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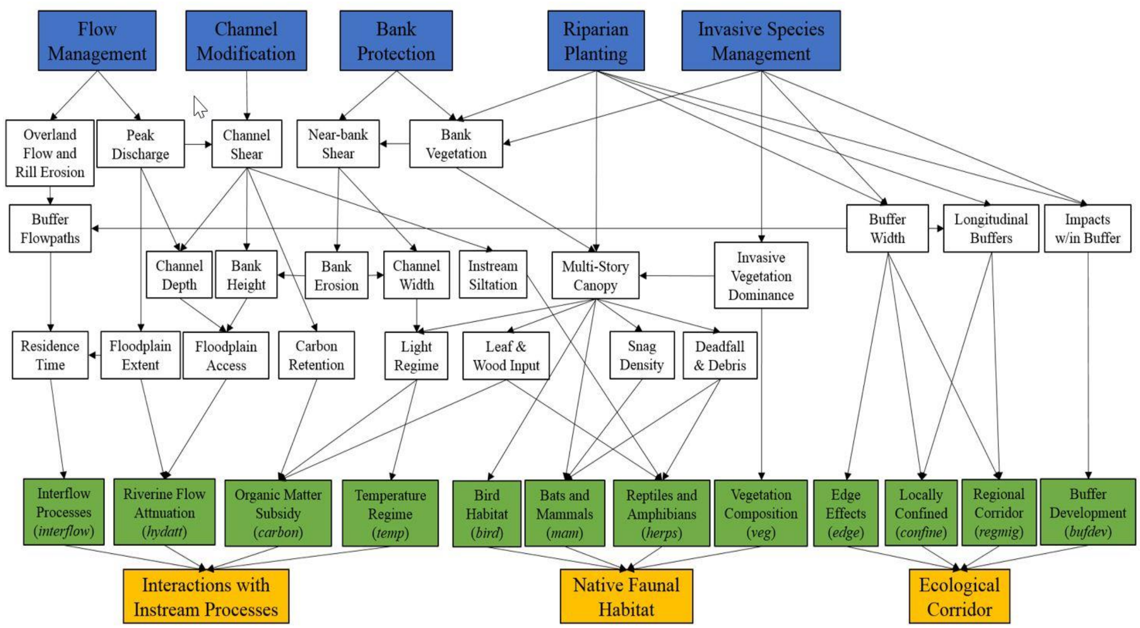
Simple Model for Urban Riparian Function (SMURF), Version 1.0 (DRAFT FOR ERDC REVIEW)

S. Kyle McKay, Miranda K. Goss, Frank M. Veraldi, and Laura L. Mattingly

September 2021



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Ecosystem Management and Restoration
Research Program

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Final report

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Under “Three Forks of Beargrass Creek Ecosystem Restoration Feasibility Study”

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Abstract

Aquatic ecosystem degradation is often an indirect by-product of high societal demand on urban waters. Urban stream and riparian restoration are challenging endeavors constrained by available lands, legacy effects of historic land use, multiple objectives, and finite resources. Stream assessment tools have been developed for rapid application and restoration prioritization in this context. While these models typically include riparian variables, they are often inherently focused on in-channel outcomes. Here, we develop a Simple Model for Urban Riparian Function (SMURF), which is designed as a rapid assessment technique for highly urbanized environments. The SMURF was developed following a common modeling process of conceptualization, quantification, evaluation, application, and communication. Three major categories of outputs are addressed: (1) indirect effects of riparian zones on instream processes, (2) riparian areas as important providers of native faunal habitat, and (3) riparian zones as ecological corridors and sources of resilience in highly disturbed areas. The model uses a combination of rapid field assessment protocols and desktop geospatial assessments applied independently to left and right banks. The SMURF was developed and applied in the context of the Beargrass Creek ecosystem restoration study in Louisville, Kentucky; however, the modeling approach is adaptable to other urban riparian zones.

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Preface

This study was conducted for the USACE Louisville District under the "Three Forks of Beargrass Creek Ecosystem Restoration Feasibility Study." This study was also conducted in partnership with the Ecosystem Management and Restoration Research program under the direction of Dr. Brook Herman, Acting Program Manager. Dr. Jennifer Seiter-Moser, CEERD-EZT, was the Acting Technical Director for Civil Works Environmental Engineering and Sciences.

The work was performed by the ERDC Environmental Laboratory, USACE Louisville District (LRL), and USACE Chicago District. At the time of publication, Ms. Lynn Escalon was Acting Chief, Ecological Resources Branch (CEERD-EEE), and Mr. Mark Farr was Chief, CEERD-EE. The Deputy Director of ERDC-EL was Dr. Jack Davis and the Director was Dr. Edmond Russo.

COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters

1 Introduction

1.1 *Background*

Cities contain more than half of the global population, and urban residency is more than 80% in the United States (World Bank 2020). Growing urban centers often lead to degraded streams and riparian zones with stressors resulting from change in land use, increased runoff, altered water quality from sanitary and storm sewer inputs, reduced extent of ecosystems, and other factors (Wenger et al. 2009). Subsequent changes in geomorphology, lost biodiversity, and reduced ecosystem function are well-documented, and collectively, these stressors and effects are often described as the "urban stream syndrome" (Walsh et al. 2005, Paul and Meyer 2006, Booth and Bledsoe 2009). In response, stream and riparian restoration have grown into large areas of professional practice (Bernhardt et al. 2005), requiring integrated solutions spanning organizations and disciplines (Deason et al. 2010).

