# Scientific Support for the Wyoming Stream Quantification Tool Version 2.0

## Wyoming Stream Technical Team

Army Corps of Engineers
Omaha District

Ecosystem Planning & Restoration

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http://www.nwo.usace.army.mil/Missions/Regulatory-Program/Wyoming/Mitigation/

https://ribits.ops.usace.army.mil/

https://stream-mechanics.com/stream-functions-pyramid-framework/

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# Version

| Version | Date finalized | Description |
|---|---|---|
| 1.0 | July 2018 | Initial version provided as a companion to WSQT v1.0 |
| 2.0 | June 2023 | The following edits were made with reference to scoring and reference curves. For a complete list of updates from v1 to v2, refer to the WSQT v2.0 User Manual.<br>• Added flow alteration module.<br>• Flow alteration and plan form parameters were removed from the reach-scale assessment.<br>• Baseflow and bankfull dynamics parameters were added to the reach-scale assessment.<br>• Side channel metric was added to assess floodplain connectivity parameter.<br>• Percent fines metric replaced the size class pebble count analyzer for bed material characterization parameter.<br>• Riparian extent replaced the riparian width to assess the riparian vegetation parameter.<br>• Aggradation ratio metric was removed from bed form diversity parameter.<br>• Reference curves were also updated, including land use coefficient, bank height ratio, entrenchment ratio, greenline stability rating, percent riffle, all four riparian metrics, and native fish species richness.<br>Relevant sections of this document have been updated accordingly. |

# Acronyms

BANCS – Bank Assessment for Non-point source Consequences of Sediment

BEHI/NBS – Bank Erosion Hazard Index / Near Bank Stress

BHR – Bank Height Ratio

CFR – Code of Federal Register

CN – Curve numbers

CNHP – Colorado Natural Heritage Program

CWA §404 – Section 404 of the Clean Water Act

EPA – US Environmental Protection Agency

ER – Entrenchment Ratio

FAM – Flow Alteration Module

FF – Functional Feet

GSR – Greenline Stability Rating

HSI – Habitat Suitability Indices

LWD – Large woody debris

LWDI – Large Woody Debris Index

MWAT – Maximum Weekly Average Temperature

MWR – Meander Width Ratio

NRCS – Natural Resource Conservation Service

NRSA – National Rivers and Streams Assessment

RH&H – Reach Hydrology and Hydraulics

RIVPACS – River Invertebrate Prediction and Classification System

SFPF – Stream Function Pyramid Framework

SGCN – Species of Greatest Conservation Need

SQT – Stream Quantification Tool

TMDL – Total Maximum Daily Load

USACE – United States Army Corps of Engineers

USDOI – United States Department of Interior

USFWS – United States Fish and Wildlife Service

WDEQ/WQD – Wyoming Department of Environmental Quality, Water Quality Division

WDRS – Width Depth Ratio State

WGFD – Wyoming Game and Fish Department

WSII – Wyoming Stream Integrity Index

WSIT – Wyoming Stream Impact Tool

WSMP – Wyoming Stream Mitigation Procedure

WSQT – Wyoming Stream Quantification Tool

WSTT – Wyoming Stream Technical Team

WYPDES – Wyoming Pollutant Discharge Elimination System

# Glossary of Terms

Affected stream length – Pertaining to the flow alteration module (FAM), the length of stream defined at the upstream end where impacts or flow protection would initiate, and at the downstream end by the location of the next water rights user, significant tributary junction, or terminus beyond which the flow modification has no material effect on SQT parameters.

Alluvial valley – Valley formed by the deposition of sediment from fluvial processes. See also definitions for confined alluvial valley and unconfined alluvial valley.

Armoring – Any rigid, human-made stabilization practice that permanently prevents lateral migration processes. More natural approaches to reduce excessive bank erosion, like toe protection and/or bioengineering, are not considered armoring. Examples of armoring include rip rap, gabion baskets, concrete, and other engineered materials that prevent streams from meandering.

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 (Leopold and Wolman 1957). Bankfull can also be referred to as the effective discharge, dominant discharge, or channel forming discharge.

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

Colluvial or V-shaped valley – Valley formed by the deposition of sediment from hillslope erosion processes. Colluvial valleys are bowl-shaped and typically confined by terraces or hillslopes. Colluvium is material that originates on the hillslopes and moves down slope through mass wasting processes to the valley bottom. These valleys are confined and support straighter, step-pool type channels (e.g., Rosgen A, B, Bc, F). These valley types typically have a valley width ratio less than 7 and a meander width ratio less than 3. V-shaped valleys are often found in steep gradient headwater valleys.

Concentrated flow points – Storm drains, outfalls, or erosional features, such as swales, gullies, or other channels that are created by anthropogenic impacts. Natural ephemeral tributaries and outlets of stormwater best management practices are not considered concentrated flow points in this method.

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 (33 CFR §332.2).

Condition score – A score from 0.00 to 1.00 that represents the condition or quality of a metric based on the departure from a reference condition. Metric-based condition scores (see also index value) are averaged to characterize condition for each parameter, functional category, and overall project reach.

Confined alluvial valley – Valley formed by the deposition of sediment from fluvial processes, typically confined by terraces or hillslopes that supports transitional stream types between step-pool and meandering or where meanders intercept hillslopes (e.g., Rosgen C, Bc). These valley types typically have a valley width ratio less than 7 and a meander width ratio between 3 and 4.

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 (33 CFR §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 (33 CFR §332.2).

Field value – A field or desktop-derived measurement or calculation input into the WSQT 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 (33 CFR §332.2).

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

Functional category – The organizational levels of the stream quantification tool: Reach Hydrology and Hydraulics, Geomorphology, Physicochemical, and Biology. Each category is defined by functional statement(s).

Functional feet (FF) – Functional feet are the primary unit for communicating functional lift and loss. The functional feet for a stream reach are calculated by multiplying an overall reach condition score by the project reach length. The change in functional feet (∆FF) is the difference between the Existing FF and the Proposed FF.

Functional lift – The difference in the condition score or functional feet before and after restoration or a permitted impact which results in improved function.

Functional loss – The difference in the condition score or functional feet before and after restoration or a permitted impact which results in a loss of function.

Function-based parameter – A measure which characterizes a condition at a point in time, or a process (expressed as a rate) that describes and supports the functional statement for a given functional category.

Geomorphic pools – Pools that remain intact over time and across a range of flow conditions and are associated with large planform features. Examples include pools associated with the outside of a meander bend (streams in alluvial valleys) and downstream of a large cascade or step (streams in colluvial valleys).

Index values – Dimensionless values between 0.00 and 1.00 that express the functional capacity and relative condition of a metric field value compared with reference condition. Index values convert the different units used in the assessment methods to one scale. These values are derived from reference curves for each metric. Index values are combined to create parameter, functional category, and overall reach condition scores (see condition score).

Large woody debris (LWD) – Dead and fallen wood over 1m in length and at least 10 cm in diameter at the largest end.

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 value 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).

Multi-thread channel – A multi-thread channel consists of at least 3 primary flow paths that are active at baseflow for most of the reach length.

Native species – Riparian plant species that are native per the USDA PLANTS Database http://plants.usda.gov. Native cover excludes species that are introduced (i.e., non-native or naturalized).

Native flow – Estimates of the stream flows that would result from natural hydrologic processes such as rainfall-runoff and snowmelt-runoff without anthropogenic influence at a given location.

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.

Project reach – A homogeneous stream reach 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. Multiple project reaches may exist in a project area where there are variations in stream physical characteristics and/or differences in project designs.

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 §332.2). Reference aquatic resources represent the full range of functional capacity characterized by SQT condition scores or index values.

Reference condition – The relative functional capacity of reference standard resources, characterizing the range of natural variability under undisturbed or least disturbed condition and representing the subset of reference aquatic resources that exhibit the highest level of function. In the SQT, this condition is considered functioning, culturally unaltered, or pristine for the metric being assessed (see Reference standard).

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 others, to best represent the degree of departure from a reference condition for a given field value. These curves are used to determine the index value for a given metric in a project reach.

Reference standard – The subset of reference aquatic resources that are least disturbed and exhibit the highest level of function (see Reference condition).

Representative sub-reach – A length of stream within the project reach that is selected for field data collection of parameters and metrics. Sub-reach length and relative location within the project reach will vary by parameter.

Restoration potential – The highest level of restoration that can be achieved based on an assessment of the contributing catchment, reach-scale constraints, and the results of the reach-scale function-based assessment (Harman et al. 2012).

Riffle – Riffles are shallow, steep-gradient channel segments typically located between pools. Riffles are the river's natural grade control feature (Knighton 1998) and are sometimes referred to as fast-water channel units (Hawkins et al. 1993; Bisson et al. 2017). For purposes of the SQT, in meandering streams riffles broadly represent the section between lateral-scour pools known as a crossover, regardless of bed material size. Therefore, the term riffle also refers to the crossover section (ripples) in a sand bed channel or the cascade section of steep mountain streams. Riffles are measured from head of riffle to head of pool; thus, runs are considered riffles and glides are considered pools.

Riparian extent – The observed riparian extent reflects the percentage of the historic or expected riparian extent that currently contains riparian vegetation and is free from utility-related, urban, or otherwise soil disturbing land uses. The expected riparian extent corresponds to (Merritt et al. 2017):

1) Substrate and topographic attributes -- the portion of the valley bottom influenced by fluvial processes under the current climatic regime,
2) Biotic attributes -- riparian vegetation characteristic of the region and plants known to be adapted to shallow water tables and fluvial disturbance, and
3) Hydrologic attributes -- the area of the valley bottom flooded at the stage of the 100-year recurrence interval flow.

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

Side channels – Small open water channels that are connected to the main channel at one or both ends at a depth of at least one-half the bankfull riffle maximum depth.

Significant pools – Significant pools must be deeper than the riffle, have a concave shaped bed surface and a width that is at least half the width of the channel. The pool may also have a flatter water surface slope than the riffle; however, this is not always the case, e.g., a pool downstream of a log in a steep-gradient channel. Significant pools are often associated with in-stream structures, wood, boulders, convergence, or backwater in the main channel.

Stream Functions Pyramid Framework (SFPF) – The Stream Functions Pyramid is comprised of five functional categories 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, metrics (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 in this document to represent stream compensatory mitigation methods including rehabilitation, reestablishment, and enhancement.

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 performance standards.

Unconfined alluvial valleys – Wide, low gradient (typically less than 2% slope) valleys that support meandering and anastomosed stream types (e.g., Rosgen stream types C, E, $D_A$). In alluvial valleys, rivers adjust pattern without intercepting hillslopes. These valleys typically have a valley width ratio greater than 7 (Carlson 2009) or a meander width ratio greater than 4 (Rosgen 2014).

Wyoming Stream Impact Tool (WSIT) workbook – The Microsoft-Excel workbook file used to evaluate loss at impact sites.

Wyoming Stream Quantification Tool (WSQT) – The WSQT consists of two workbooks, the WSQT workbook and the WSIT workbook. The WSQT are spreadsheet-based calculators that score the difference in stream condition and functional feet before and after restoration or impact activities to determine functional lift or loss, and can also be used to determine restoration potential, develop monitoring criteria, and assist in other aspects of project planning (see WSQT workbook and WSIT workbook).

WSQT workbook – The Microsoft-Excel workbook file used to evaluate change in condition at project reaches.

Wyoming Stream Technical Team (WSTT) – Group tasked with developing function-based parameters, measurement methods, and reference standards for the WSQT.

# Chapter 1. Background and Introduction

The purpose of this document is to describe the scientific underpinnings of the Wyoming Stream Quantification Tool (WSQT) and the rationale behind the reference curves used to develop dimensionless index scores. The WSQT 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) presents the SFPF and provides supporting references and rationale for the organizational framework and its components. The WSQT is one of several Stream Quantification Tools (SQTs) that have been developed for use in specific states, including North Carolina (Harman and Jones 2017), Tennessee (TDEC 2018), Georgia (USACE 2018), Colorado (USACE 2020a), Minnesota (MNSQT SC 2020) and Alaska (Alaska Stream Quantification Tool Steering Committee 2021).

The original version of this document (WSTT 2018) was the first of its kind to be developed in conjunction with a SQT; early versions of other state SQTs included only a List of Metrics without detailed supporting documentation. Since WSTT 2018 was published, science support documents have been developed for other state SQTs, and some sections of this document have been updated to include information from those documents where the same metrics and/or reference curves are applied.

This document expands on the concepts presented in the SFPF and the WSQT v2.0 User Manual (USACE 2023) to provide the scientific and technical rationale behind selection of the reference curves and metrics included in the WSQT. Information on how to use the WSQT or collect data for use in the WSQT is not included in this document but can be found in the WSQT v2.0 User Manual.

Section 1.1 provides a summary of the SFPF, including definitions of function-based parameters, metrics and reference curves.

Section 1.2 provides background on the WSQT and key considerations in applying the SQT.

Section 1.3 provides a summary of the watershed context for determining restoration potential.

Section 1.4 describes reference curve development and how key concepts of reference standard and functional capacity are used in the tool.

Section 1.5 gives an overview of how the WSQT calculates the overall reach condition score, along with weighting considerations.

Section 1.6 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 1.7 provides the general criteria used to select function-based parameters and metrics from the SFPF and new metrics developed specifically for the WSQT.

Section 1.8 provides a general summary of the datasets used to develop reference curves and the tool's data gaps and limitations.

Section 1.9 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 chapter consists of:

- A description of the parameter and why it was included, reasons for selecting metrics, and in some cases, why other metrics were not selected;
- A description of metrics used to characterize the parameter; and
- A description of how reference curves were developed and any associated stratifications, 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 USACE 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 5 categories: system dynamics, hydrologic balance, sediment processes and character, biological support, and chemical processes and pathways (see Table 1 in Fischenich 2006). The SFPF builds on the work completed by Fischenich (2006) by organizing stream functions into a conceptual hierarchical 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?

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 performance standards (reference curves) that represent departure from, or attainment of, reference condition. The selection of function-based parameters used in the WSQT and their relationship to reference condition are discussed in more detail in the following sections.

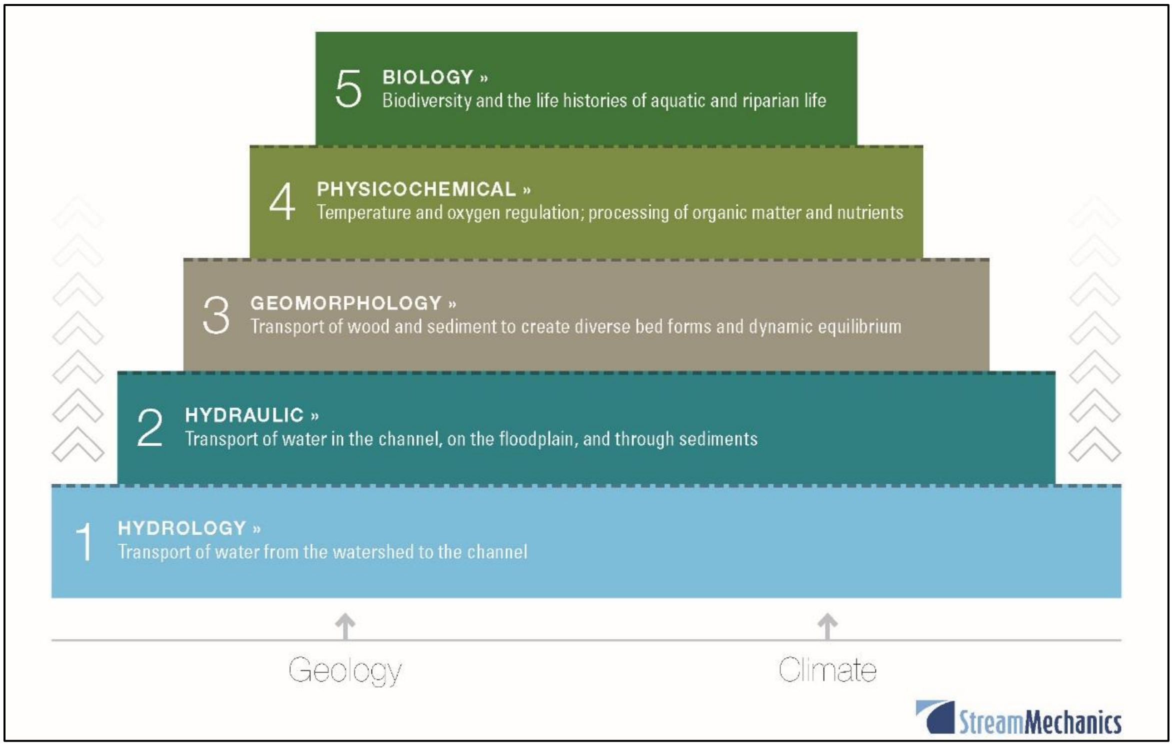



*Figure 1-1: Stream Functions Pyramid (Image from Harman et al. 2012).*

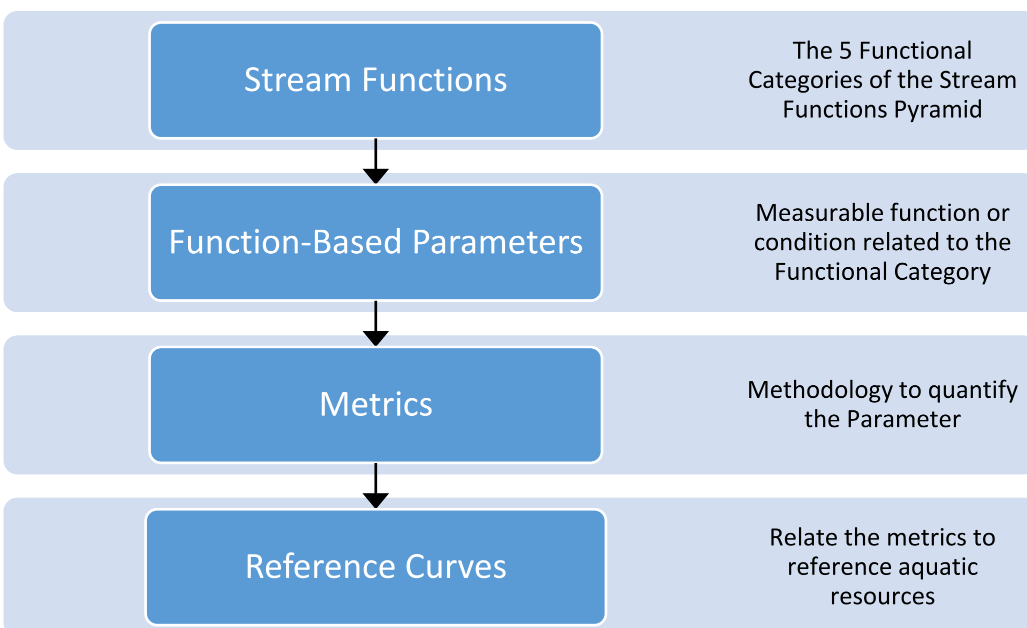



*Figure 1-2: Stream Functions Pyramid Framework. Note: terms have been modified from Harman et al. (2012) to reflect WSQT application.*

## 1.2. Background on the WSQT

The SFPF has informed the development of the WSQT, which was originally modified from the North Carolina SQT (Harman and Jones 2017). The WSQT is a tool that consolidates the components of the SFPF into an excel workbook to characterize stream ecosystem functions at a specific project reach. The WSQT 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 WSQT development and regionalization process, which are relevant to the stream systems found within the state of Wyoming.

Most other SQTs calculate an overall reach score from all five functional categories presented in the SFPF, while the Georgia SQT calculates an overall reach score from three of the five (hydraulics, geomorphology and biology). The CSQT and WSQT merge the original hydrology and hydraulics categories into a new combined category (referred to as the reach hydrology and hydraulics category; RH&H), leading to an overall reach score calculated using four categories. This change to Colorado and Wyoming SQTs was made due to the small number of parameters and metrics selected in both categories and the consequent disproportionate weighting those parameters and metrics were allocated. Differences among the SQTs are primarily due to decisions made at the state-level in consideration of state-specific priorities and resources.

All the metrics selected for the WSQT are structural or compositional attributes that indicate condition at a given point-in-time. Metrics and their associated condition scores 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 macroinvertebrates or fish, which are assessed in the biology functional category.

Assessment data are input into the WSQT, where data for each metric is translated into an index value 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 to relate site-specific data to functional capacity using index values; index values range from 0.00 to 1.00 and functional capacity descriptions are described in Section 1.4 below.

**Key Considerations**

The WSQT and scientific support document have been developed to respond to specific regulatory and policy requirements and program needs and tailored to meet the function-based approaches set forth in the 2008 Compensatory Mitigation Rule, as well as the needs of the WGFD and WDEQ for their stream monitoring and restoration programs. As such, there are several considerations that are critical in understanding the applicability of the tool:

- The parameters and metrics in the tool were, in part, selected due to their sensitivity in responding to reach-scale changes associated with the types of activities commonly encountered in the Clean Water Act Section 404 (CWA §404) program and commonly used in stream restoration. These parameters do not comprehensively characterize all structural measures or processes that occur within a stream.
- The WSQT is designed to assess the same metrics at a site over time to provide information on the degree to which the condition of the system changes following an

impact or restoration activity. Unless the same parameters and metrics are used across all sites, it would not be appropriate to compare scores across sites.

- The WSQT itself does not score or quantify watershed condition. Watershed condition reflects the external elements that influence functions within a project reach and may affect project site selection or the restoration potential of a site (see Section 2.2 of the WSQT v2.0 User Manual).
- The WSQT is not a design tool. There may be more appropriate function-based parameters and analyses which are critical to a successful project design but sit outside of the scope of the WSQT. The WSQT instead measures the physical, chemical, and biological responses or outcomes related to a reach-scale project.

## 1.3. Watershed Context

Understanding the watershed processes that contribute to the condition at a project site is a critical component to any project. Anthropogenic modification to stream processes can occur via direct and indirect pathways. Direct pathways include effects on reach-scale processes like channel modification, removal of riparian or aquatic vegetation, flow alteration or introduction of non-native species. Indirect pathways often include alterations to watershed-scale processes, like land use changes, that occur away from the stream or distributed throughout a watershed (Roni and Beechie 2013).

The focus of this tool is on the change to reach-scale ecological variables following a project, particularly indicators tied to direct pathways of anthropogenic modification using a reach-based approach. Because catchment condition is not likely to change following reach-scale activities, it is not included as part of the scoring within the tool itself. However, the catchment context is critical to understanding the reference condition, as well as the restoration potential at a site. Thus, the WSQT incorporates a stepwise process to consider catchment and reach-scale variables and their influence on the restoration potential of project reaches. The restoration potential process (described in Section 2.2 of the WSQT v2.0 User Manual) informs whether a project could achieve full restoration potential or may be otherwise limited by factors outside the control of a practitioner. Processes can occur at a reach-scale or a broader watershed scale, and the setting influences the current and potential condition of a reach. Hydrologic, geomorphic, and biologic process drivers (Castro and Thorne 2019), both anthropogenic and natural, influence the restoration target and reference stream type selection.

The WSQT includes a catchment assessment in the stepwise process to determine restoration potential at a project site, which takes into consideration the watershed context and catchment-scale limiting factors affecting a project site. The catchment assessment was modified by the WSTT from the North Carolina SQT to consider anthropogenic modifications common in Wyoming, including flow alteration. The catchment assessment is a qualitative approach intended to identify watershed-scale factors that may limit the restoration potential at a project site. Restoration potential is defined as the highest level of restoration that can be achieved based on the condition of the watershed, project constraints at the reach scale, and the existing condition of the project reach (Harman et al. 2012). Full restoration potential indicates that the project can return a site to reference standard, including biological functions. Partial restoration potential means that improvements can be made, but not all functions can be returned to a reference condition (Beechie et al. 2013; see also best attainable condition per Stoddard et al. 2006).

## 1.4. Development of Reference Curves

The WSQT 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 as functional loss and lift, and relate to the definition of debits and credits 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 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 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 (see 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 relate the measured condition to expected, or reference, condition. Scaling functional capacity relative to reference systems is a common approach for functional and condition assessments (e.g., Johnson et al. 2013; Miller et al. 2015; EPA 2020). 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 and credit release schedules.

To account for natural variability among stream systems, reference curves for specific metrics may be stratified by differences in stream type, ecoregion, reference community type, slope, valley type or thermal regime. Stratification varies by metric (see Appendix A).

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 data values already identified in the State of Wyoming’s technical publications or the literature (e.g., based on water quality standards, channel classification, or existing indices).
2. Where literature values were not available, threshold values were developed using data from national and regional resource surveys and other available datasets. In evaluating reference datasets, the team considered the degree of departure from reference condition using percentiles of regional reference condition to identify the threshold

values. For example, the interquartile range of reference sites within a dataset may be used to identify the 0.70 and 1.00 field values for developing a reference curve. This is similar to other approaches that identify benchmarks or index values (Hawkins et al. 2010, BLM 2017). When using existing datasets, this document relied on the definitions of reference condition provided by the authors.

3. Where existing data or literature was limited, expertise of members of the WSTT was relied on to identify threshold values. In some instances, the decision was made to not identify a threshold value and instead interpolate index values from a best fit line from data or literature values that were available.

*Table 1-1: Functional Capacity Definitions for the WSQT.*

| Functional Capacity | Definition | Index Value Range |
|---|---|---|
| Functioning | A functioning index 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. In other words, it is functioning at reference condition. [1] A score of 1.00 represents minimally impacted to pristine condition. A range of index values (0.70-1.0) represents the range of natural variability in field values that may occur across reference sites, including least disturbed and minimally disturbed sites within reference datasets. | 0.70 to 1.00 |
| Functioning-at-risk | A functioning-at-risk index 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 does not reflect reference condition nor is significantly degraded or impaired. | 0.30 to <0.70 |
| Not functioning | A not functioning index 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, and an index value of 0.00 represents a condition that provides no functional capacity for that metric. | 0.00 to <0.30 |

Following the identification of these threshold values, reference curves were fit using linear relationships between 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 metric section below. Reference curves and threshold values were

[1] The reference standard concept aligns with the definition laid out by Stoddard et al. (2006) for a reference condition for biological integrity.

determined for each metric individually. Therefore, a stream reach may achieve a functioning index value for one parameter, e.g., large woody debris, and not others. Metric index values are then combined to provide a reach score (Section 1.5).

## 1.5. Calculating Reach-scale Condition

The architecture and scoring of the WSQT 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. While the WSQT v2.0 User Manual recommends a subset of parameters and metrics be evaluated for all projects (e.g., reach runoff, floodplain connectivity, bankfull flow dynamics, lateral migration, bedform diversity and riparian vegetation), the tool includes a broader set of parameters that may better align with a project's function-based goals and objectives. For example, a practitioner may choose not to monitor (or receive credit for) physiochemical and biological parameters, and the WSQT would then calculate scores based only on the subset of parameters and metrics that were input into the tool.

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 of this approach is the flexible architecture – metrics and parameters can be added to or subtracted from the tool based on new scientific understandings and parameter selection can vary based on 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.

Index values are generated for each metric, and then combined to provide a 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 the score (refer to the WSQT v2.0 User Manual for discussion of parameter and metric selection). Metrics not assessed are simply not included in the score; they are not scored as a zero.
- Parameter scores are averaged to create a functional category score.
- Functional category scores are weighted, multiplied by stream length, and then summed to calculate a functional feet value for the reach (see Section 1.6).

Functional category weighting is fixed, regardless of the number of metrics, parameters or functional categories assessed. As noted in Section 1.2, the WSQT combines the hydrology and hydraulic categories from the stream functions pyramid into one category called reach hydrology and hydraulics (RH&H). The RH&H category is weighted to provide 30% of the overall score; geomorphology provides 30%; and physicochemical and biology each provide 20% of the overall score. The RH&H and geomorphology functional categories were weighted at 60% of the total score, reflecting the number and breadth of parameters in these categories. The weighting for the physicochemical and biological categories (20% weighting each) is slightly less than the other two categories because they can be heavily influenced by changes in watershed-scale processes outside of the project reach and often take longer to show improvement post restoration (Fischenich 2006). Functional improvement in these categories often occurs due to improvements in hydrology, hydraulics and geomorphology functions if catchment-scale stressors do not themselves limit physicochemical or biological improvements.

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 can be realized if only RH&H and Geomorphology categories are assessed and monitored. Meanwhile, monitoring one or more metrics in all four 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. The maximum overall condition score achievable by monitoring only RH&H and geomorphology parameters is 0.60, which is consistent with other SQTs.

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 the WSQT v2.0 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 10% to the overall potential score, whereas if large wood is also evaluated, each parameter would contribute 7.5% of the overall potential score.

*Table 1-2: Implicit Parameter and Metric Weighting that Results from Averaging.*

| Functional Category | Category Weight | Function-based Parameters (no.) | Parameter Weight* | Metrics (no.) | Metric Weight* |
|---|---|---|---|---|---|
| Reach Hydrology and Hydraulics | 0.3 | 4 | 10% | 8 | 3.3-10% |
| Geomorphology | 0.3 | 5 | 6-10% | 14 | 2-10% |
| Physicochemical | 0.2 | 2 | 10-20% | 4 | 10-20% |
| Biology | 0.2 | 2 | 10-20% | 5 | 3.3-20% |
| Add on Modules: (score is added to total from Project Summary worksheet) | | | | | |
| Flow Alteration Module | 0.2 | 1 | 20% | 6 | 3.3-4% |

**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 are applied.*

The WSQT also includes a flow alteration module whose structure and scoring differ from the scoring within the reach-scale condition assessment. The flow alteration module generates a functional feet value that is added to the total project functional feet value presented in the Project Summary worksheet. The flow alteration module assesses six metrics, which are averaged to calculate a flow alteration module score. The flow alteration module only assesses hydrology, and thus the module score is weighted by 20%. This weighted score is then multiplied by affected reach length to calculate the functional feet value (refer to Chapter 2).

**Interpreting Condition Scores**

When all four functional categories are assessed, the overall condition score can be interpreted as a percent of full functional capacity. For example, if the overall condition score is 0.60, the reach is 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 compare the overall score with the input selections.

To improve communication about the stream context, 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. So, 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).

## 1.6. Calculating Functional Feet

The WSQT 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, 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 (∆FF), is the amount of functional lift or loss within a project reach.

The ∆FF is intended to serve as the unit of measure for calculating debits and credits. Harman et al. (2021) define a unit of measure as “feet, area, or other physical dimensions used alone, or applied to assessment output scores to provide a common unit for comparison with other projects (debit and credit calculations).” Many programs continue to rely on stream length or area measurements alone as the unit of measure, while others apply ratio-based approaches, combine physical dimensions with activities (e.g., changes to channel geometry) or combine physical dimensions with output scores from stream assessments to calculate credits or assign credit ratios (ELI et al. 2016, Harman et al. 2021).

Because it incorporates both length and quantitative measures of stream condition, ∆FF better integrates changes in condition into crediting and debiting approaches. Combining ecological assessment with length or areal measure (e.g., stream or valley length/area) provides more scientific credibility in the calculation of debits and credits than a length or areal measure alone (Harman et al. 2021). The functional feet unit provides an integrated unit of measure that can be compared across sites better than condition scores or stream length/area measures alone, and thus serves as the bridge between the condition assessment and application within a debit/credit policy framework for program implementation.

Stream length is included in the functional feet unit to provide scale to the condition score. For example, a small project, such as a culvert removal, may result in a large change between the proposed and existing condition scores, 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 is consistent with other established USACE District compensatory stream mitigation programs, where a variety of factors are multiplied by stream length to create a debit or credit; and the product of quality and length represents a common currency for a debit and credit calculations (ELI et al. 2016).

The WSTT 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 measure instead of stream length. An approach using stream width by stream 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 major challenges with an approach that relies on channel width is that width often changes. In the western U.S., flow alteration has led to substantial changes in hydrology followed by adjustments in channel form, including narrower channels. Where flows cannot be restored, restoration approaches may include accelerating this channel evolution to improve stream condition and underlying processes and including width in the credit calculation would lead to less potential for credit. In addition, practitioners commonly design a wider width than the final target. The channel narrows during the monitoring years as vegetation becomes established on the streambanks. The vegetation increases boundary roughness, which deposits sediment on the bank and narrows the channel width. So, this natural and positive process would result in the practitioner losing area between the design and monitoring phases. Attempts to predict the final width would be difficult and create more uncertainty than relying on length alone. Because of these implementation challenges, the WSTT decided to not pursue this approach.

*Valley area:* Another approach that was considered was using valley area instead of stream length. This approach has merit, as it characterizes the stream and floodplain corridor in a more holistic way and better accounts for floodplain functions and stream systems that include stream-wetland complexes and/or multi-thread channels. 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. The Corps currently accounts for permitted impacts in linear feet or aquatic resource area (e.g., Nationwide Permit impact thresholds, data entry into ORM database) and only regulates activities within aquatic resource boundaries (e.g., within a delineated wetland or the ordinary high-water mark of streams), and it is unclear how a valley-based approach could align with current practices for accounting for impacts. Additional discussions and research on implementation are needed before adopting a valley-based approach across all projects. This may be considered for future versions of the WSQT.

The unit of measure in the WSQT is functional feet because it conforms with many existing stream mitigation approaches while improving the link between activities and changes in condition. Stream length can be effectively applied in single-thread stream systems, although it is more limited in multi-thread stream types where other approaches may be better suited (Harman et al. 2021). Future versions of the WSQT and WSMP 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.

## 1.7. Function-Based Parameters in the WSQT

The WSQT is designed to consider 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 WSQT incorporates many of the functions and parameters outlined in Fischenich (2006) and Harman et al. (2012). Recognizing that not all projects will have the same objectives or components, the WSQT allows for flexibility in selecting 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 performance standards and monitoring can be targeted for that specific project. Parameters included in the WSQT could assist in setting performance standards for projects with goals to restore instream flows, 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 WSQT is listed in Chapter 17. Rationale for selecting a parameter and its metrics, and why other metrics were not used, is provided in Table 1-3 and 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 watershed scale may affect both existing and potential condition scores and are considered in the catchment assessment and determination of restoration potential (see Section 1.2 and the WSQT v2.0 User Manual for details).
- Ability to develop reference curves for each metric. Information needs to be available to characterize the reference aquatic resources and relate conditions to a reference standard.
- Flexibility in the level of effort for data collection and analysis. Under CWA §404, the level of analysis and documentation should be commensurate with the scale and scope of the project (2008 Mitigation Rule, 33 CFR §332.3). The USACE routinely evaluates projects where stream impacts range from minor, localized impacts to projects with direct and secondary impacts spanning broad geographic scales.

- Applicable and meaningful in Wyoming. Wyoming is a high elevation, headwaters state characterized by low precipitation (6-20” in the basins and plains and 20-70” in the mountains). Wyoming contains variable soils and parent materials and has minimal urban development; abundant federal public lands managed for multiple uses including rangeland, extractive industries and recreation; and highly allocated and diverted surface water rights.

Sinuosity was included as a metric for a plan form parameter in the reach condition assessment of the WSQT v1.0. While sinuosity is important in appropriate design of single-thread channels, sinuosity has been removed from the scoring of reach condition in the WSQT v2.0.

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 that has noted 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 (Doyle et al. 2015).

In addition to deleting sinuosity, multiple changes were made to the metrics and parameters in WSQT v2.0, including the addition of a flow alteration module to replace the flow alteration parameter, addition of baseflow dynamics and bankfull dynamics parameters and metrics, addition of a side channel metric within floodplain connectivity, addition of a percent fines metric to replace the prior bed material characterization metric, and deletion of the aggradation ratio metric. In addition to these modifications, reference curves for some metrics were also updated, including land use coefficient, bank height ratio, entrenchment ratio, greenline stability rating, percent riffle, all four riparian metrics, and native fish species richness. Relevant sections of this document have been updated accordingly.

*Table 1-3: A Summary of the Parameters Included in Harman et al. (2012) and Rationale for Inclusion or Exclusion from the WSQT.*

| Functional Category | Parameter from the Stream Functions Pyramid Framework | Included in WSQT (Yes/No) | Rationale |
|---|---|---|---|
| Hydrology | Channel Forming Discharge | Yes | Aspects of the flow regime are characterized in the Flow Alteration Module (Chapter 2). |
| | Precipitation/Runoff Relationship | | |
| | Flood Frequency | | |
| | Flow Duration | | |
| | Reach Runoff** | Yes | See Chapter 3. |
| Hydraulics | Flow Dynamics | Yes | Baseflow dynamics tailored to coldwater species habitat requirements (Chapter 4) and bankfull flow dynamics (Chapter 5) have been added to WSQT v2.0. |
| | Groundwater/Surface Water Exchange | No | Difficult to assess and develop reference curves. |
| | Floodplain Connectivity | Yes | See Chapter 6. |
| Geomorphology | Channel Evolution | No | Considered when determining restoration potential and selecting stream types. |
| | Sediment Transport Competency and Capacity | No | Not recommended by SFPF for showing functional lift/loss. *Highly recommended as part of the design process. |
| | Large Woody Debris | Yes | See Chapter 7. |
| | Bank Migration/Lateral Stability | Yes | See Chapter 8. |
| | Bed Material Characterization | Yes | See Chapter 9. |
| | Bed Form Diversity | Yes | See Chapter 10. |
| | Riparian Vegetation | Yes | See Chapter 11. |
| Physicochemical | Organic Carbon | No | Difficult to develop reference curves. |
| | Bacteria** | No | Difficult to develop reference curves, WY water quality criteria are more related to human health than aquatic ecosystem function. |
| | Water Quality (Dissolved Oxygen, pH, and Conductivity) | No | Dissolved oxygen is related to temperature and was not prioritized for inclusion in this version of the WSQT. Conductivity and pH were also not prioritized for inclusion. |
| | Water Quality (Temperature) | Yes | See Chapter 12. |
| | Nutrients | Yes | See Chapter 13. |
| Biology | Macrophyte Communities | No | Uncommon in stream mitigation monitoring. |
| | Microbial Communities | No | Uncommon in stream mitigation monitoring. |
| | Landscape Connectivity | No | Requires assessments beyond the project reach; scale of connectivity is typically species specific. |
| | Macroinvertebrate Communities | Yes | See Chapter 14. |
| | Fish Communities | Yes | See Chapter 15. |

** 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 SQT's.*

## 1.8. Data Sources, Data Gaps, and Limitations

As described in Section 1.4, the development of reference curves implemented in the WSQT sometimes relied on data from national and regional resource surveys and other available datasets. Some larger datasets were used to inform reference curves for multiple metrics, and those datasets are introduced here.

**Compiled Geomorphic Reference Dataset:**

Geomorphic reference datasets collected by the WY Game and Fish Department (WGFD) and the US Forest Service (USFS) were compiled for the WSQT. The dataset from WGFD was collected at approximately 20 sites throughout the mountainous regions of Wyoming between 2003 and 2006. The USFS dataset was collected from the Shoshone National Forest in the Middle Rockies region of Wyoming between 2003 and 2014 and consists of approximately 40 sites. The longitudinal profiles, cross sections, and bed material data from both datasets were reviewed as part of the quality assurance project plan. Sites that passed the review were included in the study. In August 2016 the WSTT revisited several reference sites from the WGFD dataset to apply the proposed WSQT methodology, verify the reference data from the dataset, and confirm bankfull determinations.

This dataset, referred to as the compiled geomorphic reference dataset in the remainder of this document, represents reference standard sites and was used to develop reference curves for metrics that describe floodplain connectivity and bed form diversity.

**National Rivers and Stream Assessment (NRSA) Dataset:**

The 2009 National Rivers and Streams Assessment dataset (NRSA; EPA 2016), was reviewed to determine which metrics in the dataset could be used to inform the development of reference curves within the WSQT. The NRSA dataset includes a variety of metrics associated with LWD and riparian vegetation. Data were compiled from sites in Wyoming and surrounding states and grouped into EPA Level III ecoregions. Specific attributes from the dataset are referred to in this document and descriptions are provided to relate NRSA attributes to stratification or metrics within the WSQT.

The NRSA dataset was used to develop reference curves for metrics that describe the large woody debris parameter. NRSA datasets include sites across a range of condition, from reference standard to degraded. The WSQT Beta Version relied on this dataset to develop reference curves for riparian vegetation metrics, however changes in data collection methods in v1.0 reduced the relevancy of these datasets.

**Colorado Natural Heritage Program (CNHP) Dataset:**

The WSTT acquired a riparian vegetation dataset from the Colorado Natural Heritage Program (CNHP; Kittel et al. 1999). The purpose of this study was to characterize riparian community types across Colorado. While this dataset does not contain any data points from Wyoming, Colorado and Wyoming have overlapping ecoregions with similar riparian community assemblages. Data from the following ecoregions in Colorado were used in developing reference curves: Southern Rockies, Wyoming Basin, Colorado Plateau, Arizona/New Mexico Plateau, High Plains and Southwest Tablelands.

The CNHP dataset included condition ratings for all sites, scored as A, B, C and D. For developing reference curves, (A) sites were considered reference standard based on ecological conditions and (D) sites were considered degraded. Since the dataset was collected over multiple years and the methods were refined as the program progressed, the sites identified as B and C were removed from the analysis following discussions with CHNP. The dataset also identified whether sites were primarily herbaceous or woody, similar to the reference vegetation cover stratification used in the WSQT. There was no distinction between forested and scrub-shrub communities in the CNHP dataset. In the original analysis of this dataset for WSQT v1.0, the WSTT relied on these identifiers to separate out woody and herbaceous sites for analysis. However, the data analysis was revised for the CSQT v1.0, and instead of relying on the herbaceous or woody identifiers, sites were stratified as either woody or herbaceous depending on whether they had greater than or less than 20% woody cover, respectively (Carsey et al. 2003).

The dataset consisted of species level cover data. Reference curves for woody vegetation cover and herbaceous vegetation cover were developed by summing absolute cover values categorized by stratum. Species in the dataset identified as graminoid or forb were grouped into the herbaceous stratum, shrub species cover values were combined with tree species cover values into a woody stratum. This dataset, referred to as the CNHP dataset in the rest of this document, was used to develop reference curves for riparian vegetation cover metrics.

**Stratification by Ecoregion:**

Several metrics described in this document are stratified by ecoregion, but sample sizes within each EPA Level III ecoregion were variable. Wyoming includes three geophysical ecoregions: Central Rocky Mountains, Wyoming Intermountain Basins, and Western Great Plains, which are similar to EPA Level I ecoregions. To improve sample sizes, the WSTT decided to group ecoregion data into broader ecoregions that align with the three geophysical regions described above: Mountains, Basins, and Plains. EPA Level III ecoregions were grouped into these broader ecoregion classifications, as shown in Table 1-4.

*Table 1-4: EPA Level III Ecoregion Groupings used for Data Analysis.*

| Mountains | Basins | Plains |
|---|---|---|
| Southern Rockies | Wyoming Basin | High Plains |
| Middle Rockies | Colorado Plateau | Northwest Great Plains |
| Wasatch/Uinta Mountains | Arizona/New Mexico Plateau | Southwestern Tablelands |

**Data Gaps and Limitations:**

The WSTT recognizes there are limitations to the approaches outlined herein to develop reference curves. There is a large diversity of stream types in Wyoming, due to differences in landform, climate and geology, which in turn influence the hydrogeomorphic context of streams. The WSTT has tried 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 limitations in this type of approach.

Rigorously accounting for regional variability among sites requires large datasets and statistically derived conclusions. These types of reference datasets were not always available for metrics included in this tool. Over time, it may be possible to revise certain reference curves as more data become available and the WSQT is used in ecoregions throughout the state. It is important to remember, however, that this tool is intended to compare pre- and post-project conditions at a site. As such, it is not a stand-alone condition assessment; it is a “delta” (change measurement) tool. The difference between existing and future site conditions is the most important element. For example, a site may not attain reference standard condition, but it may show improvements that translate into an accrual of functional capacity.

Some metrics and their reference curves are applicable for the entire state. Others are stratified by ecoregion, valley type, stream type, reference community type, etc., with reference curves for each (See Chapter 17). In some instances, data were not available for all regions or stream types, and the WSTT recommended not applying metrics in certain areas or types. Specific data gaps and limits to applicability are addressed within each metric description and are identified in Chapter 17. Future versions of the tool will benefit from additional data collection and analysis.

The WSQT can be applied in all stream settings in Wyoming. However, not all metrics are applicable or have been tested in ephemeral or intermittent streams, braided and anastomosed streams, and beaver-influenced systems. Some parameters are applicable within intermittent and/or ephemeral systems (Table 1-5), although the reference standards may not be representative because they have been developed with data from perennial systems. Most parameters include metrics that are applicable in perennial and intermittent braided or anastomosing systems (Table 1-5), although reference curves have not been developed specifically for these streams. Additionally, modifications to sampling methods may be needed to accommodate these stream types.

Several metrics rely on bankfull depth 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. Additional guidance on bankfull identification was added to the WSQT v1.0 User Manual in response to comments received during beta testing. For example, when possible, localized regional curves should be used to verify the bankfull determination; and once a bankfull feature/stage has been determined, that feature/stage should be used for all future assessments at a project site to improve repeatability. To further improve consistency in identifying bankfull, procedures to verify bankfull and a bankfull verification form were added to the WSQT v2.0 User Manual. These procedures include scenarios where flow alteration rather than incision has reduced floodplain connectivity.

*Table 1-5: Applicability of Metrics Across Flow Permanence and in Multi-thread Systems. An 'x' denotes that one or more metrics within a parameter is applicable within these stream types.*

| Applicable Parameters | Perennial | Intermittent | Ephemeral | Multi-thread Channels |
|---|---|---|---|---|
| Flow Alteration | x | x | x | x |
| Reach Runoff | x | x | x | x |
| Baseflow Dynamics | x | x | | x |
| Bankfull Flow Dynamics | x | x | x | |
| Floodplain Connectivity | x | x | x | x (BHR only) |
| Large Wood | x | x | x | x |
| Lateral Migration | x | x | x | x |
| Bed Material Characterization | x | x | x | x |
| Bed Form Diversity | x | x | | |
| Riparian Vegetation | x | x | x | x |
| Temperature | x | Where baseflows extend through sampling period | | x |
| Nutrients | x | | | x |
| Macroinvertebrates | x | | | x (perennial only) |
| Fish | x | x | | x |

Some key limitations are highlighted here:

- The WSQT was developed and tested primarily in single thread, perennial stream systems. Thus, some data collection methods and reference curves may have limited applicability in ephemeral or intermittent streams, stream-wetland complexes, and braided or anastomosing systems. Work is ongoing to clarify and broaden the application of the tool in these systems.
- A limited number of Rosgen stream types are used to stratify some metrics and parameters in the tool, and thus the tool is limited in capturing the geomorphic diversity of natural channel types, including multi-thread/anastomosing and natural canyon systems. The tool architecture allows for future changes to be made to accommodate other stratification approaches (e.g., hydrogeomorphic classification approaches). Additional data collection and analyses would be required, but future changes may be made to the tool to accommodate a broader range of stream types.
- Most metrics in the tool rely on wadeable data collection methods, and as such, the sampling efficiency and applicability of reference curves in larger rivers is unknown.
- By design, the WSQT is a reach scale, point-in-time tool. However, through routine monitoring, the WSQT can show trends or changes in condition that can be tied to channel evolution models.
- As a reach-based evaluation, the tool does not evaluate or consider secondary (indirect) effects in reaches upstream or downstream of the sampled reach. Additional analyses may be needed to evaluate these effects associated with a project. For example,

restoration of aquatic organism passage can have an important indirect influence outside of a reach.

- The WSQT relies on structural measures and indicators instead of measuring stream processes directly. However, the WSTT has tried to select reasonable surrogates to characterize underlying processes and surrogates are only applied within a functional category. For example, bedform diversity is a surrogate for sediment transport. Both are in the geomorphology category. Bedform diversity is not used as a surrogate for biology, i.e, if the bedforms metrics have high index values (a good riffle/pool sequence) it is not assumed that the macroinvertebrate community (biology functional category) is also in good condition.
- The tool allows for parameter/metric selection to vary between sites. Therefore, the same information may not always be collected across all sites. The condition score at one site may not be reflective of the same suite of parameters as a condition score at another site. Thus, the WSQT should be used to characterize condition changes at a specific site and not as part of an ambient monitoring program unless the same parameters and metrics are used consistently across all sites.
- The roll-up scoring for the WSQT has a simple approach to weighting, instead of relying on a more rigorous, statistically derived approach to calibration and scoring.
- Because multiple datasets and sources were used to develop reference curves, sample sizes and the level of uncertainty varies across metrics and across stratified reference curves within metrics. Additional testing and data collection will be beneficial to inform future versions of the tool.

