ind | > 3 - 7% | present | > 3 - 7% | present | > 3 - 7% |
| Att 4 Dom | | | < 45 - 55% | = alt 1[1] | |
| Att 5 % Ind | < 30 - 40% | = alt 1[1] | < 15 - 25% | = alt 1[1] | < 25 - 35% |
| Att 5 Dom | < 10 - 20% | = alt 1[1] | < 10 - 20% | = alt 1[1] | < 15 - 25% |
| Sensitive EPT taxa | > 2 - 5 | = alt 1[1] | present | = alt 1[1] | > 2 - 5 |
| **BCG Level 4** | N=19 | | N=18 | | N=12 |
| Total taxa | > 16 - 24 | | > 14 - 22 | | > 16 - 24 |
| Att 1+2+3 % taxa | > 3 - 7% | | > 0 - 4% | | > 3 - 7% |
| Att 1+2+3 % Ind | present | | > 0 - 2% | | present |
| Att 5 % taxa | | | < 20 - 30% | | |
| Att 5 % Ind | < 35 - 45% | | < 30 - 40% | | < 25 - 35% |
| Att 5 Dom | < 20 - 30% | | < 15 - 25% | | < 20 - 30% |
| **BCG Level 5** | N=26 | | N=13 | | N=2 |
| Total taxa | > 12-20 | | > 11 - 16 | | > 11 - 16 |
| Att 5 % taxa | < 50 - 60% | | < 55 - 65% | | < 35 - 45% |
| Att 5 Dom | < 45 - 55% | | < 55 - 65% | | < 55 - 65% |
| **BCG Level 6** (no rules) | N=5 | | N=1 | | N=3 |

[2] **“= alt 1” the rule is the same as given under Alt 1 for this metric**

**Table 13.** Decision rules for macroinvertebrate assemblages in cold and cool waters. Modified from Gerritsen and Stamp (2013). Minnesota sites only

| Metric | 9 Southern Coldwater | | 8 Northern Cold-cool | |
|---|---|---|---|---|
| **BCG Level 2** | N=1 | | N=16 | |
| Total taxa | > 11 - 16 | | > 16 - 24 | |
| Att 1+2 taxa | | | > 2 - 5 | |
| Att 1+2 % taxa | > 7 - 13% | | | |
| Att 1+2 % ind | | | > 4 - 10% | |
| Att 1+2+3 % taxa | > 25 - 35% | | > 25 - 35% | |
| Att 1+2+3 % Ind | > 25 - 35% | | > 25 - 35% | |
| Att 5 Dom | < 3 - 7% | | | |
| Sensitive EPT % Ind | > 7 - 13% | | > 7 - 13% | |
| **BCG Level 3** | N=17 | | N=10 | |
| | **Alt 1** | **Alt 2** | **Alt 1** | **Alt 2** |
| Total taxa | > 11 - 16 | = alt 1[1] | > 16 - 24 | = alt 1[1] |
| Att 1+2 taxa | | | present | n/a |
| Att 1+2+3 % taxa | > 15 - 25% | > 35 - 45% | > 15 - 25% | = alt 1[1] |
| Att 1+2+3 % Ind | > 7 - 13% | > 3 - 7% | > 7 - 13% | > 35 - 45% |
| Att 4 Dom | < 45 - 55% | = alt 1[1] | | |
| Att 5 % Ind | < 15 - 25% | = alt 1[1] | | |
| Att 5 Dom | | | < 7 - 13% | = alt 1[1] |
| Sensitive EPT % taxa | > 7 - 13% | = alt 1[1] | > 7 - 13% | = alt 1[1] |
| **BCG Level 4** | N=20 | | N=4 | |
| Total taxa | > 6 - 10 | | > 11 - 16 | |
| Att 1+2+3 % taxa | > 7 - 13% | | > 7 - 13% | |
| Att 1+2+3 % Ind | > 3 - 7% | | present | |
| Att 5 % Ind | < 35 - 45% | | < 55 - 65% | |
| Sensitive EPT | present | | present | |
| **BCG Level 5** | N=5 | | N=4 | |
| Total taxa | > 6 - 10 | | > 11 - 16 | |
| Att 5 % taxa | < 55 - 65% | | | |
| Att 5 Dom | | | < 55 - 65% | |
| **BCG Level 5** | N=0 | | N=0 | |

[2] **“= alt 1” the rule is the same as given under Alt 1 for this metric**

## 4.2 Model Performance

Model performance was compared to the panel assignments (i.e., the calibration data set), and is shown in Table 14. The initial effort included panel ratings of a smaller, independent data set to assess the model's post-calibration performance. However, these data were later used to adjust the model. Accordingly, model performance can only be judged based on the calibration data set.

