TDOT Department of Transportation

U.S. Department of Transportation
Federal Highway Administration

Advancing Urban Stream Restoration/ Enhancement Practices for Compensatory Mitigation Credits

Research Final Report from (the University of Tennessee, Knoxville) | (John Schwartz, Jason Brown, Jackson Bogach, Grace Long, Jain Song, and Ghada Diab) | April 30, 2024

Sponsored by Tennessee Department of Transportation Long Range Planning
Research Office & Federal Highways Administration

DISCLAIMER

This research was funded through the State Planning and Research (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under ***RES #2019-04: Advancing Urban Stream Restoration/Enhancement Practices for Compensatory Mitigation Credits.***

This document is disseminated under the sponsorship of the Tennessee Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Tennessee and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Tennessee Department of Transportation or the United States Department of Transportation.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
RES 2019-04		

4. Title and Subtitle	5. Report Date
Advancing Urban Stream Restoration/Enhancement Practices for Compensatory Mitigation Credits	April 2024
	6. Performing Organization Code
7. Author(s) John Schwartz, Jason Brown, Jackson Bogach, Grace Long, Jain Song, and Ghada Diab	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Tennessee Dept. of Civil & Environmental Engineering Knoxville, Tennessee 37996	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. RES 2019-04
12. Sponsoring Agency Name and Address Tennessee Department of Transportation 505 Deaderick Street, Suite 900 Nashville, Tennessee 37243	13. Type of Report and Period Covered May 2022- July 2024
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Tennessee Department of Transportation Research is required to provide compensatory mitigation credits per Section 404 of the Clean Water Act and Tennessee's Aquatic Resource Alteration Permit program when aquatic resource losses occur from highway construction. The Tennessee Stream Quantification Tool (TN SQT V.1) was created in 2019 to generate debits from impacts and credits from proposed restoration. After implementation of the TN SQT V.1 practitioners and TDOT staff identified multiple issues with its use mostly in urban streams. Research for this project used Beaver Creek in Knox County as a case study to compare the TN SQT V.1 with a revised version (TN SQT V.2) that better supports mitigation credit generation from the restoration of urban streams. The TN SQT V.2 was improved through a reduction in overall parameters to be assessed in the field, and providing alternative parameters for those requiring bankfull indicators when none are present. The Beaver Creek case study found that the existing condition scores between the two SQT versions resulted in an 11% increase in mitigation functional feet credits with the use of V.2 compared with V.1. A second component of this research project advanced the design of pool-riffle sequences, particularly useful for urban stream restoration. The pool depth prior to a riffle should be at least 1 meter. Overall, this project demonstrated that there is potential to obtain mitigation credits in urban streams on public lands, and that due to hydromodification it is suggested the use of an ecohydraulic approach can improve restoration.

17. Key Words	18. Distribution Statement
STREAM QUANTIFICATION TOOL, COMPENSATORY MITIGATION CREDITS, STREAM RESTORATION	No restriction. This document is available to the public from the sponsoring agency at the website http://www.tn.gov/

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	xxx	

Acknowledgement

The research project was completed in collaboration with TDOT staff, Paul Purnell in the Environmental Mitigation Office. Knox County Stormwater Program staff aided in locating the project site, and supported the research team with geographical information and site data as needed. Natalie Burger with Knox County is recognized this support. We thank the students in the University of Tennessee Knoxville, Stream Restoration design class in Spring 2019 whom conducted field surveys and assessments for the prospectus report. We thank Dr. Bahareh Shoghli for her SWAT modeling effort to estimate the changing channel design flows as upper Beaver Creek continues to be developed to an ultimate built-out period. We thank Cole Emmett for preparing CAD drawings of the proposed restoration project among Beaver Creek at Powell. A key part of this grant was the development of the revised version of the SQT, which was an outcome of a TN SQT Review Working Group consisting of professional consultants, an in-lieu fee program, TDEC staff, and USACE-Nashville District Office staff. We thank their efforts to identifying issues and making recommendations to the original version of the TN SQT.

Executive Summary

When the Tennessee Department of Transportation (TDOT) constructs highways causing aquatic resource losses to rivers and streams they are required to mitigate those losses per Section 404 of the Clean Water Act (CWA) regulated by the US Army Corps of Engineers (USACE) and the US Environmental Protection Agency (USEPA), and Tennessee's Aquatic Resource Alteration Permit (ARAP) program under the Tennessee Department of Environment and Conservation's (TDEC). Stream restoration projects are implemented to generate compensatory mitigation credits compensating for aquatic resource losses caused by construction activities. Credits can be obtained through mitigation banks, in-lieu fee programs, and permittee-responsible mitigation. In 2019, TDEC and the USACE Nashville District Office began requiring the newly developed Tennessee Stream Quantification Tool (TN SQT V.1) to compute mitigation debits and credits. However, after one year in use by practitioners, TDOT and other SQT users identified multiple issues with its performance quantifying functional condition scores particularly in urban streams. Supporting this observation, two studies found that the TN SQT V.1 parameters did not account for functional lift, where one study documented a restored reach of Beaver Creek (Knox County) achieved a Tennessee macroinvertebrate Index (TMI) score of 32, which under state Water Quality Standards infers that reach is fully supporting. However, the TN SQT V.1 existing condition score (ECS) was 0.59 indicating that that reach is classified as functioning-at-risk. In addition, a TDEC (2020) study found among four Ecoregion 67 reference streams ECS averaged 0.71, which is slightly above 0.70, the bottom of the range for fully functioning (0.70-1.0). One of the major issues with the TN SQT V.1 identified by practitioners was the required use of bankfull dimensions which they found problematic in urban streams where indictors may not exist or not stable representing rapidly adjusting channel morphology. Other issues were identified and summarized in this TDOT project report.

With multiple issues identified by users of the TN SQT V.1, under a TDEC-sponsored project a working group of stream restoration practitioners, mitigation providers, and the USACE/TDEC regulatory community was formed in August 2020 to identify and summarize the debit-crediting issues, and make recommendations for a revised version. Consistent with the objectives of this project, a revised version of the TN SQT was drafted and finalized in 2023, identified here within as the TN SQT V.2. A TN SQT V.2 was finalized in 2023 and described as part of this project report. Supporting TDOT, the draft revisions considered how SQT parameters would achieve credits from restoration projects in highly altered streams, particularly in urban watersheds. Overall, the TN SQT V.2 assessment procedures are simpler thus it is anticipated to reduce costs.

Restoration of urban streams can be challenging because rapid channel adjustment occurs from hydromodification, as increased flow from greater runoff exceed the capacity of the channel to carry such increased flows. A typical stream response is the degradation of riffle morphology which mesohabitat is essential for stream ecosystems. To design a stable riffle under these conditions requires the use of engineering hydraulics, and a key morphological feature to design is the transition from a pool into an existing or artificially-constructed riffle. Constructing stable riffles in urban streams can provide additional mitigation credits with use of the TN SQT.

The objectives of this TDOT research project are: 1) to compare the potential mitigation credits obtained from the TN SQT V.1 and a revised version TN SQT V.2 for an urban stream restoration project based on a mitigation prospectus report, and 2) to assess an improvement to ecohydraulic design methods for urban stream restoration/enhancement that are more cost effective by applying fundamental geomorphic, hydraulic, and ecological principles at the channel reach-scale.

For this project, a stream site was selected on publicly-owned land in Knox County and along a TDOT highway easement. Jointly decided with Knox County staff and TDOT Paul Purnell, the stream restoration site selected was on Beaver Creek and a tributary at Powell, Tennessee. In addition to the project on publicly-owned land, stream banks were observed to be highly eroding, and due to prior historic channelization and the channel incising, riffles bed morphology was mostly absent. The tributary channel was eroding excessively. Thus due to these impacts, this site needed restoration of habitat to improve the aquatic biota within this area of Beaver Creek. Pre-construction stream assessments were completed including geomorphic and habitat surveys. A stream assessment also included all the TN SQT V.1 input parameters among the hydrology, hydraulics, geomorphology, physiochemical, and biology categories. Assessments were completed in 2019 and the collected data provided the basic information for the prospectus report. Four reaches were identified with the restoration potential for mitigation credit generation, where three reaches were on mainstem Beaver Creek, and one reach was on the lower section of the tributary. The prospectus report describes the proposed restoration practices including bank stabilization with toe protection, riffle creation, stormwater runoff infiltration, invasive species removal, riparian buffer planting, a side channel reconnection, and tributary channel erosion controls. Applying the TN SQT V.1, the total number of mitigation credits for all four reaches was estimated at 342 functional feet (FF).

A final revision of the draft TN SQT V.2 was completed in April 2023. A pilot training with the TN SQT V.2 was given in August 2023 including participates from TDEC, USACE (Nashville and Memphis District Offices), and TDOT. A user manual is a work in progress, and will need to go through the public hearing process before the revised TN SQT is final, thus what presented here within could be subject to minor changes. A table with the functional categories and function-based parameters are provided in this report. In general, the revisions included:

- A reduction in the total number of parameters measured and scored, with the goal of reducing the time to complete a site ECS score with V.2 of the TN SQT.
- Reworked the arrangement of the functional categories, and aimed that each would have a similar number of parameters not to weight any one category in the worksheet roll-up

procedure. This rearrangement results in two Geomorphology categories, and combining Physiochemical and Biology categories into one: Water Quality/Biology.

- Promoted the restoration of floodplains and enhanced floodplain infiltration.
- Addressed issues of identifying bankfull indictors, by removing most parameters that rely on bankfull measures, and providing functional capacity alternatives for some function-based parameters.
- Parameter performance relations (reference standards) were updated for those that vary regionally to better reflect ecoregions differences.
- Simplified field datasheet into a single form, and the spreadsheet entry aligns with field datasheet with calculations more efficient. Reporting is simplified.
- In general, migration credit "currency" was not substantially different the between the original and proposed SQTs.

Applying the TN SQT V.2 for the same four Beaver Creek reaches, the total number of mitigation credits was estimated at 380 functional feet. For this case study, the revised TN SQT V.2 provided 11% more FF credits than V.1. The functional category with the greatest increase in ECS was Hydraulics because in the TN SQT V.1 it relies on two parameters requiring bankfull measured, and the Beaver Creek mainstem reaches lacked bankfull indicators. Therefore, this category's TN SQT V.2 non-bankfull alternative was applied increasing ECS between 0.35 to 0.50 for the three mainstem reaches. Within the Geomorphology category, ECS increased for the TN SQT V.2 by 0.06-0.19 for the four study reaches. The difference in this TN SQT V.2 category provides greater weight to riparian vegetation and for these reach sites there is good vegetation on one side of the stream. The combined Physiochemical (Water Quality) and Biology category also showed an increase in ECS with the TN SQT V.2 for the mainstem reaches between 0.10 and 0.19. The Hydrology category was the one category that decreased in ESC with the addition function-based parameter for floodplain storage, thus likely decreased due to the urban development in the floodplain. For this category, ECS decreased between 0.08 and 0.15 among the four project reaches. Because the four project reaches in Beaver Creek constitute a small dataset, a greater exploration of comparing TN SQT V.1 and V.2 was undertaken for 15 stream reaches in east and middle Tennessee. In general, this assessment found that total ECS for the TN SQT V.1 and V.2 were similar for stream reaches with higher functional capacity. For reaches with lower functional capacity (total ECS < 0.6), the TN SQT V.2 appears to provide a greater ECS than the TN SQT V.1. This finding is consistent with what was found for the assessment of the Beaver Creek project reaches, an urban stream with generally lower functional capacity.

The project objective exploring the potential improvement to the riffle design for urban stream restoration applying a 3D hydrodynamic model was conducted on a simulated section of stream. The topographic template for the simulated stream model was based on a reach of Beaver Creek. Specifically, the modeling experiment was to explore what entrance slope from the pool into the riffle dissipates erosional energy thus velocities so that a designed artificial riffle will remain stable. For this modeling experiment the FLOW3D® model was used to estimate turbulent kinetic energy (TKE) for different riffle entrance slopes where a greater TKE infers greater energy dissipation. Energy dissipation at this location is needed to prevent the formation of a high-velocity fluid jet that can erode a constructed riffle. This modeling experiment found that a pool depth of 1 meter before a riffle showed the sufficient reduction in erosional velocities at the riffle entrance. To note, the exit pool depth did not influence the riffle velocities. This modeling experiment concluded that the pool depth before a riffle is important in the restoration design of a self-maintaining artificial riffle. Future research should examine simulations with different turbulence closure models, which would better quantify model output uncertainties.

Key Findings

- Using Beaver Creek in Knox County as a case study, a prospectus report was generated for the purpose to estimate the mitigation credits that are possible in an urban stream; in total 342 function feet (FF) were possible through restoration practices generated mostly from bank stabilization, riffle creation, and riparian vegetation improvements.
- Generation of mitigation credits for urban stream restoration projects using the parameters in the TN SQT V.1 appear to be limited apparently due to the required bankfull measures, when urban streams may not have or have unreliable bankfull indicators; an outcome of this finding is it affects the possible economically feasible of a project.
- The TN SQT V.2, the revised version of the SQT appears to quantify functional condition to a greater extent than V.1, where for the Beaver Creek case study 11% more FF mitigation credits were generated.
- Design of pool-riffle sequences for stream restoration in third-order streams should specify a 1 meter bed elevation difference from pool to riffle.

Key Recommendations

- Use public lands in urban watersheds to achieve compensatory mitigation credits per permittee-responsible mitigation applying the TN SQT V.2.
- Use the revised version of the TN SQT, and in urban stream where there are no bankfull indicators use the alternative SQT parameters.
- Restoration design of pool should be at least 1 meter in depth deeper from the downstream riffle bed structure for riffle stability in urban streams.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Problem Statement

When the Tennessee Department of Transportation (TDOT) constructs highways causing aquatic resource losses to rivers and streams they are required to mitigate those losses per Section 404 of the Clean Water Act (CWA) regulated by the US Army Corps of Engineers (USACE) and the US Environmental Protection Agency (USEPA), and Tennessee's Aquatic Resource Alteration Permit (ARAP) program under the Tennessee Department of Environment and Conservation (TDEC). Stream restoration projects are implemented to generate compensatory mitigation credits to compensate for aquatic resource losses caused by construction activities. Credits can be obtained through mitigation banks, in-lieu fee programs, and permittee-responsible mitigation. Before the 2010s, the Tennessee Stream Mitigation Program (TSMP) was the sole in-lieu fee program in which TDOT relied on for compensatory mitigation credits however TSMP was unable to supply the demand for credits. Though this credit availability has improved since 2010s with new in-lieu fee programs and banks approved in Tennessee, TDOT still is in a need for a stable supply of mitigation credits. Furthermore, to credit availability, current stream restoration practices commonly used are expensive to construct, particularly in urban watersheds. However, the mitigation need is generally the greatest in urban areas because those are the locations where aquatic resource impacts occur most often from highway construction. New cost-effective approaches for urban stream restoration/enhancement design and construction are needed that can be approved by both the federal and state environmental regulatory communities, where these projects can receive sufficient credits to cost-effective to construct.

In addition to the construction cost of current stream restoration practices, credit costs have increased as a result of the USACE Nashville District Office and TDEC implementing the Tennessee Stream Quantification Tool (TN SQT V.1) to compute mitigation debits and credits. In general, the regulatory community recognized the need for a more quantitative and consistent approval process for compensatory mitigation debit-credit ratios, thus TDEC developed this tool with Stream Mechanics, Inc. The TN SQT V.1 was issued for public comment in January 2018, and TDEC responses to public comments were published in June 2018. The TN SQT V.1 was fully implemented in 2019, though its performance was never fully tested. After one year in use by practitioners, TDOT, and others, multiple issues were identified with its performance quantifying functional condition scores.

Thus, in August 2020 under a TDEC-sponsored project, a working group of stream restoration practitioners, mitigation providers, and the USACE/TDEC regulatory community was formed to identify and summarize the debit-crediting issues with the TN SQT V.1, and make recommendations for a revised version (TN SQT V.2). A TN SQT V.2 was finalized in 2023 and described as part of this project report. Supporting TDOT, revisions considered how parameters would achieve credits from restoration projects in highly altered streams, particularly in urban watersheds. Overall, the assessment procedures are simpler thus it is anticipated to reduce costs. A research question remains how the TN SQT V.1 will differ from V.2 in generating mitigation credits, and this question needs to be examined particularly for urban streams.

1.2 Purpose of Work

The objectives of this research project are: 1) to compare the potential mitigation credits obtained from the TN SQT V.1 and a revised version TN SQT V.2 for an urban stream restoration project based on a design prospectus mitigation report, and 2) to assess an improvement to ecohydraulic design methods for urban stream restoration/enhancement that are more cost effective by expanding on the applied geomorphic and ecological principles in Schwartz et al. (2015). In addition, a pilot training course for TDOT staff will be conducted on the revised TN SQT (V.2) with emphasis on urban stream restoration.

1.3 Scope of Work

The scope of work includes three tasks. These tasks lead to generating a final project report and pilot training for the TN SQT (V.2). The three tasks are as follow.

1.) Urban Stream Restoration Project Design: In Task 1, a restoration project on a stream in Knox County was selected with consultation with TDOT Paul Purnell and County Stormwater Program staff. The selected project adjoins public lands in the County and TDOT Emory Road highway corridor in order to secure required conservation easements. The project site was on Beaver Creek adjacent to Powell High School and Powell Station Park. Geomorphic, physical habitat, riparian vegetation, and aquatic biota data were collected to segment reaches to assess the functional existing condition score (ECS) of each for input into TN SQTs. This effort supports Task 2 below, comparing the V.1 and V.2 of the TN SQT. Results of this data collection effort will also generate a pre-design prospectus mitigation report.

2.) Mitigation Credits for Urban Stream Restoration: Based on the proposed project described in Task 1 and a generated prospectus report, the potential permittee-responsible mitigation credits were computed using the TN SQT V.1. The revised version TN SQT V.2, an outcome of the SQT Review Working Group is summarized in this report. It was tested on the Beaver Creek project site, where existing condition scores (ECS) data between V.1. and V.2 of the TN SQT for mitigation credit generation. The overarching goal of the project is to assist in promoting a new marketplace for credits from municipal public lands, particularly those cities with Phase II stormwater programs, and to demonstrate credit value for smaller projects.

3.) Fundamental Research for Urban Stream Restoration: An ecohydraulic design approach will be applied for Task 3 using the FLOW3D (computational fluid dynamics) model to investigate the hydraulics at the transition slope between designed riffle-pool sequences for improved mesohabitat stability. In addition, the River2D model will be used to research improvements for habitat quality modeling by integrating fluvial geomorphology, engineering hydraulics, and stream ecology. The BSTEM model will be used to examine different bank stability techniques for restoration design. Outcomes per use of these three models will advance how cost-effective improvements can be incorporated into natural channel design (NCD) restoration techniques in urban streams.