## 1.9. Revisions to WSQT and Reference Curves

Reference curves included in the WSQT, and this document will be reviewed and updated as needed. If additional datasets and/or literature values are provided 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* (EPA 2003) and considered for inclusion in the tool.

Additionally, the WSQT architecture is flexible and can accommodate additional parameters and metrics in future versions of the tool.  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 or literature references and should follow the framework for identifying threshold values and index scores that is outlined in this document. Additionally, the user should include information on data collection approaches, including experience required. See David et al. (2021) for additional background on selecting metrics and reference data for stream assessment in the regulatory program.

Technical feedback may be submitted at any time to the USACE Wyoming Regulatory Office at [address] or contact the office at [number]; an email address can be provided on request.

# Chapter 2. Flow Alteration Module

Dams, water allocation, and effluent discharges can play a significant role in altering the hydrology at a project reach. Altering the magnitude, duration, frequency, timing, and/or rate-of-change of the flow regime can impact geomorphic and ecological functions of the stream (Poff et al. 1997). The resulting effect on a stream ecosystem varies depending on what aspects of the natural flow regime are modified and the significance of the flow alteration. In a literature review characterizing ecological responses to altered flow regimes, Poff and Zimmerman (2010) found that both macroinvertebrate and fish populations declined with increases and decreases in flow magnitude, yet much of the published literature focused on large flow alterations, i.e., greater than 50% change from natural conditions. The authors noted that the study was “not able to extract any robust statistical relationships between the size of the flow alteration and the ecological responses,” which hints at the difficulty in assigning reference curves for flow alteration metrics.

The WSQT v1.0 included a flow alteration parameter with one metric (baseflow alteration), which could be applied in projects proposing modification to the baseflow regime, including additional withdrawal or augmentation, or exchanges or operational changes at a dam or diversion site. This metric was limited, as it only addressed impacts to the identified project reach even though flow changes may extend beyond the boundaries of the reach. Further, the single metric within the parameter only characterized changes in baseflow, which is insufficient for projects that propose alteration of other aspects of the flow regime. The WSTT has considered alternative approaches to include in v2.0 and decided to remove the flow alteration parameter and replace it with the flow alteration module (FAM) that was developed for the CSQT v1.0 (USACE 2020b).

The FAM provides a basic characterization of flow regime that allows users to estimate the potential flow changes associated with impact or mitigation projects to inform compensatory mitigation decisions (USACE 2020b). The FAM is applicable at sites where modifications to hydrology are proposed and is intended to encourage mitigation approaches that restore components of the native flow regime. For the purposes of the WSQT, native flows are the estimates of the stream flows that would result from natural hydrologic processes such as rainfall-runoff and snowmelt-runoff without anthropogenic influence at a given location.

While multiple approaches have been developed to characterize and evaluate hydrologic alteration (e.g., Richter et al. 1996; Olden and Poff 2003) and identify environmental flows that maintain important stream processes (e.g., Annear et al. 2004; Poff et al. 2010; Sanderson et al. 2012), such efforts often rely on extensive hydrologic modeling and stakeholder processes to develop thresholds or benchmarks (Poff et al. 2010). The flow alteration module is more limited than these approaches, but still provides a basic characterization of flow regime to evaluate potential flow changes at a project scale. The flow alteration module provides this basic characterization by comparing current and proposed hydrology within a reach to the native flow regime.

The WSTT recognizes that flow alteration is ubiquitous in streams in Wyoming and the western U.S. and should be considered when evaluating the watershed condition and restoration potential of a site. For projects that do not propose to alter the flow regime, hydrologic modeling and ecological flow analyses will be outside the scope of the WSQT but should still be considered in project planning and design. Flow alteration can have wide-ranging impacts throughout a watershed and some impacts from altered hydrology can take decades or longer to resolve in the system. Understanding historical and current alterations in the flow regime are critical to developing a successful restoration project design, and appropriate hydrologic analyses should be undertaken (Roni and Beechie 2013). Note that this module does not substitute for these analyses, nor does it fully characterize the hydrologic condition of a reach. Instead, this module characterizes potential changes in condition associated with project-specific changes in hydrology at the reach scale. Examples of project-specific changes in hydrology may include changes in dam operations, increases or decreases in municipal or agricultural water use, and acquisition or preservation of water rights for environmental flows.

The module and metrics for flow alteration were provisionally developed for the CSQT (USACE 2020a) and are subject to testing and revision. The remainder of this chapter is reproduced with minor edits from USACE (2020b) for adaptation and use in the WSQT.

**Module Structure and Scoring:**

The flow alteration module is included as a worksheet in the WSQT and WSIT workbooks. This module is intended to calculate the functional feet value related to **changes in operational commitments, acquisition/change of existing water rights, or new facilities that enable the proposed hydrology to occur.**

The module is separate from the reach-scale condition assessment because the functional feet value is calculated using a different reach length than the other metrics within the SQT. Because flow alteration has the potential to affect longer stream reaches than a project reach and monitoring requirements for flow alteration differ from reach-scale restoration, the flow alteration module calculates functional feet using an affected stream length. Affected stream length includes the entire stream length affected by the project-specific flow alteration (i.e., from the upstream extent where impacts or flow protection would initiate to the downstream location of the next water rights user, significant tributary junction, or terminus beyond which the flow modification has no measurable effect on functional capacity). Depending on the project, affected stream length may extend beyond the project, be equivalent to the length of the project, and/or only include some project reaches within a project (Figure 2-1).

The architecture and scoring of the FAM follows the architecture and scoring in the WSQT. The FAM estimates the change in condition at an impact or mitigation site by calculating the difference between existing (pre-project) and proposed (post-project) condition scores. The difference between existing and proposed condition scores is multiplied by affected stream length to calculate the functional feet for the module. The change in functional feet from the affected stream length is then weighted by 20% and added to the project reach functional feet values to calculate the total project functional feet score. This weighting was done to ensure that the functional feet value for the FAM was scaled similarly with the functional categories within the WSQT, which each contribute 20-30% of the overall functional feet value for a project. FAM scores are the average of metric index values. Index values are generated for each metric field value input by the user. Metrics that are not assessed are not included in the score, i.e., they are not scored as a zero.

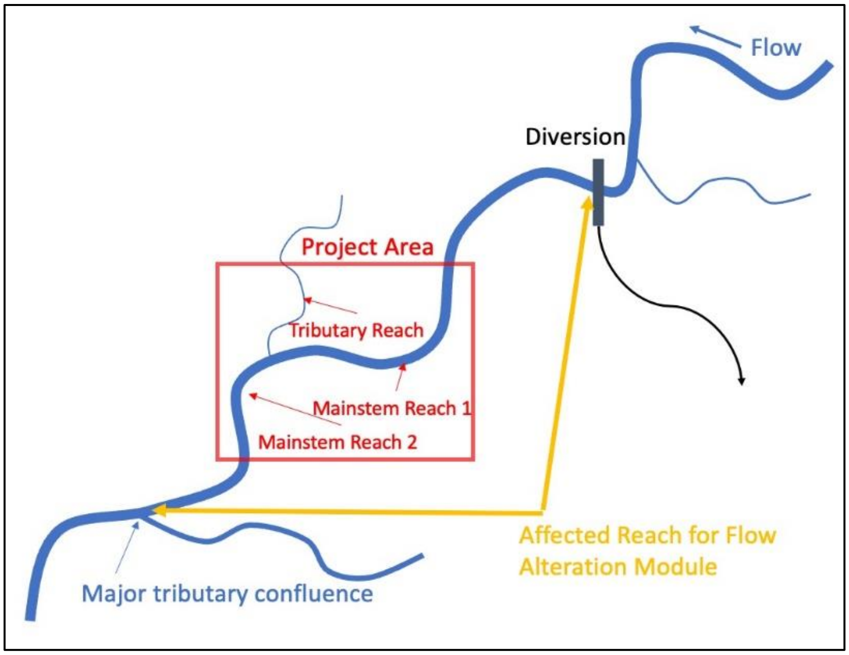



*Figure 2-1a: Affected Reach Length Scenarios for the Flow Alteration Module. The affected reach length encompasses the stream length from the diversion point to the nearest major tributary confluence downstream and includes Mainstem Reach 1 and 2, but not the Tributary Reach (note: in this example, the tributary within the project area does not contribute substantial flow compared with the mainstem).*

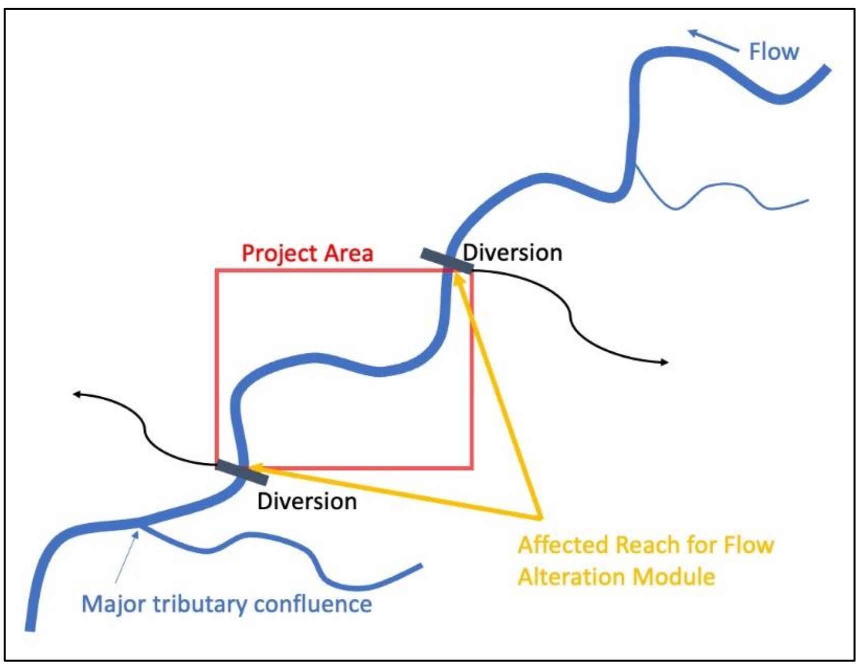



*Figure 2-1b: Affected Reach Length Scenarios for the Flow Alteration Module. The affected reach length encompasses the stream length from the diversion point to the next point of diversion downstream. Because the project area extends from one diversion point to the next, the affected reach length is the same as the total project reach length.*

**Metric Selection:**

In the development of the Watershed Flow Evaluation Tool (WFET), Sanderson et al. (2012) evaluated ecologically relevant flow metrics (Olden and Poff, 2003) using Indicators of Hydrologic Alteration (IHA; Richter et al. 1996). The analyses relied on gage data and Colorado's StateMod hydrologic modeling approach. In their study, Sanderson et al. identified five IHA metrics that were compatible and sufficiently accurate to be useful in the flow analysis: mean annual flow, mean August flow, mean September flow, mean January flow, and mean annual peak daily flow.

Multiple aspects of the natural flow regime, including extreme low flows, baseflows, high flow pulses, small floods, and large floods are important to maintain ecological processes (Mathews and Richter 2007). The flow alteration module characterizes the following: extreme low flows using a 7-day minimum metric; late season baseflow using August and September mean flow metrics; winter baseflows using January mean flow metrics; high flow pulses using a mean annual peak flow metric; and overall flow volume using a mean annual flow metric. The six-metric module does not include metrics for frequency, duration, timing, or rate of change. However, substitution or removal of flow metrics will be considered on a case-specific basis where alternative metrics would better represent the flow regime of the stream. Example substitutions may include:

- The user can opt to use either August or September, or select an alternative month to represent summer baseflow when mean August or September Flow (Q) values are not representative of late season baseflow due to the local climate and hydrologic regime, e.g., August monsoons.
- In intermittent streams, the mean August, September and January Q metrics can be replaced with month(s) that are critical to spawning for native fish based on local climate and hydrologic regime.
- In intermittent streams, the 7-day minimum metric may be replaced with the number of zero flow days.

**Metrics:**

- Mean Annual Q (O/E)
- Mean Aug Q (O/E)
- Mean Sept Q (O/E)
- Mean Jan Q (O/E)
- Mean Annual Peak Daily Q (O/E)
- 7-Day Minimum (O/E)

**Reference Curve Development:**

Reference curves for the metrics in the flow alteration module are adapted from the reference curves developed for the flow alteration metric from the WSQT v1.0 and have been incorporated without edits from the CSQT (USACE 2020b).

In 2010, Poff and Zimmerman published a literature review characterizing ecological responses to altered flow regimes. The authors found that both macroinvertebrate and fish populations declined with increases and decreases in flow magnitude, and much of the published literature focused on large flow alterations, i.e., greater than 50% change from natural conditions. In a study on flow alteration at stream gage sites throughout the U.S., Carlisle et al. (2010) observed biological impairment in some sites with hydrologic alteration of 0-25% and in an increasing percentage of sites beyond 25% hydrologic alteration. Zorn et al. (2008) predicted that adverse resource impacts would occur on most types of rivers with withdrawals greater than 17–25% of index flow. Binns and Eisermann (1979) considered the relationship of late summer baseflows to average annual flows to support trout.

Richter et al. (2012) proposed a presumptive flow standard for environmental flow protection (Table 2-1) which is applied to daily flow values and relies on a dataset that includes daily natural flows (baseline and native (unregulated) flows). The daily natural flows (expected conditions) define the “baseline” flow data to which measured daily flows are compared (Richter et al. 2012).

*Table 2-1: Presumptive Flow Standard. Adapted from Richter et al. (2012).*

| Deviation from Natural Daily Flow (+/-) | Level of Protection | Description |
|---|---|---|
| ≤ 10% | High | The natural structure and function of the riverine ecosystem will be maintained with minimal changes. |
| 11 – 20% | Moderate | There may be measurable changes in structure and minimal changes in ecosystem functions. |
| > 20% | N/A | Likely result in moderate to major changes in natural structure and ecosystem functions, with greater risk associated with greater levels of alteration in daily flows. |

The flow alteration module metrics rely on the presumptive standard (Richter et al. 2012) to define threshold values. The presumptive standard considers flow alterations as a proportion of native flow values and is applied to all metrics in the flow alteration module. The following criteria were used to develop the reference curve (Table 2-2):

- The maximum index score (1.00) equates to a native flow value (e.g., a deviation of 0 or an O/E value of 1.0). In line with the presumptive standard defined by Richter et al. (2012), 90% to 110% of the expected flow value would also yield an index value of 1.00.
- The minimum index score (0.00) equates to deviation of factor of 1, or an O/E value of 0.0 for flow decreases or 2.0 for flow increases. These values are based on best professional judgement, recognizing that substantial deviation from the native flow regime is likely to impact stream structure and function.

A linear curve was fit between the defined values (Table 2-2 and Figure 2-2).

*Table 2-2: Threshold values for Flow Alteration Module Metrics (O/E).*

| Index Value | Field Value |
|---|---|
| 1.00 | 0.90 – 1.10 |
| 0.00 | 0.00, ≥ 2.00 |

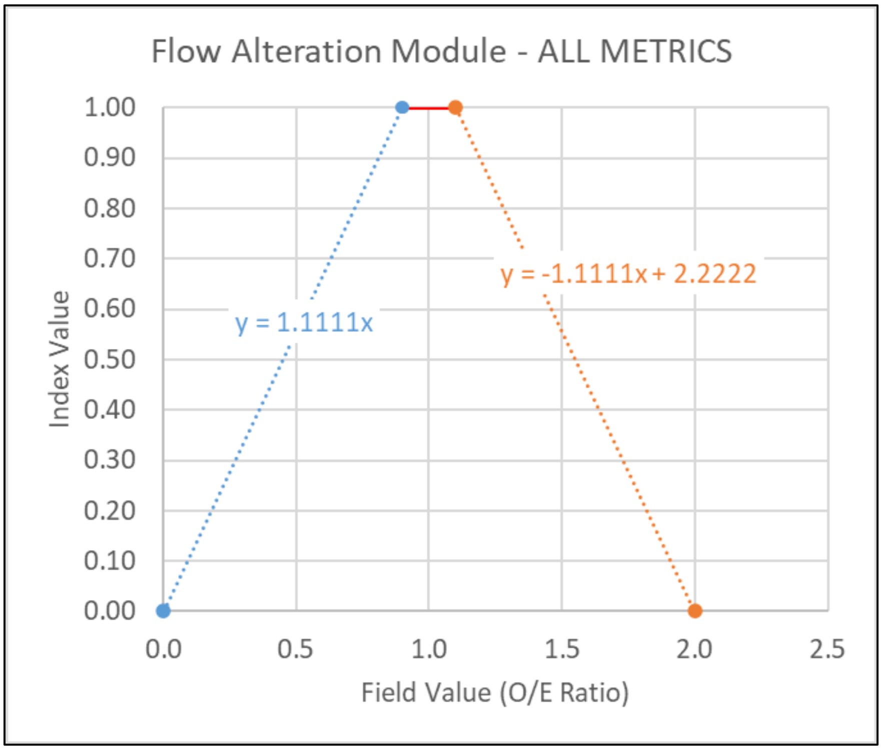



*Figure 2-2: Flow Alteration Module Metrics Reference Curve.*

The CSQT steering committee evaluated the flow alteration module using data from 16 gaged sites in Colorado ranging from 6,280 to 9,990 ft elevation and 3 to 3,971 square mile drainage areas (USACE 2020b). The case study included sites with minimally altered flow conditions and sites where flow has been altered by reservoirs, trans-mountain diversions, or both. Generally, the altered sites had metric field values that fell within the not-functioning or functioning-at-risk range of index values which yielded overall module scores ranging from 0.25 to 0.57. For the altered sites, mean Annual Q was most altered at sites with trans-mountain diversions and main-channel reservoirs, as were mean August Q, mean September Q, and mean January Q. Two of the altered sites yielded overall module scores in the functioning range of scoring. The first was affected by mainstem dams but has a relatively intact flow regime, with only moderately altered peak and late summer flows likely buffered by alluvial storage in the floodplain that maintains baseflow into the late season. The second had August and September flows that were significantly diminished, while the other aspects of the flow regime were relatively intact.

Module scores for the minimally altered sites fell within the functioning range of index scores, indicating that although they may have some anthropogenic modification, the modification was minimal. Some of these sites exhibited relatively high degrees of altered January Q, but this may be related to data quality associated with ice, seasonally unavailable gage data, or because relative error increases as the magnitude of the flows decreases.

**Limitations and Data Gaps:**

Recognizing the level of effort that is typically undertaken to develop environmental flow standards, this is a very simplified approach. Because a single reference curve was applied for all metrics, the reference curve may not accurately capture the hydrologic conditions that support geomorphic, physicochemical, and biology functioning in all streams. Zorn et al. (2008) noted that some rivers in Michigan are more sensitive to withdrawals than others and Richter et al. (2012) note that the presumptive standard may not be sufficient to protect ecological values in smaller or intermittent streams. Application across multiple flow regimes is needed to determine whether additional stratification, alternate metrics or refined reference curves are needed.

The module is also limited in that it does not characterize all ecologically relevant aspects of the flow regime (Poff et al. 1997; Mathews and Richter 2007). Baseflow hydroperiod and patterns during the winter can have important ramifications for the biological community, especially fish populations. A more comprehensive approach to evaluating flow alteration may be needed to adequately characterize other aspects of the flow regime (Annear et al. 2004; Poff et al. 2010) and this flow alteration module should not be used as a substitute for these more rigorous analyses. Furthermore, the metrics currently included in the flow alteration module are primarily tailored to hydrologic regimes that have a large snowmelt signature. Adaptation of the module for application in non-snowmelt systems should be made on a case-specific basis and should consider the dominant or important aspects of the hydrologic regime, given local variation in climate and other process drivers.

The flow alteration module requires three separate datasets in its current configuration: native hydrology, current hydrology, and proposed hydrology. In some parts of the state, native hydrology may be difficult to quantify. Furthermore, hydrologic assessments range in complexity and magnitude of errors. Designers should have the expertise to perform these assessments and be able to analyze and defend the results.

# Chapter 3. Reach Runoff Parameter

**Functional Category:** Reach Hydrology & Hydraulics

**Function-based Parameter Summary:**

The reach runoff parameter focuses on the infiltration and runoff processes of the land within the portion of the catchment that drains directly into the project reach (lateral drainage area). This parameter characterizes the land use and stormwater routing in the lateral drainage area adjacent to the project area, which could be altered at the reach or project scale. Land use practices in the lateral drainage area impact the amount of runoff and the pollutants entrained and transported to the receiving stream reach. For example, multiple studies have shown that increases in impervious cover are linked to decreased stream health (Scheuler et al. 2009), while agricultural practices can contribute sediment, nutrients, and other pollutants (EPA 2005). 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. 2013; ELI and TNC 2014). The lateral drainage area plays a role in multiple primary functions of healthy stream ecosystems 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.

While reach-scale projects may be strategically located as part of larger watershed plans, projects are limited in their ability to influence the upstream catchment hydrology transporting runoff from upstream in the watershed to the project reach. Land use changes indirectly influence watershed-scale processes but these changes often occur away from the stream and are distributed throughout a watershed (Beechie et al. 2013). This parameter does not characterize runoff from the contributing watershed upstream of the project reach. A broad characterization of the upstream contributing catchment is used to evaluate restoration potential but is not directly scored within the WSQT. Flow regime represents cumulative watershed processes and can be especially important where projects alter hydrology within or beyond the project reach (see Flow Alteration Module, Chapter 2).

The WSQT includes two metrics under this parameter to evaluate impacts of and incentivize improvements in stormwater management and land management practices on a reach-scale that can contribute to cumulative progress in a larger watershed.

The land use coefficient metric quantifies anthropogenic land use and land covers that alter the hydrologic processes within the lateral drainage area. Land use changes can alter interception, infiltration, evapotranspiration, snowpack distribution and melting, and runoff routing and is thus an indicator of changes to magnitude, volume, rate of change, and frequency of the full spectrum of flow events.

The concentrated flow points metric addresses practices that result in impacts to storm-flow routing, typically increasing water velocities to more effectively drain the landscape. This metric was developed to address large lateral drainage areas where restoration practices limited to the riparian corridor may not have measurable changes to the land use coefficient field value in the SQT. The size of the lateral drainage area can vary widely between projects, and larger stream reaches and unconfined valleys can also have large lateral drainage areas, meaning that typical restoration practices may not affect the land use coefficient field value in the WSQT. However, larger lateral drainage areas are likely to have more concentrated flows. Therefore, the land use coefficient and concentrated flow metrics are intended to be applied together.

**Metrics:**

- Land Use Coefficient
- Concentrated Flow Points

## 3.1. Land Use Coefficient

**Summary:**

The WSQT uses an area weighted land use coefficient to numerically quantify the impact of various land uses on reach runoff (NRCS 1986). The metric 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 land use coefficient.

Land use coefficient values are provided in the WSQT v2.0 User Manual along with methods for data collection and metric calculation. Land use coefficients are based on curve numbers (CN) developed by the Natural Resource Conservation Service (NRCS) in Urban Hydrology for Small Watersheds (NRCS 1986), commonly known as the TR-55. Curve number values presented in TR-55 are determined based on soil type, land use, and surface condition. Higher CN values, nearer 100, indicate more runoff potential and lower values, nearer 0, indicate less runoff potential. These land use coefficients are not intended to predict changes in runoff, but to serve as an indicator of land use change and the potential for generating runoff in the lateral drainage area. The curve numbers for urban land uses trends 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, curve number and runoff potential increases.

**Reference Curve Development:**

To focus solely on land use change rather than infiltration capacity of soils, land use coefficients used in the WSQT were adapted from TR-55 and applied across generalized land use descriptors. Curve numbers corresponding to one hydrologic soil group, group B, were selected. 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 (NRCS 2007).

TR-55 provides land use coefficients for various natural, agricultural and urban land uses across a range of condition. For example, woods that are protected from grazing and have litter and brush covering the soil are considered good condition and the land use coefficient is 55. For comparison, the land use coefficient for woods in poor condition, i.e. where forest litter, small trees, and brush are destroyed by heavy grazing or regular burning, is 66. Urban land uses have higher land use coefficients as the percent of impervious surfaces increases. For example, commercial and business districts have a land use coefficient of 92 while residential districts with 1/4 acre lots have a land use coefficient of 75.

Land use coefficients for natural land cover types in good condition are always less than 68 and often less than 60, while land use coefficients for agricultural lands typically range from 70 to 80. The land use coefficients for urban land uses trends 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, an area-weighted land use coefficient will increase.

For the WSQT v2.0, land use tables were simplified to make calculation of the metric more efficient. These simplified land use tables combine multiple land uses into fewer categories, with coefficients assigned to these combined categories using best professional judgement. To simplify land cover descriptions, the curve number corresponding to “good condition” (or average of curve numbers when applicable), were assigned for the simplified land use descriptions. A table of land use coefficients is presented in Table 3-1 and in the WSQT v2.0 User Manual. Consideration was also given to the potential influence of recent wildfire activity on runoff processes and land use coefficients (Yochum and Norman 2015), however, the WSTT decided to address this on a case-specific basis instead of incorporating into the land use table.

To develop a reference curve associated with land use changes, land use coefficients that correspond to natural land cover were considered to represent a functioning range of index values (0.70-1.00), with the lower coefficient (45) assigned an index value of 1.00. The minimum index value 0.00 equated to a land use coefficient of 80, 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. Threshold values are presented in Table 3-1.

Stratification by reference riparian vegetation cover type (woody or herbaceous) was considered since herbaceous communities have less roughness and higher runoff potential than forested communities, but this stratification was not used since the reference riparian vegetation community rarely extends to the entire drainage area and thus, would not be representative of the area-weighted land use coefficient for the entire lateral drainage area.

A broken-linear curve was applied for this metric (Figure 3-1) and is steeper in the not functioning and functioning-at-risk range of scoring than in the functioning range, allowing for a broader range of land use coefficients within the functioning range to account for natural variability.

*Table 3-1: Threshold Values for Land Use Coefficients.*

| Index Value | Field Value |
|---|---|
| 1.00 | ≤ 45 |
| 0.70 | 62 |
| 0.00 | ≥ 80 |

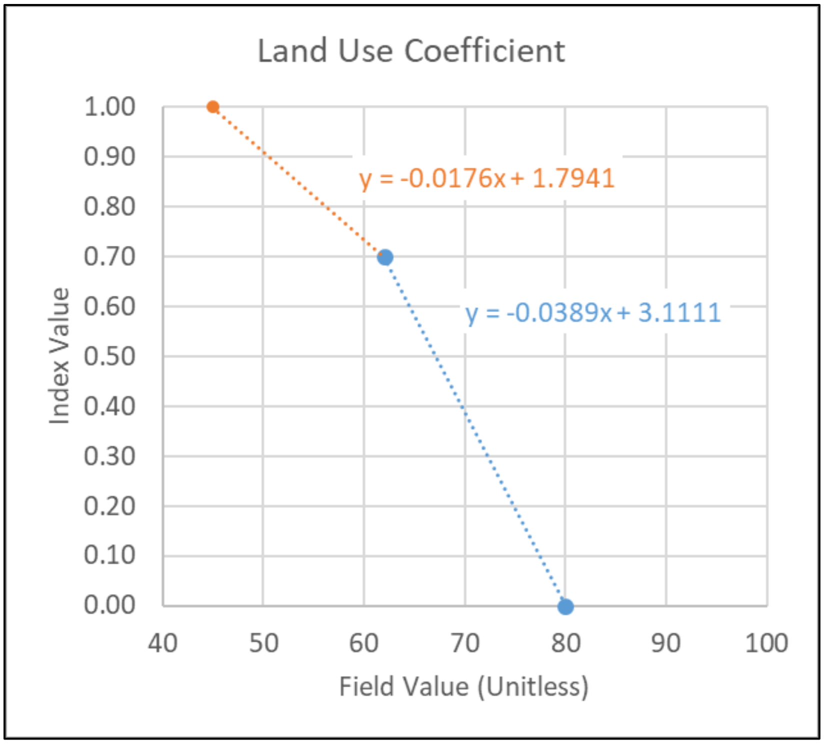



*Figure 3-1: Land Use Coefficient Reference Curve.*

**Limitations and Data Gaps:**

The land use coefficients for this metric are derived from curve numbers but assume all soils are moderately drained. Therefore, the metric does not account for the variation in infiltration capacity, impermeable layer depth, or other characteristics important to estimating runoff volumes. Additionally, curve numbers are used to predict runoff volumes and therefore their application as land use coefficients does not accurately account for relative pollution loads coming from different land uses.

There are limitations of scale associated with this metric as the size of the project easement or area compared to the size of the lateral drainage area will influence how much index scores may change in response to land use changes in the project area. Reaches with larger lateral drainage areas would need to acquire and revegetate more land to achieve a similar amount of lift as a project with a smaller lateral drainage area.

Similarly, there are limitations related to the size of the project easement or area compared to the size of the upstream catchment - the larger the contributing catchment area upstream, the less of an influence the lateral drainage has in maintaining stream functions within the project reach. For example, a reach located far downstream from the headwaters may be more affected by hydrologic changes occurring upstream than from land use change in the lateral drainage area. Alternatively, improving land use condition in small streams near the headwaters may have a greater relative effect. These limitations could be addressed through stratification and development of additional reference curves. Considering relative watershed location (e.g., the proportion of land area within the lateral drainage area compared with the entire watershed area) could account for the relative impact of direct drainage to the channel vs. in-channel delivery from upstream.

Stratification based on natural land use types may also improve this metric. Natural land cover varies in runoff and infiltration potential. For example, natural grasslands function differently than forests, with different curve numbers and land use coefficients, but both may represent a pristine or reference standard condition. Also, this 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. Stratification would better account for these differences.

This metric has received limited testing and would benefit from additional application and testing in Wyoming. 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. This is important since even small amounts of impervious cover (e.g., 10%) in a watershed can result in significant loss of stream function (Booth and Jackson 1997; Schueler et al. 2009). As the WSQT is tested and applied, this metric may be updated.

## 3.2. Concentrated Flow Points

**Summary:**

This 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, road cuts 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 construction sites. The concentrated flow point channelizes water that would otherwise flow towards the stream channel as sheet flow, throughflow or groundwater. 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. 2013).

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 threshold values for this 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). The WSTT agreed the absence of anthropogenic concentrated flow points reflected a pristine condition, and the presence of one or more concentrated flow points per 1,000ft would no longer reflect full functional capacity. Based on this logic, the threshold values shown in Table 3-2 were created, and a linear curve was fit to these values (Figure 3-2).

*Table 3-2: Threshold Values for Concentrated Flow Points.*

| Index Value | Field Value |
|---|---|
| 1.00 | 0 |
| 0.69 | 1 |

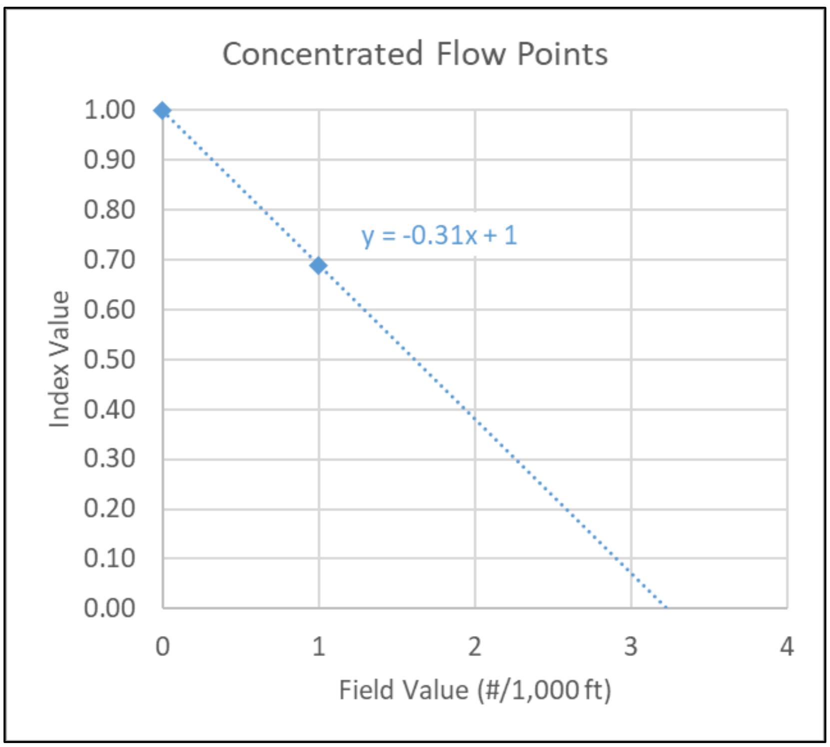



*Figure 3-2: Concentrated Flow Points Reference Curve.*

**Limitations and Data Gaps:**

This metric was developed for use in the North Carolina SQT and was incorporated into the WSQT and subsequent SQTs. It will need additional testing and review as it is applied to project sites, particularly in degraded stream reaches and urban areas.

The 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. Some SQT regionalization efforts are exploring ways to revise and improve the concentrated flow points metric, e.g., to focus on volume rather than number. As the work progresses, the WSQT may be updated.

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. Alternatively, if the project includes restoration of natural sinuosity but does not reduce the number of concentrated flow points, the metric could show lift solely as a result of the increased channel length, rather than a reduction in the actual number of concentrated flow points. These types of examples will need to be dealt with on the policy side until the metric is modified to address these types of issues. Language has been added to the WSQT v2.0 User Manual to describe how to estimate proposed condition scores, and this should assist with these limitations.

# Chapter 4. Baseflow Dynamics Parameter

**Functional Category:** Reach Hydrology & Hydraulics

**Function-based Parameter Summary:**

The baseflow dynamics parameter was added to the WSQT v2.0 to capture the ecological effects of changing channel dimensions on baseflow habitat. This parameter and its metrics were developed for use in the CSQT (USACE 2020a). This chapter is reproduced with minor edits from USACE (2020b) for adaptation and use in the WSQT.

The addition of the baseflow dynamics parameter incentivizes multi-stage channels and captures the impacts of channel widening. Hydraulic habitat modeling is a useful tool for understanding the baseflow dynamics necessary to maintain optimal habitat for biota and is one of several common approaches to evaluate environmental flow requirements in streams (Acreman and Dunbar 2004). There are many approaches available to characterize useable habitat area and baseflow dynamics (Espegren 1996; Annear et al. 2004), and some newer approaches are being developed to reduce the cost and level of effort associated with many existing methods (Wilding et al. 2014). Several hydraulic metrics have been identified as critical components of habitat maintenance flows and have been used for several decades in western states to inform minimum flow guidelines (Nehring 1979; Espegren 1996; Annear and Conder 1984; Lobb 2020).

In intermittent and perennial streams, baseflow is the flow that is sustained between higher magnitude peaks in the hydrograph (e.g., following snowmelt or other precipitation events). The objective of this parameter is to characterize habitat conditions within the reach during baseflow conditions. Baseflow is characterized in this parameter using the average of the mean daily flow values during the low flow period, typically in the late summer or early fall of the monitoring year. While the flow dynamics above baseflow (small flow pulses, bankfull flows, etc.) shape the channel, baseflow plays an important role in supporting water quality, water supply, and habitat (Price 2011). Baseflow volume and dynamics impact contaminant concentrations, water temperature, and available habitat area.

Two out of the three hydraulic parameters identified in Nehring (1979) and Annear and Conder (1984), average depth and average velocity, are included to characterize baseflow dynamics. This parameter requires evaluation of both metrics at riffle features within the reach. Percent of bankfull wetted perimeter was also considered by the WSTT and CSQT Steering Committee, but the metric was not included. While wetted perimeter is included in many models that determine minimum instream flow recommendations, it is not included in habitat suitability index models (HSI).

The parameter is currently only applicable in coldwater streams (Wyoming temperature tiers I and II). The WSTT considered expanding applicability to warmwater stream systems but recognized the diversity of habitat needs within warmwater systems would require a more complex approach relying on alternative metrics. Numerous factors, including natural range, turbidity, intermittency, stream size, pool depth, substrate, vegetation, and large wood influence the natural distribution of warmwater fishes (Quist et al. 2003). Pool depth complexity is particularly important in supporting native fish populations in intermittent, flashy systems (Fausch and Bramblett 1991). Many of these factors are captured in other parameters and metrics within the SQT, for example, pool depth ratio, large woody debris, riparian vegetation, bed material characterization, and flow alteration.

**Metrics:**

- Average Velocity (fps)
- Average Depth (ft)

## 4.1. Average Velocity

**Summary:**

Baseflow velocity is a critical component of habitat maintenance flows. Riffle baseflow velocity has been found to directly affect macroinvertebrate survival and trout egg incubation (Nehring 1979).

The mean velocity of a cross section at baseflow is calculated as the baseflow discharge divided by the wetted area at baseflow. For the SQT, cross section surveys are collected at three riffle features and the results are averaged to determine an average riffle velocity at baseflow in the reach.

**Reference Curve Development:**

Average velocity minimum criteria are presented in the Evaluation of Instream Flow Methods and Determination of Water Quantity Needs for Streams in the State of Colorado (Table 4-1; Nehring 1979). These criteria are similar to those used in habitat retention method approaches in Wyoming (Annear and Conder 1984; Lobb 2020).

*Table 4-1: Minimum Flow Requirements Over Riffles (Nehring 1979).*

| Bankfull Width (ft) | Average Depth (ft) | Percent Wetted Perimeter* (%) | Average Velocity (fps) |
|---|---|---|---|
| 1-20 | 0.2 | 50 | 1.0 |
| 21-40 | 0.2-0.4 | 50 | 1.0 |
| 41-60 | 0.4-0.6 | 50-60 | 1.0 |
| 61-100 | 0.6-1.0 | ≥70 | 1.0 |

** Baseflow wetted perimeter as a percent of bankfull.*

Due to the varying velocity requirements for multiple species during different life stages, a reference curve was not developed for the velocity metric. Instead, the average velocity for the minimum flow requirements developed by Nehring (1979) was used to calculate the parameter score. Where velocities are less than 1.0 fps, the parameter will score a 0.00, regardless of the field value for average depth metric. Where velocities exceed the 1.0 fps, they will not influence or inform the parameter score. Note that there may be settings where this parameter should not be applied because average velocities are naturally below this minimum flow value.

**Limitations and Data Gaps:**

This metric has received limited testing since originally developed for Colorado and would benefit from application and testing in Colorado and Wyoming. Future versions of the tool may consider whether a more comprehensive approach to characterizing velocity may be useful.

## 4.2. Average Depth

**Summary:**

Depth is one of the most important hydraulic criteria for maintaining fish passage (Nehring 1979). Nehring (1979) concluded that "average depth should be the primary criterion on which minimum flow recommendations are determined since it is the first factor to become limiting in almost twice as many instances as average velocity and wetted perimeter combined."

The mean depth of a cross section at baseflow is calculated as the wetted cross-sectional area divided by the wetted top width. For the SQT, cross section surveys are collected at three riffle features and the results are averaged to determine an average depth at baseflow in the reach.

**Reference Curve Development:**

Reference curves were developed using established minimum flow criteria for habitat retention methods (Nehring 1979, Annear and Conder 1984), as well as average depth criteria from Habitat Suitability Index models. The minimum flow criteria shown in Table 4-1 were used to define the minimum index value of 0.00, as these criteria consider the maximum body depth of the largest fish present.

Habitat Suitability Indices (HSI) consider various habitat metrics that influence habitat suitability by species and life stage, and score metrics on a 0.0 to 1.0 scale. HSI for multiple coldwater species were reviewed (Hickman and Raleigh 1982; Raleigh 1982; Raleigh et al. 1984; Raleigh et al. 1986; Wesche et al. 1987; Shuler and Nehring 1993) and the 1.00 scores from the average depth HSI variable were used to inform the maximum index value of 1.00 in the SQT (Table 4-2). Where differences between HSI results occurred between species or studies, maximum index values were selected following consultation with Colorado Parks and Wildlife fisheries biologists. The WSTT reviewed this effort to ensure consistency and applicability with habitat suitability in Wyoming.

Reference curves are stratified by stream width and temperature tier as shown in Table 4-2 and Figure 4-1. To translate the stratification from Colorado to Wyoming temperature tiers, the representative species within each Colorado temperature tier (Table 11.4, USACE 2020b) were compared to the thermal guilds identified in Mandeville et al. (2019). Additional consideration may be given to additional stratification by life stage following additional research and testing.

*Table 4-2: Threshold Values for Average Depth.*

| Index Value | Field Values by Bankfull Width (ft) and Temperature Tier | | |
|---|---|---|---|
| | Tier-I & W < 20ft | Tier-I & W > 20ft | Tier -II |
| 1.00 | ≥ 1.0 | ≥ 1.5 | ≥ 2.3 |
| 0.00 | ≤ 0.2 | ≤ 0.4 | ≤ 0.6 |

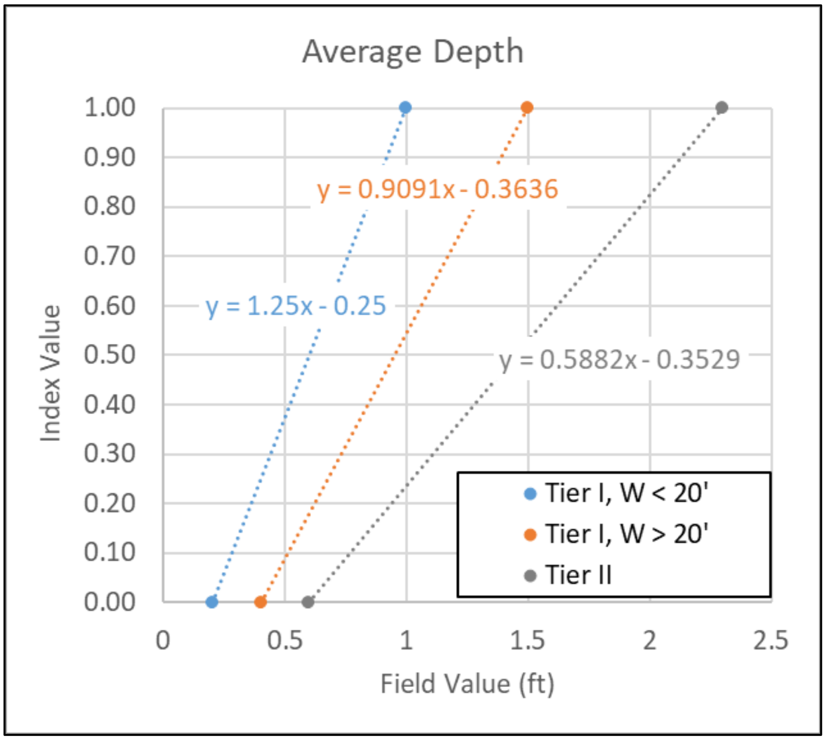



*Figure 4-1: Average Depth Reference Curves.*

**Limitations and Data Gaps:**

Nehring (1979) notes that transect-based R2CROSS methods do not have a direct link to the biological condition of a stream. For this metric, reference curves were based on habitat preferences identified in HSI models, recognizing that some of these curves may be outdated or not representative of the habitat needs for all life stages of fish. Newer curves are available for some species and life stages and additional updates to this parameter may be needed as new information is available in the literature, including stratification or additional metrics to capture the habitat suitability for different life stages. For example, Allyón et al. (2010) does not propose upper limit depth criteria for adult brown trout, while Louhi et al. (2008) suggest shallower depths are necessary to support brown trout spawning.

# Chapter 5: Bankfull Flow Dynamics Parameter

**Functional Category:** Reach Hydrology & Hydraulics

**Function-based Parameter Summary:**

A bankfull flow dynamics parameter was added to the WSQT v2.0 to capture the benefits and impacts to higher level functions that result from changing channel dimensions. This parameter was initially developed for the Alaskan Interior SQT (AKSQTint), and this chapter is reproduced with minor edits from Alaska Stream Quantification Tool Steering Committee (2021) for adaptation and use in the WSQT.

Flow dynamics refers to the interaction of flowing water within the stream bed and banks and can be quantified by stream velocity, shear stress, and stream power. Bankfull flow dynamics influence channel geometry and characterize the stream's ability to transport sediment sourced from upstream, the stream bed, and streambanks (Harman et al. 2012). Channel adjustment (e.g., aggradation and degradation) is the channel's response to changes in flow dynamic characteristics, including stream velocity, shear stress, and stream power. Channel geometry adjustments and resulting changes in stream type are detailed in Rosgen's Channel Succession Scenarios (Rosgen 2006) and other channel evolution models (Cluer and Thorne 2014).

Width/depth ratio state (WDRS) is the single metric within this parameter to characterize channel adjustments. The WSQT v1.0 included a metric called aggradation ratio under the bed form diversity parameter to capture the extensive deposition associated with aggradation. However, this metric has been removed from the WSQT v2.0 and replaced with the WDRS as a hydraulic metric. This metric is appropriate within reach hydrology and hydraulics, as it informs how water and sediment are transported within the channel and serves as an indicator for changes in flow dynamics that support geomorphic sediment transport processes. This application is consistent with Harman et al. (2012) and is within the same functional category as the baseflow dynamics parameter, which was also added to the WSQT v2.0.

A channel's dimensions are a result of the water and sediment volumes that are transported to a reach. When sediment supply exceeds sediment transport capacity, aggradation (channel fills with sediment) generally occurs (Wilcock et al. 2009). This is often a natural process, especially in glacial valleys where braided stream channels are common. However, direct channel modification or indirect changes to watershed hydrology can also cause aggradation; for example, channel enlargement can occur following land disturbing activities (Wohl 2004). Note that this metric has been developed for single-thread, wadeable streams in non-glacial alluvial and colluvial valleys and is not applicable in multi-thread streams.

**Metric:**

- Width/Depth Ratio State (WDRS)

## 5.1. Width/Depth Ratio State (WDRS)

**Summary:**

The width/depth ratio (W/D) is the bankfull riffle width divided by the mean depth (Rosgen 2014). A small W/D indicates a narrow and deep channel while a larger W/D indicates a wide and shallow channel. Mean depth is the riffle bankfull cross-sectional area divided by the riffle bankfull width.

The W/D ratio state (WDRS) described by Rosgen (2014) assesses departure from a reference standard caused by downcutting, streambank erosion, excessive deposition, or direct mechanical impacts. The WDRS method assesses increases and decreases in W/D to quantify departure from reference. Relative to reference, increasing W/Ds represent aggradation risk and decreasing W/Ds represent degradation risk. The field value is calculated as the ratio of a reference W/D where the reference W/D is selected by the user. The reference W/D can come from the representative riffle cross-section, a riffle cross-section at a reference reach, or through the design process.

**Reference Curve Development:**

The channel stability descriptions for the WDRS from Rosgen (2014) are provided in Table 5-1. Values greater than 1.0 indicate aggradation potential. The stable range is 1.0 to 1.2, meaning that observed W/Ds are 100% to 120% of the reference W/D. As the ratio increases, the risk of aggradation increases. When the value exceeds 1.4 of the reference W/D, the channel is likely to be unstable due to aggradation.

As shown in Table 5-1, WDRS values less than 1 indicate degradation potential. The stable range is 0.8 to 1.0, meaning that the observed W/Ds are 80% to 100% of reference W/Ds. As the ratio decreases, the risk of degradation increases. However, a decrease in WDRS values could indicate progress toward greater stability (a Rosgen C stream evolving into a Rosgen E stream as vegetation establishes and bank stability increases; Rosgen 2014). The degradation potential is only assessed when the stream is also incised as indicated by the bank height ratio (BHR; Rosgen 2014). Therefore, for implementation in the WSQT, the rising limb of the reference curve (observed W/Ds that are less than 1.0 of the reference W/D) will score a 1.00 unless the BHR field value is greater than 1.2. Rosgen (2014, page 3-37) states that “the decrease category is rated as high risk only when accompanied by a BHR that is greater than 1.0.” A BHR value of 1.2 was considered consistent with the functioning range of scoring for the BHR metric (refer to Section 6.1).