1.2 *Three Forks of Beargrass Creek Feasibility Study*

Beargrass Creek in Louisville, Kentucky is a representative example of common urban stream management challenges. Three main branches, the South Fork, Middle Fork, and Muddy Fork, drain this small watershed (~59 mi^2, Figure 1). Wetlands and forests were historically drained to support residential, commercial, and industrial land uses as the Louisville region grew. Some reaches were channelized to increase conveyance, and further geomorphic change occurred as a result of increased runoff from urban development. To confront these challenges, the U.S. Army Corps of Engineers (USACE) Louisville District (LRL) and Louisville Metropolitan Sewer District (MSD) are partnering to identify actions that could restore aquatic ecosystems in the watershed. The two primary objectives of the projects are: (1) To reestablish quality and connectivity of *riverine* habitats and (2) To reestablish quality and connectivity of *riparian* habitats.

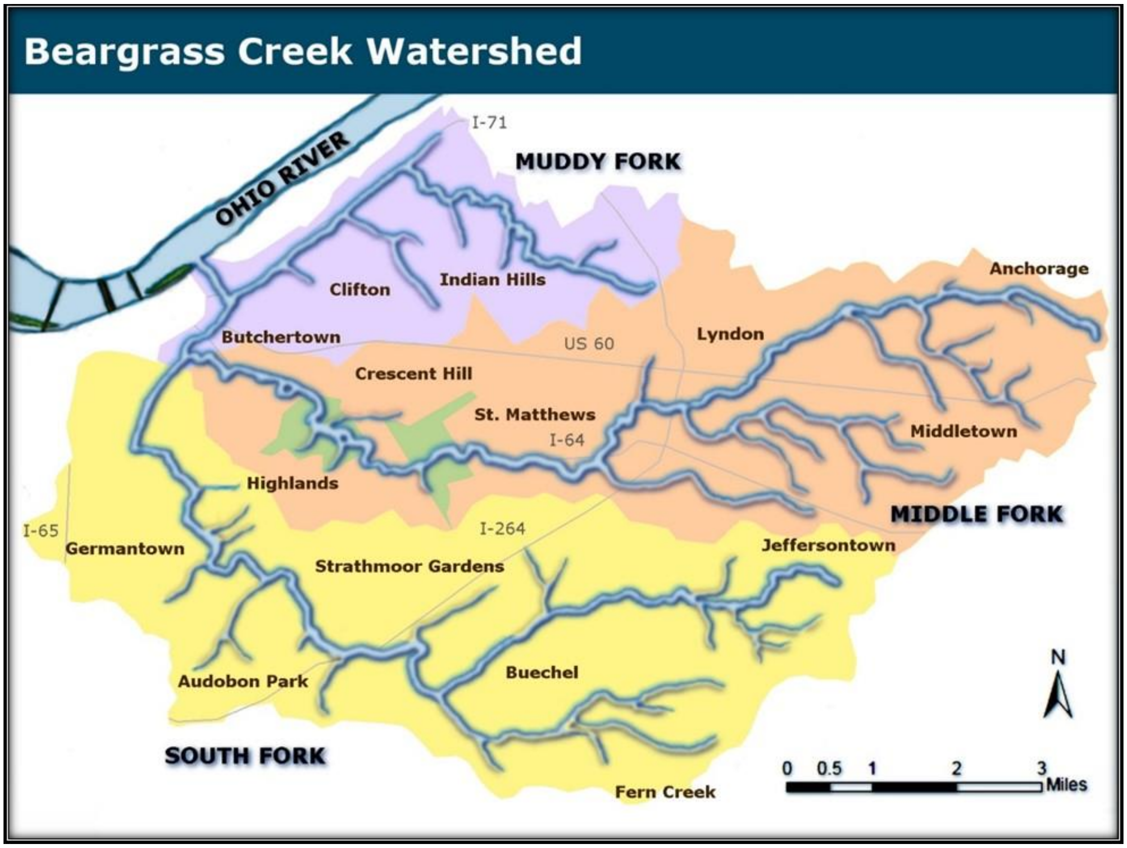

Figure 1. Beargrass Creek watershed.

1.3 *Problem Statement*

Many assessment methods and tools have been developed to support and inform urban watershed restoration projects. These tools are often centered on specific project outcomes such as hydrologic or geomorphic change (e.g., Bledsoe et al. 2007 and Bledsoe et al. 2012, respectively), taxa-specific metrics (e.g., Guilfoyle et al. 2008), or wetland processes (e.g., Ainslie et al. 1999). Rapid assessment techniques have also been developed to assess multiple aspects of stream processes, such as the Rapid Bioassessment Protocol (Barbour et al. 1999), the Stream Visual Assessment Protocol (Newton et al. 1998, Bjorkland et al. 2001), the Qualitative Habitat Evaluation Index (Rankin 2006), and many site-specific adaptations (e.g., Rowe et al. 2009, McKay et al. 2018ab). However, these methods largely focus on instream processes with an indirect emphasis on riparian outcomes.

The conceptual and numerical models presented here seek to articulate and quantify the general ecological condition of urban riparian zones for informing watershed management and restoration actions. The following goals guided model development:

- Models should focus on key aspects of riparian condition and function.

- Models should be capable of distinguishing the relative effects of different magnitudes and types of stream and riparian restoration actions.

- Models should be applicable within typical USACE project planning timelines, which means they should rely on common sources of existing data, be informed through desktop analyses, or may be parameterized by rapidly collected field surveys.

- Models should be adaptable to new information and data as project planning proceeds.

- Models should be developed within the context of the Beargrass Creek project, but seek to maintain flexibility for other systems where possible.

