Scientific Support for the Minnesota Stream Quantification Tool

MNSQT Steering Committee

United States Environmental Protection Agency

US Army Corps of Engineers®
St. Paul District

Board of Water and Soil Resources

Minnesota Pollution Control Agency

Department of Natural Resources

Stream Mechanics

Ecosystem Planning & Restoration

Scientific Support for the Minnesota Stream Quantification Tool (Version 1.0)

October 2020

Citation:

Minnesota Stream Quantification Tool Steering Committee (MNSQT SC). 2020. Scientific Support for the Minnesota Stream Quantification Tool, Version 1.0. U.S. Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds (Contract # EP-C-17-001), Washington, D.C.

Acknowledgements

The scientific support for the Minnesota Stream Quantification Tool (MNSQT) was developed to provide the technical basis for the reference curves included in the MNSQT. This document is adapted for Minnesota from the Scientific Support for the Colorado Stream Quantification Tool (CSQT SC 2019b). Additionally, this document has benefited from the knowledge gained during the regionalization of other SQTs nationwide and incorporates and addresses concerns from extensive state and federal reviews. The development of the MNSQT and supporting documents for Minnesota was funded by United States Environmental Protection Agency (USEPA) Region 5, USEPA Headquarters and United States Corps of Engineers (USACE) Headquarters through a contract with Ecosystem Planning and Restoration (contract # EP-C-17-001).

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Many others provided valuable contributions to the Minnesota documents, including: Nathan Mielke (MPCA), who provided input on fish and macroinvertebrate metrics and assemblage data; Jesse Anderson who provided input on water quality parameter metrics and associated data; Mike Trojan (MPCA), who provide input, review, and comment on the MIDS Rv coefficient metric; and Doug Norris (MN DNR]), Nick Proulx (MN DNR), David Demmer (MN BWSR), Mike Miller (WI DNR), April Marcangeli (USACE), who provided valuable input, review, and comment throughout regionalization and document development. Will Harman (Stream Mechanics), Thomas Barrett, Sara Donatich, Amy James, Cidney Jones, and LeeAnne Lutz (EPR) provided technical support and regionalization support under EPA Contract No. EP-C-17-001. Peer review on draft versions of this document were provided by Julia McCarthy (EPA Region 8), Ed Hammer (EPA Region 5), and Melanie Burdick (EPA Region 5). Peer review and contract support was provided by Brian Topping (EPA Headquarters).

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Version

Version	**Date finalized**	**Description**
1.0	October 2020	Original version

Acronyms

BEHI – Bank Erosion Hazard Index
BHR – Bank height ratio
BMP – Best management practice
CFR – Code of Federal Regulations
CN – (Runoff) curve numbers
Corps – United States Army Corps of Engineers (also, USACE)
CSQT – Colorado Stream Quantification Tool
CWA 404 – Clean Water Act Section 404
DNR – Department of Natural Resources
DO – Dissolved oxygen
EDA – Environmental Data Access system (product of MPCA)
EPA – United States Environmental Protection Agency (also, USEPA)
ER – Entrenchment ratio
FF – Functional feet
HSG - Hydrologic soil group
IBI – Index of biotic integrity
LWD – Large woody debris
LWDI – Large woody debris index
MN BWSR – Minnesota Board of Water and Soil Resources
MIDS – Minimal impact design standards
MNSQT – Minnesota Stream Quantification Tool
MNSQT SC – Minnesota Stream Quantification Tool steering committee
MPCA – Minnesota Pollution Control Agency
NBS - Near Bank Stress
NLCD – National Land Cover Database
NRCS – Natural Resource Conservation Service
R_v – Site runoff coefficient
SFPF – Stream Function Pyramid Framework
TALU – Tiered Aquatic Life Uses and Biological Criteria
TMDL – Total maximum daily load
TSS – Total suspended solids
USACE – United States Army Corps of Engineers (also, Corps)
USDA – United States Department of Agriculture
USEPA – United States Environmental Protection Agency (also, EPA)
USGS – United States Geologic Survey
W/D – Width-to-depth ratio
WDRS – Width Depth Ratio State

Glossary of Terms

Alluvial valley – Valley formed by the deposition of sediment from fluvial processes.

Bankfull – Bankfull is a discharge that forms, maintains, and shapes the dimensions of the channel as it exists under the current climatic regime. The bankfull stage or elevation represents the break point between channel formation and floodplain processes (Wolman and Leopold 1957).

Catchment – Land area draining to the downstream end of the project reach.

Colluvial valley – Valley formed by the deposition of sediment from hillslope erosion processes, typically confined by terraces or hillslopes.

Condition – The relative ability of an aquatic resource to support and maintain a community of organisms having a species composition, diversity, and functional organization comparable to reference aquatic resources in the region (33CFR 332.2).

Condition score – Metric-based index values are averaged to characterize condition for each parameter, functional category, and overall project reach.

ECS = Existing Condition Score

PCS = Proposed Condition Score

Credit – A unit of measure (e.g., a functional or areal measure or other suitable metric) representing the accrual or attainment of aquatic functions at a compensatory mitigation site. The measure of aquatic functions is based on the resources restored, established, enhanced, or preserved. (33CFR 332.2)

Debit – A unit of measure (e.g., a functional or areal measure or other suitable metric) representing the loss of aquatic functions at an impact or project site. The measure of aquatic functions is based on the resources impacted by the authorized activity. (33CFR 332.2)

Debit Calculator workbook – A Microsoft-Excel spreadsheet-based calculator that determines the functional loss due to proposed impacts.

Effective riparian area – The area adjacent to and contiguous with the stream channel that supports the geomorphological dynamic equilibrium of the stream. It is typically a corridor associated with a stream reach where, under natural conditions, the valley bottom is influenced by fluvial processes under the current climatic regime; riparian vegetation characteristic of the region and plants known to be adapted to shallow water tables and fluvial disturbance are present; and the valley bottom is flooded at the stage of the 100-year recurrence interval flow. (Merritt et al. 2017)

Effective vegetated riparian area – The portion of the effective riparian area that contains riparian vegetation and is free from utility-related, urban, or other soil disturbing land uses.

Field value – A field measurement or calculation input into the MNSQT for a specific metric. Units vary based on the metric or measurement method used.

Functional capacity – The degree to which an area of aquatic resource performs a specific function (33CFR 332.2).

Functions – The physical, chemical, and biological processes that occur in ecosystems (see 33CFR 332.2).

Functional category – The organizational levels of the Stream Functions Pyramid: hydrology, hydraulics, geomorphology, physicochemical, and biology (Harman et al. 2012). Each category is defined by a functional statement.

Functional feet (FF) – Functional feet is the primary unit for communicating functional lift and loss and is calculated by multiplying a condition score by stream length. ∆FF is the difference between the existing FF and the proposed FF.

Functional statement – A description of the functions within each functional category in the Stream Functions Pyramid Framework (Harman et al. 2012).

Function-based parameter – A structural measure that characterizes a condition at a point in time, or a process (expressed as a rate) that describes and supports the functional statement of each functional category (Harman et al. 2012).

Index value – Dimensionless value between 0.00 and 1.00 that expresses the relative condition of a metric field value, as compared with reference standards. These values are derived from reference curves for each metric. Index values are combined to create parameter, functional category, and overall reach scores.

Measurement method – A specific tool, equation, or assessment method used to inform a metric. Where a metric is informed by a single data collection method, metric and measurement method are used interchangeably (see metric).

Metric – A specific tool, equation, measured values, or assessment method used to evaluate the condition of a structural measure or function-based parameter. Some metrics can be derived from multiple measurement methods. Where a metric is informed by a single data collection method, metric and measurement method are used interchangeably (see measurement method).

Minnesota Stream Quantification Tool (MNSQT) – The MNSQT is a spreadsheet-based calculator that scores stream condition before and after restoration or impact activities to determine functional lift or loss, respectively, and can also be used to determine restoration potential, develop monitoring criteria and assist in other aspects of project planning. The MNSQT is comprised of two workbooks, the MNSQT and Debit Calculator. Because both are based on principles and concepts of the SFPF, they have some overlapping components. In addition, references to the MNSQT can describe concepts that are applicable within both the MNSQT and Debit Calculator workbooks.

Minnesota Stream Quantification Tool steering committee (MNSQT SC) – The group that worked on the development of the MNSQT and contributed to various aspects of this document.

Performance standards – Observable or measurable physical (including hydrological), chemical, and/or biological attributes that are used to determine if a compensatory mitigation project meets its objectives (33 CFR 332.2).

Project area – The geographic extent of a project. This area may include multiple project reaches where there are variations in stream physical characteristics and/or differences in project designs within the project area.

Project reach – A homogeneous stream segment within the project area, i.e., a stream segment with similar valley morphology, stream type (Rosgen 1996), stability condition, riparian vegetation type, and bed material composition. Long project reaches may contain representative sub-reaches (see definition below).

Reference aquatic resources – A set of aquatic resources that represent the full range of variability exhibited by a regional class of aquatic resources as a result of natural processes and anthropogenic disturbances (33 CFR 332.1).

Reference curves – A relationship between observable or measurable metric field values and dimensionless index values. These curves take on several shapes, including linear, polynomial, bell-shaped, and other forms that best represent the degree of departure from a reference standard for a given field value. These curves are used to determine the index value for a given metric at a project site.

Reference standard – The subset of reference aquatic resources that are least disturbed and exhibit the highest functional capacity. In the MNSQT, this condition is considered functioning for the metric being assessed and ranges from least disturbed to minimally disturbed, to pristine condition.

Representative sub-reach – A length of stream within a project reach that is selected for field data collection of parameters and metrics. The representative sub-reach is typically 20 times the bankfull width or two meander wavelengths (Leopold 1994).

Riparian vegetation – Plant communities contiguous to and affected by shallow water tables and fluvial disturbance.

Stream Functions Pyramid Framework (SFPF) – The Stream Functions Pyramid is comprised of five functional categories (see functional category) stratified based on the premise that lower-level functions support higher-level functions and that they are all influenced by local geology and climate. The SFPF includes the organization of function-based parameters, measurement methods, and performance standards to assess the functional categories of the Stream Functions Pyramid (Harman et al. 2012).

Stream restoration – The manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a former or degraded aquatic resource (33 CFR 332.2). The term is used more broadly in this document to represent multiple stream compensatory mitigation methods including re-habilitation, re-establishment, and enhancement.

Stream/wetland complex – A stream channel or channels with adjacent riverine wetlands located within the floodplain or riparian geomorphic setting, where **overbank flow from the channel(s) is the primary wetland water source** (Brinson et al. 1995). Stream types may be single-thread or anastomosed. Common stream types for stream/wetland complexes include Rosgen E, Cc-, and D_A.

Threshold values – Criteria used to develop the reference curves and index values for each metric. These criteria differentiate between three condition categories: functioning,

functioning-at-risk, and not functioning and relate to the Performance Standards defined in Harman et al. (2012).

Chapter 1 Background and Introduction

The purpose of this document is to provide the scientific underpinnings of the Minnesota Stream Quantification Tool and Debit Calculator (MNSQT) and the rationale for the conversion of measured stream condition into dimensionless index scores. The MNSQT is an application of the Stream Functions Pyramid Framework (SFPF), outlined in *A Function-Based Framework for Stream Assessment and Restoration Projects* (Harman et al. 2012). Harman et al. (2012) present the SFPF and provides supporting references and rationale for the organizational framework and its components. The MNSQT is one of several Stream Quantification Tools (SQTs) that have recently been developed for use in specific states, including Wyoming (WSQT; USACE 2018a), North Carolina (Harman and Jones 2017), Tennessee (TDEC 2018), Georgia (USACE 2018b) and Colorado (CSQT; USACE 2020a).

This document is based on the scientific support documents from Colorado and Wyoming (CSQT SC 2019 and WSTT 2018 respectively) and has been modified for Minnesota with input from the Minnesota Stream Quantification Tool Steering Committee (MNSQT SC). The MNSQT differs from the CSQT in many aspects, and this document has been edited to reflect the regionalization of the tool to Minnesota streams. However, some chapters in this document are reproduced with minor edits from the Scientific Support for the CSQT (CSQT SC 2019 and USACE 2020b).

This document expands on the concepts presented in the SFPF and the MNSQT User Manual (User Manual; MNSQT SC 2019) to provide the scientific and technical rationale behind selection of the reference curves and metrics. Information on how to use the MNSQT or collect data for use in the MNSQT is not included in this document but can be found in the User Manual.

Section 1.1 provides a summary of the SFPF terminology, including function-based parameters and metrics. Also provides background for the MNSQT and key considerations in applying the MNSQT.

Section 1.2 provides a summary of the catchment context for determining restoration potential.

Section 1.3 provides a description of reference curve development and describes how key concepts of reference standard and functional capacity are used in the tool.

Section 1.4 gives an overview of how the MNSQT calculates the overall reach condition scores.

Section 1.5 discusses the selection of functional feet as the primary unit for communicating functional lift and loss within the tool, and its use in informing debits and credits.

Section 1.6 provides the general criteria used to select function-based parameters and metrics from the SFPF and new metrics included in the MNSQT.

Section 1.7 provides a general summary of the datasets used to develop reference curves and the tool's data gaps and limitations.

Section 1.8 provides information on the process for revising reference curves and metrics.

After the Introduction and Background, the remainder of the document is organized by function-based parameter. Each parameter description includes a summary of why it was included, reasons for selecting the metrics, and in some cases, why other metrics were not selected. Then, a description of metrics used to quantify the parameter is provided. Each metric section provides the rationale for developing reference curves and any stratifications, followed by data gaps and limitations.

1.1. Background on the Stream Functions Pyramid Framework (SFPF)

In 2006, the Ecosystem Management and Restoration Research Program of the United States Army Corps of Engineers (Corps) noted that specific functions for stream and riparian corridors had yet to be defined in a manner that was generally agreed upon and could be used as a basis for management and policy decisions (Fischenich 2006). To address this need, an international committee of scientists, engineers, and practitioners defined 15 key stream and riparian zone functions aggregated into five categories: system dynamics, hydrologic balance, sediment processes and character, biological support, and chemical processes and pathways (see Table 1 in Fischenich 2006). The committee noted that restoration of hydrodynamic processes, sediment transport processes, stream stability, and riparian buffers could lead to improvements in dependent functions that typically require time to establish, such as diverse biological communities, nutrient processes, diverse habitats, and improved water and soil quality. The SFPF builds on the work completed by Fischenich (2006) by organizing stream functions into a hierarchical structure to create a conceptual model for restoration practitioners to use in communication and the development of function-based assessments.

The SFPF organizes stream and riparian functions into five functional categories: Hydrology, Hydraulics, Geomorphology, Physicochemical, and Biology (Figure 1-1). This organization recognizes that foundational functions, like watershed hydrology and sediment transport processes, generally support higher-level functions like aquatic animal life histories, and that all functions are influenced by local geology and climate. Cause and effect can flow from top to bottom as well, e.g., beavers (biology) can affect hydrology, and riparian communities can influence hydraulics and geomorphology through wood inputs, rooting depths, and floodplain roughness. However, the primary thought process for this framework is this: what supporting processes are needed to restore a particular function? With this perspective, the beaver example would change to: what functions are needed to support a healthy beaver population?

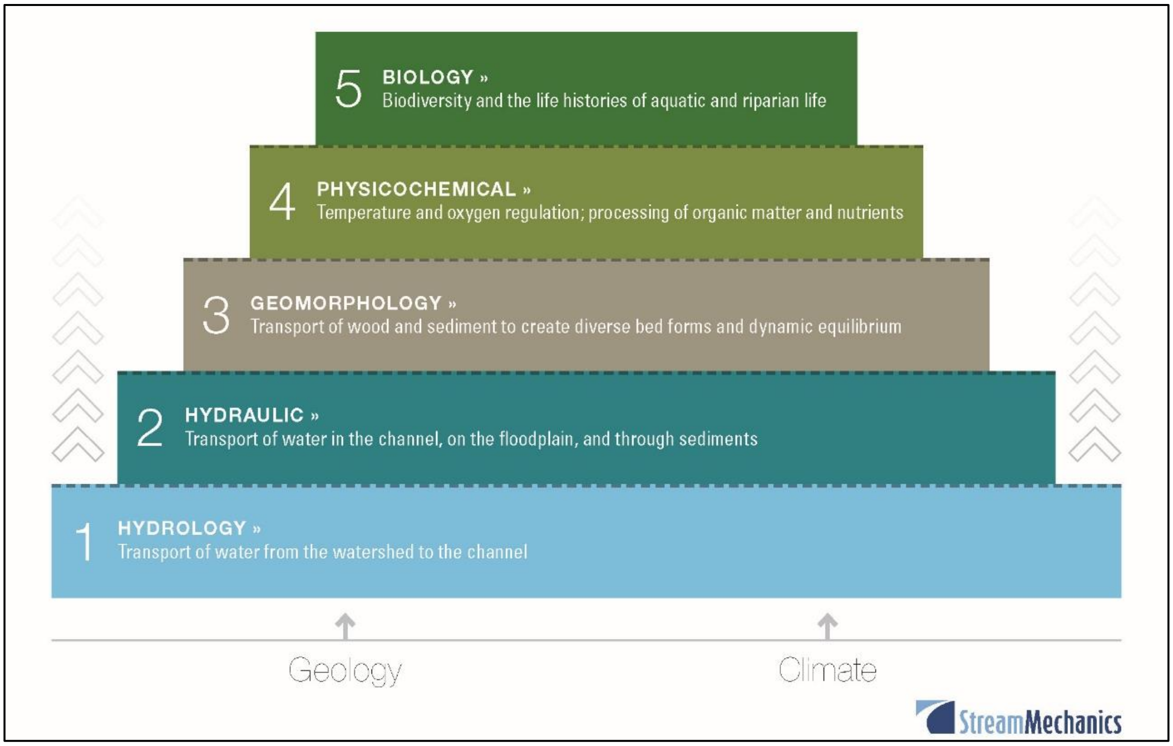

Figure 1-1: Stream Functions Pyramid
(Image from Harman et al. 2012)

Within each of the five functional categories, the SFPF outlines parameters and methods to quantify the degree to which a stream ecosystem is functioning (Figure 1-2). In this framework, function-based parameters describe and support the functional statements of each functional category, and the measurement methods (metrics) are specific tools, equations, measured values, and/or assessment methods that are used to quantify the function-based parameter. The SFPF presents two types of function-based parameters and metrics: structural indicators, which describe a condition at a point in time, and functions expressed as a rate that tie directly to a stream process (e.g., bank erosion rates). Each metric is compared against reference standards (reference curves) that represent departure from, or achievement of, reference standard. The selection of function-based parameters used in the MNSQT and their relationship to reference standards are discussed in more detail in the following sections.

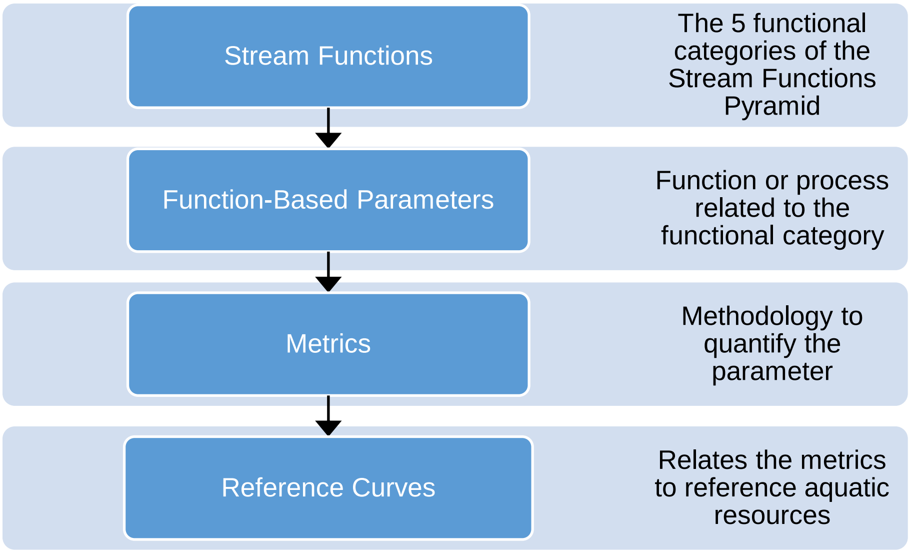

Figure 1-2: Stream Functions Pyramid Framework
(Note: terms have been edited to match MNSQT application)

1.2. Background on the MNSQT

The SFPF has informed the development of the MNSQT, a tool that consolidates the components of the SFPF into an Excel workbook to quantify stream ecosystem functions at a specific project reach. The MNSQT includes a sub-set of function-based parameters and metrics listed in Harman et al. (2012) along with new parameters and metrics identified as part of the MNSQT development and regionalization process, which are relevant to the stream systems found within the state of Minnesota.

All the metrics selected for the MNSQT are structural or compositional attributes that indicate condition at a given point-in-time. Metrics serve as surrogates for stream functions (33 CFR 332.2) related to the function-based parameters selected for a given functional category. For example, bed form diversity is a partial surrogate for sediment transport processes, which is a geomorphology function. Bed form diversity is NOT a surrogate for macroinvertebrate functions because it is in a different functional category (biology).

Assessment data are input into the MNSQT, where data for each metric are translated into index values via a set of reference curves, thus converting a variety of units into a standardized unitless score. Reference curves have been derived for each metric that relate site-specific data to degrees of departure from reference standard. Index values range from 0.00 to 1.00 and relate to the functional capacity descriptions described in Section 1.3 below.

Though the MNSQT and this scientific support document have been developed to apply the function-based approaches set forth in the 2008 Compensatory Mitigation Rule (33 CFR 332.3), the MNSQT can also be applied to restoration projects outside of the Clean Water Act Section 404 (CWA 404) and Rivers and Harbors Act Section 10 regulatory context.

Key Considerations

The following concepts are critical in understanding the applicability and limitations of this tool:

- The parameters and metrics in the tool were, in part, selected due to their sensitivity in responding to reach-scale changes associated with common regulatory stream restoration related activities. These parameters do not comprehensively characterize all structural measures or processes that occur within a stream.
- The MNSQT is designed to assess the same metrics at a site over time, thus providing information on the degree to which the condition of the stream system changes following impacts or restoration activities. Unless the same parameters and metrics are used across all sites, it would not be appropriate to compare scores across sites.
- The MNSQT is not a design tool. Many function-based parameters are critical to a successful restoration design but sit outside of the scope of the MNSQT. The MNSQT measures the hydraulic, geomorphological, and ecological responses or outcomes related to a project at a reach scale.
- The MNSQT itself does not score or quantify catchment condition. Catchment condition reflects the external elements that influence functional capacity within a project reach and is important to consider when selecting and determining the restoration potential of a site. These considerations are addressed in Chapter 3 of the User Manual.
- Some data collection methods and reference curves may have limited applicability in ephemeral and intermittent streams, and stream/wetland complexes.
- Most metrics in the tool rely on wadeable data collection methods. Applicability of reference curves in non-wadeable rivers is unknown.
- The MNSQT is a reach-scale, point-in-time tool. Reference curves do not incorporate time, and therefore do not estimate the future trajectory of a restoration project outside of the monitoring period.
- As a reach-scale tool, the MNSQT does not automatically evaluate secondary (indirect) effects in reaches upstream or downstream of the project reach. Additional reaches would need to be defined and assessed in order to quantify the changes in condition related to the indirect effects of improving longitudinal connectivity, fish passage projects, beaver re-introduction, reducing bank erosion, and other projects that have effects beyond the original reach limits.
- Sample sizes and the level of uncertainty varies across metrics and across stratified reference curves within metrics because multiple data sets and data sources were used to develop reference curves.

1.3. Development of Reference Curves

The MNSQT calculates the **change in condition** at a project site following an impact or restoration activity and allows the user to draw reach-scale conclusions on changes in functional capacity pre- and post-project. These changes in functional capacity are referred to in the MNSQT as functional loss and lift and can be used to inform debits and credits as defined in the 2008 Mitigation Rule (33 CFR 332.3). Functional lift or loss is the difference in condition or functional feet within a project reach before and after restoration or a permitted impact.

Reference curves are used in the MNSQT to relate point-in-time condition measurements to functional capacity and standardize all metrics to an ecologically relevant scale. Reference curves were developed to assign index values that reflect a range of condition and relate field values for each metric to functional capacity, i.e., functioning, functioning-at-risk, and not functioning condition (Table 1-1). Describing the functional characteristics, attributes, and condition of ecosystems is a traditional approach to describing functional capacity (Proper Functioning Condition per Prichard et al. 2003).

Reference curves were developed by first partitioning the index value range (0.00-1.00) into three categories (Table 1-1) which characterize the degree to which the measured condition differs from a reference standard condition (Hawkins et al. 2010). Other assessment methods have taken similar approaches to scale, or score, functional capacity compared to reference systems (e.g. Johnson et al. 2013; Nadeau et al. 2018). Thresholds were defined for each metric to demarcate the index values for not functioning/functioning-at-risk (0.30) and functioning-at-risk/functioning (0.70) categories. These thresholds and their corresponding field values for each metric were determined by evaluating existing datasets, literature sources, or relying on thresholds developed in other assessments or approaches. For purposes of mitigation, these threshold values can also provide a quantitative, objective approach to monitoring and can be used to inform performance standards.

Calculating Change in Condition

It is important to remember that this tool is intended to compare pre- and post-project conditions at a site. As such, the difference between existing and future site conditions is the most important element.

Reference curves are used in the MNSQT to relate point-in-time condition measurements to functional capacity and standardize all metrics to an ecologically relevant scale.

To account for natural variability among stream systems, reference curves for specific metrics may be stratified by differences in stream type, river use class, river nutrient regions, reference community class, or valley type. Stratification varies by metric and is described in the individual metric sections of this document.

To develop reference curves, field values were identified for each metric that would serve as thresholds between the categories of functional capacity outlined in Table 1-1. Three approaches were taken to identify these threshold values:

1. Where possible, thresholds were derived from field values already identified in the state of Minnesota’s technical publications and/or peer-reviewed literature or both (e.g., based on water quality standards or existing indices).
2. Where published values were not available, threshold values were developed using data from national and regional resource surveys and other available regional datasets. In evaluating reference datasets, the team considered the degree of departure from reference standard to identify threshold values. For example, the interquartile range of reference standard sites within a dataset may be used to identify the 0.7 and 1.0 field values for developing a reference curve. This is similar to other approaches that identify benchmarks or index values (e.g., BLM 2017; Nadeau et al. 2018). In the use of existing datasets, this document relied on the definitions of reference standard condition provided by the authors.

This is similar to other approaches that identify benchmarks or index values (e.g., BLM 2017; Nadeau et al. 2018).

3. Where existing data or literature were limited, expertise of members of the MNSQT SC were relied on to identify threshold values. In some instances, the decision was made to not identify thresholds between all categories and instead extrapolate index values from a best fit line from available data or literature values.

Table 1-1: Functional capacity definitions used to define threshold values and develop reference curves for the MNSQT

Functional Capacity	Definition	Index Value Range
Functioning	A functioning value means that the metric is quantifying or describing the functional capacity of one aspect of a function-based parameter in a way that **supports aquatic ecosystem structure and function.** The reference standard concept aligns with the definition for a reference condition for biological integrity (Stoddard et al. 2006). A score of 1.00 represents an un-altered or pristine condition (native or natural condition). A range of index values (0.70-1.00) is used for characterizing reference standard to account for natural variability, recognizing that reference standard datasets include sites that reflect least disturbed condition (i.e., the best available conditions given current anthropogenic influence per Stoddard et al. 2006).	0.70 to 1.00
Functioning-at-risk	A functioning-at-risk value means that the metric is quantifying or describing one aspect of a function-based parameter in a way that **may support aquatic ecosystem structure and function**, but not at a reference standard level**.** In many cases, this indicates the parameter is adjusting in response to changes in the reach or the catchment towards lower or higher function. This range characterizes a grey area, where a resource is neither achieving a reference standard nor is significantly degraded or impaired.	0.30 to 0.69
Not-functioning	A not functioning value means that the metric is quantifying or describing one aspect of a function-based parameter in a way that **does not support aquatic ecosystem structure and function.** An index value less than 0.30 represents an impaired or severely altered condition relative to reference standard, and an index value of 0.00 represents a condition that provides no functional capacity for that metric. Index values of 0.00 are often the minimum value possible for a metric.	0.00 to 0.29

Following the identification of these threshold values, linear relationships were fit to these threshold values. These continuous curves allow index scores to account for incremental changes in field values, which is important for determining a change in the pre- and post-project condition. If a non-linear fit was used, the rationale for selecting an alternative fit is provided in the specific metric section below. Reference curves and threshold values were determined for each metric individually. Therefore, a reach may achieve a reference standard index value for one metric, e.g., large woody debris index (LWDI), and not others. Metric index values are then combined to provide a reach score (Section 1.4).

1.4. Calculating Reach-Scale Condition

The architecture and scoring of the MNSQT is simple to allow for flexibility in selecting function-based parameters and metrics and to allow for additions or exchanges of parameters in the future with advances in stream science. This approach differs from assessment approaches that rely on rigorous statistical analyses for metric selection, calibration, and scoring (Stoddard et al. 2008). There are obvious limitations to this simpler approach. However, a benefit is the flexible architecture: metrics and parameters can be added to or subtracted from the tool based on new scientific understandings or site-specific considerations without requiring substantial reanalysis of the weighting in the tool. For example, for a specific site or analysis, the same weighting and metrics would be used for each monitoring event to preserve the rigor of the comparison, but additional metrics could be applied at another site based on a different set of site objectives. Because the **focus of the tool is on the difference between before and after conditions,** flexibility was prioritized over a rigorous approach to weighting (given that scoring will be handled the same for before and after conditions).

Index values are generated for each metric and then combined to provide parameter and functional category scores, as described below:

- Metric index values are averaged to calculate a parameter score. Only the metrics assessed at a given project reach are used to calculate these scores (refer to the User Manual for guidance on parameter and metric selection).
- Parameter scores are averaged to calculate a functional category score.
- Functional category scores are weighted and then summed to calculate a reach condition score.

The functional category weighting is fixed, regardless of the number of metrics, parameters or functional categories assessed; each functional category (e.g. hydrology) provides 20% of the functional feet value. The maximum condition and functional feet value that can be achieved is affected by the number of functional categories assessed. For example, only 60% of the potential functional feet value will be realized at a site if only reach hydrology, hydraulics, and geomorphology parameters are assessed and monitored. Meanwhile, monitoring one or more metrics in all five functional categories would result in achieving 100% of the potential functional feet value. The weighting incentivizes restoration practitioners to attempt to improve and monitor physicochemical and biology parameters even if they may not reach full restoration potential.

Because parameter and metric selection can vary based on site-specific considerations, the proportional weighting of each metric will vary from site to site as the number of metrics or parameters measured varies (Table 1-2). If only the basic suite of metrics identified in section 2.3 in the User Manual are evaluated, each of those metrics will contribute more to each functional category score when compared with application of all metrics or parameters within a functional category. For example: if a user evaluates lateral migration, bed form diversity, and riparian vegetation in the geomorphology category, each parameter will contribute 6.7% to the overall potential score; whereas, if large wood is also evaluated, each parameter would contribute 5.0% to the overall potential score.

Table 1-2: Implicit parameter and metric weighting that results from averaging for perennial streams

Functional Category	Category Weight	Function-based parameters (no.)	Parameter weight*	Metrics (no.)	Metric weight*
Hydrology	20%	1	20%	3	10-20%
Hydraulics	20%	1	20%	2	10-20%
Geomorphology	20%	5	4-6.7%	14	1-5%
Physicochemical	20%	3	6.7-20%	3	6.7-20%
Biology	20%	2	10-20%	2	10-20%

**Calculated based on the parameters and metrics that would be applied in combination per parameter selection. Note: higher percentage is if only basic suite of parameter/metrics that are applicable to all flow types are applied.*

Interpreting the Condition Score

When all five functional categories are assessed, the overall condition score can be interpreted as a percent of pristine condition. For example, if the overall condition score is 0.60, the reach is considered functioning at 60% of pristine for the parameters that were assessed. There could still be unknowns in condition if optional parameters are not assessed.

The overall condition score reflects the stream type, flow regime, and landscape setting that is characterized in the input and stratification table. For example, a 0.60 could represent a perennial, third order (Strahler 1957) stream, or the same 0.60 could represent an ephemeral, first order stream. The perennial stream could be located in a prairie ecoregion and the ephemeral stream could be in a headwater mountain ecoregion. Therefore, it is important to consider the input selection when comparing the overall scores. Unless the same parameters and metrics are used across all sites, it would not be appropriate to compare scores across sites.

To improve communication about the overall score, flow regime and channel size indicators have been attached to the score. Flow regime is denoted by a P, I, or E to represent perennial, intermittent, or ephemeral, and the Strahler stream order method is used to denote stream size. A 1, 2, 3 etc. is added to the score to show the stream order. Using the example above, the perennial, third order stream with a 0.60 overall score will show up as 0.60 (P3). The first order ephemeral channel will show up as a 0.60 (E1).

1.5. Calculating Functional Feet

The MNSQT estimates the change in condition at an impact or mitigation site by calculating the difference between existing (pre-project) and proposed (post-project) condition. Existing, proposed, and post-project monitoring condition scores are then scaled for project size by multiplying these condition scores by stream length to calculate functional feet. In a stream with an existing condition score of 1.00, one functional foot would equal one linear foot of stream. When condition is less than 1.00, or not all functional categories are measured, the functional feet are no longer equivalent to stream length. The difference between proposed and existing functional feet values, referred to as the change in functional feet (ΔFF), is the amount of functional lift or loss within a project reach.

The ∆FF is intended to serve as the basis for calculating debits and credits. Many programs continue to rely on activity or ratio-based approaches to calculate credits or assign credit ratios based on changes to channel geometry (ELI et al. 2016; Table 1-3). Ratio-based approaches rely on areal or length measurements regardless of condition. **The purpose of the MNSQT is to generate a unit that better integrates changes in condition into crediting and debiting approaches**. The functional feet calculation made in the MNSQT and Debit Calculator workbooks incorporates stream length (existing and proposed) with **quantitative measures of stream condition that also include the floodplain and riparian corridor.** The functional feet unit is more representative of ecological function than a length or areal measure (e.g., stream length or area) alone. The functional feet unit serves as the bridge between the condition assessment and application within a debit/credit policy framework for program implementation because it provides a unit of measure that can be added together and compared across sites better than condition scores alone. The functional feet approach is used to generate debits and credits in the following states: WY (USACE 2018a), TN (TDEC 2018), GA (USACE 2018b), and CO (USACE 2020a).

The inclusion of stream length in the functional feet unit adds scale to normalize the condition score. For example, a small project such as a culvert removal, may yield a substantial difference between the proposed and existing condition score but a relatively small change in functional feet because the reach is very short. A very long project with moderate condition improvement will produce a bigger change in functional feet because of its scale. The use of stream length follows that of other Corps Districts with established compensatory stream mitigation programs, which use a variety of factors that are then multiplied by stream length to create a debit or credit (Table 1-3). This product of quality and length is a common currency for debit and credit calculations (ELI et al. 2016).