*Table 5-1: Width/Depth Ratio State Categories (Rosgen 2014).*

| Width/Depth Ratio State | | Stability Rating |
|---|---|---|
| Degradation Potential | Aggradation Potential | |
| 0.8 – 1.0 | 1.0 – 1.2 | Stable |
| 0.6 – 0.8 | 1.2 – 1.4 | Moderately Stable |
| 0.4 – 0.6 | 1.4 – 1.6 | Unstable |
| 0.2 – 0.4 | 1.6 – 1.8 | Highly Unstable |

Thresholds for WDRS were developed by defining the maximum and minimum scores for the functioning and not-functioning categories in the WSQT, where the maximum score corresponds to the highly unstable 1.8 and the minimum score corresponds to the highly unstable 0.2 delineations in Table 5-1. The 0.00 index value was informed by these thresholds. The index value of 1.00 was set to a metric field value of 1.0 which means the observed W/D is 100% of the reference W/D.

Threshold values for the reference curve are presented in Table 5-2 and the reference curve is depicted in Figure 5-1.

*Table 5-2: Threshold Values for Width/Depth Ratio State.*

| Index Value | Field Value |
|---|---|
| 1.00 | 1.0 |
| 0.00 | ≤ 0.2; ≥ 1.8 |

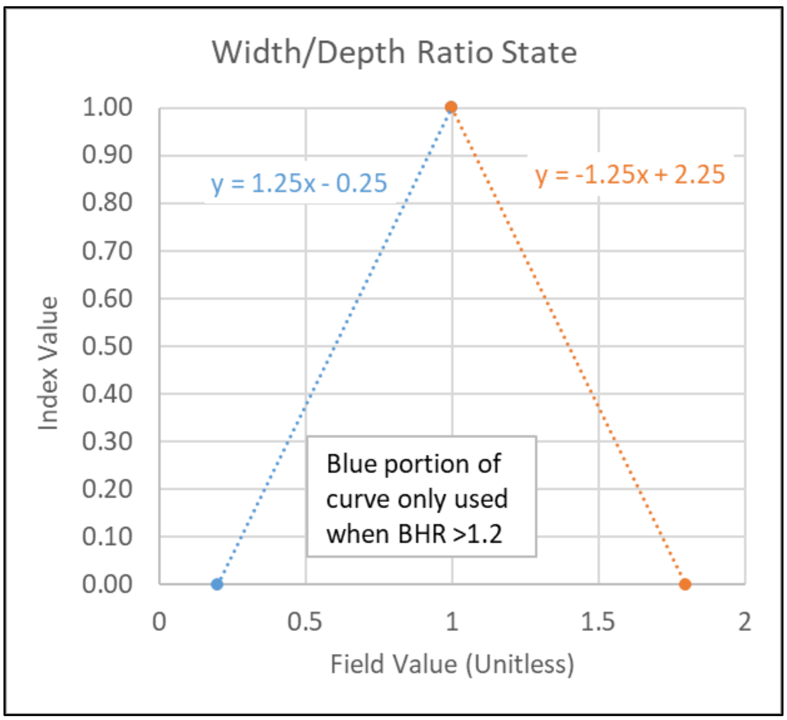



*Figure 5-1: Width/Depth Ratio State Reference Curves.*

**Limitations and Data Gaps:** If bankfull dimensions are not accurately determined for a site, then the W/D will not accurately represent the hydraulics in the reach. Additional information on verifying bankfull information was added to the WSQT v1.0 User Manual in response to comments received during beta testing. Recognizing that bankfull features can be difficult to identify in the field, particularly following flow alteration, specific procedures and data forms to identify and verify bankfull were added to the WSQT v2.0 User Manual. These procedures include scenarios where flow alteration rather than incision has reduced floodplain connectivity.

# Chapter 6. Floodplain Connectivity Parameter

**Functional Category:** Reach Hydrology & 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). The floodplain of a stream is the area commonly inundated during high flows or floods. Harman et al. (2012) provide detailed definitions and examples of floodplains and flood prone areas. For example, floodplains that consist of alluvium are associated with meandering streams in alluvial valleys. Flood prone areas and bankfull benches are narrower than floodplains and exist in confined or colluvial valleys. Flood prone areas and bankfull benches are flat depositional features that provide some energy dissipation for higher flows. Floodplains, bankfull benches and flood prone areas are assessed as floodplain connectivity in the WSQT.

When a channel is connected to its floodplain, flood flows can inundate the floodplain and spread out across the landscape while in-channel velocities can maintain bed forms without excessive erosion. While it is a common perception that a straight and deep channel can move flood waters quickly downstream, channelization often displaces flooding and increases flood damage downstream of the channelization (Schoof 1980). Channels that are not connected to their floodplain lose the capacity to store water and sediment in the floodplain during large storm or snowmelt events. The functional loss associated with channelization and berm or levee construction is not limited to displaced flooding, but can also lead to 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). 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).

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 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 characterize floodplain connectivity.

Stage-discharge relationships characterize whether flood flows are observed, applying a hydrologic model to predict various discharges (e.g., the 2-year, 5-year, 10-year return interval events) with channel dimensions used to predict the water stage, or elevation, associated with each discharge value. The value obtained from the stage-discharge relationship would be the flow (Q) contained within the banks of the channel. If that flow is a large and infrequent flood event, then the channel is not connected to its floodplain. For example, a channel that conveys a 5-year flood event is not well-connected to the floodplain. Typical return intervals for bankfull discharge range from 1.1 to 2.0-year return intervals (Mulvihill and Baldigo 2012; Moody et al. 2003; Emmert 2004). A return interval metric was considered in the CSQT Beta Version to characterize stage-discharge relationships; however, this metric was removed following beta testing and instead procedures to identify and verify bankfull were added to the WSQT v2.0 User Manual. The WSTT decided to incorporate these procedures in v2.0, including for scenarios where flow alteration rather than incision has reduced floodplain connectivity.

As two-dimensional modeling becomes more used in stream restoration projects, hydraulic parameters like Froude and Reynolds numbers may be added to SQTs. For example, studies have shown Froude and Reynolds number preferences by wild and hatchery-raised cutthroat trout, which can be used as an aide in developing reference standards (Bates 2000).

The BHR and ER metrics were selected for use in the tool because they are physical measurements practitioners and regulators can determine in the field and rely on a bankfull indicator or regional curve. A gage station or model is not required. Recognizing that bankfull features can be difficult to identify in the field, particularly following flow alteration, procedures to identify and verify bankfull were added to the WSQT v2.0 User Manual.

The WSQT v2.0 includes the addition of a side channel metric to this parameter. This metric was initially developed for the floodplain connectivity parameter in the CSQT (USACE 2020a) to account for the importance of side channels (e.g., sloughs and side channels, natural chute cut-offs, and connecting oxbow ponds) in the hydraulic and geomorphic functioning of alluvial valleys. While side channels provide many habitat functions, they also connect the main channel to the floodplain through the hyporheic zone, fostering water transfers between the surface and subsurface and creating thermal variability and refugia (Fernald et al. 2006; Arrigoni et al. 2008; Burkholder et al. 2008; Oct et al. 2015; Nadeau et al. 2018). Thus, including side channels as a metric for floodplain connectivity emphasizes their role in distributing water on the floodplain and through sediments.

**Metrics:**

- Bank Height Ratio
- Entrenchment Ratio
- Percent Side Channels

## 6.1. Bank Height Ratio

**Summary:**

The bank height ratio (BHR) is a measure of channel incision, or the degree to which flood flows can access (are connected to) an active floodplain or bankfull bench. The BHR is defined as the depth from the top of the low bank (the lowest identifiable bank) to the thalweg divided by the depth from the bankfull elevation to the thalweg (Rosgen 1996). In a stable high functioning stream with ideal floodplain connectivity, the bank height (depth) should be equal to the bankfull height (depth); in other words, the bankfull discharge is just contained within the bankfull channel and discharges greater than bankfull will access the floodplain or bankfull bench (Rosgen 2009). Therefore, 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.

For the WSQT, BHR is measured at every riffle in the representative sub-reach, and a weighted BHR is then calculated from these measurements. Methods for data collection and metric calculation are in the WSQT v2.0 User Manual.

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 recurrence interval. 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, resulting in even larger floods being contained in the channel, and decreasing floodplain connectivity as the channel evolves through predictable stages (Cluer and Thorne 2014). 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:** Reference curves for this metric have been updated for WSQT v2.0.

The BHR metric was developed by Rosgen (2009) as a measure of channel incision as shown in Table 6-1. 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 6-1).

*Table 6-1: Bank Height Ratio Categories.*

| Channel Incision Descriptions by Rosgen (2009) | | Performance 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 |

The BHR categories from Rosgen (2009) and Harman et. al (2012) were evaluated for Wyoming using the compiled geomorphic reference dataset described in Section 1.8. The compiled geomorphic reference dataset consists of 61 sites that report BHR (Table 6-2). Because bank height ratio was used as a quality assurance measure in compiling the dataset, sites that would be considered deeply incised (BHR greater than 1.5) were not included in the reference dataset. About three-quarters of the sites from this dataset had a BHR of less than 1.2.

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 this 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.

*Table 6-2: Statistics for BHR from the Compiled Geomorphic Reference Dataset.*

| Statistic | BHR |
|---|---|
| Number of Sites (n) | 54 |
| Average | 1.09 |
| Standard Deviation | 0.11 |
| Minimum | 1.00 |
| 25$^{th}$ Percentile | 1.00 |
| Median | 1.00 |
| 75$^{th}$ Percentile | 1.19 |
| Maximum | 1.50 |

A threshold of 1.5 was used to differentiate index values within the functioning-at-risk and non-functioning ranges. BHRs of greater than 1.5 were considered non-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.

In the WSQT v1.0, a BHR of 1.2 was used to define the 0.70 index value. This value aligned with the 75$^{th}$ percentile from the dataset and the criteria identified in Table 6-1. In the WSQT v2.0, the reference curve for this metric was updated to remove this threshold value, and only relying on 1.0 and 0.30 index values to generate a reference curve. This was done to simplify the reference curve, providing a consistent slope throughout the range of index values. The 0.70 value is now slightly less than 1.2.

The thresholds identified in Table 6-3 were plotted and a best-fit line was derived to provide a single equation to calculate index values from field values (Figure 6-1).

*Table 6-3: Threshold Values for Bank Height Ratio.*

| Index Value | Field Value |
|---|---|
| 1.00 | 1.0 |
| 0.30 | 1.5 |

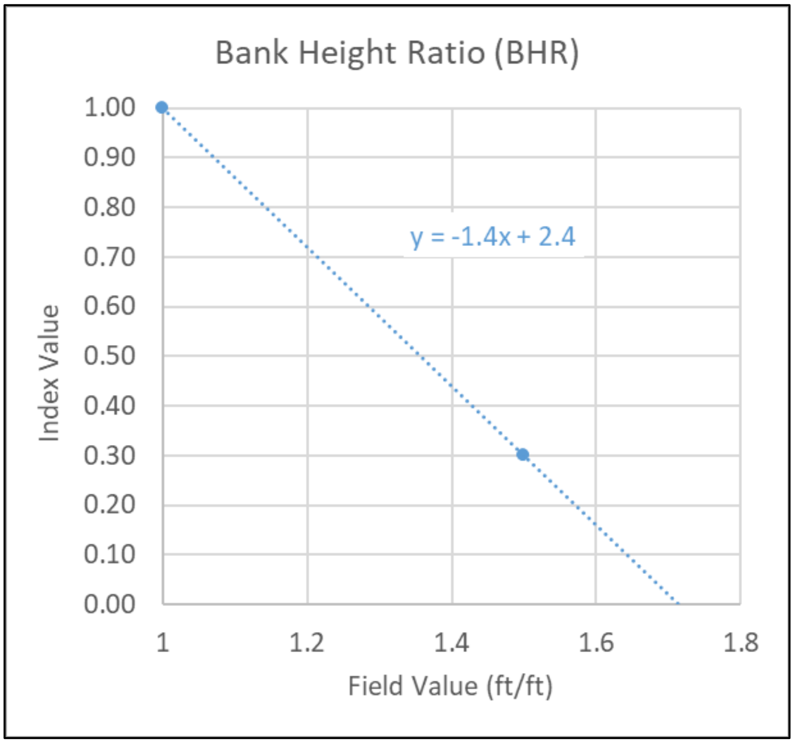



*Figure 6-1: Bank Height Ratio Reference Curve.*

**Limitations and Data Gaps:**

If bankfull dimensions are not accurately determined for a site, then the bank height ratio will not accurately represent the incision processes. When possible, localized regional curves and flood frequency analysis should be used to verify the field indicators of bankfull. Additional information on verifying bankfull information was added to the WSQT v1.0 User Manual in response to comments received during beta testing. Recognizing that bankfull features can be difficult to identify in the field, particularly following flow alteration, specific procedures and data forms to identify and verify bankfull were added to the WSQT v2.0 User Manual. These procedures include scenarios where flow alteration rather than incision has reduced floodplain connectivity.

## 6.2. Entrenchment Ratio

**Summary:**

The entrenchment ratio (ER) is a ratio of the flood prone area width divided by the bankfull riffle width. 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 based on physical measurements (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 this metric are provided in the WSQT v2.0 User Manual.

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 floodprone width is small compared to the width of the channeling. Large ERs are found in alluvial valleys where large flow events can spread out laterally. ER naturally varies by valley shape and are therefore used as a primary metric in differentiating stream types (Rosgen 1996). ER can be a useful indicator of functional capacity as many anthropogenic alterations (e.g., levees, berms, and channelization) constrict the natural extent of floodplains and decrease floodplain connectivity.

For F and G channels that represent degraded streams, these systems should be compared against the reference stream type, as informed by channel evolution processes (Rosgen 2009) and described in the WSQT v2.0 User Manual. For example, if the existing stream type is a degraded Gc in an alluvial valley, the reference stream type and reference curve would be a C or E stream type. Selection of the appropriate reference stream type is important for consistently applying this metric and determining a condition score in the tool. Guidance is provided in the WSQT v2.0 User Manual to assist practitioners in identifying the reference stream type.

**Reference Curve Development:** Reference curves for this metric have been updated for WSQT v2.0.

Entrenchment Ratio (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 those in between 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 and by modeling a bankfull discharge and 50-year recurrence 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 Da's, with less confined streams like E's having 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 6-4 after considering the differences among stream types. The performance 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 6-4: Entrenchment Ratio Performance 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 criteria proposed by Harman et al. (2012) were evaluated for Wyoming using the compiled geomorphic reference dataset described in Section 1.8 of this manual. The compiled geomorphic reference dataset consists of 61 sites that report ER. Of these sites, three were identified as outliers and removed from the analysis and three sites were classified as F channels and were also removed from the analysis. The statistics for ER stratified by stream type are provided in Table 6-5 and Figure 6-2.

*Table 6-5: Statistics for ER from the Compiled Geomorphic Reference Dataset.*

| Statistic | ER by Stream Type | | | |
|---|---|---|---|---|
| | B | C* | E | Cb |
| Number of Sites (n) | 22 | 15 | 8 | 10 |
| Average | 1.8 | 3.7 | 5.5 | 3.4 |
| Standard Deviation | 0.5 | 1.1 | 3.3 | 1.5 |
| Minimum | 1.2 | 2.4 | 2.3 | 1.5 |
| 25$^{th}$ Percentile | 1.5 | 2.9 | 3.3 | 2.4 |
| Median | 1.8 | 3.5 | 5.0 | 3.2 |
| 75$^{th}$ Percentile | 2.2 | 4.4 | 6.5 | 3.9 |
| Maximum | 2.8 | 6.8 | 12.5 | 6.9 |

**excludes Cb streams*

Bankfull width was used as a denominator of this metric, and thus stratification by stream size was not needed. Scaling by bankfull width accounts for the differences in stream size that may otherwise be relevant in determining flood prone width. Bankfull dimensions vary greatly throughout the country due to differences in climate and runoff characteristics; however, bankfull regional curves can be used to calibrate field identifications (Blackburn-Lynch et al. 2017).

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. The compiled geomorphic reference dataset did not include A stream types, but they are likely represented by confined-valley stream types as they naturally occur in confined valleys.

The WSTT evaluated the performance standards in Table 6-4 using the compiled geomorphic reference dataset to develop the threshold values in Table 6-6. Updates were made to thresholds and reference curves in WSQT v2.0. Thresholds and updates are described below.

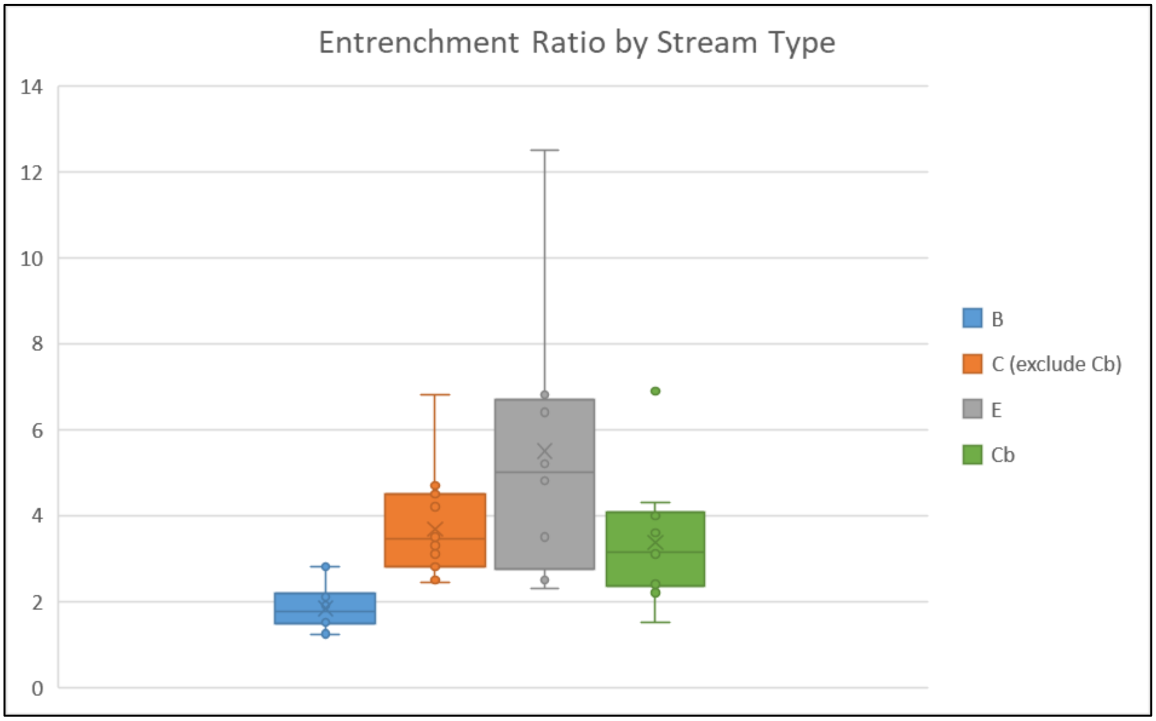



*Figure 6-2: Box plots for ER from the Compiled Geomorphic Reference Dataset.*

For C and E stream types:

- In the WSQT v1.0, C and E stream types were grouped together since they typically occur in the same valley types and C stream types have the potential to evolve into an E stream (Rosgen 2009). In WSQT v2.0, separate reference curves were developed for these stream types. Further, in WSQT v2.0, Cb stream types were separated from other C stream types since Cb stream types are located in confined alluvial or colluvial valleys. The 0.70 threshold values are the same for E, C and Cb streams, but the functioning maximum index scores vary.
- An ER of 2.2 was used to define the threshold between functioning and functioning-at-risk for C and E stream types (Table 6-4). This update was made in WSQT v2.0 to align the threshold values with the classification criteria from Rosgen (1996). In other words, if the ER meets the criteria to be an E or C stream type, then it is functioning as an E or C stream.
- In the geomorphic reference dataset, there was quite a bit of variability in the upper bounds of ER values for C, Cb and E stream types. In WSQT v2.0, E stream types were separated out from C and Cb stream types to define the maximum index score. As

shown in Table 6-5, the 75th percentile for C, Cb and E stream types were 4.2, 3.9, and 6.7 respectively. These values were used to set the maximum index score.

- While an ER of 2.0 was used in WSQT v1.0 to define the threshold between not-functioning and functioning-at-risk, this was removed for v2.0 to simplify the reference curves. Instead, an ER of 1.0 was used to set the 0.00 threshold. 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. In other words, if the ER is 1.0 there is not a floodplain or floodplain bench; there is no flood prone area.

For B stream types:

- While an ER of 1.2 was used in the WSQT v1.0 to define the threshold between functioning-at-risk and not-functioning, this was removed for v2.0 to simplify the reference curves. Instead, an ER of 1.0 was used to set the 0.00 threshold. 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. In other words, if the ER is 1.0 there is not a floodplain or floodplain bench; there is no flood prone area.
- An ER of 1.4 was selected as the threshold between functioning and functioning-at-risk. This aligns the threshold value with the classification criteria from Rosgen (1996), was selected by Harman et al. (2012), and is supported by the 25th percentile value from the compiled geomorphic reference dataset (1.5).
- The ER value that yields the maximum index value was set at 2.2 which is the 75th percentile value from the compiled geomorphic reference dataset and the typical value used in the stream classification system as a break between B stream types and C and E stream types (Rosgen 2009).

The best-fit line for the plotted threshold values was derived using multiple linear relationships. The final reference curves are shown in Figure 6-3 (a-d).

*Table 6-6: Threshold Values for Entrenchment Ratio.*

| **Index Value** | **Field Values by Stream Type** | | | |
|---|---|---|---|---|
| | A, B, Ba, Bc | C | E | Cb |
| 1.00 | ≥ 2.2 | ≥ 4.2 | ≥ 6.7 | ≥ 3.9 |
| 0.70 | 1.4 | 2.2 | 2.2 | 2.2 |
| 0.00 | 1.0 | 1.0 | 1.0 | 1.0 |

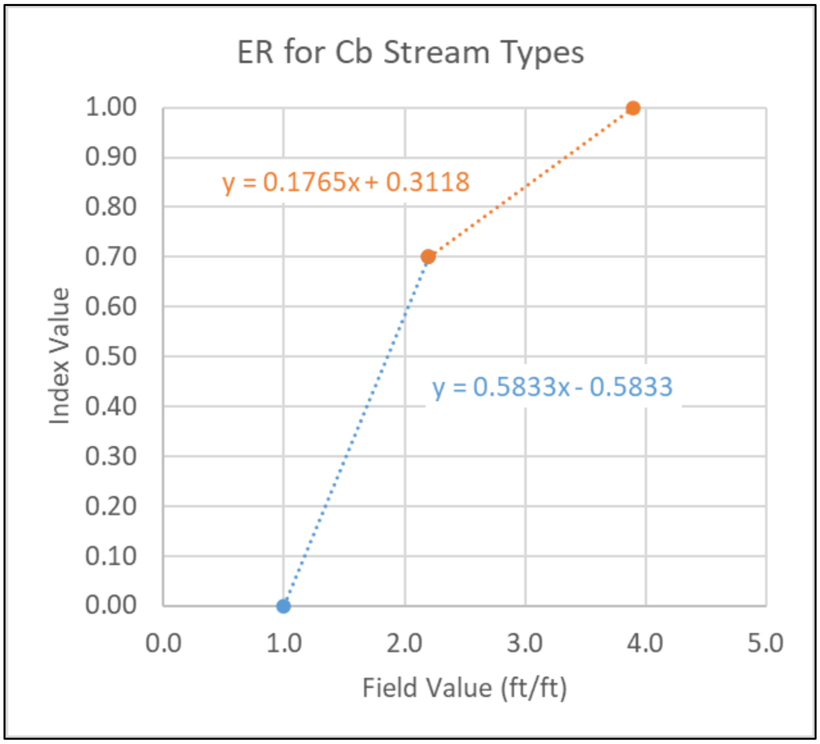



*Figure 6-3a: Entrenchment Ratio Reference Curve for Cb Stream Types.*

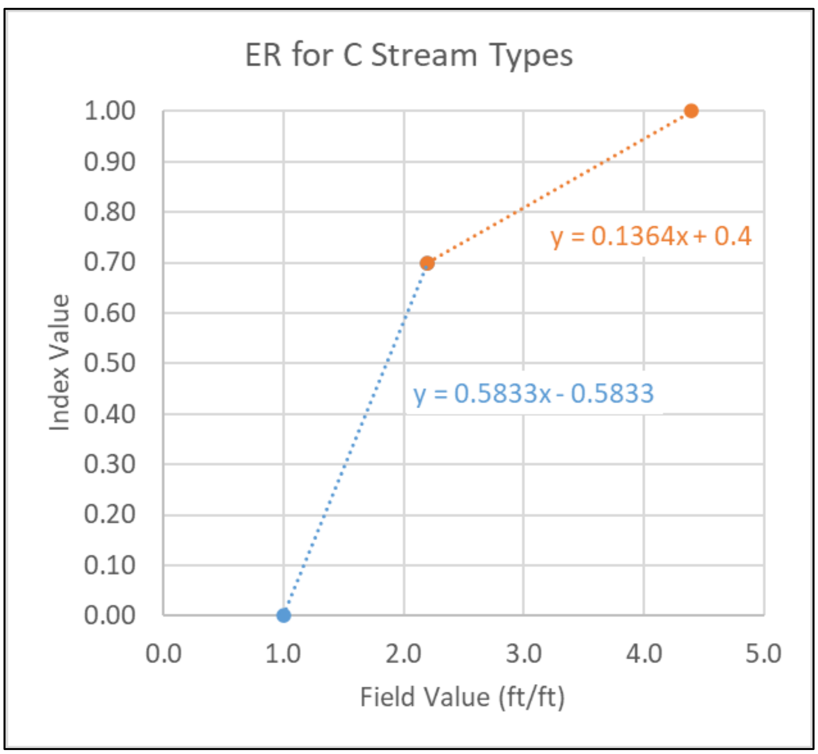



*Figure 6-3b: Entrenchment Ratio Reference Curve for C Stream Types.*

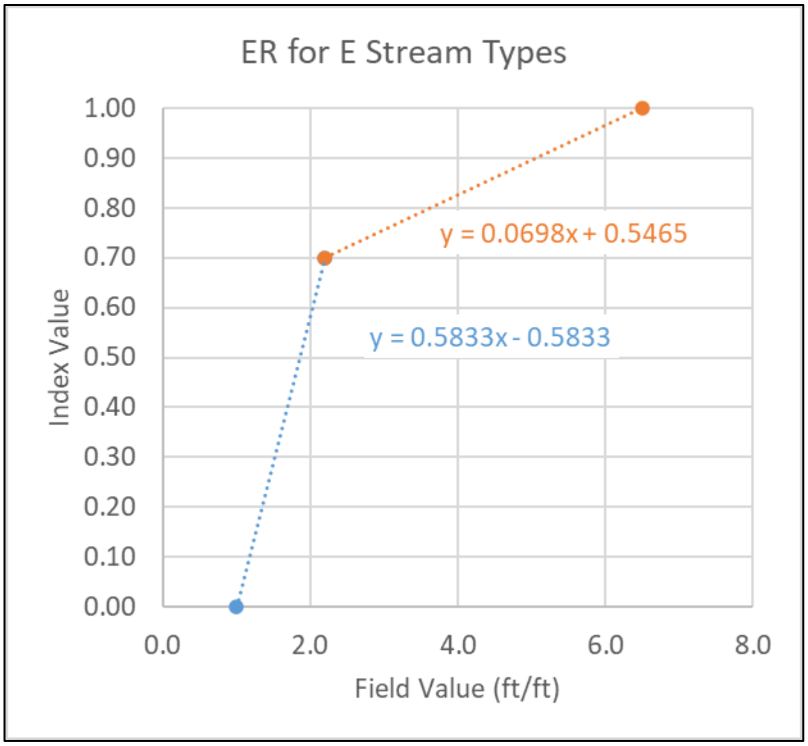



*Figure 6-3c: Entrenchment Ratio Reference Curve for E Stream Types.*

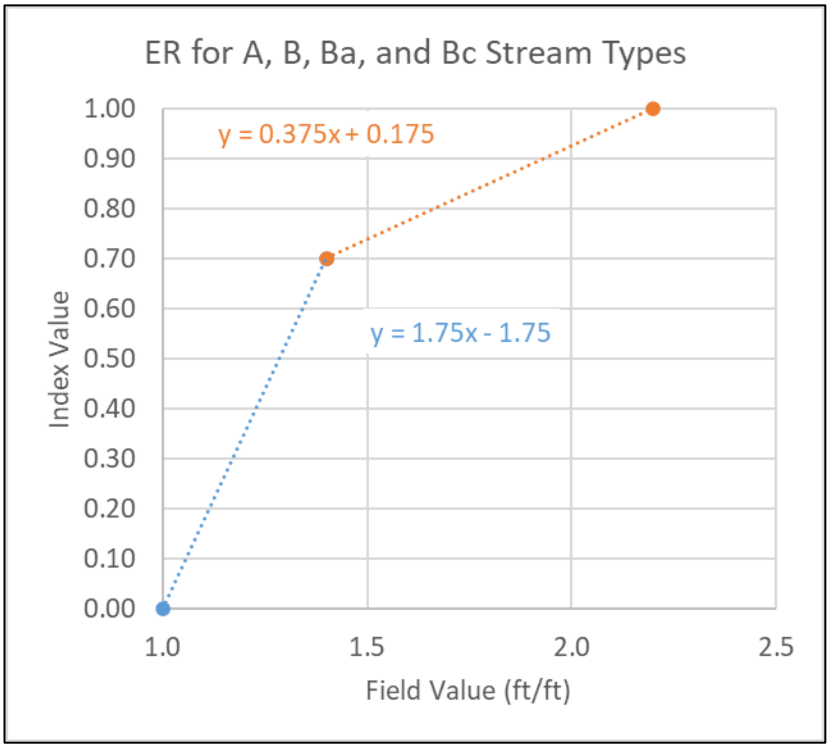



*Figure 6-3d: Entrenchment Ratio Reference Curves for A, B, Ba and Bc Stream Types.*

**Limitations and Data Gaps:**

If bankfull dimensions are not accurately determined for a site, then the entrenchment ratio will not accurately represent entrenchment processes. Additional information on verifying bankfull information was added to the WSQT v1.0 User Manual in response to comments received during beta testing. Recognizing that bankfull features can be difficult to identify in the field, particularly following flow alteration, specific procedures and data forms to identify and verify bankfull were added to the WSQT v2.0 User Manual. These procedures include scenarios where flow alteration rather than incision has reduced floodplain connectivity.

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, this 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).

## 6.3. Percent Side Channels

**Summary:**

The percent side channel metric was added to the WSQT v2.0 to account for the importance of side channels (e.g., sloughs and side channels, natural chute cut-offs, and connecting oxbow ponds) in the hydraulic and geomorphic functioning of alluvial systems. This metric was initially developed for use in the CSQT (USACE 2020a). This section is reproduced with minor edits from USACE (2020b) for adaptation and use in the WSQT.

Side channels can provide thermal refugia (Fernald et al. 2006; Torgersen et al. 2012), habitat refugia during high flows, and may also be used as spawning habitat if they contain the ideal depths, velocities, and substrate size for targeted species (Pitlick and Steeter 1998). They may also provide critical juvenile rearing habitat for various fish species, as well as refuge from larger predatory fish (Brown and Hartman 1987; Angermeier and Schlosser 1995; Sommer et al. 2001; Fausch et al. 2002). In Wyoming, side channels have been documented to provide important overwintering and spawning habitats (Johnson 1994; Gelwicks 2002; Sanderson 2007; McElroy 2021). In general, side channels increase hydraulic and geomorphologic habitat diversity and can create conditions that support a diverse assemblage of species during different life stages.

Side channels include all open channels connected to the main channel of the project reach that carry water between baseflow and half-bankfull, even if it is only connected at one end, e.g., a slough or backwater channel. Floodplain channels that are not connected on either end to the main channel are not considered a side channel, an example being an oxbow that is filled on both ends (Landers et al. 2002; Nadeau et al. 2018). In addition, channels that are only inundated at bankfull and higher flows are not included. While this may vary from other definitions of side channel, backwater areas provide valuable habitat.

This metric estimates the percent of the project reach length that has side channels and is only applicable in alluvial valleys. Side channels were considered an important metric for inclusion in the Oregon Stream Function Assessment Method (SFAM; Nadeau et al. 2018), and their approach was used to inform this metric in Colorado (USACE 2020b) and Wyoming.

**Reference Curve Development:**

Reference curves for the WSQT and CSQT are adapted from the reference curves in the Oregon SFAM (Table 6-7; Nadeau et al. 2018). The SFAM is similar to the SQT in that it scores metrics on a 0.0 to 1.0 scale, with scores between 0.7 and 1.0 indicating a high functioning system. Nadeau et al. (2018) compiled data from multiple studies showing that increases in side channel habitat leads to increases in coho smolt production. While Colorado and Wyoming do not support the same fish assemblages as Oregon, members of the CSQT SC and WSTT recommended the metric and reference curves be tested for use in these states.

*Table 6-7: Threshold Values for Side Channel Metric Presented in the Oregon SFAM (Nadeau et al. 2018).*

| Index Value | Field Metric |
|---|---|
| 1.00 | 100 |
| 0.70 | 50 |
| 0.30 | 10 |
| 0.00 | 0 |

While the side channels metric is not stratified in the SFAM, Nadeau et al. (2018) notes that side channels are more common within alluvial valleys. In the CSQT (2020), stratification was added within alluvial valleys to create separate reference curves for confined alluvial and unconfined alluvial valleys. The WSTT agreed with this approach and proposes the same two reference curves in Wyoming. The threshold values for perennial streams in unconfined alluvial valleys adopted the thresholds within the SFAM shown in Table 6-7. A second set of thresholds was developed for perennial streams in confined alluvial valleys (Table 6-8). Best professional judgement was used to determine threshold values for the confined alluvial valleys. Confined alluvial valley threshold values were reduced to better represent that confined valley widths cannot support as much secondary channel length. Linear reference curves (Figure 6-4) were fit to the threshold values shown in Table 6-8.

*Table 6-8:Threshold Values for Percent Side Channels.*

| Index Value | Field Values by Valley Type | |
|---|---|---|
| | Unconfined Alluvial Valleys | Confined Alluvial Valleys |
| 1.00 | ≥ 100 | ≥ 50 |
| 0.70 | 50 | 25 |
| 0.30 | 10 | 5 |
| 0.00 | 0 | 0 |

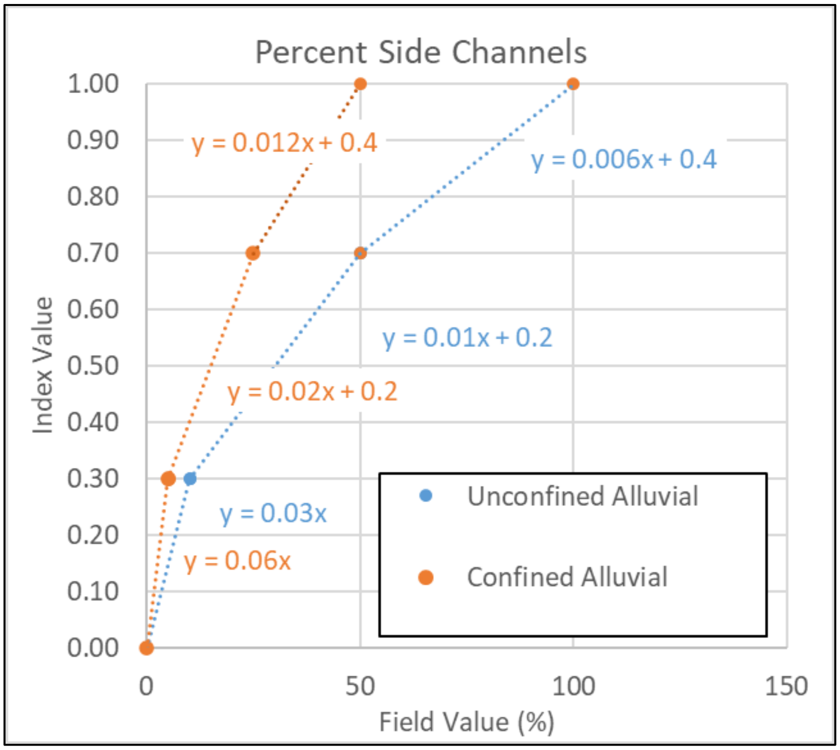



*Figure 6-4: Percent Side Channels Reference Curves*

**Limitations and Data Gaps:**

This metric was developed largely based on data from the Pacific Northwest and best professional judgment. While there are studies documenting the benefits of side channels in Wyoming (Johnson 1994; Gelwicks 2002; Sanderson 2007; McElroy 2021), this metric would benefit from additional validation, review and refinement as the tool is applied. In particular, the reference curves for streams in confined alluvial valleys would benefit from testing at field sites.

This metric is also limited in that it only measures the presence of side channels and not the quality of the side channels. The hydraulic conditions within both the side channel(s) and the main channel are not characterized by this metric and it is possible that suitable habitat conditions for target species are not met merely by the presence of side channels.

It would be useful to apply this metric in settings where beaver are present or anticipated, particularly where beaver dams comprise large portions of a valley's flood-prone area or otherwise create complex networks of channels that are difficult to measure or map.

# Chapter 7. 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) that are transported or stored in the channel, floodplain and flood prone area (USBR and 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 to recruit LWD. Therefore, this parameter is not applicable to streams that naturally lack forested catchments, riparian gallery forests, or other streams that naturally have a supply of LWD.

There are numerous metrics available to assess large woody debris. Complex methods include individual piece and jam counts within the channel and floodplain, along with characterization of wood size, type, location and volume (Wohl et al. 2010). The Large Woody Debris Index (LWDI; Davis et al. 2001) outlined below provides a similar characterization of LWD in a single index value for a 328-foot (100-meter) reach. Complex approaches like these provide information about how the presence and configuration of wood affects reach-scale functions. For example, large diameter and long pieces of wood and jams within the channel that cannot be readily mobilized, have a greater influence on in-stream functions than a small piece of wood near the top of bank that is easily mobilized. More simplified approaches, such as piece counts, are also 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 influence of wood within the channel.

The WSQT includes two metrics to characterize LWD within streams: 1) the Large Woody Debris Index (LWDI) and 2) the 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.

**Metrics:**

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

## 7.1. Large Woody Debris Index (LWDI)

**Summary:**

This 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 (pieces and debris dams) based on their 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 (length and width in relation to bankfull dimensions, diameter); 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.

The LWDI is a moderately robust measure that is not overly complex. The LWDI requires a moderate level of effort and can typically be completed in one hour or less per project reach. Methods for the LWDI are described in *Application of the Large Woody Debris Index: A Field User Manual* (Harman et al. 2017). However, Davis et al. (2001), the original methodology, should be consulted first, as Harman et al. (2017) was compiled to answer questions that came up while applying the original methods.

**Reference Curve Development:**

The WSTT, WDEQ and WGFD collected LWDI data at 22 reference standard sites in Wyoming to develop reference curves for the WSQT. Data were collected at minimally disturbed sites primarily in the mountains, but a few sites were within the basin ecoregion of the state. Table 7-1 shows the statistics for these data. Data collection efforts are continuing to improve the dataset and reference curves. No stratification of this metric was included due to the small reference dataset in Wyoming.

*Table 7-1: Statistics for the Wyoming LWDI Reference Standard Dataset. All values are per 328 feet (100 meters) of stream.*

| Statistic | LWDI Value |
|---|---|
| Number of Sites (n) | 22 |
| Average | 689 |
| Standard Deviation | 416 |
| Minimum | 17 |
| $25^{th}$ Percentile | 433 |
| Median | 656 |
| $75^{th}$ Percentile | 948 |
| Maximum | 1583 |

The following threshold values were proposed based on this dataset and presented in Table 7-2:

- The median of the reference dataset was used to determine the maximum index score (the median value of 656 was rounded up to 660). The median value was used instead of the 75th percentile to account for lower potential for LWD in plains and basins ecoregions. While there are sites from across the state in the dataset, there are more sites in the mountains where higher LWD presence is expected. Also, there are a few sites in the reference dataset that exhibit LWDI values greater than 1000, and these may have been influenced by recent fires or insect mortality.
- The 25th percentile of the reference dataset was used to inform the threshold between functioning and functioning-at-risk index values. The 25th percentile value of 433 was rounded to 430.
- Due to a lack of LWDI data from degraded sites, no field values were used to define a threshold between functioning at risk and non-functioning index values. Index values within this range are interpolated from the reference curve.

Two sites were evaluated in Colorado as part of the regionalization of the CSQT (USACE 2020b), a reference site and a restored site. Both sites scored at the upper range of functioning-at-risk, which is consistent with the field observations made by CSQT SC members in the field. The reference site in Colorado had a large number of pieces, however, most of these pieces were relatively small in size and movable; therefore the LWD presence was not contributing as significantly to channel structure and roughness as reference sites observed in Wyoming.

*Table 7-2: Threshold Values for the LWDI (per 328 feet or 100 meters).*

| Index Value | Field Value |
|---|---|
| 1.00 | ≥ 660 |
| 0.70 | 430 |
| 0.00 | 0 |

A reference curve (Figure 7-1) was derived from the threshold values presented above. A broken linear curve was used to calculate index values.

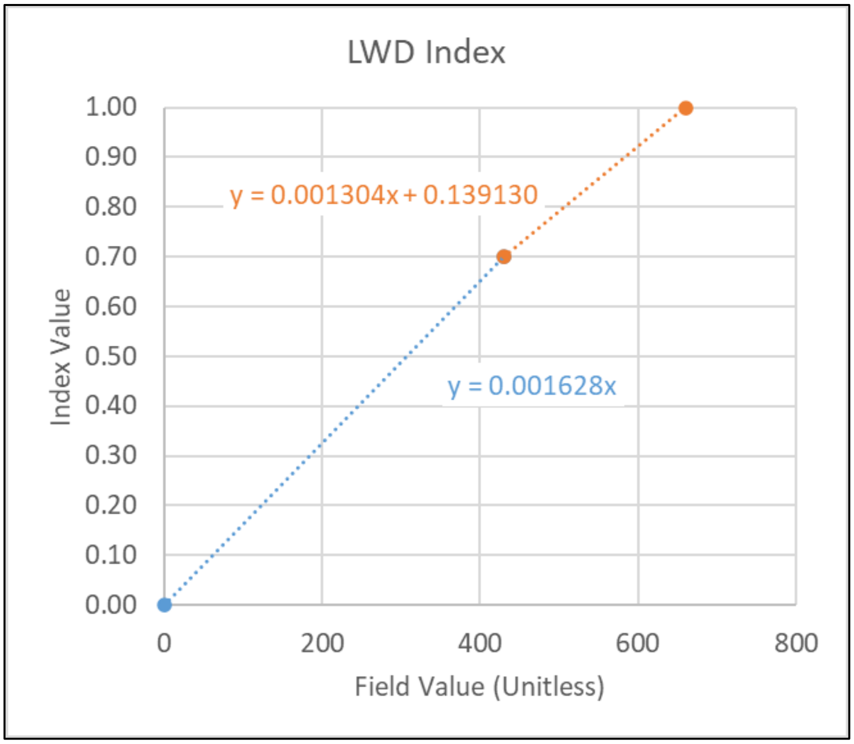



*Figure 7-1: LWDI Reference Curve.*

**Limitations and Data Gaps:**

The LWDI is a new metric for Wyoming streams and the reference curves in the WSQT are developed from a relatively small sample size located primarily within the mountain ecoregion. As more data are collected, further refinement and stratification of these data and reference curves may be possible. Stratification could consider the role of ecoregion, drainage area, valley type, forest age, canopy type, and other variables (Wohl 2011; Wohl and Beckman 2014).

This metric is not applicable to streams without forested catchments, riparian gallery forests, or other streams that naturally have a limited supply of LWD. During beta testing, it was noted 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 does not qualify as LWD. Additional guidance is provided in the WSQT v2.0 User Manual to address these situations.

## 7.2. Number of Large Wood Pieces per 328 feet (100 meters)

**Summary:**

This metric is a count of the LWD pieces in a 100-meter section of the reach, where each piece is counted separately, including within debris dams. To be considered LWD, 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). 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:**

Reference curves were developed using the NRSA dataset, described in Section 1.8, which includes a variety of metrics associated with LWD, including the number of pieces per 100 meters. Reference curves were validated using the LWDI data described in the previous section. However, since the LWDI scores dams separately than pieces, the total number of pieces was estimated by assuming all dams only contained three pieces of LWD (Table 7-3). Therefore, these estimated piece counts are likely lower than the actual number of pieces that would be collected with the WSQT methods.

The methods used to collect the NRSA data (i.e., number of LWD pieces in/above the wetted channel within 100m; all sizes) were similar to the LWD piece count developed for the WSQT. There is one notable distinction between the two data collection methods: the NRSA method is an average number of pieces per 100 meters of stream, whereas the WSQT procedure collects data on the 100-meter segment within the reach that would yield the highest value. Therefore, the piece counts from NRSA are likely lower than the number of pieces that would be collected with the WSQT methods.

An effort was made to identify reference sites within the NRSA dataset using legacy tree size, riparian vegetation condition, absent canopy, and other attributes available within the NRSA dataset. However, a multivariate analysis was beyond the scope of this analysis and no single attribute was thought suitable to describe reference condition for LWD. As such, the NRSA dataset for this metric includes all reference aquatic resources, including reference standard and degraded sites. Future data analyses and collection efforts will continue to improve the dataset and reference curves.

Stratification of the data by region was explored using the NRSA dataset. Stratification by bankfull width and dominant canopy type (coniferous, deciduous, mixed, or evergreen) were also considered. However, many of the NRSA sites listed the dominant canopy as absent, indicating that there was no canopy at the site. Bankfull width was considered as a surrogate for stream size or drainage area, but no meaningful trend was identified using bankfull width as an independent variable. The dataset was not large enough to stratify by both ecoregion and bankfull width and produce meaningful results. Therefore, the WSTT analyzed data by ecoregion since the ecoregion may represent differences in the riparian community and LWD source material.

The statistics for the NRSA LWD dataset are provided in Table 7-3 and Figure 7-2. Note that the NRSA dataset includes both reference standard and degraded sites, and the 25$^{th}$ percentile and median values for all three ecoregions are low. The average and 75$^{th}$ percentile values indicate that streams in the mountains tend to have the most wood and streams in the basins tend to have the lowest amount of wood. While these differences could be used to produce separate reference curves for the ecoregions, there are multiple sites in both the plains and basins that exhibited large amounts of LWD, as seen in the 95$^{th}$ percentile values in Table 7-3. Some sites within the basins and plains ecoregions may occur in forested areas that provide significant source material, but these sites could not be differentiated in the dataset. Thus, a single reference curve was applied to all ecoregions at sites occurring within naturally forested watersheds or riparian gallery forests.

*Table 7-3: Statistics for Number of LWD Pieces from the NRSA Dataset.*

| Statistic | Number of LWD pieces/100m by Ecoregion | | | Number of LWD pieces/100m All NRSA Data | LWDI Estimated Piece Counts |
|---|---|---|---|---|---|
| | Basins | Mountains | Plains | | |
| Number of Sites (n) | 64 | 38 | 68 | 170 | 22 |
| Average | 4 | 9 | 5 | 6 | 30 |
| Standard Deviation | 9 | 15 | 8 | 11 | 19 |
| Minimum | 0 | 0 | 0 | 0 | 1 |
| 25th Percentile | 0 | 0 | 0 | 0 | 23 |
| Median | 1 | 3 | 1 | 1 | 28 |
| 75th Percentile | 2 | 13 | 6 | 7 | 45 |
| 95th Percentile | 24 | 28 | 21 | 26 | 57 |
| Maximum | 49 | 80 | 45 | 80 | 74 |

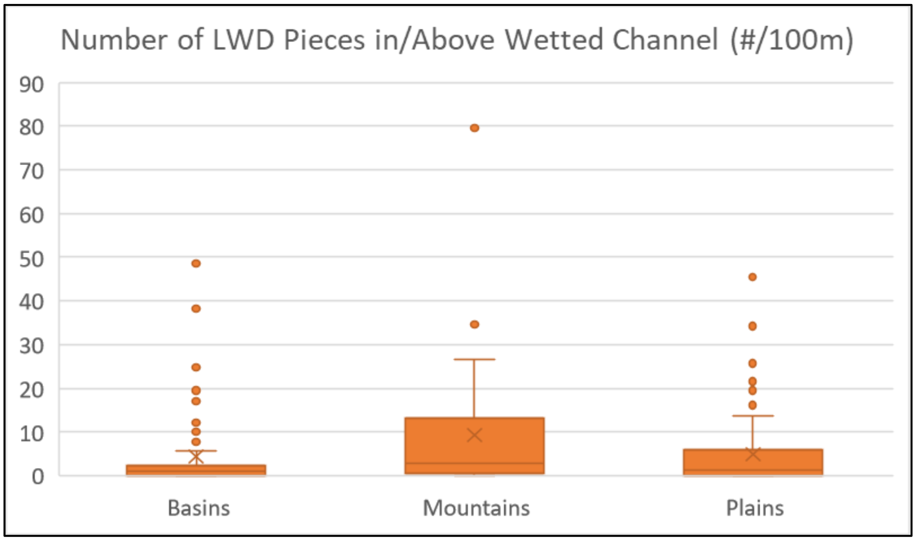



*Figure 7-2: Box plots for Number of LWD Pieces from the NRSA Dataset.*

Based on the assumption that the LWD parameter would not be applicable for many sites within the basins and plains, the reference curve was developed using the data from the mountain ecoregion. The following threshold values were used to inform the curve (Table 7-4):

- The 95th percentile from the NRSA sites within the mountains matched the median value from the LWDI estimated piece count. The median value from the latter dataset was used to define the maximum index score for the LWDI metric. The 95th percentile from the mountains was used to define the maximum index score for this metric.