1.4 *Report Overview*

This report presents development and application of the Simple Model for Urban Riparian Function (SMURF). An index-based modeling framework (i.e., a habitat-suitability-style, quantity-quality approach) is applied to assess patch-scale effects. Index models combine assessments of habitat quantity (typically an area-metric like acres) with a multi-variate assessment of habitat quality (a 0 to 1 "suitability" score). Three major functional categorical outcomes are included in this model: (1) indirect effects on in-stream processes, (2) habitat provision for native fauna, and (3) the role of riparian zones as ecological corridors. The model is executed in the R statistical software language, and this report provides documentation of the technical details, use, and relevant information for USACE model approval and certification (EC 1105-2-412, PB 2013-02). The following sections summarize the major elements of model development:

- *Model Development Process*: Summarizes how the model was developed through a combination of literature review and engagement with the Beargrass Creek project development team.

- *Conceptualization*: Describes the overarching view of the structure and function of riparian ecosystems captured by the model.

- *Quantification*: Reviews the technical details of the models (i.e., suitability index curves and numerical structure).

- *Evaluation*: Assesses the models relative to underlying scientific theory, numerical accuracy, and usability.

- *Application*: Describes application of models for the Beargrass Creek ecosystem restoration study led by USACE Louisville District, specifically assessment of the existing watershed conditions.

- *Communication*: Describes the communication strategy for presenting model outcomes to USACE team members, non-federal sponsors, and other interested parties.

2 Model Development Process

SMURF development followed a common ecological modeling process of conceptualization, quantification, evaluation, application, and communication (Grant and Swannack 2008; Swannack et al. 2012). The model was developed iteratively with the model development team (i.e., authors of this document) and the larger Beargrass Creek project development team. An outline of model structure was presented prior to field data collection, and the field team made recommendations on the structure and assessment of variables. The model development team subsequently programmed, tested, and evaluated the numerical algorithms. Finally, models were documented with accompanying peer-reviewed literature support, where available.

Quality assurance procedures were followed throughout the modeling process and detailed throughout this report. Overall, the SMURF was developed using principles of "open science," which embrace transparency in all phases of technical analyses including scoping, data sharing, analytical code, and published products (Hampton et al. 2015). For instance, conceptual models were iteratively developed with input from the modeling and project development teams. Numerical code was extensively documented, and input data are provided for future use (Appendix C). Models were programmed by the lead author (SKM) and code was subsequently interrogated by another author (DDHA). Finally, models were developed with the "reproducible research" tool R Markdown, which allows developers to integrate documentation and numerical code. These processes cannot guarantee error-free analyses; however, best practices were sought to minimize the occurrence of errors.

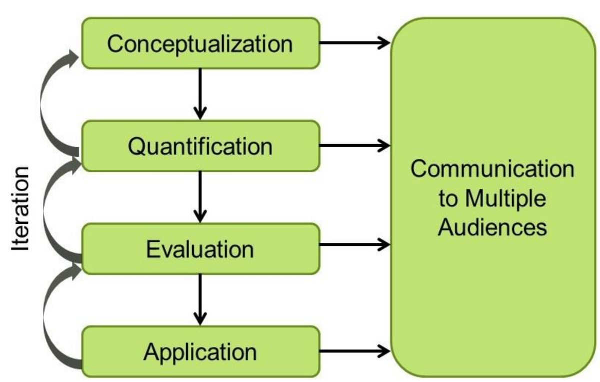

Figure 2. Ecological model development process (modified from Grant and Swannack 2008).

3 Conceptualization

Conceptual models are "descriptions of the general functional relationships among essential components of an ecosystem," and ecosystems can be conceptualized in a variety of media including narrative descriptions, tables, schematics, flow charts, and others (Fischenich 2008). Conceptual models have particular utility in interdisciplinary undertakings like ecosystem restoration, where they have proven useful for tasks ranging from objective setting (McKay et al. 2012) and stakeholder buy-in (McKay et al. 2020a) to numerical model development (Swannack et al. 2012) and design of restoration alternatives (Fischenich 2008). Here, we focus on conceptual models as a means to numerical model development, but these models also provide a mechanism for communicating links between restoration actions and focal outcomes of the Beargrass Creek project.

We followed a generalized, seven-step process for developing an urban riparian zone conceptual model (Fischenich 2008; Table 1). In doing so, we drew heavily from a long history of stream and riparian conceptual models (e.g., the Channel Evolution Model, Simon 1989; the River Continuum Concept, Vannote et al.; urban stream impact models, Wenger et al. 2009). Specifically, we developed a simple box-and-arrow style model linking potential restoration actions with key categories of ecological outcomes (Figure 3). The model shows how restoration actions directly influence key intermediate process and model variables, and how those variables are subsequently combined into overarching categorical outcomes related to effects on instream processes, faunal habitats, and the role of riparian zones as ecological corridors.

Table 1. Stepwise development of the SMURF conceptual model (following steps in Fischenich 2008).

Step	Simple Model for Urban Riparian Function (SMURF)
1. State the model objectives.	To inform development of a rapid numerical modeling approach for assessing the overarching aspects of riparian condition and function in urban environments.
2. Bound the system of interest.	Riparian zones in urban areas with a preliminary emphasis on Midwestern streams. Riparian zones are defined outward from the top of streambanks to a maximum extent of 100m. Models are intended for independent application to riparian areas on river-left and river-right (looking downstream).
3. Identify critical model components within the system.	Model variables were identified through review of existing stream assessment models as well as peer-reviewed literature.
4. Articulate relationships among model components.	Given the emphasis on management applications, common families of stream and riparian restoration actions were identified (blue boxes) and linked to intermediate processes (white boxes). These intermediate outcomes were then linked to primary model variables (green boxes) and ultimately the three major functional categories (yellow boxes).
5. Represent the conceptual model.	A box-and-arrow style graphic was used to communicate linkages between model components (Figure 3).
6. Describe the expected pattern of behavior.	The processes linking restoration actions and model outcomes are described more mechanistically in the model quantification section of this report.
7. Test, review, and revise.	All conceptual (and numerical) models were developed iteratively among the authorship team, the Beargrass Creek project planning team, technical staff collecting field data, and independent colleagues not actively engaged in development.