Chapter 2 Literature Review

2.1 Stream Compensatory Mitigation

Stream restoration is a major industry in the United States, and primarily driven in many states by compensatory mitigation, as promulgated under Section 404 of the Clean Water Act (Bernhardt et al. 2005). The 1990 Memorandum of Agreement (MOA) between USEPA and the USACE established guidelines for the level of mitigation required for aquatic resource loss, including Step 1 to avoid impacts, Step 2 to minimize impacts, and Step 3 to compensate impacts when unavoidable. The 2008 Final Mitigation Rule, CWA §325 and §332 required "no net loss" of stream function through compensatory mitigation and a means to quantify it (Somerville 2010). Thus, USEPA/USACE has worked to develop a quantifiable tool for estimating "functional lift" from potential stream restoration projects to acquire mitigation credits, where restoration in general can mean various methods such as stream establishment, enhancement, and preservation (Doyle and Shields 2012; Harman et al. 2012). Three compensatory mitigation mechanisms are available to offset unavoidable impacts to streams including mitigation banks, in-lieu fee programs, and permittee-responsible mitigation. The Tennessee Stream Mitigation Program (TSMP) was the sole in-lieu fee program in which TDOT relied on for compensatory mitigation however their design approach and construction methods for stream restoration can be constraining and expensive making it difficult to find project sites and obtain approval by the Interagency Review Team (IRT).

2.2 Stream Restoration Design Approaches

Stream restoration design approaches and methods have evolved over time, however the dominant approach applied is the NCD methodology (Rosgen, 1996; Hey 2006). NCD relies on a geomorphic reference site where channel morphological dimensions are measured relative to a bankfull stage. These measurements of channel features are converted to dimensionless ratios and applied to the restoration site. Regional curves are used for basic design of channel cross-sectional width, depth, and area, which rely on the hydraulic geometry concept assuming a geomorphologically-equilibrium condition (Knighton 1998; Thorn et al. 1998). With stream classification per Rosgen (1994), this form-based approach can be effectively applied in watersheds where the hydrological processes, riparian vegetation and/or land use are not rapidly changing. However, Simon et al. (2007) modeled various stream conditions illustrating various issues that can occur with the NCD approach when streambank soil characteristics are not carefully assessed. It has also been observed that in urban watersheds with increases in impervious land cover, hydrological changes greatly impact stream morphology (Wade et al. 2003; Bernhardt and Palmer 2007; O'Drisscoll et al. 2010). In urban watersheds, the hydrological and geomorphological processes are not in equilibrium (Annable et al. 2011). In this case, the basic assumption for the use of hydraulic geometry relationships is violated and not appropriate for the NCD approach. Other restoration tools are available for use in both threshold and alluvial channels (Shields et al. 2003). The USACE has a manual on a methodology that considers hydrology (Copeland et al. 2001).

Improvements in stream restoration tools have also included the use of multi-dimensional hydraulic models (Schwartz and Herricks 2007; Rhoads et al. 2011, Schwartz et al. 2015). Hydraulic models provide the means to compute critical shear stresses among complex channel morphologies so that a designer can use the appropriate in-stream structures for bank and bed protection, i.e., large woody debris, toe rock, J- hook weir and others. The Bank Stability and Toe Erosion Model (BSTEM) developed at the USDA National Sedimentation Laboratory is an assessment tool that considers both fluvial erosion and geotechnical failures of streambanks, which has now been incorporated into the HEC-RAS model (ACOE 2015). Its ease of use makes it a practical design tool, which can be applied to examine various design options, such as the use of bank toe rock protection and different types of bank vegetation for geotechnical stability. A project by Simmons (2014) used the mini- jet device and BSTEM to determine what spacing is needed for vegetation plantings for stream restoration projects. The mini-jet device is used to measure soil erodibility and critical shear stress on streambank locations (Al-Madhhachi et al. 2013). Simmons (2014) found that in general a spacing of 1.4 m is appropriate to achieve a factor of safety from geotechnical failure above 1.3. Mahalder et al. (2018) applied the mini-jet device across Tennessee among the four TDOT regions and developed predictive equations for soil erodibility and critical shear stress based on basic soil properties. Other useful restoration design tools include GeoTools (Bledsoe et al. 2007), CONCEPTS model (Langendoen 2000), STREAMS geomorphic analysis model (Powell et al. 2006), and the USFWS RiverRAT (Beechie et al. 2010).

2.3 Elements of Stream Ecological Functions

To mitigate aquatic resource losses by incorporating ecological functional lift elements to the design process, stream restoration/enhancement must include ecological criteria (Schwartz and Herricks 2008); Palmer et al. 2014; Schwartz 2016). Schwartz (2002) developed an approach that integrates principles from fluvial geomorphology, engineering hydraulics, and stream ecology over multiple flow stages. This approach relies on identifying impaired fish community composition and mesohabitat structure and focuses on building the necessary habitat quality for increased biodiversity. It also relies on fluvial geomorphology and engineering hydraulics to ensure long-term maintenance of physical mesohabitat structure. This approach is particularly useful in urban streams where hydrology has been modified from development, and the channel is often constrained from civil infrastructure, such as roads, bridges, water and sewer pipeline crossings, and adjacent buildings. A watershed scale assessment on biological connectivity is conducted to ensure that biota can migrate from stream reaches with diverse ecosystems to restored reaches to repopulate those newly constructed habitats. A project utilizing this approach was completed at Beaver Creek in Knox County (Schwartz et al. 2015). This site has been continually monitored for several years before construction to the present. Similar to other studies in urban stream restorations, fish populations will diversify whereas benthic macroinvertebrate populations only improve slightly if at all (Tullos et al. 2006; Sudduth et al. 2011).

A stream assessment study funded by a Tennessee Healthy Watersheds Initiative (THWI) grant investigated the geomorphic and biotic responses from urban stream restoration and evaluated the ECS using the TN SQT V.1 (Schwartz et al. 2020). The study design included three stream categories and four streams per category; they were: urban impaired (UI), urban restored (UR), and ecoregion reference (ER) streams. Results from the study found that the predictability of urban stream functional condition was best determined using a Rapid Geomorphic Assessment (RGA) developed by the USDA National Sedimentation Laboratory and the Rapid Bioassessment Protocols (RBPs) developed by the USEPA (Barbour et al. 1999). Applying the TN SQT V.1, ECS for the UI, UR, and ER streams were: 0.53, 0.55, and 0.71, respectively (summarized below in the following table). The key findings were that the TN SQT V.1 did not differ between UI and UR streams though one restored site on Beaver Creek achieved ecological improvements as noted by a Tennessee Macroinvertebrate Index (TMI) score of 32. ECS for ER streams ranged from 0.69 to 0.75, barely classified as functional per the TN SQT functional condition criteria. Though this study's dataset was limited, it does suggest that the TN SQT V.2 does not appropriately scale a stream functional condition.

ECS	Urban Impaired		Urban Restored		Ecoregion Reference	
	Baker Cr.	0.47	Williams Cr.	0.52	Mill Run	0.69
	Beaver Cr.	0.58	Beaver Cr.	0.59	Indian Cr.	0.70
	Friar Br.	0.58	Friar Br.	0.53	Dry Cr.	0.70
	Third Cr.	0.42	Third Cr.	0.56	Big War Cr.	0.75
Avg.	**0.53**		**0.55**		**0.71**	

2.4 Ecohydraulics Habitat Restoration for Urban Streams

Natural stream morphology can be impacted by increased impervious surface from urbanization, resulting in greater peak flow and runoff volumes (Rhoads 1995). Channelization is a common impact to streams introducing straight, trapezoidal channels to align with land use change, increased flow conveyance for drainage (Rhoads et al 2011). In urban streams, increased runoff from hydromodification and reduction is gravel sediment supply can cause rapid geomorphic adjustments to the channel morphology, typically degrading pool-riffle sequences (Gregory et al. 1994; MacRae 1997; Pizzuto et al. 2000; O'Drisscoll et al. 2010). Degradation is due to the increased flow velocities resulting in erosion of bed and banks and threatens habitat quality. Geomorphological features of streambed and varying flow patterns such as pool-riffle sequences are fundamental to sustaining diverse stream ecosystems (Milan 2013; Biron et al. 2011). The degradation of habitat, water quality and geomorphologic conditions of streams because of channelization and urban hydromodification represent a major concern for stream health. Mitigation efforts via channel restoration apply geomorphological, hydraulic, and ecological principles to bring back modified streams to natural fluvial condition (Rhoads et al. 2011; Schwartz 2016).

Pool-riffle sequence is a bedform commonly found in gravel bed streams with intermediate gradient less than 5%. Pools have a deeper and narrower cross section compared to riffles, the spacing between riffle centers ranges between 5 to 7 bed unit width (Knighton 1998; Keller and Melhorn 1978). To maintain pool-riffle sequence, hydraulics deposit bedload sediment to sustain dynamic equilibrium under 1.5-to-2-year return frequency flow. Mechanisms for sustaining pool-riffle structure are the velocity reversal hypothesis, reach scale helical flow and turbulence scaling. Previous studies observed a flow jet, where the magnitude, shape and location of the jets change according to the discharge and pool depth. Strong jet generates local turbulence, increasing the shear stress and erosion potential. Shallow pools have less vertical turbulence compared to deeper pools that experience stronger vertical turbulence in the shallow part of the cross section (Caamano et al. 2010; Lisle 1987).

Construction of pool-riffle sequence is key for stream restoration designs to successfully support recovery of impaired ecosystems (Emery et al. 2003; Schwartz and Herricks 2005, 2008). However, design criteria for pool-riffle construction and maintenance is limited and needs improvement. Along a stream longitudinal profile, riffles occur at widening channel cross sections, whereas pools occur at narrowing sections (Knighton 1998). For steady flow with a constant discharge, the mass continuity concept is applied, where the cross-section average velocity is a function of the cross-section area. Hence when the cross section is widened, the average velocity is reduced and vice versa (Schwartz et al. 2015; Rhoads 2020). The velocity reversal hypothesis states that at high discharge (e.g., bankfull discharge), the pools experience higher velocity and shear stresses that lead to scouring while at low discharge, riffles have higher velocities and shear stress than pools (Schwartz et al. 2015; Keller and Florsheim 1993). The goal is to create stable riffles. This is accomplished when the flow is decelerated across riffles to prevent scouring because any sediment transported to the pool is likely to be deposited, lowering the riffle elevation (Milan 2013).

Restoration efforts by Schwartz et al. (2015) created pool-riffle sequences in the channel by widening the channel cross section at four locations (riffles) and deepening the pools to create acceleration-deceleration velocity patterns. The study used River2D to examine the change in water depth and velocity caused by widening and deepening the pools. The Beaver Creek stream restoration project by Schwartz et al. (2015) provided some interesting results and new questions to research. Questions include using hydraulics to better design the morphological transitions between riffles and pools, enhanced bank stability by better understanding soil and vegetation properties, and applying a species traits assessment as described in Schwartz (2016). Others have identified the need to improve our understanding of geomorphic processes at riffle-pool structures, a key mesohabitat feature in streams.

From the observations and modeling findings from Schwartz et al. (2015), the primary objective of this project is to describe the relationship between the geometric design parameters of the pool-riffle sequence and the turbulence energy across the channel cross-section for an artificial channel and natural channel using 3D simulation. Geometric design of the pool includes the face slope of the riffle and depth of water across the pool for a widened channel across the riffle and completely straight channel. Energy dissipation should be achieved at the entrance slope of the riffle due to the converging flow in the vertical direction. The ideal geometric design is one that eliminates the thalweg jet across the riffle.

Chapter 3 Methodology

3.1 Stream Restoration Design for Mitigation Credits

Task 1 consisted of the design of an urban stream restoration project generating a prospectus report so that ECSs can be estimated for potential mitigation credits for this proposed restoration project. The design incorporated ecohydraulic procedures as published in Schwartz (2016), which was successfully implemented on Beaver Creek in the Halls Crossing area in 2012 (Schwartz et al. 2015).

For this project, a stream site was selected on a publicly-owned land in Knox County and along a TDOT highway easement. The selection process was jointly decided by Knox County staff, TDOT Paul Purnell, and UTK John Schwartz. Knox County conducted a survey in which six stream sites were identified with severe bank erosion and within public-owned property. The site selected was at Powell, Tennessee on Beaver Creek and a tributary to it. The pre-construction stream assessment was completed including geomorphic and habitat surveys as described in the USEPA EMAP document (Kaufmann et al. 1999), channel stability surveys as described by Simon and Klimetz (2008), and bioassessment survey as described by Barbour et al. (1999). The stream assessment also included all the TN SQT V.1 input parameters among the hydrology, hydraulics, geomorphology, physiochemical, and biology categories. It was completed in 2019 and collected data provided the basic information for the prospectus report.

In this study, the TN SQT V.1 was applied on the selected Beaver Creek Powell site so that the potential mitigation credits could be estimated, representing the functional lift from the proposed restoration project. A revision of the TN SQT V.1 was completed (V.2) with the aim to provide a more cost-effective methodology for determining debits and mitigation credits for TDOT. The TN SQT V.2 is described as part of Task 2 (Section 3.2 below), and ECSs are compared between V.1 and V.2 for the Task 1 project.

3.2. TN SQT V.1 and V.2 Condition Scores Comparison

As noted above in Section 3.1, ESCs for the Beaver Creek stream restoration project was compared between V.1 and V.2 of the TN SQT. Methodology to compute ESCs applied the TN SQT User's Manual for V.1 (TDEC 2019), and a draft user manual for V.2 generated by Schwartz et al. (2024). For this report, the TN STQ V.2 categories and metrics are briefly described. The comparison between the TN SQT V.1 and V.2 is qualitative based on the credits generated for the same site and the proposed restoration project.

3.3. Advances in Ecohydraulics Stream Restoration Design

The objective for Task 3 is to explore potential improvement to the riffle design for stream restoration, a hydrodynamic modeling study was conducted to explore what entrance slope from the pool into the riffle dissipates erosional velocities so that riffle remain stable. Prior research by

Schwartz et al. (2015) found that entrance slope into the riffle was a key design parameter to dissipate excessive erosive energy into that constructed channel unit. In that study's project the slope parameter was identified and the slope entrance steepened in design and construction. However, it was not fully explored how to optimize hydraulic energy loss through the pool-riffle transition. The transition slope has been found to also be critical for ecological integrity and biodiversity (Schwartz and Herricks 2008). Excessive erosive energy in open channel flow can be expressed by turbulence kinetic energy (TKE), but required advanced measurement devices and models to quantify a time-series of velocities in three dimensions (3D). The velocity vector dimensions are: 1) downstream [x], 2) laterally perpendicular to the downstream direction [y], and 3) vertically perpendicular to the downstream direction [z]. Because many urban stream riffles have been removed or degraded, designing a stable riffle is critically important to restoring an urban stream's ecosystem.

The basic study design for this task is to model TKE for different riffle entrance slopes at the pool-riffle transition on a simulated stream channel. The FLOW3D® model was used to estimate TKE; a commercially available model. FLOW3D® is a three-dimensional computational fluid dynamics (CFD) software that solves open channel flow, free-surface problems. FLOW3D solves Navier-Stokes equation in x, y and z direction for each finite volume cell, applying conservation of mass and momentum concepts. Topo2STL utility in Flow 3D has been used to generate a Stereolithography (STL) file format for the geometry of the simulated channel. Also, Civil 3D was utilized to generate more complex geometry. The original channel geometry was rotated by 51˚ to ensure that the flow is perpendicular to the channel cross section. The surveyed points were normalized to the x-y-z origin (0,0,0) to ensure the geometry lies in the positive quadrant.

3.3.1 Model Set-up for Impaired Channel Pool-Riffle Sequences

An impaired reach on Beaver Creek at Halls Crossing Park was selected to provide the channel morphological template to apply the FLOW3D® model and test the riffle entrance slopes for TKE (Fig. 3-1). Three finite volume meshes were created in FLOW3D, using cell sizes of 0.2 m, 0.25 m and 0.3 m, with resultant mesh size of 0.6, 2 and 3 million, respectively. Further grid independence tests shall be conducted, however for this study a moderate cell size of 0.25 m was used in the rest of experimental simulations. The convergence of the solution is assessed based on the time vs the size of the timestep. When the model reaches a stable computational time, it is considered to have reached convergence. Moreover, the maximum pressure residual and convective volume error plots (percentage of fluid volume lost between inlet and outlet of the domain) against time are taken as additional convergence reference.

Initial FLOW3D® model runs based on the Beaver Creek template as shown in Figure 1, and used to test different boundary conditions to ensure stable simulation with best convergence. Inlet boundary condition was tested for velocity inlet, volumetric flow rate inlet and pressure inlet. The velocity inlet showed the best steady state solution convergence compared to pressure inlet. Thus, a velocity-inlet of 0.4 m/s (x-axis) and -0.4 m/s (y-axis) and continuative outlet in the x-axis were assigned. Initial conditions for velocity and water elevation were assigned to 0.56 m/s and 2.1 m, respectively. The turbulence model technique applied the renormalized group (RNG) theory for the initial simulations. Though for subsequent simulations, the k-epsilon model, a two-equation closure scheme turbulence model was used as it is the turbulence model most commonly applied to these types of studies and reported in published literature (Sturm 2021).