- The 75th percentile from the NRSA sites within the mountains was used to define the threshold between functioning and functioning-at-risk. The 25th percentile from the LWDI dataset was used to define the threshold between functioning and functioning-at-risk for the LWDI metric, but because the NRSA dataset contains non-reference standard sites and the LWDI dataset does not, it did not make sense to similarly rely on the 25th percentile.

A broken linear curve was fit to the threshold values (Figure 7-3).

*Table 7-4: Threshold Values for the Number of LWD Pieces per 100 meters.*

| Index Value | Field Value |
|---|---|
| 1.00 | ≥ 28 |
| 0.70 | 13 |
| 0.00 | 0 |

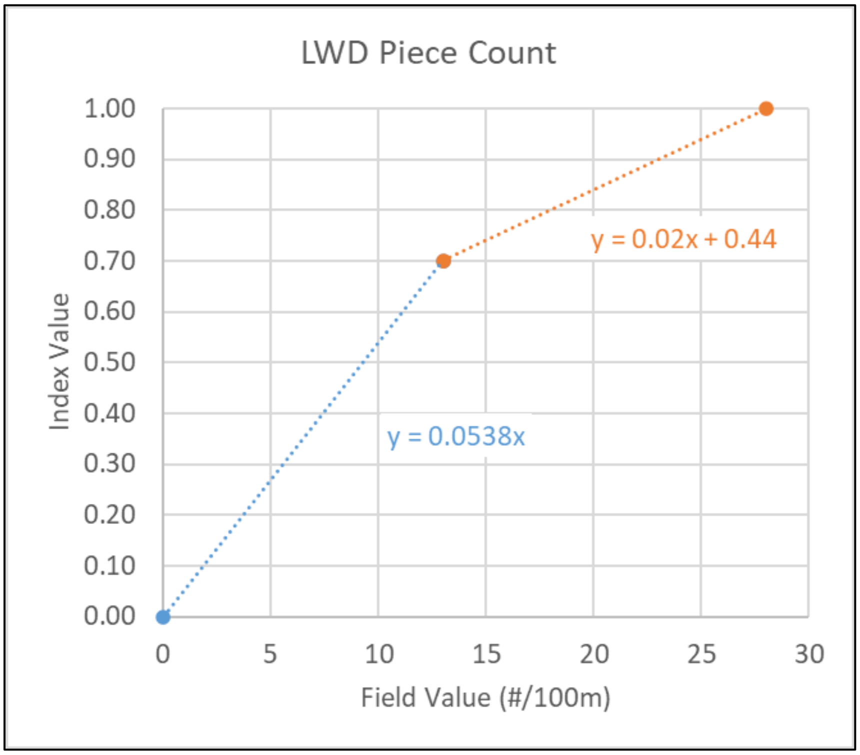



*Figure 7-3: Number of LWD Pieces Reference Curve.*

**Limitations and Data Gaps:**

This metric is not applicable to streams without forested catchments, riparian gallery forests, or other streams that naturally have a limited supply of LWD. During beta testing, it was noted that streams in scrub-shrub or willow dominated systems may have substantial wood in the channel associated with willow jams, but the size of the pieces does not meet the definition of LWD provided in the LWDI method. Additional guidance is provided in the WSQT v2.0 User Manual to address these situations using the LWDI, but not for the piece count metric. In these instances, it may be beneficial to use the LWDI instead of this metric.

As more data are collected, further refinement and stratification of these data and development of multiple reference curves may be possible. Stratification could consider the within-ecoregion differences associated with drainage area, forest age, valley type, canopy type, and other variables.

# Chapter 8. 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. Local rates of bank erosion are influenced by many factors, including flow properties, bank material composition, climate, seepage and soil moisture, channel geometry and biology (Knighton 1998). Natural processes of lateral migration vary by stream. 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). Natural rates of bank erosion can be altered by anthropogenic factors, such as land use change, changes in drainage patterns, reservoir development, bank stabilization structures and other activities which modify sediment processes at the watershed and reach scale (Knighton 1998; 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 migration rates vary naturally by stream type and can be affected by changes in sediment processes at the watershed and reach scale (Roni and Beechie 2013). Lateral stability is one of the original parameters described in Harman et al. (2012). Readers should refer to Harman et al. (2012) for additional discussion of bank migration and lateral stability processes, and stream types that are susceptible to lateral migration versus those where migration is naturally constrained.

There are multiple approaches that can be used to measure lateral migration processes and condition (Harman et al. 2012). Some of these approaches include:

- Aerial imagery interpretation of bank retreat, measurements of belt width divided by bankfull width (meander width ratio), and visual assessment of bank cover and stability by photointerpretation of land use and cover types (Rosgen 1996; NRCS 2007).
- Semi-quantitative measures of bank cover and stability measured over the entire reach length (BLM 2017; WDEQ 2022; Binns 1982).
- 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, called BSTEM (Bank Stability and Toe Erosion Model) 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).
- Greenline Stability Rating characterizes the live perennial vascular plants and other natural stabilizing elements on or near the water's edge and provides a rating of bank stability for a subsampled section of the reach (Winward 2000).
- Measures of the extent of bank erosion and/or armoring within a reach (NRCS 2007).

The Lateral Migration parameter includes four metrics: the Greenline Stability Rating, dominant BEHI/NBS, percent eroding streambank and percent armoring. The dominant BEHI/NBS and percent eroding streambank 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 eroding streambank characterizes the extent of the problem. The Greenline Stability Rating metric can be collected instead of the BEHI/NBS assessment and is of similar complexity. The percent armoring metric should be used in project reaches where armoring has been or intends to be implemented.

The four 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. Sediment transport analyses are critical in understanding watershed and reach-scale processes and should be relied on to evaluate and develop design alternatives (Roni and Beechie 2013). These analyses are not currently incorporated into the tool, although sediment transport and channel evolution models are used to inform restoration potential (Section 1.3) and should be included in the design process.

**Metrics:**

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

## 8.1. Greenline Stability Rating

**Summary:**

There is a strong interrelationship between amount and kind of vegetation along the water’s edge and bank stability. Late successional plant communities are indicators of resilience, stability and reference condition (Youngblood et al. 1985; Winward 2000; MacFarlane et al. 2017). Evaluation of the types of vegetation along the greenline provides a good indication of a streambank vegetation’s ability to buffer the hydrologic forces of moving water (Winward 2000).

The Greenline Stability Rating (GSR) is collected along the greenline, which is a linear grouping of live perennial vascular plants on or near the water’s edge, generally slightly below the bankfull stage. The primary purpose of the GSR is to provide an index rating of the natural capacity of vegetation to protect streambanks against erosion as well as enhancing streambank strength, as they filter sediments and, with the forces of water, they build/rebuild eroded portions of streambanks (Winward 2000). The metric also characterizes anchored rocks or logs large enough to withstand the forces of water encountered on the greenline edge as a natural, stable percentage of the greenline in place of the vegetation.

The GSR is calculated by multiplying the percent composition of each community type along the greenline by the stability class rating assigned to that type and calculating the average value for the representative sub-reach. The WSQT allows for two methods to measure GSR: 1) the original data collection procedures described in Winward (2000), or 2) the Modified Winward Greenline Stability Rating procedures described in USDOI (2011). The latter integrates a more systematic approach to collecting data by using plots instead of paces and calculating stability ratings by key species rather than community types to improve precision and includes additional species stability ratings not identified in Winward (2000).

**Reference Curve Development:** The reference curve for this metric has been updated for WSQT v2.0.

The threshold values and reference curve for the WSQT are constructed on the index rating classes established by Winward (2000) as shown in Table 8-1.

*Table 8-1: Greenline Stability Rating and Functional Capacity.*

| GSR | Stability Description | Functional Capacity |
|---|---|---|
| 1-2 | Very Low | Not Functioning |
| 3-4 | Low | |
| 5-6 | Mid | Functioning-At-Risk |
| 7-8 | High | Functioning |
| 9-10 | Excellent | |

The WSQT threshold value between not functioning and functioning-at-risk is set at 5 (between low and mid) and the threshold between functioning-at-risk and functioning is set at 7 (between mid and high) as shown in Table 8-1 and Figure 8-1. A narrow range of the mid rating class is representing functioning-at-risk on the reference curve. Originally, a polynomial equation was fit to these threshold values, however, in the WSQT v2.0, this is updated, and linear equations are fit between the threshold values. These curves were compared with the WSTT data collection from 2016 (Table 8-2).

In August 2016, the WSTT visited several sites to apply the proposed WSQT methodology for assessing riparian vegetation. These sites were considered to represent minimally disturbed reference standard sites. However, because they are located on public lands, they have likely been subject to some historical use, including grazing and/or timber removal. In evaluating the datasets and proposed benchmarks, the WSTT concluded it was reasonable to characterize these sites as functioning or (high) functioning-at-risk. These sites have the potential to support a healthy aquatic ecosystem and were not in a clearly degraded state.

*Table 8-2: Greenline Stability Rating at Reference Sites Visited by the WSTT.*

| Site | Ecoregion | GSR |
|---|---|---|
| Wood River, above Middle Fork | Mountains | 6.1 |
| Middle Fork Wood River | Mountains | 6.9 |
| Middle Fork Wood River - Upstream | Mountains | 7.4 |
| Jack Creek | Mountains | 8.0 |

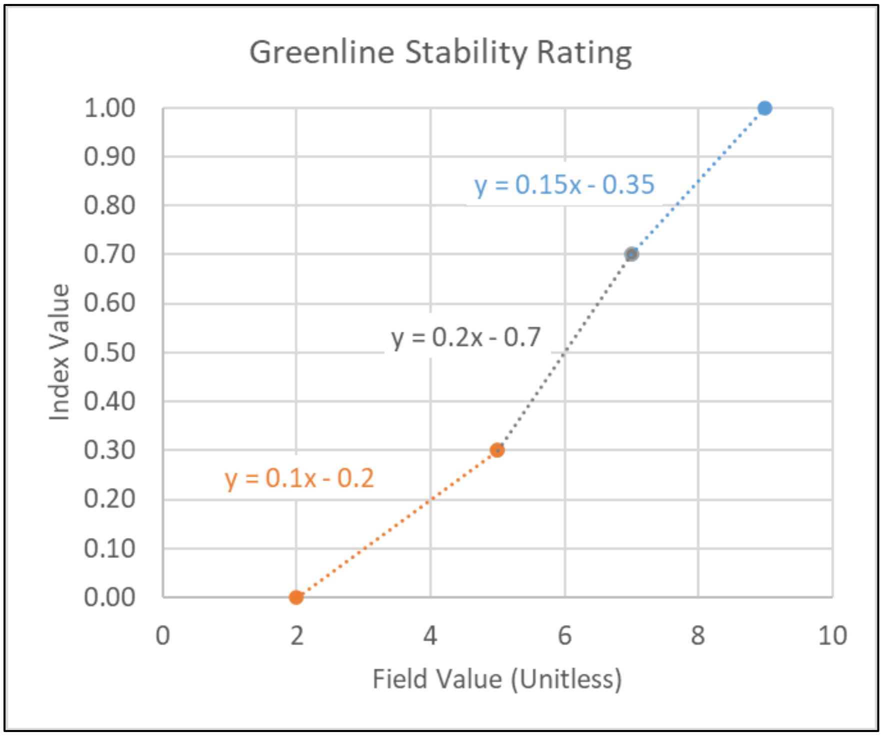



*Figure 8-1: Greenline Stability Rating Reference Curve.*

**Limitations and Data Gaps:**

As described above, two methods may be employed to produce the GSR. The same methodology must be used for pre- and post-condition/project use. Results may vary and not be comparable between projects where different methodology are performed. The original Greenline publication only includes stability class information for riparian (plant) community types of the Intermountain/Rocky Mountain Region (Youngblood et al. 1985), while USDOI (2011) has notably expanded the list of bank stability ratings for other species and community types in the western United States. The MIM Technical Reference (USDOI 2011 Table H1. p. 136) also outlines procedures for developing a relative stability value based on general rooting characteristics assigned by the authors or with reference to the literature.

The number of feet of anchored rocks or logs, large enough to withstand the forces of water, encountered along the greenline edge are counted as a natural, stable percentage of the greenline in place of the vegetation. A potential limitation of this method is differentiation between natural stabilizing elements and unnatural armoring such as exposed riprap that can artificially elevate the stability rating. Armoring treatments in many systems can be considered an adverse impact or form of functional loss. In these cases, use of this metric should be applied in conjunction with the percent armoring metric.

The GSR becomes less valuable in steeper (greater than 4 percent gradient) streams because the large, anchored rocks are generally less susceptible to management activities (Winward 2000). Additionally, for large rivers where hydrology is largely regulated by landform features (i.e., geology) instead of vegetation, the GSR may also be less valuable (Winward 2000).

## 8.2. Dominant BEHI/NBS

**Summary:**

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 2006). BEHI and NBS ratings are determined based on collecting field measurements and visual observations. The BEHI portion of the streambank assessment includes the evaluation of streambank height, depth and density of roots, vegetation cover and bank angle (Rosgen 1996, 2006). 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, including 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 for the reach. Thus dominant BEHI/NBS is the mode rating for the reach. 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 WSQT v2.0 User Manual.

Regionalization efforts for the BANCS model have met with mixed results when BEHI/NBS ratings have been used to predict erosion rates (McMillan et al. 2017). However, using the dominant BEHI/NBS rating to characterize the severity of the relative risk of bank erosion, *rather than* trying to predict a quantitative erosion rate, places the focus on the potential for accelerated bank erosion due to geotechnical and hydraulic forces. BEHI/NBS is included in the WSQT 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 method assesses both geotechnical (BEHI) and hydraulic (NBS) forces, which is unique among rapid methods. This is important because vertical banks devoid of vegetation may visually appear to be eroding, but if the hydraulic forces acting against the bank are very low, and bank materials are cohesive and non-stratified, there may be little to no bank erosion potential.
3. It is a common method 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 BEHI and NBS ratings were tested with field data collected in Colorado and Wyoming, as described in Rosgen (1996). Each combination of BEHI and NBS rating is assigned to one of four stability categories (Table 8-3; Rosgen 2008). The WSTT converted these stability categories into functional capacity ratings as follows: stable represents functioning, moderately unstable represents functioning-at-risk, and unstable and highly unstable represent not functioning.

*Table 8-3: Dominant BEHI/NBS Stability Ratings Provided in Rosgen (2008). (VL) is very low; (L) is low; (M) is moderate; (H) is high; (VH) is very high; etc.*

| Stable | Moderately Unstable | Unstable | Highly Unstable |
|---|---|---|---|
| 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 |

** Ratings were included in two categories. The erosion rate curves based on data from Colorado were consulted to remove duplicate values from the table.*

Because the metric relies on categorical data, reference curves were not developed. Instead, the ratings and categories from Table 8-3 were assigned to a functional capacity category, with specific index values assigned based on relating the stability ratings to functional capacity as described below and shown in Table 8-4.

- The ratings within the stable category were considered to represent a functioning condition (1.00). Stable in this context indicates that functioning streams migrate laterally at appropriate rates and maintain their cross-sectional area and sustain functioning riparian vegetation while their position on the landscape may change.
- The ratings within the moderately unstable category were considered to represent a functioning-at-risk range of condition (0.30-0.69).
- The ratings within the unstable and highly unstable categories were considered to represent a not-functioning condition (0.00-0.29).

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

*Table 8-4: 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 |
| 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 | L/VL, L/L, L/M, L/H, L/VH, M/VL |

**Limitations and Data Gaps:**

This 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 BEHI will not accurately represent erosion processes. Information on verifying bankfull stage is provided in the WSQT v2.0 User Manual.

## 8.3. Percent Streambank Erosion

**Summary:**

This metric estimates the percent of the streambank within a reach that is actively eroding, according to BEHI/NBS ratings. The percent eroding streambank metric provides a measure of the extent of bank erosion, whereas the dominant BEHI/NBS rating provides the magnitude of active bank erosion. BEHI/NBS ratings that represent non-eroding and actively eroding banks are listed in Table 8-5. These ratings were categorized by the WSTT; all stable and some moderately stable ratings were categorized as non-eroding. The field value is calculated by adding the length of BEHI/NBS ratings that represent actively eroding banks from the left and right banks and dividing it by the total bank length (e.g., project reach length times two). Multiply by 100 to report the percentage of bank length that is eroding Note that riffle sections that are not eroding and depositional areas like point bars are not evaluated in the BEHI/NBS assessment, but these sections are included when calculating the total bank length (denominator) for this metric. The assumption is that those banks would rate similarly to the non-erodible bank category, and eroding banks that represent an ongoing level of impairment will be represented by the ratings in the actively eroding banks category.

This 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.

*Table 8-5: BEHI/NBS Stability Ratings that Represent Actively Eroding and Non-eroding Banks.*

| Non-eroding Banks | Actively Eroding Banks |
|---|---|
| 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/L, H/M, H/H, H/Ex, VH/VL, Ex/VL, Ex/L Ex/M, Ex/H, Ex/VH, VH/VH, Ex/Ex |

**Reference Curve Development:**

The Wyoming Habitat Quality Index (HQI) for trout streams (Binns 1982) contains a metric that scores the length of eroding bank according to the following criteria:

- 100% to 75% eroding banks are inadequate to support trout,

- 74% to 50% provide very limited potential,
- 49% to 25% provide limited potential,
- 24% to 10% provide moderate potential to support trout, and
- 9% to 0% eroding banks are completely adequate to support trout.

Based on these criteria, a minimum index value of 0.00 was assigned where percent streambank erosion exceeded 75% of bank length.  Members of the WSTT that have applied the HQI methods across Wyoming have rarely observed values greater than 10% eroding streambanks among reference standard streams, and thus concluded this to be a reasonable threshold between functioning and functioning-at-risk index scores. The thresholds identified in Table 8-6 were used to develop reference curves (Figure 8-2). It was not possible to fit a single equation to the threshold values, so a broken linear curve was used to differentiate between the functioning range of index values and the not functioning and functioning-at-risk range. The threshold between not-functioning and functioning-at-risk is interpolated rather than assigned a specific value.

*Table 8-6: Threshold Values for Percent Streambank Erosion.*

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

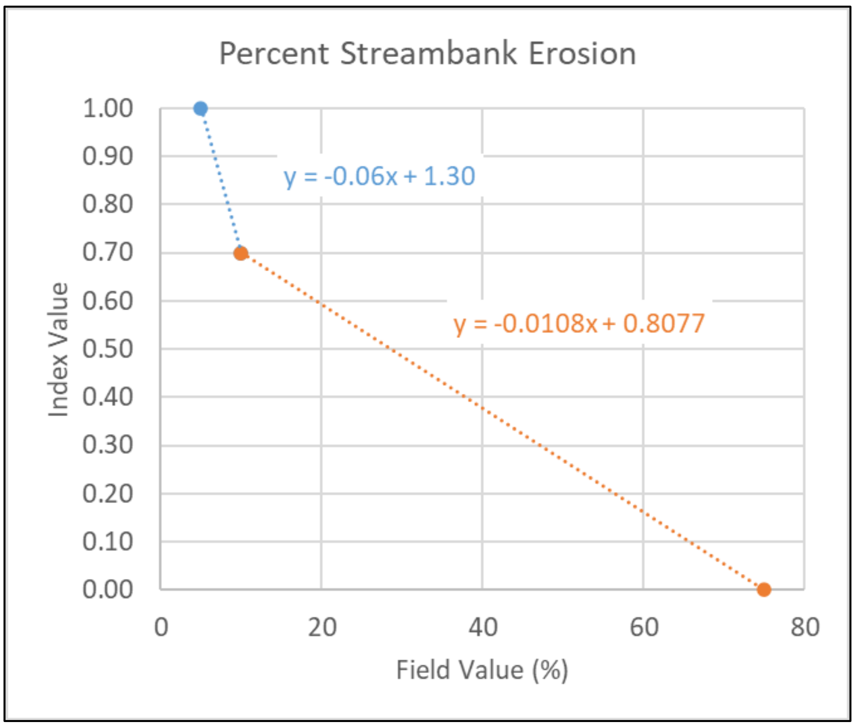



*Figure 8-2: Percent Streambank Erosion Reference Curve.*

**Limitations and Data Gaps:**

This 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.

## 8.4. Percent Streambank Armoring

**Summary:**

Bank armoring is a common technique to stabilize banks and/or prevent lateral migration, and involves the establishment of hard structures (e.g., rip rap, gabion baskets, concrete or other engineered materials that prevent streams from meandering) along the bank edge. Literature shows that bank armoring can have both positive and negative effects on aquatic functions (Henderson 1986; Fischenich 2003; Reid and Church 2015). 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 (Henderson 1986; Fischenich 2003; Reid and Church 2015). In Colorado, CPW has documented little beneficial effects of armoring on native species habitat except for the native Front Range transition species of stonecat (*Noturus flavus).* Negative effects include loss of fish habitat, sediment and wood input, and biological diversity; and impacts to floodplain development and channel evolution through prevention of natural rates of lateral migration (Henderson 1986; Fischenich 2003). Bank armoring can also lead to accelerated bank erosion and changes in sediment dynamics in adjacent, non-armored reaches. Studies documenting the effects of reach-scale streambank armoring on geomorphology, biology, and the ecosystem at large are preliminary and call for more research (Stein et al. 2013; Reid and Church 2015).

Recognizing the adverse consequences of armoring treatments in streams, the WSTT has included a basic bank armoring metric in the lateral migration parameter. For purposes of the SQT, bank armoring is defined as any rigid, human-made stabilization practice that permanently prevents lateral migration processes. More natural approaches to reducing excessive bank erosion, like toe protection and/or bioengineering, are not considered armoring. In many systems armoring treatments can be considered an adverse impact or form of functional loss, and the other metrics included to describe this parameter do not adequately capture the functional loss associated with hard armoring practices. The armoring metric should only be used if armoring techniques are present or proposed in the project reach. 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:** Index scoring for this metric has been updated for WSQT v2.0.

Even though there are some positive benefits to armoring, the negative impacts to ecological function generally outweigh the positives. Furthermore, hard armoring does not support natural sediment processes and function. While most research has shown a negative relationship between armoring and functional impairment in streams, there were no studies found that explicitly evaluated the relationship between the extent of armoring to functional impairment. The following threshold values were proposed by the WSTT (Table 8-7):

- Because hard armoring would be absent in reference standard sites, a field value of 0% was assigned an index value of 1.00.
- Thirty percent armored was assigned an index score of 0.00 and a linear curve was established between the two points (Figure 8-3). Setting the minimum index value at 30% armored length seemed reasonable to the WSTT, as it means that almost a third of the project reach is armored. At this level of armoring, the reach could be considered channelized and functional loss of channel migration processes could be severe.

In v1.0, the WSTT recommended that the other metrics in lateral migration not be measured if more than 75% of the reach is armored. In the WSQT v2.0, the WSTT has updated this recommendation to apply where more than 50% of the reach is armored. At this magnitude, the armoring is so pervasive that lateral migration processes would likely have no functional value. Further, the WSQT now includes an override in the parameter score based on a high percent armoring field value. If more than 50% of the reach is armored, the metric and parameter will score a 0.00.

*Table 8-7: Threshold Values for Percent Streambank Armoring.*

| Index Value | Field Value (%) |
|---|---|
| 1.00 | 0 |
| 0.00 | 30 |

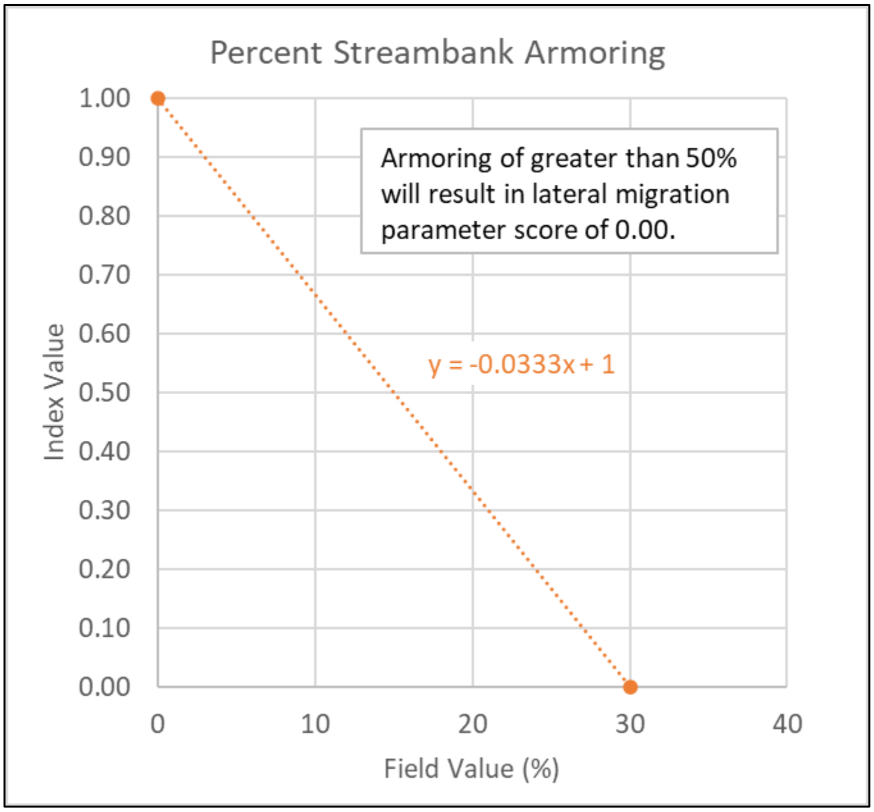



*Figure 8-3: Percent Armoring Reference Curve.*

**Limitations and Data Gaps:**

Although a majority of literature and available studies 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 as the WSQT is implemented.

# Chapter 9. Bed Material Characterization Parameter

**Functional Category:** Geomorphology

**Function-based Parameter Summary:**

The interaction between flowing water and sediment transport creates bed forms, which provide the critical habitats for macroinvertebrates, fish and other organisms (Allan 1995). Streams that are in balance with the hydrologic and sediment transport processes in the watershed are said to be in dynamic equilibrium. This means that the stream bed is not aggrading nor degrading over time, and that lateral adjustments do not change the cross-sectional area, even though its position on the landscape may change (Hack 1960).

Human activities have had substantial and wide-ranging effects on sediment processes in streams (Wood and Armitage 1997; Wohl 2004), including land use activities that have modified and often accelerated the input of sediments into streams. In-channel sources of sediment, including banks, mid-channel and point bars, and fine material deposition areas, can be modified via flow alteration and changes in bank stability. Non-channel sources within the catchment, largely from hillslope erosion processes, can be altered when exposed soils are subject to erosion, when mass failures or landslides occur, where urban development alters the timing and magnitude of runoff events, and when other human activities alter the availability and rate of sedimentation into streams.

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; Benoy et al. 2012). Additionally, multiple fish species build spawning beds out of gravel; and fine sediment accumulation can reduce the quality of spawning habitats and reduce 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.

The WSQT v1.0 included a grain size metric based on Bevenger and King (1995); however, this metric was replaced in v2.0 with a percent fines metric informed by WDEC datasets. The WSTT had previously considered an embeddedness metric, but existing metrics (e.g., Rosgen 2014; EPA 2016) are qualitative. The riffle stability index (Kappesser 2002) 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. However, this method was not included in the WSQT because it is only applicable to B3 and F3b stream types, and most mitigation/restoration activities occur in C4 and B4c stream types. 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. These metrics include calculations for heterogeneity, sorting, Fredle index, a gradation coefficient, and a sediment coefficient of variation. Datasets to determine reference curves for these metrics are generally not available. Other metrics could be added in the future as reference data and/or processing tools become available.

Improvements have been made to this parameter in WSQT v2.0 by replacing the prior metric with the percent fines metric informed by Wyoming field data. This new metric no longer relies on comparison with a reference site, which eliminates the uncertainties around selection of an appropriate reference that were described in WSTT (2018). The WSQT includes one metric to evaluate this parameter, percent fines (<2mm). Fines are bed material samples from a project reach that are smaller than 2mm in intermediate diameter. The metric and reference curves were developed using data from WDEQ, as described below. This metric is similar to bed material characterization metrics applied in other SQTs (e.g., AKSQTint, Alaska Stream Quantification Tool Steering Committee 2021).

**Metric:**

- Percent fines (<2mm)

## 9.1. Percent Fines (<2mm)

**Summary:**

The percent fines (<2mm) metric characterizes the proportion of riffle bed material that are smaller than 2mm in intermediate diameter. This metric is informed by pebble counts conducted within riffles, where one hundred particles are randomly collected at evenly spaced intervals along a transect, across the entire active width of the channel bed at a particular feature. Particles are characterized by the measurement of the intermediate axis.

Fine sediments represent smaller bed material grain sizes and can be used to evaluate whether there are changes in deposition of fine sediment within a project reach. When streambeds have increased or excessive sedimentation, or “fining”, streambed habitat such as pools or riffles become impaired, with implications for aquatic species habitat, food acquisition, and reproduction (Zweig and Rabeni, 2001; Sutherland et al., 2002; Griffith et al., 2009). Research from agricultural streams in New Brunswick, Canada (Benoy et al. 2012) has shown correlations between Ephemeroptera-Plecoptera-Trichoptera (EPT) relative abundance (%) and geomorphic criteria (% fines < 2mm, % fines < 6.4mm, and median particle size). Benoy et al. (2012) also found that these geomorphic criteria were strongly correlated to land use disturbance (i.e., agricultural coverage and riparian zone integrity).

The percent fines metric is applicable for gravel and cobble bed streams where in-channel or non-channel sediment sources and/or transport of those sediments within the stream have been modified by human activities. Examples include areas with accumulation of fine sediments due to bank erosion or land use change, or where flow alteration may lead to additional fine sediment accumulation or scour and armoring. Projects that reduce bank erosion along a long project reach or restore flushing flows may be able to show a reduction in fine sediment deposition (Harman et al. 2012). Changes in land management practices can result in the delivery of fine sediment to streams, which can impact aquatic habitat bedform features.

**Reference Curve Development:**

Reference curves were developed using data provided by WDEQ, as well as literature values presented within Benoy et al. (2012). Benoy et al. (2012) proposes ecological thresholds for deposited sediments using data collected within agricultural watersheds in New Brunswick, Canada. Ecological thresholds relate to geomorphic criteria (percent fines <2mm, percent fines <6.4mm and median particle size) and were developed using regression-tree analysis.

The WDEQ dataset is based on probabilistic assessments of the entire state between 2010 and 2021, broken into five “basin-like” subunits, with each basin having more than 50 randomly selected sites on order 2 and greater, perennial or near perennial, and non-wilderness or national park streams. The dataset includes more than 250 sites across the state that are not biased toward good or poor physical conditions; sites are characterized as reference, non-reference, or degraded. Sites with incomplete bed material data were removed from the dataset. Sites with a reach-wide median particle size <2mm were also removed from the dataset, although degraded or non-reference sites may have a natural condition in which the median particle size is larger than observed.

Each site in the WDEQ dataset has a reach wide pebble count for classification (weighted pool vs non-pool) and a riffle-only pebble count. The percent clay, percent silt, and percent sand within the riffle-only pebble counts were summed to generate the percent fines within the riffle sample. For this analysis, non-reference and degraded are evaluated together as non-reference (Figure 9-1), and there are a total of 31 reference sites and 142 non-reference sites included in the analysis. Reference sites had a minimum reach-wide median particle size of 14mm; the maximum percent fines observed at a reference site was 16% fines; the median value at reference sites was 1% fines (Table 9-1).

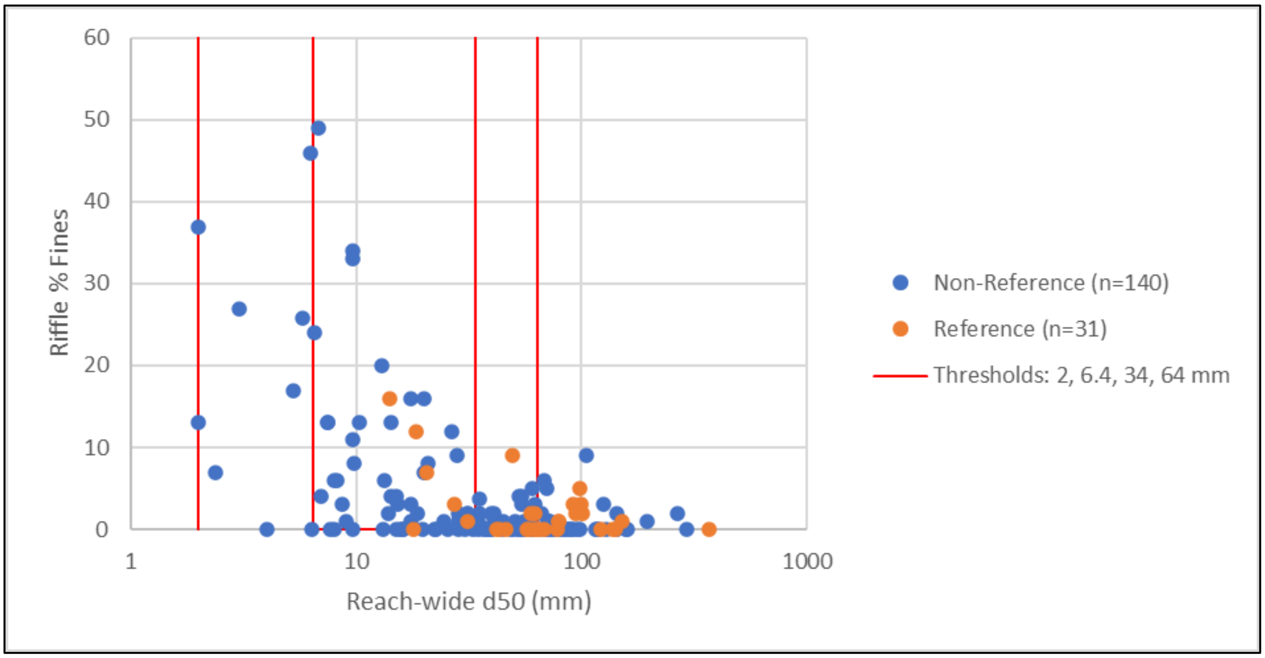



*Figure 9-1: Percent Fines in Reference and Non-reference Sites from the WDEQ Dataset.*

*Table 9-1: Statistics for Percent Fines (<2mm) from the WDEQ Dataset.*

| Statistic | Reference Sites % Fines | Non-reference Sites % Fines |
|---|---|---|
| Number of Sites (n) | 31 | 142 |
| Average | 2 | 4 |
| Standard Deviation | 4 | 9 |
| Minimum | 0 | 0 |
| $25^{th}$ Percentile | 0 | 0 |
| Median | 1 | 1 |
| $75^{th}$ Percentile | 3 | 4 |
| $95^{th}$ Percentile | 14 | 26 |
| Maximum | 16 | 49 |

Stratification by median particle size was considered. However, a one factor ANOVA test showed no significant difference between the range of values for gravel bed sites (2mm ≤ d50 < 64mm) and sites with coarser bed material (d50 ≥ 64mm) in reference streams. As such, a single curve was proposed for all sites with gravel beds or coarser (Figure 9-2).

The following logic was used to develop threshold values (Table 9-2) and reference curves:

- While the WDEQ dataset included many sites exhibiting 0% fines, it is likely that fine are present in the bed, but larger material is more prevalent (fines embed the larger particles). Thus, the WSTT decided that setting the maximum index score (1.00) at 0% fines would not be accurate. A value of 5% fines was considered reasonable as reference and used for the 1.00 score.
- The 0.70 index value (threshold for functioning) was set at 15% fines. The 15% fines (<2mm) value is consistent with the ecological threshold (14.8%) from Benoy et al. (2012) and is between the $95^{th}$ percentile (14%) and maximum value (16%) observed in the reference sites from the WDEQ dataset.
- The 0.00 value was set to 50% fines, which equates to the median particle size measured in the riffle feature is 2mm or smaller. Sites with reach-wide pebble counts containing 50% or more materials of this size class are classified as sand bed channels and this metric is not applicable. Therefore, streams expected to have gravel beds, or coarser, with greater than 50% fines have no functional capacity for this parameter.

*Table 9-2: Threshold Values for Percent Fines (<2mm).*

| Index Value | Field Value *(%)* |
|---|---|
| 1.00 | ≤ 5 |
| 0.70 | 15 |
| 0.00 | ≥ 50 |

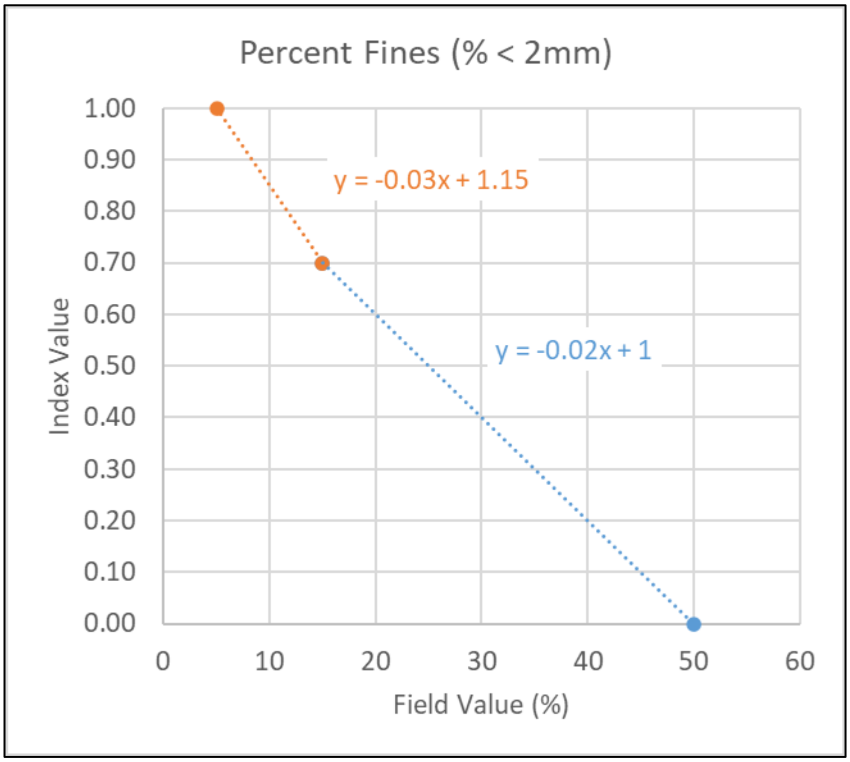



*Figure 9-2: Percent Fines (<2mm) Reference Curve.*

**Limitations and Data Gaps:**

This metric only applies to gravel or cobble bed streams where a high percentage of fines is not the natural condition.

No stratification was proposed for this metric; however, it may be useful to consider in future versions of the tool following application and testing. Underlying geology in different ecoregions, alluvial versus colluvial valleys, and/or differences in stream reach slope may play a significant role in the naturally occurring percent of fines within the streambed.

# Chapter 10. 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 forces 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 that comprise the dominant stream bed forms in alluvial and colluvial valleys in Wyoming. This parameter evaluates bedform pattern in relation to expected patterns in channels with similar valley 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 valley and channel slope, size of bed material (clay, silt, sand, gravel, cobble, boulder, bedrock), flow regime and other factors. These bed forms reflect local variations in the sediment transport rate and are expressed as lateral and vertical variations in stream bed elevation (Knighton 1998), dissipating energy and creating habitat diversity through the formation of faster or slower, deeper or shallower sequences with coarser or finer sediment.

Numerous classifications of bed form exist (Knighton 1998). At a broad level, bed forms can be grouped into three categories: sand bed forms (e.g., ripple, dunes, plane beds and anti-dunes), gravel/cobble bed forms (e.g., 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 due in part to more hyporheic flow. Meanwhile pools provide fish habitat and thermal refugia, support thermal regulation, provide energy dissipation, and are an indication of how the stream is storing and transporting sediment (Knighton 1998; Allan 1995; Hauer and Lamberti 2007). Without the diversity of riffles and pools, there is also a potential loss of diversity in macroinvertebrates and fish (Fischenich 2006; Mathon et al. 2013).

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, pool spacing and depth variability. Aggradation ratio is useful for characterizing aggradation processes in riffle sections and was included in WSQT v1.0. Aggradation ratio was removed in WSQT v2.0 and replaced with an alternative hydraulic metric (see Chapter 5 for additional discussion). Many qualitative methods are also available to assess bedforms and in-stream habitats (Somerville and Pruitt 2004; Somerville 2010) but were not considered for the WSQT because quantitative measures are available and regularly used by practitioners.

The WSQT includes three metrics to characterize bed form diversity: pool spacing ratio, pool depth ratio and percent riffle. These metrics are often used by practitioners in quantitative geomorphic assessments of riffle-pool and step-pool sequences (Knighton 1998; Harrelson et al. 1994; Rosgen 2014; and ELI et al. 2016). 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. Note: in the WSQT, riffles include the crossover between meander bends; this allows the straight section in sand bed streams to also be considered “riffles.” Typically, the riffle term is limited to gravel bed streams (Knighton 1998), however, identifying all crossovers as riffles allows for consistent assessment methods.

- **Metrics:**
- Pool Spacing Ratio
- Pool Depth Ratio
- Percent Riffle

## 10.1. Pool Spacing Ratio

**Summary:**

Adequate pool spacing and the depth variability created from alternating riffles supports dynamic equilibrium and habitat-forming processes (Knighton 1998; Hey 2006). The pool spacing ratio metric measures the distance between the deepest thalweg 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 obstructions). 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 WSQT. 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 of the SQT has shown that median values in the functioning range allow for pattern heterogeneity and do not incentivize designs with equal pool spacing.

Studies have documented a connection between pool spacing ratios and channel stability and complexity, as pools serve to dissipate energy at high flows (Langbein and Leopold 1966; Gregory et al. 1994; Laub et al. 2012). If a meandering stream has a low pool spacing, it follows that riffle length will also be short, with more energy transferred to the banks and sometimes the floodplain. Evaluations of numerous stream restoration and mitigation projects by the lead contractors 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.

F and G channels that represent degraded streams should be compared against the reference stream type, as informed by channel evolution processes (Cluer and Thorne 2014; Rosgen 2014) and described in the WSQT v2.0 User Manual. For example, if the existing stream type is a degraded Gc in an alluvial valley, the reference stream type would be a C or E. Selection of the appropriate reference stream type is important for consistently applying this metric and determining scores in the tool. To improve consistency, additional discussion has been added to the WSQT v2.0 User Manual to assist practitioners in identifying the reference stream type.

**Reference Curve Development:**

Reference curves for Wyoming were based on analysis of the compiled geomorphic reference dataset described in Section 1.8. The compiled geomorphic reference dataset consists of 51 sites that report pool spacing ratio. Data collection methods measured pool spacing ratio between the head, or beginning, of sequential pools rather than between the deepest point of sequential pools. The pool spacing calculations were revised to match the WSQT methodology based on maximum pool depth locations and station data from longitudinal profiles at each site.

The metric accounts for differences in stream size by using bankfull width as the denominator. *S*caling by bankfull width accounts for the differences in stream size that may otherwise be relevant in determining pool spacing. Bankfull dimensions may vary based on differences in climate and runoff characteristics; however, bankfull regional curves can be used to calibrate field identifications (Dunne and Leopold 1978; Blackburn-Lynch et al. 2017).

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). The compiled geomorphic reference dataset was assessed to determine whether stratifications based on drainage area or region were also appropriate (see discussion in Section 10.3). Trends in the data were not apparent for these variables, so they were not used to stratify data. Results stratified by stream type are shown in Table 10-1 and Figure 10-1. Note, two reference stream channels were identified as F stream types and two outliers were identified in their stream type groupings and removed from the analysis.

Given that single-thread perennial streams exhibit a range of stable pool spacing, the WSTT combined the data analysis shown in Table 10-1 and Figure 10-1 with best professional judgement to derive the threshold values and reference curves shown in Table 10-2 and Figure 10-2.

The 25$^{th}$ and 75$^{th}$ percentile values for each stream type were used to characterize the reference standard range of index scoring in the WSQT. Modifications to the threshold values were considered using best professional judgement. The WSTT considered adjustments depending on whether the reference curves allowed for natural variability and did not incentivize homogeneous designs. Modifications to the threshold values were made as follows: If a value was considered too low and had the potential to cause stability problems, the value was increased. If the value was considered too high and would limit the number of pools, and therefore habitat, the value was lowered. For example, meandering streams (C and E) can have stability problems if the pool spacing is too low and habitat loss if pool spacing is too high. In moderate gradient streams (B), stability problems occur if the pool spacing is too far apart.

However, an exception to this is projects that create a long succession of step-pools without a high enough percentage of riffles, i.e., the length is mostly pool.

*Table 10-1: Statistics for Pool Spacing Ratio from the Compiled Geomorphic Reference Dataset.*

| Statistic | Pool Spacing Ratio by Stream Type | | | | |
|---|---|---|---|---|---|
| | E | C | Cb | B | Bc |
| Number of Sites (n) | 9 | 13 | 7 | 15 | 3 |
| Average | 6.9 | 4.5 | 3.9 | 4.5 | 5.3 |
| Standard Deviation | 3.2 | 1.9 | 1.6 | 2.5 | 3.4 |
| Minimum | 3.3 | 1.7 | 2.3 | 1.3 | 2.8 |
| 25th Percentile | 4.5 | 3.2 | 2.7 | 2.4 | 3.4 |
| Median | 4.9 | 4.4 | 3.1 | 4.1 | 4.0 |
| 75th Percentile | 9.0 | 6.1 | 5.1 | 6.7 | 6.6 |
| Maximum | 12.8 | 7.3 | 6.4 | 9.4 | 9.2 |

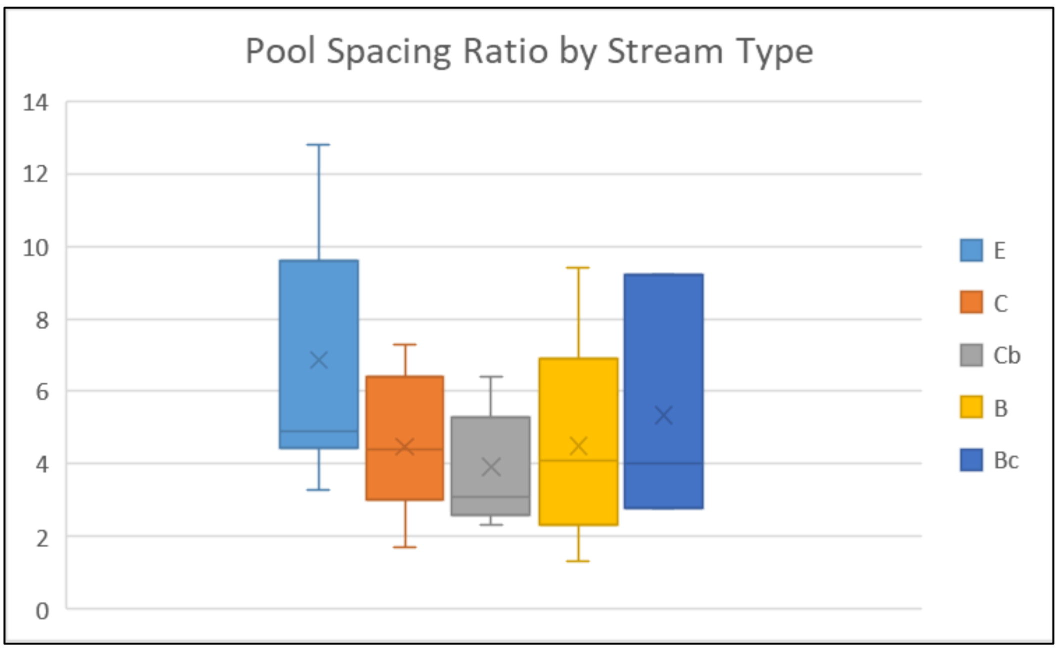



*Figure 10-1: Box plots for Pool Spacing Ratio from the Compiled Geomorphic Reference Dataset.*

Since the compiled geomorphic reference dataset was limited to reference standard streams, the not-functioning range was extrapolated from the reference curves fit to the threshold values identified in Table 10-2. These curves were reviewed to determine if the not-functioning values were reasonable based on stability and habitat considerations.