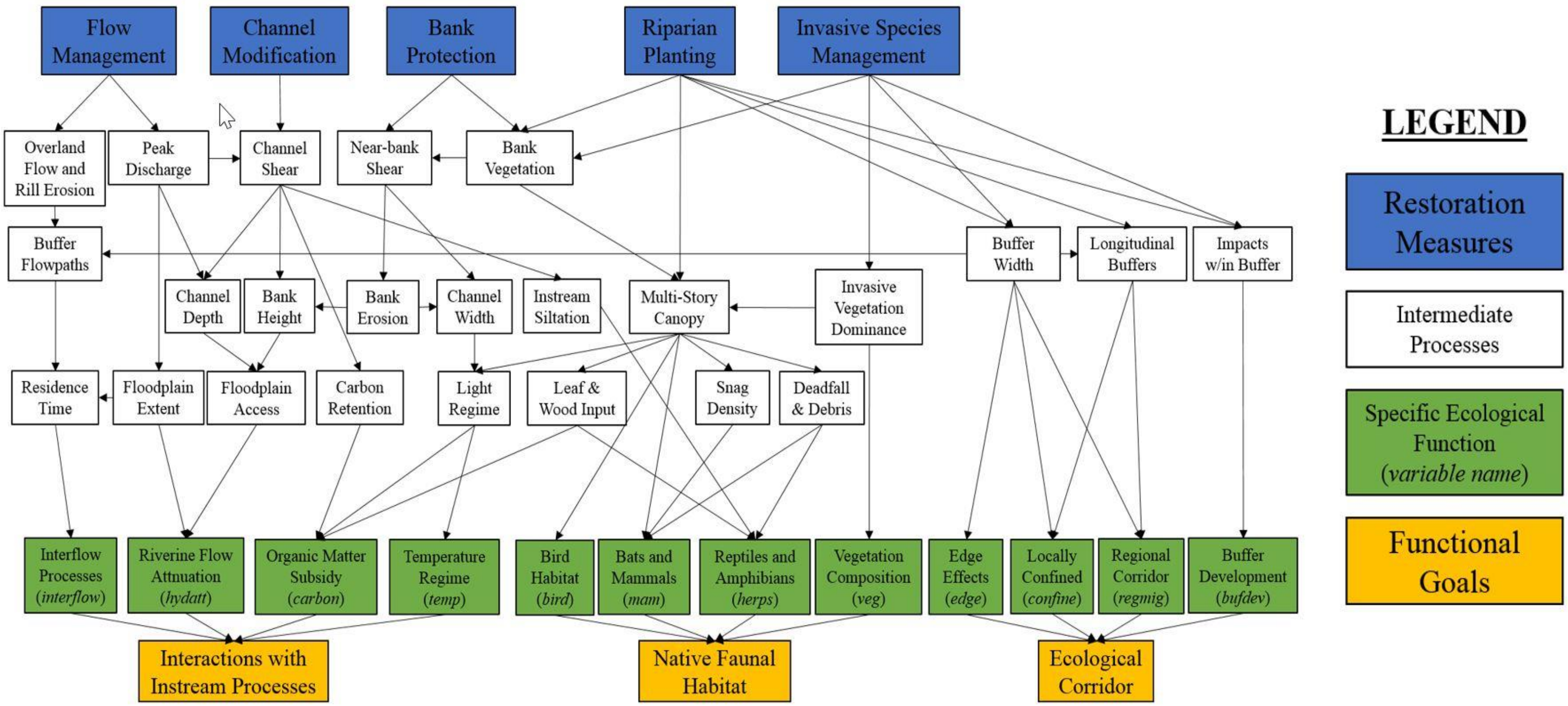

Figure 3. SMURF Conceptual Model.

4 Quantification

The quantification phase of ecological model development formalizes the conceptual model in terms of mathematical relationships, model parameters, and a numerical algorithm (Grant and Swannack 2008). This section describes the SMURF model structure and provides background on the theoretical underpinnings of the model, protocols for compiling inputs, and the associated numerical toolkit.

SMURF uses an index-based modeling framework (i.e., a habitat-suitability-style, quantity-quality approach) to assess patch-scale effects. Index models combine metrics of habitat quantity with a multi-variate assessment of habitat quality. Quality is typically assessed as a 0 to 1 score of the "suitability" of a site (i.e., 0=unsuitable, 1=ideal). The model is intended to be applied to a relatively homogenous patch of riparian ecosystem (e.g., the left bank riparian area as delineated from aerial photography) to provide a "snapshot" in time of the system condition. Table 2 summarizes key issues of SMURF scoping relative to model quantification.

Three major functional categorical outcomes are included in SMURF: (1) indirect effects on instream processes, (2) habitat provision for native fauna, and (3) the role of riparian zones as ecological corridors. These basic riparian functions are well-described in the broader literature on riparian function (e.g., Wenger 1999, Medina et al. 2016), and categories are generally derived from Fischer and Fischenich's (2000) review of the subject. For SMURF, the three modules provide independent assessments of habitat quality, which are then combined into an overarching index of riparian quality. The modules and assessment protocols are described in detail in subsequent sections, and each index is composed of multiple model variables (Table 3).