The MNSQT SC considered several alternatives to the length-based approach, including a functional-area product and a valley-area measure. Both are discussed briefly below:

Functional-area product: This approach would rely on an area-based unit of measure instead of stream length (e.g., PADEP 2014). An approach using stream area (e.g., stream width multiplied by length) may better account for the size differences between small and large streams, including a greater amount of aquatic habitat in a larger stream. The unresolved challenges with an approach that relies on channel width is that width often changes as a response to natural and anthropogenic influences. Attempts to predict the final width would be difficult and create more uncertainty than relying on length alone because it could change each year. Another problem is that multiplying by width incentivizes practitioners to design larger channels, which can be counter-productive to increasing functional lift. Finally, this option does not address the importance of the floodplain and riparian corridor and is therefore not an improvement over length in this regard.

Valley area: Another approach that was considered was using valley area (valley length times valley width) instead of stream length. This approach has merit, as it characterizes the stream and floodplain corridor in a more holistic way. However, the major challenge with this approach is in accounting for the net loss or gain in stream length, an important consideration in the regulatory program. For example, an increase in stream length would not be accounted for in a stream restoration project. And conversely, a channelization project that reduces stream length would not count as a loss. The Corps currently accounts for permitted impacts in linear feet or aquatic resource area (e.g., Nationwide Permit impact thresholds, data entry into OMBIL

Regulatory Module [ORM] database) and only regulates activities within aquatic resource boundaries (e.g., within a delineated wetland or the ordinary high water mark of streams); it is unclear how a valley-based approach would align with current impact accounting practices.

Additional discussions and research on implementation are needed before adopting a valley-based approach across all projects. Therefore, this approach may be considered for future versions of the MNSQT.

The unit of measure in the MNSQT Version 2.0 (MNSQT) is functional feet because it conforms with many existing stream mitigation approaches while improving the link between activities and changes in condition. Future versions of the MNSQT may accommodate alternate or modified approaches, as discussed above, but more consideration on how these approaches could be implemented on the debit and credit side is needed before this selection is made.

Table 1-3: Debit and credit approaches that consider a combination of condition and stream length Adapted from ELI et al. (2016)

State/Corps District	General Debit Approach	General Credit Approach
Nebraska (2012)	***Impact Units = (Stream Condition Index Score) x (stream length)*** Includes a condition assessment procedure and impact/mitigation calculator predicting proposed condition.	***Mitigation Units = (Stream Condition Index Score) x (stream length)*** Same assessment and calculator used to compare impact and compensation sites.
South Pacific Division (2015)	Mitigation Ratio Checklist factors in several multipliers but can also incorporate functional assessment data via a before-after-mitigation-impact (BAMI) spreadsheet to determine baseline ratio.	Mitigation Ratio Checklist - both impact and mitigation info are input into same checklist
Pennsylvania (2014)	***Compensation Requirement (CR) = (area of impact) x (PE) x (RV) x (CI)*** PE = project effect factor based on severity of impacts RV = resource value based on categories of resource quality CI = condition index value from condition assessment CR is calculated for each aquatic resource function category and summed for total debit.	***Functional Credit Gain (FCG) = (area of project) x (RV) x (CV) x (CI diff)*** RV= same as debits CV = compensation value based on level of benefit (1-3) CI diff = condition index differential value based on difference in existing and predicted condition
Galveston (2013)	***Compensation requirement (CR) = (Δ resource condition) x (impact factor) x (stream length)*** Like Pennsylvania, but CR is not calculated separately for each functional category.	Credits defined by level of effort (e.g., reestablishment is 3 credits/LF, rehabilitation or enhancement is 1 credit/LF) and factors related to the riparian buffer.
Norfolk (2004)	***Compensation Requirement = (length of impact) x (RCI) x (IF)*** RCI = reach condition index is a weighted average of categorical condition indices for four parameters (channel condition, riparian buffer, instream habitat, channel alteration) IF = impact factor based on the severity of impact (0-1)	***Compensation Credit = restoration credit +enhancement credit + riparian buffer credit + adjustment factor credit*** Credits defined by level of effort (e.g., restoration is 1 credit/LF, enhancement is 0.09-0.3 credit/LF, etc.) and other adjustment factors (e.g., T&E or watershed preservation)

State/Corps District	General Debit Approach	General Credit Approach
West Virginia (2011)	***Unit Score = (Index Score) x (stream length)*** Debit tables used to calculate index score (0-1), considers West Virginia Stream and Wetland Valuation Metric (WVSWVM) which incorporates assessment methods using project specific data, and factors like temporal loss and site protection.	***Unit Score = (Index Score) x (stream length)*** Index score derived from credit tables. Unit scores are calculated at mitigation site over three intervals (existing, post-construction & maturity).

1.6. Function-Based Parameters in the MNSQT Version 2.0

The MNSQT considers a suite of functional indicators that are sensitive to anthropogenic modification of reach-scale processes, i.e., the types of activities (both impact and mitigation projects) that are common in the CWA 404 dredge and fill permitting program. The tool also considers related ecosystem functions that could similarly be affected by these activities, including changes to water quantity, water quality, and biological communities. The MNSQT incorporates many of the functions and parameters outlined in Fischenich (2006) and Harman et al. (2012). The User Manual identifies a basic suite of parameters and metrics included that should be evaluated for all projects. Recognizing that not all compensatory mitigation projects will have the same objectives or components, the MNSQT allows for flexibility in selecting additional parameters for specific projects. ELI et al. (2016) noted that regulatory protocols should allow for function-based goals and objectives that are project specific, clearly stated, and feasible so that reference standards and monitoring can be targeted for that specific project. Parameters included in the MNSQT could assist in setting reference standards for projects with goals to restore habitat, restore targeted fish communities, improve water quality, or implement other project-specific objectives.

The complete set of function-based parameters and metrics used in the MNSQT is listed in Appendix A. Rationale for excluding parameters and metrics that were included in the original SFPF document (Harman et al. 2012) is provided in Table 1-4. Rationale for including parameters and metrics is briefly provided in Table 1-4 and detailed throughout this document in the parameter summaries. The overarching criteria used to select parameters and metrics included the following:

- Ability to link the parameters to the functional statement in the SFPF and ability to link the metrics to restoration or impact activities. The metric that informs the functional capacity of the parameter should be responsive to activities.
- Parameters and metrics should be reach-based. Changes in metrics should occur at a reach scale where restoration and impact activities occur. Note: stressors and perturbations that occur at a catchment scale may affect both existing and proposed condition scores and are considered in the catchment assessment and determination of restoration potential (see Section 2.2 and the MNSQT User Manual for details).
- Ability to develop reference curves representative of MN conditions for each metric. Information needs to be available to characterize the reference aquatic resources and relate this range of conditions to a reference standard.

- Flexibility in the level of effort for data collection and analysis. Corps Guidance (RGL 08-03) articulates that the level of analysis and documentation for evaluating applications under CWA 404 should be commensurate with the scale and scope of a project.
- Applicable and meaningful in Minnesota. Minnesota is relatively flat and comprised of plains and low hills formed by glaciers. The state contains three major river basins that drain to the Gulf of Mexico, Hudson Bay and Lake Superior. Each basin contains unique geologic, land use, vegetation, and climate that influence the watershed, valley, and stream characteristics. The size of the stream systems in Minnesota ranges from small headwaters that flow into the Great Lakes and the Mississippi River up to larger stream systems. Additionally, there are many low gradient/ wetland-rich stream systems and multiple stream use classes that parameters, metrics, and resulting projects should account for when information is available.

Table 1-4: Summary of parameters considered for the MNSQT and rationale for inclusion or exclusion

Functional Category	Parameter	Included in MNSQT (Yes/No)	Rationale
Hydrology	Channel Forming Discharge	No	Better suited for the design phase of a project rather than to show functional lift and loss. Hard to develop reference standards given the significant lag time for many of these parameters. Primary use in design is to size the channel, the effects of channel size shows up in other parameters, like Floodplain Connectivity.
	Precipitation/Runoff Relationship		
	Flood Frequency		
	Flow Duration		
	Reach Runoff **	Yes	See Chapter 2. Changes in land cover, land use, and stormwater routing within the lateral drainage area impact the magnitude, duration, frequency, timing, and rate of change of runoff hydrographs entering the project reach.
Hydraulics	Flow Dynamics	No	Difficult to show functional lift and loss from stream activities. Typically included in SQTs where flow diversions and augmentations are prevalent.
	Groundwater/Surface Water Exchange	No	Difficult to assess and develop reference curves. Better suited for academia.
	Floodplain Connectivity	Yes	See Chapter 3. A major driver of in-stream and riparian function and channel stability.
Geomorphology	Channel Evolution	No	Considered in determination of restoration potential and selection of reference stream type.
	Sediment Transport Competency and Capacity*	No	Not recommended by Function-Based Framework for showing functional lift/loss; difficult to develop reference standards. Effects of sediment transport processes show up in other parameters like Floodplain Connectivity, Bedform Diversity, and Lateral Migration. Recommended as part of the design process.
	Large Woody Debris (LWD)	Yes	See Chapter 4. Major driver of stream functions (channel stability, fish and invertebrate habitat) in watersheds that support forests.
	Lateral Migration	Yes	See Chapter 5. A good parameter for showing how impacts contribute to sediment supply and

			how restoration activities reduce sediment supply.
	Bed Material Characterization	Yes	See Chapter 6. Can be used to show that impact activities increase proportion of fine sediments, and that restoration activities can reduce proportion of fine sediments. Applicable in gravel bed streams with sandy banks.
	Bed Form Diversity	Yes	See Chapter 7. Used to show in-stream habitat through a riffle-pool sequence. Also a surrogate for sediment transport processes and channel stability.
	Riparian Vegetation	Yes	See Chapter 8. A major driver of channel stability in geomorphology. Supported by hydrology and hydraulics in determining species composition. Supports denitrification and organic carbon processes, provides stream shading and is a source of wood. Provides allochthonous input for macroinvertebrate food and provides wood for habitat for macroinvertebrate communities in biology.
Physicochemical	Organic Carbon	No	Difficult to develop reference curves. Difficult to assess.
	Bacteria**	No	Difficult to develop reference curves; MN water quality criteria are more targeted for human health than aquatic ecosystem function. E. coli standards are designed to protect aquatic recreational use by preventing illness associated with swimming and wading.
	Total Suspended Solids (TSS)**	Yes	See Chapter 11. Excessive TSS is a widespread problem throughout MN. Excessive TSS can harm aquatic life, degrade aesthetic and recreational qualities, and make water more expensive to treat for drinking.
	Water Quality (pH and Conductivity)	No	Conductivity and pH are good indicators of overall stream health but they are typically not affected by reach-scale stream restoration activities. Thus, these metrics typically do not demonstrate functional lift and loss. Therefore, conductivity and pH were not prioritized for inclusion in this version of the MNSQT.
	Water Quality (Temperature and Dissolved Oxygen [DO])	Yes	See Chapters 10 and 11. Temperature is a major driver of supporting cool- and cold-water fish. Large-scale stream restoration projects can show a positive change in this parameter. DO is included for now but is less likely to show a change than temperature.
	Nutrients	No	The River Eutrophication Standard is a 2-part standard, with a causative variable (total phosphorus) and a response variable that indicates the presence of eutrophication (sestonic chlorophyll-a, DO flux, BOD5 or pH). Unable to develop reference standards for MN streams.
	Macrophyte Communities	No	Uncommon in stream mitigation monitoring.
Biology	Microbial Communities	No	Uncommon in stream mitigation monitoring.

	Landscape Connectivity	No	Requires assessments beyond the project reach. Reference standards are typically species specific. Can be included by using the SQT at a watershed scale.
	Macroinvertebrate Communities	Yes	See Chapter 12. Strong indicator of aquatic health. Many of the below parameters are included to support macroinvertebrate communities. Supports healthy fish communities.
	Fish Communities	Yes	See Chapter 13. Apex predator for perennial and some intermittent streams. Many of the parameters in the SQT are included to support fish communities.
** The Function-Based Framework refers to Harman et al. (2012) which provides more information about these parameters and why they are recommended for the design phase and not for characterizing lift or loss.* *** These parameters were not included in Harman et al. (2012) but were added later to this or other SQTs.*			

Rationale for Excluding Sinuosity

During the development of the MNSQT, sinuosity was considered as a metric for a plan form parameter. While sinuosity is important in the design of single-thread channels, the MNSQT does not include sinuosity for the scoring of reach condition.

The following experiences led to the removal of the sinuosity metric and plan form parameter:

- The way sinuosity was included as a metric within the plan form parameter results in over-valuation of that metric.
    - Sinuosity is already captured in the SQT scoring because of the use of functional feet (i.e., increasing or decreasing stream length results in a relative increase or decrease in functional feet).
    - Plan form improvements are quantified in pool spacing between geomorphic pools in meandering systems.
- Sinuosity measurements can be highly variable when measured on a reach-scale. In some projects submitted to the Corps, there was a lot of variability in determining valley length, particularly in confined reaches, which drastically affected sinuosity values (e.g., stream length was drastically reduced, but sinuosity values did not change pre- and post-project because of related design changes to the floodplain).
- While there are concerns that eliminating the sinuosity metric might lead to overly sinuous designs, there is some research on the economics of stream restoration (Doyle et al. 2015) that notes that practitioners are generally not incentivized to create overly sinuous channels to maximize credit returns because there are risks associated with implementing designs that may fail.

1.7. Data Sources, Data Gaps, and Limitations

Data Sources:

As described in Section 1.3, due to the lack of MN data at the time of development, the reference curves included in the MNSQT sometimes relied on data from national and regional resource surveys and other available datasets, particularly for the hydraulics and geomorphology metrics. As additional hydraulic and geomorphic data are made available from

MN streams, the reference curves can be further evaluated and updated as needed (see Section 1.8).

Potential data sources were evaluated using the five assessment factors outlined by the Science Policy Council in *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information*, including applicability and utility; evaluation and review; soundness; clarity and completeness; and uncertainty and variability (USEPA 2003). Datasets that are either compiled into one dataset from smaller datasets or are used to inform more than one metric are introduced below. **Datasets used to inform singular metrics are introduced in the corresponding chapter.**

<u>Reference Datasets:</u>

- Jennings & Zink (2017; TN): This dataset, referred to as “Jennings & Zink (TN)” throughout this document, represents reference standard sites and was used to develop reference curves for metrics that describe floodplain connectivity (ER) and bed form diversity (pool spacing ratio and pool depth ratio).

  Jennings & Zink (2017) was contracted by Tennessee Department of Environment and Conservation (TDEC) to develop regional curves and collect hydraulic and geomorphic data to plan and evaluate design ranges for channel morphology in stream restoration projects.

  Cross-section data were collected statewide from 114 reference sites across the following ecoregions: Blue Ridge (ecoregion 66); Ridge and Valley (ecoregion 67); Southwestern Appalachians and Central Appalachians (ecoregions 68/69); Interior Plateau (ecoregion 71); and the Southeastern plans and Mississippi Valley Loess Plains (ecoregions 65/74).

  Large woody debris was collected from 92 references sites across the ecoregions.

  Bedform data were collected at 31 sites across the ecoregions.

  BHR was used as a quality assurance measure to ensure reference quality: 8 of the 114 reference sites were deeply incised (BHR > 1.5) and were removed from the dataset because they were not considered to represent reference standard condition. Additionally, four F sites were removed from the analysis for entrenchment ratio because these stream types are naturally entrenched. Only two of the four F stream types in this dataset actually had channel pattern morphology data (one cobble bed and one sand bed). However, these data were not included in analyses due to small sample size.

- Lowther (2008; NC): This dataset, referred to as “Lowther (NC)” throughout this document, represents reference standard sites and was used to develop reference curves for metrics that describe bed form diversity: pool depth ratio and pool spacing ratio.

  As part of an NC State University master’s thesis, hydraulic and geomorphic data were collected from the Piedmont ecoregion of North Carolina at: 19 geomorphic reference standard sites. BHR was used as a quality assurance measure to ensure reference quality. All sites were considered reference quality due to BHRs near 1.0 (Lowther 2008). One site was removed from analysis due to its unique character as an E5b stream type and small sample size. The dataset consisted of 16 C and E and two Bc stream types.

- Zink et al. (2012; NC & TN): This dataset, referred to as “Zink et al. (NC)” throughout this document, represents reference standard sites and was used to develop reference curves for metrics that describe bed form diversity: pool spacing ratio and percent riffle.

  Geomorphological data were collected from 14 alluvial streams in the mountains of North Carolina and Tennessee from watersheds without urbanization or impacts from logging (Joyce Kilmer⁄Slickrock Wilderness of NC and TN). These data are thus considered reference standard. Slopes ranged between 1.4 and 10.4% and characterize and A and B stream types.

- Harman & Clinton (NC & WV): This dataset, referred to as the “Harman & Clinton (NC & WV)” throughout this document, represents reference standard sites and was used to develop reference curves for metrics that describe bed form diversity: pool spacing ratio and percent riffle.

  The dataset is a composite dataset of six sites, where the NC data are compiled from an NC State University master’s thesis and the West Virginia dataset in an unpublished dataset collected by Harman.

- Michigan Department of Environment, Great Lakes, and Energy (MI EGLE): This dataset, referred to as “MI EGLE” throughout this document, represents reference standard sites and was used to develop reference curves for metrics that describe bed form diversity: pool spacing ratio, pool depth ratio, and percent riffle.

  Geomorphological data were collected from 16 reference sites in Michigan. One site was removed due to a very large drainage area. Of the 15 sites, four were Bc stream type and 11 were C and E stream types.

<u>Data Gaps and Limitations</u>:

There is a large diversity of stream types in MN due to differences in landform, climate and geology, which in turn influence the hydrogeomorphic context of streams. We aimed to develop a tool that is broadly applicable across different hydrologic and geomorphic regimes through the stratification process and simple scoring but recognize that there will always be gaps with this approach.

Some metrics and their reference curves are applicable for the entire state. Others are stratified by stream type, river use class, river nutrient regions, reference community class, valley type, etc., with reference curves for each (see Appendix A). In some instances, data were not available for all regions or stream types, and thus application of certain metrics may be limited. Specific data gaps and limits to applicability are addressed within each metric description and are identified in Appendix A. Future versions of the tool will benefit from additional data collection and analysis.

Rigorously accounting for regional variability among sites requires large datasets and statistically derived conclusions. These types of datasets were not always available for metrics included in this tool. It will be possible to revise certain reference curves as more data become available (see Section 1.8). It is important to remember, however, that this tool is intended to compare pre- and post-project conditions at a site. As such, the difference between existing and future site conditions is the most important element.

A lack of available statewide datasets from Minnesota led the MNSQT SC to use datasets from other regions to develop reference standards. As data in Minnesota are collected using the methods outlined in the MNSQT and become available, revisiting reference standards and considering stratifying variables is encouraged.

In general, not all metrics are applicable to or have been tested in ephemeral or intermittent streams, stream/wetland complexes, and beaver-influenced systems. A stream/wetland complex is a stream channel or channels with adjacent riverine wetlands located within the floodplain or riparian geomorphic setting, where overbank flow from the channel(s) is the primary wetland water source (Brinson et al. 1995). Stream types may be single-thread or anastomosed. Common stream types for stream/wetland complexes include Rosgen E, Cc-, and D_A. An example of a stream/wetland complex within a single thread stream corridor is shown in Figure 1-3.

Several metrics rely on bankfull depth or width to account for differences in stream size. Inaccuracies and/or inconsistencies in determining bankfull dimensions for a site will affect the way these metrics are characterized in the tool. Therefore, guidance on bankfull identification is provided in the User Manual Appendix A.

Figure 1-3: Example of a stream/wetland complex within a single thread stream corridor

Table 1-5 shows which parameters are applicable to different stream flow and channel types. Additionally, modifications to sampling methods may be needed to accommodate data collection in stream/wetland complexes or non-wadable streams.

Table 1-5: Applicability of metrics across flow type and in stream/wetland complexes

Applicable Parameters	Perennial	Intermittent	Ephemeral	Stream/Wetland Complexes (Anastomosed, D_A)	Stream/Wetland Complexes (Single thread, E/Cc-)
Reach Runoff	x	x	x	x	x
Floodplain Connectivity	x	x	x	x[1]	x
Large Woody Debris	x	x	x	x	x
Lateral Migration	x	x	x	x	x
Bed Material Characterization	x	x	x	x	x
Bed Form Diversity	x	x			x
Riparian Vegetation	x	x	x	x	x
Temperature	x	Where baseflows extend through sampling period		x	x
Dissolved Oxygen	x			x	x
TSS	x			x	x
Macroinvertebrates	x			x	x
Fish	x			x	x

An ‘x’ denotes that one or more metrics within a parameter is applicable within these streams

1 - ER not applicable for stream/wetland complexes with D_A stream types.

Future Work:

- Work is ongoing to consider how to broaden the applicability of the tool in ephemeral and intermittent streams, and stream/wetland complexes with multiple channels (anastomosed).
- The SQT is not intended to compare streams to another resource type (e.g. wetlands, impoundments). However, some agencies are investigating ways to use the SQT for dam removal projects that convert lentic systems back into lotic systems.
- As additional data become available through testing, future versions of the tool will be updated.

1.8. Revisions to the MNSQT and Reference Curves

Reference curves included in the MNSQT and this document will be reviewed and updated, as needed. If additional data and/or literature values are provided during the public comment period or in the future, they will be evaluated using the five assessment factors outlined in *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information* (USEPA 2003) and considered for inclusion in the tool.

Additionally, the MNSQT architecture is flexible and can accommodate additional parameters and metrics that are accompanied by reference curves. If a user is interested in proposing additional parameters or metrics for incorporation into the tool, they should provide a written proposal for consideration. The proposal should include data sources and/or literature references and should follow the framework for identifying threshold values and index scores that is outlined in this document. Such proposals will be considered in future versions of the tool.

Technical feedback may be submitted at any time to the Technical Services Section, St. Paul District US Army Corps of Engineers, 108 5th Street East, Suite 700, St. Paul, Minnesota 55101 or call (651) 290-5525; or email StPaulSQT@usace.army.mil.

Chapter 2 Reach Runoff Parameter

Functional Category: Hydrology

Function-based Parameter Summary:

This parameter focuses on the hydrologic transport of water from the portion of the catchment that drains laterally into the reach. Changes in land cover, land use, and stormwater routing within the lateral drainage area can impact water quality (sediment, nutrients or other pollutants) as well as the magnitude, duration, frequency, timing, and rate of change of runoff hydrographs entering the project reach (Beechie et al. 2012; ELI and TNC 2014).

The reach runoff parameter is limited to quantifying changes that occur within the lateral drainage area. A qualitative characterization of the upstream contributing catchment is used to evaluate the restoration potential of a project reach (see Section 1.2) but is not directly scored within the MNSQT. The reach runoff parameter only evaluates the lateral drainage area given that projects are often limited in their ability to influence hydrologic conditions upstream of the project reach.

The lateral drainage area impacts the amount of runoff and the pollutants entrained in and transported to the receiving stream reach. Multiple studies have shown that increases in impervious cover are linked to decreases in stream health (Schueler et al. 2009), and agricultural practices can contribute sediment, nutrients, and other pollutants (USEPA 2005). The lateral drainage area plays a role in supporting the structure and function of stream ecosystems as described by Fischenich (2006): maintaining surface water storage processes, surface/subsurface water exchange, quality and quantity of sediments, necessary aquatic and riparian habitats, water and soil quality, and landscape pathways. Including the reach runoff parameter in the MNSQT incentivizes stormwater management and land management practices on a reach-scale that can contribute to cumulative progress in a larger watershed.

Reach Runoff Parameter Metrics:

- Land Use Coefficient
- Concentrated Flow Points
- Best Management Practice (BMP) Minimal Impact Design Standard (MIDS) Runoff Coefficient (R_v Coefficient)

The MNSQT includes three metrics under the reach runoff parameter: land use coefficient, concentrated flow points, and BMP MIDS R_v coefficient. The BMP MIDS R_v coefficient metric has been added to the MNSQT to address the hydrologic impacts of projects that include stormwater BMPs on land adjacent to the project reach. Multiple SQTs include land use coefficient and concentrated flow points metrics.

The land use coefficient and concentrated flow metrics are intended to be applied together. The BMP MIDs R_v coefficient is an optional metric that should be used only when BMPs are proposed on land adjacent to the stream restoration project. If the BMP MIDS R_v coefficient is used, the land use coefficient and concentrated flow points metrics are not used.

2.1. Land Use Coefficient Metric

The MNSQT uses an area-weighted land use coefficient to quantify the impact of various land uses on reach runoff within the lateral drainage area. An area-weighted land use coefficient is calculated by delineating areas of different land uses within the lateral drainage area of a stream reach, assigning a land use coefficient to these areas, and then calculating an area-weighted coefficient.

Land use coefficients are based on runoff curve numbers (CN) developed by the Natural Resource Conservation Service (NRCS) in Urban Hydrology for Small Watersheds (NRCS 1986), commonly referred to as TR-55. CNs quantify the runoff potential due to land use and infiltration capacity of underlying soils. TR-55 presents CN values for various natural, agricultural, and urban land uses across a range of soil types and surface conditions. CN values for urban land uses trend higher than agricultural lands depending on the percent of impervious cover associated with various cover type descriptions. Therefore, as the lateral drainage area is cultivated or developed, the CN value and runoff, CN values were simplified to remove hydrologic soil group (HSG) and focus on land use/land cover since improving underlying soils is infeasible and/or cost-prohibitive for practitioners.

Reference Curve Development:

The reference curve for land use coefficient was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

The MNSQT SC evaluated and adopted this metric and the reference curves from the CSQT Beta Version. However, the MNSQT SC revised land uses adopted from TR-55 to reflect land use covers in MN (see Section 2.5 in User Manual).

CN values were adopted for HSG B. Group B was selected because soils outside of the riparian corridor generally correspond to hydrologic soil groups A and B. Additionally, riparian land cover is proportionally smaller than non-riparian cover in a watershed. To be more conservative, hydrologic soil group B, which exhibits moderate infiltration rates when wetted and moderately to well drained soils, was selected as a representative soil instead of A, which exhibits high infiltration rates when wetted and well to excessively drained soils (USDA and NRCS 2007).

Stratification by riparian vegetation cover (woody or herbaceous) was considered because herbaceous communities have less roughness and higher runoff potential than forested communities. However, this stratification was not incorporated because the riparian vegetation community is rarely present within the entire lateral drainage area. Thus, this stratification would not be representative of the area-weighted land use coefficient for the entire lateral drainage area.

A broken-linear curve was applied for the land use coefficient metric (Figure 2-1) to allow for a broader range of functioning land use coefficients. The curve is steeper in the not functioning and functioning-at-risk range of scoring than in the functioning range to account for natural variability. The following threshold values were used to inform the curve (Table 2-1).

- Functioning: Field values of 40 and 68 were set to index values of 1.0 and 0.70, respectively.

- Functioning-at-risk: The regression line was extrapolated from the not functioning category because the datasets did not provide explicit field values for this condition category.
- Not Functioning: A field value of 80 was set to the index value of 0.0, as this value indicates a significant amount of developed lands within the lateral drainage area, and this level of land use change likely contributes to substantially altered reach-scale hydrology.

Table 2-1: Threshold Values for Land Use Coefficients

Index Value	Field Value
1.00	40
0.70	68
0.00	80

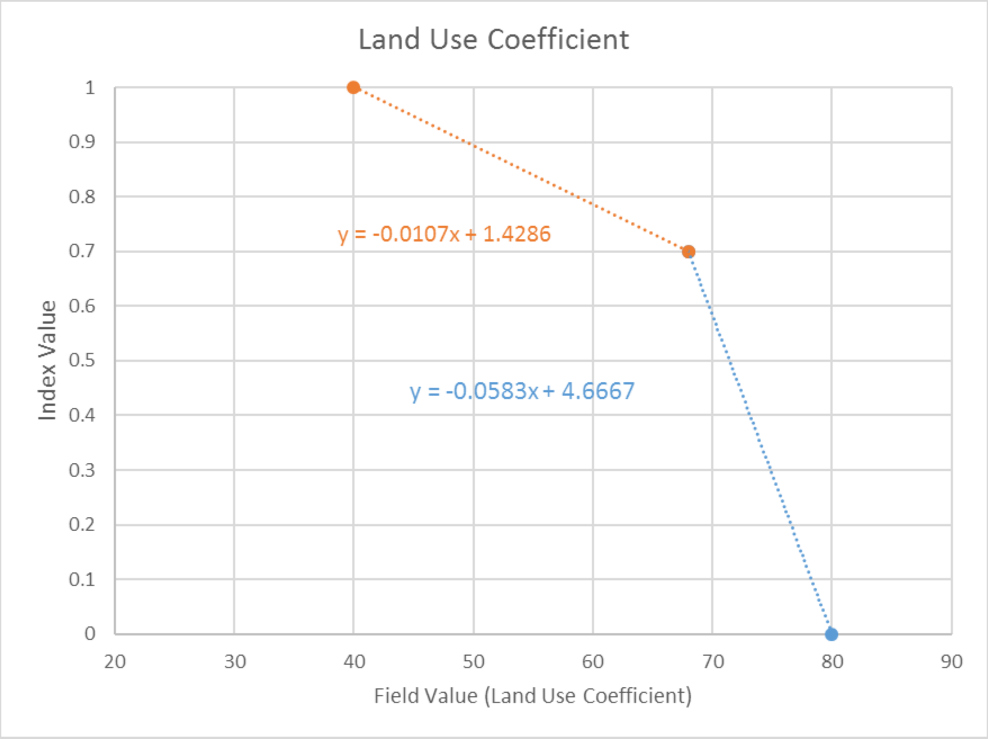

Figure 2-1: Reference Curves for Land Use Coefficient

Limitations and Data Gaps:

The land use coefficient metric does not account for variation in infiltration capacity, impermeable layer depth, or other characteristics important to estimating runoff volumes. Additionally, land use coefficients do not account for relative pollution loads coming from different land uses.

The size of the project area compared to the size of the lateral drainage area will influence how much index scores change in response to land use. Reaches with larger lateral drainage areas would need to acquire and revegetate more land to achieve a lift similar to projects with a smaller lateral drainage area.

Similarly, the relative catchment location (e.g., the proportion of land area within the lateral drainage area compared with the entire catchment area) could impact the relative impact of direct drainage to the channel versus in-channel delivery from upstream. The larger the contributing upstream catchment area, the less influence the lateral drainage has in maintaining stream functions. A reach located far downstream from the headwaters may be more affected by hydrologic changes occurring upstream than from land use changes in the lateral drainage area. Alternatively, improving land use condition in small streams near the headwaters may have a greater relative effect. The limitation of not accounting for project size versus lateral drainage area and of the relative catchment location could be addressed through stratification and development of additional reference curves.

Stratification of the natural land use types would better account for differences associated with various natural land uses. Natural land cover varies in runoff and infiltration potential. For example, natural prairies function differently than broadleaf forests, with different curve numbers and land use coefficients, but both may represent a pristine or reference standard condition. Also, the land use coefficient metric may be less sensitive to changes between natural land cover types and developed land uses where natural land use coefficients are more similar to developed land use types.

The land use coefficient metric has received limited testing and would benefit from additional application and testing in Minnesota. It would also benefit from sensitivity testing and comparison to other indicators of altered stream processes.

2.2. Concentrated Flow Points Metric

The concentrated flow points metric assesses the number of concentrated flow points that enter the project reach from adjacent land uses per 1,000 linear feet of stream. The adjacent land use is assessed from the upstream to downstream ends of the project reach. Concentrated flow points are defined as erosional or constructed features (e.g., concrete swales, rills, gullies, ditches, or other conveyances) created by anthropogenic modifications on the landscape that alter or concentrate runoff into the stream. These types of features can be caused by agricultural practices that result in irrigation return flow or cut and fill activities associated with roads or building sites that intercept water otherwise heading downslope as throughflow or groundwater and bring it to the surface. Alterations in runoff processes associated with land use changes are common, particularly due to changes in or removal of vegetation; increased impervious surface area; soil compaction and decreased infiltration; and interception of subsurface flows and routing to streams (Beechie et al. 2012).

Overland flow typically erodes soils relatively slowly through sheet flow; however, anthropogenic impacts can lead to concentrated flows that erode soils quickly, transporting water and sediment into receiving stream channels (Al-Hamdan et al. 2013). Three primary drivers that cause sheet flow to transition to concentrated flow include discharge, bare soil fraction, and slope angle (Al-Hamdan et al. 2013). Anthropogenic changes to runoff characteristics often create new conveyances, where flows are concentrated and routed more quickly to streams. Channels are also constructed to drain the landscape, e.g. agricultural ditches or concrete swales connecting parking lots to stream channels and gutter systems to route rainwater away from structures. Even hiking or game trails can intercept and concentrate runoff.

Stream restoration projects can reduce concentrated flow that directly enters the project reach by dispersing flow in the floodplain, increasing surface roughness, regrading to flatten slopes, removing roads and ditches, filling ditches, and restoring riparian vegetation. Development can negatively impact streams by creating new concentrated flow points such as stormwater outfalls. Stormwater best management practices can be used to address these outfalls, enhance infiltration, and reduce outfall velocity.

Reference Curve Development:

The reference curve for concentrated flow points was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

The MNSQT SC evaluated and adopted this metric and the reference curves from the CSQT Beta Version. The threshold values for the concentrated flow points metric were based on best professional judgement, as literature values were not available that quantified relationships between the number of concentrated flow points and stream stability or aquatic life. However, there is a clear negative relationship between concentrated flows and degradation of stream stability and aquatic life (Hammer 1972). It was assumed that the absence of anthropogenic concentrated flow points reflected a reference standard, and the presence of one or more concentrated flow points per 1,000 ft no longer reflected a reference standard condition.

The following threshold values were used to inform the curve (Table 2-2 and Figure 2-2):

- Functioning: A field value of 0 was set to the index value of 1.0.
- Functioning-at-risk: A field value of 1 was set to the 0.69 index value.
- Not Functioning: The regression line was extrapolated from the Functioning category because the datasets did not provide explicit field values for this condition category.