For C stream types, a two-sided reference curve was developed to account for stability issues associated with low ratios and habitat issues associated with high ratios. Field values of 4.0 and 6.0 were selected to equal an index value of 1.00. A 4.0 was selected rather than the 25$^{th}$ percentile value of 3.2 to provide more certainty that a sinuosity of 1.2 could be achieved. Likewise, a 3.7 was set as the 0.70 index value to equal the low end of the reference condition. As ratios become less than this, pool spacing is reduced and the potential for instability goes up. Experience from the authors have shown that low pool spacing values can lead to instability especially in newly constructed channels. The field value of 6.0 closely equates to the 75$^{th}$ percentile value of 6.1 from the compiled geomorphic dataset. A pool spacing ratio of 7.0 was set at the 0.70 based on discussions with the WSTT. The team decided that values greater than 7.0 would begin to equal fewer pools per reach and not support fish communities at a reference condition. A 7.0 is also very close to the maximum value observed in the reference dataset.

For Cb stream types, field values of 3.8 and 5.0 were selected to equal an index value of 1.00, and 3.0 and 6.0 for the 0.70 index value. These values are slightly lower than the C stream type because steeper streams have a lower sinuosity and closer pool spacing. However, since a sinuosity of 1.2 or slightly higher is a possibility, the 1.00 was set higher than the 25$^{th}$ percentile value to help avoid stability problems. The upper end of 5.0 closely equates to the 75$^{th}$ percentile.

The logic for developing reference standards for E stream types is the same as the C since they exist in similar valley types. However, since the sinuosity is generally higher in E stream types, the pool spacing values can be lower. This is not evident in the reference data shown in Figure 10-1 but has been observed in E's across the country. Figure 10-1 may be different due to the low sample size and the resulting combination of E stream types with greatly different slopes and valley types. Until more data are collected, the WSTT decided that it was more conservative, from a stream stability and habitat perspective, to use the values shown in Table 10-2.

*Table 10-2: Threshold Values for Pool Spacing Ratio.*

| Index Value | Field Values by Stream Type | | | | |
|---|---|---|---|---|---|
| | E | C | Cb | B and Ba | Bc |
| 1.00 | 3.5 – 5.0 | 4.0 – 6.0 | 3.7 – 5.0 | ≤ 3.0 | ≤ 3.4 |
| 0.70 | 3.0, 6.0 | 3.7, 7.0 | 3.0, 6.0 | 4.0 | 6.0 |
| 0.00 | ≤ 1.8, ≥ 8.3 | ≤ 3.0, ≥ 9.3 | - | ≥ 7.5 | - |

For B and Ba stream types, the 25th and 75$^{th}$ percentile values are 2.4 and 6.7, respectively. Generally, lower pool spacing values are better from a stability and habitat perspective if the riffle percentage is appropriate, e.g., too much pool length has been observed by the authors to create major instability problems. Therefore, the 0.70 index value was reduced to a 4.0 to encourage spacing ratios less than 6.7 and promote channel stability and habitat. Any value under 3.0 was set at an index value of 1.00 to discourage practitioners from over-structuring a stream if it wasn't needed for stability. A 0.00 index value was assigned to any field value over 7.5 due to the lack of pool habitat that this would create and potential instability (headcutting) that could occur. The logic is the same for Bc stream types, but the values were increased slightly to account for the lower slope. Lower slope streams can have pool spacing values that are slightly higher than their steeper counterparts without having stability problems.

Linear relationships were fit to threshold values using the above criteria. Since both low and high pool spacing impact stability and complexity in meandering channels, the reference curves are parabolic shaped. Low values are not functioning, and high values are not functioning. A middle range of values supporting stream stability and pool-habitat quality are considered functioning. These relationships are shown in Figures 10-2a and 10-2b. It is important to remember that the values in the WSQT are medians; therefore, a range of values can be used in the design process. Field testing of the SQT has shown that median values in the functioning range still allow for pattern heterogeneity and do not incentivize designs with equal pool spacing.

Reference streams with moderate gradients (between 3 and 5%) have naturally lower pool spacing ratios, indicating an inverse relationship between slope and pool spacing (Whittaker 1987; Chin 1989). Unlike meandering streams, moderate gradient systems dissipate less energy laterally and more energy vertically. In moderate gradient streams, low ratios represent functioning conditions from a stability and habitat perspective. Therefore, the reference curves in Figures 10-2c and 10-2d do not show a loss of function with lower index values.

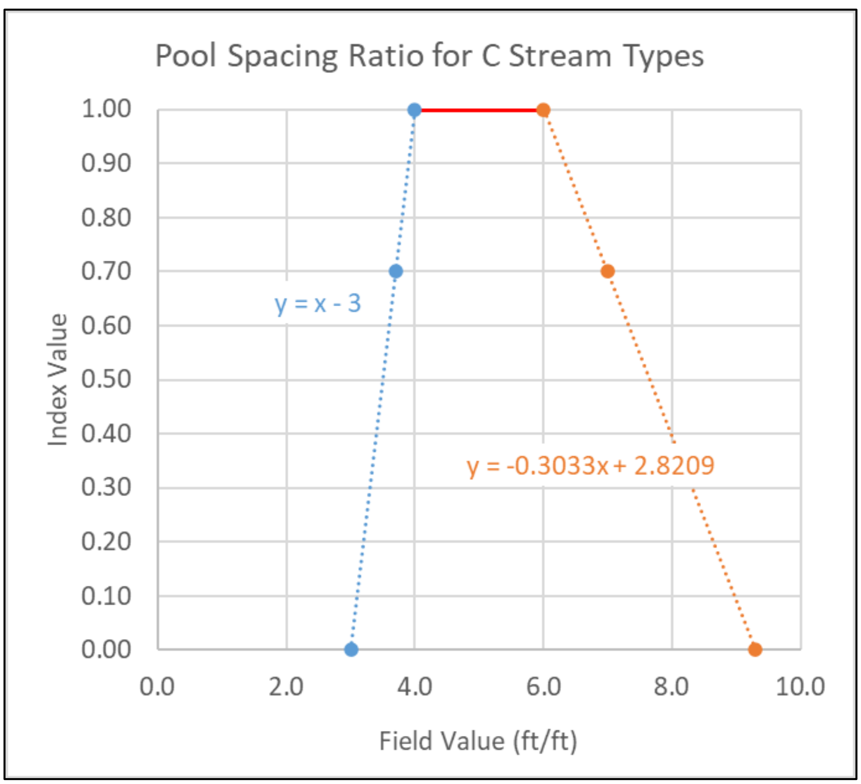



*Figure 10-2a: Pool Spacing Ratio Reference Curve for C Stream Types.*

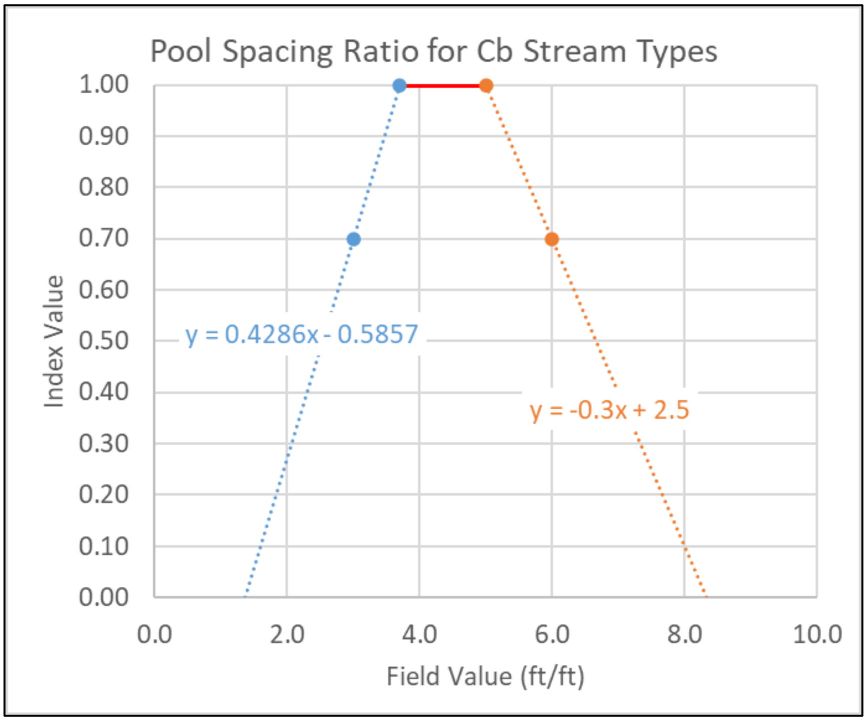



*Figure 10-2b: Pool Spacing Ratio Reference Curve for Cb Stream Types.*

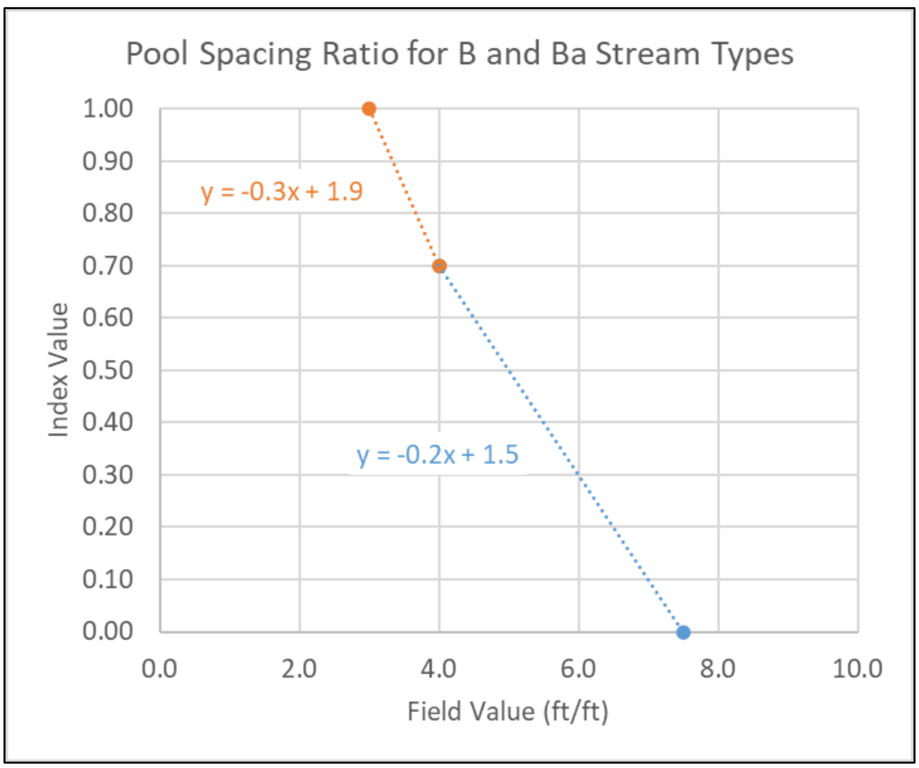



*Figure 10-2c: Pool Spacing Ratio Reference Curve for B and Ba Stream Types.*

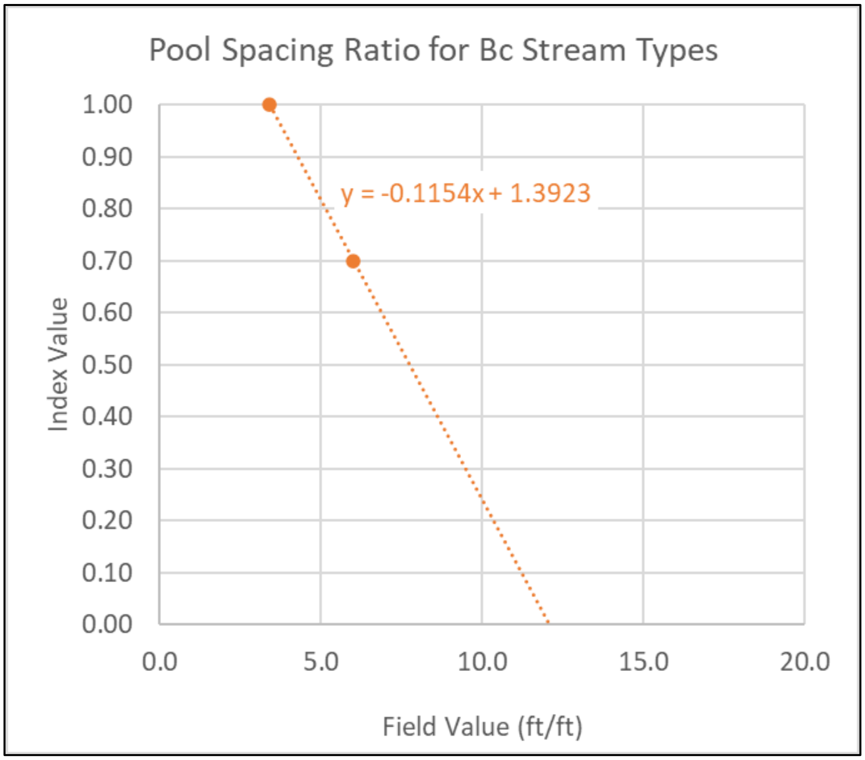



*Figure 10-2d: Pool Spacing Ratio Reference Curve for Bc Stream Types.*

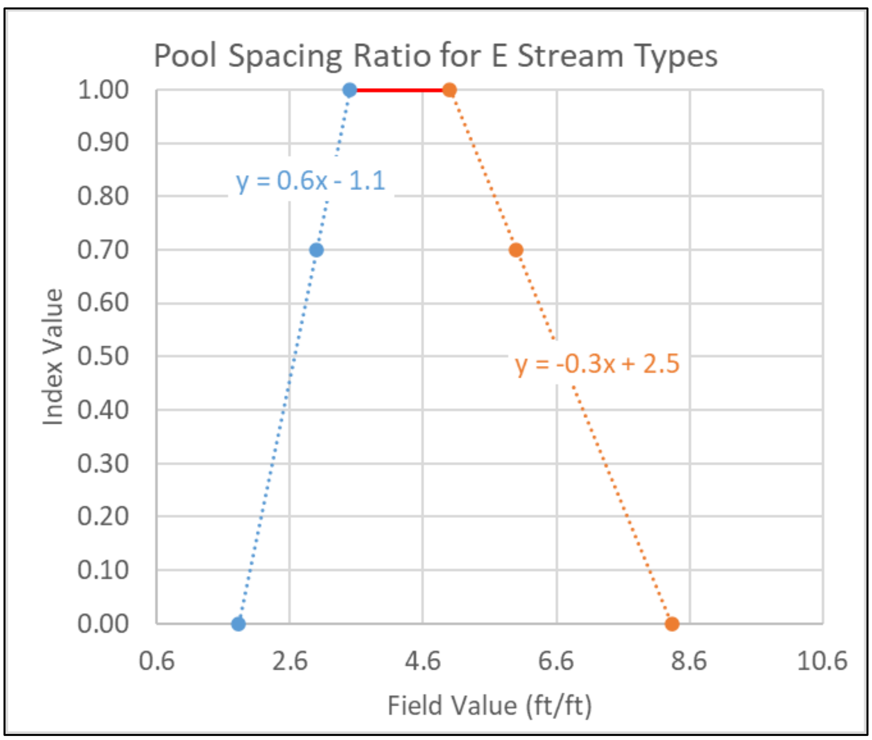



*Figure 10-2e: Pool Spacing Ratio Reference Curve for E Stream Types.*

**Limitations and Data Gaps:**

The primary limitation of this metric is the small sample size required in the assessment sub-reach. The assessment sub-reach will likely consist of only 3 geomorphic pool spacing measurements in a meandering channel.

The presence of bedrock can influence pool spacing, and thus it may not be appropriate to include bedform diversity metrics when evaluating natural bedrock channels. Pool spacing and 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 may not accurately reflect the bedform diversity. When possible, localized regional curves should be used to verify the bankfull determination. Once a bankfull feature/stage has been determined, that feature/stage should be used for all future assessments. Additional information on verifying bankfull information was added to the WSQT v1.0 User Manual in response to comments received during beta testing. Further, specific procedures and data forms to identify and verify bankfull were added to the WSQT v2.0 User Manual. These procedures include scenarios where flow alteration rather than incision has reduced floodplain connectivity.

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, this metric is not applicable to braided (D) stream types with multiple channels or ephemeral channels because a predictable pool spacing is not typically found in these environments (Bull and Kirby 2002).

The reference curves were derived using a geomorphic reference dataset primarily from the mountainous regions of Wyoming. Additional testing is desirable to determine whether different reference curves will be necessary for the basins and plains regions.

This metric stratifies reference curves by Rosgen stream type. Other geomorphic classification approaches may also be appropriate for stratifying reference curves for this metric (Buffington and Montgomery 2013) and may broaden the applicability of this metric to additional morphologies common to Wyoming. Additional data collection and analyses would be required to adapt the tool and reference curves for use with other classification approaches.

## 10.2. Pool Depth Ratio

**Summary:**

This metric measures the bankfull depth of the deepest point of each pool within the representative sub-reach. 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 the bankfull mean riffle depth to calculate the dimensionless pool depth ratio. The average pool depth ratio from a sampling reach is entered as the field value into the WSQT. The average is used instead of the median because typically the sample size is larger and the range lower than the pool spacing ratio.

Pool depth ratio can provide information of how the stream is transporting and storing sediment. 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:**

Reference curves for Wyoming were based on analysis of the compiled geomorphic reference dataset described in Section 1.8. The compiled geomorphic reference dataset consists of 54 sites that report pool depth ratio. The dataset was assessed to determine whether stratification based on stream type, bed material, slope, or region (see discussion in Section 10.3) were appropriate. Scaling for stream size is accounted for in the metric by using the bankfull mean depth as the denominator.

Differences in slope and region were not apparent, and only slight differences were noted based on stream type or bed material (Figure 10-3). The median values for Rosgen C, B, and E stream types are similar, but there is slightly more variability between the 75$^{th}$ percentiles and the minimum and maximum values. For bed material, there is a slightly higher median value for cobble-bed streams, but the range of depths is higher for the gravel-bed streams. Note that there were no sand bed streams in the dataset.

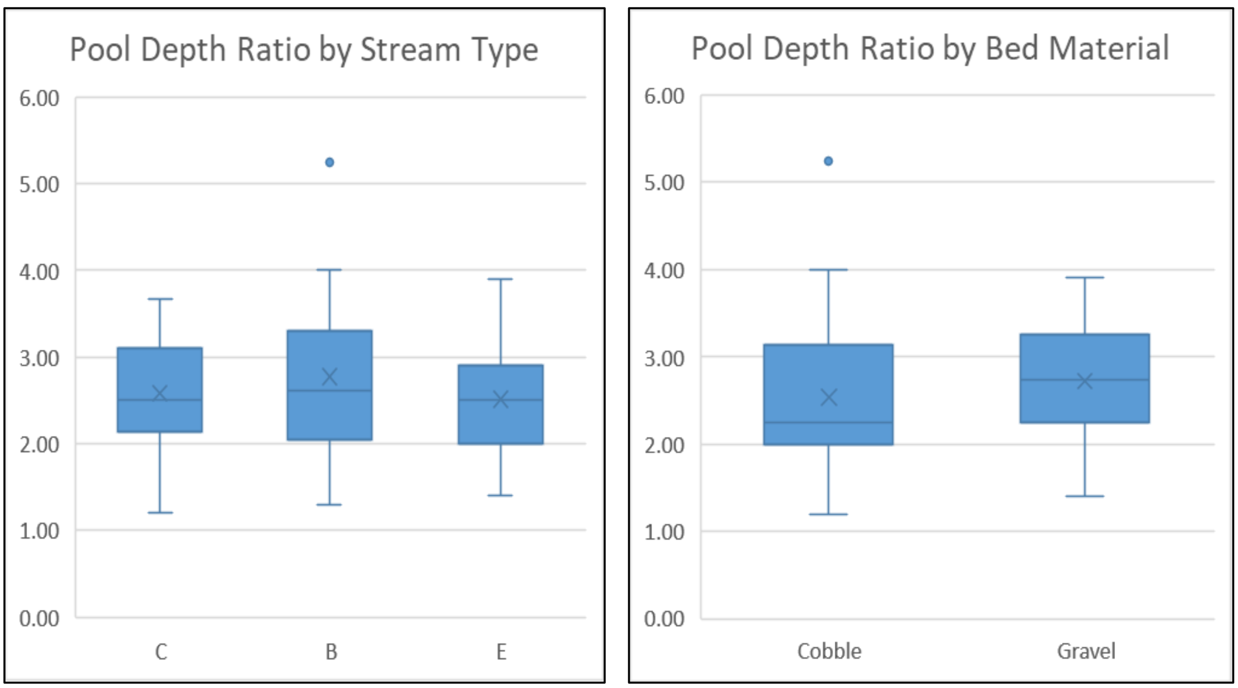



*Figure 10-3: Box plots for Pool Depth Ratio from the Compiled Geomorphic Reference Dataset.*

Because there were no meaningful differences in pool depth ratio based on stream type or bed material, one reference curve was implemented for all streams without stratification. The statistics for the compiled geomorphic reference dataset are provided in Table 10-3.

*Table 10-3: Statistics for Pool Depth Ratio from the Compiled Geomorphic Reference Dataset.*

| Statistic | Pool Depth Ratio |
|---|---|
| Number of Sites (n) | 54 |
| Average | 2.7 |
| Standard Deviation | 0.8 |
| Minimum | 1.2 |
| 25th Percentile | 2.2 |
| Median | 2.5 |
| 75th Percentile | 3.2 |
| Maximum | 5.3 |

Using the premise that deep pools have greater ecological benefits than shallow pools, the threshold for the lower end of the functioning range was set at 2.2 to match the 25th percentile from the compiled geomorphic reference dataset. The minimum index value of 0.00 was set at 1.0, which means that no pools occurred that were greater than the bankfull mean depth. The maximum index value (1.00) was determined using the 75th percentile of 3.2. Because all data in Table 10-3 came from reference standard reaches, no threshold value was selected for the functioning-at-risk and non-functioning ranges. Threshold values are shown in Table 10-4. A broken linear relationship was fit to the identified threshold values to develop the reference curve (Figure 10-4).

*Table 10-4: Threshold Values for Pool Depth Ratio.*

| Index Value | Field Value |
|---|---|
| 1.00 | ≥ 3.2 |
| 0.70 | 2.2 |
| 0.00 | 1.0 |

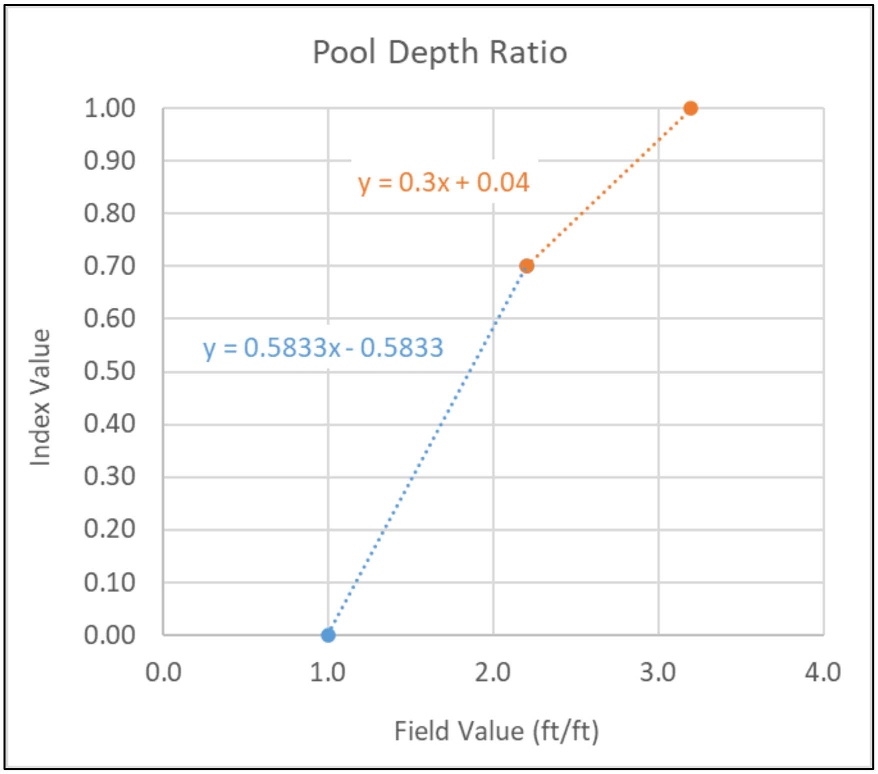



*Figure 10-4: Pool Depth Ratio Reference Curve.*

**Limitations and Data Gaps:**

If bankfull dimensions are not accurately determined for a site, then the pool depth ratio will not be accurate. When possible, localized regional curves and flood frequency analysis should be used to verify the field indicators of bankfull. Information on verifying bankfull information is provided in the WSQT v2.0 User Manual.

The compiled geomorphic reference dataset used to derive the reference curves is from single-thread, perennial streams in the mountainous regions of Wyoming. Testing is desirable to determine whether additional or modified reference curves are needed for the basins and plains regions, and in intermittent, ephemeral, and braided systems. Sand bed streams may have lower pool depth ratios but should be evaluated using the WSQT recognizing that the current reference curves may not accurately characterize the level of functioning in these systems.

## 10.3. Percent Riffle

**Summary:**

This metric measures the length of riffles (including runs) within the representative sub- reach. For the SQT, the definition of riffles includes the crossover section in sand bed streams, where the crossover is the straight section of channel between two meander bends. 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, and both are needed to support 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). 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 this metric have been updated for WSQT v2.0.

Reference curves for Wyoming are based on analysis of the compiled geomorphic reference dataset described in Section 1.8. The dataset included profile data that identified bed features, and these data were used to calculate a percent riffle for each of 51 reference sites in the mountainous regions of Wyoming; one site was removed as an outlier.

The compiled geomorphic reference dataset was assessed using various possible stratifications including bioregion, stream type, drainage area, slope and bed material. Streams from the volcanic mountains and valleys bioregion (volcanic region) had higher percent riffle values than the rest of the data (Table 10-5). Based on this observation, the decision was made to develop unique reference curves for the volcanic region. This stratification was explored for other bed form diversity metrics as well, but the WSTT concluded that the result did not warrant separate stratification for these other metrics.

Once the data were stratified by bioregion, the dataset was evaluated for differences in percent riffle based on other factors. Trends in percent riffle based on stream type, bed material and drainage area were not observed in the data; differences in percent riffle were observed in streams of different slope. For the sites outside the volcanic region, channels with higher slopes had more riffle length. A 3% slope break matches well with other literature showing that mountain streams with slopes greater than 3% often have stair-like appearance (Chin 1989; Abrahams et al. 1995) and are riffle dominated. These trends matched professional experience of the WSTT. Stratification for this metric included the volcanic and non-volcanic regions, with streams outside the volcanic region also stratified by slope (Table 10-5).

Note that within the reference dataset, the minimum slope for streams sampled in the volcanic region was 1.3%. As such, in the WSQT v2.0, the WSTT has included an option for users to opt out of applying the volcanics reference curve for sites within that region where stream slope is less than 1.3%. In these settings, users can instead use the <3% slope reference curve to calculate index values.

*Table 10-5: Statistics for Percent Riffle from the Compiled Geomorphic Reference Dataset.*

| Statistic | Percent Riffle (%) | | Percent Riffle (%) Volcanic Region |
|---|---|---|---|
| | Slope < 3% | Slope ≥ 3% | |
| Number of Sites (n) | 20 | 6 | 24 |
| Geomean | 52 | 72 | 80 |
| Average | 55 | 73 | 81 |
| Standard Deviation | 18 | 8 | 10 |
| Minimum | 28 | 60 | 61 |
| 25th Percentile | 39 | 68 | 76 |
| Median | 57 | 74 | 82 |
| 75th Percentile | 69 | 78 | 89 |
| Maximum | 88 | 83 | 95 |

The WSTT identified the thresholds presented in Table 10-6 using the stratification and data outlined above:

- For stream with low slope (< 3%), the functioning range of scoring was set equal to the interquartile range observed in the compiled geomorphic dataset. The maximum index score within the functioning range was determined using best professional judgement.
- The number of sites with a slope of 3% or greater was limited and the WSTT used best professional judgement to set the functioning range of scoring equal to the range of values observed in the dataset. The maximum index score within the functioning range was set equal to the interquartile range observed in the compiled geomorphic dataset.
- For streams within the volcanic region, the functioning range of scoring was set equal to the interquartile range observed in the compiled geomorphic dataset. The maximum index score within the functioning range was determined using best professional judgement. Note, there was a numerical error in this reference curve in WSQT v1.0 and this error have been corrected in WSQT v2.0 so the reference curve accurately represents the logic described above.
- Since the compiled geomorphic reference dataset was limited to reference streams, the not functioning range was determined by extrapolating the curves.
- In WSQT v2.0, all reference curves were updated to add 0.00 index values that equate to 0% and 100% riffle, as this would reflect a lack of diversity in bedform and thus no functional capacity for this parameter.

The best-fit relationship for percent riffle is a two-sided reference curve, which reflects less function in systems where there is both a very high or a very low percent riffle. Channel stability and macroinvertebrate habitat can be negatively affected by low percent riffle, and fish habitat can be negatively affected by high percent riffle (Clifford and Richards 1992). Linear relationships were fit to identified threshold values (Figure 10-5). The results were reviewed by the WSTT to determine the applicability and appropriateness of percent riffle's role in supporting bedform diversity.

**Limitations and Data Gaps:** The compiled geomorphic reference dataset that was the primary reference in deriving the reference curves is from the mountainous regions of Wyoming and testing is needed to determine whether different reference curves will be necessary for the basins and plains regions.

*Table 10-6: Threshold Values for Percent Riffle.*

| Index Value | Field Value (%) | | |
|---|---|---|---|
| | Slope < 3% | Slope ≥ 3% | Volcanic Region |
| 1.00 | 50 – 60 | 68 – 78 | 80-84 |
| 0.70 | 39, 69 | 60, 83 | 76, 89 |
| 0.00 | 0, 100 | 0, 100 | 0, 100 |

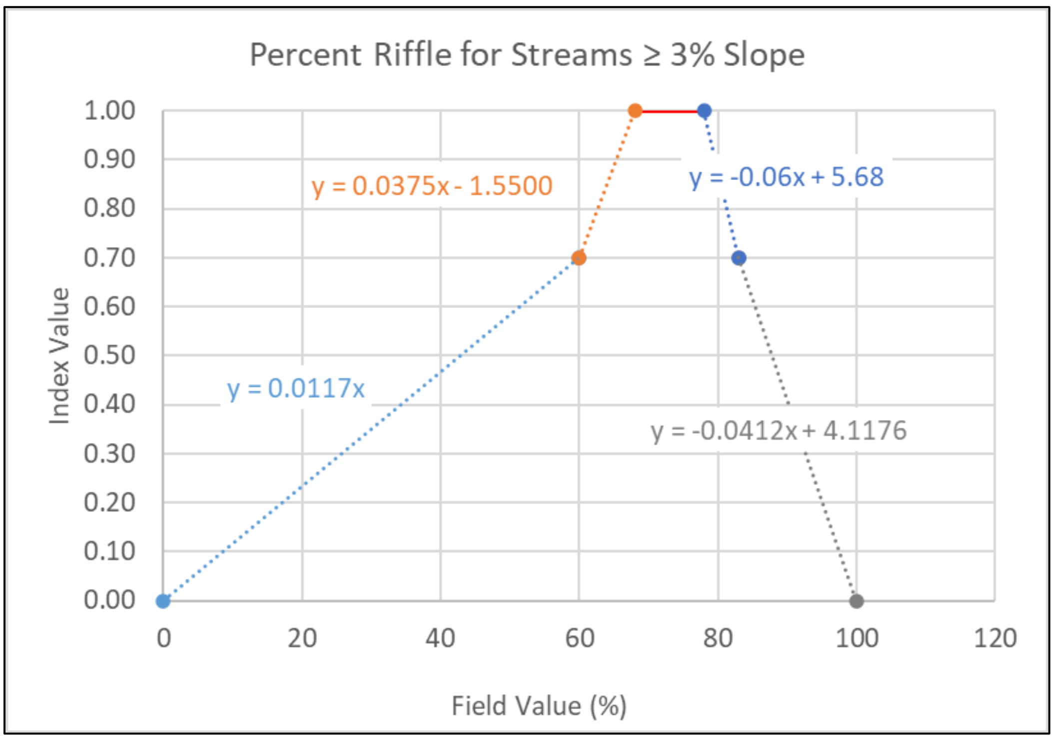



*Figure 10-5a: Percent Riffle Reference Curve for Streams with ≥3% Slope.*

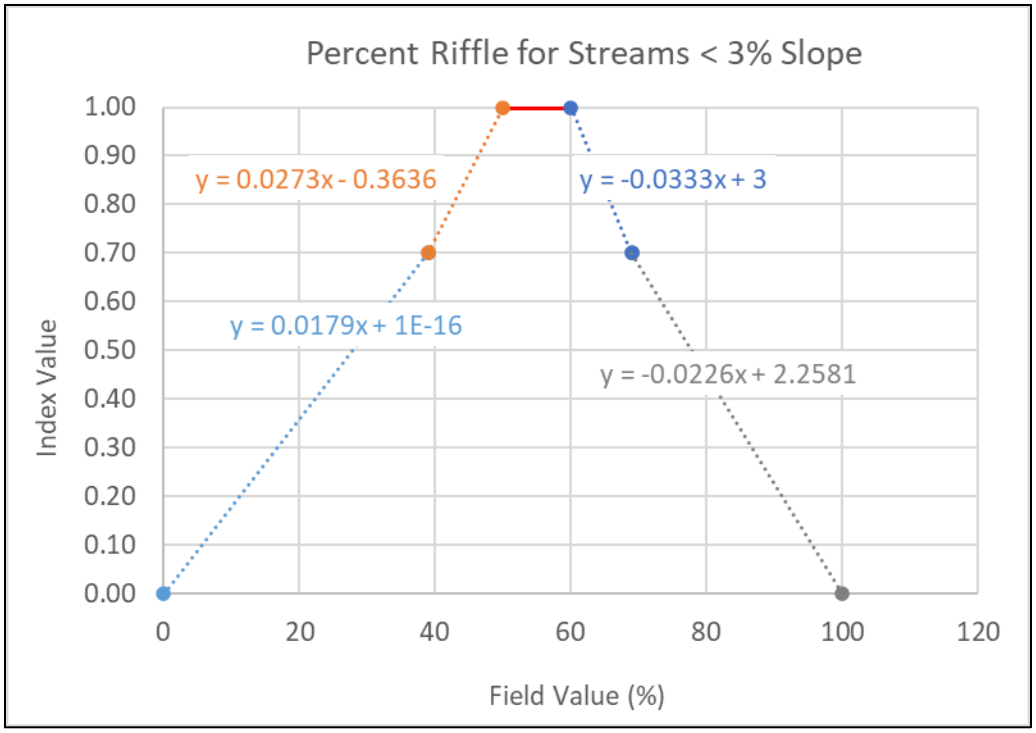



*Figure 10-5b: Percent Riffle Reference Curve for streams with <3% Slope.*

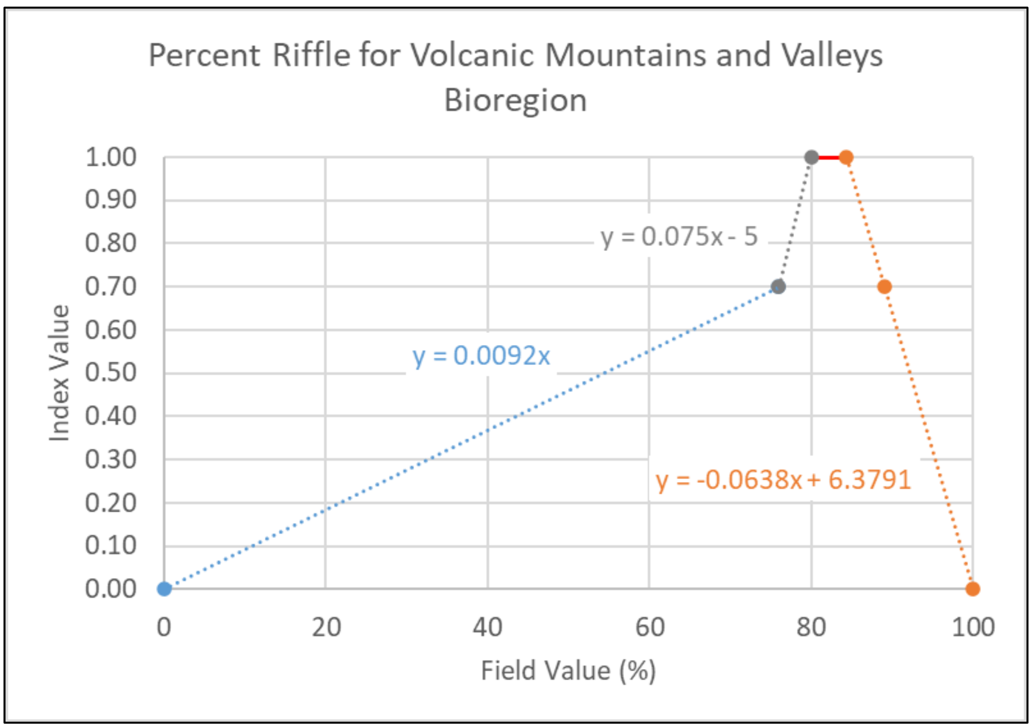



*Figure 10-5c: Percent Riffle Reference Curve for the Volcanic Mountains and Valley Bioregion.*

# Chapter 11. Riparian Vegetation Parameter

**Functional Category:** Geomorphology

**Function-based Parameter Summary:**

Riparian areas are zones of direct interaction between aquatic and terrestrial ecosystems characterized by distinct biological, geomorphic and hydrologic processes (Gregory et al. 1991). Riparian plant communities play a critical role in supporting channel stability, as well as physicochemical and biological processes, and that is why 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
- Filteration of excess nutrients, sediments, and pollutants
- Source of woody debris
- Floodplain roughness
- Carbon and nutrient contributions
- Terrestrial habitat
- Plant diversity, species richness, and functional integrity

Some of these riparian functions are structural, such as stream shading or floodplain roughness, while other functions are influenced by the composition of riparian plant communities. As such, it is important to include riparian vegetation metrics that characterize both the structure and composition of these communities.

Seven metrics for riparian vegetation were included in the WSQT Beta version, and all but one assessed the left and right bank separately to account for variations in stream bank ownership and land use. These metrics included a riparian width ratio, woody and herbaceous vegetation cover, non-native plant cover, hydrophytic vegetation cover, stem density, and the greenline stability rating. Four metrics were carried forward into the WSQT v1.0 riparian parameter: riparian width, absolute woody vegetation cover, absolute herbaceous vegetation cover and percent native cover. These metrics consolidate data collected from both banks into a single WSQT reporting value per metric, which is standard among other methods. The WSQT 2.0 includes the same metrics from v1.0, although the method and metric to characterize riparian width has been modified following beta testing and application and is now referred to as riparian extent.

The WSTT prioritized the use or adaptation of existing programmatic methodologies, particularly those with regional datasets or indices that could be used for the development of reference curves. The WSQT Beta Version included a combination of techniques borrowed from 1) NRSA (EPA 2009); 2) Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) (BLM 2017); 3) Corps of Engineers Hydrogeomorphic (HGM) Approach (Hauer et al. 2002); 4) Corps of Engineers Arid West Regional Supplement (USACE 2008); and 5) USDA Forest Service Monitoring the Vegetation Resources in Riparian Areas (Winward 2000). In the WSQT Beta Version, the NRSA dataset was used to develop reference curves.

Following beta testing and field training exercises, the decision was made to change data collection methods to improve repeatability and consistency and allow for extrapolation of species information to draw inferences on vegetation composition and/or to apply additional regulatory performance standards at mitigation sites. Availability of species-level data from the CNHP dataset (Kittel et al. 1999) allowed the WSTT the opportunity to more closely align methods with existing protocols required by the USACE for wetland delineations (Section 1.8).

Data collection includes visual estimates of the percent absolute cover of each plant species within nested plot types to determine vegetation abundance, structure, composition and complexity. Data collection aligns with the methods outlined in the 1987 Wetland Delineation Manual and regional supplements (USACE 1987; USACE 2008; USACE 2010a; USACE 2010b). USACE field staff and many practitioners are already familiar with these methods, and wetland delineations will likely be required for most stream projects that also contain wetlands in the project area.

Other metrics included in the WSQT Beta Version but not included in v1.0 or v2.0, include stem density and hydrophytic vegetation cover. Stem density is related to woody vegetation cover, serving as an indicator of recruitment and establishment of woody vegetation following disturbance. Both stem density and woody vegetation cover metrics characterize the amount of woody vegetation, yet absolute woody vegetation cover is preferable because of the relation of canopy cover to root cover and the biophysical functions of shrubs as a primary component of western riparian systems. Stem density may be requested by a regulatory agency as an additional regulatory performance standard within the first 5 years of a full restoration project to obtain a better indication of recruitment or establishment of woody vegetation but has not been incorporated into the tool.

Hydrophytic vegetation cover overlaps with the riparian extent metric, which is defined, in part, using characteristic riparian vegetation, and is thus captured in riparian extent, albeit at a coarser scale. The riparian extent metric is also preferable because it is an indicator of the extent of hydrologic connectivity. Hydrophytic vegetation may be considered in future versions of the tool, as shifts in vegetation composition can be a valuable, direct indicator of changes in underlying processes (e.g., hydrology, flow regime, floodplain connectivity) associated with a project. Additional data collection and analysis related to hydrophytic vegetation and other compositional metrics is being considered. Hydrophytic vegetation data can be obtained via the data collection methods for the WSQT, and this will allow the WSTT to evaluate how this metric could be developed and applied in the future.

The Greenline Stability Rating metric was retained in the WSQT v1.0 and v2.0 but was moved to the lateral migration parameter. While it is informed by the presence of riparian vegetation, the WSTT felt it was more appropriate as an indicator of bank stability and was thus moved to serve as an alternative to the BEHI/NBS assessment within the lateral migration parameter.

Data from WSQT Beta Version field testing were used to inform reference curve development. In addition, the CNHP dataset was used to evaluate the WSQT cover metrics and reference curves. The CNHP dataset was selected because it is extensive, overlaps with ecoregions in Wyoming, and had the species-level data that aligns with the selected methods. The CNHP dataset also provided reasonable sample sizes across a range of stream condition. Results from this dataset indicate that herbaceous vegetation cover and native vegetation cover are good predictors of site condition.

In the WSQT and CSQT Beta Version, it was recommended to evaluate both herbaceous and woody vegetation cover metrics at all sites irrespective of stream condition. For the CSQT v1.0, additional analyses were performed to assess this recommendation. Specifically, a Wilcoxon two-sample test was conducted to determine whether there were significant differences between reference and degraded sites in the dataset using current stratifications. For woody sites, there were no statistically significant differences in herbaceous vegetation cover between reference and degraded sites, and likewise for herbaceous sites, there were no statistically significant differences in woody cover between reference and non-reference sites. As such, the recommendation to apply either the woody or herbaceous vegetation cover metrics based on the reference expectation was modified: if the reference expectation is >20% woody cover, the woody cover metric should be applied and if the reference expectation is <20% woody cover, the herbaceous cover metric should be applied. In the WSQT v2.0, herbaceous cover field values should be included at all sites, but these values will not contribute to the riparian vegetation parameter score in sites with woody reference vegetation.

**Metrics:**

- Riparian Extent
- Woody Vegetation Cover
- Herbaceous Vegetation Cover
- Percent Native Cover

## 11.1. Riparian Extent

**Summary:**

The riparian extent metric, developed specifically for the WSQT, has been updated for WSQT v2.0. Instead of being calculated using measurements of riparian width from four locations within the project area, the metric now relies on a calculation of riparian area extent for the entire project area. This modification was made to provide a more accurate characterization of riparian extent, and to allow for the use of desktop area measurement tools with field verification. These updates were made to improve consistency in measurements and improve efficiency in calculating and verifying measurements in the field.

Riparian extent is the proportion of the expected riparian area that currently contains riparian vegetation and is free from anthropogenic disturbance, including urban development, intensive agricultural land uses, resource extraction and changes in hydrology. This metric characterizes the current area occupied by riparian vegetation, as compared with the reference expectation for that site. The current, observed riparian area is a measure of the current extent of the riparian zone after considering anthropogenic disturbance, and this metric is informed by a combination of remote data and field verification at the time of the assessment. The reference expectation, or expected riparian area, is an estimate of the natural or historic extent of the riparian area. Riparian width is driven by valley controls and reach-scale influences (Polvi et al. 2011). As such, the riparian extent metric uses an O/E approach to identify the current extent of the riparian zone compared with the expected extent based on reach-scale processes and drivers. The expected riparian area is delineated using hydrologic, geomorphic, and biotic indicators on the landscape or meander width ratio where natural indicators of riparian extent are no longer observable due to development. Additional information on data collection methods is provided in the WSQT v2.0 User Manual.

Characterizing the natural, or expected, extent of riparian zones is important, as functioning riparian zones influence (and are influenced by) many instream and floodplain processes (Fischer and Fischenich 2000; Mayer et al. 2006). Many existing methodologies focus on fixed buffer widths, yet these approaches can be limited as they don’t account for the natural variability in riparian zone widths, and thus may not adequately characterize their functional significance. For example, in high gradient headwater streams, riparian zones are naturally narrow, and may not extend as far as a fixed buffer width. Alternatively, in broad, alluvial systems, a fixed buffer width may only characterize a small fraction of the floodplain or riparian area extent. Thus, the approach outlined here is intended to better characterize the natural functional capacity of riparian zones, by comparing the current riparian extent against the expected, or reference, extent determined from the predominant processes that control riparian zones.

According to Merritt et al. (2017), the edge of a riparian area can be determined using three criteria:

- Substrate attributes—the portion of the valley bottom influenced by fluvial processes under the current climatic regime,
- Biotic attributes—riparian vegetation characteristic of the region and plants known to be adapted to shallow water tables and fluvial disturbance, and
- Hydrologic attributes—the area of the valley bottom flooded at the stage of the 100-year recurrence interval flow (Ries et al. 2008).

*Substrate and topographic attributes:* The extent of the riparian zone is driven by topographic and geomorphological patterns, as well as the dominant hydrological processes (Polvi et al. 2011; Salo et al. 2016). For example, in a study on riparian zones in the Colorado Front Range, Polvi et al. (2011) found that riparian width was correlated with gradient and valley geometry (e.g., connectedness, valley width and entrenchment. Even in altered systems, substrate, topographic and geomorphic indicators may be present to determine the expected extent of the riparian zone. These indicators may include terracing or other breaks in slope between the bankfull and valley edge, fluvial deposited sediments, or a lack of upland soil formation. In areas of extensive floodplain development where natural topographic or geomorphic indicators are not identifiable, a meander width ratio based on valley type should be used to determine the expected riparian area.

*Biotic attributes:* Riparian areas have distinctly different vegetation species and/or more robust growth forms than adjacent areas. Riparian areas are often characterized by the predominance of hydrophytic species that have adapted to shallow water tables and fluvial disturbances. It should be noted that in many areas of Wyoming, riparian communities are comprised of a combination of hydrophytic and upland species, including greasewood and sagebrush. The presence of upland species does not preclude an area from being classified as riparian, however, the absence of any hydrophytic species likely would. Similarly, where riparian areas contain species similar to adjacent areas, more vigorous or robust growth forms should be observed in order to classify it as a riparian area (USFWS 2009).