Table 2. Summary of model scoping for SMURF.

Aspect of Model Scoping	**Simple Model for Urban Riparian Function (SMURF)**
General approach	Index-based, habitat-style model
Treatment of spatial processes	Spatially lumped, patch-scale model where user decides on the unit of analysis (left and right bank riparian zones are assessed separately)
Treatment of time	Single moment in time
Input data type	Combination of rapid, field assessment and desktop, geospatial analyses
How are forecasts conducted	Initial field and desktop data are adjusted based on other modeling or professional judgment
Intended application	Preliminary assessment of urban riparian zones in the context of management actions (e.g., restoration)
Major assumptions	(1) Patch-scale models adequately capture the complexity of a connected, interdependent riparian mosaic, (2) Assessments are a snapshot in time not dependent upon prior time periods, (3) Forecasts can be reliably obtained from adjustment of parameters based on professional judgment, (4) Models are being applied for relative comparison rather than absolute prediction, and (5) SMURF omits variables that may be important in other ecosystems because it was developed in the context of the Beargrass Creek restoration project and regional context.

Table 3. Overview of the quality sub-models in the SMURF. The modules are explained in more detail in Sections 4.1 (instream), 4.2 (fauna), and 4.3 (corridor) of this report.

General Outcome	Specific Outcome	Proxy Metric(s) used in SMURF
Indirect effects on instream function (instream)	Flow attenuation (hydatt)	(1) Incision Ratio = bank height / bankfull depth
	Interflow processes (interflow)	(1) Average buffer width, (2) Qualitative flowpath score
	Temperature and light regulation (temp)	(1) Shading = canopy height / bankfull width, (2) Percent of stream with canopy cover
	Organic matter dynamics (carbon)	(1) Qualitative canopy structure score, (2) Qualitative instream retention score
Native faunal habitat (fauna)	Avian taxa (birds)	(1) Qualitative canopy structure metric
	Small mammals and bats (mammals)	(1) Qualitative canopy structure metric, (2) Snag density, (3) Deadfall density
	Reptiles and amphibians (herps)	(1) Deadfall density, (2) Leaf litter, (3) Instream embeddedness
	Vegetation composition (veg)	(1) Invasive species dominance of plant community
Role as an ecological corridor (corridor)	Buffer development (bufdev)	(1) Qualitative development score
	Edge effects (edge)	(1) Edge density = edge length / buffer area
	Local confinement (confine)	(1) Percent of reach with buffer less than 25 feet wide

Each model variable is translated into a 0 to 1 “suitability curve” to provide a consistent scale across diverse processes. Equations for suitability curves are derived from the Toolkit for interActive Modeling (TAM, Carrillo et al. 2020). Each suitability curve was derived from a combination of literature review and professional judgment of the Beargrass Creek project development team. Specific resources are highlighted as each suitability curve is presented, but four types of resources were generally consulted in constructing suitability curves:

- General descriptions of riparian processes (Wenger 1999, Fischer and Fischenich 2000, Medina et al. 2016, Johnson et al. 2018, Carothers et al. 2020) and existing assessment approaches (Smith et al. 2005, Lin et al. 2008, Guilfoyle et al. 2009).

- Stream rapid assessment protocols like the Rapid Bioassessment Protocol (Barbour et al. 1999), the Stream Visual Assessment Protocol (Newton et al. 1998, Bjorkland et al. 2001), the Qualitative Habitat Evaluation Index (Rankin 2006), and similar site-specific adaptations (e.g., Rowe et al. 2009, McKay et al. 2018ab).

- Hydrogeomorphic method (HGM) manuals for wetland assessment in western Kentucky (Ainslie et al. 1999), eastern KY streams (Noble et al. 2010), and associated model validation reports (Sweeten and Ford 2016).

- Regional studies of stream and riparian ecosystems as they relate to existing assessment methods (KDOW 2011), geomorphic outcomes (Parola et al. 2007, Agouridis et al. 2011), and habitat of key taxa such as birds (Kelly 2018), bats (Hammond et al. 2016, Richardson 2017), and others (Larson et al. 2003).

Each of the three main modules is assessed independently as a 0 to 1 index of ecosystem quality. Overall ecosystem quality is computed as the combination of the quality scores for each module. The modules are combined using a geometric mean, which assumes that deficiency in any modules can limit overall system quality. For instance, unsuitable habitat (i.e., $I_{fauna} = 0$) can drive even ideal assessments of the instream and corridor modules (i.e., $I_{instream} = 1$ and $I_{corridor} = 1$) to a low overarching index ($I_{SMURF} = 0$). The modules are each viewed as equally important contributions to overall riparian function, and no "weighting" of outcomes is applied.

$$I_{SMURF} = (I_{instream} I_{fauna} I_{corridor})^{1/3}$$

Where I_{SMURF} is an overarching index of ecosystem quality, $I_{instream}$ is an index of a riparian zone's contribution to instream processes, I_{fauna} is an index of patch habitat quality for native fauna, and $I_{corridor}$ is an index relative to the system's role as an ecological corridor. All indices are quality metrics scaled from 0 to 1, where 0 is unsuitable and 1 is ideal.

The overall quality index can be combined with the area of a given patch to derive a quality-weight area metric, a so-called "habitat unit." Habitat units should be assessed separately for left and right bank riparian areas.