Table 2-2: Threshold Values for Concentrated Flow Points

Index Value	Field Value
1.00	0
0.69	1

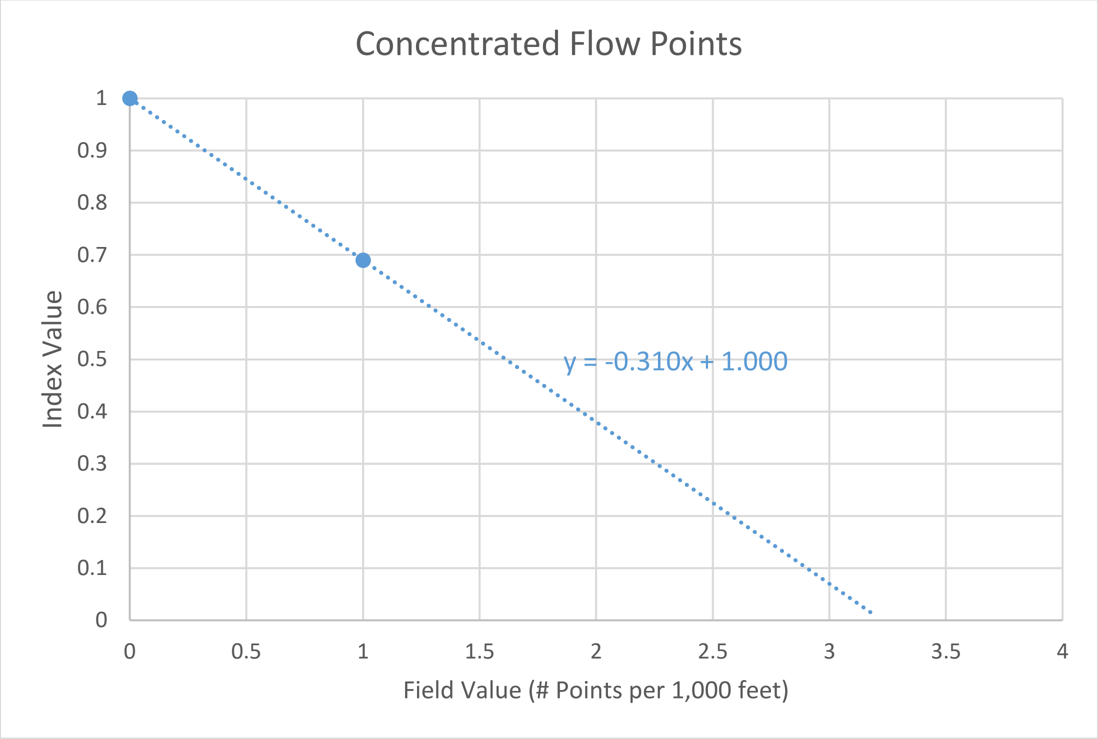

Figure 2-2: Reference Curve for Concentrated Flow Points

<u>Limitations and Data Gaps:</u>

The concentrated flow points metric does not consider the type or size of the concentrated flow points, only the number. Considering the cumulative volume of runoff water produced by the flow points, differences in their type, or their contributing drainage area relative to the lateral drainage area would make this a more meaningful metric. For example, one large, concentrated flow point may deliver more water (with lower quality) than three or more small conveyances.

There are other limitations of using a simple count per linear foot of stream. For example, a practitioner could be incentivized to take three concentrated flow points, merge them together, and create one larger flow point, which may not result in any actual improvements in the stream condition. As another example, if the project restores natural sinuosity but does not reduce the number of concentrated flow points, the tool would show lift solely as a result of the increased channel length, rather than an attempt by the practitioner to reduce the actual number of concentrated flow points. These types of examples will need to be addressed through guidance and policy until the metric is modified to address these types of issues.

The concentrated flow points metric was developed for use in the North Carolina SQT and was incorporated into the MNSQT. Because it is a relatively new metric, it will need additional testing and review as it is applied to project sites, particularly in degraded stream reaches and urban areas. This metric was initially intended to complement the land use coefficient metric and incentivize reach scale practices that improve infiltration and runoff processes of the land that drains directly into the stream reach from the lateral drainage area.

2.3. BMP MIDS R_v Coefficient Metric

The MNSQT uses the runoff coefficient (R_v) from the Minimal Impact Design Standards (MIDS) calculator to quantify the impact of applying best management practices (BMPs) to adjacent uplands in urban environments. This metric was derived from the annual stormwater runoff volume calculation from the Minnesota Pollution Control Agency (MPCA) MIDS calculator. To quantify the impact of applying BMPs, the user must use the MIDS calculator[1] to calculate the existing runoff coefficient (R_v) and then calculate the effective R_v for the proposed condition.

The runoff coefficients are based on soil type and land use. Higher values, nearer 0.95, indicate more runoff potential and lower values, nearer 0, indicate less runoff potential. To focus on land use change rather than infiltration capacity of soils, runoff coefficients used in the calculator to develop metric field values in the MNSQT were selected to adequately represent a land use and reduce subjectivity.

The MIDS calculator is a tool designed to quantify reductions in post-development runoff and pollutant loading using a variety of low impact development practices. The tool calculates the amount of stormwater volume and pollutant reduction that can be achieved by installing stormwater BMPs. The MIDS calculator quantifies the benefits of various BMPs in terms of volume, total phosphorous, dissolved phosphorus, and total suspended solids.

Reference Curve Development:

The reference curve for BMP MIDS R_v coefficient was developed by the MNSQT SC.

The annual stormwater runoff volume is calculated using a weighted runoff coefficient (Collins et al. 2008) for various natural, managed turf, and urban land uses across hydrologic soil type conditions. The runoff coefficients for forest/open space range from 0.02 to 0.05 over the four soil types, while the runoff coefficients for managed turf (disturbed soil) range from 0.15 to 0.25. The runoff coefficient for impervious cover is 0.95 for all four soil types. Therefore, as the lateral drainage area is cultivated or developed, the runoff coefficient and annual stormwater runoff volume increases. A table of the runoff coefficients for each soil type is provided for MNSQT users in the MNSQT User Manual.

To develop a reference curve associated with changes in the runoff coefficients, the threshold values were based on best professional judgement (Table 2-3 and Figure 2-3):

- Functioning: Coefficients that correspond to natural land cover (0.02 – 0.05) were considered to represent a functioning range of index values (0.70-1.00), with the lower coefficient (0.02) assigned an index value of 1.00.
- Functioning-at-risk: The functioning at risk regression line was extrapolated from the functioning and not functioning thresholds.

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[1] The MIDS calculator, web-based manual, and supporting information is available at https://www.pca.state.mn.us/water/enhancing-stormwater-management-minnesota

- Not functioning: Coefficients that corresponded to disturbed soil and increased development within the lateral drainage area (0.25 – 0.95) were considered to represent the not functioning range of index values (0.29 – 0.00). The minimum index value 0.00 equated to a land use coefficient of 0.95, as this value indicates a significant amount of developed lands within the lateral drainage area, and this level of land use change likely contributes to substantially altered reach-scale hydrology.

Table 2-3: Threshold Values for BMP MIDS R_v Coefficients

Index Value	Field Value
1.00	0.02
0.70	0.05
0.30	0.25
0.00	0.95

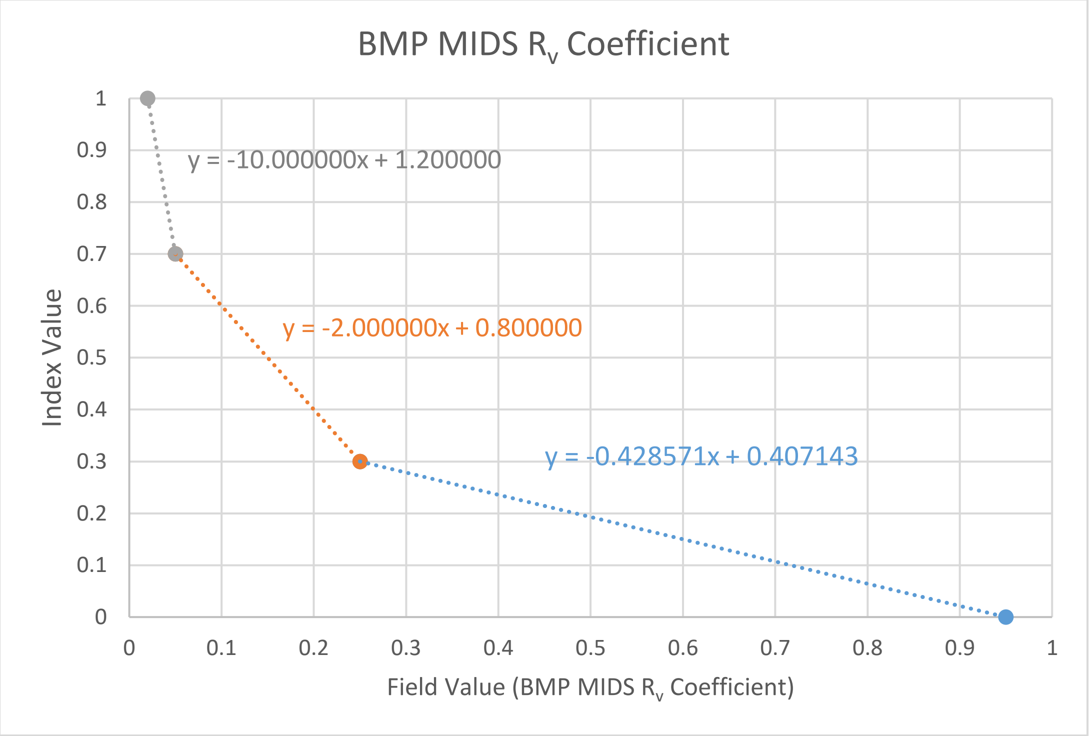

Figure 2-3: Reference Curves for BMP MIDS R_v Coefficients

Limitations and Data Gaps:

This BMP MIDS R_v coefficient metric does not account for the variation in infiltration capacity, impermeable layer depth, or other characteristics important to estimating runoff volumes. Additionally, runoff coefficients do not account for relative pollution loads coming from different land uses.

The size of the project area compared to the size of the lateral drainage area will influence how much index scores change in response to the BMPs. Reaches with larger lateral drainage areas would need to include larger or multiple BMPs to achieve a lift similar to projects with a smaller lateral drainage area.

Similarly, the relative catchment location (e.g., the proportion of land area within the lateral drainage area compared with the entire catchment area) could impact the relative impact of direct drainage to the channel versus in-channel delivery from upstream. The larger the contributing upstream catchment area, the less influence the lateral drainage has in maintaining stream functions. A reach located far downstream from the headwaters may be more affected by hydrologic changes occurring upstream than from BMPs in the lateral drainage area. Alternatively, the use of BMPs in the lateral drainage area of small streams near the headwaters may have a greater relative effect.

BMP MIDS R_v coefficient has received limited testing and would benefit from additional application and testing in Minnesota. It would also benefit from sensitivity testing and comparison to other indicators of altered stream processes, including percent impervious surface, particularly in areas with more urban development.

Chapter 3 Floodplain Connectivity Parameter

Functional Category: Hydraulics

Function-based Parameter Summary:

Floodplain connectivity is one of the most important function-based parameters for stream restoration work (Fischenich 2006) because it is a driver for many geomorphic and ecological functions (Wohl 2004). Floodplains and bankfull benches (also called flood-prone areas) are assessed as floodplain connectivity in the MNSQT. The floodplain of a stream is inundated during moderate to high flows or floods and is formed by sediment deposition during overbank flooding under present climatic conditions by (Leopold 1994). Floodplains consist of alluvium and are associated with meandering streams in alluvial valleys. Bankfull benches are narrower than floodplains and exist in confined or colluvial valleys. Bankfull benches are flat depositional features that provide some energy dissipation for higher flows (Harman et al 2012). Rosgen (2002) defines a flood-prone area as “the area adjacent to the stream that is inundated or saturated when the elevation of the water is at twice the maximum depth at bankfull stage.”

The functional loss associated with channelization and berm or levee construction includes displaced flooding, loss of bedform diversity, downcutting and incision, increased erosion, and loss of fish species and biomass (Darby and Thornes 1992; Hupp 1992; Kroes and Hupp 2010; Richer et al. 2015; Kondratieff and Richer 2018). Severely incised channels can also lower the local water table, draining riparian wetlands or otherwise impacting the local riparian community (Harman et al. 2012). While it is a common perception that a straight and deep channel can move floodwaters quickly downstream, they cause flood damage downstream of the channelization (Schoof 1980). Incised channels cannot store water and sediment in the floodplain during large storm or snowmelt events. When a channel is connected to its floodplain, flood flows can inundate the floodplain and spread out across the landscape allowing in-channel velocities to maintain bed forms without excessive erosion. In a comparison between an incised stream and a similar, non-incised stream, the incised stream had significantly higher turbidity, solids, total nitrogen and phosphorous and chlorophyll concentrations, and lower fish diversity and biomass than the non-incised stream (Shields et al. 2010).

Floodplain Connectivity Parameter Metrics:

- Bank Height Ratio
- Entrenchment Ratio

The SFPF (Harman et al. 2012) describes three measurement methods for the floodplain connectivity parameter: bank height ratio (BHR), entrenchment ratio (ER), and stage-discharge relationships. BHR is a surrogate measure of channel incision and the relative frequency that flood flows could reach the floodplain, while ER estimates the lateral extent of floodplain inundation (Rosgen 1996). Together these metrics can be used to characterize floodplain connectivity.

3.1. Bank Height Ratio Metric

The bank height ratio (BHR) is a measure of channel incision and indicates whether a stream is or is not connected to an active floodplain or bankfull bench. BHR is defined as the depth from the top of the low bank to the thalweg divided by the depth from the bankfull elevation to the thalweg (Rosgen 1996). BHR is included in the Minnesota Pollution Control Agency's (MPCA) Channel Condition and Stability Index (CCSI) and is referred to as "degree of incision" metric.

In a stable high functioning stream with ideal floodplain connectivity the bank height (depth) should be equal to the bankfull height (depth). Thus, any discharge greater than bankfull accesses the floodplain or bankfull bench but bankfull discharge is contained within the bankfull channel (Rosgen 2009). The BHR relates the stage of the flow that can access the adjacent floodplain (in alluvial valleys) or bankfull bench (in colluvial valleys) to the bankfull stage. For example, a BHR of 2.0 means that it takes two times the bankfull stage for flows to access the floodplain, indicating the stream is incised and disconnected from its former floodplain.

Simon and Rinaldi (2006) found that while non-incised channels dissipate some of the erosive energy of high flows across the floodplain, incised channels within the same region contain flows of greater magnitude and return interval. (The return interval is based on the probability that a given storm event will be equaled or exceeded in any given year.) Greater BHR values are characteristic of an unstable condition, deeper and often wider channels, and higher return interval for flows leaving the channel. As greater flows with increased erosive power are confined to the channel, BHR increases as the streambed lowers or degrades. Active degradation is often signaled by head cutting (bed erosion manifested as a step or sudden grade drop that propagates headward), downstream of which the BHR is increased. This results in even larger floods being contained in the channel, and a decrease in floodplain connectivity as the channel evolves through predictable stages (Cluer and Thorne 2013, Rosgen 2009, Schumm et al. 1984). Sullivan and Watzin (2009) found that measurements of bank height ratio, as an indicator of floodplain connectivity, were significantly correlated to fish assemblage diversity.

Reference Curve Development:

The reference curve for BHR was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

The BHR metric was developed by Rosgen (2009) as a measure of channel incision as shown in Table 3-1. Harman, et al. (2012) translated channel incision descriptions from Rosgen (2009) into functioning, functioning-at-risk, and not functioning categories that indicate the degree of incision and the relative functional capacity of incised streams (Table 3-1).

Table 3-1: Bank Height Ratio Categories

Channel incision descriptions by Rosgen (2009)		**Reference standards by Harman et al. (2012)**	
BHR	Degree of Channel Incision	BHR	Functional Capacity
1.0 – 1.1	Stable	1.0 – 1.2	Functioning
1.1 – 1.3	Slightly Incised		
1.3 – 1.5	Moderately Incised	1.3 – 1.5	Functioning-at-risk
1.5 – 2.0	Deeply Incised	> 1.5	Not functioning

Stratification by stream size is built into the metric by using the bankfull depth as the denominator. Bankfull depth varies throughout the country due to differences in climate and runoff characteristics; however, there are predictable, documented relationships that predict bankfull dimensions for streams in the same physiographic or hydrologic region (Dunne and Leopold 1978; Blackburn-Lynch et al. 2017; Torizzo and Pitlick 2004). Stratification by valley type was considered to address differences in floodplains, e.g., between alluvial and colluvial valleys. However, because the BHR metric focuses on the ability of flood flows to access areas outside the channel and not the extent of floodplain inundation, the decision was made not to stratify by valley type.

Threshold values were developed based on the Rosgen (2009) and Harman et all (2912) BHR categories in Table 3-1. A threshold of 1.5 was used to differentiate index values within the functioning-at-risk and not- functioning ranges. BHRs of greater than 1.5 were considered not functioning, consistent with the supporting literature classifying these as deeply incised channels with a greater likelihood of vertical instability (Rosgen 2009). Deeply incised streams (e.g., BHR > 1.7) provide extremely rare or no floodplain connectivity. A channel that contains any significant flood event, e.g., a 10- year or 25-year recurrence interval, is likely to experience significant erosion during a large precipitation event and transport water and sediment downstream instead of dispersing them across the floodplain.

The thresholds identified in Table 3-2 were plotted and a best-fit line was derived to provide a single equation to calculate index values from field values (Figure 3-1).

Table 3-2: Threshold Values for Bank Height Ratio

Index Value	Field Value
1.00	1.0
0.70	1.2
0.30	1.5

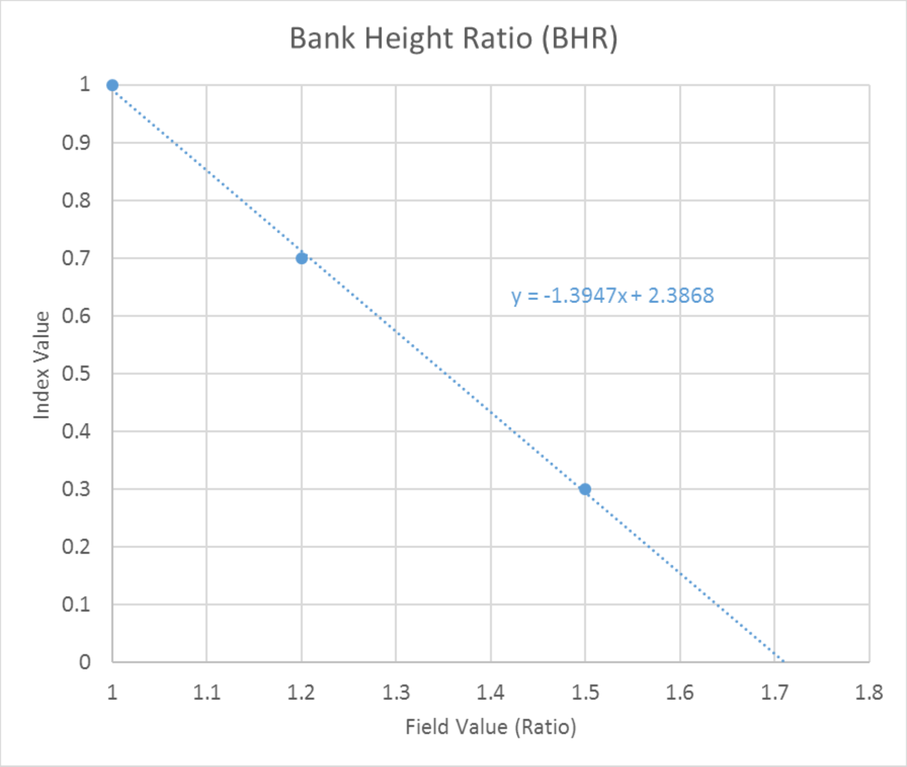

Figure 3-1: Bank Height Ratio Reference Curve

Limitations and Data Gaps:

Further refinement and stratification of these data and reference curves is encouraged as data are collected in MN.

BHR often relates to the stage (water level) and corresponding return interval at which water leaves the channel and inundates a floodplain or terrace. By contrast, in watersheds where the hydrology has been severely altered, the return interval associated with a floodplain surface may dramatically increase (or decrease). For example, the return interval may increase from 1.5 years to 5 years downstream from new impoundments that reduce the frequency (increase the return interval) of flood events. The change in the return interval and stage at which water leaves the channel converts the active floodplain to a terrace. The BHR will not detect this change initially because the floodplain appears to be intact and the stream does not appear to be incised because the depth from the streambed to the top of the bank has not changed, though eventually a smaller channel will develop within the former channel as reduced flood flows fail to scour riparian areas and transport less bed sediment.

If bankfull dimensions are not accurately determined for a site, then the bank height ratio will not accurately represent the incision processes. Information on verifying bankfull information is provided in the User Manual.

3.2. Entrenchment Ratio Metric

The entrenchment ratio (ER) is a ratio of the flood-prone area width divided by the bankfull riffle width, where the flood prone area width is the width of the floodplain at a depth that is twice the bankfull maximum riffle depth (Rosgen 2009). The ER metric is a physically based method (i.e., can be measured in the field at any time), and can be assessed in any stream with a bankfull indicator or regional curve. Instructions for collecting and calculating the field value for ER are provided in the User Manual.

While BHR measures channel incision and whether a stream is connected to an active floodplain or bankfull bench, ER estimates the lateral extent that floodwaters can spread across a valley. A stream is considered entrenched when flooding is horizontally confined, i.e. the flood prone width is small compared to the width of the channel. Large ERs are found in alluvial valleys where large flow events can spread out laterally. ER naturally varies by valley shape and is therefore used as a primary metric in differentiating stream types (Rosgen 1996). ER can also be a useful indicator of functional capacity as many anthropogenic alterations (e.g. levees, berms, and channelization) constrict the natural extent of floodplains and thereby decrease floodplain connectivity.

Reference Curve Development:

Reference curves for ER were developed by the MNSQT SC.

ER is a primary metric in determining the Rosgen stream type: entrenched stream types (A, G and F streams) have ER values less than 1.4 ±0.2; slightly entrenched stream types (E and C stream types) have ER values greater than 2.2 ±0.2; and streams with ER values in between 1.4 ±0.2 and 2.2 ±0.2 are considered moderately entrenched (B stream types; Rosgen 1996). The values used to delineate between stream types were empirically based on data collected by Rosgen. The flood prone width (the ER numerator) was based on the elevation at a depth of two times bankfull max depth. The cross-section width approximated by two times bankfull max depth came from modeling a bankfull discharge and 50-year return interval flood through typical cross sections representing various stream types. The ratio of the depth of the 50-year flood to the bankfull depth ranged from 1.3 to 2.7 for all stream types except the D_A channels. Less confined streams like E channels have lower ratios (the larger the horizontal area floodwaters can occupy, the lower the difference in stage between a small flood and a large one). A “typical” ratio of 2.0 was selected to calculate the elevation of the flood prone width for all stream types, as a generalized comparison of confinement (Rosgen 1996).

Harman et al. (2012) translated the adjective descriptions of entrenchment used by Rosgen (1996) into functioning, functioning-at-risk, and not functioning categories as shown in Table 3-3 after considering the differences among stream types. The reference standards were based on the stream type delineations listed above and the ±0.2 that “allows for the continuum of channel form” (Rosgen 1996).

Table 3-3: Entrenchment Ratio Reference Standards from Harman et al. (2012)

ER for C and E Stream Types	ER for B and Bc Stream Types	Functional Capacity
> 2.2	> 1.4	Functioning
2.0 – 2.2	1.2 – 1.4	Functioning-at-risk
< 2.0	< 1.2	Not functioning

The MNSQT SC evaluated criteria proposed by Harman et al. (2012) using the WY, Jennings & Zink (TN), and Donatich et al. (NC) reference datasets.

Reference curves were developed from a compiled dataset including data from WY, TN, and NC. The WY dataset was compiled from two reference datasets collected by the Wyoming Game and Fish Department and the US Forest Service (USFS). The dataset consists of 61 sites composed of 22 B, 27 C, nine E and three F Rosgen stream types. BHR was used as a quality assurance measure to ensure reference quality: 2 of the 61 reference sites were deeply incised (BHR > 1.5) and were removed from the dataset because they were not considered to represent reference standard condition. Additionally, the three F sites were removed from the dataset for several reasons, including small sample size and because F stream types are an atypical target for restoration. Additionally, they are naturally incised which makes the ER metric not applicable.

The WY geomorphic reference dataset consists of 61 sites that report ER. Of these sites, two sites were identified as degraded (BHR >1.5) and three sites were classified as F channels and were thus, removed from the analysis. The Jennings & Zink (TN) dataset consists of 110 sites that report ER. One site classified as an F channel and nine were classified as reference-degraded (BHR >1.5) and were removed from the analysis. Also, seven sites were reported with an ER >10.0, without an exact number. Thus, a conservative value of 10.01 was used for analyses.

Donatich et al. (2020) implemented the NC SQT v3 protocol in the Piedmont ecoregion of North Carolina at: 18 geomorphic reference sites, 1 biological reference site, 9 restored sites, and 6 degraded sites. The restored and degraded sites were not considered in developing reference curves for the MNSQT. BHR was used as a quality assurance measure to ensure reference quality: 6 of the 18 geomorphic reference sites were deeply incised (BHR > 1.5) and were removed from the dataset because they were not considered to represent reference standard condition. This reference dataset subset included one Bc stream type and 11 C and E stream types.

The statistics for ER stratified by stream type are provided in Table 3-5 and Figure 3-2.[2]

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[2] This is distinct from the BHR analyses where the datasets were presented separately. Datasets were combined due to the stratification of ER.

Table 3-4: Statistics for ER from the reference standard sites within the WY, Jennings & Zink (TN), and Donatich et al. (NC) reference datasets

	Rosgen Stream Type		
Statistic	**B**	**C**	**E**
Number of Sites (n)	44	73	48
Average	1.8	4.3	6.4
Standard Deviation	0.4	2.4	4.7
Minimum	1.2	1.5	2.3
25th Percentile	1.5	2.8	3.5
Median	1.8	3.6	4.9
75th Percentile	2.2	4.8	8.9
Maximum	2.8	12.7	29.9

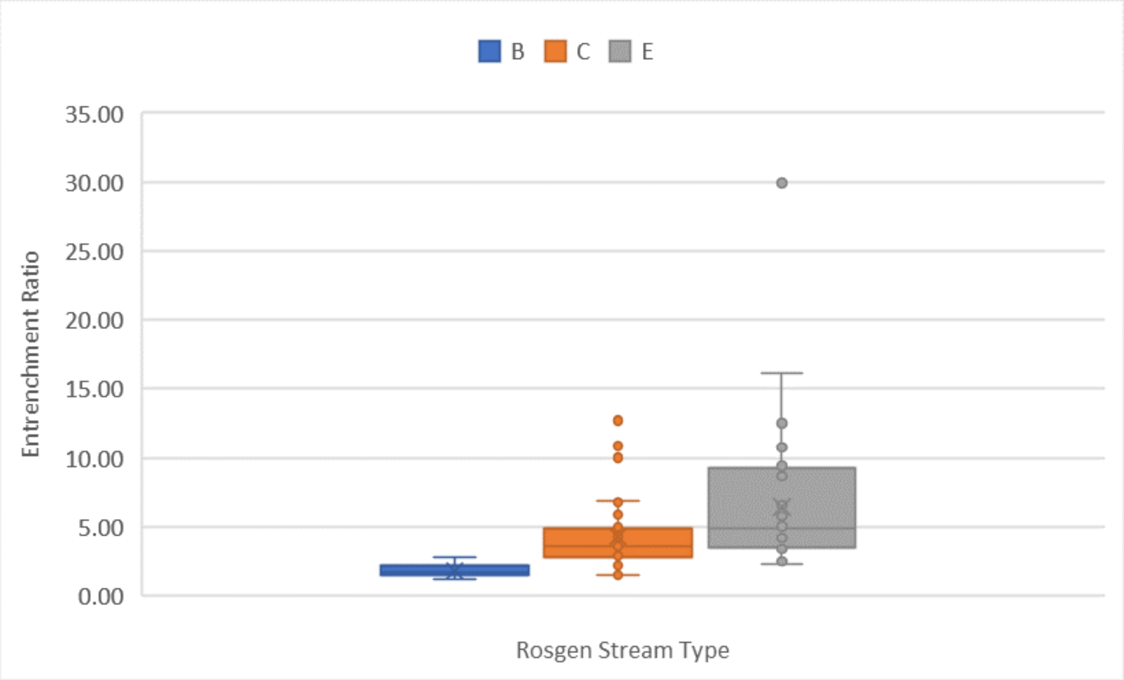

Figure 3-2: Box Plots for ER from the WY, Jennings & Zink (TN), and Donatich et al. (NC) reference datasets, stratified by Rosgen stream type

Stratification by stream size is not needed for the ER metric since bankfull width is the denominator of the ratio. *S*caling by bankfull width accounts for the differences in stream size that may otherwise be relevant in determining flood prone width.

Stratification was needed to account for the natural variability in flood prone width, and therefore entrenchment ratios, across stream and valley types. Stream type was used to stratify the reference curves, and stream types were grouped into relevant valley types. Stream types in confined valleys naturally have low entrenchment ratios and include the following stream types: A, B, Ba, and Bc. Stream types in wider, alluvial valleys include C and E stream types. Only one A stream type was included in the datasets (Jennings & Zink (TN)); however, A streams are likely represented by confined-valley stream types as they naturally occur in confined valleys.

The reference standards presented by Harman et al. (2012) (Table 3-3) were evaluated using the WY, Jennings & Zink (TN), and Donatich et al. (NC) reference datasets (Table 3-4) to develop the threshold values in Table 3-6.

For B stream types:

A summary of the threshold values is provided below and shown in Table 3-6:

- Functioning: Field values of 1.4 and 2.2 were set at 0.70 and 1.00 index values, respectively. The ER values of 1.4 and 2.2 are used to delineate B stream types (Rosgen 2009). Additionally, the ER value of 2.2 is the 75th percentile value for B stream types from the reference data in Table 3-4.
- Functioning-at-risk: The regression lines were extrapolated from the functioning and not functioning thresholds because the datasets did not provide explicit field values for this condition category.
- Not functioning: A field value of 1.0 was set at 0.00. An ER value of 1.0 is the minimum value for this ratio and physically means that the flood prone width is equal to the bankfull width and the stream is entrenched.

For C stream types:

A summary of the threshold values is provided below and shown in Table 3-6:

- Functioning: Field values of 2.2 and 5.0 were set at 0.70 and 1.00 index values, respectively. The ER value of 2.2 is the value used to delineate between Rosgen stream types for C streams (Rosgen 2009). The ER value of 5.0 is the 75th percentile value for C stream types from the reference data in Table 3-4, rounded to the nearest whole number.
- Functioning-at-risk: A threshold value between the functioning-at-risk and not functioning category was not assigned because the reference datasets did not provide explicit field values for this condition category.
- Not functioning: A field value of 1.0 was set at 0.00. An ER value of 1.0 is the minimum value for this ratio and physically means that the flood prone width is equal to the bankfull width and the stream is entrenched.

For E stream types: The best-fit line for the plotted threshold values was derived using multiple linear relationships.

The final reference curves are shown in Figures 3-3 through 3-5.

Table 3-5: Threshold Values for Entrenchment Ratio

Index Value	Rosgen Stream Type		
	B	C	E
1.00	2.2	5.0	9.0
0.70	1.4	2.2	2.2
0.0	1.0	1.0	1.0

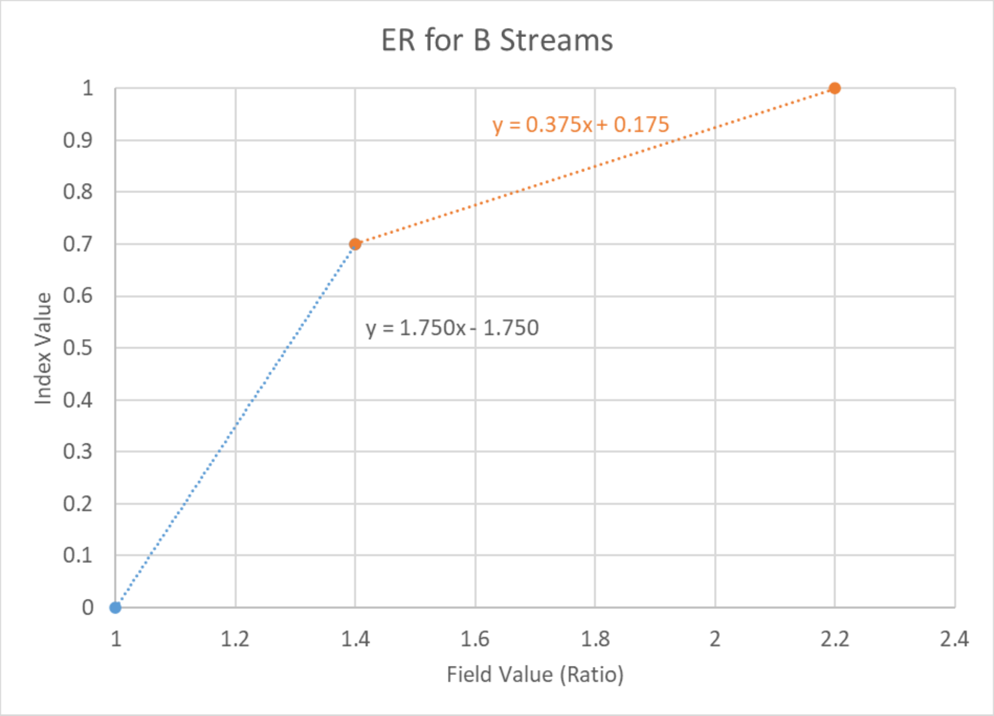

Figure 3-3: Entrenchment Ratio Reference Curves for B Streams

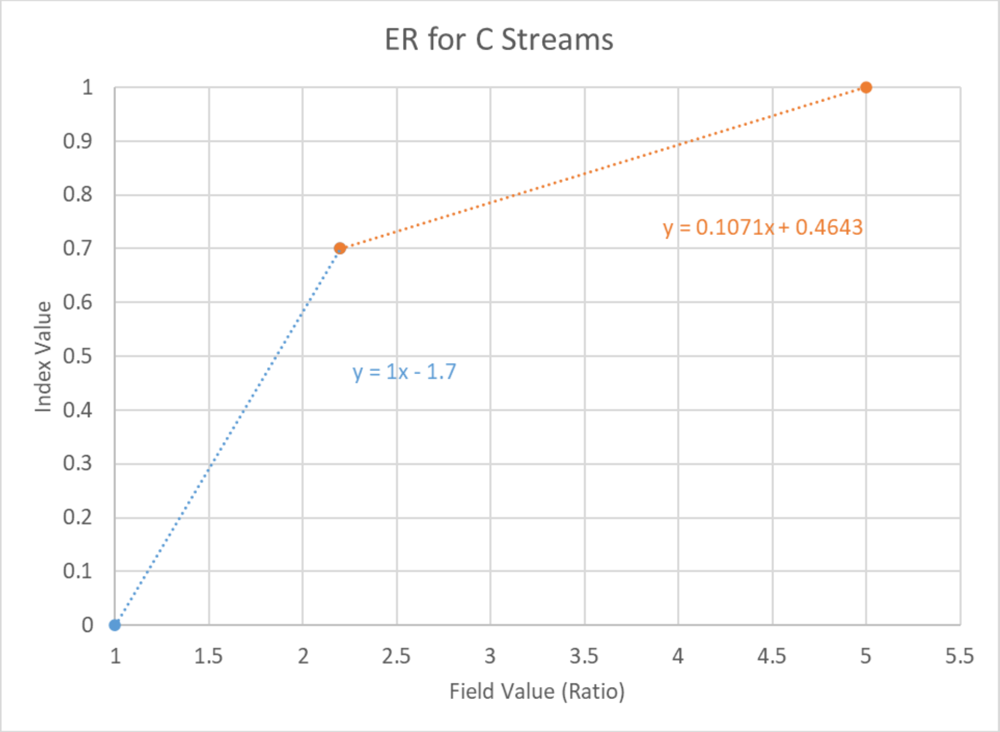

Figure 3-4: Entrenchment Ratio Reference Curves for C Streams

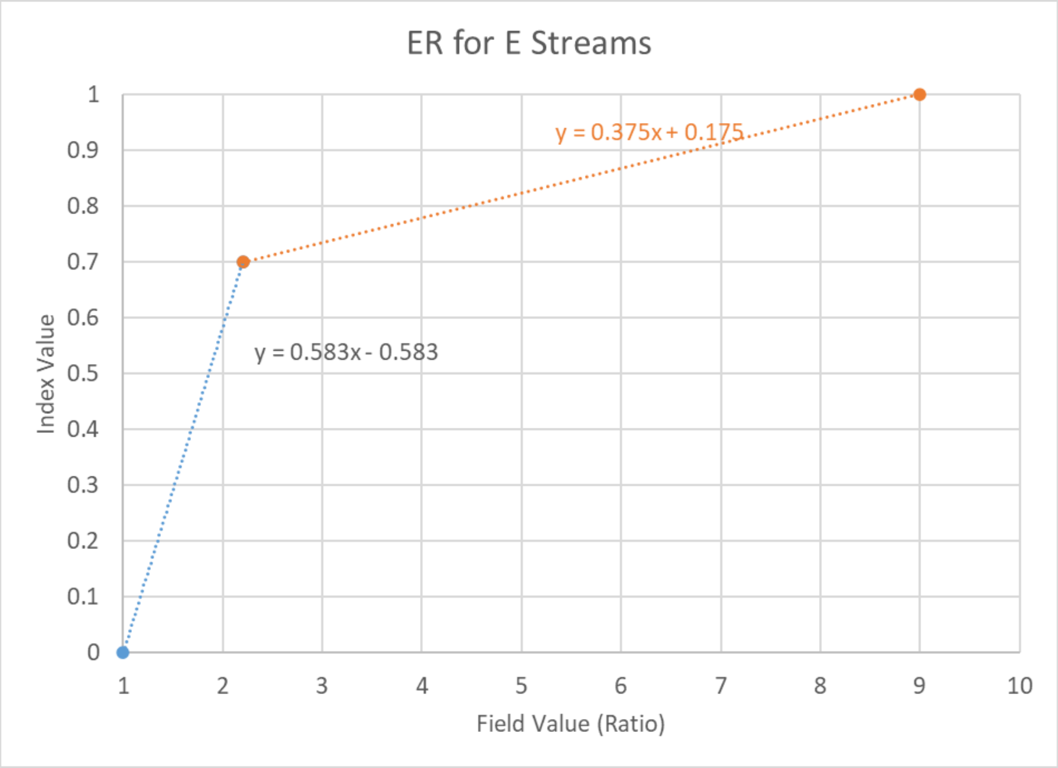

Figure 3-5: Entrenchment Ratio Reference Curves for E Streams

Limitations and Data Gaps:

Further refinement and stratification of these data and reference curves is encouraged as data is collected in MN.