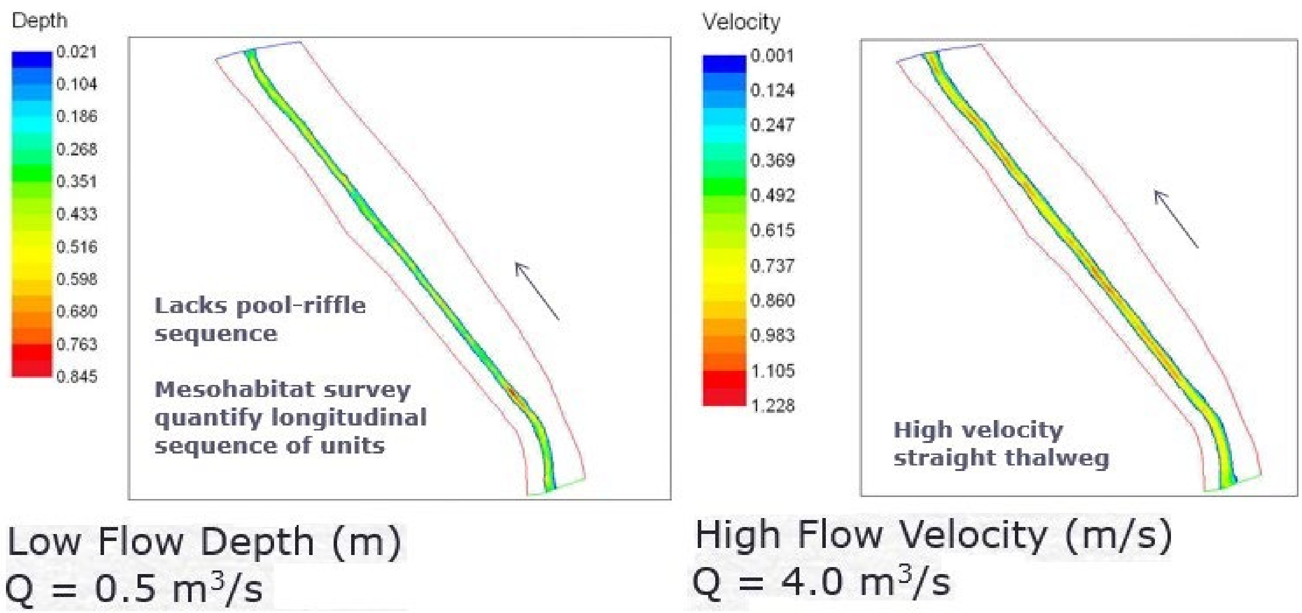
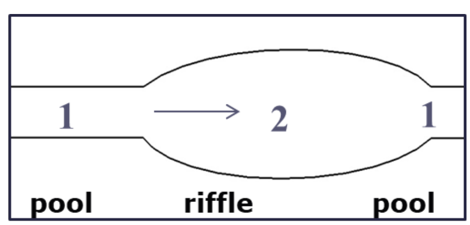


Figure 3-1. Plan view of the Beaver Creek site used as the topo base to develop the simulated channel morphology as show for depth (m) for low-flow 0.5 m^3/s and velocity (m/s) for high-flow 4 m^3/s.

3.3.2 Development of Modeled Artificial Pool-Riffle Sequences

The geomorphic concepts applied for design of a stable riffle included creating high-flow acceleration-deceleration zones along the stream profile by widening the channel width at the constructed riffle locations. By widening the riffle cross-sectional area, high-flow velocities are reduced compared with the pool areas, which creates a gravel depositional zone whereas the pool is in scour condition, maintaining the channel depth. This concept is termed the velocity and/or shear stress reversal hypothesis (Keller and Florsheim 1993; Clifford 1993; Sear 1996). Concepts also include geomorphic equilibrium by satisfying bedload sediment capacity (Copeland et al. 2001). As noted above, the concept under investigation by this study is the role the riffle entrance slope plays in hydraulic energy dissipation for geomorphic stability. Other ecological concepts were applied based on habitat structure and enhancing biodiversity.



From the geomorphic concepts, a proposed reach plan view was created with four constructed riffles, and topographic points entered into the model surface structure. The modeled reach and survey points are shown in Figure 3-2. To investigate a single constructed riffle design, a single artificial pool-riffle sequence model was developed for use with the FLOW3D software. The plan view of the modeled artificial riffle is shown in Figure 3-3, and longitudinal view is shown in Figure 3-4. Model specifications for the different physical parameters applied are listed in Table 3-1. Equations for model analysis are described in Appendix A, and analysis included three model simulations to summarize energy dissipation by examining the model TKE output.

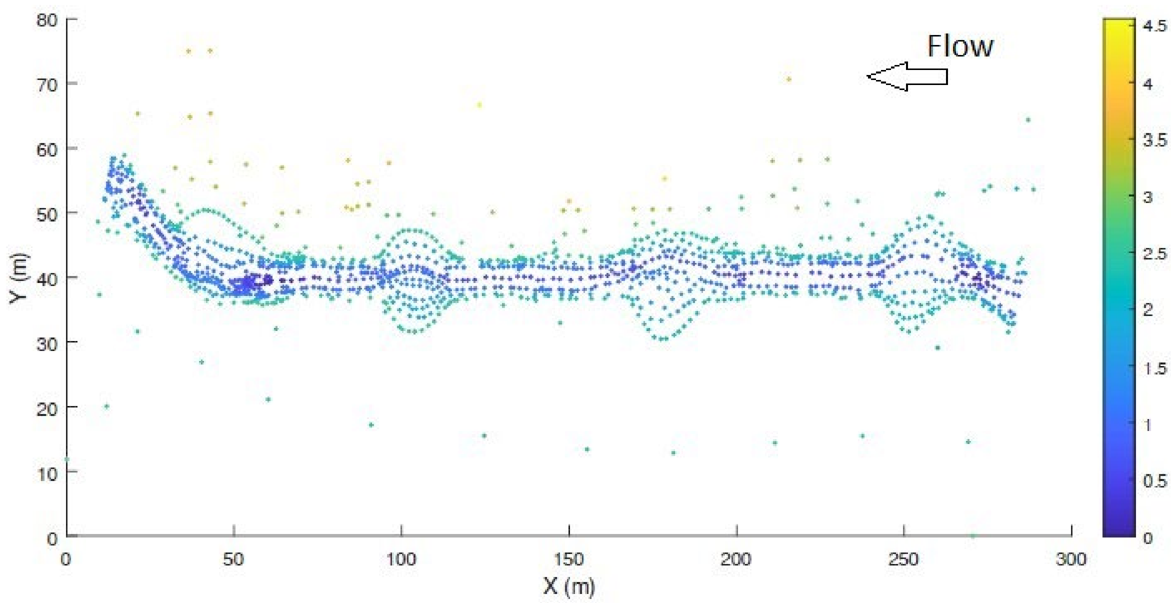


Figure 3-2. Template Elevation survey/model data point for the reach with proposed constructed riffles. Color legend is for elevations in meters based on an arbitrary vertical datum.

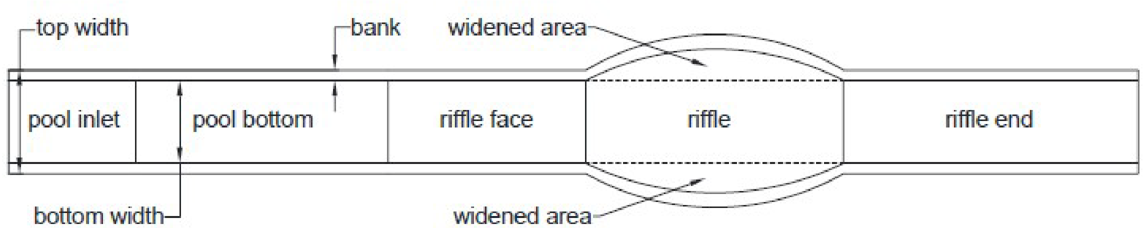


Figure 3-3-3. Plan view of the artificial pool-riffle sequence used for FLOW3D modeling.

The modeled artificial pool-riffle sequence is composed of the pool, riffle and widened area. Since the pool-riffle sequence is based on a basic channel, the bottom of this segment is set as the original point when computing the position and elevation of the other points. The basic channel is determined by the side slope, longitudinal slope, channel height from bottom to top and top width (also the channel unit width). Geometric equations used for modeling and analysis are summarized in Appendix A.

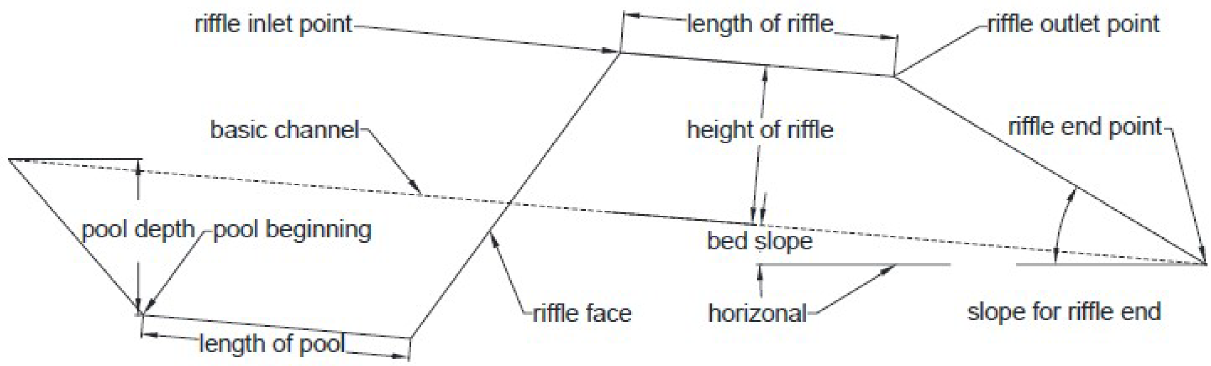


Figure 3-4. Longitudinal view of the artificial pool-riffle sequence used for FLOW3D modeling.

Table 3-1. Hydraulic model components and independent input variables of the impaired Beaver Creek study site. * = to be investigated.

Model Component	Independent Variables	Value	Unit
Channel	Side slope	1	--
	Longitude Slope	0.001	--
	Height	3	m
	Top Width	9	m
Pool	Beginning Position	15	m
	Depth	*	m
	Length	10	m
Riffle	Inlet Position	35	m
	Height	0.5	m
	Length	27	m
	Ending Position	75	m
	End Slope	0.04	--
Riffle Widened Area	Width	24	m
	Side Slope	5.33	--

3.3.3 Geometry and Study Design for Modeled Artificial Pool-Riffle Sequences

The bankfull depth was assumed to be approximately 1.5 m. However, 3 m for channel height was used for generating the geometry to allow enough space for the water wave before the flow becomes steady. This value was determined after several simulation attempts which are described in Chapter 4 Results. According to the model/survey data, the pool-riffle dimensions were summarized in Table 3-1. The plan view of the modeled generated points for the pool-riffle geometry is shown as Figure 3-5.

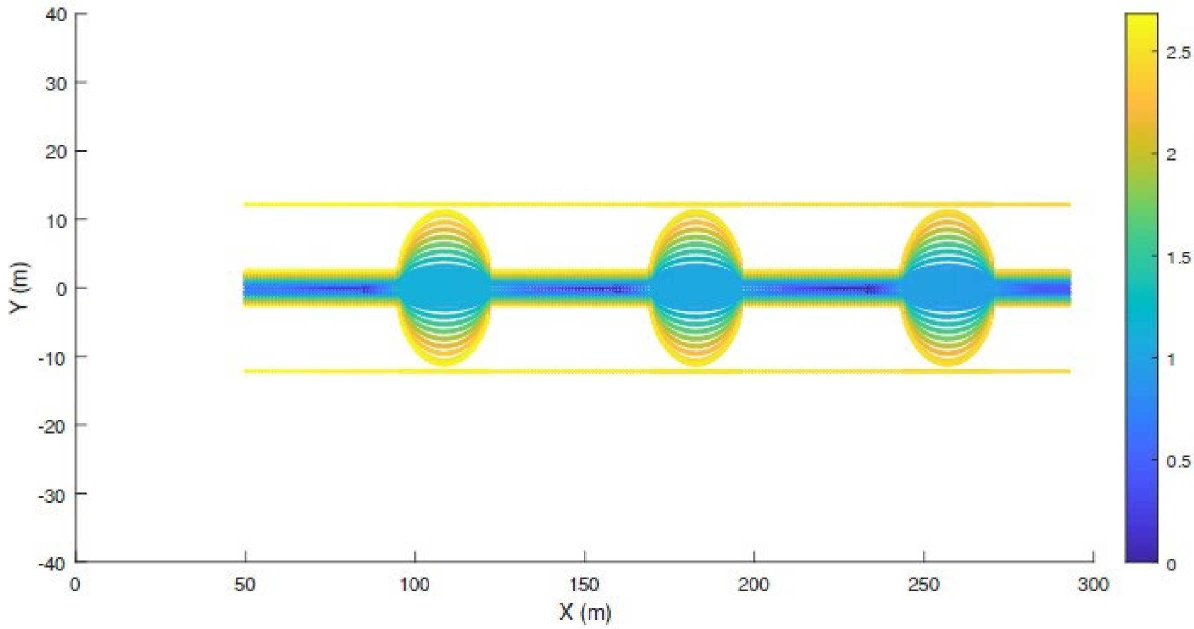


Figure 3-5. Plan view of the idealized artificial pool-riffle sequences for a restoration reach based on model/survey data points, and used in the FLOW3D model. Elevation units in meters.

3.3.4 FLOW3D Model Mesh Size, and Initial and Boundary Conditions

The mesh size is set to 0.2 m considering both the convergence and computing time. And the velocity is found to be the most effective inlet boundary condition for the simulation to reach steady state. The outflow boundary condition is chosen for the outlet for lack of information in that cross section. The upper boundary is set to the pressure to guarantee a free water surface. Other boundaries are set to wall condition to confine the flow region. A summary of the simulation boundary conditions set in the FLOW3D model were:

X_{min} = velocity
X_{max} = outflow
Y_{min}, Y_{max}, Z_{min} = wall
Z_{max} = pressure

The bankfull discharge is assumed to be 4 m^3/s, and the water surface elevation is set to 1.5 m higher than the channel bottom at the channel inlet point. According to the data in Table 3-1, the velocity is computed to be 0.54 m/s.

Chapter 4 Results and Discussion

4.1 Stream Restoration Design for Mitigation Credits

As defined in the methodology (Section 3.1), Task 1 consisted of a preliminary design of an urban stream restoration project generating a prospectus report so that TN SQT V.1 ESCs can be estimated for potential mitigation credits for this proposed restoration project. The selected project site was a main stem reach and tributary of Beaver Creek at Powell, Tennessee. The following sections are a summary of the prospectus report generated for the project, with greater details of the report can be found in Appendix B.

4.1.1 Restoration Project Goals and Objectives

The Beaver Creek at Powell experiences high flood flows on a regular basis causing severe bank erosion. Due to upstream urbanization, the stream channel does not have the capability to carry flood flows, even floods of a one-year return frequency. Due to high shear stresses experienced from these frequent floods, erosion of the stream banks has exposed tree roots throughout the reach and evidence of collapsing bank material (Figure 4-1). In addition, stream bed and mesohabitat diversity is lacking where the channel consists dominantly of a long, deep pool. The primary goal of this restoration design is to protect the banks from further degradation, and improve mesohabitat bedform diversity and microhabitats. The proposed restoration project includes natural armoring of banks, removing trees with exposed roots that have the potential to collapse in the near future, and providing channel structure to promote stability pool-riffle sequences.

Figure 4-1. Photos of main stem Beaver Creek at Powell downstream of Brickyard Road and adjacent to Powell Station Park, Knox County, Tennessee.

4.1.2 Restoration Project Site and Assessment Reaches

The restoration project site is within a developed area of Powell, Tennessee in which the watershed upstream continues to be urbanized. The project site is located within the Lower Clinch River 8-Digit Hydrologic Unit Code (HUC 06010207) and within two HUC-12 subwatersheds (HUC 060102070201 & HUC 060102070202). The catchment area of the watershed draining to the downstream end of the project reach is 53.6 mi^2. The project reach mostly lies within EPA Ecoregion 67f.with a portion in Ecoregion 67i being characterized by southern limestone/dolomite valleys and rolling hills.

The restoration project site was segmented into six reaches. The total main-channel stream length is an 1836 linear foot stretch of Beaver Creek and segmented into three reaches denoted as BC1, BC2, and BC3 (Table 4-1; Figure 4-2). The total compensatory mitigation (CM) area totals 9.6 acres. The upstream end of the project site within the main channel begins at the Brickyard Road Bridge, with coordinates of N Lat 36.02697, W Long -84.02732. The downstream portion ends at the property line of Powell Station Park, owned by Knox County, with coordinates of N Lat 36.02472, W Long -84.03226. The Brickyard Road bridge runs overtop the stream at the beginning of the project reach. There are also two unnamed tributaries (UT1 & UT2) that flow into Beaver Creek within the project site. However, only UT2 is considered in compensatory mitigation because UT1 is currently on private property. UT2 is partially an ephemeral grassy swale (UT2-R1) and partially an intermittent stream (UT2-R2 and UT2-R3). BC and UT2 sites were considered for mitigation credits because they adjoin public property or state road easements.

Table 4-1. Location coordinates, lengths, drainage area for the Beaver Creek project reaches.

Reach ID	Upstream Coordinates		Downstream Coordinates		Stream Length (ft)	Drainage Area (mi^2)
BC1	36.02697	-84.02732	36.02663	-84.02844	349.2	52.56
BC2	36.02663	-84.02844	36.02594	-84.03033	621.5	52.58
BC3	36.02594	-84.03033	36.02484	-84.03235	865.5	53.71
UT2-R1	36.02772	-84.03305	36.02648	-84.03297	440.8	1.07
UT2-R2	36.02648	-84.03297	36.02554	-84.03268	361.8	1.08
UT2-R3	36.02554	-84.02268	36.02491	-84.03218	286.6	1.09

4.1.3 TN SQT V.1 Existing Conditions Scores

Reach BC1 is the upmost reach of the main project channel, beginning at the Brickyard Road bridge. The segment is 349 ft long. The reach is generally a straight, deep pool feature with mostly silt and clay bed material. Sinuosity is very close to a value of 1.0. This reach differs from the other two main stem reaches in that it has fewer riparian large trees. There are no riffles in this reach, so floodplain connectivity and bed form diversity were not able to be calculated in the TN SQT V.1. Downstream Reaches BC2 and BC3 were similar geomorphologically but had large tress in the riparian corridor. However, on the stream side adjacent to the Powell High School and a section downstream by TVA powerlines, the riparian width is < 50 ft in some locations. Reach BC3 has a well-developed side channel but not connected hydrologically to the main channel. Physiochemical data for the reach comes from July-August 2013 TDEC water quality data from station 'BEAVE024.7KN'. This TDEC WQ station had the most current data in closest proximity to the project site. Physiochemical data for this reach, as well as all other reaches on the main channel classify as functioning at-risk. The other functional categories that were calculated, hydrology and geomorphology, also classify as functioning at-risk.

The tributary UT2 is an ephemeral/intermittent stream channel and consists of three segmented reaches. Reach UT2-R1 is an ephemeral grassy swale that receives discharge from W Emory Road and Powell High School and runs through Powell Station Park. There is minimal riparian vegetation, except a few large trees scattered throughout the 441-ft reach. Reach UT2-R2 is 361.9 feet in length and has a coarse-gravel bed. The tributary has a few headcuts that are causing downcutting and increased bank erosion. There are many pieces of large woody debris, and several large in-channel trees that divert flows into the banks. Reach UT2-R1 and UT2-0R2 are ephemeral and scored as a wet-weather conveyance, and not estimated for mitigation credits using the TN SQT V.1. Reach UT2-R3 has a wider buffer area, with a greater number of trees per acre then the two upstream reaches. The reach is 286.6-ft long and has mostly a silt/sand bed. Shallow roots and a lack of root density make this reach highly susceptible to bank erosion. There is evidence of highly eroded banks, with a total of 25.3% of the banks actively eroded. Debris jams have caused disconnections of the tributary's channel, and side channels have formed as a result of these jams. The ECS for UT2-R3 is not functioning as computed by the TN SQT V.1.