4.1 *Indirect Effects on Instream Function* ($I_{instream}$)

USACE restoration programs explicitly target, "restoration opportunities that are associated with wetlands, riparian and other floodplain and aquatic systems" (USACE 2000, ER 1105-2-100, Page 3-24). The instream module addresses the mechanisms by which a riparian zone alters ongoing processes in the neighboring stream. In particular, four main outcomes are assessed: (1) Longitudinal connectivity associated with riverine flow attenuation, (2) Lateral connectivity associated with interflow processes, (3) Temperature and light regulation, and (4) Organic matter subsidy from riparian zones to stream ecosystems. The variables associated with each of these processes are presented below along with any proxy metrics used to assess effects on instream condition. The instream index ($I_{instream}$), was assessed as the arithmetic mean of the four metrics.

$$I_{instream} = \frac{hydatt + interflow + temp + carbon}{4}$$

Where $I_{instream}$ is an index of a riparian zone's contribution to instream processes, $hydatt$ is a suitability index for longitudinal connectivity associated with flow attentuation, $interflow$ is a suitability index for lateral river-floodplain connectivity associated with interflow processes, $temp$ is a suitability index associated with temperature and light regulation, and $carbon$ is a suitability index for organic matter dynamics. All variables are quality metrics scaled from 0 to 1, where 0 is unsuitable and 1 is ideal. Figure 4 summarizes all suitability curves associated with instream function.

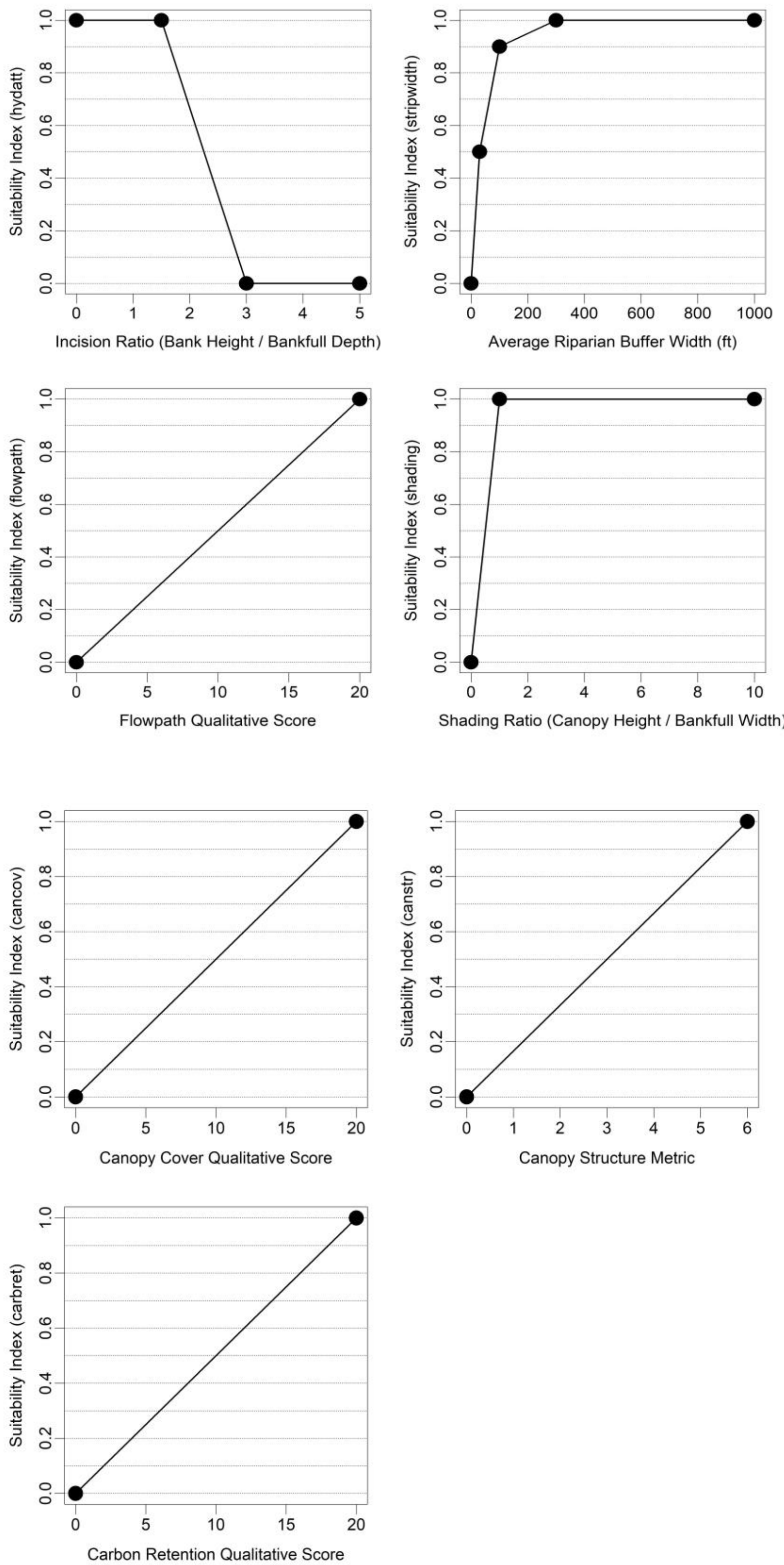

Figure 4. Suitability curves for the instream module.

Hydrologic Attenuation (*hydatt*)

River-floodplain connectivity is an important bi-directional process influencing the ecological health of both systems. This metric assesses the role of riparian areas in slowing down and attenuating river flows, which is particularly important in urban streams with "flashy" hydrologic response. In an unaltered stream, the bankfull condition generally refers to the incipient point of flooding, which indicates the long-term channel shape in response to a watershed's hydrologic regime and geology. Owing to hydrologic change, many urban streams are incised, and rivers are often disconnected from floodplains.