The datasets used to develop reference curves were largely composed of B, C and E stream types. One A stream type was included in the combined reference datasets. However, because A and B streams are both located in confined valley types, they were grouped together. Reference curves were not developed for naturally occurring F and G stream types. If the stream is a naturally occurring F or G stream type, e.g., located in a canyon or gorge setting, a reference curve must be developed for this stream type before this metric is evaluated. Additionally, the ER metric is not applicable to braided (D) stream types since the width of the channels is often the same as the valley width (Rosgen 2009).

Selection of the appropriate reference stream type is important for consistently applying the ER metric and determining a condition score in the tool. Guidance is provided in the User Manual to assist practitioners in identifying the reference stream type. For example, F and G channels that represent degraded streams should be compared against the proposed, or reference stream type, as informed by channel evolution processes (Cluer and Thorne 2013; Rosgen 2014).

If bankfull dimensions are not accurately determined for a site, then the ER will not accurately represent entrenchment processes. Information on verifying bankfull is provided in Appendix A.

Chapter 4 Large Woody Debris Parameter

Functional Category: Geomorphology

Function-based Parameter Summary:

Inputs of large wood, commonly referred to as large woody debris (LWD), provide an important structural component of many streams and floodplains. LWD can take the form of dead, fallen logs, limbs, whole trees, or groups of these components (also known as debris dams and jams) that are transported or stored in the channel, floodplain, and flood prone area (U.S. Bureau of Reclamation [USBR] and U.S. Engineer Research and Development Center [ERDC] 2016). LWD influences reach-scale sediment transport and hydraulic processes by: 1) creating sediment and organic matter storage areas; 2) increasing substrate diversity and habitat for benthic macroinvertebrates and cover for fish; 3) creating depth variability where large pieces span the channel and produce pools; 4) sometimes increasing local bank erosion and increasing sediment supply; and 5) providing boundary roughness and flow resistance (Wohl 2000). The LWD parameter is applicable where the upstream watershed or adjacent land area has historically supported (or has the potential to support) trees large enough and close enough to recruit LWD. Therefore, this parameter is only applicable at project sites where trees/wood is a natural component of the riparian corridor.

There are numerous metrics available to assess large woody debris. The method in Wohl et al. (2010) counts individual pieces and jams within the channel and floodplain, and characterizes wood size, type, location and volume. Similarly, the large woody debris index (LWDI) outlined below provides a characterization of LWD in a single index value. Approaches like these provide information about how the presence and configuration of wood affects reach-scale functions. For example, long, large diameter pieces of wood and jams embedded within the channel have a greater influence on in-stream functions than a small, easily mobilized piece of wood near the top of bank. Simpler LWD characterization approaches, such as piece counts, are used as rapid indicators of LWD. These approaches provide less detailed information on the composition and structure of wood in the channel but can serve as simple indicators of the prevalence of wood within the channel.

Large Woody Debris Parameter Metrics:

- Large Woody Debris Index (LWDI)
- Number of Pieces per 328 feet (100 meters)

Either metric can be applied at a project site; however, users should not enter data for both metrics. The MNSQT SC prefers the LWDI metric, particularly for restoration. The number of pieces metric was maintained in the MNSQT as a rapid alternative for this version of the MNSQT since it is included in all other SQTs.

4.1. Large Woody Debris Index (LWDI) Metric

The large woody debris index (LWDI) metric is a semi-quantitative measure of the quantity and influence of large woody debris within the active channel, up to and including the top of banks, per 328 feet (100 meters) of channel length. A piece must be at least 10 cm in diameter at one end (Wohl 2000; Davis et al. 2001) and over 1 meter in length (Davis et al. 2001) to be considered LWD. The index does not include LWD beyond the top of bank on the floodplain or terrace. The index was developed by Davis et al. (2001) and evaluates LWD based on its ability to retain organic matter, provide fish habitat, and affect channel/substrate stability. The LWDI weights this ability for each piece or debris dam by characterizing 1) size (diameter, and the relation of length and width to bankfull dimensions); 2) location in relation to the active channel or during high flows; 3) type (bridge, ramp, submerged, buried); 4) structure (plain to sticky for organic matter retention); 5) stability during high flows; and 6) orientation relative to stream bank. Higher scores indicate greater functional influence on instream processes. Debris dam scores are weighted by a magnitude of 5.

Reference Curve Development:

The reference curve for LWDI was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

There was no dataset available in Minnesota to regionalize this metric. The MNSQT SC decided to include the metric and use the reference curves from the CSQT Beta Version. The reference curve development for this metric is documented in WSTT (2018). Data collected by Harman and others at reference sites across the United States, with an emphasis on the southeast region, show similar ranges to the values observed in Wyoming. The threshold values and reference curve for this metric are provided in Table 4-1 and Figure 4-1, respectively.

Table 4-1: Threshold Values for the LWDI (per 328 feet or 100 meters)

Index Value	Field Value
1.00	660
0.70	430
0.00	0

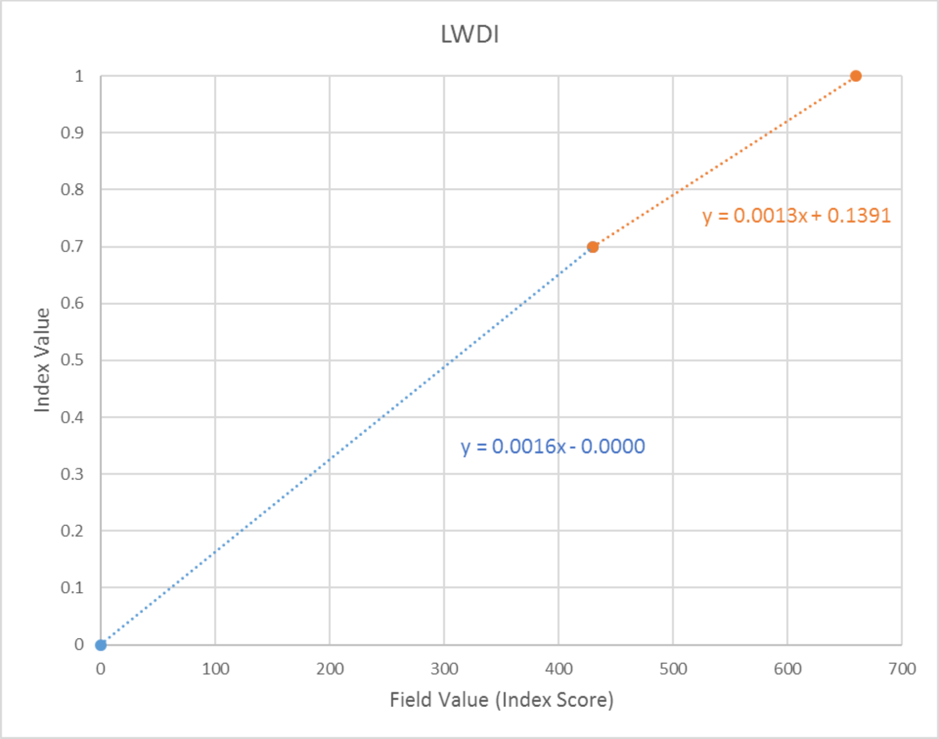

Figure 4-1: LWDI Reference Curves

Limitations and Data Gaps:

The LWDI is a new metric for streams in Minnesota. The reference curves were developed from a relatively small dataset primarily from the mountains of Wyoming. Data collection in Minnesota is needed. Further refinement and stratification of reference curves are encouraged as data is collected in Minnesota. Future stratification could consider the role of ecoregion, drainage area, valley type, forest age, canopy type, and other variables (Wohl 2011; Wohl and Beckman 2014).

LWDI is not applicable to streams where trees/wood are not a natural component of the riparian corridor. Note that streams in scrub-shrub or willow dominated systems may have wood in the channel associated with willow jams, but the size of the pieces do not qualify as LWD. Guidance is provided in the User Manual to address these situations.

4.2. Number of Large Wood Pieces Metric

The number of large wood pieces metric is a count of the LWD pieces in a 100-meter (328-ft) section of the reach, where each piece is counted separately (including within debris dams). A piece must be at least 10 cm in diameter at one end (Wohl 2000; Davis et al. 2001) and over 1 meter in length (Davis et al. 2001) to be considered LWD. The count does not include LWD beyond the top of bank on the floodplain or terrace. This method is a straight-forward, rapid assessment of LWD presence, and is an indicator of its overall structural influence of LWD within the stream.

Reference Curve Development:

The reference curve for number of LWD pieces was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

The number of large wood pieces is provided as a rapid alternative to the LWDI metric and as such, reference curves should yield comparable results. As the reference curves for the LWDI metric were adopted from the CSQT Beta Version, the reference curves for this metric were similarly adopted. The reference curve development for number of large woody debris pieces is documented in WSTT (2018). Data collected by Harman and others at reference sites across the United States, with an emphasis on the southeast region, show similar ranges to the values observed in Wyoming. The threshold values and reference curve for this metric are provided in Table 4-2 and Figure 4-2, respectively.

Table 4-2: Threshold Values for the Number of LWD Pieces per 100 meters

Index Value	Field Value
1.00	28
0.70	13
0.00	0

Figure 4-2: Number of LWD Pieces Reference Curves

Limitations and Data Gaps:

The reference curves for the number of large wood pieces metric were adopted from the Colorado SQT Beta Version and based on data from ecoregions in and around Colorado and Wyoming. Data collection and analysis in Minnesota is needed. Further refinement and stratification of reference curves are encouraged as data is collected in Minnesota. Future stratification could consider the role of ecoregion, drainage area, valley type, forest age, canopy type, and other variables (Wohl 2011; Wohl and Beckman 2014).

The number of LWD pieces is not applicable to streams where trees/wood are not a natural component of the riparian corridor. For willow dominated systems, the LWDI metric should be used instead of LWD pieces. This is because in-stream wood associated with willow jams do not qualify as LWD based on size criterion.

Chapter 5 Lateral Migration Parameter

Functional Category: Geomorphology

Function-based Parameter Summary:

Lateral migration is the movement of a stream across its floodplain and is largely driven by processes influencing bank erosion and deposition. Natural processes of lateral migration vary by stream; some systems maintain dynamic equilibrium while moving across the landscape. A channel in dynamic equilibrium maintains its cross-sectional area while moving across the landscape; that is, lateral erosion and deposition are approximately equal. Systems naturally in disequilibrium, like some braided streams, ephemeral channels, and alluvial fans may naturally experience higher rates of bank erosion as they alternate between aggrading, incising or avulsing states due to natural patterns in sediment and hydrologic processes (Roni and Beechie 2013).

This parameter is included in the geomorphology functional category because it provides information about sediment supply/transport and dynamic equilibrium processes. Lateral stability is one of the original parameters described in Harman et al. (2012). Bank migration and lateral stability processes, and stream types that are susceptible to lateral migration versus those where migration is naturally constrained are described in Harman et al. (2012).

There are multiple approaches that can be used to measure or estimate lateral migration processes and condition. Some of these approaches include:

- Interpretation of aerial imagery to estimate bank retreat rates; measure belt width divided by bankfull width (meander width ratio); assessment of bank cover and stability based on land use and cover types (Rosgen 1996; NRCS 2007).
- Semi-quantitative field measures of bank cover and stability measured over the entire reach length (BLM 2017; WDEQ 2018; Binns 1982).
- Measurements and visual estimates of bank characteristics and hydraulic conditions using the Bank Erosion Hazard Index/Near Bank Stress approach (BEHI/NBS; Rosgen 2014).
- Measurements of bank erosion using surveyed cross sections, bank profiles or bank pins (Rosgen 2014).
- A modeling program, such as BSTEM (Bank Stability and Toe Erosion Model) , which is an intensive approach if data are not available for model calibration, and a moderately intensive approach if data are available (Simon et al. 2009).
- Measures of the extent of bank erosion and/or percent armoring within a reach (NRCS 2007).

Lateral Migration Parameter Metrics:

- Dominant BEHI/NBS
- Percent Streambank Erosion (%)
- Percent Armoring (%)

Three of the four metrics from the WSQT v1.0 lateral migration parameter are also used in the MNSQT: dominant BEHI/NBS, percent streambank erosion and percent armoring. The dominant BEHI/NBS and percent streambank erosion metrics rely on BEHI/NBS assessment and are intended to be used together. The dominant BEHI/NBS metric characterizes the magnitude of erosion, and the percent streambank erosion characterizes the extent of the problem. The percent armoring metric should be used instead of BEHI/NBS where riprap or other hardened bank stabilization treatments have been or are intended to be implemented within the reach. Percent armoring should be used in combination with the percent streambank erosion metric, characterizing the extent of armoring and the extent of bank erosion.

The dominant BEHI/NBS, percent streambank erosion, and percent armoring metrics in this parameter are measures of channel condition that serve as indicators of altered processes, but do not characterize lateral migration rates or sediment processes themselves.

5.1. Dominant BEHI/NBS Metric

The Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) are two bank erosion estimation tools from the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model (Rosgen 2009). BEHI and NBS ratings are determined based on collecting field measurements and visual observations. The BEHI assessment includes the evaluation of streambank height, depth and density of roots, vegetation cover, and bank angle. From the streambank assessment, a categorical BEHI risk rating is assigned, from very low to extreme. Methods with differing levels of rigor can be employed to measure NBS (Rosgen 2006). All methods determine channel flow characteristics, such as water-surface slope and direction of velocity vectors, to assign an NBS risk rating, which also ranges from very low to extreme.

The dominant BEHI/NBS is the rating that occurs most frequently based on length. For example, a dominant BEHI/NBS rating of High/High means that most of the assessed length (e.g., outside meander bends) has this rating. Instructions on how to measure the dominant BEHI/NBS rating is provided in the User Manual.

Regionalization efforts for the BANCS model have been met with mixed results when BEHI/NBS ratings have been used to predict erosion rates (McMillan et al. 2017). The MNSQT uses BEHI/NBS to identify the potential for accelerated bank erosion due to geotechnical and hydraulic forces and does not use it to predict the rate of erosion. Thus, BEHI/NBS is included in the MNSQT for the following reasons:

1. It is rapid to moderate in terms of time required to collect data depending on the way it is implemented. Rosgen (2014) outlines several data collection approaches to measure BEHI and NBS depending on study objectives and site conditions.
2. By integrating two ratings, the metric assesses both geotechnical (BEHI) and hydraulic (NBS) forces, which is unique among rapid methods. This is important because vertical banks devoid of vegetation may appear to be eroding, but if the hydraulic forces acting against the bank are very low there may be little to no bank erosion.
3. BEHI and NBS assessments are common methods used by practitioners of natural channel design, which is a common approach used in compensatory stream mitigation programs (ELI et al. 2016).

Reference Curve Development:

The reference curve for dominant BEHI/NBS was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

Rosgen (2008) assigns each combination of BEHI and NBS rating to one of four stability categories (Table 5-1). Local BEHI/NBS studies (Oknich 2017; Lenhart and Nieber 2015) were compared to the reference standards from the CSQT Beta Version. The CSQT Beta Version (CSQT SC 2019) used the stability categories from Table 5-1 to determine functional capacity scores as follows: stable represents functioning, moderately unstable represents functioning-at-risk, and unstable and highly unstable represent not functioning. The MNSCT SC evaluated these delineations and the associated scoring were considered acceptable for the MNSQT.

Table 5-1: Dominant BEHI/NBS stability ratings provided in Rosgen (2008)

Stable	Moderately Unstable	Unstable	Highly Unstable
VL/VL, VL/L, VL/M, VL/H, VL/VH, VL/Ex, L/VL, L/L, L/M, L/H, L/VH, M/VL	M/L, M/M, M/H, L/Ex, H/VL, H/L*	M/VH, M/Ex, H/M, H/H*, VH/VL, Ex/VL, Ex/L	H/Ex, Ex/M, Ex/H, Ex/VH, VH/VH, Ex/Ex
Key: (VL) is very low, (L) is low, (M) is moderate, (H) is high, (VH) is very high, etc. ** The table above differs slightly form the source reference*			

Because the metric relies on categorical data, reference curves were not developed. Instead, the ratings and categories from Table 5-1 were assigned index values based on relating the stability ratings to functional capacity as described below and shown in Table 5-2.

- Functioning: Ratings within the stable category were considered to represent a functioning condition and set to the index value of 1.00. Note: Stable doesn't mean that functioning streams do not laterally migrate, but they migrate at appropriate rates and maintain their cross-sectional area while their position on the landscape may change.
- Functioning-at-risk: The ratings within the moderately unstable category were set to index values between 0.30 and 0.69.
- Not functioning: The ratings within the unstable and highly unstable categories were set to index values between 0.0-0.29.

Note: Within these index ranges, the ratings were assigned an index value based on the severity of the instability, with more unstable ratings receiving lower scores.

Table 5-2: Index Values for Dominant BEHI/NBS

Index Value	Field Value
0.00	H/VH, H/Ex, VH/VH, VH/Ex, Ex/M, Ex/H, Ex/VH, Ex/Ex
0.10	M/Ex
0.20	M/VH, H/M, H/H, VH/M, VH/H

Index Value	Field Value
0.30	M/H, Ex/L, Ex/VL
0.40	H/L, VH/L
0.50	H/VL, VH/VL, M/M
0.60	L/Ex, M/L
1.00	VL/VL, VL/L, VL/M, VL/H, VL/VH, VL/Ex, L/VL, L/L, L/M, L/H, L/VH, M/VL
Key: (VL) is very low, (L) is low, (M) is moderate, (H) is high, (VH) is very high, etc.	

Limitations and Data Gaps:

The dominant BEHI/NBS metric is applicable to single-thread channels where the reference condition is a stable channel. In this context, “stable” does not mean that lateral migration is not occurring, but rather that the channel maintains dynamic equilibrium. For systems with naturally high rates of bank erosion, this metric should not be assessed.

If bankfull dimensions are not accurately determined for a site, then the bank height ratio component of the BEHI will be inaccurate. Information on verifying bankfull information is provided in the User Manual.

5.2. Percent Streambank Erosion Metric

The percent streambank erosion metric uses the BEHI/NBS rating to estimate the percent of the actively eroding streambank within a reach. The percent streambank erosion metric provides a quantitative measure of the **extent** of active bank erosion (length of reach experiencing erosion), whereas the dominant BEHI/NBS rating provides the **magnitude** of active bank erosion based on quantitative and qualitative variables (the severity of the erosion). The percent streambank erosion metric field value is calculated by adding the lengths of the left and right banks that scored a BEHI/NBS rating that represents actively eroding banks and dividing it by the total bank length (e.g., reach length times two). The BEHI/NBS ratings that represent non-eroding and actively eroding banks are listed in Table 5-3.

Table 5-3: BEHI/NBS stability ratings that represent actively eroding and non-eroding banks

Non-eroding Banks	Actively Eroding Banks
VL/VL, VL/L, VL/M, VL/H, VL/VH, VL/Ex, L/VL, L/L, L/M, L/H, L/VH, L/Ex, M/VL, M/L	M/M, M/H, M/VH, M/Ex, H/VL, H/L, H/M, H/H, H/VH, H/Ex, VH/VL, VH/L, VH/M, VH/H, VH/VH, VH/Ex Ex/VL, Ex/L Ex/M, Ex/H, Ex/VH, Ex/Ex
Key: (VL) is very low, (L) is low, (M) is moderate, (H) is high, (VH) is very high, etc.	

Reference Curve Development:

The reference curve for percent streambank erosion was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

WSTT (2018) set threshold values for functional capacity as shown in Table 5-4 based primarily on the experience of the Wyoming Game and Fish Department in assessing reference quality streams and the Habitat Quality Index for Wyoming trout streams described in the *Habitat Quality Index Procedures Manual* (HQI; Binns 1982). (These thresholds were adopted by the CSQT SC into the CSQT Beta Version). The MNSQT SC evaluated these thresholds and found them to be reasonable and comparable to scoring of a similar metric in the MPCA Stream Habitat Assessment (MPCA 2017a). The MSHA assessment includes a bank erosion metric to assess riparian zone health that scores the length of bank erosion within a reach as severe (>75%), heavy (50-75%), moderate (25-50%), little (5-25%), and none (<5%).

The following threshold values were used to inform the curve (Table 5-4 and Figure 5-1).

- Functioning: A field value of ≤ 5% was set to the 1.0 index value. Since all streams have some amount of bank erosion, the thresholds for the functioning range of scoring reflect small amounts of bank erosion. Anything ≤ 5% of streambank erosion will yield an index value of 1.00; this is consistent with the MSHA assessment that recognizes 5% and the difference between no bank erosion and little bank erosion.
- Functioning-at-risk: A field value of 10% was set to the 0.7 index value. WSTT (2018) provides the justification using an HQI, citing 10% as the threshold between streams adequate to support trout and having potential to support trout. The 10% value was reviewed by the MNSQT SC and considered representative of MN reference streams.
- Not functioning: A field value of 75% was set to the 0.0 index value. This equates to ¾ of the streambank within the representative sub-reach actively eroding and corresponds with the severe bank erosion threshold from the MSHA assessment. Seventy-five (75 %) was reviewed by the MNSQT SC and considered appropriate.

The thresholds identified in Table 5-4 were used to develop reference curves (Figure 5-1). It was not possible to fit a single equation to the threshold values, so a broken linear relationship was used to differentiate between the Functioning range of index values and the Not Functioning and Functioning-at-Risk range.

Table 5-4: Threshold Values for Percent Streambank Erosion

Index Value	Field Value (%)
1.00	≤ 5
0.70	10
0.00	≥ 75

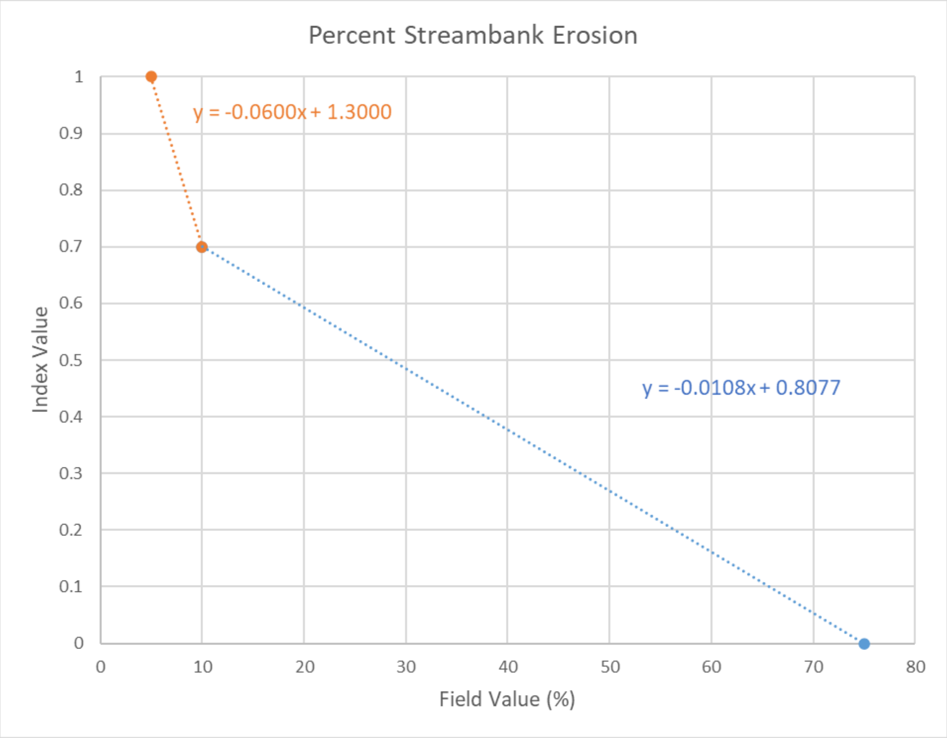

Figure 5-1: Percent Streambank Erosion Reference Curves

<u>Limitations and Data Gaps:</u>

Considering reference curves were based on habitat quality indices from Wyoming, further refinement and stratification of these data and reference curves is encouraged as data is collected in MN.

Similar to the applicability of the BEHI/NBS metric, the percent streambank erosion metric is applicable to single-thread channels where the reference channel is stable (see discussion in Section 5.1). For systems with naturally high rates of bank erosion, the percent streambank erosion metric should not be assessed.

The percent streambank erosion metric does not distinguish between sections of bank that are naturally stable from those that are anthropogenically hardened or armored. In many systems, armoring treatments can be considered an adverse impact or form of functional loss. Where armoring is present, use of this metric should be applied in conjunction with the percent armoring metric.

5.3. Percent Armoring Metric

Bank armoring is a common technique to stabilize banks and/or prevent lateral migration. Armoring is the establishment of hard structures (e.g., riprap, gabion baskets, concrete or other engineered materials that prevent streams from meandering) along the bank edge. More natural approaches to reducing bank erosion, like toe-wood and/or other non-hard bioengineering techniques, are not counted as armoring. Literature shows that bank armoring can have positive and negative effects on aquatic functions (Fischenich 2003; Henderson 1986). Beneficial effects of armoring may include the creation of localized fish habitat (pool and cover formation) and the reduction in excessive bank erosion and sediment supply. Negative effects to stream functions include loss of fish habitat, loss of biological diversity, loss of streambank vegetation and riparian habitat, degradation of riverine ecosystems, and impacts to floodplain development and channel evolution by preventing natural rates of lateral migration (Fischenich 2003; Henderson 1986). Bank armoring can also lead to accelerated bank erosion and changes in sediment dynamics in adjacent reaches.

Recognizing the adverse consequences of armoring treatments in streams, the MNSQT includes a basic bank armoring metric in the lateral migration parameter. In many systems armoring treatments can be considered an adverse impact or form of functional loss. Other metrics of the lateral migration parameter do not adequately capture the functional losses associated with hard armoring practices. The armoring metric should only be used if armoring techniques are present or proposed in the project reach. If banks are not unnaturally armored in the project reach, a field value should not be entered. To calculate the armoring field value, measure the total length of armored banks (left and right) and divide by the total bank length (e.g., project reach length times two). Multiply by 100 to report the percentage of bank length that is armored.

Reference Curve Development:

The reference curve for percent armoring was developed by the MNSQT SC.

No studies explicitly evaluated the relationship between the extent of armoring to functional impairment by stream length. Therefore, best professional judgment was used to set threshold values (Table 5-5 and Figure 5-2):

- Functioning: Because hard armoring would be absent in reference standard sites, a field value of no armoring (0%) was assigned an index value of 1.00.
- Not functioning: Fifty percent (50%) armored was assigned an index score of 0.00 and a linear relationship was established between the two points (Figure 5-2). Setting the minimum index value at 50% armored stream length seemed reasonable, as it means that half of the project reach is armored on both sides of the channel or one side is armored throughout the reach. At this level of armoring, the reach could be considered channelized and functional loss of channel migration processes could be severe.

Based on best professional judgement, if more than 75% of the reach is armored, it is recommended that the other metrics in the lateral migration parameter not be measured. At this magnitude, the armoring is so pervasive that lateral migration processes would likely have no functional value.

Table 5-5: Threshold Values for Percent Armoring

Index Value	Field Value (%)
1.00	0
0.00	50

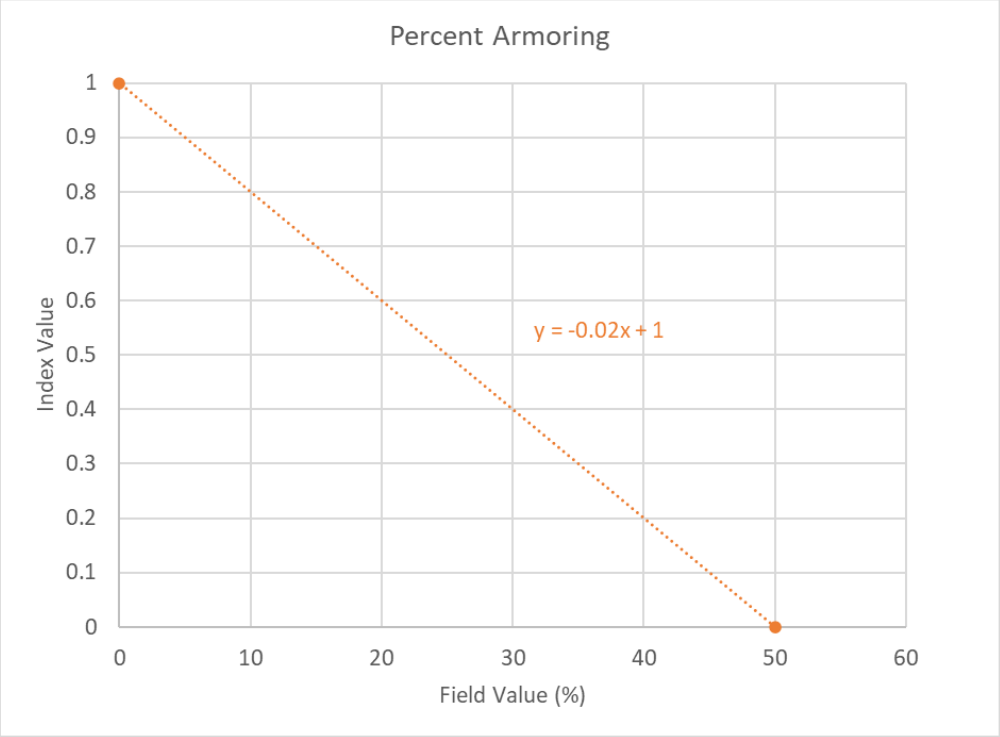

Figure 5-2: Percent Armoring Reference Curve

<u>Limitations and Data Gaps:</u>

While the literature documents a negative relationship between bank armoring and multiple stream functions, no information could be found relating the extent of armored stream banks to functional loss. Therefore, the reference curves are based solely on best professional judgement. The reference curves for this metric will benefit from validation and testing.

Chapter 6 Bed Material Characterization Parameter

Functional Category: Geomorphology

Function-based Parameter Summary:

The ecological effects of fine-sediment accumulation are ubiquitous and wide-ranging (Wood and Armitage 1997). The size and stability of bed material has been linked to macroinvertebrate abundance and diversity (Hussain and Pandit 2012). Additionally, multiple fish species build spawning beds out of gravel, and fine sediment accumulation can reduce the quality of fish spawning habitats and egg survival (summarized in Wood and Armitage 1997). Characterizing bed material provides insight into sediment transport processes (Bunte and Abt 2001) and whether these processes are functioning in a way that supports suitable habitat for a functioning ecological community (Allan 1995).

There are many ways that sediment transport can be directly measured and modeled, however, many of these approaches are time and data intensive (Harman et al. 2012). Monitoring the ecosystem responses to reach-scale impacts or restoration efforts necessitate a simpler indicator. Evaluating the bed material can provide insight into whether sediment transport processes are functioning to transport and distribute sediments in a way that can support the stream ecosystem.

The MNSQT does not include the second metric from Harman et al (2012) that characterizes bed material called the Riffle Stability Index (Kappesser 2002). The Riffle Stability Index has been used in Rosgen B3 and F3b stream types, which have slopes ranging between 2 and 4% to show if upstream sediment supply is depositing on riffles. Results are placed into three bins that closely relate to functioning, functioning-at-risk, and not functioning. It is a simpler method than the Size Class Analyzer, but would not be applicable to as many projects, as most mitigation/restoration activities occur in C4 and B4c stream types. It is a metric that could be considered in future versions of the MNSQT.

There are many other methods for developing grain-size distributions and performing associated calculations (Bunte and Abt 2001). Laub et al (2012) provides several metrics that use grain size distributions to assist in determining bed complexity: calculations for heterogeneity, sorting, Fredle index, a gradation coefficient, and a sediment coefficient of variation. These metrics were not used in the MNSQT because reference values by metric were unavailable. However, these metrics could be added in the future as reference data and/or processing tools become available.

Bed Material Characterization Parameter Metric:

- Size Class Pebble Count Analyzer (p-value)

The MNSQT only includes one metric to evaluate the bed material characterization parameter, the Size Class Pebble Count Analyzer. The Size Class Pebble Count Analyzer was developed by the Rocky Mountain Forest and Range Experiment Station to assess cumulative watershed effects of land management practices on changes to grain size distributions (Bevenger and King 1995). An embeddedness metric was considered for this parameter but existing metrics (e.g. Rosgen 2014 and USEPA 2016) are qualitative, and it was decided to not include them in the MNSQT.