The performance range of the fish models was 77 % to 89% correct, and the benthic models were 79% to 98% correct, in replicating the panel decisions. All of the model assignments were within one level of the majority panel opinion.

**Table 14.** Automated model performance at replicating panel decisions.

| Fish | | | Benthic macroinvertebrates | | |
|---|---|---|---|---|---|
| **Stream Class** | **N** | **% Correct** | **Stream Class** | **N** | **% Correct** |
| Prairie Rivers (1) | 75 | 76% | Prairie Rivers (north and south) (2) | 29 | 90% |
| Northern Forest Rivers (4) | 47 | 87% | Northern Forest River (1) | 37 | 76% |
| Wetland-lacustrine Streams (7) | 32 | 84% | Southern Riffle-run (5) | 47 | 89% |
| Southern Wadeable Streams (2) | 35 | 74% | Northern Forest Riffle-run (3) | 37 | 78% |
| Northern Wadeable Streams (5) | 37 | 84% | Southern Hardwood Glide-pool (6) | 37 | 86% |
| Southern Headwaters (3) | 32 | 88% | Northern Forest Glide-pool (4) | 35 | 86% |
| Northern Headwaters (6) | 30 | 77% | Prairie Glide-pool (7) | 52 | 87% |
| Southern Coldwater (10)* | 47 | 89% | Southern Coldwater (9)* | 43 | 98% |
| Northern Coolwater (11)* | 42 | 81% | Northern Coolwater (8)* | 34 | 79% |
| **Total** | 377 | 82% | **Total** | 351 | 86% |

* Southern coldwater and northern coolwater were initially developed in Gerritsen and Stamp (2013), and modified here.

## 5.0 DISCUSSION AND CONCLUSIONS

The Minnesota BCG is promising as a basis for decision criteria for Tiered Aquatic Life Use (TALU) development.

### 5.1 The BCG as an Assessment Tool

The conceptual model of the BCG, as developed in Davies and Jackson (2006), incorporated ecological theory as well as widespread empirical experience of working aquatic ecologists. Development of an index that reflects the BCG required quantitative mapping of biological information into the conceptual and theoretical model. The mapping, or calibration, process of the index is simultaneously quantitative, empirical, and conceptual.

- The BCG is calibrated using a data set, but also requires ecological considerations with wide expert agreement. The result is intended to be more general than a regression analysis of biological response to stressors.

- The BCG uses universal attributes (attributes I to VI) that are intended to apply in all regions. Specifics of the attributes (taxon membership, attribute levels indicating good, fair, poor, etc.) do vary across regions and stream types, but the attributes themselves and their importance are consistent.

- The BCG requires descriptions of the classes or levels, from pristine to degraded. Although this requires extra work at the outset, it ensures that future information and discoveries can be related back to the baseline level descriptions. Level descriptions are not perfect or static—they will be altered by increases in knowledge.

The BCG may be more robust than current indexes because it allows for nonlinear responses, as well as having requirements for combinations of metric values in the condition classes. Also, the it is not conceptually tied to “best available” sites as an unalterable benchmark. Although best available sites are used as a practical ground truth, it is recognized at the outset that these sites are typically less than pristine, and may be a lower level (e.g., BCG levels 2, 3, 4).

### 5.2 The BCG and Aquatic Life Use

The terms “Use”, “Designated Uses”, and “Aquatic Life Use” have specific meanings for water quality management in the context of the Clean Water Act. A state defines the uses for its waters, and develops physical, chemical and biological criteria to protect those uses. Minnesota’s Tiered Aquatic Life Uses (TALUs) are aquatic life uses that are matched more closely to the Designated Uses, rather than a single one-size-fits-all aquatic life use (USEPA, 2005). The BCG, as a universal yardstick, is intended to be used in setting biological criteria to match specific TALUs. It is important to note that levels of the BCG are NOT equivalent to TALUs, although a given TALU level may be set to a level of the BCG. The BCG is a scientific measurement yardstick only; it does not express policy decisions and breakpoints for designated uses.