Geomorphologists and engineers have developed a variety of metrics for assessing geomorphic condition and change. The SMURF uses a relatively simple (but crucial) metric of channel change to provide a general snapshot of a stream's geomorphic status. The incision ratio (also known as bank height ratio, sensu Harman and Jones 2016) is the ratio of bank height to the bankfull depth. As channels undertake the evolutionary process above, channel bottoms incise leaving bank heights much greater than those typically observed in unmodified systems. In an unmodified stream, the "bankfull" condition can be defined as the depth at which a channel overflows onto the floodplain (Shields et al. 2003), but the bankfull depth is often significantly less than bank height in altered streams (Harman and Jones 2016). Bankfull depth was identified and measured based on field indicators such as wrested vegetation and tops of sediment depositional features (e.g., point bars). Bank height was identified and measured based on the perceived elevation of historic floodplains. A simple schematic field guide was constructed as a reference for observers (Appendix B).

Here, the incision ratio (i.e., bank height / bankfull depth), is used as a proxy for the degree of river-floodplain connectivity and the associated attenuation of flows. An incision ratio near 1 would indicate ideal conditions with little evidence of geomorphic incision and frequent connectivity between the river and floodplain. Conversely, an incision ratio above 3 would indicate highly disturbed conditions with a high degree of downcutting. This metric has been used widely in other stream restoration projects to quantify the relative condition of the channel and inform design targets. For instance, Harman and Jones (2016) identify thresholds in geomorphic performance relative to incision as: less than 1.3 is highly functioning, between 1.3 and 1.5 is functioning at risk, and greater than 1.5 is not functioning. Similar thresholds have been used in other regions (IA DNR 2018). For SMURF, an incision ratio of 1.5 is used as a threshold for the decline in floodplain function, although many functions may decline at lower thresholds as described above. The following equation presents the SMURF suitability curve associated with hydrologic attenuation.

$$hydatt = \begin{pmatrix} 1.0 & incision < 1.5 \\ 2.0 - 0.667 * incision & incision = 1.5 - 3.0 \\ 0.0 & incision >= 3.0 \end{pmatrix}$$

Where $hydatt$ is a suitability index for longitudinal connectivity associated with flow attentuation, $incision = \frac{H_{bank}}{H_{bankfull}}$ is the incision ratio, H_{bank} is bank height, and $H_{bankfull}$ is bankfull depth.

Future analyses could include alternative metrics such as a direct assessment of floodplain extent such as the hydraulic top width for a 5-year flood divided by the hydraulic top width for a 1-year flood or the entrenchment ratio (i.e., ratio of the width of the flood-prone area to the surface width of the bankfull channel).

Interflow Processes ($interflow$)

Riparian zones serve as important ecotones between upland systems and streams, and hillslope scale effects are important benefits of riparian zones on stream processes. Riparian zones often directly affect both overland flow and shallow subsurface processes like interflow. Fischer and Fischenich (2000) distinguish these types of benefits as those related to riparian areas as vegetated buffer strips, which play important roles in moderating nonpoint source pollution and the associated impacts on stream ecosystems. The SMURF uses two metrics for assessing interflow mechanics, buffer width and a qualitative flowpath metric.

Dozens of studies have examined the roles of riparian buffer width and slope on sediment and water quality processes (See reviews by Wenger 1999 and Fischer and Fischenich 2000). Slope plays an important role in these processes as well, particularly in steep sloped systems; however, this factor was eliminated to minimize analytical burden. Based on a meta-analysis of buffer efficacy, Wenger (1999) identified 25% slope as a generalized cutoff for riparian zones capable of providing these functions, and

SMURF should not be applied in areas with slopes greater than 25%. More generally, slopes greater than 15% could affect riparian function (and model performance), and caution should be taken in model application.

Studies show that wider riparian zones provide enhanced benefits to interflow processes and associated storage and processing of sediment, nutrients, and other constituents. Notably, there appear to be diminishing returns after the first 30 ft (10 m) providing a substantial amount of benefit. As such, the reachwide average buffer width (W_{buffer}) was computed in a Geographic Information System (GIS) and used to compute a metric of benefits relative to a riparian zone's role as a vegetated buffer stip. Appendix B presents additional details on measurement protocols.

$$stripwidth = \begin{pmatrix} 0.0167 * W_{buffer} & W_{buffer} = 0 - 30 \\ 0.33 + 0.0057 * W_{buffer} & W_{buffer} = 30 - 100 \\ 0.85 + 0.0005 * W_{buffer} & W_{buffer} = 100 - 300 \\ 1.0 & W_{buffer} >= 300 \end{pmatrix}$$

Where $stripwidth$ is a suitability index for the hydrologic and water quality benefits associated with a wide buffer strip and W_{buffer} is the average width of the riparian buffer in a reach as delineated in GIS (in ft).

Wenger (1999) highlights the importance of flow paths through buffers versus those flowing around a system. A simple qualitative scoring system and associated schematic guide (Appendix B) were developed to assess hydrologic flows through riparian areas. Specifically, the metric emphasized the importance of urban development and drainage networks in "short circuiting" flow paths and reducing residence time of interflow processes.

$$flowpaths = 0.05 * S_{flowpaths}$$

Where $flowpaths$ is a suitability index for preferential flowpaths through the riparian buffer strip and $S_{flowpaths}$ is a 0-20 qualitative scale defined in Appendix B.