*Hydrologic attributes:* Riparian extent can relate to flow stage for a specified recurrence interval, although this relationship varies across process domains (Polvi et al. 2011). For example, Polvi et al. (2011) found that in high elevation unconfined valleys the riparian extent is significantly broader than the 100-year stage; in high elevation confined valleys it aligns with the 100-year stage; in unconfined low elevation montane systems, it is not well predicted by 10, 50 or 100-year flow stages; and in confined low elevation montane systems, the riparian extent aligns with the 10-year recurrence interval (and is significantly narrower than the 50 and 100-year stage). Recognizing the challenges in flow-based predictors of riparian extent, Merritt et al. (2017)

conservatively recommend the use of the 100-year recurrence interval flow stage to delineate riparian area extent. Where hydrologic attributes have been influenced by anthropogenic modification, they may no longer be useful to predict expected riparian extent but could still be used to inform the current extent of the riparian area.

There are many types of anthropogenic disturbance that can affect riparian areas, including modification of streamflows via dams and diversions, stream channelization, direct modification of riparian ecosystems (e.g., urban and agricultural land uses, grazing, timber extraction and mining), as well as disturbances that modify water and sediment production in the upstream watersheds (Goodwin et al. 1997). The riparian extent metric calculates the proportion of the expected riparian area that currently contains riparian vegetation and is free from anthropogenic disturbance, including urban development, intensive agricultural land uses, resource extraction and changes in hydrology. While some types of anthropogenic disturbance are readily observable, including impervious surfaces, manicured lawns or other managed vegetation, or intensive grazing, other disturbances to the riparian area, e.g., caused by incision or flow diversion, are more difficult to identify. The WSQT v2.0 User Manual provides direction on how to calculate existing and expected riparian area to inform this metric.

**Reference Curve Development:** Reference curves for this metric have been updated for WSQT v2.0.

The riparian width metric and reference curves was originally developed for WSQT v1.0. Updates to this metric and its reference curves were made following beta testing in Colorado (USACE 2020b), and these updates have been incorporated into WSQT v2.0.

This metric was developed to replace fixed buffer width approaches included in other SQTs (e.g., Harman and Jones 2017, TDEC 2018). Limited data and peer reviewed literature are available to inform thresholds and reference curves, as much of the existing literature is related to fixed-width buffers. 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 riparian and floodplain connectivity or remove stressors and human 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 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 segment within its watershed context. For this metric, reference curves were stratified by valley confinement to account for differences in hillslope and valley bottom processes that influence riparian extent in confined and unconfined valleys (Table 11-1).

Once stratified into valley types, the WSTT considered how potential stressors in the floodplain or adjacent stream area and changes to the hydrologic regime can influence the degree to which riparian zones function, and in turn, support instream functions. For example, whether the extent of riparian zone 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 (Fischer and Fischenich 2000; Sweeny and Newbold 2014). In confined and colluvial valleys, where streams and riparian zones are constrained by hillslope processes, riparian width is naturally narrower, and consequently, stressors within that area could be disproportionately higher. A reduction in riparian area of 30% would likely reflect a substantially altered, or not functioning condition, with little remaining flood prone area and a reduced capacity to recruit wood and organic matter and buffer the stream from sediment or pollutant influxes. This magnitude of riparian area loss may no longer support instream and floodplain functions. In unconfined valleys, where riparian areas are naturally broader, a greater proportion of the riparian area may be affected (e.g., 60%) before a similar loss in functionality might occur.

In WSQT v2.0, adjustments were made to the reference curve to encourage and incentivize restoration activities that restore riparian and floodplain connectivity and/or remove stressors from the riparian zone (Figure 11-1). Reference curves were expanded to allow for more lift in the non-functioning range of condition. As shown in Table 11-1, the minimum index value (0.00) was adjusted to equal a field value of 0%, where the absence of riparian vegetation reflects no functional capacity. The threshold values used to define the 0.00 index value in WSQT v1.0 were then used to set the threshold between functioning-at-risk and non-functioning.

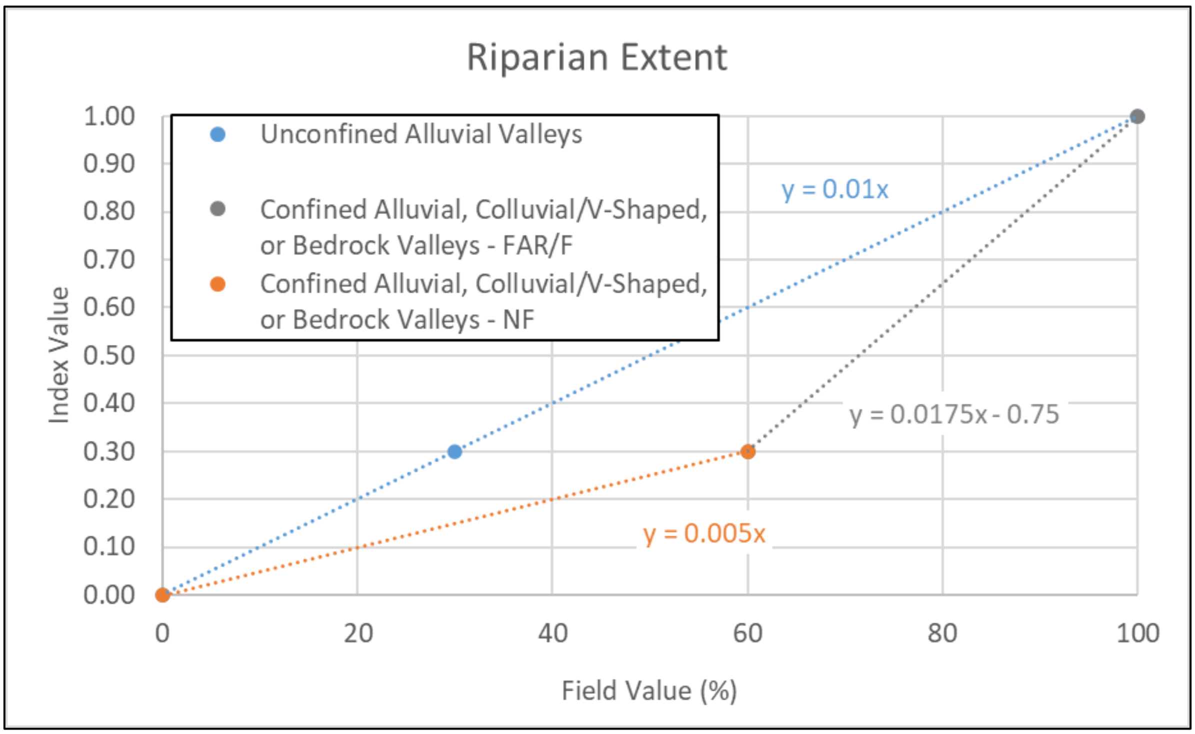



*Figure 11-1: Riparian Extent Reference Curves.*

*Table 11-1: Threshold Values for Riparian Extent.*

| Index Value | Field Value (%) | |
|---|---|---|
| | Unconfined Alluvial Valleys | Confined Alluvial and Colluvial Valleys |
| 1.00 | 100 | 100 |
| 0.30 | 30 | 60 |
| 0.00 | 0 | 0 |

**Limitations and Data Gaps:**

Because this is a new metric developed for use in the WSQT 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 area beyond the valley type approach applied here. The metric would benefit from additional validation, review and refinement as the tool is applied.

Beta testing revealed challenges in measuring the expected riparian width in the field, including difficulties in accurately measuring straight line distances in dense vegetation and a lack of readily observable geomorphic and hydrologic features in degraded sites, which are often no longer present due to site grading and/or development. Updates were made to WSQT v1.0 to address this issue, including several alternatives for determining the expected riparian width, including use of aerial photography, digital elevation models or calculations of a meander width ratio. Following additional testing and review to evaluate the relative accuracy and applicability of these approaches, significant modifications were made to this metric in WSQT v2.0, including modification of methods to measure riparian area instead of width. Continued testing and review will likely yield further improvements as the method is applied.

## 11.2. Woody Vegetation Cover

**Summary:**

Riparian areas in Wyoming are predominately characterized by a woody canopy (Youngblood et al. 1985; Jones and Walford 1995; Walford 1996; Walford et al. 2001; Jones et al. 2001). As noted above, in many areas of Wyoming, riparian communities are comprised of a combination of hydrophytic and upland species. Woody assemblages in Wyoming include willow-dominated scrub-shrub communities, cottonwood gallery forests, birch/alder scrub-shrub communities, spruce woodlands, as well as black greasewood shrub communities and silver sagebrush shrub communities.

Many riparian areas in the western U.S. are heavily influenced by changes in land use, fire regimes, grazing, flow modification and the influx of non-native and invasive species (Macfarlane et al. 2017). Tamarisk (*Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) have been prolific invaders, and many restoration efforts target the management and eradication of these invasive species (Shafroth et al. 2002). Riparian areas in the plains and basins that historically (pre-European settlement) contained patches of timber or brush were progressively reduced to herbaceous communities for over a century due to the rise of the plains horse culture, migration of white pioneers, and the advance of farming and stock-raising (West and Ruark 2004).

Because of the characteristic role woody vegetation plays in riparian areas, a woody vegetation metric is important to include in the WSQT. Woody vegetation cover provides an indication of the longevity and sustainability of perennial vegetation in the riparian corridor (Kaufmann et al. 1999; Kaufmann and Hughes 2006). The woody cover metric is based on a visual plot-based vegetation assessment. The field value for this metric (averaged across all plots) reflects the sum of the absolute cover of all woody species and can be greater than 100% cover. Methods are outlined in the WSQT v2.0 User Manual.

**Reference Curve Development:**

Reference curves for this metric have been updated for WSQT v2.0 following new analysis and revised reference curves in Colorado (USACE 2020b).

In the WSQT Beta Version, the NRSA dataset (EPA 2016) was used to develop reference curves and inform data collection methods. However, following beta testing and field training exercises, the decision was made to change data collection methods to align with the 1987 Wetland Delineation Manual methods, as the USACE field staff and many practitioners are already familiar with this form of data collection. These methods provide absolute cover by species, which is different than the approach used in the beta version. Because of this, the NRSA dataset, which relies on relative cover by strata, was considered no longer applicable for developing reference curves. The WSTT relied on CNHP datasets (see Section 1.8) and a small data collection effort in Wyoming to inform the reference curves for this metric.

*Colorado Natural Heritage Program:* Woody vegetation cover values were calculated for woody sites in the CNHP dataset, described in Section 1.8. Woody vegetation cover values were developed by summing absolute cover values for all woody species. Shrub species cover values were combined with tree species cover values into a combined woody stratum. Statistics were derived from the CNHP dataset for the reference standard (R) and degraded (D) sites within each ecoregion (Table 11-2). Sample sizes were limited, particularly for degraded sites and for all sites within the plains and tablelands (included in the plains ecoregion).

Multiple options were evaluated for stratification, including ecoregion, CDPHE biotype, and valley entrenchment, to determine whether there were significant differences between reference and degraded sites in the dataset. When the dataset was stratified by ecoregion, significant differences between reference and degraded sites were observed (USACE 2020b). Stratification by CDPHE biotype also showed significant differences between reference and degraded sites for mountains and transitional ecoregions, but not for plains. Only a subset of sites within the dataset could be evaluated for valley entrenchment, and of these, only unconfined multi-threaded sites (Rosgen D stream types) showed significant differences in woody cover between reference and degraded sites. These results support the stratification of this metric by ecoregion.

*Table 11-2: Statistics for Woody Vegetation Cover from the CNHP Dataset. Degraded (D) and Reference Standard (R) Sites.*

| Statistic | Woody Vegetation Cover (%) by Ecoregion and Condition | | | | | | |
|---|---|---|---|---|---|---|---|
| | Mountains | | Basins | | Mountains and Basins | Plains | |
| | D | R | D | R | R | D | R |
| Number of Sites (n) | 11 | 336 | 0 | 49 | 385 | 11 | 6 |
| Average | 68 | 96 | - | 116 | 98 | 95 | 57 |
| Standard Deviation | 44 | 38 | - | 46 | 42 | 49 | 29 |
| Minimum | 0 | 22 | - | 0 | 21 | 51 | 24 |
| $25^{th}$ Percentile | 46 | 68 | - | 90 | 69 | 76 | 53 |
| Median | 71 | 92 | - | 116 | 94 | 92 | 59 |
| $75^{th}$ Percentile | 95 | 117 | - | 137 | 122 | 101 | 69 |
| $95^{th}$ Percentile | 104 | 166 | - | 205 | 177 | 157 | 75 |
| Maximum | 104 | 258 | - | 211 | 258 | 207 | 106 |

In the basins and plateau ecoregions (both included in the basins category), the CNHP cover values were substantially higher than the other ecoregions. Cover values may be higher because the data collection within the xeric ecoregions (basins) in Colorado followed a sampling methodology using large plot sizes (e.g., $50m^2$-$500m^2$), potentially resulting in an overestimation of cover. Further, Macfarlane et al. (2017) modeled pre-European settlement native land cover and showed that current riparian vegetation showed significant to large (33 to >66%) departure from historic conditions in the Utah and Columbia River basin watersheds, with riparian vegetation conversions being primarily from native riparian to invasive and upland woody vegetation types. There may be few areas that truly represent reference standard condition on the landscape due to the long history of land use, flow modification and grazing that is prevalent in the Eastern Xeric and Wyoming Basins. Given these limitations, the WSTT decided to combine the Mountains and Basins datasets and develop a single, combined reference curve.

*WSTT data collection:* In August 2016 and fall of 2017, the WSTT visited several sites to apply the proposed WSQT methodology for assessing riparian vegetation. These sites were considered to represent minimally disturbed reference sites. However, because they are located on public lands, they have likely been subject to some historical use, including grazing and/or timber removal. The woody vegetation cover values from these sites are presented in Table 11-3. Note, these data reflect cover values by lifeform, and thus are lower than absolute cover value by species.

*Table 11-3: Woody Vegetation Cover at Reference Sites Visited by the WSTT.*

| Site | Ecoregion | Woody Vegetation Cover (%) |
|---|---|---|
| Wood River, above Middle Fork | Mountains | 53 |
| Middle Fork Wood River | Mountains | 47 |
| Middle Fork Wood River – Upstream | Mountains | 44 |
| Jack Creek | Mountains | 76 |
| Sand Creek (2017) | Basins | 46 |

*Analysis*: In general, the following criteria were used to establish the thresholds (Table 11-4) between the three functional categories:

- The 75th percentile of reference standard sites were used to determine the maximum index value of 1.00.
- The 25th percentile values from reference standard sites was used to determine the threshold between functioning and a functioning at risk condition.
- The 75th percentile cover values from degraded sites were used to inform the threshold between functioning at risk and not functioning condition. Where sufficient data were not available, this threshold would not be identified; and values within these index ranges would be determined from the reference curve.
- Minimum index values were set at 0% woody vegetation cover. Even a small amount of woody vegetation recruitment would lead to cover values of 1% or greater.

*Table 11-4: Threshold Values for Woody Vegetation Cover.*

| Index Value | Field Value (%) | |
|---|---|---|
| | Mountains and Basins | Plains |
| 1.00 | ≥ 122 | 69 - 76 |
| 0.70 | 69 | -, - |
| 0.30 | - | -, 101 |
| 0.00 | 0 | 0, - |

In the mountain and basins ecoregions, the 75th percentile value (122% cover, n=385) from the combined ecoregion dataset was used to characterize the maximum index value (1.00), meaning any site with absolute woody vegetation cover of 122% or greater would receive a maximum index score. The 25th percentile from the CNHP dataset (69% cover, n=385) was used as the threshold value between functioning and functioning-at-risk index values.

The WSTT did not identify the break between non-functioning and functioning-at-risk due to a lack of data resolution, and instead decided to fit the reference curve and allow this break to be extrapolated from the regression equation. The 25th percentile value from the CNHP mountain degraded sites was 46% woody vegetation cover (n=11), which falls within the functioning-at-risk range of index scores from the curve. While it may be appropriate to consider these degraded sites as not-functioning and assign them lower index values, the WSTT felt a more conservative approach was appropriate due to the natural variability in woody riparian ecosystems. In the WSQT v2.0, the mountains and basins reference curve was updated to apply a linear regression curve between threshold values, instead of the polynomial curve previously applied in WSQT v1.0.

In developing the reference curve (Figure 11-2a), the WSTT took into consideration the data collected from mountain and basins field sites by the WSTT in Wyoming, which showed a range of cover values from 44-76%. (Note that these cover values were collected with a different methodology – absolute cover by species values at these sites would be higher). These sites were in good condition, and had healthy, diverse riparian communities. However, cover values at these sites may be lower than a pristine condition due to historical and current anthropogenic use, including grazing and/or timber harvest. The sites in the Wood River basin were characterized by broad, connected floodplains that had micro topography consisting of multiple hummocks, swales, and cobble bars. These conditions support establishment of diverse herbaceous and scrub-shrub floodplain mosaics, which are an ecologically desirable outcome in many ecoregions despite lower cover values (Kleindl et al. 2015). The woody vegetation was naturally patchy and interspersed with areas of herbaceous vegetation. In evaluating the datasets and proposed benchmarks, the WSTT concluded it was reasonable to characterize these sites as functioning or (high) functioning-at-risk. These sites have the potential to support a healthy aquatic ecosystem and were not in a clearly degraded state.

The combined CNHP dataset in the plains ecoregion had small sample sizes for both reference and degraded sites. In this dataset, degraded sites consistently had higher woody vegetation cover than reference sites. This could be due to several factors, including the augmentation of flows on the high plains from irrigation practices, or shifts in riparian community type (Scott et al. 2000; Richardson et al. 2007; Macfarlane et al. 2017). Historically, woody communities along streams in the plains would be characterized by cottonwood gallery forests and willows (West and Ruark 2004), and many are now composed of regionally introduced mixed deciduous forest species and/or shrub that tolerate a broader range of environmental factors and land uses (Jones and Walford 1995; Kittel et al. 1999). An evaluation of the NRSA dataset found that non-reference sites had, on average, lower cover values than reference sites, but some sites showed a similar pattern to the CNHP dataset, with much higher cover values than the reference sites. Because of these trends in the data, the WSTT decided to develop a two-sided reference curve that captured woody vegetation cover values that were both lower and higher than reference standard condition (Figure 11-2b).

Due to the small size of the reference dataset, a threshold value between functioning and functioning-at-risk condition was not defined, and the reference curve was fit using the threshold values identified in Table 11-4. In the WSQT v1.0, the median and 75$^{th}$ percentile values from the reference standard sites were used to define the maximum index value of 1.00. This has been updated for WSQT v2.0, and the 75th percentile of reference standard sites (69%, n=6) was used to determine the maximum index value of 1.00 on the rising limb of the reference curve. This update was made for consistency with other metrics, which rely on the 75th percentile to define the 1.00 value. On the falling limb of the reference curve, thresholds were updated to use the 25th percentile value for the degraded sites (76%, n=11) to define the maximum index value of 1.00. This value is within 1% of the 95th percentile value of the reference sites. Because the falling limb of the reference curve was included to address the pattern of degraded sites having higher woody vegetation than reference, the WSTT felt that relying on data from degraded sites was appropriate.

Because the CNHP degraded sites were consistently higher cover values than the reference sites, the 75th percentile from the degraded sites in the CNHP dataset (101%, n=11) was used to determine the break between functioning-at-risk and not functioning on the right side of the reference curve. On the left side of the reference curve, the break between non-functioning and functioning-at-risk was not identified due to a lack of data resolution. Instead, the WSTT decided to fit the reference curve, and allow this break to be extrapolated from the regression equation. The 25th percentile of the reference standard dataset was 53% cover, which falls within the functioning range of index values in the reference curve. Woody vegetation cover of 0% was assigned a minimum index value of 0.00, which allows for a range of woody cover values to score within the functioning-at-risk and functioning condition ranges, recognizing ecosystem and flood dynamics that create diverse vegetation floodplain mosaics in a plains environment (Jones and Walford 1995; Kleindl et al. 2015).

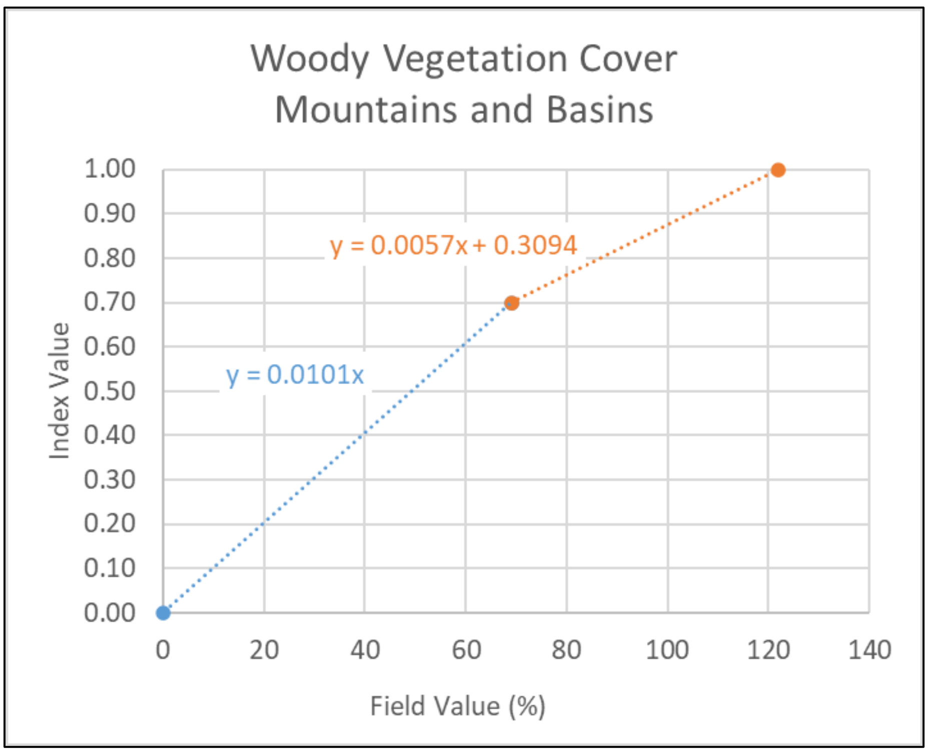



*Figure 11-2a: Woody Vegetation Cover Reference Curve for Mountain and Basin Ecoregions.*

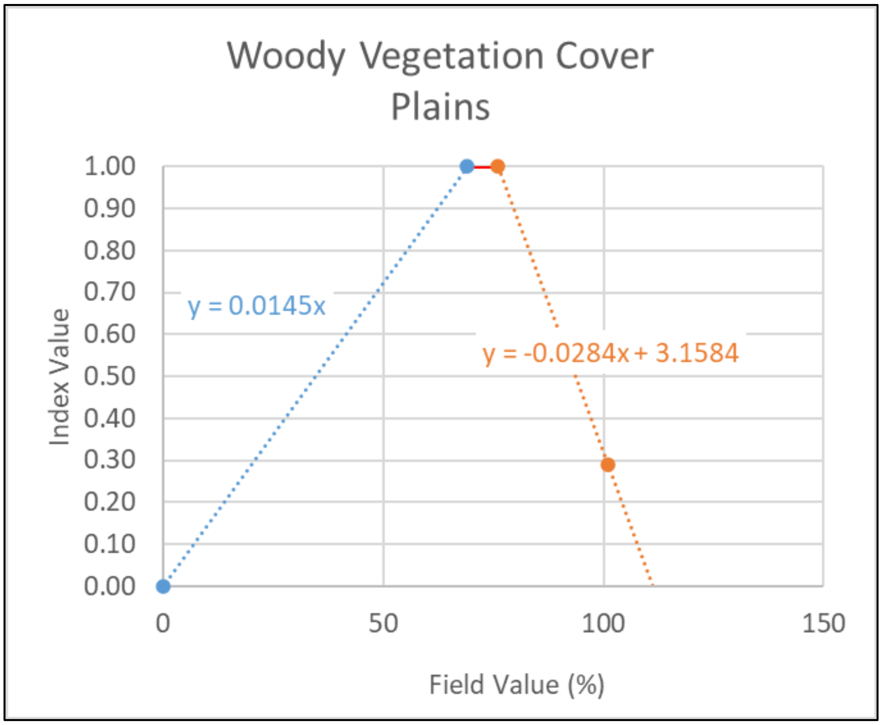



*Figure 11-2b: Woody Vegetation Cover Reference Curve for Plains Ecoregion.*

**Limitations and Data Gaps:**

The CNHP dataset has limitations, including the obvious geographic boundaries of the state. The WSTT assumed that the CNHP dataset would be relevant and translatable to Wyoming due to the overlapping ecoregions and similarity between riparian community types in Colorado and Wyoming. The CNHP dataset includes data collected between 1992 and 1999; with no sites revisited recently. Additional analysis of these sites may be useful to understand whether changes in climate or other large-scale influences have altered the reference expectation for riparian areas in this region.

The reference curve development for the WSQT would benefit from additional Wyoming-specific data to validate the criteria and curves identified above. Additional data would also allow for us to consider whether additional stratification or refinement beyond ecoregion could occur. For example, there was a broad range in cover values across reference standard conditions. The Wood River site had moderate amounts of woody cover due to the naturally patchy nature of the floodplain area. As such, additional stratification within ecoregions, e.g., by valley type, slope, stream size or target community composition, would allow us to further refine these reference curves and identify more specific restoration targets.

The metric does not differentiate between upland and hydrophytic woody vegetation cover. This may attribute a higher level of functioning to degraded systems that have transitioned to an upland dominated woody community. Additional data and research are required to better understand how naturally prevalent upland species are within riparian areas in Wyoming. Many plains and basin riparian systems support upland scrub-shrub communities. While these are often associated with more degraded, incised systems, they can also occur naturally due to specific soil conditions and in more arid areas with lower water tables.

A major challenge is also differentiating between streams of varying flow permanence. The WSTT did not differentiate or evaluate differences in woody riparian vegetation cover across perennial, intermittent, or ephemeral systems. It is likely ephemeral streams would naturally sustain lower densities of woody vegetation, and thus would benefit from their own set of reference curves and criteria. This metric should still be applied in ephemeral stream systems, but these systems may generally score lower than their perennial counterparts.

## 11.3. Herbaceous Vegetation Cover

**Summary:**

While many riparian areas in Wyoming are predominately characterized by a woody canopy (as noted above), a ground layer of herbaceous vegetation is often also present. These herbaceous species are an important component of the riparian community, as they are often providing surface roughness and cover in the early stages of succession following fluvial disturbances (Youngblood et al. 1985; Winward 2000). Hydrophytic herbaceous vegetation, including sedges and rushes, 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 et al. 1985; West and Ruark 2004). While the historical distribution of these communities is not well known, Kittel et al. (1999) describes over 30 riparian plant assemblages that are predominantly herbaceous vegetation.

Many riparian areas in the western U.S. are heavily influenced by changes in land use, fire regimes, grazing, flow modification, and the influx of non-native and invasive species (Macfarlane et al. 2017). Many riparian communities contain non-native upland pasture grasses and forage forbs due to agricultural land use and cattle grazing. These species are adapted to a range of moisture regimes and thrive in mesic conditions supported by both connected and disconnected floodplains (Youngblood et al. 1985). Introduced species are very competitive except in highly connected floodplains where anaerobic soil conditions generally support wetland obligate native species (USACE 2008; USACE 2010a; USACE 2010b). Over grazing, frequent fire regimes, woody brush control and channel incision can promote secondary succession and invasion of non-native herbaceous species as well as native upland grasses, which lack root structures to stabilize streams (Youngblood et al. 1985; Jones and Walford 1995; Winward 2000; MacFarlane et al. 2017). Riparian areas dominated by these species can perpetuate degraded conditions.

An herbaceous vegetation cover metric is included in the WSQT and contributes to scoring for sites with a reference expectation of less than 20% woody cover. Consideration was given to applying herbaceous cover at all sites (herbaceous and woody) because of the value it provides as a component of early succession riparian communities as well as its sensitivity to disturbance. Because of this importance, users are recommended to calculate the field value for this metric and enter it into the WSQT, but it will only contribute to scoring at sites with less than 20% woody cover. Consideration was also given to applying both an herbaceous cover metric and a native/non-native herbaceous species metric at all sites. The WSQT v2.0 only includes the herbaceous cover metric, as non-native herbaceous species are captured in the native cover metric. The herbaceous vegetation cover metric is based on a visual plot-based vegetation assessment. This metric represents the sum of absolute aerial cover of herbaceous species collected within 1-meter or 5-meter plots. Methods are outlined in the WSQT v2.0 User Manual.

**Reference Curve Development:**

Reference curves for this metric have been updated for the WSQT v2.0 following new analysis and revised reference curves in Colorado (USACE 2020b).

The herbaceous cover reference curve was developed using the CNHP dataset (as described in Section 1.8), the Northern Rocky Mountain Hydrogeomorphic Manual (Hauer et al. 2002), and a small data collection effort in Wyoming. While the WSQT v1.0 included reference curves for herbaceous cover at both woody and herbaceous sites, the WSQT v2.0 only includes a single reference curve to score herbaceous cover at sites where the reference vegetation community is herbaceous. This decision was made following a revised analysis of the CNHP dataset (described below). Data on herbaceous cover in woody sites is still retained in this section, as it may still be useful for developing performance standards or target conditions.

In the WSQT Beta Version, the NRSA dataset (EPA 2016) was used to develop reference curves and inform data collection methods. However, following beta testing and field training exercises, the decision was made to apply one method for all vegetation cover metrics that aligns with the 1987 Wetland Delineation Manual, as the USACE field staff and many practitioners are already familiar with this form of data collection. These methods provide absolute cover by species, which is different than the approach used in the beta version. Because of this, the NRSA datasets, which rely on relative cover by strata, were considered no longer applicable for developing reference curves.

*Colorado Natural Heritage Program:* Herbaceous vegetation cover values were calculated for sites in the CNHP dataset, described in Section 1.8. Reference curves for WSQT v2.0 rely on the revised data analysis, where sites were stratified as either woody or herbaceous depending on whether they had greater than or less than 20% woody cover, respectively. For woody sites, there were no significant differences in herbaceous vegetation cover between reference and degraded sites. Significant differences in herbaceous vegetation cover were observed at herbaceous sites, but not woody sites (Figure 11-3). As such, a reference curve has only been developed for herbaceous sites where the reference expectation is <20% woody cover, and this metric will only be scored in the SQT at sites with an herbaceous reference expectation. The reference curve for herbaceous cover at woody sites included in WSQT v1.0 has been removed from WSQT v2.0. Herbaceous vegetation cover values were developed by summing absolute cover values categorized by stratum. Species in the dataset identified as graminoid or forb were grouped together into the herbaceous stratum.

Additional options were evaluated for stratification, including by ecoregion, CDPHE biotype and valley entrenchment. Results did not yield any statistically significant differences between reference and degraded sites with these stratifications. There were, however, statistically significant differences between reference and degraded sites when looking at all data combined. As such, the dataset was not stratified beyond reference community type. This is consistent with the stratification approach taken in HGM, described below (Hauer et al. 2002).

Statistics were derived from the revised CNHP dataset for the reference standard (R) and degraded (D) sites for each cover type (Table 11-5).

*<u>Analysis</u>:* The revised CNHP dataset was used to develop threshold values and reference curves for this metric (Table 11-6, Figure 11-4). In general, the following criteria were used to establish the breaks between the functional categories:

- The 75$^{th}$ percentile of reference standard sites (119%, n=96) was used to determine the maximum index value of 1.00.
- The 25$^{th}$ percentile of reference standard sites (74%, n=96) was used to determine the break between functioning and functioning at risk condition.
- Due to small sample sizes, the threshold between functioning-at-risk and non-functioning condition was not identified a priori; values within these index ranges are determined from the reference curve.
- The minimum index value was derived from the 5$^{th}$ percentile of all reference and degraded sites combined (35%, n=101) due to the small sample size for degraded sites. The WSTT felt it was important to incentivize a minimum threshold of herbaceous cover.

Note that the threshold values for herbaceous cover in herbaceous community types vary substantially from the variable sub-index scores identified by Hauer et al. (2002), likely because the values in Hauer et al. (2002) are based on select hydrogeomorphic cover types located exclusively in the northern Rocky Mountains.

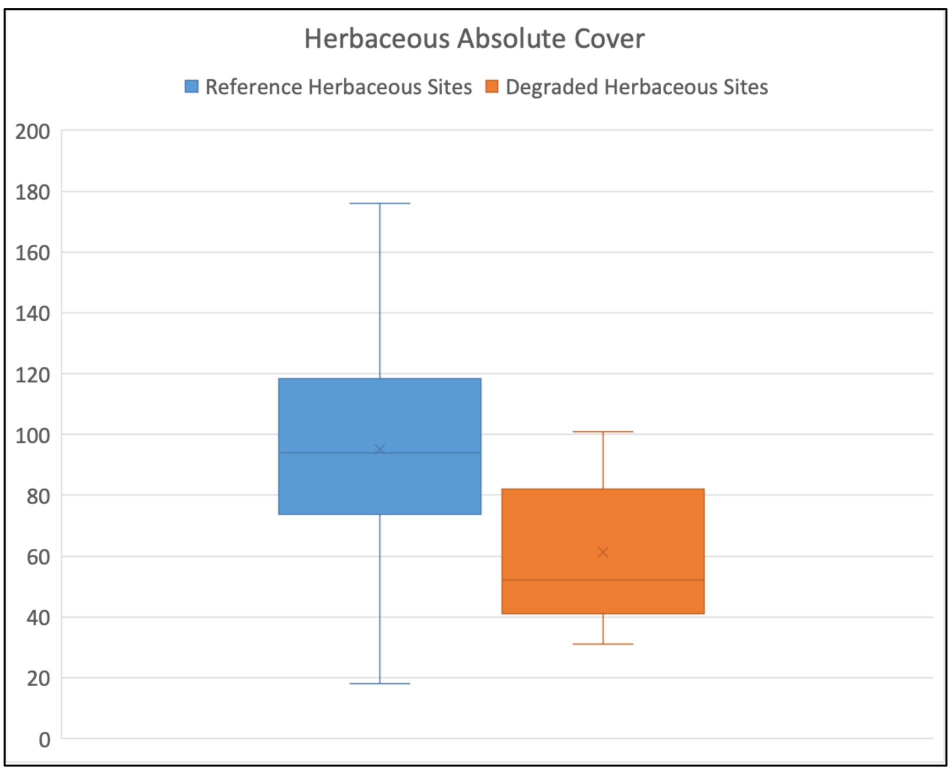



*Figure 11-3a: Box Plots for Herbaceous Vegetation Cover from CNHP Dataset. Stratified by condition (reference or degraded).*

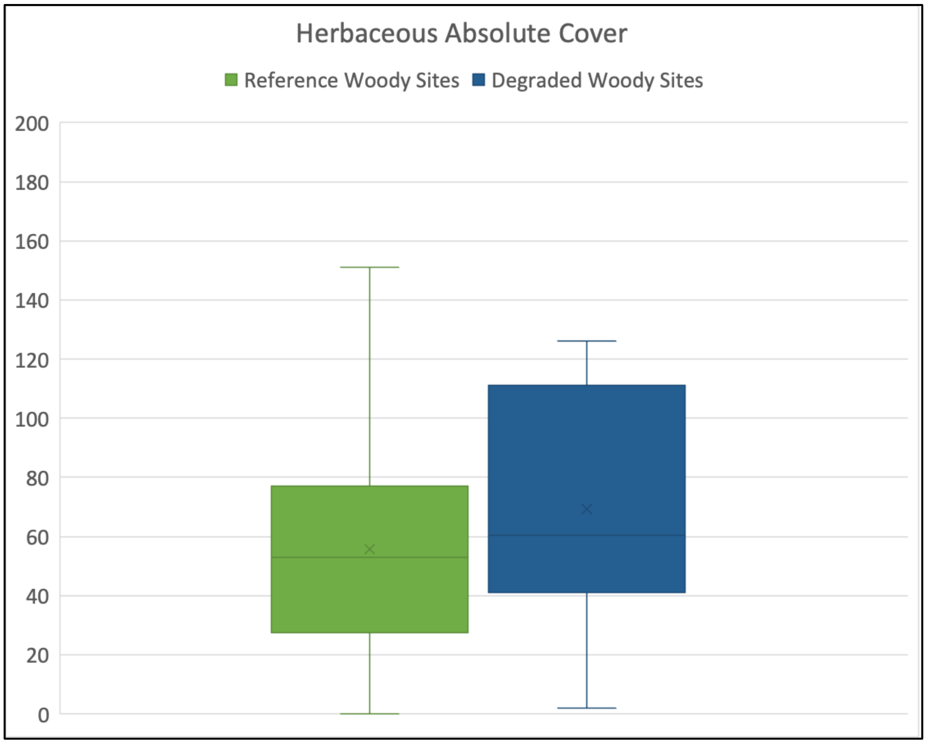



*Figure 11-3b: Box Plots for woody sites from the CNHP Dataset. Stratified by condition (reference or degraded).*

*Table 11-5: Statistics for Herbaceous Vegetation Cover from the Revised CNHP Dataset. Degraded (D) and Reference Standard (R) Sites.*

| Statistic | Herbaceous Vegetation Cover (%) by Reference Community Type and Condition | | | |
|---|---|---|---|---|
| | Woody | | Herbaceous | |
| | D | R | D | R |
| Number of Sites (n) | 25 | 391 | 5 | 96 |
| Average | 69 | 56 | 61 | 95 |
| Standard Deviation | 43 | 36 | 29 | 34 |
| Minimum | 2 | 0 | 31 | 34 |
| 5th Percentile | 10 | 6 | 33 | 36 |
| 25th Percentile | 41 | 28 | 41 | 74 |
| Median | 61 | 53 | 52 | 94 |
| 75th Percentile | 111 | 77 | 82 | 119 |
| 95th Percentile | 126 | 120 | 97 | 152 |
| Maximum | 126 | 183 | 101 | 176 |

*Table 11-6: Threshold Values for Herbaceous Vegetation Cover Within the Herbaceous Reference Vegetation Cover Type.*

| Index Value | Field Value |
|---|---|
| 1.00 | ≥ 119 |
| 0.70 | 74 |
| 0.00 | ≤ 35 |

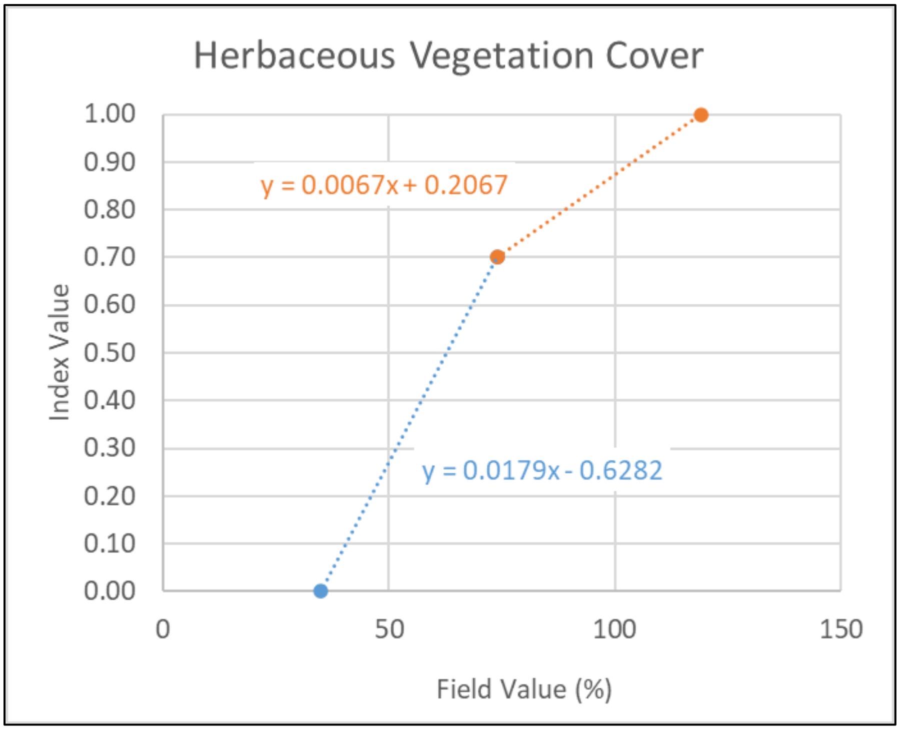



*Figure 11-4: Herbaceous Vegetation Cover Reference Curves for the Herbaceous Reference Vegetation Cover Type.*

**Limitations and Data Gaps:**

The CNHP dataset had limitations due to sample size and the obvious geographic boundaries of the state. Thus, the WSTT had to assume the CNHP dataset would be relevant and translatable to Wyoming due to the overlapping ecoregions and similarity between riparian community types in Wyoming. The CNHP dataset includes data collected between 1992 and 1999; with no sites revisited recently. Additional analysis of these sites may be useful to understand whether changes in climate or other large-scale influences have altered the reference expectation for riparian areas in this region.

The reference curve development for the WSQT would benefit from additional Wyoming-specific data to validate the criteria and curves identified above. It is uncertain how prevalent naturally occurring herbaceous-only riparian reference communities are due to historically altered landscapes, current land uses and altered flow regimes (Jones and Walford 1995; West and Ruark 2004; Macfarlane et al. 2017). The only certain reference herbaceous communities are 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 et al. 1985; West and Ruark 2004). Additional data would also allow for us to consider whether additional stratification or refinement beyond reference community type could occur. This would allow us to consider natural variability in herbaceous cover that would occur across stream sizes, elevations, soil types or between different target herbaceous community composition.

The WSTT did not differentiate or evaluate differences in herbaceous riparian vegetation cover across perennial, intermittent, or ephemeral systems, and are uncertain if this metric plays a substantial role in differentiating between streams of varying flow permanence. This metric should still be applied in ephemeral stream systems, but these systems may generally score lower than their perennial counterparts.

## 11.4. Percent Native Cover

**Summary:**

Many riparian areas in the western U.S. are heavily influenced by changes in land use, fire regimes, grazing, flow modification and the influx of non-native and invasive species (Macfarlane et al. 2017). Tamarisk and Russian olive have been prolific invaders, and many restoration efforts target the management and eradication of these invasive species (Shafroth et al. 2002). Many riparian areas in the plains and basins that historically (pre-European settlement) contained patches of timber or brush were eventually and progressively reduced to mixed origin herbaceous communities due to the migration of white pioneers, the advance of farming and stock-raising and the introduction of non-native pasture grasses (West and Ruark 2004).

This metric represents relative cover of native species and is calculated by absolute cover of native species divided by absolute cover of all species at a site. The maximum field value for this metric is 100% cover.

**Reference Curve Development:** Reference curves for this metric have been updated for WSQT v2.0 to adopt revisions implemented in Colorado (USACE 2020b).

Reference curves for this metric are based on data from the CNHP dataset (see Section 1.8) and a small data collection effort in Wyoming. In the WSQT Beta Version, the NRSA dataset (EPA 2016) was used to develop reference curves and inform data collection methods. However, following beta testing and field training exercises, the decision was made to use a single, species-level approach for all vegetation cover metrics and change data collection methods to align with the 1987 Wetland Delineation Manual methods, as the USACE field staff and many practitioners are already familiar with this form of data collection. These methods provide absolute cover by species, which is different than the approach used in the beta version. Because of this, the NRSA dataset, which rely on relative cover by strata, were considered no longer applicable for developing reference curves.

*Colorado Natural Heritage Program:* Percent native cover values were calculated from sites in the CNHP dataset, described in Section 1.8. Percent native cover was calculated by summing the absolute cover values for all native species and dividing by the total absolute cover value for a site. Statistics were derived from the CNHP dataset for the reference standard and degraded sites (Table 11-7). Sample sizes were limited, particularly for degraded sites and for all sites within the plains and tablelands (included in the plains category) ecoregions.

*Table 11-7: Statistics for Percent Native Cover from the CNHP Dataset.*

| Statistic | Percent Native Vegetation Cover (%) | |
|---|---|---|
| | Degraded | Reference |
| Number of Sites (n) | 27 | 487 |
| Average | 77 | 98 |
| Standard Deviation | 18 | 5 |
| Minimum | 43 | 57 |
| 5th Percentile | 48 | 89 |
| 25th Percentile | 65 | 98 |
| Median | 84 | 99 |
| 75th Percentile | 91 | 100 |
| Maximum | 100 | 100 |

Percent native cover was consistent across reference standard sites within all ecoregions and reference community types (Figure 11-5), with one exception. In the plains ecoregion at woody reference community types, percent native cover values were lower at both reference and degraded sites than within other ecoregions. This could be reflective of land use, flow modification and grazing at the sites included in the dataset. Due to the small sample sizes of this subset, and the consistency across other ecoregions and community types, the WSTT decided not to stratify by ecoregion or reference community type.

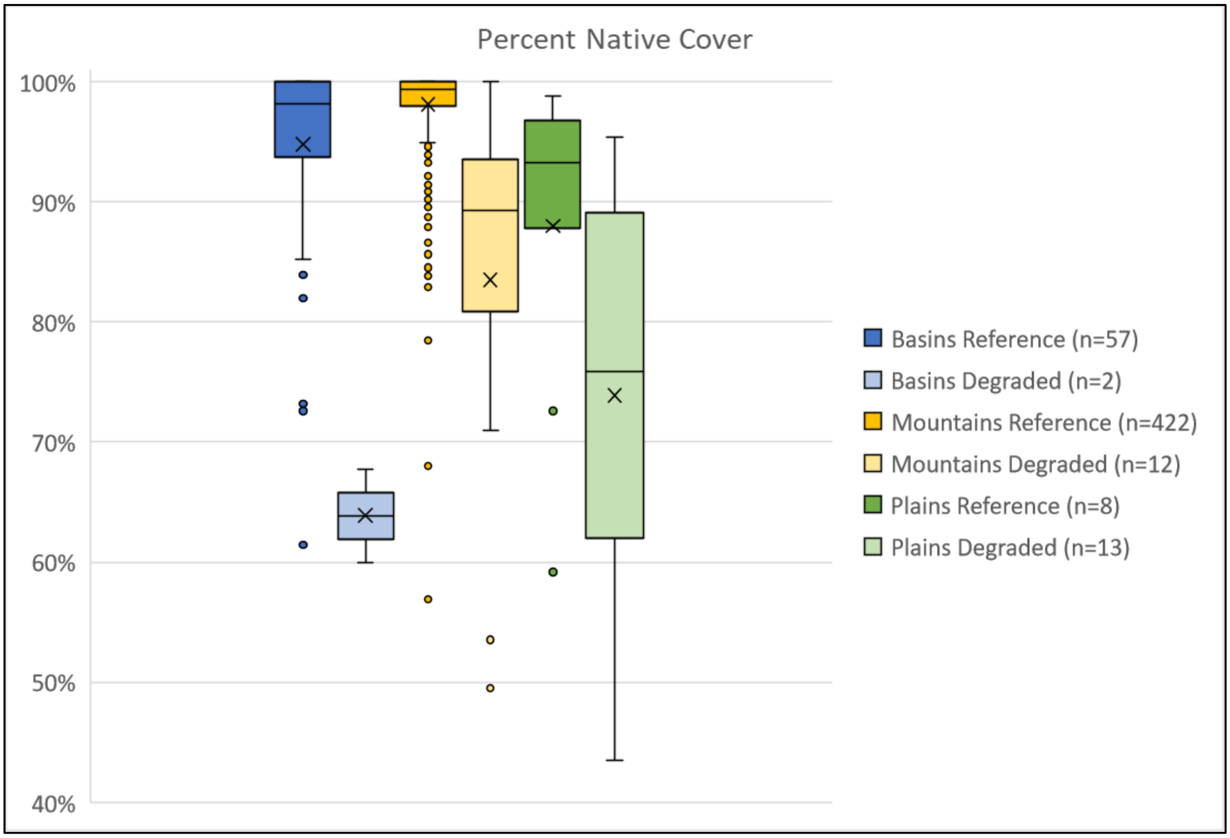



*Figure 11-5: Box Plots for Percent Native Cover from the CNHP Dataset. Stratified by condition (reference or degraded) and ecoregion (basins, mountains and plains).*

*WSTT data collection:* In August 2016 and fall of 2017, the WSTT visited several sites to apply the proposed WSQT methodology for assessing riparian vegetation. These sites were considered to represent minimally disturbed reference standard sites. However, because they are located on public lands, they have likely been subject to some historical use, including grazing and/or timber removal. The percent native cover values from these sites are presented in Table 11-8.