Designated Uses are intended to be set at the highest attainable use for a water body, taking into account natural limitations or irreversible physical (infrastructure) alterations to the habitat or watershed (e.g., existing urban infrastructure, flood control, harbor facilities, irrigation, etc.). Infrastructure is not always irreversible: roads can be modernized, many older dams and obstructions are being removed from streams, habitat can be restored, etc. Designated uses thus also include potential quality or condition that may not currently be attained, but could be attained with appropriate controls or restoration. Thus, Aquatic Life Uses can be set according to the biological potential of waterbodies, not according to their current condition.

The BCG provides a powerful approach for an operational monitoring and assessment program, for communicating resource condition to the public and for management decisions to protect or remediate water resources. The levels of the BCG are biologically recognizable stages in condition of stream waterbodies. As such, they can inform a biological basis for biological criteria and regulation of Minnesota's waterbodies. Adoption of the BCG as an assessment tool in the context of multiple Aquatic Life Uses (Tiered Uses) yields the technical tools for protecting Minnesota's highest quality waters, as well as developing realistic restoration goals for urban and agricultural waters. The BCG allows practical and operational implementation of multiple aquatic life uses in a state's water quality criteria and standards.

## 5.3 Technical Recommendations

We recommend the following:

- Test rules with new (unassessed) sites to determine model and panel concordance. As new data are added to Minnesota's biological database, panel assessments for a subset of these data should be performed to test the models to ensure that the models are broadly applicable to streams across the state. Identification of sites that do not fit the current BCG models can be used to refine these models to improve their performance. Expansion of the calibration dataset will reduce "over fitting" to the original dataset. This approach can also help to identify stream reaches that do not fit into the current stream classification framework and may need site-specific criteria or a new stream classification.
- The fish logic rules and model were the most troublesome to develop and readjust to the two headwaters categories: Northern Headwaters and Southern Headwaters. In part, this was due to the small number of species in these small streams, and the few fish species found in these habitats tended to be tolerant. This resulted in a limited assemblage of species and tolerances that make assessments problematic, both by the panel and the model. However, the models developed for these classes reasonably predicted panel decisions (77-88%). We recommend that the fish BCG for the two headwater stream classes be reviewed further to demonstrate that the BCG rules are consistent and reliable.

## 6.0 LITERATURE CITED

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*. Second Edition. EPA/841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Castella, E., and M.C.D. Speight. 1996. Knowledge representation using fuzzy coded variables: an example based on the use of Syrphidae (Insecta, Diptera) in the assessment of riverine wetlands. *Ecological Modelling* 85:13-25.

Chirhart, J. 2003. *Development of a Macroinvertebrate Index of Biological Integrity (MIBI) for Rivers and Streams of the St. Croix River Basin in Minnesota*. Minnesota Pollution Control Agency, St. Paul, MN.

Davies, S.P., and S.K. Jackson, 2006. The Biological Condition Gradient: A descriptive model for interpreting change in aquatic ecosystems. *Ecological Applications* 16:1251-1266.

Demicco, R.V. 2004. Fuzzy Logic and Earth Science: An Overview. In *Fuzzy Logic in Geology*, R.V. Demicco and G.J. Klir (eds.), pp. 11-61. Elsevier Academic Press, San Diego, CA.

Demicco, R.V., and G.J. Klir. 2004. Introduction. In *Fuzzy Logic in Geology*, R.V. Demicco and G.J. Klir (eds.), pp. 1-10. Elsevier Academic Press, San Diego, CA.

Droesen, W.J. 1996. Formalisation of ecohydrological expert knowledge applying fuzzy techniques. *Ecological Modellin*g 85:75-81.

Genet, J., and J. Chirhart. 2004. *Development of a Macroinvertebrate Index of Biological Integrity (MIBI) for Rivers and Streams of the Upper Mississippi River Basin*. Minnesota Pollution Control Agency, St. Paul, MN.