Overall, the ECS from the TN SQT V.1 ranged from 0.37 to 0.39 for the three Beaver Creek main stem reach sites, and an ECS of 0.17 for the tributary UT2-R3 reach (Table 4-2). Individual SQT worksheets for each project reach can be found in Appendix B (Figures B.11 through B.46). Because of the low non-functioning ECS, and being below the SQT required functional score of 0.4, these project reaches would only achieve few mitigation credits, and the tributary likely none. A major issue with the TN SQT V.1 is it required riffle structures to obtain bankfull depth and width, thus greatly impacting scoring for the geomorphic parameters. SQT field protocols indicate the need for three stable riffles. Bankfull measures are required for six of the SQT parameters and if bankfull indicators are absent computing an ESC is problematic. Though a qualitative observation, the TN SQT V.1 does not reflect the functional quality of the main stem reaches since it apparently supports aquatic organisms with locals fishing for largemouth bass. Section 4.2 more comprehensively summarizes issues with the TN SQT V.1 based on a working group of practitioners and regulators.

Table 4-2. Summary of TN SQT V.1 ECS and PCS for the six project reaches on Beaver Creek main stem and tributary, and the potential functional lift.

Restoration Reach	Existing Condition Score (ECS)	Proposed Condition Score (ECS)	Functional Lift Credits
BC1	0.37	0.43	0.06
BC2	0.37	0.42	0.05
BC3	0.39	0.44	0.05
UT2-R3	0.17	0.28	0.11

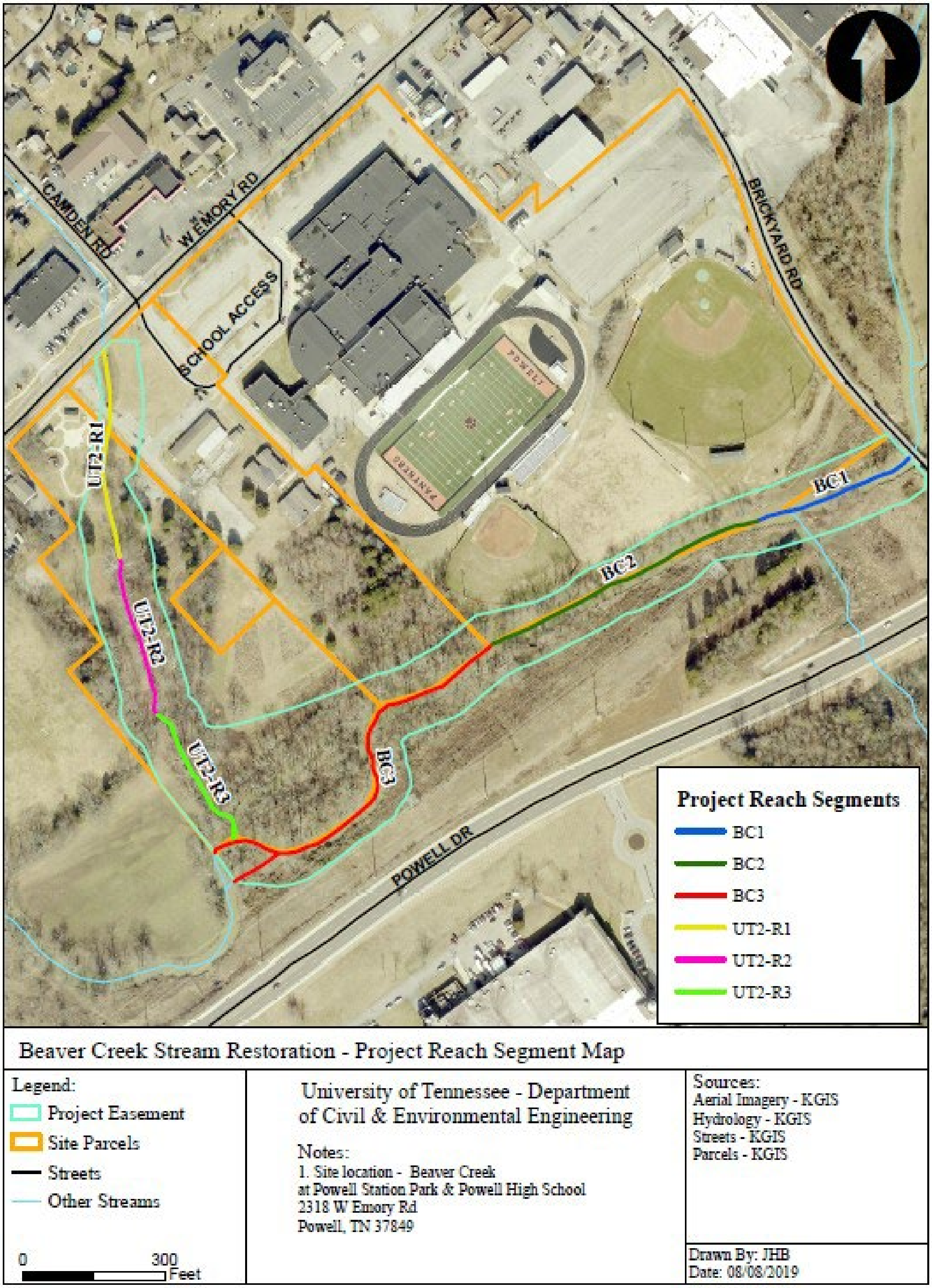


Figure 4-2. Location of Beaver Creek stream restoration six project site reaches (BC1, BC2, BC3, UT2-R1, UT2-R2, and UT2-R3).

4.1.4 Proposed Restoration Project Elements

In general, urban stream restoration for compensatory mitigation credits can be limited by easement constraints, interference with utilities, and upstream sources of pollutants from urbanization. However, there are some opportunities related to bank stabilization, in-stream habitat enhancements, and riparian vegetation plantings, which can improve functional conditions but not to a pristine condition. A full description of the restoration practices proposed for the Beaver Creek project site are in the prospectus report in Appendix B (Section B.6.2). A summary of the proposed restoration practices follows.

Overall, the rationale for this project site selection was due to excessively eroding banks along the main stem Beaver Creek, therefore alleviating this erosion through bank protection measures is a primary focus. Reach BC1 is the most upstream reach of the main channel lacking riparian vegetation, thus large trees will be planted to re-establish the riparian buffer and construct bank protections as eroding stream banks. Reach BC2 has sections with heavily eroded banks. In stream structures will be put in place to protect these banks. Submerged boulders are proposed to be placed at the toe of the bank in eroded areas. Boulders will deflect high stress flows away from the bank. They will also create minor microhabitats that are currently lacking throughout the reach. Rootwads or submerged rock vanes are proposed to be used in areas with extreme erosion. Both options will protect the bank and toe, as well as creating lateral habitat. Reach BC3 has existing features that will be utilized to improve the geomorphology and biology of the reach. Two of the sections with unnatural riffles caused by prior debris jams will be extended laterally and longitudinally. New course materials are proposed to be introduced to strengthen them as natural riffle sequences. Also, stream banks are to be extended in these areas to reduce flows and create more riffle habitat. There are also three side channels that do not become inundated during baseflows. By opening these channels, the stresses during baseflow and moderate-level flooding will also be reduced.

The tributary reaches are excessively eroded contributing large amount of fine sediment to Beaver Creek. Arresting this excessive channel erosion is the primary focus of tributary restoration. Reach UT2-R1 is ephemeral consisting of an established grassy swale that transports water from urbanized areas into a tributary that discharges into Beaver Creek. Reach UT2-R2 in an ephemeral channel with excessive bed and bank with a few headcuts and areas of active, extreme erosion. Through a field assessment applying the Tennessee UT2-R1 andUT2-R2 were scored as wet-weather conveyances therefore TDEC would not provide credit and the ACOE likely will not with the new interpretation of Waters of the US. Therefore, TN SQT assessment scores were not completed for these two reaches. To prevent further downcutting, grade control measures and a step-pool system will be installed. Reach UT2-R3 is disconnected from itself due to an extreme debris jam. A small culvert that was placed within the channel to transport flow caused the debris jam. It is recommended to remove both the culvert and the debris jam to reconnect the tributary. This will improve bank erosion and floodplain connectivity.

4.1.5 Potential Mitigation Credits and Functional feet

The proposed condition scores (PCS) are based on proposed restoration projects on the Beaver Creek main stem and tributary as described above and summarized in Table 4-2. The PSC and functional feet gained, or mitigation credits are summarized in Appendix B per the TN SQT V.1 worksheets (Figures B.17 through B.20). Overall, the PCS from the TN SQT V.1 remained small compared with the ECS. PCS were between 0.42 and 0.44 for the Beaver Creek main stem three reach sites and 0.28 for the tributary reach UT2-R3. In terms of functional feet, mitigation credits are summarized in Table 4-3. These TN SQT V.1 worksheets are also shown in Appendix B (Figures B.21 through B.24).

Very little functional lift credits were achieved from the proposed restoration, which restoration practices are standard and applied widely. The functional lift credits for the four project reaches ranged from 0.05 to 0.11, and in terms of functional feet (FF) the credits ranged from 21 to 259 with the total FF project only providing 342 functional feet of mitigation credits. It is likely this length of functional feet may not be economically feasible although being on public land and not having to purchase conservation easements would assist in reducing the overall project costs.

Although the functional lift or credits gained from the proposed restoration projects are small, completing such a project would benefit the stream by reducing excessive fine sediment currently affecting water quality, and enhancing both riparian and in-stream habitat structure. It appears the TN SQT V.1 does not adequately quantify such improvements, therefore its use in urban stream restoration will be limited. This outcome with the TN SQT V.1 is problematic because Schwartz et al. (2015) found urban stream restoration projects can have significant improvements to stream ecosystems. Issues identified and addressed in a revised TN SQT (TN SQT V.2) are summarized in Section 4.2 below.

Table 4-3. Summary of existing and proposed functional feet (FF), and mitigation credits for the six project reaches on Beaver Creek main stem and tributary.

Project Reach	Mitigation Approach	Existing FF	Proposed FF	Mitigation Credits
BC1	Enhancement	129	150	21
BC2	Restoration	230	261	31
BC3	Restoration	338	597	259
UT2-R3	Enhancement	49	80	32
Total		**746**	**1,088**	**342**

4.2 TN SQT V.1 and V.2 Condition Scores Comparison

4.2.1 Summary Review of TN SQT V.1

The first version of the Tennessee Stream Quantification Tool (TN SQT V.1) and Debit Tool were implemented in 2019. The TN SQT V.1 was a modification of the North Carolina SQT developed by consultants Stream Mechanics and Ecosystem Planning and Restoration (TDEC 2017, 2019a) with majority input from the TDEC, USACE Nashville District Office, and the state IRT. The TN SQT V.1 is a spreadsheet with function-based parameters organized into five functional categories organized by the pyramid framework described in Harmon et al. (2012) consisting of: Hydrology, Hydraulics, Geomorphology, Physiochemical, and Biology (Figure 4-3). Within each category the number of function-based parameters varied widely, where Hydrology has 2 parameters, Hydraulics has 2, Geomorphology has 22, Physiochemical has 4, and Biology has 6 parameters. Measurement methods are defined per parameter and described in TDEC (2018). Per parameter, a field value (or desktop value) is entered and that value related to a performance curve which computes an index score between 0.0 and 1.0. Parameter index scores are averaged per category to obtain a category ECS in a spreadsheet roll-up procedure, followed by averaging each category ECS to roll-up obtaining a total ESC. The total ECS classifies streams as not functioning (0.0 – 0.29), functioning at risk (0.3 – 0.69), and functioning (0.70 – 1.0).

The TN SQT is applied for both debit and credit computations. Prior to an impact, the ECS is multiped by the reach length to obtain a value in terms of existing function feet (EFF). Based on the proposed condition from an impact, the proposed condition score (PCS) in multiplied by an Impact Severity Tier as defined in TDEC (2019b), and multiplied by stream length to obtain proposed functional feet (PFF). State rules specific the minimal PCS is 0.4 even though the field assessment scores may be lower. The difference between EFF and PFF is the debit. For compensatory mitigation credits, the functional lift is the difference between a PCS for the approved stream restoration project and the ECS, and credits computed as FF.

The TN SQT V.1 was issued for public comment in January 2018, and TDEC responses to public comments were published in June 2018. The TN SQT V.1 was fully implemented in 2019 although its performance was never fully tested. As noted in the Problem Statement (Section 1.1) after one year in use by practitioners, TDOT, and others, multiple issues were identified with its performance quantifying functional condition scores (ECS). Thus, in August 2020 under a TDEC-sponsored project, a working group of 8 stream restoration practitioners, 2 mitigation providers, and 8 from the USACE/TDEC regulatory community formed and chaired by Schwartz to identify and summarize the debit-crediting issues with the TN SQT V.1, and make recommendations for a revised version (TN SQT V.2). A summary of the issues identify follow, but it needs to be pointed out this is a collective summary from the working group and does not represent a consensus. Overall, the identified issues were utilized to make the recommendations and guided revisions to the TN SQT V.1

EXISTING CONDITION ASSESSMENT		
Functional Category	**Function-Based Parameters**	**Measurement Method**
Hydrology	Catchment Hydrology	Watershed Land Use Runoff Score
	Reach Runoff	Stormwater Infiltration
Hydraulics	Floodplain Connectivity	Bank Height Ratio Entrenchment Ratio
Geomorphology	Large Woody Debris	Large Woody Debris Index # Pieces
	Lateral Migration	Erosion Rate (ft/yr) Dominant BEHI/NBS Percent Streambank Erosion (%) Percent Armoring (%)
	Riparian Vegetation	Left - Average Diameter at Breast Height (DBH; in) Right - Average DBH (in) Left - Buffer Width (feet) Right - Buffer Width (feet) Left - Tree Density (#/acre) Right - Tree Density (#/acre) Left - Native Herbaceous Cover (%) Right - Native Herbaceous Cover (%) Left - Native Shrub Cover (%) Right - Native Shrub Cover (%)
	Bed Material Characterization	Size Class Pebble Count Analyzer (p-value)
	Bed Form Diversity	Pool Spacing Ratio Pool Depth Ratio Percent Riffle (%) Aggradation Ratio
	Plan Form	Sinuosity
Physicochemical	Bacteria	E. Coli (Cfu/100 mL)
	Organic Enrichment	Percent Nutrient Tolerant Macroinvertebrates (%)
	Nitrogen	Nitrate-Nitrite (mg/L)
	Phosphorus	Total Phosphorus (mg/L)
Biology	Macroinvertebrates	Tennessee Macroinvertebrate Index Percent Clingers (%) Percent EPT - Cheumatopsyche (%) Percent Oligochaeta and Chironomidae (%)
	Fish	Native Fish Score Index Catch per Unit Effort Score

Figure 4-3. TN SQT V.1 functional categories, function-based parameters per category and their measurement method. Full-scale TN SQT V.1 worksheets are shown in Appendix B figures.

To meet the 2008 Mitigation Rule requirements Harman et al. (2012) developed a function-based framework for stream assessments and restoration projects, and structured the framework as a pyramid, hierarchically organized in order from hydrology, hydraulics, geomorphology, physiochemical, and biology (Figure 4-4). This assessment framework incorporated some

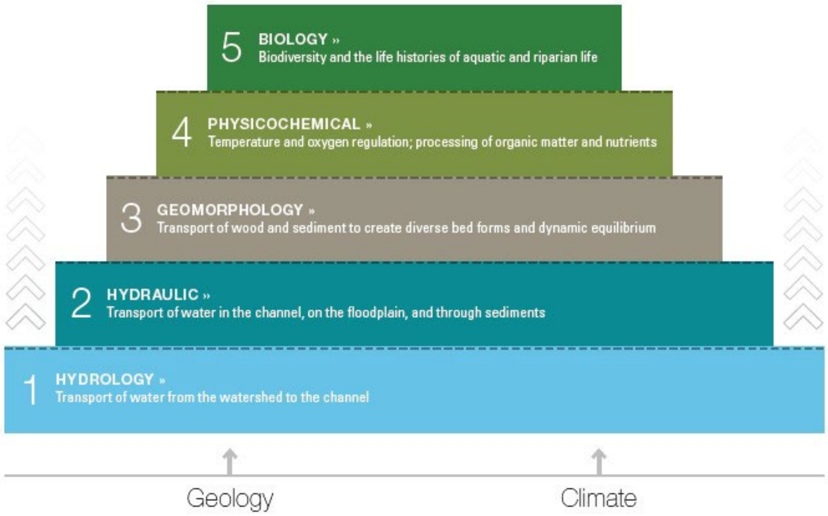


Figure 4-4. Pyramid function-based framework for assessing stream condition (Harman et al. 2012).

elements of the functional categories as published work by Fischenich (2006). Fischenich (2006) is a document produced by the Ecosystem Management and Restoration Research Program of the U.S. Army Engineer Research and Development Center, and included an international committee of scientists, engineers, and practitioners. They summarized five functional categories for assessment stream condition which could be used as guidance for stream restoration and meeting ecological outcomes. The five categories defined 15 key stream and riparian zone functions: 1) system dynamics, 2) hydrologic balance, 3) sediment processes and character, 4) biological support, and 5) chemical processes and pathways.

System Dynamics	Hydrologic Balance	Sediment Processes and Character	Biological Support	Chemical Processes and Pathways
Stream Evolution Processes	Surface Water Storage Processes	Sediment Continuity	Biological Communities and Processes	Water and Soil Quality
Energy Management	Surface / Subsurface Water Exchange	Substrate and Structural Processes	Necessary Habitats for all Life Cycles	Chemical Processes and Nutrient Cycles
Riparian Succession	Hydrodynamic Character	Quality and Quantity of Sediments	Trophic Structures and Processes	Landscape Pathways

As can be observed that the five categories in Fischenich (2006) do not exactly align with the pyramid functional-based framework (PFBF) categories. It was noted by the working group is too simple, and hierarchically liner to be useful for project design. In part, this is due to differences in assessment scale, where parameters within Hydrology and Physiochemical categories function at the watershed-scale, and those in Hydraulics, Geomorphology, and Biology categories function at the reach-scale, the scale restoration projects are implemented. The Physiological category is not hierarchically scaled to watershed system processes. The PFBF becomes a policy tool inferring, restoration projects can be meet some geomorphic assessment criteria. However, mitigation-credit generating risk is associated with the "higher" level functions in the PFBF acknowledging projects will not improve water quality and biology. Stowe et al.