*Table 11-8: Percent Native Cover at Reference Sites Visited by the WSTT.*

| Site | Ecoregion | Percent Native Cover (%) |
|---|---|---|
| Wood River, above Middle Fork | Mountains | 92 |
| Middle Fork Wood River | Mountains | 98 |
| Middle Fork Wood River - Upstream | Mountains | 100 |
| Jack Creek | Mountains | 100 |

*Analysis:* In general, the following criteria were used to establish the threshold values using the CNHP dataset. Threshold values are shown in Table 11-9.

- The 75$^{th}$ percentile of reference standard sites were used to determine the maximum index value of 1.00.
- The 75$^{th}$ percentile values from degraded sites was used to determine the threshold between functioning and a functioning at risk condition. Since threshold values are from the degraded sites, the field value of 91% native cover was used to define the upper end of the functioning-at-risk range of scoring (0.69).
- The 25$^{th}$ percentile cover values from degraded sites were used to inform the threshold between functioning at risk and not functioning condition.
- Minimum index values were extrapolated from the regression equation.

A broken linear curve was used to fit the threshold values (Figure 11-6). The minimum index value extrapolated from the curve was 46% native cover, which aligns with the 5$^{th}$ percentile from the degraded dataset (48%) and is thus a reasonable minimum value.

Data collected by the WSTT in Wyoming had percent native cover values of 92-100%, which fall within the functioning, reference standard range of index scores. As noted above, these sites were in good condition, and had healthy, diverse riparian communities, and the WSTT concluded it was reasonable to characterize these sites as functioning or (high) functioning-at-risk.

*Table 11-9: Threshold Values for Percent Native Cover.*

| Index value | Field Value (%) |
|---|---|
| 1.00 | 100 |
| 0.69 | 91 |
| 0.30 | ≤ 65 |

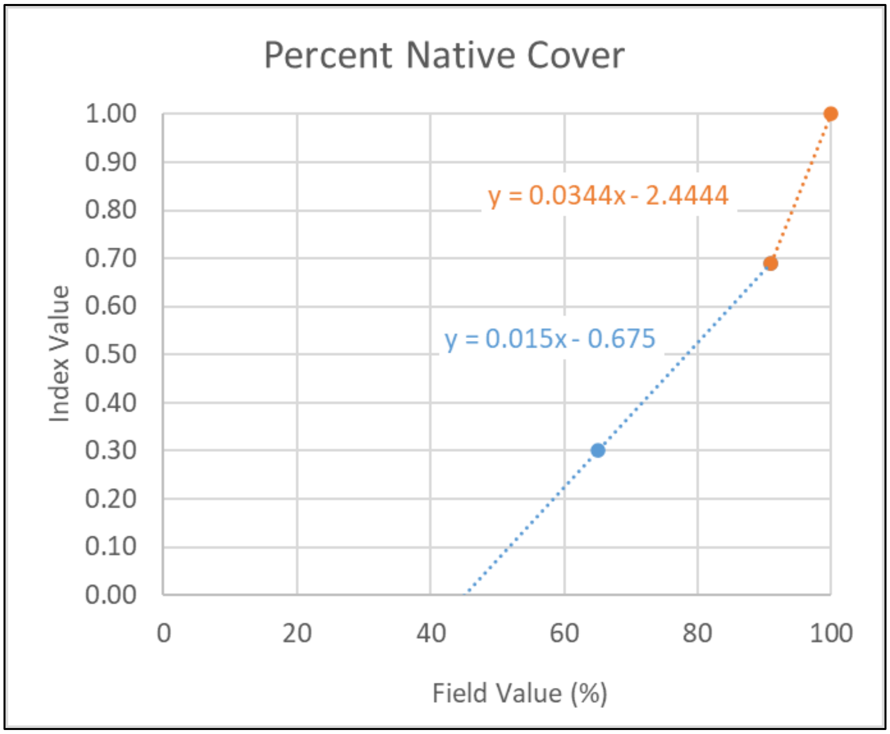



*Figure 11-6: Percent Native Cover Reference Curve.*

**Limitations and Data Gaps:**

The CNHP dataset has limitations, including the obvious geographic boundaries of the state. The WSTT assumed that the CNHP dataset would be relevant and translatable to Wyoming due to the overlapping ecoregions and similarity between riparian community types in Colorado and Wyoming.

The reference curve development for the WSQT would benefit from additional Wyoming-specific data to validate the criteria and curves identified above. Additional data would also allow for us to consider whether stratification is needed.

This metric does not differentiate between upland and hydrophytic native vegetation cover, and as such, may attribute a higher level of functioning to degraded systems that have transitioned to an upland-dominated community. Additional data and research are required to better understand how naturally prevalent upland species are within riparian areas in Wyoming. Many plains and basin riparian systems support upland scrub-shrub communities. While these are often associated with more degraded, incised systems, they can also occur naturally due to specific soil conditions and in more arid areas with lower water tables.

A major challenge is also differentiating between streams of varying flow permanence. The WSTT did not differentiate or evaluate differences in native cover across perennial, intermittent or ephemeral systems, or evaluate whether changes in flow regime may facilitate the establishment of non-native species. This metric should be applied in ephemeral stream systems but would benefit from additional data collection.

# Chapter 12. 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).

The WSQT includes one metric for this parameter, maximum weekly average temperature.

**Metric:**

- Maximum Weekly Average Temperature (°C)

## 12.1. Maximum Weekly Average Temperature (MWAT)

**Summary:**

The Maximum Weekly Average Temperature (MWAT) is a common metric for chronic thermal exposure for fish, and thermal criterion are available for streams throughout Wyoming (Peterson 2017; Mandeville et al. 2019). The MWAT is a chronic criterion that represents the upper bound of the optimum temperature range that supports specific species growth, reproduction, and survival (Brungs and Jones 1977). Temperatures that exceed this threshold may limit growth, reproduction, and survival. To calculate the MWAT, first calculate the mean daily temperature for each day in the period of record and then calculate the weekly average temperature on a seven-day rolling basis for the period of record. The MWAT is the largest of these seven-day rolling average values. For the WSQT, the period of record is the month of August. The metric is measured using in-water temperature sensors installed following procedures outlined in the EPA's 'Best Practices for Continuous Monitoring of Temperature and Flow in Wadeable Streams' (EPA 2014).

**Reference Curve Development:**

Reference curves were derived using data and information presented in Peterson (2017). The values shown in Table 12-1 are the proposed MWAT thermal criteria for Wyoming streams for the five thermal tiers (Peterson 2017). This metric is stratified by ambient stream temperature regime, where Tier I is cold, and Tier V is warm. In this study, thermal tiers and associated thermal criteria were developed using species assemblage data, laboratory-derived thermal tolerance data, and predicted mean August stream temperature as determined by the Air, Water, and Aquatic Environmental Program NorWeST model (Isaak et al. 2017). August was the period used by Issak et al. (2017) to predict summer stream temperature scenarios because of the size of available datasets in August, as well as the strong correlations between August temperatures and other commonly used temperature metrics. Modeled stream temperature data can be accessed through the NorWeST online mapper[2].

*Table 12-1: Proposed MWAT Surface Water Thermal Criteria for Wyoming Streams (Peterson 2017).*

| Thermal Tier (Stream Classification) | Mean August Stream Temperature (°C) | MWAT Criterion (°C) |
|---|---|---|
| Tier I (Cold) Criteria | < 15.5 | 18.1 |
| Tier II (Cold-Cool) Criteria | 15.5 - 17.7 | 19.3 |
| Tier III (Cool) Criteria | 17.7 - 19.9 | 22 |
| Tier IV (Cool-Warm) Criteria | 19.9 - 24.4 | 26 |
| Tier V (Warm) Criteria | > 24.4 | 29 |

The thermal criteria shown in Table 12-1 were used to derive the reference curves for each thermal tier based on the criteria described below and shown in Table 12-2.

- The MWAT criterion identified in Peterson (2017) for each thermal tier were considered to represent the threshold between an index value in the non-functioning range (<0.30) and the functioning-at-risk range. As such, the MWAT criterion equate to an index value of 0.30 as shown in Table 12-1.
- The high (warm) end of the modeled mean August stream temperature ranges shown in Table 12-1 were considered to represent the threshold between an index value in the functioning-at-risk range (0.70) and functioning range. Because an upper temperature extent is not defined for thermal tier V, the mean difference in temperature between index value 0.30 and 0.70 for thermal tiers I-IV (1.7°C) was used to determine the temperature associated with index value of 0.70 (29 - 1.7 = 27.3). A critical assumption made in developing the reference curves for MWAT is that the modeled mean August temperature from Isaak et al. (2017) represents a functioning thermal condition for both physicochemical and biological functions; and in a reference standard site, the MWAT would not exceed the mean August temperature expected for the thermal tier.

[2] https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

- Linear curves fit to the values in Table 12-2 were used to determine temperature values corresponding to index values of 1.00 and 0.00. The final reference curves were reviewed by the Wyoming Stream Technical Team and are shown in Figure 12-1.

*Table 12-2: Threshold Values for MWAT.*

| Index Value | Field Values (°C) by Thermal Tier (Stream Classification) | | | | |
|---|---|---|---|---|---|
| | Tier I (Cold) | Tier II (Cold-Cool) | Tier III (Cool) | Tier IV (Cool-Warm) | Tier V (Warm) |
| 0.70 | 15.4 | 15.5 | 17.7 | 19.9 | 27.3 |
| 0.30 | 18.1 | 19.3 | 22.0 | 26.0 | 29.0 |

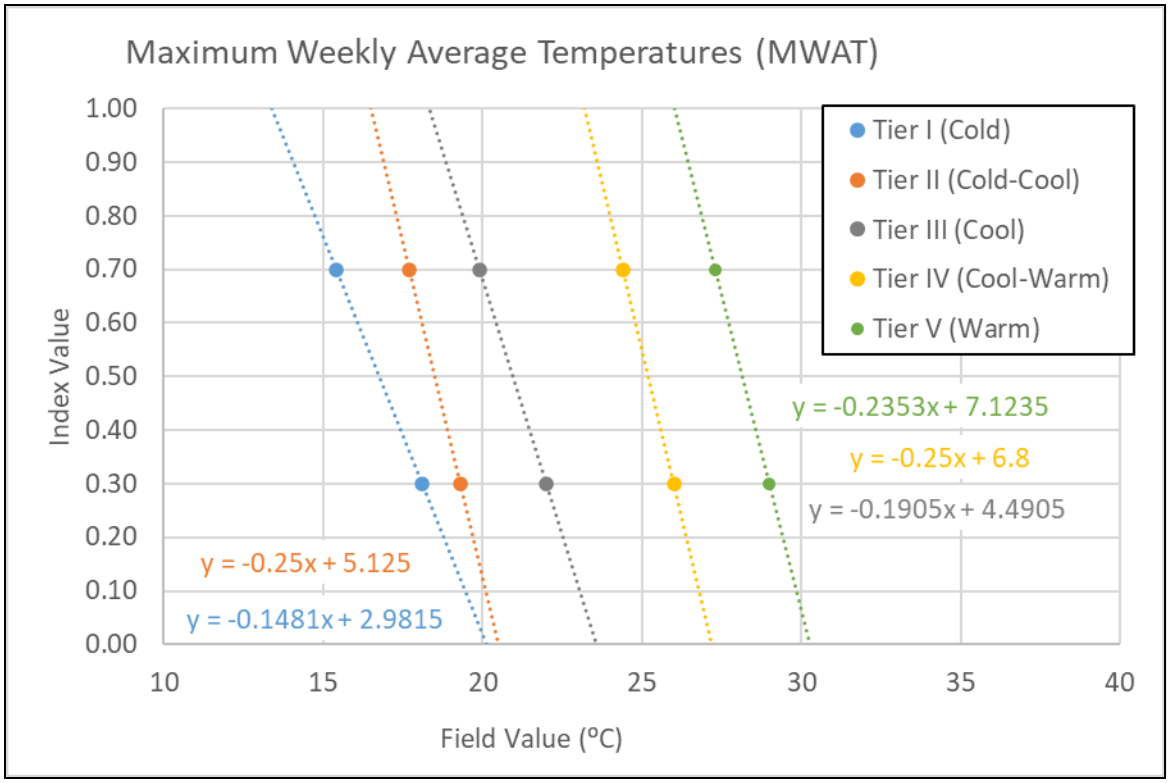



*Figure 12-1: MWAT Reference Curves.*

**Limitations and Data Gaps:**

This metric relies on the accuracy of the NorWeST historical modeled mean August temperatures for the 1993-2011 baseline period to identify the thermal tier of the stream reach. As such, the historical modeled mean August temperatures are limited by the real-world conditions occurring during the baseline period of the model, and the historical modeled mean August temperature at a particular site may reflect anthropogenic alterations to thermal regimes within temperature monitoring datasets and may not reflect pristine, natural conditions. As a result, some sites may fall within a different thermal tier compared to historical, pristine condition. However, the SQT is primarily used to compare pre- and post- project conditions and this change would still be captured within the tool. Additionally, this metric may not be applied where streams are not included in the NorWeST model unless sufficient monitoring data are available to determine the thermal tier. The NorWest temperature model data are not available within the Little Missouri, Niobrara, lower North Platte, and South Platte basins.

This metric considers colder MWATs to represent higher functioning for all thermal tiers. Some human activities, such as flow augmentation or hypolimnetic reservoir releases, may cause a stream to be colder than the natural condition. This metric does not capture the potential for impairment due to these changes.

# Chapter 13. Nutrients Parameter

**Functional Category:** Physicochemical

**Parameter Summary:**

Nutrients in stream ecosystems are necessary for growth and survival of aquatic species. Of the nutrients in stream ecosystems, nitrogen and phosphorus are the most important (Allan and Castillo 2007). Excessive nutrients from nonpoint source pollution, particularly runoff from agricultural lands, is one of the leading causes of impairment to streams in the United States (EPA 2005). While there is a minimum amount of nutrients necessary to support aquatic life, nutrient concentrations often greatly exceed optimum values which can lead to excess algae growth and result in degraded aquatic habitat and physicochemical conditions, altered fish and invertebrate communities, occasional fish kills, and aesthetic degradation.

Chlorophyll α is the predominant type of chlorophyll found in green plants and algae, and concentrations are directly affected by the amount of nitrogen and phosphorus in a stream (Dodds and Smith 2016). This metric is preferred to direct sampling of N and/or P because water column N and P concentrations can be misleading when these nutrients are largely assimilated by excess algae and plant growth.

**Metric:**

- Chlorophyll α

## 13.1. Chlorophyll α

**Summary:**

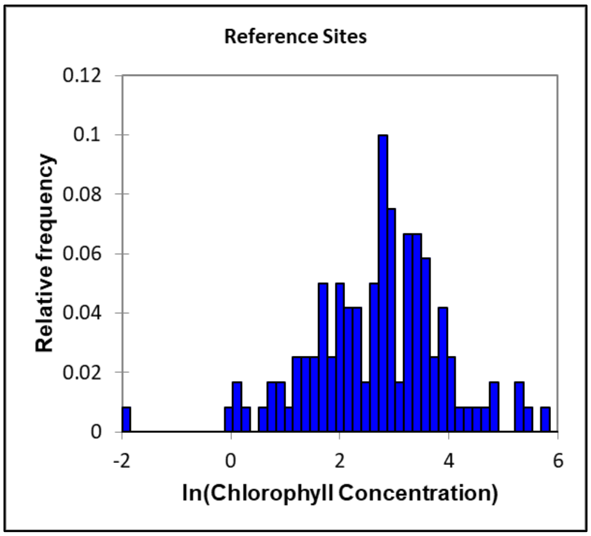
This metric is a direct measure of the concentration of chlorophyll α ($mg/m^2$) in stream riffles collected according to procedures outlined in WDEQ/WQD (2022). Chlorophyll α is the pigment that allows plants (including algae) to use sunlight to convert simple molecules into organic compounds via the process of photosynthesis and is used in the CSQT as a surrogate for nitrogen and phosphorus. The chlorophyll α metric for nutrients is only applicable within stream reaches that contain gravel or larger bed materials and where riffles are present. The sampling index period for this metric has been modified from the WDEQ/WDQ procedure to address late season changes in chlorophyll α concentrations.

**Reference Curve Development:**

The Wyoming Department of Environmental Quality (WDEQ) collects nutrient, benthic algae, and chlorophyll data in streams throughout Wyoming as part of its efforts to address nutrient pollution. There are currently no numeric criteria for Wyoming’s streams regarding chlorophyll, but the WDEQ Water Quality Division provided chlorophyll α datasets to develop reference curves for the WSQT. This dataset consisted of 467 samples that were collected between July 2007 and October 2015.

The dataset classified sites as reference, non-reference, or degraded using the procedure described by Hargett (2011). For this dataset, reference standard sites are considered to approximate best attainable, and not necessarily pristine, conditions for the ecoregion based on presence/absence of anthropogenic stressors in the watershed and reach. Many sites that are identified as degraded were classified as such due to watershed or reach-scale factors that may be unrelated to nutrients. The data were split into two datasets for the subsequent analysis: sites identified as reference standard (n = 120) and sites identified as non-reference or degraded (n = 347).

A two-sided outlier test was performed on each dataset and identified outliers were removed from the analysis. A visual assessment of the datasets indicated that the data were not normally distributed (Figure 13-1). The natural log of the data points was calculated and the XLSTAT statistical package for Microsoft Excel was used to perform a two-sided Grubbs outlier test with a 5% significance value on the transformed datasets. Twenty-six sites total were removed during the outlier test, eight from the reference standard dataset and eighteen from the non-reference and degraded dataset.



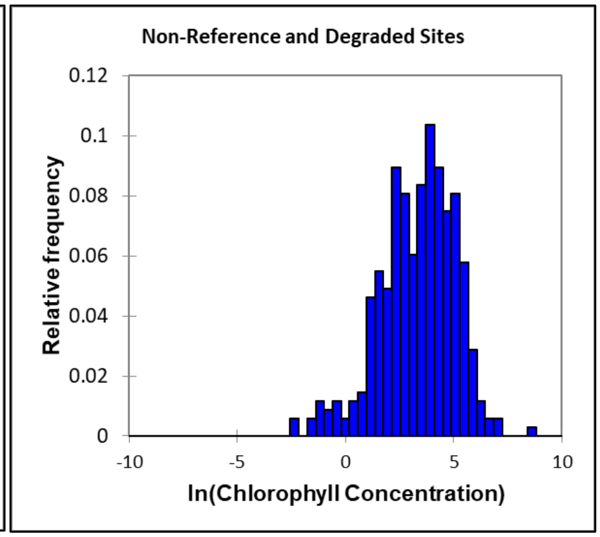




*Figure 13-1: Histogram of Chlorophyll α Concentrations (mg/m$^2$) for Reference and Non-reference Datasets.*

The datasets contained values obtained using several sampling methods based on different habitat types, e.g., epilithic (coarse substrate), episammic (pea gravel ≤5mm/sand), epidendric (woody snag), and epipelic (silt). The reference data contains mostly epilithic samples, and thus there were inadequate reference data to develop reference curves for episammic, epidendric, and epipelic samples. Therefore, in addition to the outliers, samples collected using methods other than epilithic were removed from the datasets.

WDEQ has observed late season samples with high algal biomass, but not necessarily high chlorophyll α concentrations, most likely due to chlorophyll α being in a degradation phase because of decreasing water temperatures and shortened photoperiod. Final datasets consisted of samples collected between July 15 to October 1 for the mountains and between June 15 to October 1 for the plains and basins. To address temporal variability, 81 data points were removed that fell outside of this date range.

The dataset was stratified by ecoregion (as defined in Table 1-4) to address geographic variability. Statistics for each dataset, stratified by ecoregion, are provided in Table 13-1.

*Table 13-1: Statistics for Chlorophyll α Concentrations from the WDEQ Dataset.*

| Statistic | Chlorophyll α Concentrations (mg/m$^2$) by Ecoregion and Condition | | | |
|---|---|---|---|---|
| | Mountains | | Plains and Basins | |
| | Non-Reference & Degraded | Reference Standard | Non-Reference & Degraded | Reference Standard |
| Number of Sites (n) | 50 | 60 | 183 | 13 |
| Geometric Mean | 18 | 12 | 37 | 16 |
| Average | 42 | 20 | 83 | 24 |
| Standard Deviation | 54 | 20 | 105 | 22 |
| Minimum | 1.4 | 1.4 | 1.2 | 3.4 |
| 25$^{th}$ Percentile | 5 | 6 | 13 | 9 |
| Median | 19 | 14 | 42 | 16 |
| 75$^{th}$ Percentile | 53 | 27 | 117 | 29 |
| Maximum | 228 | 100 | 625 | 79 |

The statistics for the two datasets were evaluated by the WSTT and the following decisions were made to determine the threshold values shown in Table 13-2.

- Given the non-normal distribution of the datasets and the criteria used to identify reference sites, the geometric mean from the reference standard datasets were used to inform the maximum index score.
- The threshold between functioning and functioning-at-risk index scores was determined from the 75$^{th}$ percentile from the reference standard datasets.
- The threshold between not functioning and functioning-at-risk index scores was determined from the 75$^{th}$ percentile from the non-reference and degraded datasets.
- The minimum index value for Mountains is the x-intercept from the best-fit curve.
- Because the curve for Plains and Basins does not intercept the x-axis, the minimum index value for Plains & Basins was based upon a value identified in the literature to represent a threshold for excess benthic chlorophyll independent of landform or ecoregion (Welch et al. 1988; Dodds et al. 1998; Suplee et al. 2009).

A logarithmic curve best fit the threshold values that were selected from the statistical summary of the data and the single literature value. Figure 13-2 shows the fit of the logarithmic curves to the points identified in Table 13-2. Note that the index values calculated by the WSQT differ from the threshold values identified in Table 13-2, as the threshold values were used as an initial step to define the best fit logarithmic curves. The curve equations are used to calculate index values from chlorophyll α field values in the WSQT.

*Table 13-2: Threshold Values for Chlorophyll α.*

| Index Value | Field Value (mg/m²) | |
|---|---|---|
| | Mountains | Plains & Basins |
| 1.00 | ≤ 12 | ≤ 16 |
| 0.70 | 27 | 29 |
| 0.30 | 53 | 117 |
| 0.00 | - | ≥ 150 |

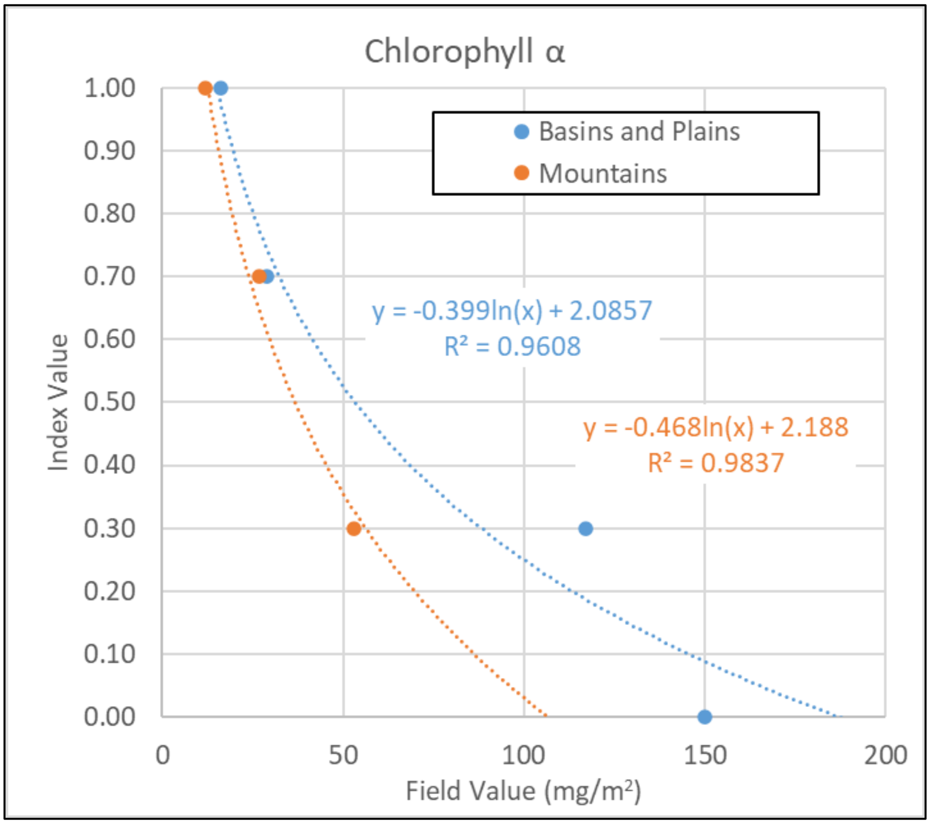



*Figure 13-2: Chlorophyll α Reference Curves.*

**Limitations and Data Gaps:**

The chlorophyll α metric is only applicable to stream reaches where epilithic samples can be collected (WDEQ 2022). This is limited to sites where riffles are present and contain gravel or larger bed materials. The dataset contained too few samples collected via episammic (pea gravel ≤5mm/sand), epidendric (woody snag), and epipelic (silt) methods to test comparability between sample sites. As such, these were excluded from the data analysis. Reference curves may be developed for these substrate types and sampling methods as more data become available.

The reference curves are based on large regional groupings and some sites may be unfairly assessed due to natural variations within regions. This limitation can be addressed as more data are gathered and further statistical analyses performed to determine statistically significant differences between regions throughout the state. Until additional data are available to further stratify and refine the reference curves, this variability should be dealt with on a case-by-case basis within the WSQT.

Use of the chlorophyll α metric to represent the nutrient parameter assumes a direct correlation between nitrogen and/or phosphorus and benthic algae growth. Factors such as water clarity, canopy cover, water temperature, and grazing by fish and invertebrates also affect benthic algae biomass, thus also chlorophyll α concentrations, but are not directly accounted for by this metric. Site specific conditions need to be considered when applying this metric.

# Chapter 14. Macroinvertebrates Parameter

**Functional Category:** Biology

**Function-based Parameter Summary:**

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). 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.

**Metrics:**

- Wyoming Stream Integrity Index (WSII)
- River Invertebrate Prediction and Classification System (RIVPACS)

## 14.1. Wyoming Stream Integrity Index (WSII)

**Summary:**

The Wyoming Stream Integrity Index (WSII) is a statewide, regionally calibrated macroinvertebrate-based multi-metric index designed to assess biological condition in Wyoming perennial streams (Hargett 2011). Wyoming Stream Integrity Index scores are calculated by averaging the standardized values of selected metrics (composition, structure, tolerance, functional guilds) derived from the riffle-based macroinvertebrate sample (WDEQ 2022). The metrics included in the WSII are those that best discriminate between reference standard and degraded waters. The assessment of biological condition is made by comparing the index score for a site of unknown biological condition to expected values derived from appropriate regional reference sites that are minimally or least impacted by human disturbance. The WSII is one of two biologic indicators of aquatic life use support used by WDEQ (Hargett 2011). Information on data collection, sample preservation, identification and enumeration and calculation of the WSII can be found in WDEQ (2022) as well as the WSQT v2.0 User Manual.

**Reference Curve Development:**

WDEQ collected 1,488 benthic macroinvertebrate samples from riffles throughout the state between 1993 and 2009 (Hargett 2011) and used this dataset to determine aquatic life use support thresholds for each bioregion (Table 14-1). According to Hargett (2011), “there are three categories of aquatic life use attainment based on biological integrity: ‘full-support’, ‘indeterminate’ and ‘partial/non-support’. The numeric thresholds for these narrative categories vary across bioregions, though all are developed using the same method. For each bioregion, scores that exceed the 25th percentile of reference calibration scores is identified as ‘full-support’ of aquatic life uses. Index scores below the 25th percentile of reference calibration scores are trisected into equal portions. Scores in the upper 1/3 of this trisection are identified as ‘indeterminate’ which is not an attainment category but is rather a designation that would require the use of ancillary information and/or additional data in a weight of evidence evaluation to determine a proper narrative assignment (e.g., full, or partial/non-support). Scores that fall in the lower 2/3 of the trisection are assigned a ‘partial/non-support’ designation which indicates the resident biota are subjected to substantial anthropogenic stressors.”

*Table 14-1: WSII Use Support Values for Each Bioregion in Wyoming (Hargett 2011).*

| Bioregion | WSII Value | |
|---|---|---|
| | Partial/ Non-Support | Full-Support |
| Volcanic Mountains & Valleys | < 46.2 | > 69.3 |
| Granitic Mountains | < 40.2 | > 60.3 |
| Sedimentary Mountains | < 34.8 | > 52.3 |
| Southern Rockies | < 32.6 | > 48.8 |
| Southern Foothills & Laramie Range | < 44.5 | > 66.7 |
| Bighorn Basin Foothills | < 40.6 | > 60.9 |
| Black Hills | < 30.7 | > 46.1 |
| High Valleys | < 32.5 | > 48.8 |
| SE Plains | < 36.7 | > 55.1 |
| NE Plains | < 38.9 | > 58.4 |
| Wyoming Basin | < 26.2 | > 39.9 |

Through consultation with WDEQ, the threshold between functioning and functioning-at-risk index values (0.70) was equated to the threshold indicating full-support of aquatic life uses. Similarly, the WDEQ threshold for partial support or non-support of aquatic life uses was equated to the threshold between functioning-at-risk and not functioning in the WSQT (0.30).

The maximum index score (1.00) in the WSQT was set equal to the 75th percentile of WSII scores at reference sites by bioregion. These values represent an attainable biological condition for reference standard sites in each bioregion of the state. The minimum index score (0.00) was set equal to the 5th percentile of the test and degraded sites WSII scores. The 5$^{th}$ percentile of the WSII scores at the test and degraded sites represents the lowest non-outlier value from non-reference standard sites in each bioregion. The WSII threshold values and reference curves are shown in Table 14-2 and Figure 14-1.

To fit the thresholds outlined in Table 14-2, linear reference curves were used.

*Table 14-2: Threshold Values for WSII Scores.*

| Bioregion | Field Values by corresponding Index Value (i) | | | |
|---|---|---|---|---|
| | i = 0.00 | i = 0.30 | i = 0.70 | i = 1.00 |
| Volcanic Mountains & Valleys | ≤ 24.9 | 46.2 | 69.3 | ≥ 88.1 |
| Granitic Mountains | ≤ 32.6 | 40.2 | 60.3 | ≥ 74.9 |
| Sedimentary Mountains | ≤ 16.6 | 34.8 | 52.3 | ≥ 70.8 |
| Southern Rockies | ≤ 5.1 | 32.6 | 48.8 | ≥ 82.2 |
| Southern Foothills & Laramie Range | ≤ 30.7 | 44.5 | 66.7 | ≥ 85.3 |
| Bighorn Basin Foothills | ≤ 3.9 | 40.6 | 60.9 | ≥ 80.8 |
| Black Hills | ≤ 12.8 | 30.7 | 46.1 | ≥ 65.7 |
| High Valleys | ≤ 17.1 | 32.5 | 48.8 | ≥ 78.2 |
| SE Plains | ≤ 10.4 | 36.7 | 55.1 | ≥ 87.0 |
| NE Plains | ≤ 1.6 | 38.9 | 58.4 | ≥ 95.8 |
| Wyoming Basin | ≤ 5.3 | 26.2 | 39.9 | ≥ 64.5 |

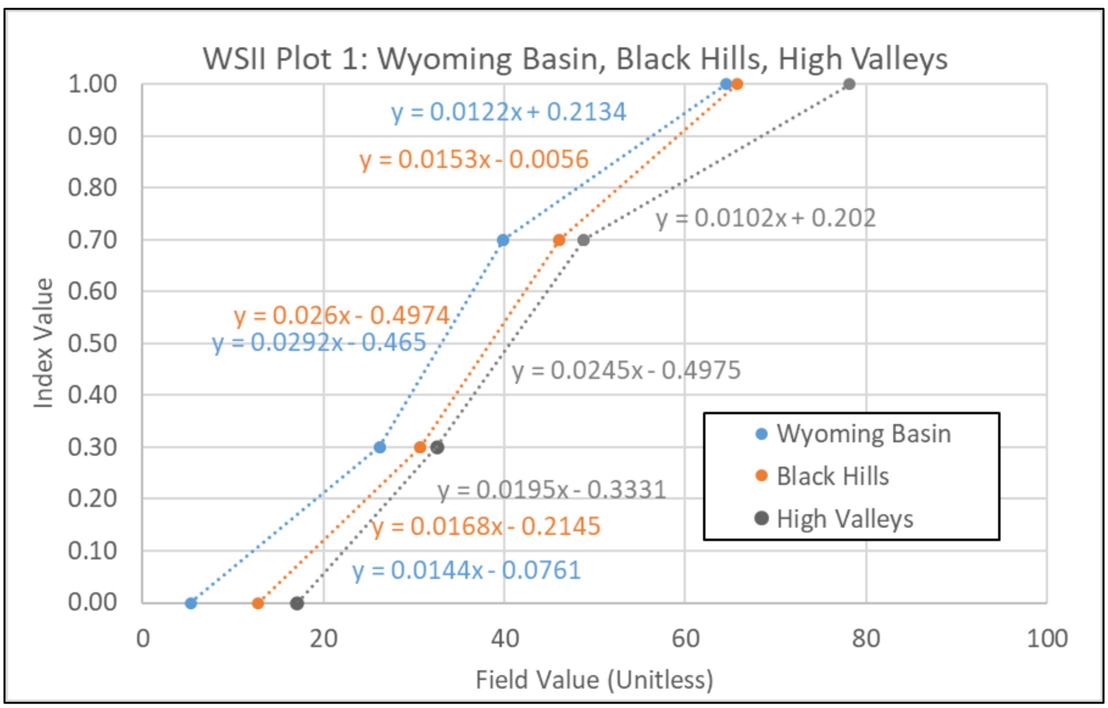



*Figure 14-1a: WSII Reference Curves for the Wyoming Basin, Black Hills, and High Valleys.*

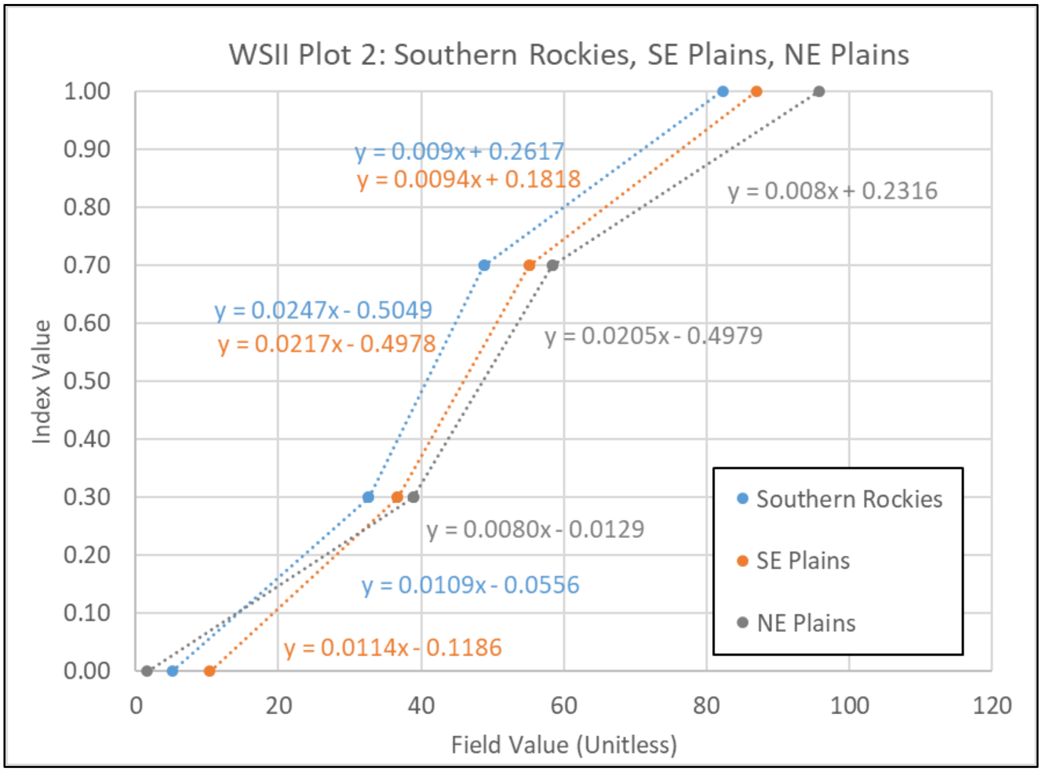



*Figure 14-1b: WSII Reference Curves for the Southern Rockies, Southeast Plains, and Northeast Plains.*

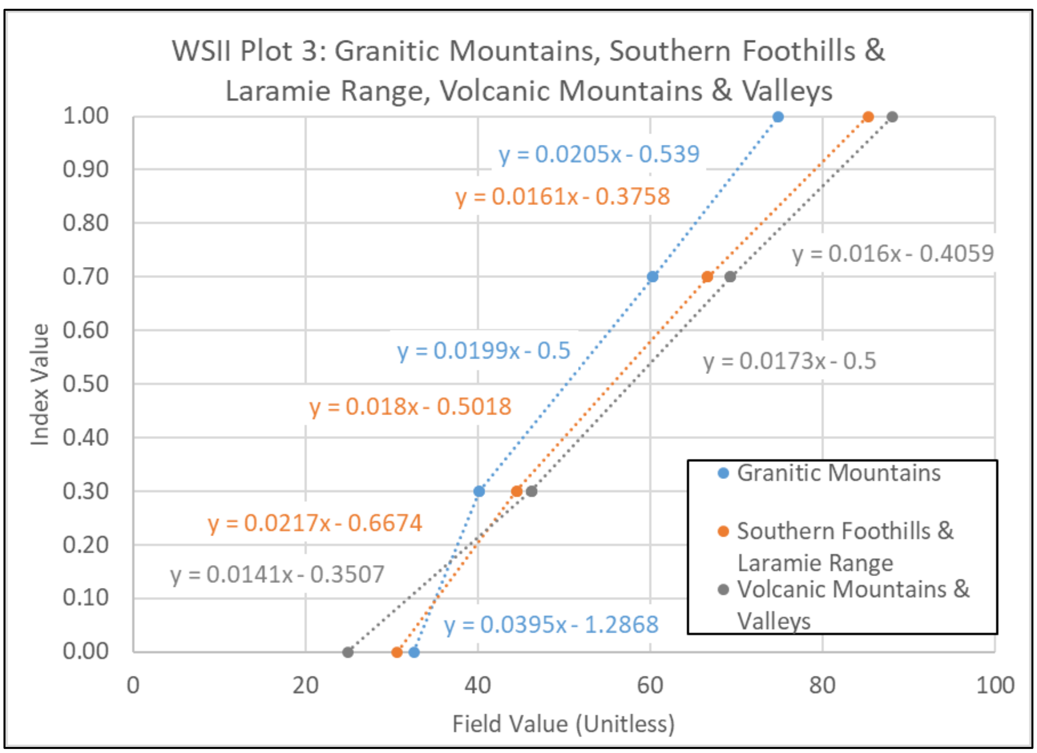



*Figure 14-1c: WSII Reference Curves for the Granitic Mountains, Southern Foothills and Laramie Range, and Volcanic Mountains and Valleys.*

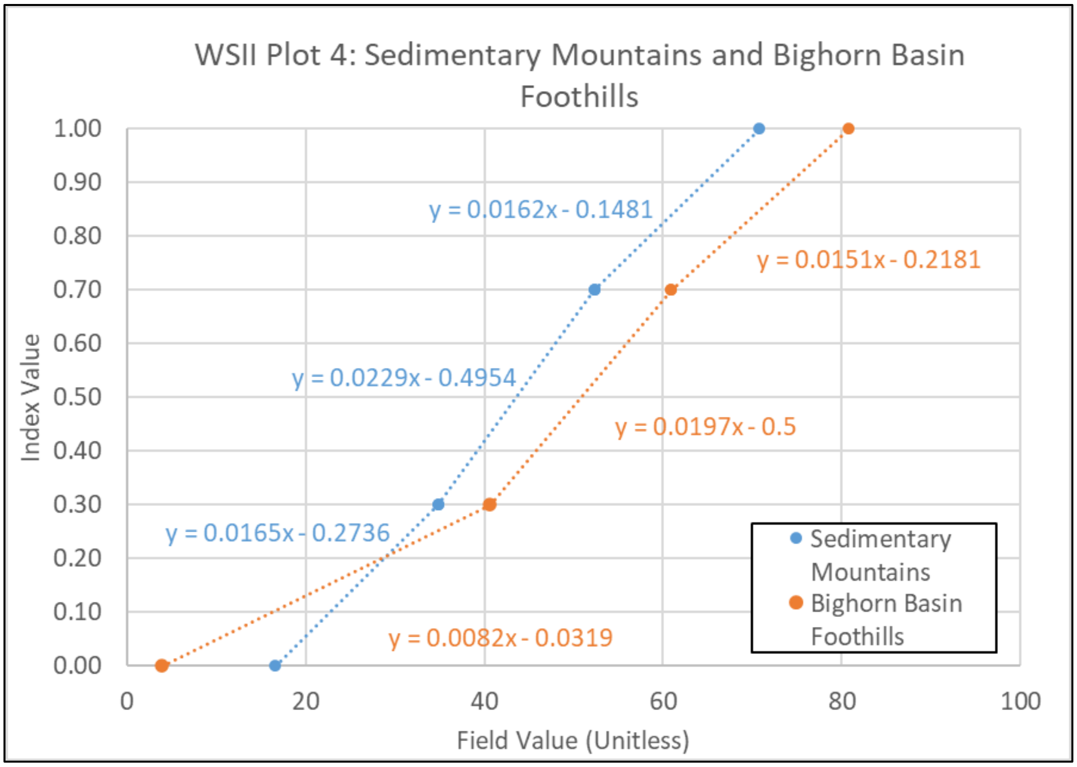



*Figure 14-1d: WSII Reference Curves for the Sedimentary Mountains and Bighorn Basin Foothills.*

**Limitations and Data Gaps:**

A complete description of WSII limitations is included in Hargett (2011). Limitations of the WSII models for the WSQT include:

- Incomplete representation of the reference condition for streams in particular regions will result in less accurate assessments of biological condition in those particular regions. This concern is most apparent in three sub-regions within the greater Wyoming Basin bioregion: streams in the Bighorn Basin of north-central Wyoming, non-montane spring-fed stream segments within the interior of the Wyoming Basin and mixed origin streams of extreme southwest Wyoming.
- Though bioregions are delineated by discrete boundaries, biota and environmental characteristics along the bioregion peripheries (i.e., ecotones) do not always follow these man-made boundaries. Thus, bioregional boundaries should be viewed as transitional, having both similarities and differences with adjacent bioregions. For that reason, expected reference conditions for stream segments located along bioregion peripheries may not necessarily be those represented in the specific bioregion where the segment resides. In addition, a stream segment whose watershed is predominantly located in an adjacent bioregion other than the bioregion where the stream segment resides may best be evaluated to the reference condition of that adjacent bioregion. In these situations, the user is encouraged to deduce the proper expected reference condition for biological

condition evaluation using reasonable ecological justifications and a weight-of-evidence approach.

- There is inadequate representation for stream segments with very small watersheds < 12 $km^2$ (< 5 $mi^2$) and those located at high montane elevations > 2,740 m (> 9,000 ft.). These stream segments may prove difficult to accurately assess with the WSII.
- Because the WSII was developed with quantitative data collected from targeted riffle/run habitats, it cannot be used to evaluate multi-habitat samples collected with dip nets or other semi-quantitative methods.
- The WSII should not be used to assign attainment category ratings on ephemeral or intermittent streams segments or extremely low-gradient lentic-type systems since the WSII was specifically developed to evaluate the biological condition from perennial lotic systems.

## 14.2. River Invertebrate Prediction and Classification System (RIVPACS)

**Summary:**

The WY RIVPACS is a quantitative multivariate biological model that makes site-specific predictions of the benthic macroinvertebrate taxa expected (E) in the absence of anthropogenic stressors for streams and rivers in Wyoming, using a network of minimally or least disturbed reference sites. Expectations are based on probabilities of reference group membership using several abiotic predictor variables (latitude, longitude, watershed area, bioregion, and alkalinity) and must be calculated by WDEQ. The ratio (O/E score) of the taxa observed in the stream (O) from the expected (E) taxa is a community-level measurement of biological condition. Information on data collection, sample preservation, identification and enumeration and calculation of the WSII can be found in WDEQ (2022) as well as the WSQT v2.0 User Manual.

**Reference Curve Development:**

WDEQ collected 1,488 benthic macroinvertebrate samples from riffles throughout the state between 1993 and 2009 (Hargett 2012). WDEQ used this dataset to determine aquatic life use support thresholds for each bioregion (Table 14-3). According to Hargett (2012), “there are three categories of aquatic life use attainment based on biological integrity: ‘full-support’, ‘indeterminate’ and ‘partial/non-support’. Development of numeric thresholds for these three narrative categories is based on interval and equivalence tests described by Kilgour et al. (1998) and applied within each of Wyoming’s eleven bioregions. This EPA-approved statistical methodology establishes ecologically reasonable numeric thresholds based on the mean, variation, and 5th percentile of reference site O/E values within a bioregion. O/E values that fall below the interval threshold are considered significantly different from the 5th percentile of reference site O/E values for that bioregion and are assigned a ‘partial/non-support’ status. O/E values that are greater than the equivalence threshold are considered statistically similar to O/E values within the 95% confidence interval of the reference site distribution and are thus assigned a ‘full-support’ status. O/E values that fall between the interval and equivalence thresholds would be considered ‘indeterminate’ which is not an attainment category but is rather a designation that would require the use of ancillary information and/or additional data in a weight-of-evidence evaluation to determine a proper narrative assignment (e.g., full or partial/non-support).”

Through consultation with WDEQ, the threshold between functioning and functioning-at-risk index values (0.70) was equated to the threshold indicating full-support of aquatic life uses. Similarly, the WDEQ threshold for partial support or non-support of aquatic life uses was equated to the threshold between functioning-at-risk and not functioning in the WSQT (0.30).

*Table 14-3: RIVPACS O/E Score Use Support Thresholds for Each Bioregion in Wyoming (Hargett 2012).*

| | RIVPACS O/E Score | |
|---|---|---|
| **Bioregion** | **Partial/ Non-Support** | **Full-Support** |
| Volcanic Mountains & Valleys | < 0.6456 | > 0.8646 |
| Granitic Mountains | < 0.6468 | > 0.8832 |
| Sedimentary Mountains | < 0.6825 | > 0.8234 |
| Southern Rockies | < 0.6208 | > 0.8917 |
| Southern Foothills & Laramie Range | < 0.6838 | > 0.8818 |
| Bighorn Basin Foothills | < 0.6310 | > 0.8445 |
| Black Hills | < 0.5940 | > 0.8813 |
| High Valleys | < 0.6847 | > 0.8599 |
| SE Plains | < 0.5144 | > 0.7813 |
| NE Plains | < 0.5199 | > 0.7500 |
| Wyoming Basin | < 0.6351 | > 0.8158 |

The maximum index score (1.00) in the WSQT was set equal to the 75th percentile of RIVPACS scores at reference standard sites by bioregion. These values represent an attainable biological condition for reference standard sites in each bioregion of the state. The minimum index score (0.00) was set equal to the 5th percentile of the test and degraded sites RIVPACS scores. The $5^{th}$ percentile of the RIVPACS scores at the test and degraded sites represents the lowest non-outlier value from non-reference standard sites in each bioregion. The RIVPACS threshold values are shown in Table 14-4.

To fit the thresholds outlined in Table 14-4, linear reference curves were used and are shown in Figure 14-2.