6.1. Size Class Pebble Count Analyzer Metric

The Size Class Pebble Count Analyzer metric is a statistical comparison between the study reach and reference reach percent of bed material fines (Bevenger and King, 1995). The Size Class Pebble Count Analyzer spreadsheet tool (v1; USDA, 2007) tests the hypothesis that the percent of fines in the study reach is the same as the percent of fines in the reference reach. This metric requires the user to perform a representative pebble count using the Wolman (1954) procedure at the study reach and a reference reach.

This Size Class Pebble Count Analyzer metric is applicable for gravel and cobble bed streams where sediment sources or sediment transport have been modified by anthropogenic activities. The Size Class Pebble Count Analyzer works well where bank erosion, land use change, or flow alteration lead to fine sediment accumulation. The instructions for the metric require the user to select an appropriate size class to compare. The User Manual recommends using the minimum size criteria for fine or medium gravel as likely candidates, 4 mm or 8 mm, respectively. Bevenger and King (1995) provide case studies from the Shoshone National Forest that compare the impacts of various disturbances. These case studies define fine sediments as those smaller than 8 mm, citing a study indicating the particles up to 6.4 mm are important to fisheries.

Reference Curve Development:

The reference curve for Size Class Pebble Count Analyzer was developed by the MNSQT SC.

The Size Class Pebble Count Analyzer spreadsheet tool (v1) (USDA 2007) tests the hypothesis that the percent of fines in the study reach is the same as the percent of fines in the reference reach. A small p-value (<0.05) represents a statistically significant difference between the study reach and reference reach, and thus indicates that is it highly unlikely that the percent of fines in the study reach is the same as the percent of fines in the reference reach. The case studies presented by Bevenger and King (1995) show that highly significant results (p-value < 0.001) were observed in the Shoshone National Forest due to fires, grazing and timber harvesting practices.

Scoring for this metric assesses whether there is a statistical difference between the percent of fines in the study reach and the percent of fines in the reference reach. When the Size Class Pebble Count Analyzer reports a p-value of 0.05 or greater, the metric will score a 1.00. When the Size Class Pebble Count Analyzer reports a p-value of less than 0.05, the metric will score a 0.00.

Limitations and Data Gaps:

The Size Class Pebble Count Analyzer metric only applies to gravel or cobble bed streams. Applying the Size Class Pebble Count Analyzer metric requires comparison with a reference standard site with similar stream and watershed characteristics, such as stream type, drainage area, geology, lithology, slope etc. Finding good reference sites can be challenging, particularly in watersheds with major land use changes. If a suitable reference reach cannot be located, then this bed material characterization metric should not be used. Note that it may be possible to identify a sediment transport reference site (with reference condition bed form diversity, lateral migration, and bed material characterization parameters) that has other watershed impairments, such as water quality impairments.

Chapter 7 Bed Form Diversity Parameter

Functional Category: Geomorphology

Function-based Parameter Summary:

Bed forms include the various channel units that maintain heterogeneity in the channel form, including riffles, runs, pools and glides (Rosgen 2014; Vermont Stream Geomorphic Assessment, Appendix M: Delineation of Stream Bed Features). The location, stability, and depth of these bed features are responsive to sediment transport processes acting against the channel boundary conditions. Bed form diversity is a function-based parameter used to assess these bed form patterns, specifically riffle-pool and step-pool sequences in alluvial and colluvial valleys. This parameter evaluates bedform pattern in relation to expected patterns in channels with similar morphology. As such, this parameter is not a direct measure of fluvial processes but is an indicator of altered hydraulic and sediment transport processes (Knighton 1998). It is one of the original parameters described in Harman et al. (2012). Readers should refer to this document for a more detailed description of how sediment transport processes affect the development of sand and gravel bedforms.

Natural streams rarely have flat uniform beds (Knighton 1998). Instead, hydraulic and sediment transport processes shape the stream bed into myriad forms, depending on channel slope, type of bed material (sand, gravel, cobble, boulder, bedrock), and other factors. These bed forms reflect local variations in the sediment transport rate and represent lateral and vertical fluctuations in the stream bed (Knighton 1998), dissipating energy and creating habitat diversity through the formation of riffle-pool sequences.

Numerous classifications of bed form exist (Knighton 1998). At a broad level, bed forms can be grouped into three categories: sand bed forms (ripple, dunes plane beds, and antidunes), gravel/cobble bed forms (riffle, run, pool, and glide) and step-pool bed forms. Bed form diversity is important because channel patterns provide a diversity of habitats that aquatic organisms need for survival. For example, macroinvertebrate communities are often most diverse in riffle habitats, and fish rely on pools for cover from aquatic and avian predators, for resting, and for thermal and solar refugia. Without the diversity of riffles and pools, there is also a potential loss of diversity in macroinvertebrates and fish (Mathon et al. 2013; Fischenich 2006).

Harman et al. (2012) list metrics that can be used to assess bed form diversity and can be quantified with field surveys, including: percent riffle and pool, facet (riffle/pool) slope, and pool spacing and depth variability. An additional metric, aggradation ratio, was not described in Harman et al. (2012) but is useful in characterizing aggradation processes in riffle sections. Many qualitative methods are also available to assess bedforms and in-stream habitats (Somerville and Pruitt 2004) but were not considered for the MNSQT because quantitative measures are available and regularly used by practitioners.

Bedform Diversity Parameter Metrics:

- Pool Spacing Ratio
- Pool Depth Ratio
- Percent Riffle

- Aggradation Ratio

The four metrics included in multiple other SQT to quantify the bed form diversity parameter (pool spacing ratio, pool depth ratio, percent riffle, and aggradation ratio) are also used in the MNSQT Version 1.0. Pool spacing ratio, pool depth ratio, and percent riffle metrics should be evaluated together to characterize the overall bed form diversity of a stream reach. Aggradation ratio should also be considered where indicators of aggradation are present, an example being a mid-channel bar within a riffle section.

Reference streams in MN were not available for developing reference curves or standards. However, Hey (2006) shows that reference reaches can be used from other locations if the stream type (Rosgen 1994) and boundary conditions are the same. In the Hey (2006) study reference reaches from the United Kingdom were compared to reference streams in the United States. Based on this understanding, the MNSQT SC and geomorphology technical team decided to develop reference curves using data from other regions in the United States for initial use. These reference data sets are from the Southeastern U.S, where boundary conditions are similar to MN (herbaceous and woody vegetation along the banks) and using stream types that will be common in MN restoration projects. As MN reference data are collected, the reference curves will be re-evaluated and updated as needed.

7.1. Pool Spacing Ratio Metric

Adequate pool spacing and the depth variability created from alternating riffle-pool sequences supports dynamic equilibrium and habitat-forming processes (Knighton 1998, Hey 2006). The pool spacing ratio metric measures the distance between the deepest location of sequential geomorphic pools (i.e., channel-spanning lateral-scour / meander bend pools or step-pools, not small pocket pools in riffle sections or created by localized scour around obstruction). The distance between geomorphic pools is divided by the bankfull riffle width to calculate the dimensionless pool spacing ratio. The dimensionless ratio allows for the comparison of values from different sites and drainage areas. For example, a pool spacing of 75 feet is meaningless without an understanding of stream size or drainage area; however, a pool spacing ratio of 4.0 can be compared across drainage areas as long as the values are from the same valley morphology, bed material, and boundary condition (Hey 2006). The median pool spacing ratio from a sampling reach is entered as the field value into the MNSQT. The median is used instead of the mean because the sample size per reach tends to be small with a wide range of values and it was thought that the median provided a better estimate of central tendency than the mean. Field testing has also shown that median values in the functioning range allow for pattern heterogeneity and do not incentivize designs with homogeneous pool spacing.

Studies have documented a connection between pool spacing ratios and channel stability and complexity (Langbein and Leopold 1966; Gregory et al. 1994; Laub et al. 2012). If a meandering stream has a low pool spacing ratio, the riffle length is also low, and energy is transferred to the banks and sometimes the floodplain. Evaluations of numerous stream restoration and mitigation projects by members of the MNSQT SC in North Carolina, New York, and other states have shown that sites constructed with low pool-spacing ratios resulted in excessive bank erosion and sometimes floodplain erosion.

In addition to the issues caused by low pool spacing outlined above, large pool spacing values are also problematic. A large pool spacing ratio essentially means that there are a small number of geomorphic pools in the reach. In alluvial valleys, this might mean that the reach is overly straight, and the habitat value is diminished because the length of pool habitat has been reduced. In colluvial or otherwise confined valleys, the lack of pools might mean there is not sufficient energy dissipation to achieve dynamic equilibrium.

Reference Curve Development:

The reference curves for pool spacing ratio were developed by the MNSQT SC.

As mentioned above, reference data sets from MN were not available. Therefore, datasets from other regions with similar stream types and boundary conditions were used (Hey 2006) to develop the initial reference standard curves. These curves will be reevaluated by the MNSQT SC once MN data are available. Several datasets, described in Section 1.7, were used, along with best professional judgement from the technical team, to develop the pool spacing ratio reference curves.

The reference curves are stratified by Rosgen stream type per guidance in Hey (2006). Furthermore, stratification by Rosgen stream type was used to account for the natural variability in pool spacing because it combines valley type and slope, which are known drivers of pool spacing (Knighton 1998). Different stream types exhibit different types of pools: C and E stream types have lateral scour pools and A and B stream types have cascade/step pools (Rosgen 2014). Thus, reference curves were developed and are presented below by stream type. The metric accounts for differences in stream size, which may otherwise be relevant to pool spacing, by using bankfull width as the denominator and converting the value into a dimensionless ratio. Thus, stream size was not pursued as an additional form of stratification because it is built into the ratio. Boundary condition was not explicitly used for stratification; however, all reference data were from regions with boundary conditions that were dominated by herbaceous and riparian vegetation.

For A and B stream types (see Table 7-1 for dataset summary):

Conceptually, low pool spacing ratios provide greater grade control than greater pool spacing ratios by increases roughness and providing greater energy dissipation. Downstream riffles, cascades, or steps provide the grade control for upstream cascades or steps. Therefore, as the value increases, the functional scores decrease. The threshold values and graphical relationships were informed by a review of several unpublished and published datasets presented in Table 7-1 (and described in section 1.7) and best professional judgement by the geomorphic technical team and their experience with bedform diversity in these systems. A summary of assigned threshold values is provided below:

- Functioning: A field value ≤ 4.0 was selected for the 1.00 index value. All values equal to or less than 4.0 receive a 1.0. This incentivizes practitioners to select the range that best fits the site rather than chasing a 1.0, and all values in this range are commonly found in reference streams.
- Functioning-at-risk: A field value of 5.0 was selected for the 0.70 index value because most of the reference data fell below 5.0.
- Not Functioning: A field value ≥ 6.5 was selected for the 0.00 index value, which is near the largest maximum value found across the datasets. This value was set instead of extrapolating the regression line to show an increase in the rate of loss as pool spacing

increases. For example, a high pool-to-pool spacing ratio in a step-pool system could result in headcutting in the absence of adequately sized bed material. These vertical stability problems have been observed by members of the geomorphic technical team while inspecting stream restoration projects in B stream types.

Table 7-1: Reference Dataset Statistics for Pool Spacing Ratio for A and B Streams

Statistic	Number of Sites (n)	Stream types	Slope range	Average	Minimum	Maximum
Harman & Clinton (NC & WV)	6	Aa+, A, B, Ba	3.3 to 15%	1.9	0.7	7.9
Jennings & Zink (TN)	4	B, Ba	5.2 – 7.1%	2.1	0.9	3.6
Zink et al. (TN & NC)	12	A, B	2 – 10.4%	1.5	0.1	7.1
Rosgen (2014)	-	B	-	-	0.3*	2.5*
**Typical values*						

For Bc stream types (see Table 7-2 for dataset summary):

Bc streams were separated out from A and B stream types because Bc streams have lower slopes (<2%; Rosgen 1996), which affects pool spacing. The average pool spacing ratios for Bc streams (1.2 – 6.6) are higher than the A and B streams (1.5 – 1.9), which matches the literature showing that pool spacing increases with decreasing slope. The average, minimum, and maximum values presented in Table 7-2 vary widely. The threshold values and graphical relationship were informed by the negative relationship between pool spacing and slope, a review of several unpublished and published datasets presented in Table 7-2 (and described in section 1.7) and best professional judgement in evaluating stream restoration projects. A summary of assigned threshold values is provided below:

- Functioning: A field value of ≤5.0 was assigned a 1.00 index value. The field value is slightly higher than the A and B stream types to represent the increasing pool spacing with decreasing slope. In these lower slope systems, pools can be farther apart than steeper systems with a lower risk of bed degradation.

- Functioning-at-risk: A field value of 6.0 was assigned a 0.70 index value. Values are slightly higher than the A and B stream types to represent the increasing pool spacing with decreasing slope.

- Not Functioning: A field value of 8.0 was set at 0.00 index value, which is near the largest maximum value found across the datasets. The technical team recognized that pools this far apart would provide very little bedform diversity and could lead to headcutting.

Table 7-2: Reference Dataset Statistics for Pool Spacing Ratio for Bc Streams

Statistic	Number of Sites (n)	Stream types	Slope range (%)	Average	Minimum	Maximum
Lowther (NC)	2	Bc	0.5	6.6	4.7	8.5
Jennings & Zink (TN)	4	Bc	0.25 – 1.96	3.5	1.8	4.5
Zink et al. (TN & NC)	2	Bc	<2	1.2	0.1	3
Rosgen (2014)	-	B	-	-	0.3*	2.5*
MI EGLE	4	Bc	-	4.2	2.3	5.5
**Typical values*						

For C and E stream types (see Table 7-3 for dataset summary):

Stratification by stream size (drainage area) was investigated. However, reference data did not reveal a substantial difference in pool spacing between C and E stream types over a range of drainage areas. Thus, C and E stream types were grouped together.

Original research by Leopold showed that pool spacing ratio ranged from 5.0 to 7.0. This was not necessarily for reference quality streams alone and the data tended to come from large rivers that could be viewed from aerial photos. Rosgen (2014) reports the same range for lateral scour pools in his field guide. Rinaldi and Johnson (1997) show that this range is lower, at least in Maryland (Midatlantic, USA). However, their study was not limited to reference streams. From the datasets (Lowther (NC), Jennings & Zink (TN), MI EGLE) the average ratios were 3.3, 4.1, and 5.0. The overall range from these data sets was 1.5 to 9.0, but few sites were above 6.0. However, it is likely that these studies included pools not associated with meander bends, which are not counted as pools for the pool spacing metric in the SQT method, and pool identification methods were not included in reports. Therefore, the lower end of the range may not well represent the SQT method which excludes these pools from the pool spacing ratio calculation. Of all the data available, more weight was placed on the Lowther (NC), Jennings & Zink (TN), MI EGLE datasets because they included reference sites only. However, best professional judgement was also applied because pool identification methods were unknown for these datasets. The threshold values and graphical relationship were informed by a review of several unpublished and published datasets presented in Table 7-3 (and described in section 1.7) and best professional judgement. A summary of assigned threshold values is provided below:

- Functioning: Field values ranging from 3.5 to 6.0 were assigned an index value of 1.00. The average ratios across the Lowther (NC), Jennings & Zink (TN), MI EGLE datasets and best professional judgement were used to inform the minimum field value. The best professional judgement was based on evaluating the successes and failures of stream restoration projects. Median pool spacing values below 3.5 tended to create stability problems, e.g. excessive bank erosion. Erosion quickly got worse with decreasing ratio values. Median pool spacing values above 6 started to affect habitat diversity. As the ratio gets larger, the number of pools decreases. In addition, to account for the potential that pools in riffles were included in some of the datasets, the field value was set at a 3.5. The maximum field value was set to 6.0 because few sites were above 6.0 for the Lowther (NC), Jennings & Zink (TN), MI EGLE datasets.

- Functioning-at-risk: The regression lines were extrapolated from the functioning and not functioning thresholds because the datasets did not provide explicit field values for this condition category, and professional judgement could not discern these differences.
- Not functioning: A field value of 1.0 was set as the index value of 0.00. This was the lowest minimum value observed across the compiled datasets. Pool-to-pool spacing ratios below this value essentially means that reach is almost all pool and that that riffles and/or cross-overs are nonexistent; it is devoid of a riffle-pool sequence. A field value of 9.0 was also set as the index value of 0.00. The was the largest maximum value observed across the compiled datasets. Pool-to-pool spacing ratios above this value indicate that the reach is composed of almost all riffle. Again, the reach is devoid of a riffle-pool sequence.

Table 7-3: Reference Dataset Statistics for Pool Spacing Ratio for C and E Streams

Statistic	**Number of Sites (n)**	**Stream types**	**Drainage Area (mi^2)**	**Average**	**Minimum**	**Maximum**
Lowther (NC)	16	C, E	0.1 - 8.2	3.3	1.7	5.4
Jennings & Zink (NC)	20	C, E	0.05 - 2.3	4.1	1.5	9
Rinaldi and Johnson (MD)**	18	C, E	-	-	1.2	4.3
Rosgen (2014)	-	C, E	-	-	5.0*	7.0*
MI EGLE	11	C, E	-	5	1.9	7
Leopold et al. (1964)**	-	C, E	-	-	5.0*	7.0*

**Typical values*
***Not necessarily reference streams*

A summary of threshold values for all stream types (Table 7-4) and reference curves (Figures 7-1 through 7-3) are presented below.

Table 7-4: Threshold Values for Pool Spacing Ratio

Index Value	**Field Values by Stream Type**		
	A and B	**Bc**	**C and E**
1.00	≤4	≤ 5.0	3.5 – 6.0
0.70	5.0	6.0	-
0.00	≥ 6.5	≥ 8.0	1.0, 9.0

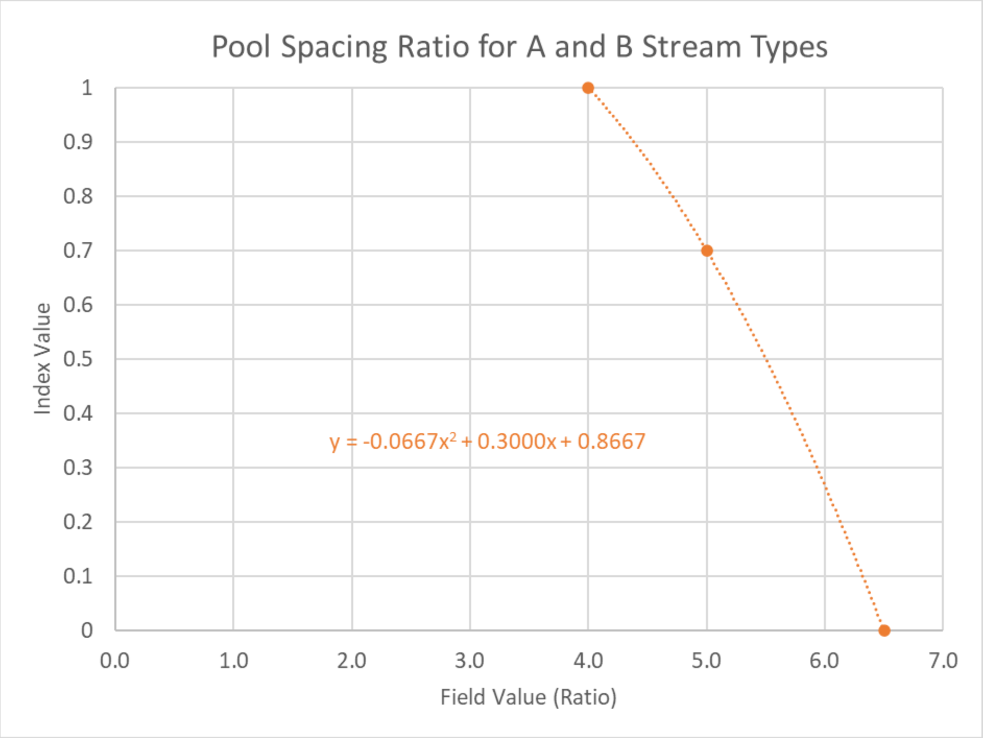

Figure 7-1: Pool Spacing Ratio Reference Curves for A and B Streams

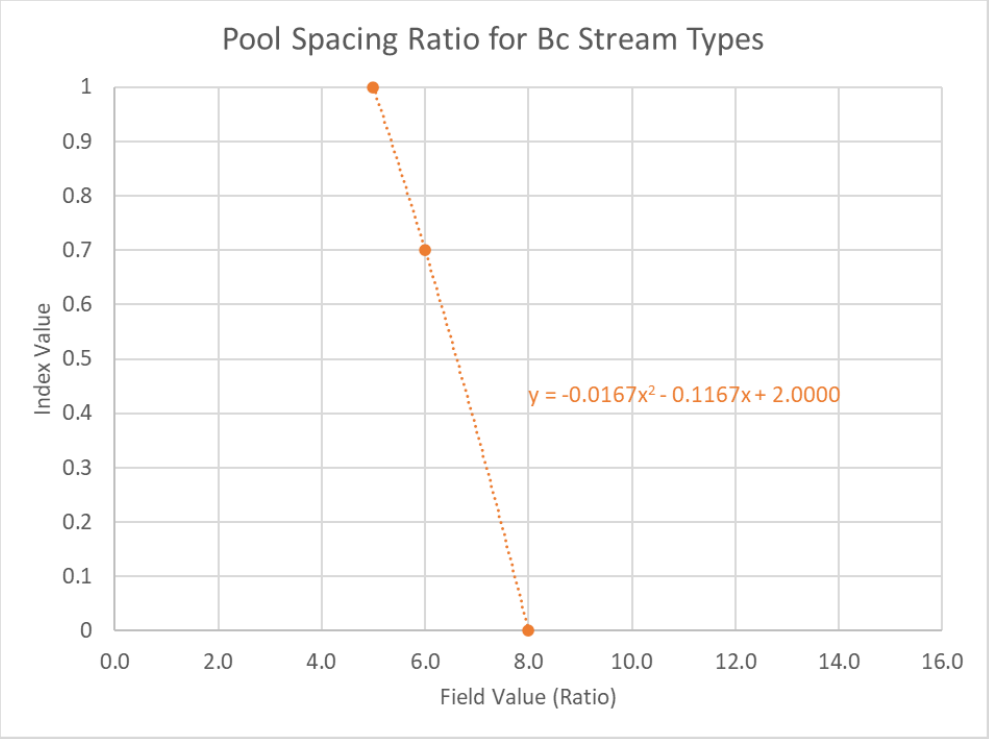

Figure 7-2: Pool Spacing Ratio Reference Curves for Bc Streams

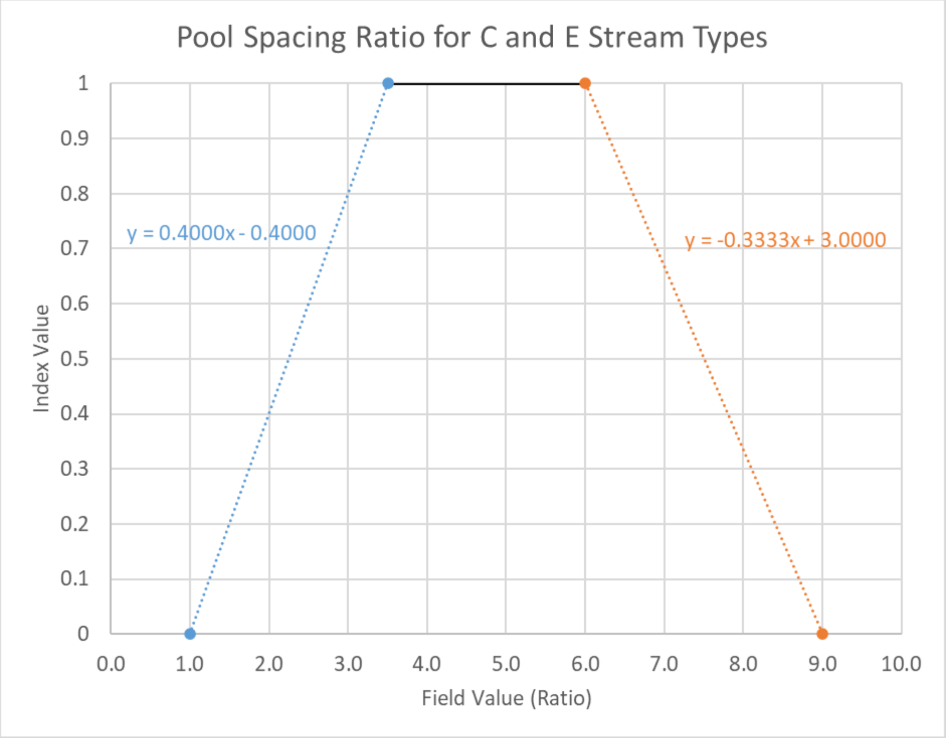

Figure 7-3: Pool Spacing Ratio Reference Curves for C and E Streams

Limitations and Data Gaps:

Further refinement and stratification of these data and reference curves will occur as data are collected in MN.

The presence of bedrock can influence pool spacing, and thus it may not be appropriate to include bed form diversity metrics when evaluating natural bedrock channels. Pool development in bedrock channels is controlled by the nature of the rock material, e.g., fractures, as opposed to lateral dissipation of energy through a meandering channel. This consideration is only applicable to channels that are dominated by bedrock (e.g., bedrock is the median size of the bed material) and not channels that simply have bedrock outcrops.

If bankfull dimensions are not accurately determined for a site, then the pool spacing ratio will not accurately represent bed forming processes. Information on verifying bankfull information is provided in the User Manual.

Reference curves were not developed for naturally occurring F and G stream types. If the stream is a naturally occurring F stream type, e.g., located in a canyon or gorge setting, this metric should not be evaluated, as no reference curves have been developed for this stream type. Additionally, pool spacing ratio is not applicable to multi-thread channels (D or DA) or ephemeral channels because a predictable pool spacing is not typically found in these environments (Bull and Kirkby 2002).

F and G channels that represent degraded streams should be compared against the proposed, or reference stream type, as informed by channel evolution processes (Cluer and Thorne 2013; Rosgen 2014) as described in the User Manual. Selection of the appropriate reference stream type is important for consistently applying this metric and determining a condition score in the tool.

Naturally straight channels, like perennial headwater streams with sand beds, are not appropriate for this metric. Pool formation in these systems is typically created by the presence of large wood, and the spacing is not predictable. Because meander bends are not present, lateral-scour pools (called geomorphic pools in the SQT) are not present. Pool spacing in alluvial valleys are only associated with these pool types; therefore, pool spacing should not be assessed.

7.2. Pool Depth Ratio Metric

The pool depth ratio metric measures the bankfull depth of the deepest point of each pool within the sampling reach. All pools, including both geomorphic pools and significant pools, are included in this metric (note: this is different than the pool spacing metric above). The bankfull pool depth is normalized by a bankfull mean riffle depth to calculate the dimensionless pool depth ratio; pool depth ratio is the max bankfull pool depth divided by the mean bankfull riffle depth from a representative riffle. Each significant pool in the reach is assessed. Then, the average pool depth ratio is calculated and entered as the field value into the MNSQT. The average is used instead of the median because typically the sample size is larger and the range lower than the pool spacing ratio.

Pools provide fish habitat and thermal refugia, support thermal regulation, provide energy dissipation, and are an indication of how the stream is transporting and storing sediment (Knighton 1998; Allan 1995; Hauer and Lamberti 2007). For example, if the outside meander bend has filled with sediment, this can be an indication of an aggradation problem, as the channel cannot transport the sediment load through the meander bend. In combination with pool spacing ratio and percent riffle metrics, the pool depth ratio characterizes the bed form diversity of a stream reach (Harman et. al. 2012).

Reference Curve Development:

The reference curve for pool depth ratio was developed by the MNSQT SC.

Several reference datasets, described in section 1.7, typical values, and best professional judgement were used to inform reference curve threshold values.

The averages among stream types were similar, ranging between 2.1 and 2.4 with the exception of the Lowther dataset (NC) (Table 7-5). Therefore, no stratification by stream type was pursued. This is consistent with all the other SQTs except NC.

Table 7-5: Reference Dataset Statistics for Pool Depth Ratio

Reference Dataset	Stream Type	Number of Sites (n)	Average	Minimum	Maximum
Jennings & Zink (TN)	A, B	4	2.1	1.8	2.3
Rosgen (2014)	A, B	-	-	1.5*	2.5*
Jennings & Zink (TN)	Bc	4	2.4	2.2	2.9
Lowther (NC)	Bc	2	2.3	1.6	3.1
MI EGLE	Bc	4	2.3	1.9	2.6
Jennings & Zink (TN)	C, E	23	2.2	1.7	3.3
Lowther (NC)	C, E	16	1.4	0.9	2.1
MI EGLE	C, E	11	2.3	1.3	3.4
Rosgen (2014)	C, E	-	-	2**	4**

**Typical values for step-pool channels*
***Typical values for C and E streams*

A summary of the threshold values is provided below and shown in Table 7-6 and reference curves are presented in Figure 7-4:

- Functioning: Field values of 2.0 and 3.0 were set at 0.70 and 1.00 index values, respectively. The average values were used to inform the 2.0 field value and the maximum values were used to inform the 3.0 field value. The average was used rather than the minimum to incentivize practitioners to design and build deeper pools. The literature shows that deep pools are important for a wide range of functions, e.g. thermal regulation and refugia. The geomorphic technical team did not want to incentivize practitioners to design and build shallow pools that could further shallow over time. Experience among the team showed that a deep pool that is built may be maintained over time; whereas, a shallow pool that is built may not be able to scour to optimal depths, especially in gravel/cobble bed streams. Field values greater than or equal to 3.0 will return a 1.00 index value to acknowledge this process In addition, it acknowledges that there is not an increase in function beyond a pool that is three times deeper than the riffle; it plateaus. This incentivizes practitioners to not over dig pools and potentially undermine the adjacent riffle.

- Functioning-at-risk: A field value of 1.5 was set at the 0.30 threshold. The thalweg of many riffles is 1.5 times greater than the mean riffle depth. Therefore, at this value, pool depths are beginning to function more like riffle depths.
- Not Functioning: Field values ≤1.1 were set at 0.00. This is because the metric is a ratio; thus, to be considered a pool the ratio must be greater than 1.0.

Table 7-6: Threshold Values for Pool Depth Ratio

Index Value	Field Value
1.00	3.0
0.70	2.0
0.30	1.5
0.00	1.1

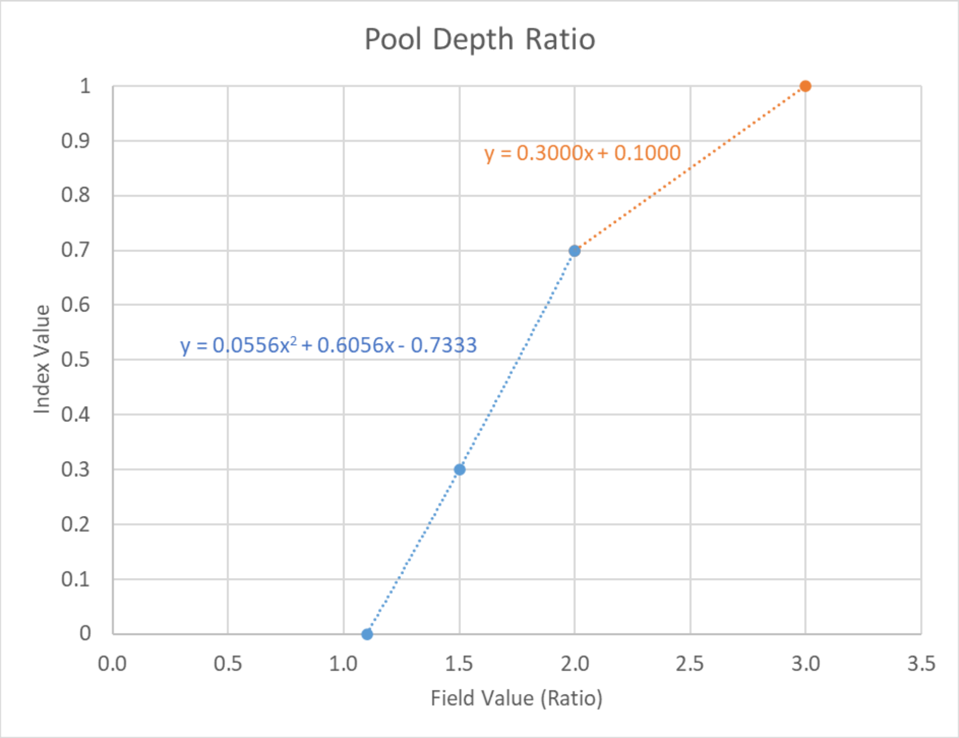

Figure 7-4: Pool Depth Ratio Reference Curves

Limitations and Data Gaps:

Further refinement and stratification of these curves will occur as data are collected in MN.

If bankfull dimensions are not accurately determined for a site, then the pool depth ratio will not accurately represent bed forming processes. Information on verifying bankfull information is provided in the User Manual.

7.3. Percent Riffle Metric

The percent riffle metric measures the length of riffles (including runs) within the sample reach. The total length of riffles and runs is divided by the total reach length to calculate the percent riffle.

Pools and riffles provide valuable habitat for various aquatic species and dissipate energy within a reach. The riffle is the natural grade-control feature of the stream, providing floodplain connection and vertical stability (Knighton 1998). The pool provides energy dissipation, habitat diversity, and more. Much of the discussion regarding stream function presented in the pool spacing ratio and pool depth metric summaries applies to this metric as well. While the pool spacing ratio quantifies the frequency of pools within a reach, this metric quantifies the relative prevalence of riffle habitat length throughout the reach. Streams that have too much riffle length also have a low percentage of pools. Conversely, streams that have a low percentage of riffle also have a high percentage of pool. The appropriate proportion of riffles and pools is necessary to support dynamic equilibrium and habitat for in-stream biota. Percent riffle works with the pool spacing and pool depth ratio metrics to characterize bed form diversity.

Reference Curve Development:

Reference curves for percent riffle were developed by the MNSQT SC.

Several reference datasets (Table 7-7), described in section 1.7, and best professional judgement were used to inform reference curve threshold values.

Stratification by Rosgen stream type was used to account for the natural variability in the extent of riffle, run, cascade, and step features because it combines valley type and slope, which are known drivers of bedform (Hey 2006; Rosgen 1994).

Table 7-7: Reference Dataset Statistics for Percent Riffle

Reference Dataset	Stream Type	Number of Sites (n)	Slope (%)	Average	Minimum	Maximum
Zink et al. (TN & NC)	Aa+	1	>10	90	-	-
Zink et al. (TN & NC)	A, B/Ba	12	2 – 10	44	18	65
Harman & Clinton (NC & WV)	A, B/Ba	4		61	54	69
Jennings & Zink (TN)	C, E	3	<2	50	44	53
MI EGLE	C, E	11	<2	40	19	54

For Aa+ stream types:

After review, the Aa+ reference data were not used to inform the MNSQTs due to lack of sufficient data and few restoration/impact sites opportunities at this slope.