(2023) and others have reported on varied ecological responses to stream restoration relying on Natural Channel Design (NCD) procedures. As noted in Fischenich (2006), stream and riparian ecosystems are complex and parameters are interrelated to reflect overall ecological health (Figure 4-5). An assessment framework should measure ecological outcomes recognizing the process linkages between watersheds and reaches (Meridian Report 2023).

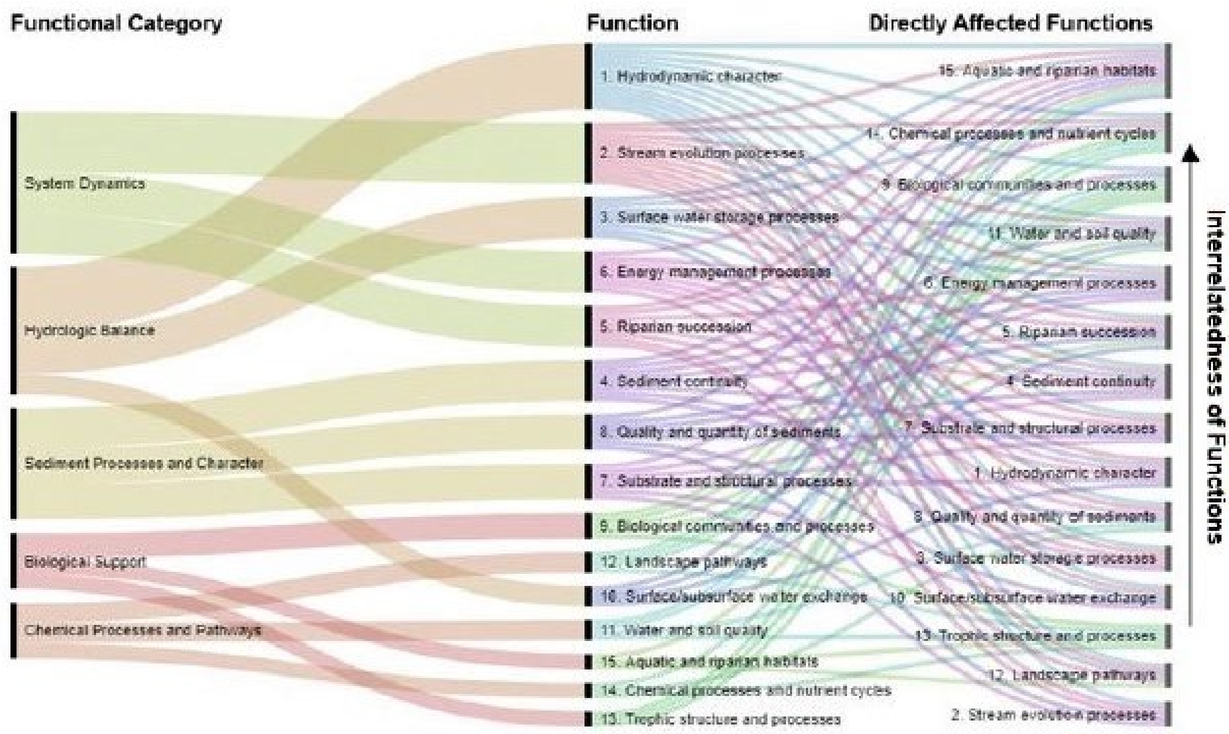


Figure 4-5. Interrelatedness of ecological functions critical to stream and riparian ecosystem health (Fischenich 2006).

Many function-based parameters and measurement methods within the Hydraulic and Geomorphology categories are NCD parameters. Though practitioners commonly use this design methodology, their use in the TN SQT V.1 leads to dictating that design methodology. Parameters in TN SQT V.1 are specific to single-thread channel restoration which limits credit generation for multi-threat channel restoration, stage-zero restoration approaches, and smaller enhancement projects such a bank stabilization. In some landscapes and watersheds NCD works well, however if not appropriate geomorphologically the use of the SQT to maximize credit generation may result to reduced stream ecological health or at a minimum a failed unstable channel. An improved SQT framework would comprehensively identify the causes for impairment to a stream's function capacity and provide credits for targeted objectives. When the SQT provides credit for single-thread channel restoration, causes to impairment may or may not be mitigated. A national group reviewing stream mitigation found similar conclusions in that current SQT-dictated (PFBF) approaches are founded on single-threat channel design creating barriers to alterative design approaches that would improve ecological outcomes (Meridian Report 2023). The Meridian Report also noted that parameters in the current SQTs are primarily form-based parameters, where parameters should be process-based thus would not dictate design methodology.

Practitioners using the TN SQT V.1 worksheet noted that it is overly complex with the number of parameters and in general the use of the worksheet. Though most practitioners were applying the rapid field collection method it was noted the effort to complete the fieldwork and then complete the worksheet was time-consuming and felt it could be simpler and the worksheet more transparent. On small streams and short project reaches the level of worksheet complexity is suggested as unnecessary. Errors in the spreadsheet calculations were noted by the group and will be corrected for the revision. Also noted by the group, the field sheet should be simpler to use and only consist of a single sheet front and back side. The four documents to assist in completing ECS by the TN SQT V.1 were not clear among the Guidance Document (TDEC 2019b) and User Manuals (TDEC 2017, 2018, 2019a). Revisions will include consolidation of user manual information into a single document and a training course to support its use. Improvements suggested for the revised user manual included better guidance on defining reach breaks for multiple project reaches to be scored and ECS computed. It was also noted more guidance is needed where to place cross-sections, and what to do if no riffles are present in a project reach.

As shown in Figure 4-3, the differences in the number of parameters per the five TN SQT V.1 categories inadvertently weight each parameter from the worksheet's roll-up procedure. As described above, parameter index scores are averaged per category to obtain a category ECS, followed by averaging each category ECS to roll-up obtaining a total ESC. The roll-up procedure results in each category weighted as 0.2 of the total ECS which inadvertently weights each parameter. For example, the Geomorphology category has 22 parameters compared to Hydraulics which has 2 therefore each Geomorphology parameter contributes much less than each Hydraulics parameter. In the Hydrology category only one parameter is consistently used, the land use runoff parameter which alone contributed to 20% of the total ECS for a project stream reach. Hypothetically if all 22 Geomorphology parameters are used, each parameter would only contribute 0.9% to the total ECS. However, it was noted that by the working group members that not all parameters are applied although measurement data for the "big four" function-based parameters must be entered. The "big four" function-based parameters are floodplain connectivity, lateral mitigation, riparian vegetation, and bedform diversity. Overall, the roll-up procedure in the TN SQT V.1 results in constraining the total ECS range between 0.5 and 0.7 for larger (3rd order) streams (Schwartz et al. 2020). A 0 or a 1 is not possible because there will always be some functional capacity and generally no stream is pristine. However, the range should better reflect the condensed range of 0.4 - 0.8.

Practitioners identified that several performance standards used to compute parameter ECS are not assessing functional capacity to what would be considered as quality stream conditions. It appears the geomorphic reference streams used to develop performance standards regionally were subjectively selected based on observation, not applying any formal selection criteria. Also, the dataset was limited by the number of sites per ecoregion. To note, there are no state standards for stream geomorphology in contrast to the standards developed for water quality and biological integrity. In addition, several parameter performance standards were not regionalized among Tennessee's ecoregions not accounting for this variation. Ecoregions across Tennessee, east to west vary greatly in their geology, climate, and vegetation. Particularly West Tennessee within Ecoregions 67 and 74 where the landscape terrain is mild compared to the landscapes east of which are forested with steep terrain. Historically, many streams in West Tennessee have been channelized for agriculture. In Middle Tennessee, the Inner Basin Ecoregion is dominated by karst topography which performance relations do not account for these hydrogeological conditions. Besides the need to improve the performance standards regionally, it was noted that performance relationships need to account for differences between large and small streams. The current SQT was not developed for processes within small streams because it was meant as a tool primarily to quantify mitigation credits through NCD procedures. However, the TN SQT is applied for debits quantifying the loss of aquatic resources. Debit calculations are commonly used for impacts on small streams. For TDOT where impacts are typically for short reaches of small streams, thus the TN SQT V.1 appears not to accurately assess stream functional condition for these streams.

Two additional observations with the performance standards were noted by the working group in terms of the condition scoring based on a performance line (y-axis the index score and x-axis the field measurement), and the sensitively to index scores for parameters that apply bankfull indicators. Functional condition as quantified by a linear relationship may not accurately reflect a stream functional capacity, where a range of measured field parameters may be fully functional, functional at risk, or not functional. It was suggested that an index score be based on parameter qualitative descriptors, clearly defined much like how scores are qualified in the Missouri Mitigation Program worksheet. Thus, some function-based parameters may be best scored within an acceptable ranged of field measurements. Addressing this issue for some hydraulic/geomorphic parameters, performance standards applied Rosgen stream type classes. However even though Rosgen stream types were classified for some performance standards, two parameters were noted as still producing unrealized index scores; they were sinuosity and pool spacing ratio.

Identifying bankfull indicators can be subjective to which indicator(s) a practitioner observes and measures. This issue was acknowledged in the USACE Missouri compensatory mitigation procedures and bankfull is not used for their crediting methodology. As noted above, bankfull misidentification can also greatly affect the ECS computed when the performance standard is a linear relationship and the slope of the linear relationship is steep. A small difference in the field measurement entered into the SQT spreadsheet can result in a substantial difference in the ECS. Working group practitioners with extensive experience noted differences in bankfull interpretation with the regulators during permit review, thus this occurrence questions the repeatability of that measure. In the TN SQT V.1 there are seven existing function-based parameters that rely on bankfull width and/or depth (Figure 4-3). Regional curves cannot be used to obtain bankfull width and depth because watershed processes are not transferable, and this method should be deleted in the user manual. Essentially, these two issues do not account for natural variability in stream systems where resilience is needed in restoration design undergoing change (Tullos et al. 2021).

In urban streams, the TN SQT V.1 was found not to adequately account for the functional capacity by the ECS generated nor the functional lift to generate mitigation credits. Observations were documented in a study per the Tennessee Healthy Watershed Initiative Study (Schwartz et al. 2020) where the average-based ECS difference between urban unrestored and restoration was small at about 0.02 (Section 2.3, pg. 6). Because the TN SQT V.1 favors crediting single-thread channels of some linear length (> 1500 feet), it is problematic to find that length where a conservation easement can be obtained. In addition to stream length there is a higher probability that infrastructure, i.e., buildings and utilities can create urban restoration constrains. In general, restoration projects in urban streams may not economically feasible for mitigation bankers and in-lieu fee programs. There are opportunities to enhance stream ecosystems with smaller projects, and those stream reaches with adjacent public properties so conservation easements can be obtained without cost. A revision to the TN SQT V.1 should accommodate smaller enhancement projects, i.e., bank stability and stormwater erosion controls through an appropriate suite of function-based parameters. Such a revision would promote permittee-responsible mitigation for short reaches of aquatic resource loss, commonly encountered by TDOT projects.

In previously altered channels or those undergoing rapid morphological changes from watershed hydromodification, assessing function-based parameters that rely on identifying bankfull indicators in the TN SQT V.1 can be problematic. Because the hydrology in urban watersheds is not stationarity, bankfull indicators are changing over time. Conceptually, bankfull measures are to represent stream channels in dynamic equilibrium therefore in streams with non-stationarity watershed hydrology these indicators do not represent a geomorphic equilibrium. Bankfull indicators may exist but are not long-term indicators of channel flow and sediment transport capacity (Simon et al. 2007; Rhoads 2020). It was noted that in urban streams, finding "stable" riffles and bankfull indicators to measure bankfull width and depth may be difficult. Finding bankfull indicators are also difficult to locate in highly altered channels such as those channelized in West Tennessee or where a stream was relocated years ago for a highway. These are engineered channels thus natural bankfull indictors do not exist, and performance standards not applicable. The current TDEC (2018) User Manual specifies locating three stable riffles to take bankfull measures, though in many cases there is less than three if not absent at all. When riffles are not present, use of other bankfull indicators are highly subjective. Regional curves are not a substitute for the lack of field-based bankfull indicators. Practitioners noted that the policy requirement that all "big four" parameters must be measured and applied in the SQT spreadsheet (noted above in this Section), most of which require bankfull measures, also limits implementing mitigation projects in urban streams. Thus, it was recommended that alternative function-based parameters be developed for a TN SQT V.1 revision. Many modern models such as hydrology and hydraulics (H&H) and bank erosion (BSTEM) models, other assessment tools, and databases are available to support parameter development so that bankfull indicators are not needed, such as USGS StreamStats to obtain flow capacity and channel cross-section dimensions.

Physical habitat is not directly incorporated into the TN SQT V.1, but indirectly assumed to be included per several function-based parameters in the Geomorphology functional category (Figure 4-3). The functional categories by Fischenich (2006) included physical habitat parameters in the Biological Support category (Figure 4-5). Much literature supports that physical habitat structure is key to ecological recovery, particularly when the species traits of the aquatic community is concerned during the design of stream restoration projects (Schwartz 2016). NCD is a geomorphic procedure to stabilize the channel and indirectly assumes habitat is improved through that design procedure. However, it does rely on the assumption of "built it and they will come" but it may not be the case if watershed stressors are not addressed through implementation of a reach-scale restoration project. Aquatic organism migration and recolonization needs to be considered for a proposed project. Practitioners noted that the SQT worksheet should incorporate specific habitat metrics per ecoregion and/or targeted species for recovery. It was also noted that habitat quality index or a selected set of its parameters, based on Barbour et al. (1999), could provide useful functional-based parameters directly measuring habitat quality. Field methods for assessing physical habitat has been well developed with many frameworks by the USEPA, US Forest Service, US Department of Agriculture (USDA) Natural Resources Conservation Service, and many state environmental agencies.

The working group identified some specific issues related to each of the five functional categories and key findings are summarized next. Within the Hydrology category, practitioners only used one parameter, the Land Use Runoff parameter which is a watershed-scale metric and for most restoration projects it can be altered unless entire watersheds are purchased and preserved. In urbanizing watersheds, the score will lower over time. As noted above being the only parameter within a category weights it as 20% of the total ECS, which tends to compress the overall ECS scale between 0.5 and 0.7. The parameter does not work for crediting, and it is more meant for debit calculations to reduce ECS for land use impacted watershed. In an effort to promote hydrology at a reach scale, more aligned with restoration projects, recommendations were to provide a functional capacity measure of floodplain infiltration, and runoff treatment in proximity of a project site. Hence, a revised version of Reach Runoff Stormwater Infiltration parameter that was more user friendly was recommended since the original description of its use was not clear. A floodplain measure was recommended that would promote floodplain protection and restoration applying side channels and wetlands. A metric for baseflow permanence for environmental flow quality was discussed but a measurement method was not concluded.

As noted above, parameters in the Hydraulics and Geomorphology categories that rely on locating bankfull indicators can be problematic in urban streams, previously alternated or engineered channels, and small higher gradient streams. Also noted above, the parameters in the TN SQT V.1 reflect those for a single-thread channel and does not accommodate functional capacity for multi-thread channels. Several parameters that rely on bankfull height or width are sensitive to the computation of a parameter ECS by the deterministic linear relationships in the performance standards. Some parameters rely on a Rosgen stream type, thus indirectly depend on bankfull indicators. The TN SQT V.1 parameters that rely on bankfull measures include: bank height ratio, entrenchment ratio, dominant BEHI/NBS, percent streambank erosion (per BEHI), pool-spacing ratio, pool depth ratio, and aggradation ratio. Practitioners found performance relations and index scores generated with the entrenchment ratio, pool-spacing ratio, and aggradation ratio were not realistic and did not accommodate differences among ecoregions. It was noted not all streams are single thread pool-riffle systems. Index scores for sinuosity and % riffle parameters were also noted as unrealistic mostly due to ecoregion differences, and differences in stream size and channel slope. It was recommended sinuosity be removed from the SQT. The entrenchment ratio is based on floodplain induction per a 50-year flood return frequency though due to the sensitivity to bankfull width is does not consistently represent the potential for floodplain connection. As a parameter meant to measure the functional capacity for floodplain connectivity, it fails to quantify how much connection, how often flooded and for how long.

Indicators of channel stability rely on Lateral Migration and Bed Form Diversity parameters. Performance relations for erosion rates need to be updated for ecoregions and natural channel resistance factors, i.e., soil type and vegetation). In the case of using BEHI/NBS it may not be a measure of systematic channel incision (stability) but rather a localized bank disturbance. Practitioners noted that guidance for selecting what banks to conduct a BEHI was not clearly stated, and there was no guidance on what NBS method to apply (there are seven possible methods that can be used). The percent erosion parameter is dependent on the BEHI measures and may not reflect its functional capacity for the entire reach. In addition to the BEHI field method being subjective, they noted it was time consuming to collect. A process-based method developed at the USDA National Sedimentation Laboratory (NSL) for channel stability assessment could be applied quickly and better represent the processes for rapid morphological adjusting channels. It is founded in science by the channel evolution model (Simon and Downs 1995).

Function-based parameters for riparian vegetation are included in the Geomorphology category although the functional capacity for various measurement parameters serve several multiple functions other than channel stability including water quality and ecological functions. Some issues identified by the SQT review working group involved that riparian buffer width should be scalable to stream size and account for differences among ecoregions. The performance relation to compute an index score for tree density does not match the USACE required performance standards for project credit release. The parameter for average diameter at breast height (DBH) was suggested to be removed because for crediting planted hardwoods take years (10+) to grow to a measurable size. However, the DBH parameter is meant to serve for debit calculations to account for the existing quality of the riparian corridor and encourage preservation of large trees in restoration design and construction. This is another parameter that works for debiting but not mitigation crediting. It was also identified under the current measurement methodology is time consuming to collect the field data. The parameters for percent native herbaceous cover and shrub cover were suggested to be deleted primarily due to the lack of performance relations relevant to ecoregion and watershed location.

Parameters in the Physiochemical category were rarely used as indicated by the practitioners because its functional capacity is dependent on watershed-scale land use activities which are not influenced by reach-scale restoration activities. A parameter for in-stream fine sediment is not included in the TN SQT V.1 but it is one parameter that could be improved by restoration practices to stabilize channel and reduce bed and bank erosion. Water quality varies over seasons and flow stages thus a single grab sample cannot accurately characterize the physiochemical functional capacity of a stream reach. This left with the question to how many samples are required to make an accurate measure of water quality for a project site. Only one parameter currently in the TN SQT V.1 may be improved through reach-scale restoration practices is *E. coli* bacteria by fencing out livestock from near the stream. It was suggested that Physiochemical category parameters be removed or made optional. Biology category parameters co-relate to Physiochemical parameters, where the Tennessee Macroinvertebrate Index (TMI) scores measure the impact of water quality of biological integrity (Barbour et al. 1999). The group suggested merging the Biology and Physiochemical category parameters. Practitioners also noted that the performance relations for TMI scores do not align with the TDEC reference standards where a TMI of 32 by statures is full supporting but the TN SQT V.1 only provided an index score (ECS) of 0.5 as functioning at risk. Also noted was the TMI performance relations needed to be better regionalized across the state's ecoregions. The parameters for fish needed further examination because the performance relations needed more data to support the computation of index scores.