*Table 14-4: Threshold Values for RIVPACS O/E Score.*

| Bioregion | Field Values by corresponding Index Value (i) | | | |
|---|---|---|---|---|
| | i = 0.00 | i = 0.30 | i = 0.70 | i = 1.00 |
| Volcanic Mountains & Valleys | ≤ 0.21 | 0.65 | 0.86 | ≥ 1.21 |
| Granitic Mountains | ≤ 0.59 | 0.65 | 0.88 | ≥ 1.09 |
| Sedimentary Mountains | ≤ 0.42 | 0.68 | 0.82 | ≥ 1.17 |
| Southern Rockies | ≤ 0.27 | 0.62 | 0.89 | ≥ 1.18 |
| Southern Foothills & Laramie Range | ≤ 0.29 | 0.68 | 0.88 | ≥ 1.20 |
| Bighorn Basin Foothills | ≤ 0.41 | 0.63 | 0.84 | ≥ 0.92 |
| Black Hills | ≤ 0.37 | 0.59 | 0.88 | ≥ 1.08 |
| High Valleys | ≤ 0.42 | 0.68 | 0.86 | ≥ 1.14 |
| SE Plains | ≤ 0.34 | 0.51 | 0.78 | ≥ 1.12 |
| NE Plains | ≤ 0.11 | 0.52 | 0.75 | ≥ 0.98 |
| Wyoming Basin | ≤ 0.15 | 0.64 | 0.82 | ≥ 1.18 |

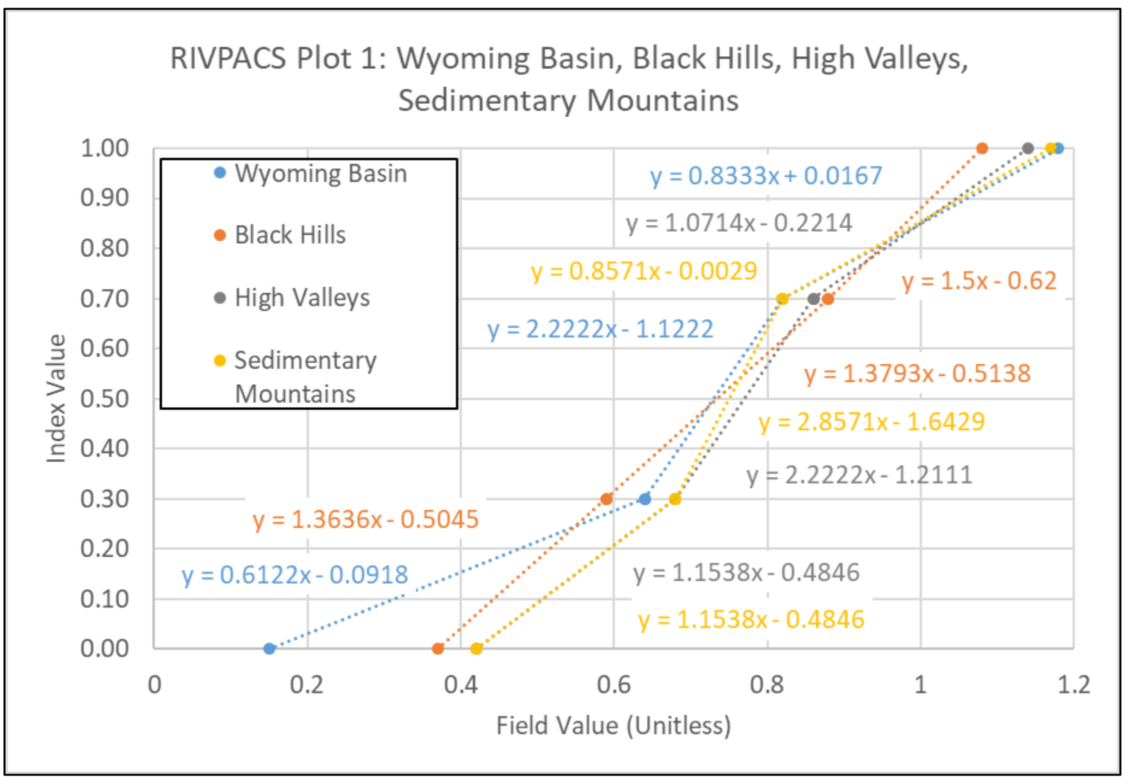



*Figure 14-2a: RIVPACS Reference Curves for the Wyoming Basin, Black Hills, High Valleys, and Sedimentary Mountains (Note: The High Valleys and Sedimentary Mountains share the same curve for index values 0.00-0.30).*

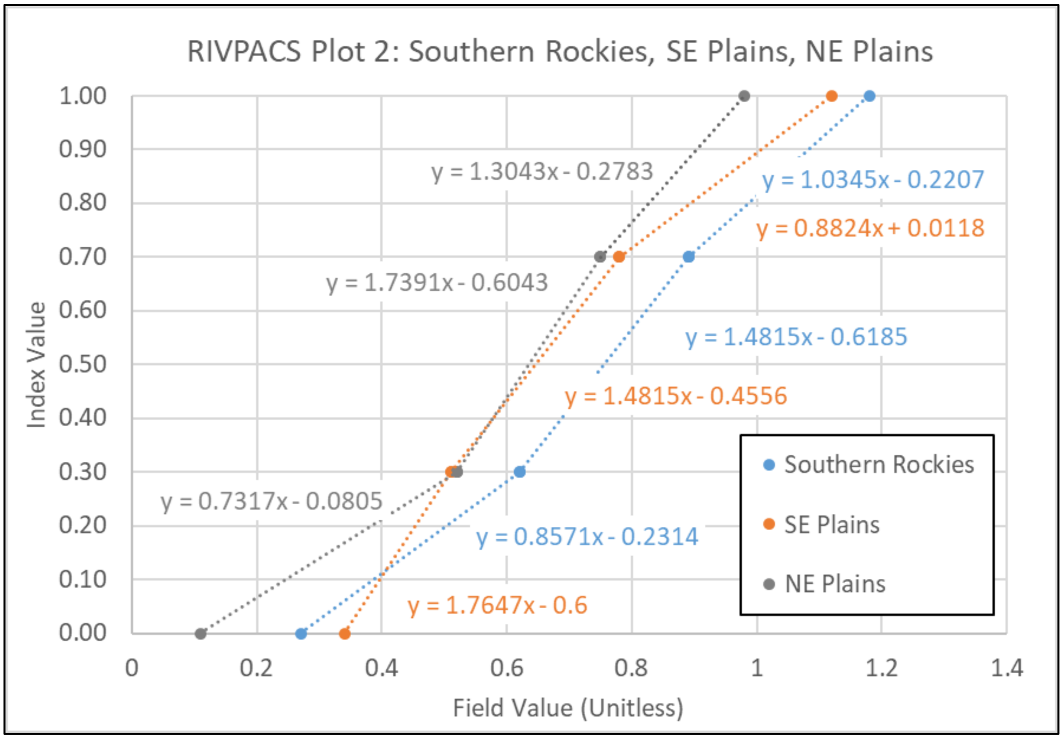



*Figure 14-2b: RIVPACS Reference Curves for the Southern Rockies, Southeast Plains, and Northeast Plains.*

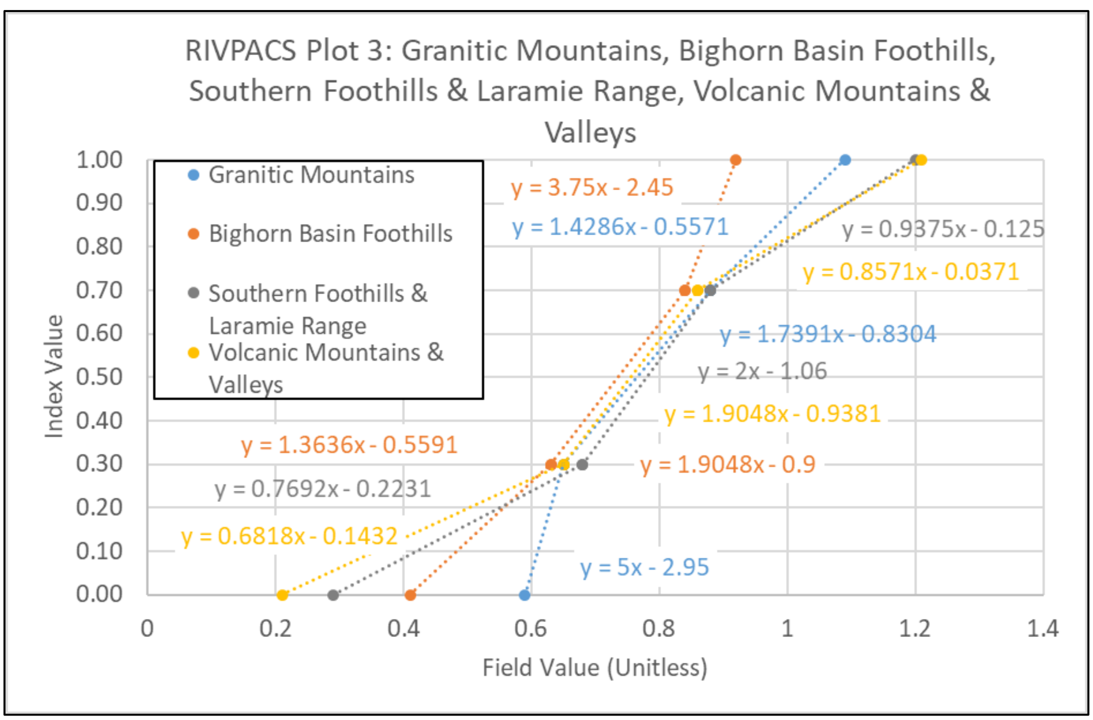



*Figure 14-2c: RIVPACS Reference Curves for the Granitic Mountains, Bighorn Basin Foothills, Southern Foothills and Laramie Range, and Volcanic Mountains and Valleys.*

**Limitations and Data Gaps:**

WY RIVPACS is designed to flag samples that fall outside the experience of the model and thus prevent extrapolation of predictions to environmental settings beyond those used in model development. In some cases, samples may be within the experience of the model, but biological condition could still be somewhat under or over-predicted by the WY RIVPACS due to:

1. Inadequate reference site representation for stream segments with very small watersheds < 12 $km^2$ (< 5 $mi^2$) and those located at high montane elevations > 2,740 m (> 9,000 ft.). These stream segments may prove difficult to accurately assess with the WY RIVPACS.
2. Inadequate reference site representation within three sub-regions of the Wyoming Basin bioregion: the Bighorn Basin of north-central Wyoming (excluding the foothills), non-montane spring-fed stream segments within the interior of the Wyoming Basin and mixed origin streams of extreme southwest Wyoming.
3. Because the WY RIVPACS was developed with quantitative data collected from targeted riffle/run habitats, it cannot be used to assign aquatic life use attainment category ratings to multi-habitat samples collected with dip nets or other semi-quantitative methods.
4. WY RIVPACS should not be used to assign aquatic life use attainment category ratings on ephemeral or intermittent streams segments or extremely low-gradient lentic-type systems since the WY RIVPACS was specifically developed to evaluate the biological condition for perennial lotic systems.

For a more complete description of WY RIVPACS limitations, see Hargett (2012).

# Chapter 15. Fish Parameter

**Functional Category:** Biology

**Function-based Parameter Summary:**

Fish are an integral part of many functioning stream systems and are an important management priority within Wyoming. 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. Wyoming contains 78 species of fish, and nearly 40% of the State's population are anglers (WGFD 2017). Wyoming streams are managed to support native species as well as native and non-native sport fisheries. Native fish assemblages vary across Wyoming's six major river basins, with the eastern warm water rivers containing a much higher native fish diversity than streams within cold-water, montane regions (WGFD 2017).

This parameter is intended to document several aspects of Wyoming fish assemblages, including the native diversity of the fish community in comparison to reference standards, the presence of Species of Greatest Conservation Need, and the biomass of sportfish populations.

Since there are no existing statewide biological indices used for fish in Wyoming, metrics and reference curves for fish were developed by the WSTT in consultation with regional fisheries biologists at the WGFD. Native fish metrics include a measure of native fish diversity and presence/absence of Species of Greatest Conservation Need (SGCN). Native fish metrics focus on presence/absence metrics instead of abundance metrics due to the large inter-annual variability that naturally occurs in native fish populations. A game species biomass metric is also included to capture post-project increases in biomass following restoration projects. This metric is only intended to be applied at restoration sites where game species are identified as a management priority by WGFD.

Reference standards for native fish species and SGCN are based on departure from the expected species assemblages within the six major river basins in Wyoming, stratified by differences in stream temperature (cold, transitional, warm) and gradient (WSQT; Appendix C). These reference standards are informed by a comparison to expected species assemblages, identified in species lists provided in the Statewide Wildlife Action Plan (WGFD 2017) and further refined through consultation with WGFD regional fisheries biologists. The reference standard is defined as the fish species that *should* be naturally present at the site *but for* anthropogenic constraints are not. Anthropogenic constraints, such as culverts, flow alteration, and downstream barriers, may limit the current presence of native fish species; and may limit the restoration potential at a site if those constraints are not removed as part of a project. The reference standard does not include species that have been extirpated and for which there are no plans or targets for reestablishment. The species assemblage lists provide a preliminary estimate of the expected number of native fish within a particular basin and thermal regime. Given the natural variability in fish assemblages within any basin due to underlying factors such as geology, flow regime, or natural barriers, the expected number of species may need to be modified based on sub-basin characteristics. The WSTT recommends project-specific coordination with WGFD regional fish biologists to account for natural factors that may influence species distribution and any necessary modifications to the species assemblage list.

**Metrics:**

- Native Fish Species Richness (% of expected)
- Species of Greatest Conservation Need (SGCN) Absent Score
- Game Species Biomass (% increase)

## 15.1. Native Fish Species Richness

**Summary:**

This metric measures native fish species richness based on presence/absence data. This metric is calculated as the observed number of native species divided by the expected number of native species. Multiply by 100 to report the percent of the expected assemblage that is observed.

Native species distributions naturally vary between river basins and within any basin due to underlying factors such as geology, flow regime and duration, water temperatures, or natural barriers. A comparison of the number of native species currently observed to the expected number of species (O/E) is an indicator of anthropogenic disturbance that locally reduces species diversity. Anthropogenic disturbances that could alter the native species assemblages include barriers, flow alteration, water quality impairments, introduction of non-native species, habitat degradation or other disturbances that could alter spawning, foraging or refugia habitats (Angermeier and Schlosser 1995). Reference standards for native fish species are derived from the expected species assemblages within the six major river basins in Wyoming, stratified by differences in stream temperature (cold, transitional, warm) and gradient (WSQT; Appendix C) and are defined in the Parameter Summary above.

**Reference Curve Development:** Reference curves were updated for the WSQT v2.0.

Reference curves were developed based on best professional judgement of regional fisheries biologists in Wyoming. Achieving 100% native species richness was considered to represent a pristine condition and was assigned an index value of 1.00. In the WSQT v1.0, the threshold value between functioning and functioning-at-risk equated to 99% native species richness, which reflected the absence of one or more native species, i.e., the system does not support full native species diversity. This threshold was updated in WSQT v2.0, following consideration of the logic used in the CSQT reference curves (USACE 2020b). For the threshold between functioning and functioning-at-risk, the threshold value was updated to reflect a native species richness value of 80%. In more naturally depauperate fish communities, which occur in some watersheds and thermal regimes throughout Colorado and Wyoming (e.g., that naturally have five or less species), less than 80% native species richness would reflect a community where one or more native species are absent.

In WSQT v1.0, the threshold between functioning-at-risk and non-functioning index scores were defined using best professional judgement. A best fit line was extrapolated, yielding a minimum index score that equated to 58% of native species present. In the WSQT v2.0, updates were made to the reference curve to encourage and incentivize native fish restoration, even in systems which may have less than 58% native species present. Thus, the threshold value between functioning-at-risk and not functioning was eliminated, and instead a minimum threshold value was defined. The minimum index value of 0.00 was set to equal 0% native species richness, i.e., when no native species are present there is no functional capacity for this metric. Threshold value and reference curves are shown in Table 15-1 and Figure 15-1.

Because the total number of native species varies across basins, as well as between the thermal regimes within a basin, the metric is normalized by the expected number of species within that basin and regime. As such, no additional stratification was considered. The presence or absence of a single species will more strongly influence the score in basins with naturally lower native species richness, however in basins with naturally low native species richness, each individual species contributes more to the species diversity at the site.

*Table 15-1: Threshold Values for Native Fish Species Richness.*

| Index Value | Field Value (% of expected) |
|---|---|
| 1.00 | 100 |
| 0.69 | 80 |
| 0.00 | 0 |

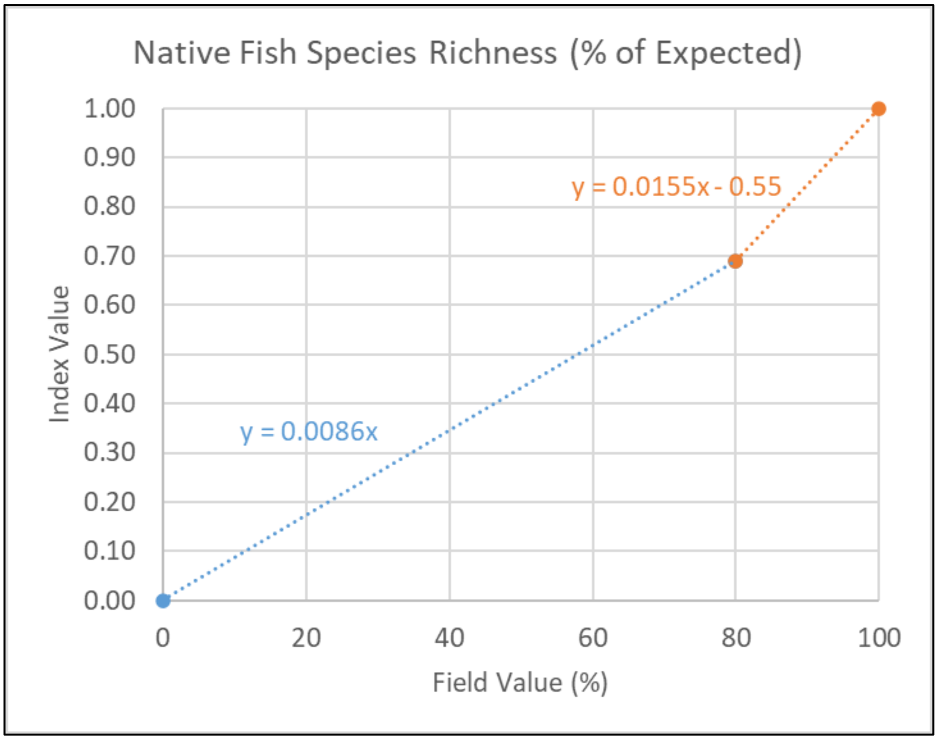



*Figure 15-1: Native Fish Species Richness Reference Curve.*

**Limitations and Data Gaps:**

There is uncertainty about the fish species that comprise the natural fish community for most locations, and it requires a judgment call by a professional fisheries biologist to establish a species list for a location. The assembled native species lists available in Table C.1 of the WSQT v2.0 User Manual provide a starting point for the potential maximum number of species at a location within a given river basin and stream temperature/gradient class. However, due to variability in sub-basin geology, flow regime and other natural factors, these lists require coordination with the WGFD prior to finalizing an expected number of native species at any given site. In addition, the “cold”, “transitional” and “warm” stream systems are not explicitly defined numerically in terms of slope or temperature. Rather, these distinctions are made in a general sense to broadly help differentiate among Wyoming’s mountain, foothill and high plains or desert systems. Ideally, ranges of actual water temperatures and stream channel slopes most often associated with specific fish species occurrence would be identified and used to develop species lists. That information is not available for all Wyoming fish species, necessitating a more general, relative approach.

## 15.2. Species of Greatest Conservation Need (SGCN) Absent Score

**Summary:**

This metric is a direct measure of the presence/absence of Species of Greatest Conservation Need (SGCN) within a reach. This categorical metric considers whether an SGCN expected to be present is observed in the reach; the metric also considers the SGCN tier of the species.

Species of Greatest Conservation Need are identified in the State Wildlife Action Plan (WGFD 2017) as those species whose conservation status warrants increased management attention and funding, as well as consideration in conservation, land use and development planning in Wyoming. For any project where this metric is used, the practitioner should consult with the regional fisheries biologist at WGFD to determine whether there is natural potential for SGCN to be present at the site. Natural potential considers natural factors, not anthropogenic constraints, that may restrict the distribution of a SGCN. The State Wildlife Action Plan classifies SGCN species into tiers where Tier 1 species have the highest conservation need, and Tier 3 species have less of a conservation need than Tier 1 or Tier 2 species. The number of species with natural potential to occur at the site in each tier is used to calculate the field value for the WSQT. If no SGCN are expected to occur within the project site, this metric would not be calculated.

**Reference Curve Development:**

The field value for this metric is a function of the number of expected SGCN that are absent from a site and the Tier of that species. Tier 1 species are weighted 3 times higher than Tier 3 species, while Tier 2 species are valued at twice as much as Tier 3 species (Table 15-2). Note that if there are no species in a tier for the site then there are no species absent for that tier.

This weighted approach was considered to reflect the relative importance of species within the tiers while remaining consistent with the management goals and approaches for SGCN by the State of Wyoming. From a restoration perspective, restoration of a Tier 1 species would provide the greatest functional lift to the fish community and should result in the highest index scores. Similarly, loss of Tier 1 species from a site should be considered a significant functional loss.

*Table 15-2: How to Determine the Field Value for SGCN Absent Score.*

| SGCN Species *(A)* | Multiplier *(B)* | Equation |
|---|---|---|
| # Tier 1 Species Absent | 3 | $C_1 = A_1 * B_1$ |
| # Tier 2 Species Absent | 2 | $C_2 = A_2 * B_2$ |
| # Tier 3 Species Absent | 1 | $C_3 = A_3 * B_3$ |
| Field Value for the WSQT = | | $C_1 + C_2 + C_3$ |

The reference criteria for this metric are categorical, and each category was assigned a specific index value score after consultation with WGFD regional fisheries biologists (Table 15-3). No reference curve was developed. If all SGCN, regardless of Tier, are present, the field value would be 0.00, and this equates to an index value of 1.00, i.e., a reference standard condition. The functioning-at-risk range of index values, representing sites that have the potential to support SGCN, includes reaches where the site lacks one Tier 3 species (index value = 0.69), or either one Tier 2 or two Tier 3 species (index value = 0.30). Sites with one Tier 1 species absent, two or more Tier 2 species absent or three or more Tier 3 species absent, were assigned an index value of zero, and were assumed to not support SGCN.

*Table 15-3: Threshold Values for SGCN Absent Score.*

| Index Value | Field Value |
|---|---|
| 1.00 | 0 |
| 0.69 | 1 |
| 0.30 | 2 |
| 0.00 | ≥ 3 |

**Limitations and Data Gaps:**

There is uncertainty about the fish species that comprise the natural fish community for most locations, and it requires a judgment call by a professional fisheries biologist to establish a species list for a location. The assembled native species lists available in Table C.1 of the WSQT v2.0 User Manual provide a starting point for the potential maximum number of SGCN at a location within a given river basin and stream temperature/gradient class. However, due to variability in sub-basin geology, flow regime and other natural factors, these lists require coordination with the WGFD prior to finalizing an expected number of SGCN species at any given site. In addition, the “cold”, “transitional” and “warm” stream systems are not explicitly defined numerically in terms of slope or temperature. Rather, these distinctions are made in a general sense to broadly help differentiate among Wyoming’s mountain, foothill and high plains or desert systems. Ideally, ranges of actual water temperatures and stream channel slopes most often associated with specific fish species occurrence would be identified and used to develop species lists. That information is not available for all Wyoming fish species, necessitating a more general, relative approach.

## 15.3. Game Species Biomass

**Summary:**

This metric is a direct comparison of pre- and post-project biomass changes and is calculated by comparing the biomass before and after a project, after normalizing the data to a nearby control site. The metric is consistent with the approach undertaken by WGFD in their monitoring of fish habitat improvement projects (Binns 1999).

This metric focuses on the productivity of native or non-native game fish species determined to be a management priority by WGFD. For purposes of this metric, game species include naturally reproducing populations of native and non-native game species; game species of potential hatchery origin should not be included in this metric, and users should consider whether this metric should be applied based on the potential for nearby stocked populations to influence biomass numbers within a project reach. Measurements of biomass can be used to infer whether there have been gains in game species productivity at restoration sites where fisheries goals and objectives have been identified. It is not intended to be applied at impact sites or to draw inferences about reductions in biomass due to anthropogenic activities.

This metric measures the increase in game fish biomass following a restoration project relative to the change observed at a control site. Fish are collected consistent with the approach outlined in Bonar et al. (2009). Fish baseline data from a nearby control reach is required to account for natural inter- and intra-annual variability in fish populations and reduce the influence of climactic or other external factors in determining increases in biomass associated with a restoration project. The control reach should be at a similar elevation and geomorphic setting as the project reach and should be of reference quality (to the extent practicable). A control reach can be located upstream or downstream from the project reach, or in a separate catchment within the same river basin as the project reach, but not immediately adjacent to the project reach. A control reach that is geographically proximate to the project reach but outside the influence of the project actions is preferred.

**Reference Curve Development:**

This metric focuses on the increase in fish biomass following a restoration project, and index values and reference curves are associated with the magnitude of change in biomass (pounds/mile) compared with baseline conditions. As such, reference curves were derived following consideration of the magnitude of change that would be considered marginal and significant.

The change in biomass metric was stratified by WGFD stream classes, recognizing that streams with an already productive fishery may be less likely to see large additional increases in productivity following a restoration project. The WGFD assigns a color-coded classification to Wyoming streams based on measured fish biomass (Annear et al. 2006). This classification identifies blue, red, yellow, and green ribbon streams and is based on pounds of sport fish per mile. Blue ribbon streams are defined as those with greater than or equal to 600 pounds of sport fish per mile and the lowest category is recognized as green ribbon with less than 50 pounds per mile. Updates to stream classification occur infrequently.

The stream classification was identified as a logical basis for stratifying game species biomass because it is judged to approximately reflect productive potential based on multiple population estimates collected over time and at many sites throughout Wyoming. A driving assumption is that streams identified as “blue ribbon” can be considered the most productive and are most likely to be closest to their biologic potential. As such, it would be relatively difficult to increase biomass in a blue ribbon stream. Conversely, the green ribbon streams are the most common class of streams, have the lowest level of productivity and are more likely expected to be below their biologic potential. The assumption is that it would be relatively easy to improve biomass in a green ribbon stream. Reference curves were developed to reflect these assumptions, and therefore require less biomass improvement in a blue ribbon stream than in a green ribbon stream.

Results compiled by Binns (1999) from a review of trout habitat restoration projects constructed by WGFD between 1953 and 1998 generally support these assumptions and show that habitat restoration projects in yellow and green ribbon fisheries yielded greater increases in biomass than in red ribbon fisheries (Table 15-4). However, green ribbon streams did not show greater increases in productivity than yellow ribbon streams and Binns (1999) inferred that these systems may be limited by watershed-scale issues that reduce the potential for greater increases in biomass. Based on these results, no stratification was proposed between yellow and green ribbon streams; the same reference curve applies to both.

Population estimates conducted on natural fish communities are known to vary widely between years due to natural variability in fish populations as well as sampling error (Dey and Annear 2001, House 1995). This background variation was considered in developing the sampling methods for this metric (e.g., multiple sampling events and the use of a control site) and in considering what change in biomass would be detectable.  Professional judgment and experience with population data in Wyoming streams suggested that at least a 5% change in biomass would have to occur to be detectable through sampling. Blue ribbon streams were thus assigned a minimum index value (0.00) for changes in biomass less than 5%. Given the assumptions above regarding differences in productivity across stream classes, minimum index values were adjusted upwards in 5% increments for each productivity class to account for the greater potential for increases across stream classes.

Thresholds for determining the reference curves were developed using professional judgment, considering the assumptions about productive capacity and population estimate variability. Binns (1999) evaluated success based on post project changes in several biomass metrics. To define success, he relied on criteria proposed by Hunt (1988), including a post-treatment percent change increase in one of the trout population metrics of 25% or more, and a change of 50%, or more for Level 1 and Level 2 success criteria, respectively. While these are arbitrary criteria, they seem reasonable and related to “the long-term annual benefits from management investments of the kind that have been made to remedy perceived deficiencies in trout carrying capacity and/or the sport fishery” (Hunt 1988, p.4).

The WSTT determined that a 25% increase in biomass is a measurable increase that could reasonably represent a substantial lift in a blue ribbon stream. In red ribbon streams, the WSTT determined that a 50% increase in biomass could reasonably represent a substantial lift. WGFD habitat improvement projects have exceeded this value in red ribbon streams (Table 15-4), with an average increase of 115% pounds/acre in red ribbon systems. Given the assumption that green and yellow ribbon streams should have the capacity to increase biomass the most, a 75% increase in biomass was identified as a realistic, measurable and substantial improvement. This value is reasonable when compared with Binns (1999), who showed increases well above 200% in yellow and green ribbon streams.

Threshold values and reference curves are shown in Table 15-5 and Figure 15-2.

*Table 15-4: Mean Empirical Values for Trout Biomass Averaged Over Habitat Improvement Projects Sorted for WGFD Stream Class. Adapted from Binns (1999).*

| Stream Class | Number of projects with measurements | Reference (lbs./acre) | Treatment (lbs./acre) | Mean % Change |
|---|---|---|---|---|
| 1 (Blue Ribbon) | 0 | - | - | - |
| 2 (Red Ribbon) | Wild Trout = 3<br>*Mixed Pop. = 5 | 64<br>52 | 122<br>106 | 104<br>115 |
| 3 (Yellow Ribbon) | Wild Trout = 15<br>*Mixed Pop. = 23 | 42<br>43 | 78<br>87 | 316<br>303 |
| 4 (Green Ribbon) | Wild Trout = 7<br>*Mixed Pop. = 8 | 28<br>31 | 83<br>85 | 248<br>230 |

***** *The mixed trout category summarizes all projects combined and include both containing only wild trout and those where fish of hatchery origin were present. (Adapted from Binns 1999)*

*Table 15-5: Threshold Values for Game Species Biomass.*

| | Field Values by corresponding Index Value (i) | | | |
|---|---|---|---|---|
| | No Functional Lift | Substantial Functional Lift | | |
| Stream Class | i = 0.00 | i = 0.30 | I = 0.70 | i = 1.00 |
| Blue Ribbon and non-trout game fish | < 5 | 5 | 25 | ≥ 40 |
| Red Ribbon | < 10 | 10 | 50 | ≥ 80 |
| Yellow/Green Ribbon | < 15 | 15 | 75 | ≥ 119 |

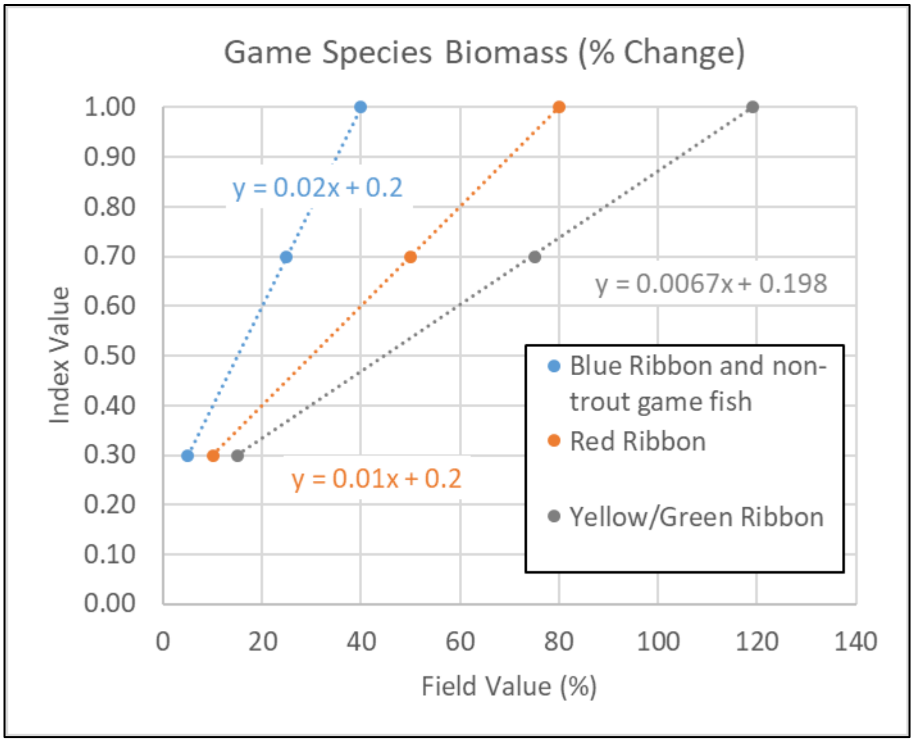



*Figure 15-2: Game Species Biomass Reference Curves.*

**Limitations and Data Gaps:**

The threshold values in Table 15-5 are based in best professional judgement and supported by previous evaluations in Wyoming. This metric would benefit from additional data analysis and case studies when project information becomes available.

This metric is built on an assumption that restoration work can increase fish biomass permanently, or at least throughout a project monitoring period of 5-10 years. This assumption is not solidly supported in the literature, though examples exist (Pierce et al. 2013). Finally, the approach mathematically ignores error associated with the population biomass estimate. A better, but more complicated approach would include the coefficient of error or other estimate variability measures.

An improvement in non-native game fish biomass could potentially lead to loss or declines in native fish species occurring within a reach. As noted above, this metric is intended to be used where native or non-native game fish species are determined to be a management priority by WGFD. Consultation with regional fish biologists is required before selecting and using this metric in the tool. This consultation should inform metric selection and project design and reduce the potential for these types of trade-offs between native and non-native species.

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# Appendix A

# WSQT List of Metrics

# List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Metrics/Units | Stratification Type | Stratification Description | Threshold Index Values i= 0.00 | i= 0.30 | i= 0.70 | i= 1.00 |
|---|---|---|---|---|---|---|---|---|
| Flow Alteration Module | Flow Magnitude | Mean Annual Flow (O/E)<br>Mean August Flow (O/E)<br>Mean September Flow (O/E)<br>Mean January Flow (O/E)<br>Mean Annual Peak Daily Flow (O/E)<br>7-Day Minimum Flow (O/E) | - | | 0.00<br>≥ 2.00 | * | * | 0.90 - 1.10 |
| Reach Hydrology and Hydraulics | Reach Runoff ● | Land Use Coefficient ● | - | | ≥ 80 | * | 62 | ≤ 45 |
| | | Concentrated Flow Points ● | - | | * | * | 1.0 | 0.0 |
| | Baseflow Dynamics | Average Velocity (ft/s) | - | | < 1.0 | - | - | - |
| | | Average Depth (ft) | Steam Temperature & Bankfull Width | Tier 1 (Cold) & Width < 20' | ≤ 0.2 | * | * | ≥ 1.0 |
| | | | | Tier 1 (Cold) & Width > 20' | ≤ 0.4 | * | * | ≥ 1.5 |
| | | | | Tier 2 (Cold-Cool) | ≤ 0.6 | * | * | ≥ 2.3 |
| | Bankfull Dynamics ● | Width-to-Depth Ratio State ● | - | | ≤ 0.2<br>≥ 1.8 | * | * | ≤ 1.0 |
| | Floodplain Connectivity ● | Bank Height Ratio (ft/ft) ● | - | | * | 1.5 | * | ≤ 1.0 |
| | | Entrenchment Ratio (ft/ft) ● | Reference Stream Type | Cb | 1.0 | * | 2.2 | ≥ 3.9 |
| | | | | C | 1.0 | * | 2.2 | ≥ 4.2 |
| | | | | E | 1.0 | * | 2.2 | ≥ 6.7 |
| | | | | A, B, Ba or Bc | 1.0 | * | 1.4 | ≥ 2.2 |
| | | Side Channels (%) ● | Valley Type | Unconfined Alluvial | 0 | 10 | 50 | 100 |
| | | | | Confined Alluvial | 0 | 5 | 25 | ≥ 50 |

* Threshold Index Values were not assigned to generate the reference curve
● Basic Suite required elements per WSMP v2

# List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Metrics/Units | Stratification | | Threshold Index Values | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Type | Description | i= 0.00 | i= 0.30 | i= 0.70 | i= 1.00 |
| Geomorphology | Large Woody Debris | LWD Index (Dimensionless) | - | | 0 | * | 430 | ≥ 660 |
| | | # Pieces | - | | 0 | * | 13 | ≥ 28 |
| | Lateral Migration ● | Greenline Stability Rating | - | | < 2 | 5 | 7 | ≥ 9 |
| | | Dominant BEHI/NBS | - | | 0.0 = 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 | 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 | - | L/VL, L/L, L/M, L/H, L/VH, M/VL |
| | | Percent Streambank Erosion (%) | - | | ≥ 75 | * | 10 | ≤ 5 |
| | | Percent Armoring (%) | - | | ≥ 30 | * | * | 0 |
| | Bed Material Characterization | Percent Fines | - | | ≥ 50 | * | 15 | ≤ 5 |
| | Bed Form Diversity ● | Pool Spacing Ratio ● | Reference Stream Type | C | ≥ 9.3<br>≤ 3.0 | * | 7.0<br>3.7 | 4.0 - 6.0 |
| | | | | Cb | * | * | 3.0<br>6.0 | 3.7 - 5.0 |
| | | | | B & Ba | ≥ 7.5 | * | 4.0 | ≤ 3.0 |
| | | | | Bc | * | * | 6.0 | ≤ 3.4 |
| | | | | E | ≤ 1.8<br>≥ 8.3 | * | 3.0<br>6.0 | 3.5 - 5.0 |
| | | Pool Depth Ratio ● | - | | 1.0 | * | 2.2 | ≥ 3.2 |
| | | Percent Riffle (%) ● | Slope | S < 3% | 0<br>100 | * | 39<br>69 | 50 - 60 |
| | | | | S ≥ 3% | 0<br>100 | * | 60<br>83 | 68 - 78 |
| | | | Bioregion | Volcanic Mountains & Valleys | 0<br>100 | * | 76<br>89 | 80-84 |
| | Riparian Vegetation ● | Riparian Extent (%) ● | Valley Type | Unconfined Alluvial | 0 | 30 | * | 100 |
| | | | | Confined Alluvial or Colluvial/V-shaped | 0 | 60 | * | 100 |
| | | Woody Vegetation Cover (%) ● | Ecoregion | Mountains or Basins | 0 | * | 69 | ≥ 122 |
| | | | | Plains | 0<br>* | *<br>101 | *<br>* | 69-76 |
| | | Herbaceous Vegetation Cover (%) ● | - | | 35 | * | 74 | ≥ 119 |
| | | Percent Native Cover (%) ● | - | | * | 65 | 91 | 100 |

* Threshold Index Values were not assigned to generate the reference curve
● Basic Suite required elements per WSMP v2

# List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Metrics/Units | Stratification | | Threshold Index Values | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Type | Description | i= 0.00 | i= 0.30 | i= 0.70 | i= 1.00 |
| Physicochemical | Temperature | MWAT ($^oC$) | Steam Temperature | Tier 1 (Cold) | * | 18.1 | 15.4 | * |
| | | | | Tier 2 (Cold-Cool) | * | 19.3 | 15.5 | * |
| | | | | Tier 3 (Cool) | * | 22.0 | 17.7 | * |
| | | | | Tier 4 (Cool-Warm) | * | 26.0 | 19.9 | * |
| | | | | Tier 5 (Warm) | * | 29.0 | 27.3 | * |
| | Nutrients | Chlorophyll (mg/m2) | Ecoregion | Mountains | * | 53 | 27 | < 12 |
| | | | | Plains or Basin | ≥ 150 | 117 | 29 | < 16 |
| Biology | Macroinvertebrates | WSII | Bioregion | Volcanic Mountains & Valleys | ≤ 24.9 | 46.2 | 69.3 | ≥ 88.1 |
| | | | | Granitic Mountains | ≤ 32.6 | 40.2 | 60.3 | ≥ 74.9 |
| | | | | Sedimentary Mountains | ≤ 16.6 | 34.8 | 52.3 | ≥ 70.8 |
| | | | | Southern Rockies | ≤ 5.1 | 32.6 | 48.8 | ≥ 82.2 |
| | | | | Southern Foothills & Laramie Range | ≤ 30.7 | 44.5 | 66.7 | ≥ 85.3 |
| | | | | Bighorn Basin Foothills | ≤ 3.9 | 40.6 | 60.9 | ≥ 80.8 |
| | | | | Black Hills | ≤ 12.8 | 30.7 | 46.1 | ≥ 65.7 |
| | | | | High Valleys | ≤ 17.1 | 32.5 | 48.8 | ≥ 78.2 |
| | | | | SE Plains | ≤ 10.4 | 36.7 | 55.1 | ≥ 87.0 |
| | | | | NE Plains | ≤ 1.6 | 38.9 | 58.4 | ≥ 95.8 |
| | | | | Wyoming Basin | ≤ 5.3 | 26.2 | 39.9 | ≥ 64.5 |
| | | RIVPACS | Bioregion | Volcanic Mountains & Valleys | ≤ 0.21 | 0.65 | 0.86 | ≥ 1.21 |
| | | | | Granitic Mountains | ≤ 0.59 | 0.65 | 0.88 | ≥ 1.09 |
| | | | | Sedimentary Mountains | ≤ 0.42 | 0.68 | 0.82 | ≥ 1.17 |
| | | | | Southern Rockies | ≤ 0.27 | 0.62 | 0.89 | ≥ 1.18 |
| | | | | Southern Foothills & Laramie Range | ≤ 0.29 | 0.68 | 0.88 | ≥ 1.20 |
| | | | | Bighorn Basin Foothills | ≤ 0.41 | 0.63 | 0.84 | ≥ 0.92 |
| | | | | Black Hills | ≤ 0.37 | 0.59 | 0.88 | ≥ 1.08 |
| | | | | High Valleys | ≤ 0.42 | 0.68 | 0.86 | ≥ 1.14 |
| | | | | SE Plains | ≤ 0.34 | 0.51 | 0.78 | ≥ 1.12 |
| | | | | NE Plains | ≤ 0.11 | 0.52 | 0.75 | ≥ 0.98 |
| | | | | Wyoming Basin | ≤ 0.15 | 0.64 | 0.82 | ≥ 1.18 |
| | Fish | Native Fish Species (% of Expected) | - | | 0 | * | 80 | 100 |
| | | SGCN Absent Score | - | | ≥ 3 | 2 | 1 | 0 |
| | | Game Species Biomass (% Change) | Stream Productivity Rating | Blue Ribbon and non-trout game fish | < 5 | 5 | 25 | ≥ 40 |
| | | | | Red Ribbon | < 10 | 10 | 50 | ≥ 80 |
| | | | | Yellow/Green Ribbon | < 15 | 15 | 75 | ≥ 119 |

* Threshold Index Values were not assigned to generate the reference curve

● Basic Suite required elements per WSMP v2

# List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Literature and data sources used to develop Reference Curves | Applicability |
|---|---|---|---|
| Flow Alteration Module | Flow Magnitude | Threshold values were derived using the principles of the presumptive standard (Richter et al. 2012). | The default metrics in the FAM are primarily tailored to hydrologic regimes with a large snowmelt signature. Adaptation of the module for application in non-snowmelt systems should be made on a case-specific basis and should consider the dominant or important aspects of the hydrologic regime, given local variation in climate and other process drivers. Substitution or removal of metrics can be considered on a case-specific basis where alternative metrics would better represent the flow regime of the stream. |
| Reach Hydrology and Hydraulics | Reach Runoff ● | Literature values from NRCS, 1986. | Applicable in all streams. |
| | | Developed by WSTT and Stream Mechanics. | |
| | Baseflow Dynamics | Threshold values were developed using established minimum flow criteria for habitat retention methods (Nehring 1979, Annear and Conder 1984), and average depth criteria from Habitat Suitability Indices (Hickman and Raleigh 1982, Raleigh 1982, Raleigh et al. 1984, Raleigh et al. 1986, Wesche et al. 1987, Shuler and Nehring 1993). | Applicable in single-thread, intermittent or perennial coldwater streams (WY Tiers I and II) that have or are proposed to have regulated flow. |
| | Bankfull Dynamics ● | Literature values from Rosgen (2014). | Applicable in all streams except multi-thread systems. |
| | Floodplain Connectivity ● | Literature values from Rosgen (2008), Harman et al. (2012) and data from the Combined Geomorphic Reference Dataset. | Applicable in all streams. |
| | | | Not applicable in naturally occuring canyon systems (e.g., F type streams) or braided (D) stream types. |
| | | Adapted from the reference curves in the Oregon SFAM (Table 6-7; Nadeau et al. 2018) | Recommended application in alluvial valleys where side channels could be supported, this includes beaver meadows and other stream-wetland complexes. Not applicable in multi-thread systems (three or more channels active at baseflow) or in steeper colluvial systems. |

* Threshold Index Values were not assigned to generate the reference curve
● Basic Suite required elements per WSMP v2

## List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Literature and data sources used to develop Reference Curves | Applicability |
|---|---|---|---|
| Geomorphology | Large Woody Debris | Data collected by WGFD, WDEQ and WSTT. | Applicable to all streams with naturally forested catchment or riparian gallery forests. |
| | | NRSA dataset (USEPA 2016) and data collected by WGFD and WSTT. | |
| | Lateral Migration ● | Literature values from Winward (2000). | Applicable in all streams with slopes less than 4%, including streams that are naturally in disequilibrium, like some systems with naturally high rates of bank erosion or response systems (e.g., braided streams, ephemeral channels, or alluvial fans). |
| | | Literature values from Rosgen (2014) and Harman et al. (2012). | Applicable to single-thread channels. Not applicable in systems that are naturally in disequilibrium, like some braided streams, ephemeral channels, alluvial fans or other systems with naturally high rates of bank erosion. |
| | | Literature values from Binns (1982). | |
| | | Developed by Stream Mechanics. | Applicable whenever man-made armoring is present or proposed in a project reach. |
| | Bed Material Characterization | Developed using data provided by WDEQ, as well as literature values presented within Benoy et al. (2012). | Applicable only in systems with a median grain size of gravel or coarser and is not applicable in natural sand or silt bed streams. |
| | Bed Form Diversity ● | Data from the Compiled Geomorphic Reference Dataset. | Applicable in all single-thread perennial and intermittent streams. Pool spacing ratio is not applicable in natural bedrock systems. |
| | | | The volcanic mountain & valley reference curve is applicable to streams in this bioregion with 1.3% slope or greater. |
| | Riparian Vegetation ● | Developed by WSTT, refined based on CSQT updates (USACE 2020b). | Applicable to all streams. Where the reference community type is herbaceous, herbaceous vegetation cover should be evaluated, whereas if the reference community type is woody, woody vegetation cover should be evaluated. Note that for CWA 404 projects with woody reference vegetation communities, herbaceous cover data should be recorded but index values will not be calculated in the WSQT. |
| | | Data from the CNHP dataset (Kittel et al. 1999) and WSTT data. | |

* Threshold Index Values were not assigned to generate the reference curve
● Basic Suite required elements per WSMP v2

# List of Metrics (LOM) for the WSQT v2.0

| Functional Category | Function-based Parameters | Literature and data sources used to develop Reference Curves | Applicability |
|---|---|---|---|
| Physicochemical | Temperature | Literature values from Peterson (2017). | Applicable to perennial streams statewide, as well as in intermittent streams where baseflow extends through August and fish are naturally present. The uncertainty of the NorWest model temperature predictions is greater for intermittent streams., however NorWeST temperature models are not available within the Little Missouri, Niobrara, Lower North Platte and South Platte Basins - sufficient monitoring data are needed in these areas to determine the thermal tier. |
| | Nutrients | Developed using data and guidance from WDEQ-Water Quality Division. | Applicable within stream reaches that contain gravel or larger bed materials and where riffles are present. |
| Biology | Macroinvertebrates | Literature values from Hargett (2011). | Not applicable to intermittent or ephemeral streams or low-gradient lentic systems; data  must be collected using targeted riffle/run quantitative methods. The following streams will be diffcult to assess with this method due to inadequate reference site representation: streams with very small watersheds < 12 km2 (< 5 mi2), streams located at high montane elevations > 2,740 m (> 9,000 ft.), streams within the Bighorn Basin of north-central Wyoming (excluding the foothills), non-montane spring-fed stream segments within the interior of the Wyoming Basin and mixed origin streams of extreme southwest Wyoming. |
| | | Literature values from Hargett (2012). | |
| | Fish | Developed by Wyoming Game and Fish and WSTT, refined based on CSQT updates (USACE 2020b). | Applicable within intermittent and perennial streams where fish are naturally present. |
| | | Developed by Wyoming Game and Fish and WSTT, and evaluated using data from Binns (1999) | |

* Threshold Index Values were not assigned to generate the reference curve
● Basic Suite required elements per WSMP v2