For A and B stream types:

More weight was placed on the Harman & Clinton dataset (NC & WV) than Zink et al. (TN) because it best matched the data collection methods outlined in the SQT. A summary of the threshold values is provided below:

- Functioning: Field values ranging from 50% to 60% were set as the 1.0 index value based on the range of average and maximum values from Harman & Clinton (NC & WV) and Zink et al. (TN) datasets. This acknowledges that a reach should be comprised of at least half riffle, run, cascade, and step features for grade control and habitat diversity purposes. As riffle extent departs from this ideal range, function is lost. The decreasing curve loses function at a slightly faster rate because projects can have stability problems if the reach has too much pool length, as it impedes sediment transport and transform the reach to a sediment sink.

- Functioning-at-risk: The regression lines were extrapolated from the Functioning and Not Functioning thresholds because the datasets did not provide explicit field values for this condition category.

- Not Functioning: Field values of 20% and 90% were set to 0.0. The 0.0 set at 20% means 80% of the reach is pool. The 0.0 set at 90% means only 10% is pool.

For C and E stream types:

A summary of the threshold values is provided below:

- Functioning: Field values ranging from 45% to 65% were set as the 1.0 index value. In general, this range is larger than the functioning range for A and B streams. The 45% value reflects the lower range presented in the MI EGLE and Jennings & Zink (TN) datasets. Best professional judgement was used to set the 65% field value. The technical team decided that reach lengths that exceeded 65% were outside the range they had observed for reference condition. Values above 65% were judged to not be optimal from a riffle-pool sequence and bed heterogeneity perspective.

- Functioning-at-risk: The regression lines were extrapolated from the Functioning and Not Functioning thresholds because the datasets did not provide explicit field values for this condition category.

- Not Functioning: Field values of 20% and 80% were set to 0.0. The 0.0 set at 20% means 80% of the reach is pool and the 0.0 set at 80% means only 20% is pool. The falling limb (between 65% and 80%) loses function at a lower rate compared to the A and B reference curve falling limb. This acknowledges that in meandering C and E streams, it is slightly worse to have more riffle than in A and B streams because there is likely more fish in these systems needing pool habitat. The rising limb slope increase slightly compared to the A and B reference curve.

Threshold values are shown in Table 7-8 and presented in Figure 7-5 and 7-6.

Table 7-8: Threshold Values for Percent Riffle

Index Value	Field Value (%)	
	A and B	C and E
1.00	50 – 60	45 – 65
0.00	20, 90	20, 85

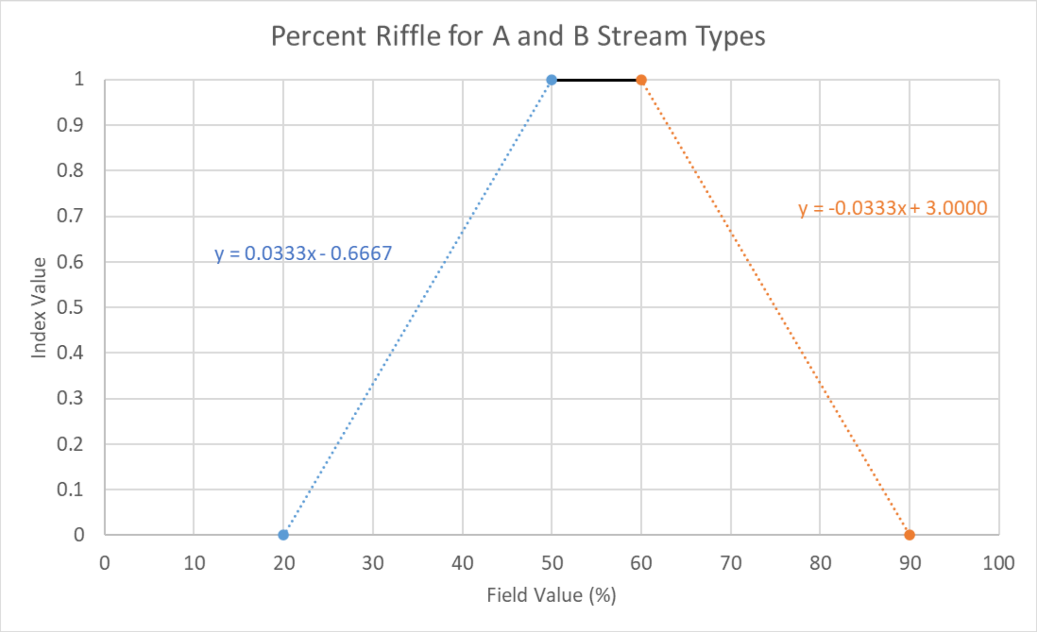

Figure 7-5: Percent Riffle Reference Curves

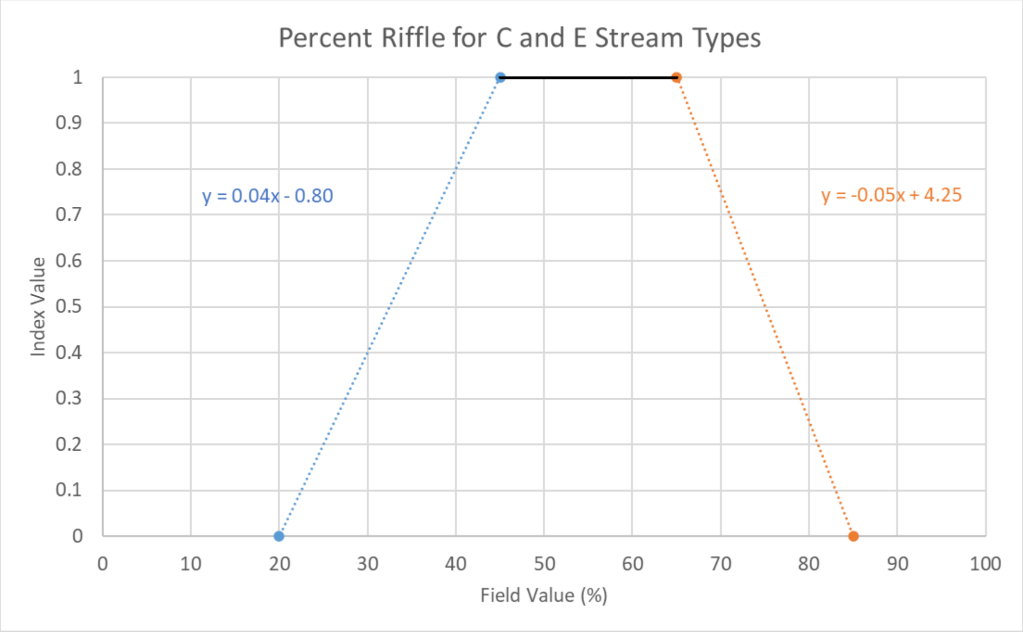

Figure 7-6: Percent Riffle Reference Curves

Limitations and Data Gaps:

A review of the southeast data confirmed threshold values presented above. However, further refinement and stratification of these data and reference curves will occur as data is collected in MN.

7.4. Aggradation Ratio Metric

Summary:

The aggradation ratio assesses the degree of aggradation in the project reach. It is the riffle width depth ratio (W/D) compared to a reference W/D. The W/D is the bankfull riffle width divided by the mean depth (Rosgen 2014). Mean depth is the riffle bankfull cross sectional area divided by the riffle bankfull width. Within the assessment segment, each riffle exhibiting signs of excessive deposition should be surveyed and the W/D calculated. The aggradation ratio is the bankfull width at the widest riffle within the representative sub-reach divided by the mean bankfull riffle depth at that riffle. This ratio is then divided by a reference width-to-depth ratio (W/D).

Deposition of sediments within a channel is a natural fluvial process, but excessive aggradation can be an indicator of sediment imbalance, where sediment supply exceeds the stream’s transport capacity. Accumulation of sediments in pools would result in a lower pool depth ratio, which is captured in the bedform diversity parameter. Similarly, accumulations of sediment in a riffle (e.g. forming a mid-channel bar) would yield a higher W/D than would be expected from a stable riffle.

Aggradation ratio was developed based on the Width Depth Ratio State (WDRS) described by Rosgen (2014) to assess departure from a reference condition caused by streambank erosion, excessive deposition, or direct mechanical impacts that lead to an over-wide channel. The WDRS method assesses increases and decreases in W/D to show departure from reference. Increasing W/Ds represent aggradation risk and decreasing W/Ds represent degradation risk. Degradation risk is assessed in the MNSQT using the BHR. Because this metric is meant to assess aggradation alone, only the increasing W/D method is used.

Reference Curve Development:

The reference curve for the aggradation ratio metric was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

There was no dataset available in Minnesota to regionalize this metric. The MNSQT SC evaluated and adopted this metric and the reference curves from the CSQT Beta Version.

Reference curves were developed using the stability ratings provided in WDRS, which show the ratio of an observed W/D over an expected W/D. The expected W/D should come from reference reach streams of the same stream type as the proposed or design stream type. In addition, hydraulic and sediment transport models, such as Torizzo an Pitlick (2004) and FLOWSED and POWERSED models (Rosgen 2009), may be used to select a channel dimension (along with slope) that yields a stable W/D. The channel stability descriptions presented by Rosgen (2014) in the WDRS are provided in Table 7-9. The stability ratings are calculated by dividing the observed W/D by the reference W/D. The stable range is 1.0 to 1.2 meaning that observed W/Ds are 100% to 120% of reference. As the ratio increases, the risk of aggradation increases. When the value exceeds 140% of reference condition, the channel is likely to be unstable due to aggradation.

Based on these values, thresholds for the aggradation ratio were developed and are shown in Table 7-10 and the curve is shown in Figure 7-7.

Table 7-9: Width Depth Ratio State Categories (Rosgen 2014)

Width Depth Ratio State	Stability Rating
1.0 – 1.2	Stable
1.2 – 1.4	Moderately Stable
1.4 – 1.6	Unstable
1.6 – 1.8	Highly Unstable

Table 7-10: Threshold Values for Aggradation Ratio

Index Value	Field Value
1.00	1.0
0.69	1.2
0.30	1.4
0.00	1.6

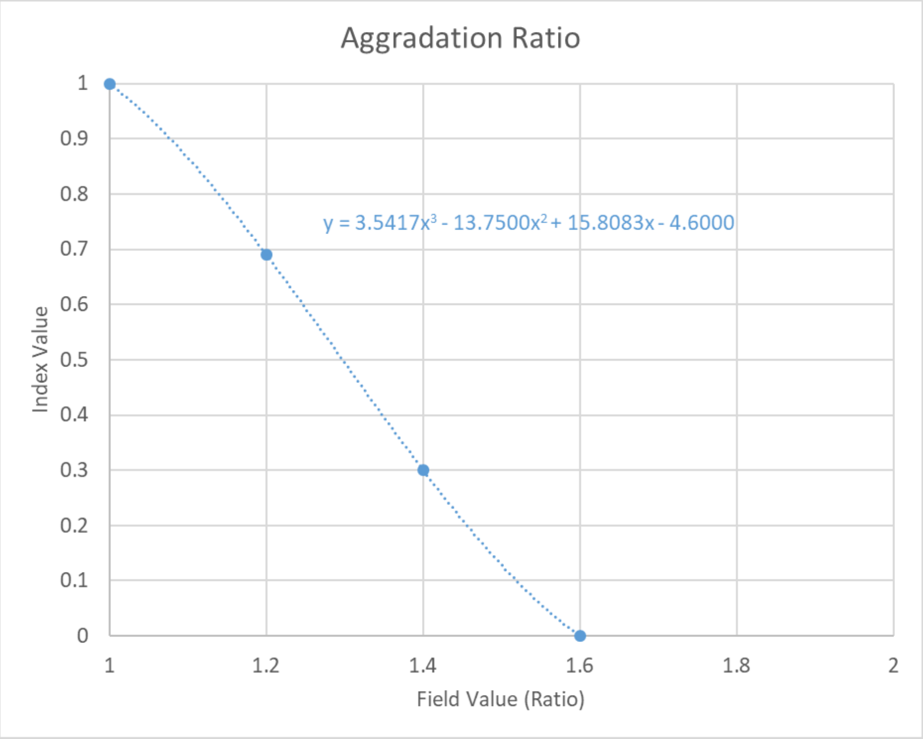

Figure 7-7: Aggradation Ratio Reference Curve

Limitations and Data Gaps:

If bankfull dimensions are not accurately determined for a site, then the aggradation ratio will not accurately represent bed forming processes. Information on verifying bankfull information is provided in the User Manual.

Aggradation ratio is not applicable to braided (D) stream types or stream/wetland complexes because the width of the channels is often the same as the valley width (Rosgen 2009).

F and G channels that represent degraded streams should be compared against the proposed, or reference stream type, as informed by channel evolution processes (Cluer and Thorne 2013; Rosgen 2014) as described in the User Manual. Selection of the appropriate reference stream type is important for consistently applying this metric and determining a condition score in the tool.

Chapter 8 Riparian Vegetation Parameter

Functional Category: Geomorphology

Function-based Parameter Summary:

Riparian vegetation is a critical component of stream ecosystem structure and function. Riparian vegetation is defined as plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent water bodies.

Minnesota's climate generally supports vigorous vegetation growth, particularly in riparian areas. Direct and sustained removal or suppression of vegetation through development and agricultural activities are the primary threat to vegetation coverage as opposed to drought and lack of soil moisture in more arid areas of the country. Riparian areas of streams in Minnesota are highly variable given the variety of stream types and the vast ecological, geological and climatic gradients across the state from east to west and north to south. These differences range from boreal forests in the northeast to prairie pothole landscapes in the southwest. This variation not only influences the plant assemblages of natural riparian areas of streams, but also the types of anthropogenic impacts that have changed these natural plant assemblages over time. Many riparian areas in Minnesota are wetland except for the active Karst topographic region in southeast Minnesota. Wetland riparian areas are typically dominated by plant species adapted to and tolerant of saturated soil conditions of varying lengths of time. Although not specific to riparian wetlands, overall, wetland vegetation quality is high but varies widely in different parts of the state. In the northeast, wetland vegetation is predominantly in exceptional to good condition. The exact opposite is true in the central, southern and western areas of the state where > 80% of the wetland extent is in fair or poor condition (MPCA 2015a). These differences reflect differing stressor exposure rates with increased agricultural-related stressors in the south, central and western portions of Minnesota.

While these plant communities are a biological component of the stream ecosystem, riparian vegetation plays such a critical role in supporting channel stability that it is included in the geomorphic level of the stream functions pyramid (Harman et al. 2012). Riparian areas support numerous instream and floodplain functions, including:

- Cover and shading
- Channel stability
- Filter excess nutrients, sediments, and pollutants
- Source of woody debris
- Floodplain roughness
- Carbon and nutrient contributions
- Terrestrial habitat
- Plant diversity, species richness, and functional integrity

The MNSQT riparian vegetation parameter uses four metrics:

- Effective Vegetated Riparian Area
- Canopy Cover
- Herbaceous Strata Vegetation Cover
- Woody Stem Basal Area

These metrics quantify the extent and structure of the riparian community. Composition metrics are not included. Other SQTs have used either a buffer width metric that is measured in feet out from the channel (e.g., Tennessee) or an observed over expected ratio riparian area metric (e.g., Wyoming). Many existing methodologies focus on establishing fixed buffer widths to represent riparian areas of streams. However, these approaches do not account for the natural variability in riparian area widths for different stream sizes and valley types and thus may not adequately characterize their functional significance. For example, in high gradient headwater streams, riparian areas are naturally narrow, and they may not extend as far as is implied with a fixed buffer width. Similarly, in broad, alluvial systems, a fixed buffer width may only characterize a small fraction of the floodplain or riparian area extent. The MNSQT attempts to account for some of this variability by using the bankfull width in combination with a meander width ratio for different stream valley types (alluvial, confined alluvial, colluvial) (Harman et. al 2012).

The canopy cover, herbaceous strata vegetation cover, and woody stem basal area metrics quantify the structure of the riparian community. These metrics include data collected from three vegetation cover strata: tree, shrub, and herbaceous. Where woody vegetation is determined to be a natural component of the riparian buffer, all four metrics should be assessed together. However, the woody stem basal area metric should not be used if woody vegetation is determined not to be a natural component of the riparian buffer. Instead, the other three metrics would be implemented.

All metrics consolidate data collected from both banks into a single MNSQT field value per metric, which is standard among other methods.

8.1. Effective Vegetated Riparian Area Metric

The effective riparian area is the area adjacent to and contiguous with the stream channel that supports the geomorphic dynamic equilibrium of the stream. The effective vegetated riparian area metric is the proportion of the effective riparian area that consists of natural vegetation. Areas that have anthropogenic induced structures or features (roads, buildings, utility lines, etc.); or agricultural vegetation that is harvested, removed or otherwise managed (crops, sod, tree farms, etc.); or low relative areal vegetation cover (≤ 50% for the MNSQT) are not considered vegetated for purposes of this metric. Identifying the effective riparian area is important, as functioning riparian areas influence (and are influenced by) many instream and floodplain processes (Fischer and Fischenich 2000, Mayer et al. 2005).

To determine the effective riparian area, the bankfull width of the stream is multiplied by the meander width ratio for the stream valley type and then an additional width is added. The added width, like the meander width ratio, varies according to stream valley type with alluvial streams having the highest width and colluvial the lowest. There are field-based observations using substrate, biotic and hydrologic attributes that could be used to estimate the effective riparian width for a specific stream reach. However, methods for using these observations to establish the riparian width lack specific reference data for Minnesota and can lead to unacceptable inconsistencies among tool users. The MNSQT chose to use this general approach that at least partly accounts for different size streams and different stream valley types.

The percent of the established effective riparian buffer area that is naturally vegetated (free of anthropogenic induced features with permanent vegetation) is the field value calculated for this metric.

Reference Curve Development:

The reference curve for the effective vegetated riparian area metric was adopted without revisions from the CSQT Beta Version for use in the MNSQT.

There is currently no dataset available in Minnesota to regionalize this metric. The MNSQT SC evaluated and adopted this metric and the reference curves from the CSQT Beta Version. However, the MNSQT SC revised the method from riparian width (%) metric in the CSQT Beta Version to effective vegetated riparian area.

Much of the existing literature is related to fixed-width buffers, so limited data and peer reviewed literature were available to inform thresholds and reference curves. Thus, reference curves were developed primarily using best professional judgement. The reference curves and thresholds are intended to encourage and incentivize restoration activities that restore floodplain connectivity or remove stressors and anthropogenic land uses from the riparian zone.

Stratification of reference curves took into consideration how hydrologic and geomorphic processes drive riparian zone development. Merritt et al. (2017) recommends stratifying riparian areas by valley type using a Hydrogeomorphic Valley Classification framework, which identifies nine valley types, but also acknowledges that other simpler classification approaches (e.g., Rosgen 1996) may also be useful to place a stream reach within its watershed context. This metric is stratified by valley type, recognizing the differences in hillslope and valley bottom processes that influence riparian extent in confined and unconfined valleys (Table 8-1).

The reference curves account for the influence of potential stressors in the floodplain or adjacent stream area and subsequent changes to the hydrologic regime of the stream reach. These stressors influence the degree to which riparian areas function, and in turn, support instream functions. For example, the extent of riparian area modification may substantially affect the recruitment of wood and organic matter, nutrient and carbon cycling, flood retention, buffering from sediment and pollutant influxes, and habitat availability (Fischer and Fischenich 2000; Sweeney and Newbold 2014). In confined and colluvial valleys, where streams and riparian areas are constrained by hillslope processes, riparian width is naturally narrower, and consequently, stressors within that area could be disproportionately higher. A 40% reduction in riparian width would substantially reduce flood prone area, reduce the capacity of the stream to recruit wood and organic matter, and reduce stream buffering from sediment and pollutant influxes. This magnitude of riparian area loss may no longer support instream and floodplain functions reflective of a not functioning condition. In unconfined valleys, where riparian areas are naturally broader, a greater proportion of the riparian area may be affected (e.g., 70%) before a similar loss in functionality might occur. Thresholds and reference curves were developed based on these values (Table 8-1 and Figure 8-1).

Table 8-1: Threshold Values for Effective Vegetated Riparian Area

Index Value	Field Value (%)	
	Unconfined Alluvial Valleys	Confined Alluvial and Colluvial Valleys
1.00	100	100
0.00	30	60

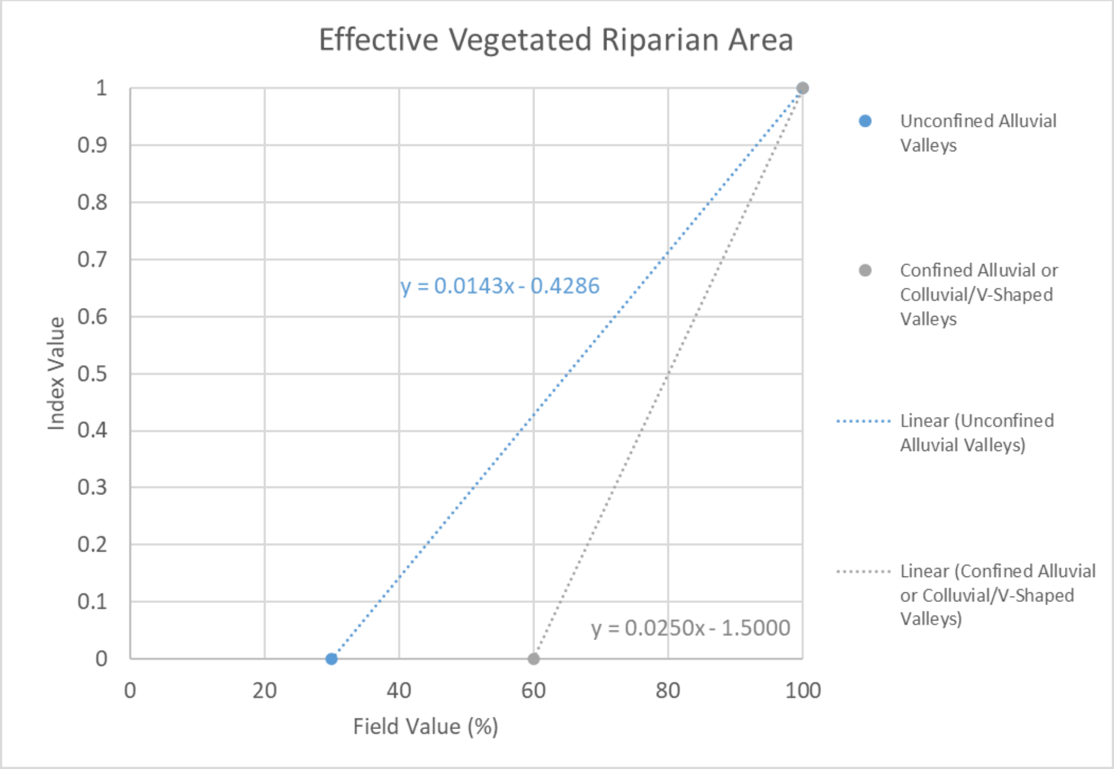

Figure 8-1: Effective Vegetated Riparian Area Reference Curves

Limitations and Data Gaps:

Because effective vegetated riparian area is a new metric, and reference curves are based on best professional judgement, additional data are needed to test and possibly expand these criteria. Reference curves may benefit from additional stratification that accounts for natural variability in riparian width beyond the valley type approach applied here. This metric would benefit from additional validation, review and refinement as the tool is applied.

8.2. Canopy Cover Metric

The canopy cover metric is determined by separately assessing the relative areal cover of the shrub and tree vegetation strata in plots, adding those values together and averaging across all plots for a single percent relative areal cover value. Methods are outlined in the User Manual.

The methodology for this metric includes a procedure for making this determination based on the natural plant community descriptions in three-volume series *Field Guides to the Native Plant Communities of Minnesota* (MN DNR, 2003, 2005a, 2005b). Data specific to canopy cover in riparian areas is lacking in Minnesota, but relative canopy cover estimates for various native communities are provided in *Field Guides to the Native Plant Communities of Minnesota* (MN DNR, 2003, 2005a, 2005b). MNSQT methodology uses these guides to identify the probable natural riparian community type along a stream reach.

<u>Reference Curve Development</u>:

Reference curves for the canopy cover metric were developed by the MNSQT SC.

Due to the variation in natural riparian communities and stressors noted in the parameter summary, reference curves were stratified to reflect whether woody vegetation was a natural component of the riparian area. The northern forested areas of Minnesota with commercially valuable timber resources have been and continue to be influenced by logging. These impacts can result in the reduction of canopy coverage in riparian areas through direct removal of trees from riparian areas and indirectly through removal of trees in the surrounding watershed which increase runoff and erosion resulting in sloughing, blow down and other processes that decrease riparian canopy cover. In prairie landscapes, fires and other natural events functioned to suppress canopy coverage in riparian areas. Agriculture and development brought about suppression of natural fires which has resulted in some riparian areas becoming dominated by woody vegetation and having high canopy coverage. Mats of herbaceous vegetation in the riparian area of many natural prairies stream reaches have been replaced with shallow-rooted woody species that are less effective at stabilizing soils and maintaining natural stream geomorphology.

There was no dataset available in Minnesota to regionalize this metric. Therefore, field values were assigned to index values using best professional judgement by applying the following logic: when woody vegetation is a natural component of a plant community, canopy coverage tends to be high as precipitation and climate are typically not limiting factors in Minnesota.

- <u>Functioning:</u> When woody vegetation is a natural component of the buffer, any field values over 80% were considered high and score an index value of 1.00.
- <u>Not functioning:</u> When woody vegetation is a natural component of the buffer, any field values below 50% were considered low and score an index value of 0.00.

When woody vegetation is not a natural component of the buffer and canopy cover is detrimental to the community, field values under 50% score an index value of 1.00 and field values over 80% score an index value of 0.00.

Based on these values, thresholds for the were developed and are shown in Table 8-2 and the curve is shown in Figures 8-2 and 8-3.

Table 8-2: Threshold Values for Canopy Cover

Index Value	Field Value (%)	
	Woody vegetation is a natural component of riparian area	**Woody vegetation is *not* a natural component of riparian area**
1.00	80	50
0.00	50	80

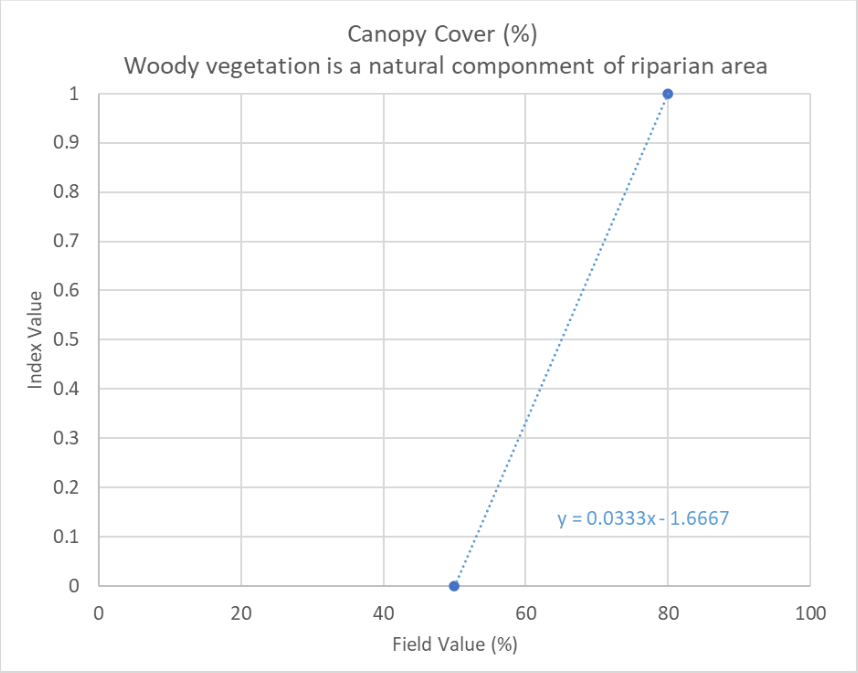

Figure 8-2: Canopy Cover Reference Curves for natural woody component

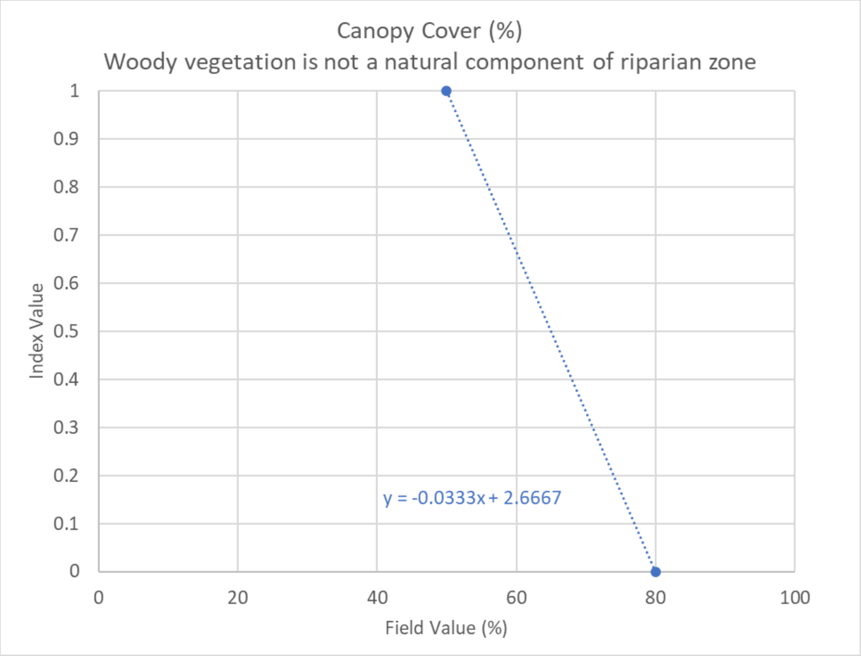

Figure 8-3: Canopy Cover Reference Curve for non-natural woody component

Limitations and Data Gaps:

The canopy cover reference curves were developed using the best available information (best professional judgement) at the time of regionalization. Further refinement and stratification are encouraged as data is collected in MN or as new regional or national datasets become available (e.g. National Stream and Rivers Assessment).

Given the effects of various anthropogenic influences over the years since European settlement (logging, farming, fire suppression, hydrologic alterations, etc.), it is difficult to identify a sufficient number of relatively unaltered stream reaches of various types to develop meaningful, data-based estimates of natural riparian area canopy coverage. A systematic effort to identify reference stream reaches and collect canopy coverage data is needed to better refine reference curves.

8.3. Herbaceous Strata Vegetation Cover Metric

Despite the stressors to riparian and wetland communities in the parameter introduction, many riparian areas throughout Minnesota retain high herbaceous vegetative cover supporting geomorphic stream functioning. Herbaceous species are an important component of the riparian community as they often provide surface roughness and cover in the early stages of succession following fluvial disturbances (Youngblood et al. 1985, Winward 2000). Herbaceous vegetation also contributes to bank stability and floodplain roughness (Winward 2000). Some riparian communities naturally support only herbaceous species, including those that support broad, highly connected floodplains with anaerobic soil conditions, or those that have natural disturbance (flood or fire) regimes that do not favor the persistence of woody species (Youngblood 1985; West and Ruark 2004), although the historical distribution of these communities is not well known. It is important to include herbaceous vegetation in the MNSQT because of the value it provides as a component of riparian communities as well as its sensitivity to disturbance.

The herbaceous strata vegetation cover metric is based on a visual plot-based vegetation assessment outlined in Appendix A.

Reference Curve Development:

The reference curve for the herbaceous vegetation cover metric was developed by the MNSQT SC.

In the absence of anthropogenic disturbances, herbaceous cover is often high because of favorable climate conditions for plant growth. High canopy coverage can reduce herbaceous growth, but even in those instances, coverage in most areas tends to be high. The MNSQT SC did not have sufficient data to tease apart the interaction of canopy and herbaceous strata. The SC relied on best professional judgment and field values over 80% were considered high, anything under 50% low and everything between those values medium. Based on these values, thresholds for the were developed and are shown in Table 8-3 and the curve is shown in Figure 8-4.

Table 8-3: Threshold Values for Herbaceous Vegetation Cover

Index Value	Field Value (%)
1.00	≥ 80
0.00	≤ 50

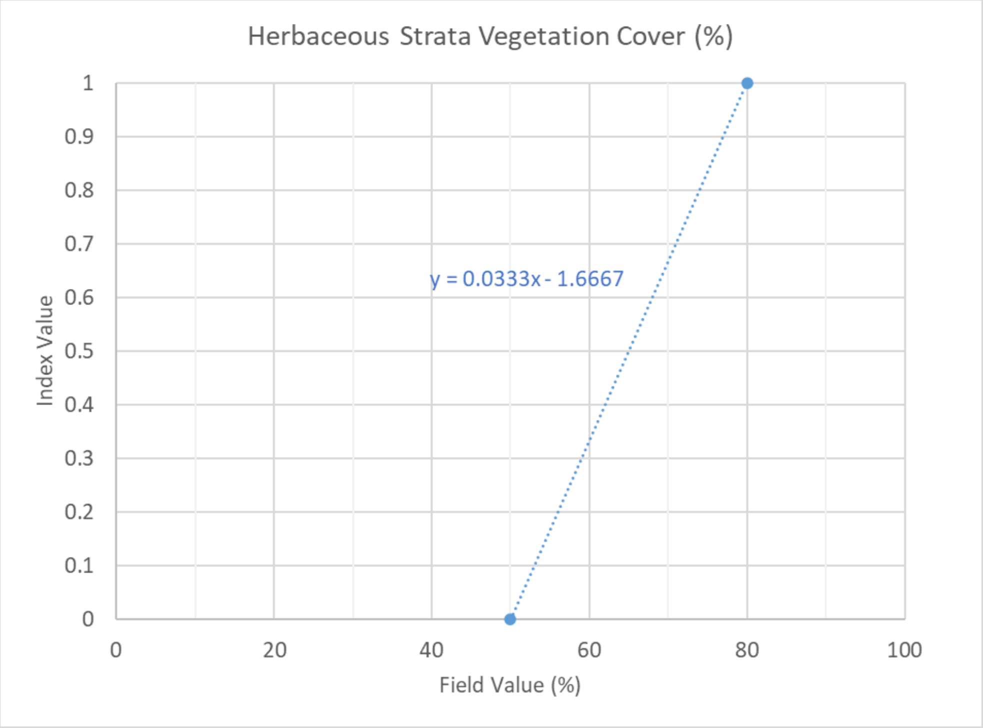

Figure 8-4: Herbaceous Strata Vegetation Cover Reference Curve

Limitations and Data Gaps:

The herbaceous strata vegetation curve was developed using the best available information (best professional judgement) at the time of regionalization. Further refinement and stratification are encouraged as data is collected in MN or as new regional or national datasets become available (e.g. National Stream and Rivers Assessment).

8.4. Woody Stem Basal Area Metric

The woody stem basal area metric is an estimate of the average amount of the effective riparian area occupied by woody stems. Woody stems intercept and slow flood and overland flows to protect against associated erosive forces. A higher basal area of woody stems will provide more attenuation of flows and protect the stream channel.

In certain ecological sections of the state, trees and shrubs are not a significant natural component of the effective riparian area of some stream reaches. In those instances, the woody stem basal area metric should not be used. Methodology for determining if trees and shrubs are a natural component of the riparian area is described in Appendix A of the User Manual.