Practitioners noted several policy related issues with the TN SQT V.1, not all listed in this summary but key issues are included below. They did recognize the need to quantify functional lift from mitigation projects noting any assessment framework is an improvement over the previously applied ratio credit method used by the IRT. However, assessment methods and quantification of functional capacity should be more flexible to account for fundamental differences in streams varying among physiographic provinces and watershed location. To main objective for restoration from a statutory framework is based on the CWA's directive to protect the physical, chemical, biological resources of the nation's waterways. Therefore, a successful mitigation project would be one where a §303d listed stream reach can be delisted after restoration. Practitioners noted a substantial reduction in credit availability and credit costs provided by the TN SQT V.1 compared to the previous applied ratio method. Suggestions were a simpler method could be used that would lessen disputes during permitting, particularly noted around the identification of bankfull indicators and its measures. It was noted that the current default index scores for parameters, particularly the “big four” parameters prevented project feasibility in urban streams and other highly degraded channels. The default index score of 0.8 for an unmeasured (or unmeasurable) parameters and total ECS are unrealistic and arbitrary, and should be lowered to 0.7. The ECS lower limit of 0.4 should be removed and allow the SQT to estimate the ECS based on its suite of function-based parameters. Both the default ESC of 0.4 and 0.8 are not scientifically justified. It was also suggested that the TN SQT should credit land protection/preservation. The current TN SQT V.1 incentivizes mitigation projects in small rural streams and should support credit generation in local stream enhancement projects particularity in urban streams were impacts are occurring from land development. Overall, the regulatory community wanted to ensure any SQT revisions work for both crediting and debiting, and the basic currency does not change.

4.2.2 Draft Revisions: TN SQT V.2

A final draft revision of the TN SQT V.2 was completed in April 2023, and a pilot training given in August 2023 including participates from TDEC, USACE (Nashville and Memphis district offices), and TDOT. Please note the draft TN SQT V.2 presented here within has not gone through the public hearing process thus could be subject to minor changes. A comprehensive user manual is under construction and once completed it will be open for public comment. In general, the revisions included:

- A reduction in the total number of parameters measured and scored, with the goal of reducing the time to complete a site SQT ECS score.
- Reworked the arrangement of the functional categories, and aimed that each would have a similar number of parameters not to weight any one category in the worksheet roll-up procedure. This rearrangement results in two Geomorphology categories, and combining Physiochemical and Biology categories into one: Water Quality/Biology (Figure 4-6).
- Promoted the restoration of floodplains and enhanced floodplain infiltration.
- Addressed the issues of determining bankfull indictors in the field, by removing most parameters that rely on bankfull measures and providing functional capacity alternatives for some parameters.
- Parameter performance relations (reference standards) were updated for those that vary regionally to better reflect ecoregions differences.
- Simplified field datasheet into a single form, and the spreadsheet entry aligns with field datasheet with calculations more efficient. Reporting is simplified.
- In general, migration credit “currency” was not substantially different the between the original and proposed SQTs.

A summary list of function-based parameters per five functional categories are presented in Table 4.4. The categories are: Hydrology, Hydraulics, Geomorphology I (Large Woody Debris and Riparian Corridor), Geomorphology II (Channel Stability and Physical Habitat), and Water Quality/Biology. Table 4.4 includes a selection guide to whether a parameter metric is always

Table 4-4. Functional categories, parameters, and measurement metrics for TN SQT V,2 including the index value weights per parameter.

Functional Category	Parameter	Metric	Selection Guide	Index Value	Parameter Score	Category Score
Hydrology	Catchment Hydrology	Watershed LUR score	always	0.067	0.067	0.2
	Reach Runoff	Stormwater Infiltration	always	0.067	0.067	
	Floodplain Storage	Infiltration Potential	always	0.067	0.067	
Hydraulics	Floodplain Connectivity	Bank-Height Ratio	bankfull available	0.1	0.2	0.2
		Entrenchment Ratio	bankfull available	0.1		
		Aggradation Ratio	bankfull available (optiona	(0.067)		
		Floodplain Inundation Freq	bankfull not available	0.1	0.2	
		Channel Incision (shear stress ratio)	bankfull not available	0.1		
Geomorphology I	Large Woody Debris	Large Woody Debris (LWD)	always	0.1	0.1	0.2
	Riparian Corridor	Buffer Width	always	0.025	0.1	
		Canopy Cover	always	0.025		
		% Invasive Woody Species	always	0.025		
		Average DBH	always	0.025		
Geomorphology II	Channel Stability	% Streambank Erosion	always	0.033	0.1	0.2
		% Streambank Armoring	always	0.033		
		Rapid Geomorphic Assessment	always	0.033		
	Physical Habitat	Wolman Pebble Count	always	0.025 (bf), 0.033 (nbf)	0.1	
		% Riffle	always	0.025 (bf), 0.033 (nbf)		
		Pool-Pool Spacing Ratio	always (alt NBF method)	0.025 (bf), 0.033 (nbf)		
		Pool Depth Ratio	bankfull available	0.025		
Biology / Water Quality	Biology	Tennessee Macroinvertebrate Index	always, unless TMI submetrics option chosen	0.2 or 0.1	0.2 or 0.1	0.2
		% Clingers	TMI submetrics option	0.2 or 0.1		
		% EPT - Chuematopsyche				
		% Oligo. & Chironom.				
	Water Quality	% Nutrient Tolerant macro	WQ option		0.1	
		Mean Nitrate-Nitrite				
		Mean Total Phosphorous				
		Geomean E. coli				

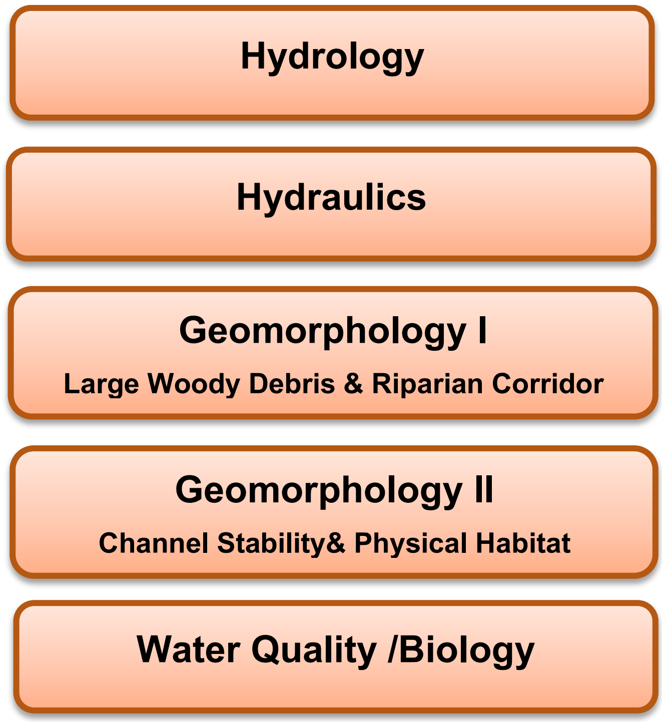


Figure 4-6. Functional categories for the TN SQT V.2, constituting the revised draft SQT framework.

required or whether it is optional. It also defines an index weight per parameter and functional category. Functional statements/attributes for functional parameters are summarized in Table 4.5.

A summary of the functional category and parameter changes follow and organized as shown in Figure 4-6 and listed in Table 4.4. Within the Hydrology category now consists of three desktop parameters so that the Land Use Runoff parameter is not the only parameter applied for this category. The Reach Runoff Stormwater Infiltration parameter was in V.1 but not used in part due to poor guidelines on its use. Procedures for its use has been updated, and the revised measurement protocols will be favorable for small urban watersheds. A new parameter, Floodplain Storage Infiltration Potential provides credit to streams with floodplains and this parameter support preservation and restoration of floodplains. Overall, promoting floodplain infiltration is the one process than can be enhanced at the reach scale. The Hydraulics category retains the two V.1 parameters that require bankfull measures, and in V.2 two alternative parameters are provided that do not require bankfull measures but retain the same measure of functional capacity attributes. A user of the TN SQT V.2 selects the bankfull metrics unless well-defined bankfull indicators are unavailable or watershed conditions will lead to long-term shifts in hydraulics and sediment transport where present indicators are not stable.

Geomorphology is divided into two functional categories where Geomorphology I consist of Large Woody Debris and Riparian Corridor parameters and Geomorphology II consists of Channel Stability and Physical Habitat parameters. In the Geomorphology I category, the Large Woody

Table 4-5. Summary of functional statements for functional parameters in the draft TN SQT V.2.

Functional Category	Sub-Category / Parameters	Functional Attribute / Functional Statement
Hydrology	▪ Catchment Hydrology ▪ Reach Runoff / Stormwater Infiltration ▪ Floodplain Storage	▪ Watershed scale runoff based on land cover/land use ▪ Enhanced infiltration of surface runoff and WQ improvements ▪ Promote infiltration on floodplains
Hydraulics	<u>Floodplain Connectivity</u> ▪ Bank Height Ratio ▪ Entrenchment Ratio ▪ Floodplain Inundation ▪ Channel Incision ▪ Aggregation Ratio	▪ BF measures of floodplain inundation and channel incision. ▪ NBF measures of floodplain inundation and channel incision. ▪ Excessive sediment deposition, habitat quality.
Geomorphology I	<u>Large Woody Debris</u> <u>Riparian Corridor</u> ▪ Buffer Width ▪ Canopy Cover ▪ Average DBH ▪ % Invasive Woody Sp.	▪ Provides channel structure associated with stream habitat quality ▪ Provides channel bank structural stability and shape for water temperature; provides for riparian habitat quality ▪ Invasive species limit vegetation diversity.
Geomorphology II	<u>Channel Stability</u> ▪ % Streambank Erosion ▪ Rapid Geomorphic Assessment ▪ % Streambank Armoring <u>Physical Habitat</u> ▪ Wolman Pebble Count ▪ % Riffle ▪ Pool Spacing Ratio ▪ Pool Depth Ratio	▪ Degree of bank erosion and rapid channel adjustment both vertical and lateral erosion. ▪ A measure of streambank habitat quality. ▪ Sediment supply/transport and bed sediment for habitat quality maintenance. ▪ Mesohabitat quality for pool habitat units
Biology / Water Quality	<u>Biology</u> ▪ TMI ▪ % Clingers, % EPT – Chuemato., % Oligo. & Chironom. <u>Water Quality</u> ▪ % Nutrient Tolerant MI ▪ NO3-+NO2-, TP ▪ E. coli	▪ Measures of biotic integrity and water quality impairment. ▪ A TMI indicator for excessive nutrients ▪ Direct chemical measure of N and TP. ▪ A measure of fecal pollution.

Debris parameter was simplified to a single measure based on number of pieces. The Riparian Vegetation parameters were reduced to four measures maintaining the original measures for buffer width and average DBH. The original tree density measure was replaced with a canopy cover measure using a densiometer. A new metric was added consisting of a measure of percent (common) invasive woody species. Overall, this revised suite of parameters and measures will reduce the field effort time. In the Geomorphology II category, three measures for channel stability are included with the elimination of the BEHI/NBS measure which was time consuming in the field, and did not represent systematic channel stability but rather local bank erosion. A new process-based metric was included, the Rapid Geomorphic Assessment (RGA) developed at the USDA NSL based on the channel evolution model. An experienced stream assessor can be complete a RGA in the field in about 15 minutes of less depending on the site stream length. The % Streambank Erosion measure was modified to not use BEHI/NBS but rather is a simple measure of % channel with observable bank fluvial erosion and mass failure. Percent armoring remains as its original V.1 measurement procedure. In this Geomorphology II category, four measures for physical habitat are included, three of which are parameters that do not require bankfull measures. They are the Wolman pebble count for bed substrate quality, % riffle, and pool-pool spacing. The Pool Depth Ratio measure requires bankfull but there is an alternative procedure for quantifying it without identification bankfull.

Water Quality/Biology category relates to biotic integrity and indicators of water quality. One only parameter is required, the TMI score, though there is an option to use three of three sub-metrics in the TMI to generate an SQT index score for this category. The performance relations for the TMI were improved to better reflect ecoregion differences. The water quality parameters are optional, but if chosen all much be completed.

4.2.3 Comparison of Mitigation Credits between TN SQT V.1 and V.1

A comparison between the TN SQT V.1 and V.2 was completed for the three main stem reaches on Beaver Creek at Powell (BC1, BC2, and BC3) and the tributary reach UT2-R3. ECS and PCS for these four reaches applying the TN SQT V.2 worksheet are summarized in Table 4.6, and individual worksheets provided in Appendix C. The comparison between the two versions of the TN SQT for the ECS are shown below in Table 4-7.

The ESC for the Beaver Creek project reaches were between 0.46 and 0.53 for the mainstem reaches, and 0.34 for the tributary reach (Table 4-6). The PSC for the Beaver Creek project reaches were between 0.66 and 0.74 for the mainstem reaches and 0.46 for the tributary reach. In terms of functional feet (FF), the total existing FF for the four project reaches was 1,039; and that estimated for the proposed FF was 1,419; thus providing 380 feet of possible mitigation credits. The TN SQT V.1 generated 342 FF of mitigation credits compared to the 380 FF per the TN SQT V.2. The difference was an increase in 38 FF of credits. It appears the TN SQT V.2 may provide some additional FF credits compared to V.1 for small projects on urban streams. However, further assessments and testing of the TN SQT V.2 is suggested since this is a very limited dataset.

Table 4-6. Summary of ECS and PCS existing and proposed functional feet (FF), and mitigation credits for Beaver Creek restoration project reaches applying the proposed draft TN SQT V.2.

Project Reach	ECS	PCS	Existing FF	Proposed FF	Mitigation Credits
BC1	0.46	0.66	160	230	70
BC2	0.52	0.67	323	416	93
BC3	0.53	0.74	459	641	182
UT2-R3	0.34	0.46	97	132	35
Total			**1,039**	**1,419**	**380**

Table 4-7. Existing Condition Scores (ECS) for TN SQT V.1 and V.2, and the comparison between versions for Beaver Creek reaches at Powell, Tennessee.

Site & SQT version	ESC for TN SQT Categories				Site Total ECS
	Hydrology	Hydraulics	Geo-morphology*	Water Quality/ Biology **	
BC1 V.1	0.52	0.00	0.33	0.50	0.37
V.2	0.44	0.50	0.39	0.60	0.46
Difference	-0.08	+0.50	+0.06	+0.10	+0.06
BC2 V.1	0.52	0.00	0.43	0.41	0.37
V.2	0.39	0.36	0.62	0.60	0.52
Difference	-0.13	+0.36	+0.19	+0.19	+0.15
BC3 V.1	0.52	0.00	0.47	0.48	0.39
V.2	0.44	0.35	0.64	0.60	0.53
Difference	-0.08	+0.35	+0.17	+0.12	+0.14
UT2-R3 V.1	0.33	0.00	0.52	---	0.17
V.2	0.18	0.09	0.71	---	0.34
Difference	-0.15	+0.09	+0.19	---	+0.17

* Geomorphology ECS for V.2 is the average between Geomorphology I and II categories.

** V.1 Physiochemical and Biology ECS averaged for the V.2 Water Quality/Biology category.

Exploring the differences between the TN SQT V.1 and V.2 for the total ECS per reach found a general increase of 0.06 - 0.15 for the mainstem sites and an increase of 0.17 for the tributary site applying the revised version of the TN SQT. The Hydrology category with the addition function-based parameter for floodplain storage actually decreased the ESC due to the development in the floodplain. However, if a floodplain remains undeveloped or protected from development this ECS for the Hydrology category would likely increase accounting for greater reach-scale infiltration on the floodplain. In the Hydraulics category for TN SQT V.1 no bankfull indicators are present among the Beaver Creek reaches thus a zero is placed in the worksheet calculator because the two parameters in this category are considered required per the “big four” categories. The TN SQT V.2 allows for a non-bankfull means to measure floodplain connectivity, therefore providing credit for this category. In the case of the Beaver Creek mainstem reaches the increase was substantial between 0.35 and 0.50 accounting for floodplain connectivity that the bankfull parameters are not able to be applied. Within the Geomorphology category, ECS increased for the TN SQT V.2 by 0.06 - 0.19 for the study reaches. The difference in this case in that the TN SQT V.2 provides greater weight to riparian vegetation and for these reach sites there is good vegetation on one side of the stream. The combined Physiochemical (Water Quality) and Biology category also showed an increase in ECS with the TN SQT V.2 for the mainstem reaches between 0.10 and 0.19. It is likely from the TMI score that was estimated since the water quality scores applied were the same with the same performance relations. As noted above, overall it appears that V.2 provides some additional credits for urban stream functional conditions.

Because the four project reaches in Beaver Creek constitute a small dataset, though meets the objectives of this study, a greater exploration of comparing TN SQT V.1 and V.2 was undertaken (Figure 4-7). In general, this assessment found that ECS for the TN SQT V.1 and V.2 were similar for stream reaches with higher functional capacity. For reaches with lower functional capacity (ECS < 0.6), the TN SQT V.2 appears to provide a greater ECS than the TN SQT V.1. This finding is consistent with what was found for the assessment of the Beaver Creek project reaches, an urban stream with generally lower functional capacity.