Gerritsen, J., and J. Stamp. 2013 . *Calibration of the Biological Condition Gradient (BCG) in Cold and Cool Waters of the Upper Midwest BCG for Fish and Benthic Macroinvertebrate Assemblages*. Prepared by Tetra Tech, Inc. for U.S. Environmental Protection Agency.

Ibelings, B.W., M. Vonk, H.F.J. Los, D.T. Van Der Molen, and W.M. Mooij. 2003. Fuzzy modeling of Cyanobacterial surface waterblooms: validation with NOAA-AVHRR satellite images. *Ecological Applications* 13:1456-1472.

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser. 1986. *Assessing Biological Integrity in Running Waters: A Method and Its Rationale*. Special publication 5. Illinois Natural History Survey.

Karr, J.R. and E.W. Chu. 1999. Restoring life in Running Waters: Better Biological Monitoring. Island Press, Washington, DC.

Klir, G.J. 2004. Fuzzy Logic: A Specialized Tutorial. In *Fuzzy Logic in Geology*, R.V. Demicco and G.J. Klir (eds.), pp. 11-61. Elsevier Academic Press, San Diego, CA.

Lyons, J. 1992. Using the Index of Biotic Integrity (IBI) to Measure Environmental Quality in Warmwater Stream of Wisconsin U.S. Forest Service. General Technical Report NC-149. Available at http:ncrs.fs.fed.us/pubs/gtr/gtr_nc149.pdf

MPCA. No date. *Invertebrate Sampling Procedures*. EMAP-SOP4, Rev. 0. Minnesota Pollution Control Agency, St. Paul, MN.

MPCA. 2009. *Fish Community Sampling Protocol for Stream Monitoring Sites*. Minnesota Pollution Control Agency, St. Paul, MN.

Niemela, S., E. Pierson, T.P. Simon, R.M. Goldstein, and P.A. Bailey. 1998. *Development of Index of Biotic Integrity Expectations for the Lake Agassiz Plain Ecoregion*. U.S. Environmental Protection Agency, Region 5, Chicago, IL. EPA 905/R-96-005.

Niemela, S., and M. Feist. 2000. *Index of Biotic Integrity (IBI) Guidance for Coolwater Rivers and Streams of the St. Croix River Basin in Minnesota*. Minnesota Pollution Control Agency, St. Paul, MN.

Niemela, S., and M. Feist. 2002. *Index of Biological Integrity (IBI) Guidance for Coolwater Rivers and Streams of the Upper Mississippi River Basin*. Minnesota Pollution Control Agency, St. Paul, MN.

Simpson, J.C., and R.H. Norris. 2000. Biological assessment of river quality: development of AusRivAS models and outputs. In *Assessing the Biological Quality of Fresh Waters: RIVPACS and Other Techniques*. J.F. Wright, D.W. Sutcliffe and M.T. Furse (eds.), pp. 125-142. Freshwater Biological Association, Ambleside, UK.

Stoddard, J.L., D.P. Larsen, C.P. Hawkins, R.K. Johnson, and R.H. Norris. 2006. Setting expectations for the ecological condition streams: The concept of reference condition. *Ecological Applications* 16:1267-1276.

USEPA. 2005. *Use of Biological Information to Better Define Designated Aquatic Life Uses in State and Tribal Water Quality Standards*. Tiered Aquatic Life Uses. Public Science Review Draft. EPA-822-R-05-001. U.S. Environmental Protection Agency, Washington, DC. < http://www.epa.gov/bioiweb1/pdf/EPA-822-R-05-001UseofBiologicalInformationtoBetterDefineDesignatedAquaticLifeUses-TieredAquaticLifeUses.pdf> Accessed June 2012.

Whittier, T.R., R.M. Hughes, J.L. Stoddard, G.A. Lomnicky, D.V. Peck, and A.T. Herlihy. 2007. A structured approach for developing indices of biotic integrity: Three examples from streams and rivers in the Western USA. *Transactions of the American Fisheries Society* 136:718–735

Wright, J.F. 2000. An introduction to RIVPACS. In *Assessing the Biological Quality of Fresh Waters: RIVPACS and Other Techniques*. J.F. Wright, D.W. Sutcliffe and M.T. Furse (eds.), pp. 1-24. Freshwater Biological Association, Ambleside, UK.