Woody stem basal area is assessed by stem counts and diameter measurements of stems at breast height in plots. Stem occupancy per sample area is averaged across all sample plots to compute a woody stem basal area for the entire riparian area of the stream reach. Woody stems near the ground surface function much like herbaceous stems and are difficult to effectively count and quantify. Measurements are taken at breast height (4.5 feet/1.37 meters) as it is a standard for measuring the diameter of trees in forestry.

Reference Curve Development:

The reference curve for the woody stem basal area metric was developed by the MNSQT SC.

Reference curves for this metric were developed using best professional judgment and regional and national basal area datasets (Table 8-4a). The compiled data indicated a wide range of functioning field values. The SC set a value of 60 ft^2/ac (13.8 m^2/ha) to the 1.0 index value under the assumption that once a certain basal area is achieved, it is likely to increase over time given the climate and conditions in the northern forested portions of MN where woody growth is pervasive. Following the same logic, a value of 40 ft^2/ac or 9.2 m^2/ha was assigned to a 0.0 index value based on forest stand guidelines from the state of Maryland for forested riparian buffers summarized in (USFWS 2013, MD DNR 1999, Palone and Todd 1997).

Reference curves were developed based on a review of thresholds shown in Table 8-4 and is shown in Figure 8-5.

Table 8-4: Datasets Utilized to Compile Threshold Values for Woody Stem Basal Area

Field Value (ft^2/ac)	Field Value (m^2/ha)	Forest Type	State or Region	Reference
Not Functioning Condition				
40	9.2	All Forests	MD	USFWS, 2013.
Functioning Condition				
60	13.8	All Forests	MD	USFWS, 2013.
60 – 80	13.8 – 18.4	Northern hardwoods	NH (Bartlett Experimental Forest)	Leak et al., 2014
80	18.4	All Forests	MN	Miles et al., 2007
44.9	10.3	~30 yr old *Unmanaged* - Northern Dry-Mesic Mixed Forest, Red-Pine-White Pine Woodland Type (FDn33a)	MN	Young et al., 2017
75.8	17.4	~30 yr old *Managed* - Northern Dry-Mesic Mixed Forest, Red-Pine-White Pine Woodland Type (FDn33a)	MN	
137.7	31.6	~100 yr old *Unmanaged* - Northern Dry-Mesic Mixed Forest, Red-Pine-White Pine Woodland Type (FDn33a)	MN	
152.6	35.0	~100 yr old *Managed* - Northern Dry-Mesic Mixed Forest, Red-Pine-White Pine Woodland Type (FDn33a)	MN	
120	27.6 (Avg)	~50 yr old Uplands (Aspen, Jack pine, etc.)	MN	Sebestyen et al. 2011
54.5	12.5 (Avg)	49 to 100 yr old Peatlands (Black spruce & hemlock)	MN	

Table 8-5: Threshold Values for Woody Stem Basal Area

Index value	Field Value (ft^2/sc)	Field Value (m^2/ha)
1.00	60	13.8
0.00	40	9.2

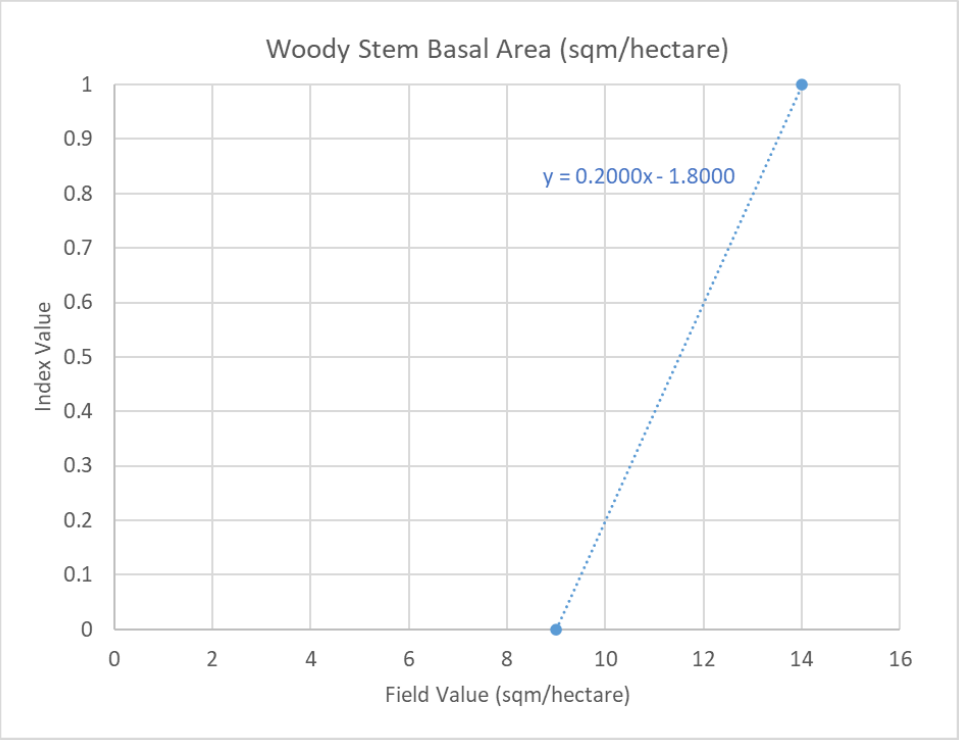

Figure 8-5: Woody Stem Basal Area Reference Curve

<u>Limitations and Data Gaps</u>:

The reference curve development for the MNSQT would benefit from additional field data to validate the criteria and curves identified above. Woody stem basal area varies greatly across plant communities due to differences in species composition and stand age classes. This metric does not account for these differences. In addition, the basal area data sets on which the reference curve is in part based are not directly correlated with stream geomorphological functioning.

Chapter 9 Temperature Parameter

Functional Category: Physicochemical

Function-based Parameter Summary:

Temperature plays a key role in both physicochemical and biological functions. For example, each species of fish has an optimal growth temperature but can survive a wider range of thermal conditions. Stream temperatures outside of a species' optimal thermal range result in reduced growth and reproduction and ultimately in individual mortality and population extirpation (Cherry et al. 1977). Water temperature also influences conductivity, dissolved oxygen concentration, rates of aqueous chemical reactions, and toxicity of some pollutants. These factors impact the water quality and ability of living organisms to survive in the stream.

Temperature assessments commonly focus on mean and maximum water temperatures, with maximum water temperatures commonly used to inform numeric water quality standards. While comparisons of site condition can be made to numeric standards (e.g., maximum temperature thresholds for aquatic biota), the use of regional reference data can provide a better indication of the degree of degradation and restoration potential than a comparison to temperature standards alone (Roni and Beechie 2013). Emerging monitoring and modeling capabilities are advancing the science on stream temperature, allowing for greater understanding of the temporal and spatial variability of temperature regimes in streams, and expanding the potential range of temperature variables that could inform condition (Steele and Fullerton 2017).

Temperature Parameter Metric:

- Summer Average Temperature (°C)

9.1. Summer Average Temperature Metric

The summer average temperature metric is the average of continuously recorded temperatures measured during the summer months of June, July, and August. Temperature measurements are collected in-situ during summer and measured using in-water temperature sensors installed following procedures outlined in *Procedure for Temperature Logger Deployment at Stream Monitoring Sites* (MPCA 2015b).

This metric is the chronic temperature criterion for waterbodies in Minnesota implemented to help prevent temperature changes that are deleterious to the resident aquatic life. The summer average temperature metric is a criterion that represents the optimum temperature range that supports specific species growth, reproduction and survival (MPCA 2018c). Temperatures that exceed this threshold may limit growth, reproduction, and survival. Additionally, coldwater fish such as trout are particularly sensitive to high temperatures (MPCA 2019a).

Reference Curve Development:

The reference curve for the summer average temperature metric was developed by the MNSQT SC.

Reference curves were based on state thermal criteria derived from historic water quality data sets collected in Minnesota. The reference curve was derived from visual interpretations of the scatterplot of percent growth average summer temperature (Figure 9-1) presented in *Technical*

Guidance for Reviewing and Designating Aquatic Life Uses in Minnesota Streams and Rivers (MPCA 2018c). The scatterplot included four temperature regime areas for coldwater streams. A thermal criteria flowchart, developed as part of an unpublished MCPA SOP for the determination of the appropriate designated use for a coldwater stream (MPCA 2018a), provides the following descriptions of the temperature regime areas document and are summarized below:

- Area 1: No trout present.
- Area 2: Trout may be present, generally in low numbers.
- Area 3: Trout are more likely to be present and in higher numbers.
- Area 4: Trout almost always present, in good numbers.

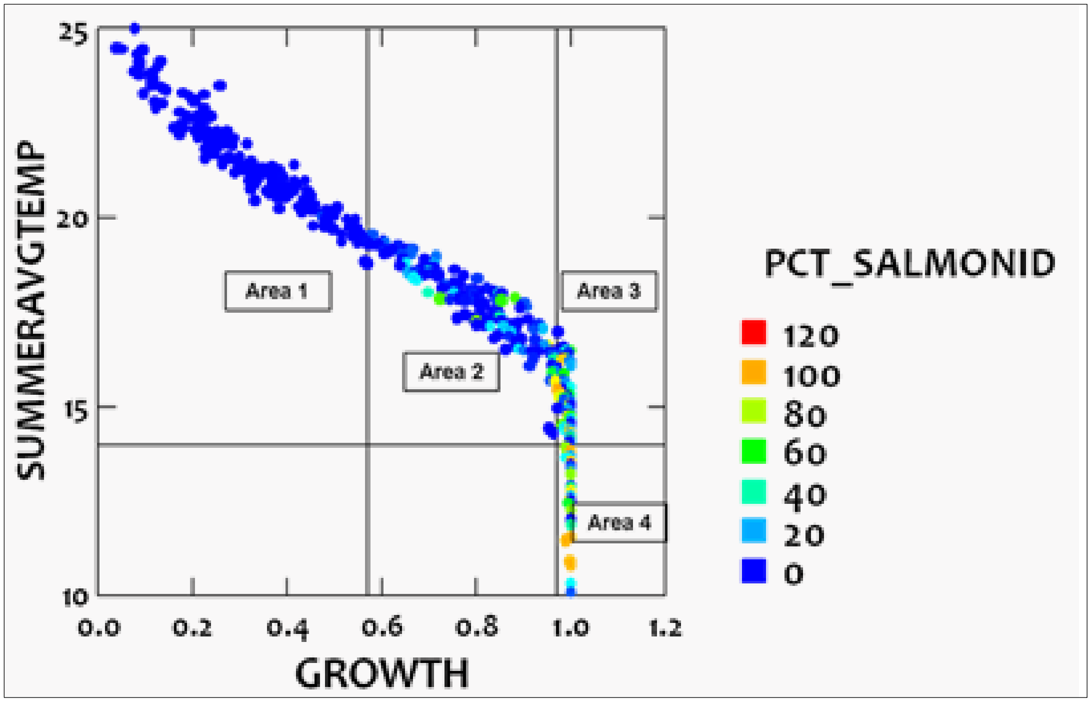

Figure 9-1: Relationship between summer (June-September) average water temperature (°C), percent of time during the summer with temperatures within the growth range for brook trout, and the percent of salmonids in streams (MPCA 2018c)

The approximate temperature for each temperature regime area were used to establish the reference curve threshold values:

- <u>Functioning:</u> Field values that ranged between the temperature range of Area 4 (between 10°C-14°C) were considered to represent a functioning range of index values (0.70 – 1.00). Field values less than or equal to 10°C were selected for 1.00 index value.
- <u>Functioning-at-risk:</u> A field value of 18°C (the upper temperature threshold between Areas 1 and Area2) was selected for the 0.30 index value.
- <u>Not Functioning</u>: A field value less than or equal to 25°C (the upper average temperature of Area 1) was selected for the 0.00 index value.

The threshold values and reference curve for this metric are provided in Table 9-1 and Figure 9-2, respectively.

Table 9-1: Threshold Values for Summer Average Temperature

Index value	Field Value
1.00	10
0.70	14
0.30	18
0.00	25

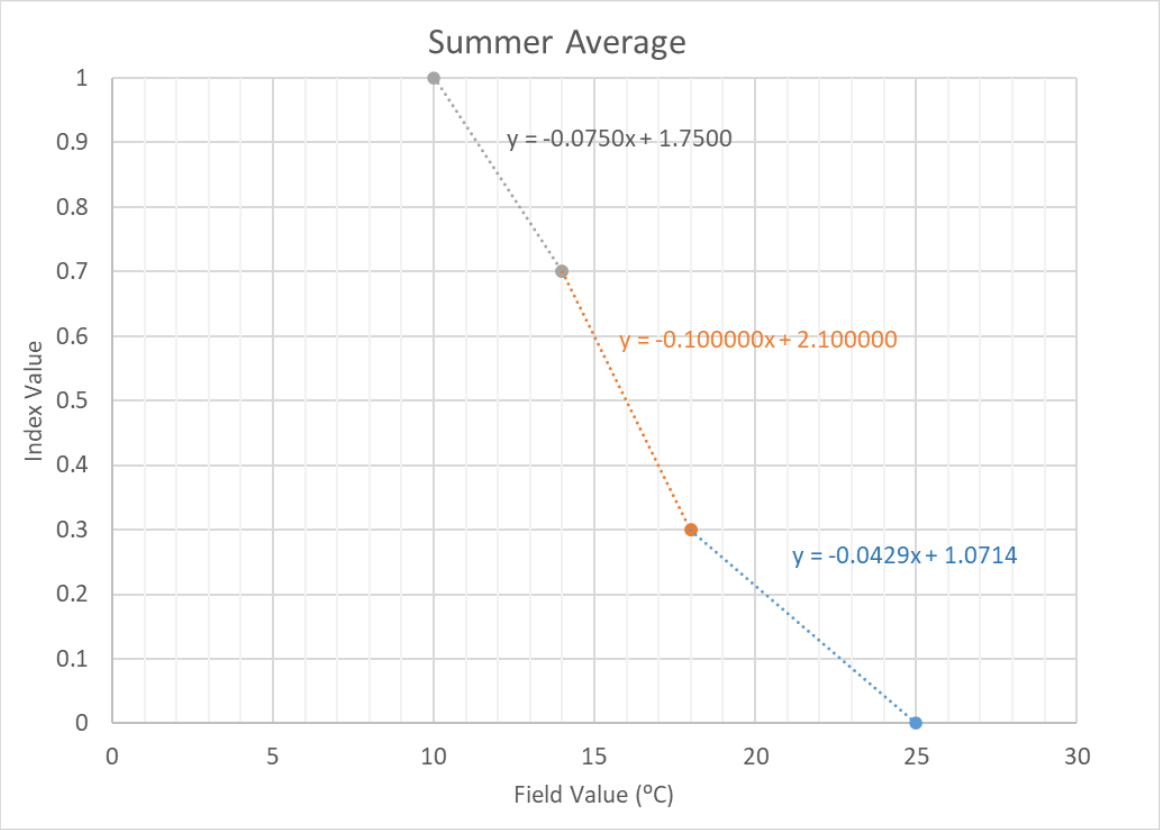

Figure 9-2: Summer Average Temperature (°C) Reference Curves

Limitations and Data Gaps:

The MNSQT’s thermal metric is based on a thermal flowchart developed by the Minnesota Pollution Control Agency to lead discussions on appropriate use designated (2A-Cold vs 2B-Warm) for the assessment of aquatic life. Most of the existing data was obtained on suspected or currently designated coldwater streams. This reference curve is only applicable to coldwater streams that should support a coldwater community. The reference curve is not applicable to non-trout streams.

Chapter 10 Dissolved Oxygen Parameter

Functional Category: Physicochemical

Parameter Summary:

Dissolved oxygen plays a key role in biological functioning and freshwater aquatic life requires adequate amounts of dissolved oxygen (DO) to survive. The amount of DO in a stream affects biological respiration rates and the solubility of chemical constituents such as inorganic nutrients (Harman et al. 2012).

Including this parameter in the MNSQT incentivizes in-stream structures and channel geometry that improves oxygenation where DO may be limiting biological and physicochemical function. DO can be improved through stream restoration practices that create eddies and induce mixing such as drop structures, habitat boulders, constructed riffles, and large woody debris. Permitted impacts that remove these types of features are likely to result in functional loss.

Dissolved Oxygen Parameter Metric:

- Dissolved Oxygen

10.1. Dissolved Oxygen Metric

The dissolved oxygen metric is the average concentration of 10 samples measured during the open-water months (April through November). The state standard for DO is expressed in terms of daily minimums and concentrations generally following a diurnal cycle. Consequently, measurements in open-water months should be made before 9:00 a.m. Measuring dissolved oxygen concentration should be conducted according to the *Standard Operating Procedures, Intensive Watershed Monitoring – Stream Water Quality Component* document (MPCA 2018b).

Reference Curve Development:

The reference curve for the dissolved oxygen metric was developed by MNSQT SC.

Reference curves were based on state water quality criteria derived from historical water quality data sets collected in Minnesota. DO standards differ depending on the use class of the water as described in the *Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment: 305(b)Report and 303(d) List* (MPCA 2019a). DO standards for each use class are as follows:

- Class 2A. Not less than 7 mg/L as a daily minimum
- Class 2Bd, 2B. Not less than 5 mg/L as a daily minimum
- Class 2D. Maintain background
- Class 7. Not less than 1 mg/L as a daily average, provided that measurable concentrations are present at all times.

Class 2 waters have aquatic life and recreation beneficial uses for which water quality control is necessary to protect aquatic or terrestrial life or their habitats or the public health, safety, or welfare. Class 7 waters are defined as Limited Resource Value waters in MN Rule 7050.0140 and for the most part are low-flow streams and ditches that are protected so as to allow secondary body contact, to preserve the groundwater for use as a potable water supply, and to protect the aesthetic qualities of the water.

The reference curves were developed based on the guidelines for parameter assessments in Table 1 of MPCA 2019a.The parameter assessment guidelines are summarized below:

- Unimpaired: When less than 10% of samples exceed the water quality standard, or the average concentration is meeting or within +/- 10% of water quality standard.
- Potentially impaired: When 10 – 25 % of samples exceed standard or the average is generally greater than 10% but less than 25% of water quality standard.
- Potentially severely impaired: When greater than 25% of samples exceed the standard or the average value is greater than 25% above standard.

For all use classes, the field values assigned to the 0.70 index value were set to the DO standard plus 10%, representing the unimpaired parameter assessment description. The field values assigned to the 0.30 index value were set to the DO standard minus 10%, representing the potentially impaired parameter assessment description.

A summary of the threshold values is provided below and shown in Table 10-1 and Figure 10-1:

- Functioning: Field values that were selected for the 0.7 index value are 10% greater than the standard criteria. The field value for the 1.00 index value was extrapolated linearly from these threshold values.
- Functioning-at-risk: Field values that were selected for the 0.30 index value are 10% lower than the standard criteria.
- Not Functioning: The field values for the 0.0 index value were extrapolated linearly from the Functioning-at-risk threshold.

Table 10-1: Threshold Values for Dissolved Oxygen

Index Value	Field Values by Use Class (mg/L)		
	2A	2B / 2Bd	7
0.70	7.7	5.5	1.1
0.30	6.3	4.5	0.9

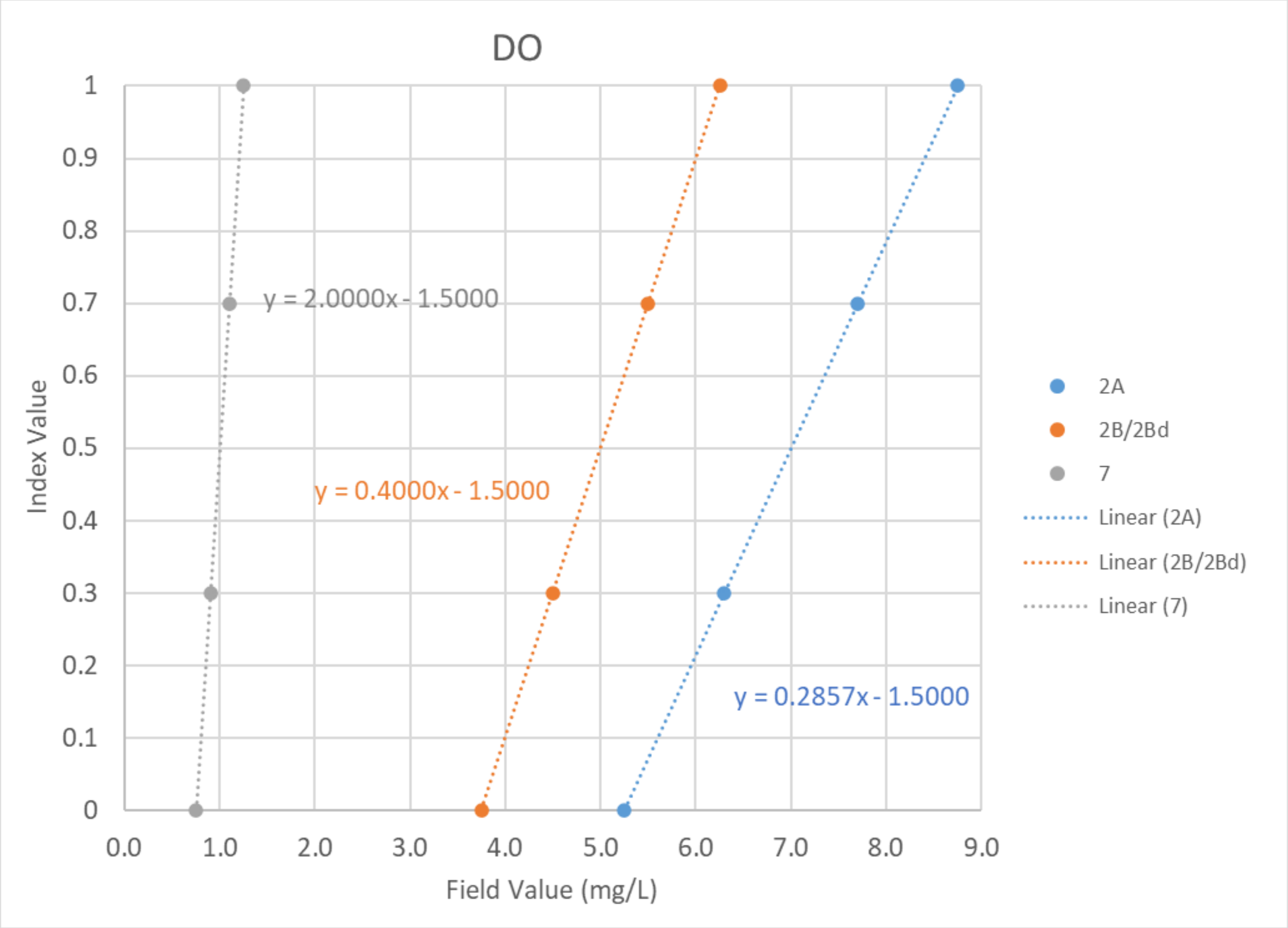

Figure 10-1: Dissolved Oxygen Concentration Reference Curves

Limitations and Data Gaps:

The current standard (MPCA 2019a) is not necessarily appropriate for all streams. Some low-gradient, heavily wetland-influenced streams may never meet the current DO standard of 5 mg/L, even though pollutant sources and anthropogenic influences are insignificant or even non-existent. In such cases, the current DO standard is not a useful indicator of the health of the water.

Chapter 11 Total Suspended Solids Parameter

Functional Category: Physicochemical

Parameter Summary:

Total suspended solids (TSS) river data in Minnesota has been collected since at least the 1950's (MPCA 2011). Levels of TSS have decreased by almost 50% over the last 30 years, mostly as a result of point source controls, but also in locations where improved cultivation practices have been put into place. The largest sources of transported sediment include agricultural runoff and construction, followed by urban runoff and streambank erosion.

TSS consists of soil particles, algae, and other materials that are suspended in water and cause a lack of clarity. Excessive TSS can harm aquatic life, degrade aesthetic and recreational qualities, and make water more expensive to treat for drinking. The link between a water quality standard and an impairment determination is the assessment protocol, which is found in the *Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment*: *305(b)Report and 303(d) List* (MPCA 2019a). Large sets of monitoring data have been used to develop transparency and TSS thresholds that identify the large majority of waters with turbidity impairments while minimizing the number of waterbodies falsely identified.

The metric included in the MNSQT is the dissolved oxygen metric.

Total Suspended Solids Parameter Metric:

- Total Suspended Solids

11.1. Total Suspended Solids Metric

Measuring total suspended solids should be conducted according to methods described in the *Guidance Manual For Assessing the Quality of Minnesota Surface Waters for Determination of Impairment: 305(b) Report and 303 (d) List* (MPCA 2019a) and *Standard Operating Procedures, Intensive Watershed Monitoring – Stream Water Quality Component* document (MPCA 2018b). The State also uses turbidity as a surrogate for TSS. The protocol for turbidity sampling is described in *Turbidity TMDL Protocol Guidance and Submittal Requirements* (MPCA 2007). This is another way to potentially acquire TSS data for use in the SQT.

Reference Curve Development:

The reference curve for the TSS metric was developed by the MNSQT SC.

Reference curves were based on state water quality criteria derived from historical data collected throughout Minnesota. Reference curves were derived using data and information presented in the *Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment: 305(b) Report and 303 (d) List* (MPCA 2019a). TSS standards differ depending on named regions or river reaches as described in the guidance manual. Additional information regarding the river nutrient boundaries and assignments as adapted for application of the Minnesota TSS water quality standards can be found in *Regionalization of Minnesota's Rivers for Application of River Nutrient Criteria* (MPCA 2019b).

Draft TSS criteria presented in the MPCA (2011) are regional in scope and based on a combination of both biotic sensitivity to TSS concentrations and reference streams/least impacted streams as data allow. Table 11-1 contains the recommended TSS criteria. Transparency values, as measured by Secchi tubes (S-tube), reliably predict TSS and can serve as surrogates. While TSS measurements themselves are generally preferred, datasets for S-tube are often more robust, and their relative strength will be considered in assessments. Because S-tube measurements are not perfect surrogates, however, their use involves a margin of safety. Therefore, the S-tube surrogate thresholds for determining if a stream exceeds the TSS standard are different than for determining if a stream meets the standard.

Table 11-1: Minnesota's TSS, Secchi tubes, and site-specific standards for named regions and river

Region or River	Use Class	TSS (mg/L)	S-tube (cm) Exceeds	S-tube (cm) Meets
All Class 2A Waters	2A	10	55	95
Northern River Nutrient Region as Modified for TSS	2B/2Bd	15	40	55
Central River Nutrient Region as Modified for TSS	2B/2Bd	30	25	35
Southern River Nutrient Region as Modified for TSS	2B/2Bd	65	10	15
Assessment season for above waters is April through September *Adapted from MPCA 2011*				

The reference curves were developed for Use Classes 2A, 2B, 2Bd based on the guidelines for parameter assessments in Table 1 of MPCA (2019). The parameter assessment guidelines are summarized below:

- <u>Unimpaired</u>: When less than 10% of samples exceed the water quality standard, or the average concentration is meeting or within +/- 10% of water quality standard.
- <u>Potentially impaired</u>: When 10 – 25 % of samples exceed standard or the average is generally greater than 10% but less than 25% of water quality standard.
- <u>Potentially severely impaired</u>: When greater than 25% of samples exceed the standard or the average value is greater than 25% above standard.

For all use classes, the field values that were selected to set the 0.70 index value were set to TSS standard minus 10%, representing the unimpaired parameter assessment description. The field values that was selected to set the 0.30 index value are set to the TSS standard plus 10%, representing the potentially impaired parameter assessment description.

A summary of the threshold values is provided below and shown in Table 11-2 and Figure 11-1:

- <u>Functioning:</u> Field values that were selected for the 0.70 index value are 10% lower than the standard criteria. The field value for the 1.00 index value was extrapolated linearly from these threshold values.
- <u>Functioning-at-risk:</u> Field values that were selected for the 0.30 index value are 10% greater than the standard criteria.

Not Functioning: The field values for the 0.00 index value were extrapolated linearly from the Functioning-at-risk threshold.

Table 11-2: Threshold Values for Total Suspended Solids by Use Class and River Nutrient Region

Index Value	Field Value (mg/L)			
	2A, N/A	2B/2Bd, North	2B/2Bd, Central	2B/2Bd, South
0.70	9.0	13.5	27.0	58.5
0.30	11.0	16.5	33.0	71.5

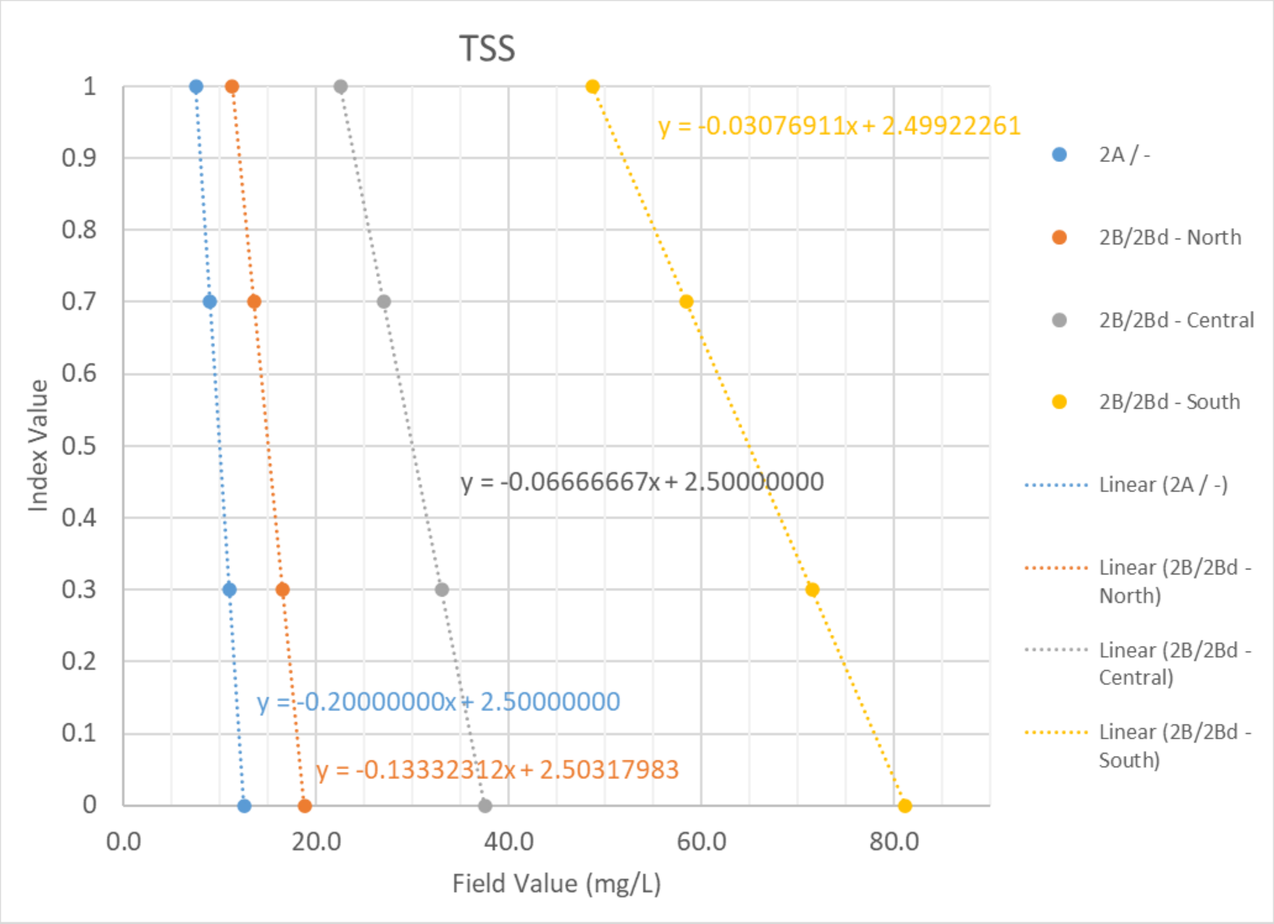

Figure 11-1: Total Suspended Solids Reference Curves

Limitations and Data Gaps:

The TSS reference standard was derived using the best available information and data at the time of regionalization, which included a long-term dataset from MN collected by MPCA. Further refinement and stratification are encouraged as data are collected in MN.

TSS concentrations have been determined to underrepresent the amount of suspended sediment, which has led the MPCA to quantify the difference between TSS and suspended-sediment concentrations (SSC).

Chapter 12 Macroinvertebrates Parameter

Functional Category: Biology

Function-based Parameter Summary:

Benthic macroinvertebrates are key components of aquatic food webs that link organic matter and nutrient resources (e.g., leaf litter, algae and detritus) with higher trophic levels. They are reliable indicators of condition because they spend all or most of their lives in water and differ in their tolerance to pollution. Macroinvertebrates respond to environmental stressors in predictable ways, are relatively easy and cost-effective to collect and identify in a laboratory, often live for more than a year, and have limited mobility. Unlike fish, macroinvertebrates cannot easily escape pollution, thus they have the capacity to integrate the effects of the stressors to which they are exposed. Benthic macroinvertebrates are relatively sessile compared to fish and can be a key indicator of local habitat conditions (e.g. silt-laden or coarse substrate). which can be particularly important in reach-scale restoration projects that result in narrower stream channels and increased velocity and sediment scour. Benthic macroinvertebrates are commonly used as indicators of stream ecosystem structure and function and were included as one of the original parameters described in Harman et al. (2012).

Macroinvertebrates Parameter Metric:

- Macroinvertebrate IBI

12.1. Macroinvertebrate IBI Metric

Macroinvertebrates are an integral part of the food web and are commonly used as indicators of stream ecosystem condition. Calculation of an index of biotic integrity (IBI) involves synthesis of macroinvertebrate community information into a numerical expression of stream health. The IBI is used by the MPCA to determine if streams are meeting their aquatic life use goals. The MPCA recognizes nine different macroinvertebrate IBI (M-IBI) classes based on stream type and the expected natural macroinvertebrate community associated with each. Stream types are defined using drainage area, geographic region, thermal regime, and gradient (MPCA 2014). The Macroinvertebrate IBI metric field value is the IBI score derived from sampling data collected within the project reach. Information on data collection, sample preservation, identification and enumeration and calculation of the macroinvertebrate IBI can be found in *Macroinvertebrate Data Collection Protocols for Lotic Waters in Minnesota* (MPCA 2017b).

Reference Curve Development:

Reference curves for the macroinvertebrate IBI metric were developed by the MNSQT SC.

Reference data curves were derived based on IBI thresholds developed by the MPCA in the following document: *Development of a Macroinvertebrate-Based Index of Biological Integrity for Minnesota's Rivers and Streams* (2014a). The data used to develop the IBI thresholds are based on historic water quality data collected throughout Minnesota. This document describes the process used in the development of M-IBI for Minnesota's rivers and streams, representing the state's first comprehensive, statewide tool for assessing the biological integrity of riverine macroinvertebrate communities. The primary intended use for this tool is the assessment of aquatic life use support by the Minnesota Pollution Control Agency (MPCA). Since the 1990s, the MPCA has utilized the IBI concept in its stream monitoring and assessment program. Narrative language within Minnesota Administrative Rule identifies an IBI calculation as the primary determinant for evaluating impairment of aquatic biota.