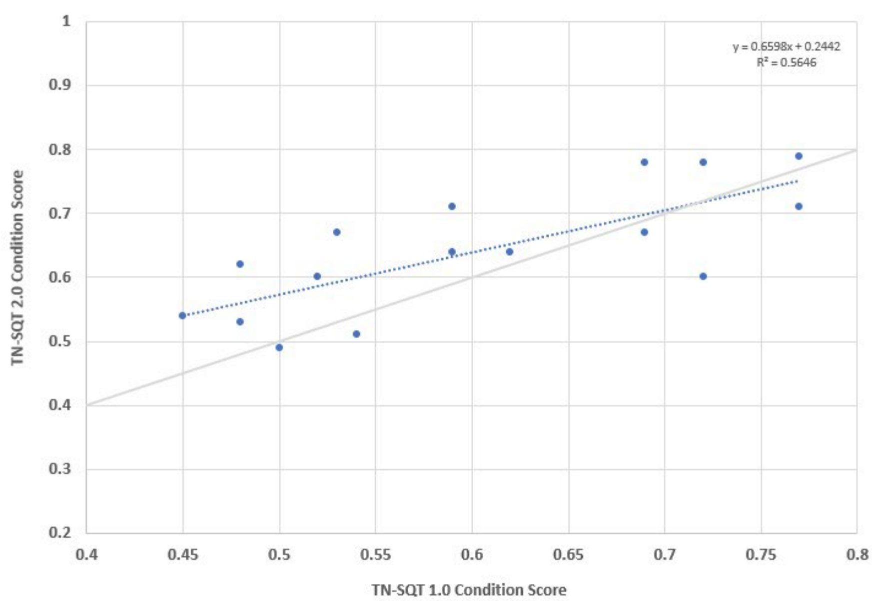


Figure 4-7. Comparing existing Condition Scores (ECS) between the TN SQT V.1 and draft V.2 for 15 sites in East and Middle Tennessee.

4.3 Advances in Ecohydraulics Stream Restoration Design

Model development conducted in the FLOW3D model included three incremental steps to address the study objectives for improving restoration design of the pool-riffle transition in a stream. Results of the model development, model outcomes, and a summary follow.

4.3.1 FLOW3D Model Development and Outcomes

The velocity of the boundary condition for the simulations in the initial modeling attempt (Attempt 1) was 1 m/s and physical characterizes summarized in Table 4-8. There are four simulations completed in Attempt 1. However, when the simulation for 0.5 m pool depth was running, the downstream channel was found submerged in some simulations because the geometry used 2 m as the channel height. Because of the usage of "overwrite" option when running new corrected simulations based on the same geometries, only the results for depth of 0.1m and 0.3m were left.

Results from the modeling Attempt 1 simulations are shown in Figure 4-8 where the x-velocity of the flows in the cross section at the inlet of the three riffles in the column order. It could be seen that the maximum x-velocity when pool depth is 0.1m is higher than that when pool depth is 0.3 m. It could be inferred that the deeper the pool is, the more strongly the water jet is dissipated. However, the determination of the relation between flow depth and pool depth needs the support of further data process because the y axes are not of the same scale. Figure 4-9 shows the longitudinal view of the turbulence kinetic energy and x velocity. The turbulence kinetic energy was obviously higher in the region where the water surface was decreasing.

Results from the modeling Attempt 2 is a set of further attempts based on Attempt 1 simulations. In Attempt 1, FLOW3D software was found to align the lowest and rightest points of the geometry to the origin at the z and y axis automatically. As a result, the geometries in this set are adjusted by Z-transformation to place the bottom of the channel inlet at the same elevation, 5 m. The water surface and x velocity for the boundary and initial condition are set to 6.6 m and 0.54 m/s, respectively. This set consists of four simulations. The pool depths and corresponding mesh parameters used for the simulations are shown in Table 4-9.

The geometries for these simulations were also generated with channel height of 2 m. The Z_{max} was set to 6.8 to avoid the water submerging the channel. However, 6.8 m is just one mesh size higher than the initial water surface elevation, leading the water filled all out the flow region

Table 4-8. Model input parameters for Attempt 1 simulations.

Pool depth (m)	Pool Exit Slope	Water Surface Elevation (m)	Z_{min} (m)	Z_{max} (m)
0.1	0.069	6.7	4.9	7.2
0.3	0.079	6.9	5.0	7.4

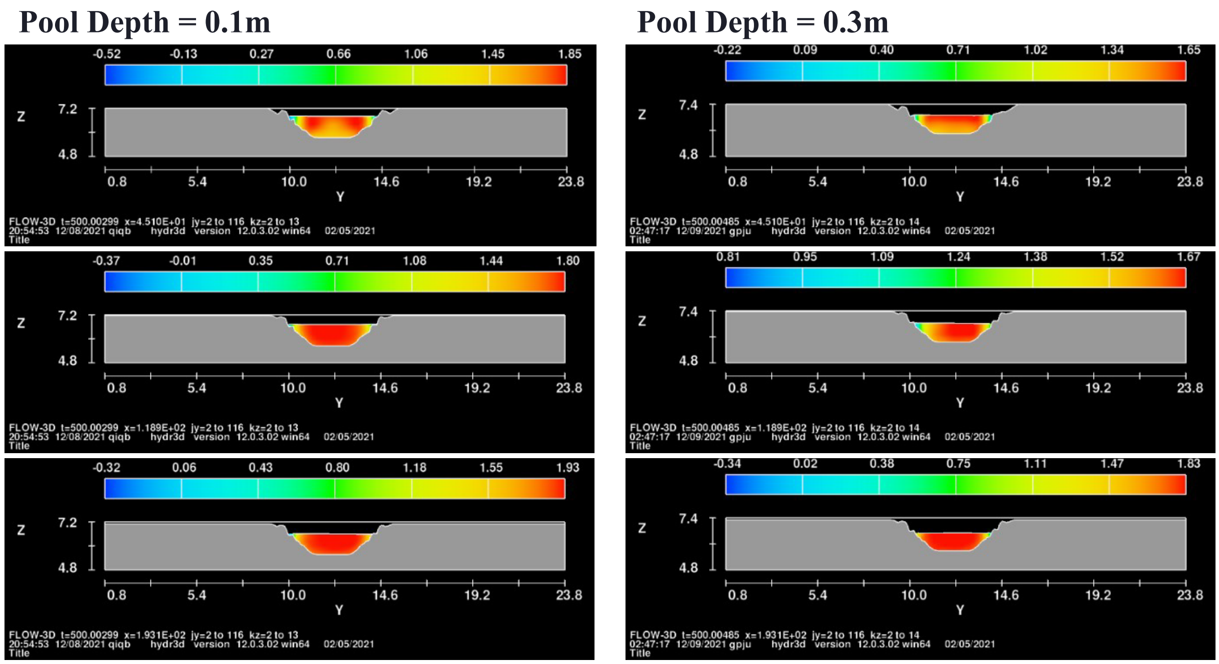


Figure 4-8. FLOW3D model output for the x velocity at the entrance of the first riffle (x = 45.1 m, 118.9 m and 193.1 m) for Attempt 1 simulations.

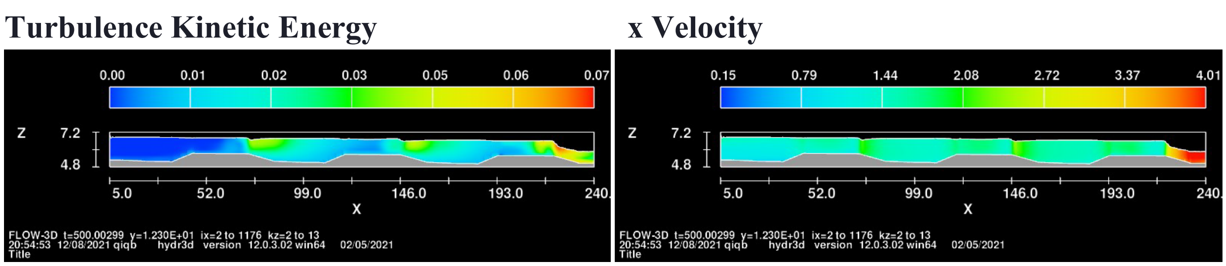


Figure 4-9. The FLOW3D model output of turbulence kinetic energy and x velocity for Attempt 1 simulations.

Table 4-9. Model input parameters for Attempt 2 simulations.

Pool depth (m)	Pool Exit Slope	Z Transformation (m)	Z_{min} (m)	Z_{max} (m)
0.1	0.069	-0.383	4.4	6.8
0.2	0.089	-0.583	4.2	6.8
0.7	0.129	-0.983	3.8	6.8
1.0	0.149	-1.183	3.6	6.8

when simulating. Figure 4-10 shows the x velocities at the cross section of the three riffle inlets. The results at the first riffle appear reasonable and is similar as the results in Attempt 1 simulations. The Attempt 2 simulation results became unstable after the water goes through the first riffle because the water jet disappears in the second and third riffle. Therefore, only the max velocity and water jet area are compared in Figure 4-11. The water jet area is calculated as the area where the velocity is higher than 90% of the max water velocity. However, for the lack of data point and the susceptible flow boundary condition, the relation between the max x velocity and pool depth is still not clear. So, this result is the relation between water jet area and pool depth.

Riffle 1 (x = 45.1m)

Riffle 2 (x = 118.9m)

Riffle 3 (x = 193.1m)

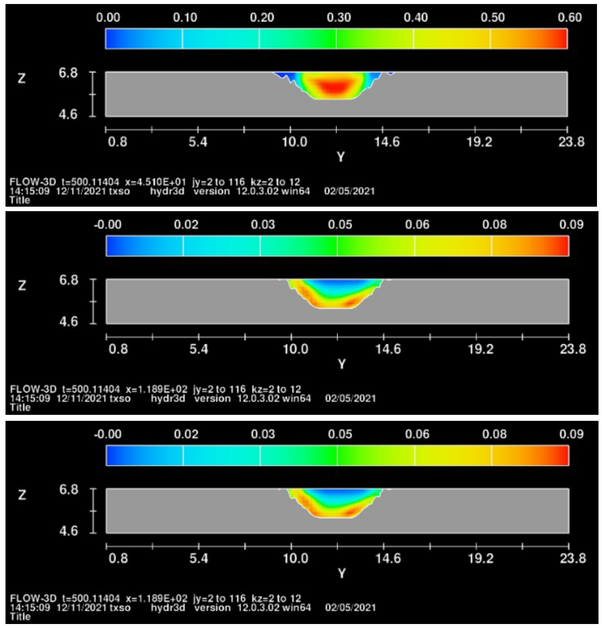


Figure 4-10. FLOW3D model output for x velocity at three riffle inlets for 0.1 m depth for Attempt 2 simulations.

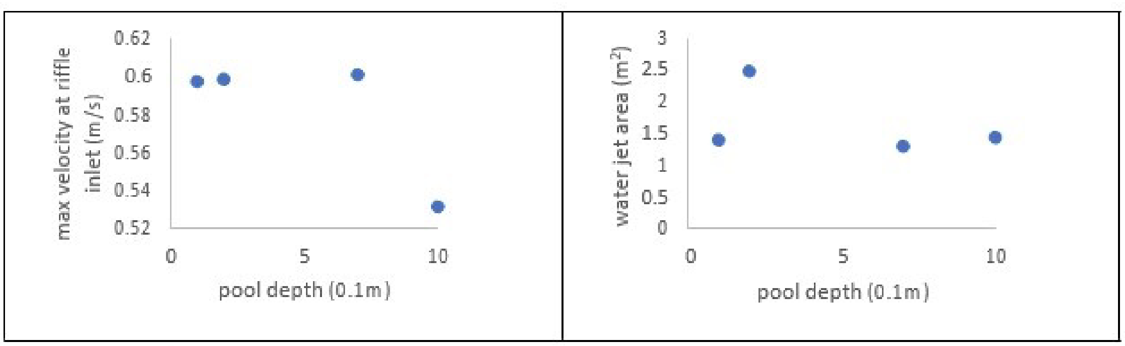


Figure 4-11. FLOW3D model output for max x velocity and flow jet area for different pool depths (in tenths of meters) for Attempt 2 simulations.

Once the mesh size is finalized, the distance between the min and max boundary in the same direction (x, y, or z) of the mesh could only be the integer times of the mesh size, or the FLOW3D software would adjust the location of the boundary. Correcting all the model errors mentioned above, new simulations were completed as Attempt 3 simulations. Once the mesh size is settled, the distance between the min and max boundary in the same direction (x, y, or z) of the mesh could only be the integer times of the mesh size, or the software would adjust the location of the boundary. Correcting all the flaws mentioned above, new simulations for Attempt 3 were initiated and modeled parameters for these simulations are in Tables 4-10.

Table 4-10. Model input parameters for Attempt 3 simulations.

Pool depth (m)	Pool Exit Slope	Z Transformation (m)	Z_{min} (m)
0.1	0.049	-0.243	4.6
0.2	0.069	-0.383	4.4
0.7	0.089	-0.583	4.2
0.6	0.109	-0.783	4.0
0.8	0.129	-0.983	3.8
1.0	0.149	-1.183	3.6

For Attempt 3 simulations, the max and mean velocity at the riffle entrance are shown in Figure 4-12. The mean velocity maintains the same trend with the max velocity. However, the velocities do not show a conspicuously decreasing trend. A potential increasing trend may exist among the water jet areas with the increasing of pool depth. The velocity of the 0.4m depth is higher than the others because the turbulence model for this simulation is different from the others.

For turbulence modeling closure, the RNG model was used in this simulation, while k-e model was used for the others. This result also leads to the outlier of the water jet area. The turbulence energy dissipation was integrated along the pool exit and shown in Figure 4-13. The dissipations show an increasing trend with the increase of the pool depth. However, the total dissipation when pool depth is 0.2 m was obviously lower than the others possibly because the flow has not become steady until the simulation completed.

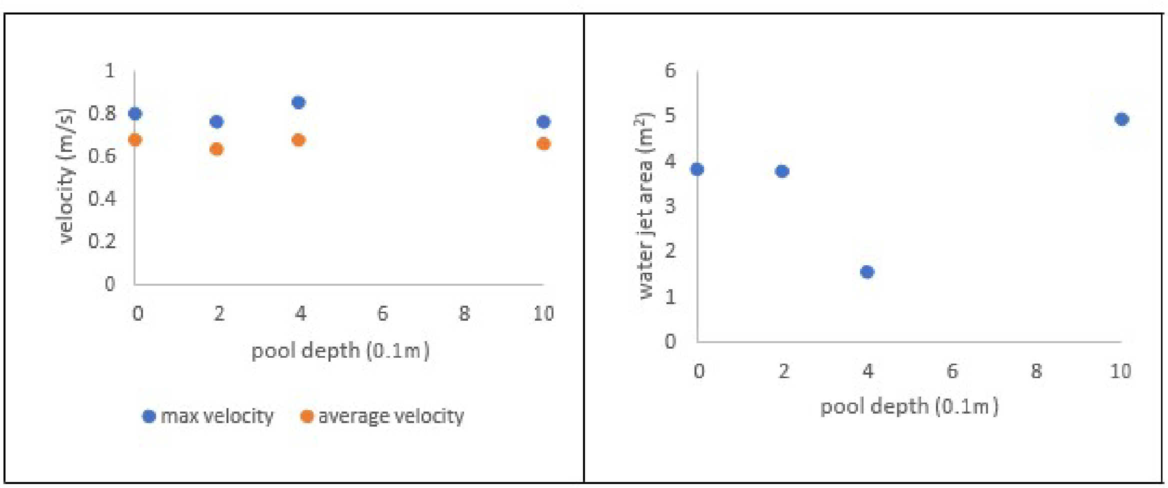


Figure 4-12. FLOW3D Attempt 3 model output for max and mean velocities at Riffle 1 entrance.

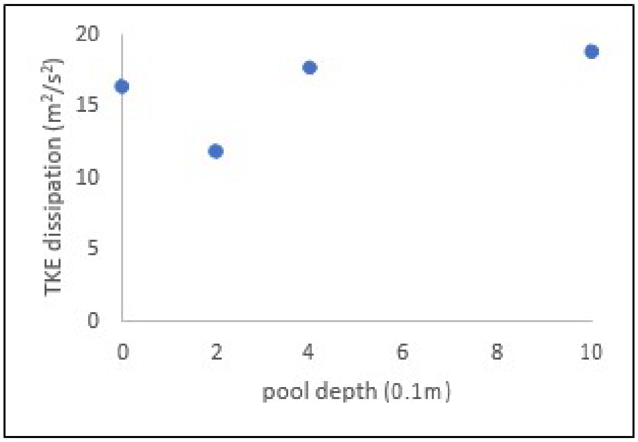


Figure 4-13. FLOW3D model output for TKE at Pool 1 exit for pool depths (in tenths of meters) for Attempt 3 simulations.

4.3.2 Summary of FLOW3D Model Outcomes

Overall, the 3D CFD simulations using the FLOW3D® model was used to investigate the relations between pool depth and riffle hydraulic characteristics to assess energy dissipation at the riffle entrance slope. The basic concept is the riffle design of greater energy dissipation at this channel longitudinal location would lead to a more stable riffle bed structure. Though this modeling experiment was to explore proof of concept, useful information was generated. Results found that for low-flow the velocities across the riffle cross-section were uniform however its magnitude decreased for increased pool depths immediately upstream of the riffle. TKE was greatest at the riffle entrance indicating greater energy dissipation and collocated with velocity deceleration. TKE was greatest at the water surface indicating turbulence scaling in the upward vertical direction from the bed boundary; this observation is consistent with hydraulic turbulence concepts described by Yalin (1992). The first riffle in the sequence of three channel units was observed with the greatest velocity and was likely an artifact of the modeling where uniform turbulent boundary conditions that were not quite attained. At high flows, downstream-directed velocities were greatest near the channel bed at the riffle entrance slope indicating flow acceleration along the channel slope bed entering the riffle. This observation is also explained by Yalin (1992) as vertical differential flow acceleration pathway convergence initiates a turbulence bursting cycle, and reported by others (Tamurrino and Gullliver 1999; Lawless and Robert 2002; Roy et al. 2004).

Model results found that a pool depth of 1 m before a riffle showed the greatest reduction in maximum velocity at the riffle entrance though the jet area basically remained the same. The exit pool depths did not influence the riffle velocities. The max velocity at the entrance of the riffle appears to be sensitive to the turbulence closure scheme, which is demonstrated by the simulation for 0.4 m pool depth in Attempt 3 simulations. Future research should examine simulations with different turbulence models to better quantify model output uncertainties. It can be concluded that the pool depth before a riffle is important in the restoration design of an artificial riffle.

Chapter 5 Conclusion

5.1 Summary of Results

This project aimed to advance stream restoration/enhancement practices in urban streams and explore the potential for TDOT to obtain compensatory mitigation credits through these practices. To reduce the cost of mitigation credits, a demonstration project assessment was completed on a section of stream with adjacent riparian corridor on public property. Use of public property in urban watersheds alleviates the cost for purchasing conservation easement. It also restores streams closer the area of impacts applying permittee-responsible mitigation. The original version of TN SQT (V.1) through its early use by TDOT staff and practitioners found few mitigation credits could be obtained in urban streams. In part this is due to the framework for the function-based parameters where many are recursive NCD design parameters requiring bankfull. In many urban streams, finding the required number of riffles to measure bankfull can be problematic. In 2020-2021, a working group of practitioners, TDEC, and USACE completed a review of the TN SQT V.1 and found multiple issues, including the above issue with bankfull but other issues as well. The issues identified are summarized in this project report, and should be referenced to attain a comprehensive review of all the issues. From the issues identified, a revised version of the TN SQT (V.2) was completed and tested. The TN SQT V.2 will require less time to complete with the reduced number of parameters to complete the fieldwork, and computing ECS and PCS in the worksheet. The TN SQT V.2 provides non-bankfull parameter alternatives to be used when no bankfull indicators can be located. The TN SQT V.2 is still in a draft form, with it being released for public comment in summer 2024.

Beaver Creek in Knox County at Powell was the project site selected to: 1) evaluate and document the potential for obtaining mitigation credits in an urban stream, and 2) assess the difference in obtaining mitigation credits for this site between the use of the TN SQT V.1 and draft V.2. The use of the TN SQT V.1 on four reaches at this project site (three main stem and one tributary reach) resulted in a low number of functional lift index scores (PCS-ESC). The lift per index mainstem reaches were 0.05 and 0.06, and the tributary was 0.11, which resulted in a total of 342 FF of mitigation credits. Though the functional lift index scores were small, FF of credits could possibly be obtained. Thus, it becomes an economic question whether this amount of FF is feasible for construction, and accounting for the reduced project cost of not having to purchase a conservation easement. However, the issue of the 0.4 policy default for the minimum ECS poses a constrain to the allowable credits that could be obtained from this proposed project. This issue is likely common for urban stream restoration projects attempting to obtain for compensatory mitigation credits. In general, the TN SQT V.1 does not favor obtaining mitigation credits though there is evidence that urban stream restoration can provide more substantial functional lift that what the SQT quantified (Schwartz et al. 2015, 2020).

Comparing the TNSQT V.1 to V.2 it was found for the Beaver Creek project reaches that mitigation credits increased by about 11%. A few probable causes for the increase is that the floodplain connectivity was accounted for with the non-bankfull measures in the TN SQT V.2. In the TN SQT V.1 function-based parameters for the Hydraulic category were not scored because bankfull indicators do not exist. The lack of stable riffles is from the historic channelization of the reaches forming long deep pools. Thus, an ESC of zero was entered for the entrenchment ratio and bank height ratio in the TN SQT V.1 spreadsheet because these are designated as the required "big four" parameters. An increase in the Geomorphology category between SQT version was likely due to the greater weight given to the riparian vegetation parameters, in which the Beaver Creek riparian vegetation is excellent on one side of the stream. Other reasons may also include the elimination of the use of BEHI and the new use of process-based channel stability parameter RGA. The RGA more accurately assesses the potential for both vertical downcutting and lateral bank erosion. The new Water Quality/Biology category in the TN SQT V.2 was greater than the average of the two TN SQT V.1 categories Physiochemical and Biology, and this increase was likely due to the use of the TMI score. More investigation is needed for this new category since in the case TMI was estimated from applying an upstream measurement. The one category that decreased was the Hydrology category because it now includes a measure of the potential infiltration on the floodplain. Since the Beaver Creek corridor has been encroached upon by development it received a lesser score. However, this could be viewed as a positive outcome because restoration on the floodplain would create greater mitigation credits through adding/ improving side channels and wetlands. This observation was the case for the BC3 reach, which generated the larger number of mitigation FF credits. Overall, the TN SQT V.2 appears to work better for urban streams however further study is needed with a larger dataset specifically-designed study to better answer this question.

A separate study to advance the construction of artificial riffles in urban streams subject to higher frequency flood events due to watershed development was completed. A modeling study was conducted using FLOW3D, a three-dimensional computational fluid dynamics (CFD) model, to explore energy dissipation as stream flow leaves a pool and enters a riffle. This modeling experiment found that a pool depth of 1 m before a riffle showed the greatest reduction in maximum velocity at the riffle entrance though the jet area basically remained the same. The exit pool depths did not influence the riffle velocities. Future research should examine simulations with different turbulence closure models, which would better quantify model output uncertainties. This modeling experiment concluded that the pool depth before a riffle is important in the restoration design of a self-maintaining artificial riffle.

5.2 Recommendations

From this research comparing the use of the TN SQT V.1 and V.2, it appears that urban stream restoration has potential to generate mitigation credits per permittee-responsible mitigation with the revised version. However, each proposed restoration site will be assessed to whether it is economically feasible to construct an urban stream restoration project in terms of the mitigation credits that can be generated. The one advantage of using public lands is there is no project cost to purchasing a conservation easement.

Use the revised version of the TN SQT should benefit TDOT permittee-response mitigation in urban streams. The advantage of using the TN SQT V.2 is applying the alternative parameters for those that require bankfull indictors. Alternative parameters can only be used if bankfull indicators are absent or unreliable to determine geomorphic equilibrium morphology, which is common in urban streams.

A training program for using V.2 of the TN SQT will offered aiding TDOT staff completing stream assessments for highway construction sites. It is recommended that TDOT staff completed the training course once offered through the Tennessee Water Resources Research Center (TNWRRC). The TNWWRC has offered a training course in the use of hydrodynamic modeling for ecohydaulics habitat restoration design. The results from the 3D modeling experiment to improve the design of pool-riffle sequences align with this course. For TDOT staff interested in this restoration design approach, it is recommended that they attend the course when offered.

References

ACOE. 2015. HEC-RAS: USDA ARS Bank Stability and Toe Erosion Model (BSTEM), Technical Reference and User's Manual, CPD-68B, USACOE Hydraulic Engineering Center, Davis, CA.

Al-Madhhachi A.T., G.J. Hanson, G.A. Fox, A.K. Tyagi, R. Bulut. 2013. Measuring soil erodibility using a laboratory 'mini' Jet. Transactions of the ASABE 56(3): 901–910.

Annable, W.K., V.G. Lounder, C.C. Watson. 2011. Estimating channel-form discharge in urban watercourses. River Research and Applications 27(6): 738-753.

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

Bernhardt, E.S., et al. 2005. Synthesizing U.S. river restoration efforts. Science 308: 636-637.

Bernhardt, E.S., M.A. Palmer. 2007. Restoring streams in an urbanizing world. Freshwater Biology 52: 738-751.

Beechie, T., J. Castro, G. Pess, C. Shea, P. Skidmore, and C. Thorne. 2010. RiverRAT: Science-based Tools for Analyzing Stream Engineering, Management, and Restoration Proposals. USFWS, NOAA Fisheries, Seattle, Washington.

Bledsoe, B.P., M.C. Brown, D.A. Raff. 2007. GeoTools: a toolkit for fluvial systems analysis. Journal of the American Water Resources Association 43(3): 757-772.

Biron, P.M., R.B. Carver, D.M. Carre. 2011. Sediment transport and flow dynamics around a restored pool in a fish habitat rehabilitation project: field and 3D numerical modeling experiments. River Research and Applications 28: 926–939.

Caamaño D., P. Goodwin, J.M. Buffington. 2010. Flow structure through pool-riffle sequences and a conceptual model for their sustainability in gravel-bed rivers. River Research and Applications 28: 377–389.

Clifford, N.J. 1993. Differential bed sedimentology and the maintenance of riffle-pool sequences. Catena 20: 447–468.

Copeland, R.R., D.N. McComas, C.R. Thorne, P.J. Soar, M.M. Jonas, J.B. Fripp. 2001. Hydraulic Design of Stream Restoration Projects. US Army Corps of Engineers, ERDC/CHL TR-01-28, Baltimore, MD.

Doyle, M.W., F.D. Shields. 2012. Compensatory mitigation for streams under the Clean Water Act: reassessing science and redirecting policy. Journal of the Amer. Water Res. Assoc. 48(3): 494-509.

Donatich, S.A. 2020. Evaluation of the Stream Quantification Tool (SQT) on Streams within the Piedmont Ecoregion of North Carolina. MS Thesis, North Carolina State University.

Emery, J.C., A.M. Gurnell, N.J. Clifford, G.E. Petts, I.P. Morrissey, P.J Soar. 2003. Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design. River Research and Applications 19: 549–553.

Fischenich, J.C. 2006. Functional Objectives for Stream Restoration. ERDC-TN-EMRRP SR-52. USACE Research and Development Center, Vicksburg, MS.

Gregory K.J., A.M. Gurnell, C.T. Hill, S. Tooth. 1994. Stability of the pool-riffle sequence in changing river channels. Regulated Rivers: Research and Management 9: 35–43.

Harman, W., R. Starr, M. Carter, K. Tweedy, M. Clemmons, K. Suggs, C. Miller. 2012. A Function-Based Framework for Stream Assessment and Restoration Projects. EPA 843-K-12-006. US Environmental Protection Agency, Washington, D.C.

Hey, R.D. 2006. Fluvial geomorphological methodology for natural stable channel design. Journal of the American Water Resources Association 42(2): 357-374.

Kaufmann, P.R, P. Levine, E.G. Robison, C. Seeliger, D.V. Peck. 1999. Quantifying Physical Habitat in Wadeable Streams. EPA/620/R-99/003. US Environmental Protection Agency, Washington, D.C.

Keller, E.A., J.L. Florsheim. 1993. Velocity-reversal hypothesis: a model approach. Earth Surface Processes and Landforms 18, 733–740.

Keller, E.A., W.M. Melhorn. 1978. “Rhythmic Spacing and Origin of Pools and Riffles.” Geological Society of America Bulletin, Vol. 89, 723–730.

Knighton, D. 1998. Fluvial Forms and Processes: A New Perspective. Holder Arnold Publ.

Langendoen, E. 2000. CONCEPTS – Conservational Channel Evolution and Pollutant Transport System. USDA National Sedimentation Laboratory, Oxford, MS.

Lawless M., A. Robert. 2001. Three-dimensional flow structure around small-scale bedforms in a simulated gravel-bed environment. Earth Surface Processes & Landforms 26: 507-522.

Lisle T.E., 1987. Using residual depths to monitor pool depths independently from discharge, USDA Forest Service Research Note PSW-394. Pacific Southwest Research Station, CA.

MacRae C.R. 1997. Experience from morphological research on Canadian streams: is control of the two-year frequency runoff event the best basis for stream channel protection? In Effects of Watershed Development and Management on Aquatic Ecosystems, Roesner LA (ed.). American Society of Civil Engineers: Reston, VA; 141–162.

Mahalder, B., J.S. Schwartz, A.M. Palomino, J. Zirkle. 2018. Relationships between streambank erosion and physical-geochemical properties of cohesive soils among physiographic regions of Tennessee, USA. Earth Surf. Processes & Landforms 43: 401-416.

Mallison, T.I. 2008. Comparing In-Situ Submerged Jet Test Device and Laboratory Flume Methods to Estimate Erosional Properties of Cohesive Soils for Bank Stability Models. MS Thesis, University of Tennessee, Knoxville.

Meridian Institute. 2023. Supporting Innovation in 404 Stream Mitigation for Improved Ecological Outcomes. https://merid.org/case-study/encouraging-innovation-in-stream-mitigation- banking/; Washington DC.

Milan, D.J. 2013. Sediment routing hypothesis for pool-riffle maintenance. Earth Surf. Process. Landf. 38, 1623–1641. https://doi.org/10.1002/esp.3395

O'Drisscoll, M., S. Clinton, A. Jefferson, A. Manda, S. McMillan. 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water 2: 605-648.

Palmer, M.A.; K.L. Hondula, B.J. Koch. 2014. Ecological restoration of stream and rivers: Shifting strategies and shifting goals. Annual Rev. Ecol. Evol. Syst. 45: 247–269.

Pizzuto, J.E., W.C. Hession, M. McBride. 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology 28(1): 79–82.

Powell, G.E, D.E. Mecklenburg, A.D. Ward. 2006. Spreadsheet Tools for River Evaluation, Assessment, and Monitoring: The STREAM Diagnostic Modules. Proceedings ASCE/EWRI Congress, Omaha, NE.

Rhoads, B.L. 2020. River Dynamics: Geomorphology to Support Management. Cambridge University Press, UK.

Rhoads, B.L., F.L. Engel, J.D. Abad. 2011. Pool-riffle design based on geomorphological principles for naturalizing straight channels. Pages 367-384 In Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. A. Simon, S.J. Bennett, J.M. Castro (Editors). American Geophysical Union.

Rhoads, B.L., 1995. Stream power: A unifying theme for urban fluvial geomorphology, in Stormwater Runoff and Receiving Systems, edited by E. E. Herricks, pp. 65–75, A. F. Lewis, Boca Raton, Fla.

Rosgen, D.L. 1994. A classification of natural rivers. Catena 22: 169-199.

Rosgen, D.L. 1996. Applied River Morphology. Wildlands Hydrology Inc., Ft. Collins, CO.

Roy, A.G., T. Buffin-Belanger, H. Lamarre, A.D. Kirkbridge. 2004. Size, shape, and dynamics of large-scale turbulent flow structures in a gravel-bed river. J. Fluid Mechanics 500: 1-27.

Schwartz, J.S., B. Alford, G.G. Fisher, J.L. Melton. 2020. Assessing Functional Lift through Improved Monitoring and Assessment Techniques for Urban Stream Restoration. Tennessee Healthy Watersheds Initiative Final Project Report, Tennessee Department of Environment and Conservation, Nashville, TN.

Schwartz, J.S. 2016. Use of ecohydraulic-based mesohabitat classification and fish species traits for stream restoration design. Water 8, 520. DOI 10.3390/w8110520.

Schwartz, J.S., K.J. Neff, F.J. Dworak, R.R. Woockman. 2015. Restoring riffle-pool structure in an incised, straightened urban stream channel using an ecohydraulic modeling approach. Ecological Engineering 78: 112-128. DOI 10.1016/j.rcoleng.2014.06.002.

Schwartz, J.S., E.E. Herricks. 2008. Fish use of ecohydraulic-based mesohabitat units in a low-gradient Illinois stream: implications for stream restoration. Aquatic Cons.: Marine and Freshwater Ecosystems 18(6): 852-866.

Schwartz, J.S., E.E. Herricks. 2007. Evaluation of pool-riffle naturalization structures on habitat complexity and the fish community in an urban Illinois stream. River Research and Applications 23: 451-466.

Schwartz, J.S., Herricks, E.E., 2005. Fish use of stage-specific fluvial habitats as refuge patches during a flood in a low-gradient Illinois stream. Can. J. Fish. Aquat. Sci. 62, 1540–1552.

Schwartz, J.S. 2002. Stream Habitat Characterized by Stage-specific Flows and Three-dimensional Geomorphological Complexity: Development of Ecological Criteria for Stream Restoration Design. Ph.D. Dissertation, University of Illinois at Urbana-Champaign.

Sear, D.A. 1996. Sediment transport processes in pool-riffle sequences. Earth Surface Process. Landforms 21: 241–262.

Shields, F.D., R.R. Copeland, P.C. Klingeman, M.W. Doyle, A. Simon. 2003. Design for stream restoration. ASCE Journal of Hydraulic Engineering 129(8): 575-584.

Simmons, P.V. 2014. A Spatial Analysis of Streambank Heterogeneity and Its Contribution to Bank Stability. MS Thesis, University of Tennessee, Knoxville.

Simon, A., P.W. Downs. 1995. An interdisciplinary approach to evaluate potential instability in alluvial channels. Geomorphology 12: 215-232.

Simon, A., S.E. Darby. 1999. The Nature and Significance of Incised River Channels. In Darby, S. & Simon, A., *Incised River Channels*, Publ. Wiley, Chichester. Chp. 1, p. 3-18.

Simon, A., L. Klimetz. 2008. Magnitude, frequency, and duration relations for suspended sediment in stable ("reference") southeastern streams. Journal of the American Water Resources Association 44(5): 1270-1283.

Simon, A., M. Doyle, M. Kondolf, F.D. Shields, B.L. Rhoads, M. McPhillips. 2007. Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43(5): 1117-1131.

Somerville, D.E. 2010. Stream Assessment and Mitigation Protocols: A Review of Commonalities and Differences. U.S. Environmental Protection Agency, Washington, D.C. EPA 843-S-12-003.

Steffler, P., J. Blackburn. 2002. Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, Introduction to Depth Averaged Modeling and User's Manual. University of Alberta, Edmonton, Alberta, Canada, 2002.

Stowe, E.S., K.N. Peterson, S. Rao, E.J. Walther, M.C. Freeman, and S.J. Wenger. 2023. Stream restoration produces transitory, not permanent changes to fish assemblages as compensatory mitigation sites. Restoration Ecology 31(5), e13903.

Sudduth, E.B., B.A. Hassett, P. Cada, E.S. Bernhardt. 2011. Testing the field of dreams hypothesis: functional responses to urbanization and restoration in stream ecosystems. Ecological Applications 21: 1972-1988.

Tamburrino A., J.S. Gulliver. 1999. Large-flow structures in turbulent channel flow. Journal of Hydraulic Research 37(3): 363-380.

TDEC. 2017. Tennessee Stream Quantification Tool V.1 Spreadsheet User Manual. Tennessee Department of Environment and Conservation, Nashville, TN.

TDEC. 2018. Data Collection and Analysis Manual, Tennessee Stream Quantification Tool V.1 & Debit Tool. Tennessee Department of Environment and Conservation, Nashville, TN.

TDEC. 2019a. User Manual, Tennessee Stream Quantification Tool V.1 & Tennessee Debit Tool. Tennessee Department of Environment and Conservation, Nashville, TN.

TDEC. 2019b. Stream Mitigation Guidelines. DWR-NR-G-01. Tennessee Department of Environment and Conservation, Division of Water Resources, Nashville, TN.

Tullos, D.D., D.L. Penrose, G.D. Jennings. 2006. Development and application of a bioindicator for benthic habitat enhancement in the North Carolina Piedmont. Ecological Engineering 27: 228-241.

Tullos, D.D., D.W. Baker, J. Crowe-Curran, M. Schwar, J.S. Schwartz. 2021. Enhancing resilience of river restoration design in systems undergoing change. Journal of Hydraulic Engineering 147(4): 03121001.

USACE. 2024. HEC-RAS User's Manual. downloaded https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/introduction-to-hec-ras.

Wade, R.J., B.L. Rhoads, J. Rodriguez, M. Daniels, D. Wilson, E.E. Herricks, F. Bombardelli, M. Garcia, J.S. Schwartz. 2002. Integrating science and technology to support stream naturalization near Chicago, Illinois. J. Am. Water Res. Assoc. 38: 931-944.

Yalin, M.S. 1992. River Mechanics; Pergamon Press: New York, NY, USA; p. 219.

Appendices

Appendix A

A. Geometric Equations Used for Simulated Pool-Riffle Structure

Appendix B

B. Beaver Creek Restoration Project: Draft Prospectus Report

Appendix C

C. Beaver Creek Restoration Project: TN SQT V.2 Worksheets