Development of the M-IBI utilized a standardized protocol created by researchers from the United States Environmental Protection Agency (USEPA) and elsewhere (Whittier et al. 2007). Minnesota's streams and rivers were first partitioned into five distinct classes, and a unique IBI was developed for each. Within each stream class, biological metrics were sequentially ranked and eliminated by a series of tests and selected for inclusion in each IBI. Among the most important tests was an evaluation of each metric's ability to distinguish most-disturbed sites from least-disturbed sites.

Minnesota has adopted water quality standards that establish a tiered aquatic life uses (TALU) framework for rivers and streams. This framework affects Class 2 (Aquatic Life) standards and the USEPA approved the Revisions to Minnesota's Water Quality Standards: Tiered Aquatic Life Uses and Biological Criteria (Minn R. ch 7050 and 7052) on June 26, 2018.

The TALU framework further classifies cold and warm water streams based on the biological condition that can be attained. The framework classifies streams into Exceptional, General, and Modified Use tiers based on an assessment of the stream's biological conditions and habitat quality (MPCA 2015c). MPCA 2015c defines the TALU tiers as follows:

Exceptional Use: High quality waters with fish and invertebrate communities at or near undisturbed conditions.

General Use: Waters with good fish and invertebrate communities that meet or should meet minimum goals.

Modified Use: Waters with legal altered habitat that prevents fish and invertebrate communities from meeting minimum goals.

The M-IBI thresholds in Table 12-1 (MPCA 2016, 2017d) were used to inform threshold values (Tables 12-2 through 12-4) and graphical relationships that informed the reference curves (Figures 12-1 through 12-3). A summary of assigned threshold values is provided below.

- Functioning: Field values that ranged between the upper confidence interval and the Exceptional Use threshold were considered to represent a functioning range of index values (0.70 – 1.00).
- Functioning-at-risk: A field value equal to the General Use interval threshold value was selected for the 0.30 index value.
- Not functioning: A field value less than or equal to the Lower Confidence Interval threshold (or the Modified Use threshold when available) was selected for the 0.00 index value.

As part of the TALU assessment, bracketing each IBI assessment threshold is a 90% confidence interval that is based on the variability of IBI scores obtained at sites sampled multiple times in the same year (i.e., replicates). Confidence intervals account for variability due to natural temporal changes in the community as well as method error. For assessment purposes, sites with IBI scores within the 90% confidence interval are considered "potentially impaired" (MPCA 2019a).

Table 12-1: Macroinvertebrate - Index of Biological Integrity Thresholds

IBI Class	Exceptional Use Threshold	Upper Confidence Interval	General Use Threshold	Lower Confidence Interval	Modified Use Threshold
Northern Forest Rivers	77	59.8	49	38.2	
Prairie Forest Rivers	3	41.8	31	20.2	
Northern Forest Streams Riffle-Run	82	65.6	53	40.4	
Northern Forest Streams Glide-Pool	76	64.6	51	37.4	37
Southern Forest Streams Riffle-Run	62	49.6	37	24.3	24
Southern Forest Streams Glide-Pool	6	56.6	43	29.4	30
Northern Coldwater	52	44.4	32	19.6	
Southern Coldwater	72	56.8	43	29.2	
Prairie Streams Glide-Pool	69	54.6	41	27.4	22

Table 12-2: Threshold Values for Macroinvertebrate IBI (Northern Class)

Index Value	Field Value			
	Northern Forest Rivers	Northern Forest Streams Riffle-run	Northern Forest Streams Glide-pool	Northern Coldwater
1.00	77.0	82.0	76.0	52.0
0.70	59.8	65.6	64.6	44.4
0.30	49.0	53.0	51.0	32.0
0.00	38.2	40.4	37.0	19.6

Table 12-3: Threshold Values for Macroinvertebrate IBI (Southern Class)

Index Value	Field Value		
	Southern Forest Streams Riffle-run	Southern Forest Streams Glide-pool	Southern Coldwater
1.00	62.0	66.0	72.0
0.70	49.6	56.6	56.8
0.30	37.0	37.0	43.0
0.00	24.0	29.4	29.2

Table 12-4: Threshold Values for Macroinvertebrate IBI (Prairie Class)

Index Value	Field Value	
	Prairie Forest Rivers	Prairie Forest Glide-pool
1.00	63.0	69.0
0.70	41.8	54.6
0.30	31.0	41.0
0.00	20.2	27.4

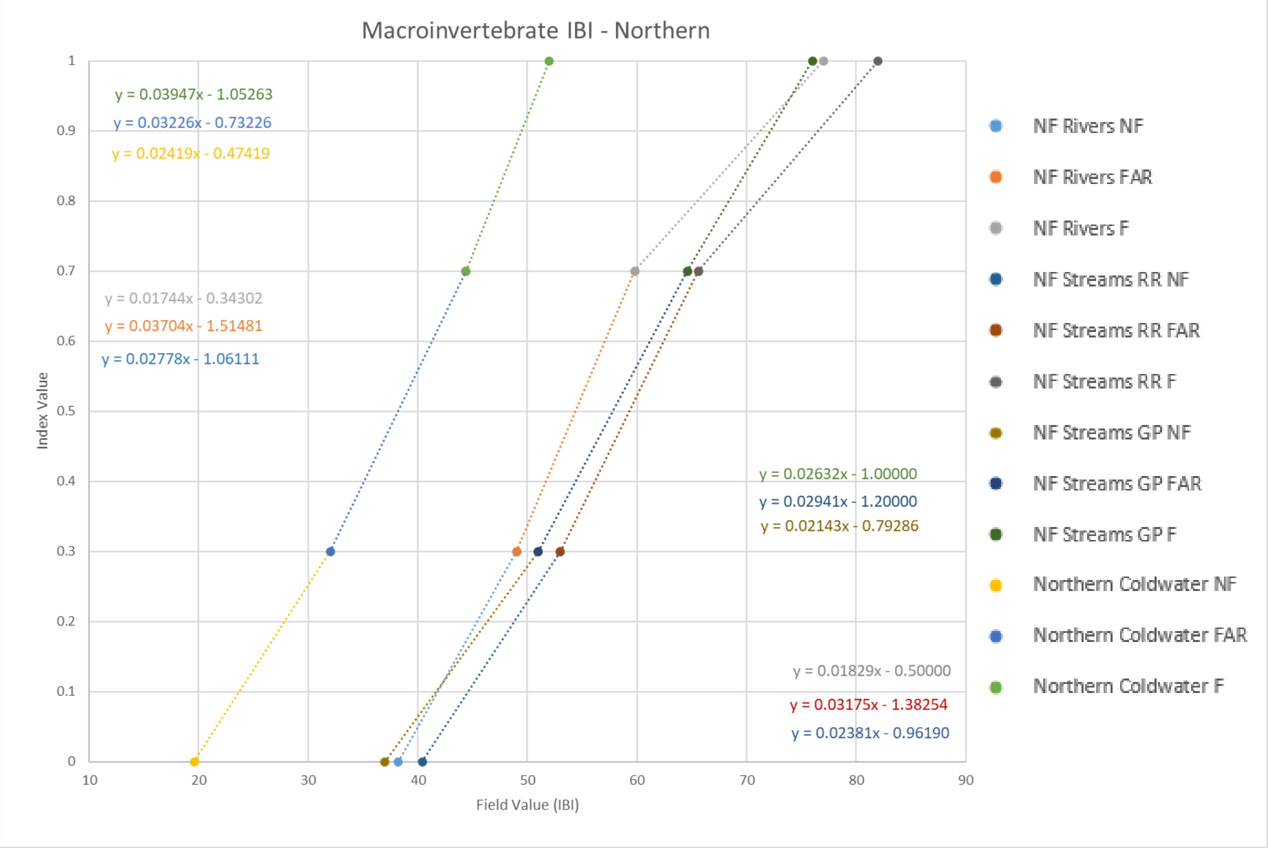

Figure 12-1: Macroinvertebrate IBI Reference Curves for Northern Classes

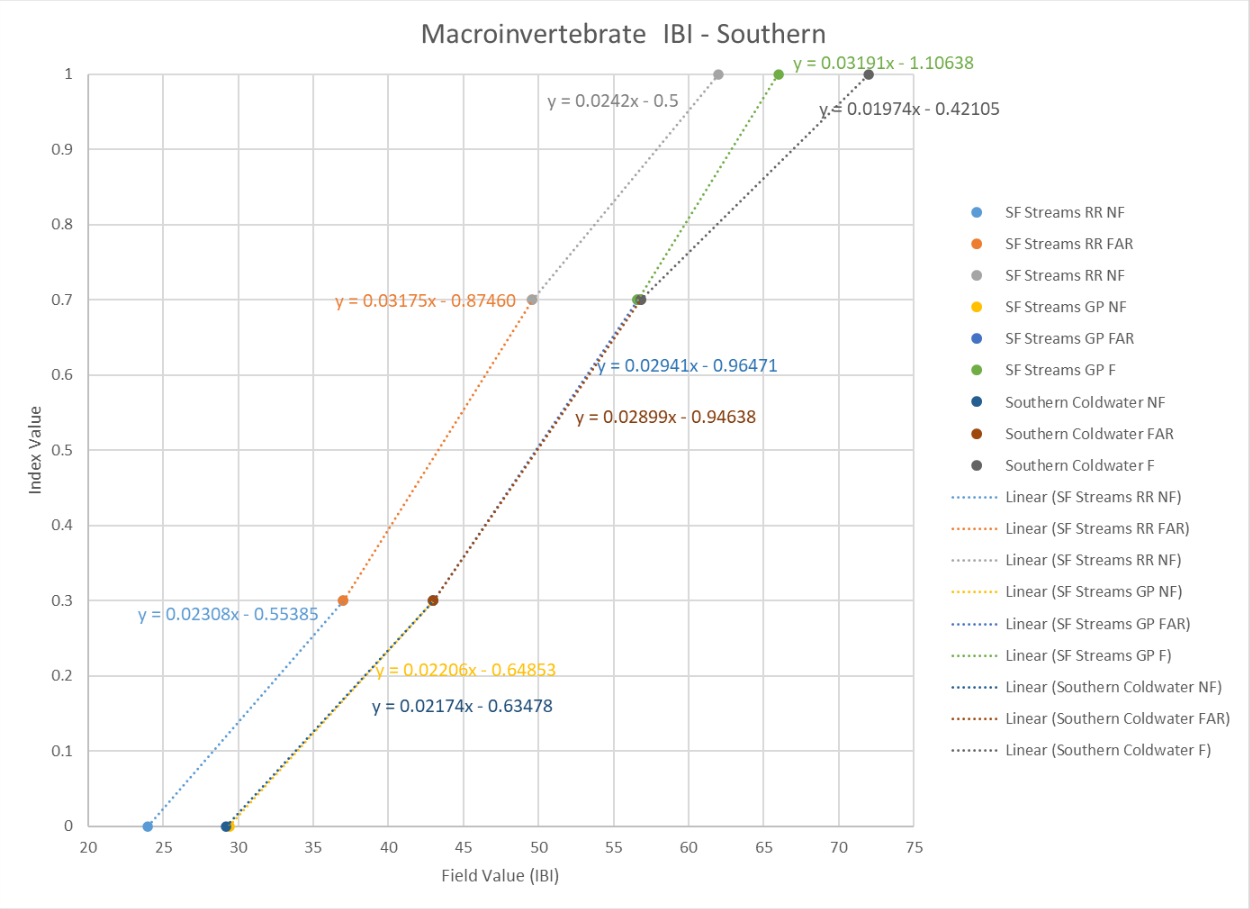

Figure 12-2: Macroinvertebrate IBI Reference Curves for Southern Classes

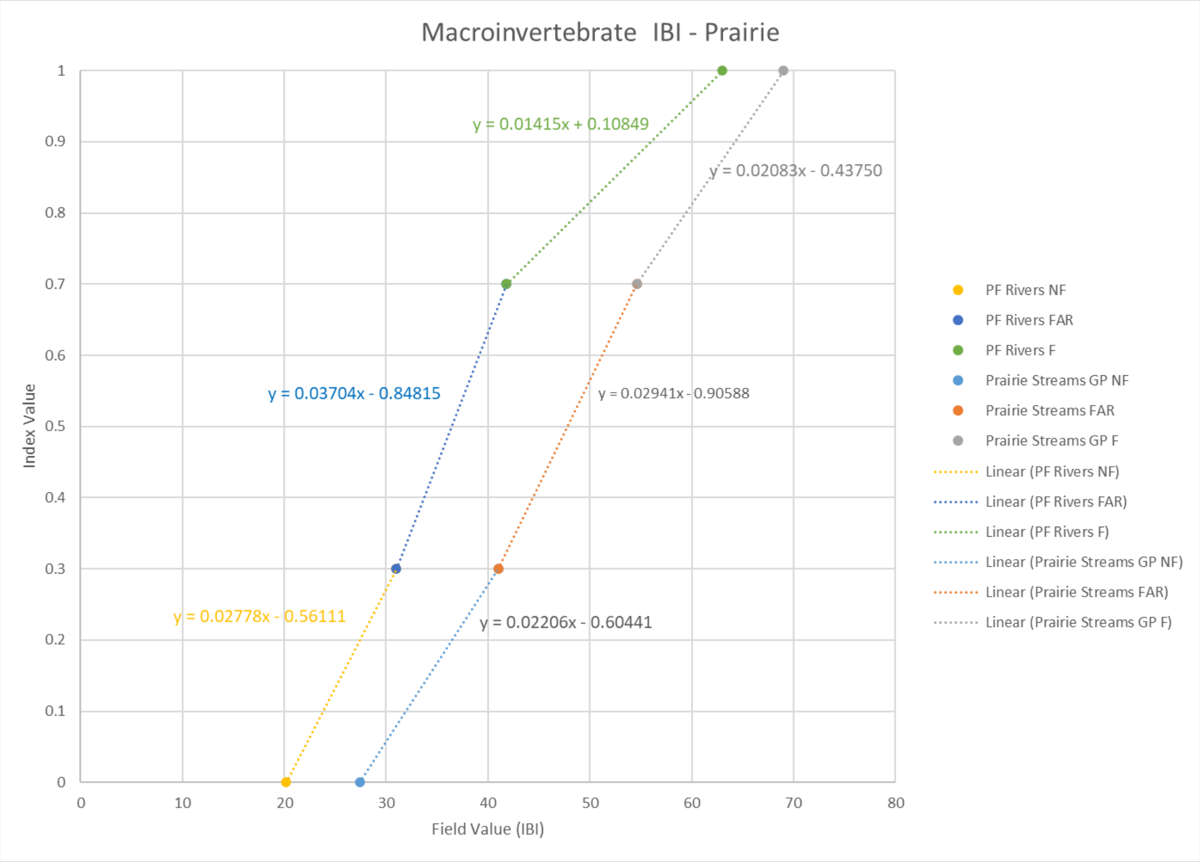

Figure 12-3: Macroinvertebrate IBI Reference Curves for Prairie Classes

Limitations and Data Gaps:

For development of a macroinvertebrate-based index of biological integrity for MN Rivers and Streams (MPCA 2014), MPCA's statewide approach encompassed both the full geographic extent and variety of lotic environments found across the state, including large rivers, moderate-sized streams, headwaters, low-gradient and coldwater streams (MPCA 2014). Some transitional habitats, such as estuaries, impoundments, wetland flowages, and "Great Rivers", fell beyond the scope of this project but future work may address the development and application of macroinvertebrate community-based indicators for these systems. Large-scale changes in environmental condition across Minnesota, or advances in the science of biological indicators may require periodic valuation of these indices to ensure their relevancy as assessment tools. The low gradient, wetland dominated nature of these systems create stream conditions with high organic carbon, low dissolved oxygen, and often little habitat due to soft sediment stream bottoms. There were not an adequate number of low gradient sites to allow for the development of a separate, low gradient, coldwater IBI, so these sites were combined with high gradient data in the IBI development process. The result being that some of the low-gradient systems have lower IBI scores relative to the entire set of northern coldwater streams.

The MPCA's fish/macroinvertebrate IBIs were developed for perennial streams. Small, intermittent/ephemeral streams are challenging environments for all aquatic biological communities. By definition, these streams do not flow continuously, and can be reduced to a series of isolated pools or are dry completely during portions of the year. This dramatic fluctuations in flow can limit the availability of habitat for these communities and present stressful chemical (dissolved oxygen, turbidity, etc.) parameters that can severely limit fish/macroinvertebrate survival, growth, and reproduction.

The MPCA’s fish/macroinvertebrate IBIs can be used in stream/wetland complexes. In some cases, the existing stream bioassessment tools may not accurately assess the quality of unique biological communities found in streams possessing predominant wetland characteristics. In these rare cases a best professional judgement approach should be used to determine the validity of the assessment results.

Chapter 13 Fish Parameter

Functional Category: Biology

Function-based Parameter Summary:

Fish are an integral part of functioning river ecosystems. Fish populations require adequate streamflow, water quality and habitat availability to support their life history requirements (Harman et al. 2012). Different species vary in their habitat and life histories and are adapted to unique stream temperature and flow regimes and they serve as important indicators of ecological health.

Fish Parameter Metric:

- Fish IBI

13.1. Fish IBI Metric

Calculation of an IBI involves synthesis of fish community information into a numerical expression of stream health. The IBI is used by the MPCA to determine if streams are meeting their aquatic life use goals. Similar to the IBI developed for macroinvertebrate, the MPCA has developed a comprehensive, statewide IBI to assess the biological integrity of riverine fish communities in Minnesota. IBI classes were first defined using watershed lines that reflect post-glacial barriers to movement, resulting in ‘north’ and ‘south’ streams. These two classes were further refined into nine total classes based on stream/watershed size, thermal regime, and gradient (MPCA 2014). The Fish IBI metric field value is the IBI score derived from fish sampling data collected within the project reach. Data collection procedures are outlined in *Fish Data Collection Protocols for Lotic Waters in Minnesota: Sample Collection, Sample Processing, and Calculation of Indices of Biotic Integrity* (MPCA 2017c).

Reference Curve Development:

Reference curves for the fish IBI metric were developed by the MNSQT SC.

Reference curves were derived based on IBI thresholds developed by the MPCA in the following document: *Development of a Fish-Based Index of Biological Integrity for Minnesota’s Rivers and Streams* (2014b). MPCA (2014) describes the process used in the development of the F-IBI for Minnesota’s rivers and streams, representing the state’s first comprehensive, statewide tool for assessing biological integrity of riverine fish communities. The data used to develop the IBI thresholds are based on historic water quality data collected throughout Minnesota. Development of the statewide F-IBI utilized a protocol developed by researchers from the USEPA and elsewhere. Minnesota’s streams and rivers were first partitioned into nine physiographic classes; a unique F-IBI was developed for each stream class. Within each stream class, biological metrics were evaluated using a series of tests. Metrics that passed these tests were ranked and a subset selected for inclusion in each IBI. The final indices included between seven and twelve metrics and demonstrated the ability to distinguish between levels of biological condition.

For the purposes of F-IBI development, Minnesota’s streams and rivers were partitioned into nine classes across two geographic regions.

- Southern Classes
    - Southern Rivers
    - Southern Streams
    - Southern Headwaters
    - Southern Coldwater
- Northern Classes
    - Northern Rivers
    - Northern Streams
    - Northern Headwaters
    - Northern Coldwater
- Statewide
    - Low Gradient

Regionalization largely follows major watershed boundaries and reflects significant post-glacial barriers to fish migration (e.g. St. Anthony Falls). The classification framework partitions natural variability in fish community structure, based largely on patterns observed among least-impacted sites. Fish communities occurring at sites within each class are more similar to each other than to those in other classes. The classification factors are unaffected by anthropogenic disturbance to ensure that the framework reflects natural variability and that the resulting F-IBI reflect impacts.

A discussion of the TALU tier descriptions (i.e. Exceptional Use, General Use, and Modified Use) and the confidence intervals is provided in Chapter 12.

The F-IBI thresholds in Table 13-1 (MPCA 2016, 2017d) were used to inform threshold values (Tables 13-2 through 13-4) and graphical relationships that informed the reference curves (Figures 13-1 through 13-3). A summary of assigned threshold values is provided below. A summary of assigned threshold values is provided below:

- Functioning: Field values that ranged between the Upper Confidence Interval and the Exceptional Use threshold were considered to represent a functioning range of index values (0.70 – 1.00).
- Functioning-at-risk: A field value equal to the General Use interval threshold value was selected for the 0.30 index value.
- Not Functioning: A field value less than or equal to the Lower Confidence Interval threshold (or the Modified Use threshold when available) was selected for the 0.00 index value.

As part of the TALU assessment, bracketing each IBI assessment threshold is a 90% confidence interval that is based on the variability of IBI scores obtained at sites sampled multiple times in the same year (i.e., replicates). Confidence intervals account for variability due to natural temporal changes in the community as well as method error. For assessment purposes, sites with IBI scores within the 90% confidence interval are considered “potentially impaired” (MPCA 2019a).

Table 13-1: Fish - Index of Biological Integrity Thresholds

IBI Class	Exceptional Use Threshold	Upper Confidence Interval	General Use Threshold	Lower Confidence Interval	Modified Use Threshold
Southern River	71	60	49	38	
Southern Streams	66	59	50	41	35
Southern Headwaters	74	62	55	48	33
Southern Coldwater	82	63	50	37	
Northern Rivers	7	47	38	29	
Northern Streams	61	56	47	38	35
Northern Headwaters	68	58	42	26	23
Northern Coldwater	60	45	35	25	
Low Gradient	70	52	42	32	15

Table 13-2: Threshold Values for Fish IBI (Northern Class)

Index Value	Field Value: Northern			
	Rivers	Streams	Headwaters	Coldwater
1.00	67.0	61.0	68.0	60.0
0.70	47.0	56.0	58.0	45.0
0.30	38.0	47.0	42.0	35.0
0.00	29.0	35.0	23.0	25.0

Table 13-3: Threshold Values for Fish IBI (Southern Class)

Index Value	Field Value: Southern			
	Rivers	Streams	Headwaters	Coldwater
1.00	71.0	66.0	74.0	82.0
0.70	60.0	59.0	62.0	63.0
0.30	49.0	50.0	55.0	50.0
0.00	38.0	35.0	33.0	37.0

Table 13-4: Threshold Values for Fish IBI (Low Gradient Class)

Index Value	Field Value
1.00	70.0
0.70	52.0
0.30	42.0
0.00	15.0

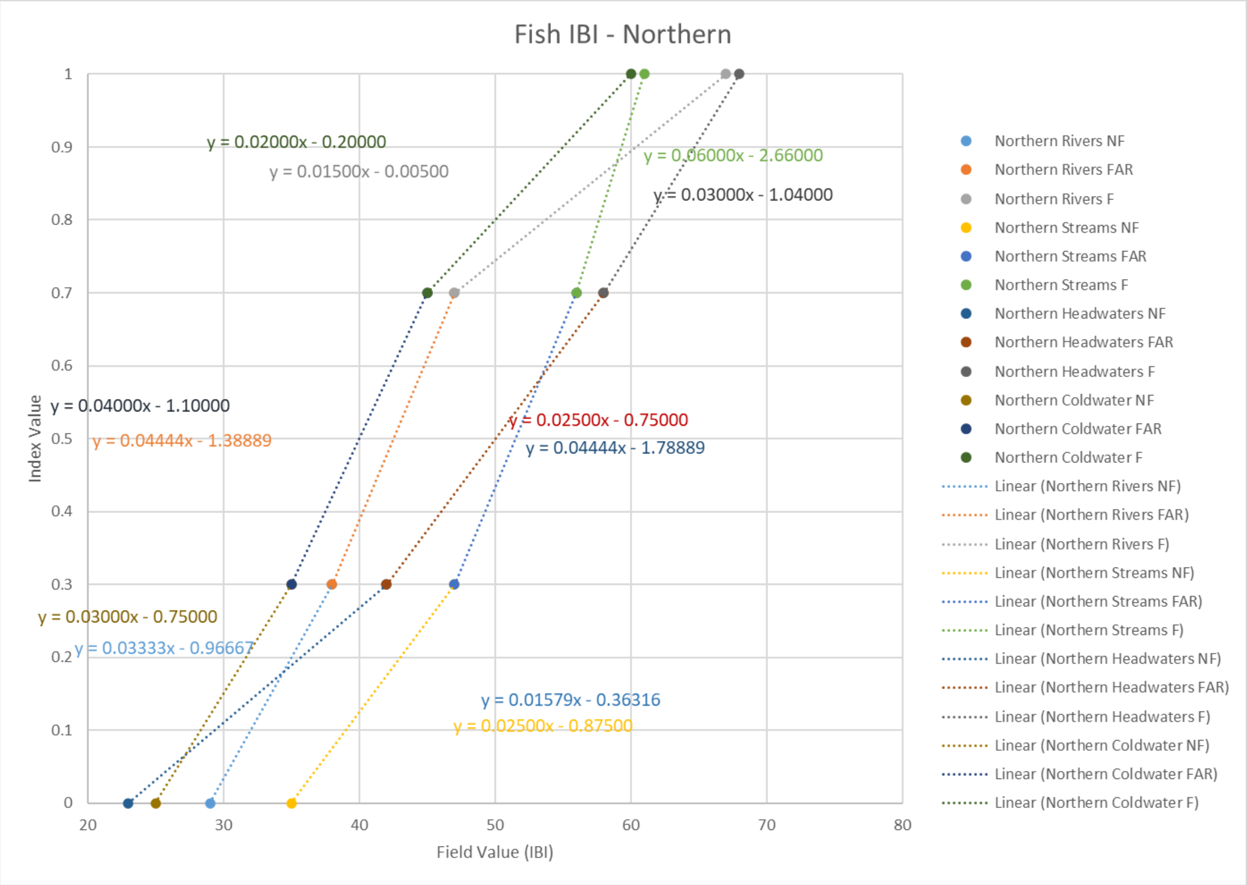

Figure 13-1: Fish IBI Reference Curves for Northern Classes

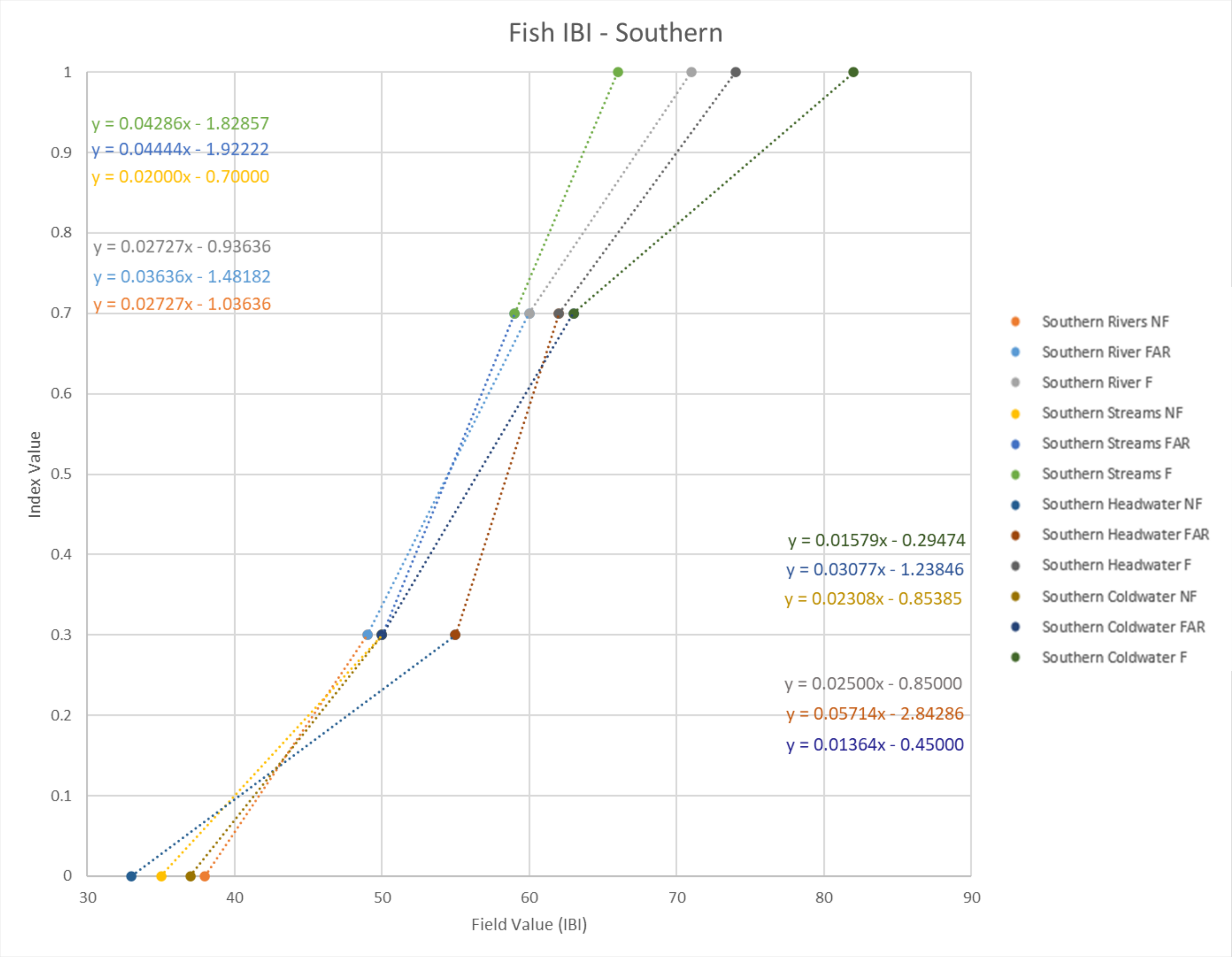

Figure 13-2: Fish IBI Reference Curves for Southern Classes

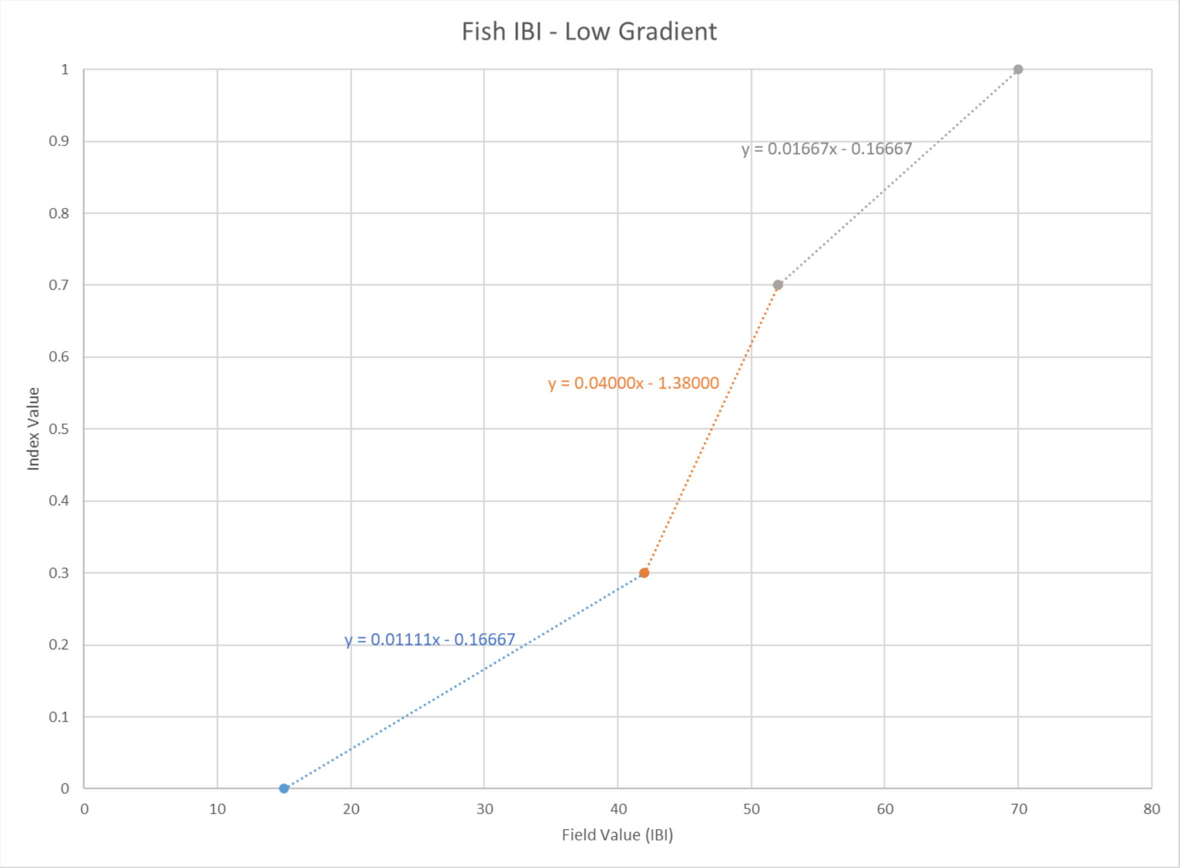

Figure 13-3: Fish IBI Reference Curves for Low Gradient Streams

<u>Limitations and Data Gaps</u>:

As emphasized in MPCA (2014), some rare and/or transitional habitats (such as estuaries, impoundments, wetland flowages, and “Great Rivers”) are not covered in the data, but future work may focus on development and application of fish community-based indicators for these systems. MPCA’s attempt in this effort was to develop a framework that would work for most rivers and streams throughout the state but also offer precision at a management-relevant scale. The importance of recognizing issues of scale cannot be overemphasized when developing an indicator that will be used to detect often subtle changes in biological condition. MPCA’s framework partitions streams into three general size classes (“headwaters,” “streams,” and “rivers”) based on watershed area – this approach is intuitive, given widespread understanding that the fish communities of large rivers differ greatly from those of small streams. The Designated Trout Stream framework established and maintained by MN DNR is typically based on historical records of stream conditions and several years of thermal monitoring. While the Minnesota Department of Natural Resource classifications may not precisely describe the thermal conditions of all streams and rivers, in general this framework effectively separates coldwater streams from cool- and warmwater systems. The State acknowledges that, in some cases, this classification may not adequately represent the natural thermal potential of a particular stream; these special cases may be identified and dealt with on an individual basis.

MPCA’s initial decision to identify distinct stream classes and proceed through metric selection within each class likely aided us in developing effective IBIs for certain types of streams. In particular, low-gradient, wetland-influenced streams have presented bioassessment challenges in Minnesota and other states.

The MPCA's fish/macroinvertebrate IBIs were developed for perennial streams. Small, intermittent/ephemeral streams are challenging environments for all aquatic biological communities. By definition, these streams do not flow continuously, and can be reduced to a series of isolated pools or are dry completely during portions of the year. These dramatic fluctuations in flow can limit the availability of habitat for these communities and present stressful chemical (dissolved oxygen, turbidity, etc,) parameters that can severely limit fish/macroinvertebrate survival, growth, and reproduction.

The MPCA's fish/macroinvertebrate IBIs can be used in stream/wetland complexes. In some cases, the existing stream bioassessment tools may not accurately assess the quality of unique biological communities found in streams possessing predominant wetland characteristics. In these rare cases a best professional judgement approach should be used to determine the validity of the assessment results.

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Appendix A: MNSQT List of Metrics