The buffer strip and flowpath metrics were combined to provide an index of the relative contribution of a riparian area to interflow processes.

$$interflow = \frac{stripwidth + flowpaths}{2}$$

Where $interflow$ is a suitability index for lateral river-floodplain connectivity associated with interflow processes.

Temperature and Light Regulation ($temp$)

Urban areas often exhibit higher stream temperatures due to increased runoff from hot impervious areas (e.g., parking lots, roofs), reduced stream shading, and delivery of warm inputs from point sources (Kaushal et al. 2010). USACE restoration actions are unlikely to alter the delivery of hot water from impervious zones upstream or point sources. However, some restoration actions have a direct impact on temperature regimes relative to stream shading. Stream temperatures have been shown to increase dramatically in forest gaps, but also reduce quickly in response to forested cover.

Two simple proxies of canopy shading are combined as an overall assessment of the role of the riparian area in temperature and light regulation. First, the ratio of the canopy height within 25 feet of the top of bank to the bankfull width is used as a surrogate for canopy shading (i.e., shading = canopy height / bankfull width). This metric provides an objective basis for assessing the relative influence of riparian forests on stream temperatures. This ratio is assessed for each bank independently based on field estimates. The metric is assumed to be ideal for any ratio greater than 1 and decline linearly to 0.

$$shading = \begin{pmatrix} \frac{H_{canopy}}{W_{bankfull}} & \frac{H_{canopy}}{W_{bankfull}} = 0 - 1 \\ 1.0 & \frac{H_{canopy}}{W_{bankfull}} >= 1.0 \end{pmatrix}$$

Where $shading$ is a suitability index for channel shading and W_{buffer} is average width of the riparian buffer in a reach as delineated in GIS (in ft).

Second, canopy cover of the channel was assessed visually from within the stream based on a qualitative scale (Appendix B, Figure B1, "Stream Canopy Cover"). Thresholds in this process are adopted from the QHEI stream assessment protocol (Rankin 2006). In addition to visual estimates, field teams are encouraged to explore other more empirical approaches such as use of a densiometer.

$$cancov = 0.05 * S_{cancov}$$

Where $cancov$ is a suitability index for canopy coverage of the stream and S_{cancov} is a 0-20 qualitative scale defined in Appendix B.

These two simple metrics were combined to provide an overall index of the relative contribution of a riparian area to temperature and light regulation.

$$temp = \frac{shading + cancov}{2}$$

Where $temp$ is a suitability index for temperature and light regulation.

Organic Matter Subsidy ($carbon$)

Stream food webs obtain energy from inside of the stream (i.e., "autochthonous" sources such as algal growth) and outside of the stream (i.e., "allochthonous" sources such as leaf litter and coarse woody debris input). The relative ratio of internally and externally derived carbon varies with size of the stream, land use conditions upstream, and level of disturbance in the riparian zone. This metric assesses the contribution of different carbon sources as a proxy for energy input and its role in driving food web structure.

First, riparian forest structure was used as a surrogate for the diversity of available carbon sources. The quality of the overstory, midstory, and understory were each assessed visually as high, medium, or low. A "high quality" assessment is assumed to be a diverse native assemblage of trees for this particular vertical layer of the forest. Diversity should be considered relative to high functioning ecosystems in the region. These qualitative assessments were translated into quantitative scores of 2, 1, and 0 for high, medium, and low, respectively. The overall canopy structure is computed as the sum of the three layers. For instance, a high quality score for each layer gives a maximum score of 6.

$$canstr = 0.1667 * (S_{overstory} + S_{midstory} + S_{understory})$$

Where $canstr$ is a suitability index for canopy structure of the riparian forest, $S_{overstory}$ is a 0, 1, or 2 score for overstory, $S_{midstory}$ is a 0, 1, or 2 score for midstory, and $S_{understory}$ is a 0, 1, or 2 score for understory.

Second, carbon sources must not only be diverse in nature, but also retained in the stream long enough to be consumed. The second metric focuses on carbon retention within the stream. A qualitative scoring system was developed to assess the potential for washout or storage of leaf matter and wood within the stream (Appendix B).

$$carbret = 0.05 * S_{carbret}$$

Where $carbret$ is a suitability index for canopy coverage of the stream and $S_{carbret}$ is a 0-20 qualitative scale defined in Appendix B.

These two simple metrics were combined to provide an overall index of the relative contribution of a riparian area to temperature and light regulation.

$$carbon = \frac{canstr + carbret}{2}$$

Where $carbon$ is a suitability index for organic matter subsidy of the riparian zone to the stream.

4.2 Native Faunal Habitat (I_{fauna})

Riparian zones are important ecosystems in their own right, and the fauna module addresses the role of riparian zones in providing habitat for diverse native fauna. Three main habitat quality outcomes are included in the SMURF assessment: (1) avian taxa, (2) select small mammals and bats, (3) reptiles and amphibians (i.e., herpetofauna). Additionally, a fourth category is included, which addresses the prevalence of invasive flora and its role in habitat quality for native fauna. The variables associated with each of these processes are presented below along with any proxy metrics used in the assessment. The native faunal habitat index (I_{fauna}), was assessed as the arithmetic mean of the four metrics.

$$I_{fauna} = \frac{birds + mammals + herps + veg}{4}$$

Where I_{fauna} is an index of a riparian zone's contribution to habitat processes, $birds$ is a suitability index for generalized avian taxa, $mammals$ is a suitability index for small mammals and bats, $herps$ is a suitability index for generalized reptile and amphibian habitat, and veg is a suitability index for vegetation community composition. All variables are quality metrics scaled from 0 to 1, where 0 is unsuitable and 1 is ideal. Figure 5 summarizes all suitability curves associated with faunal function.

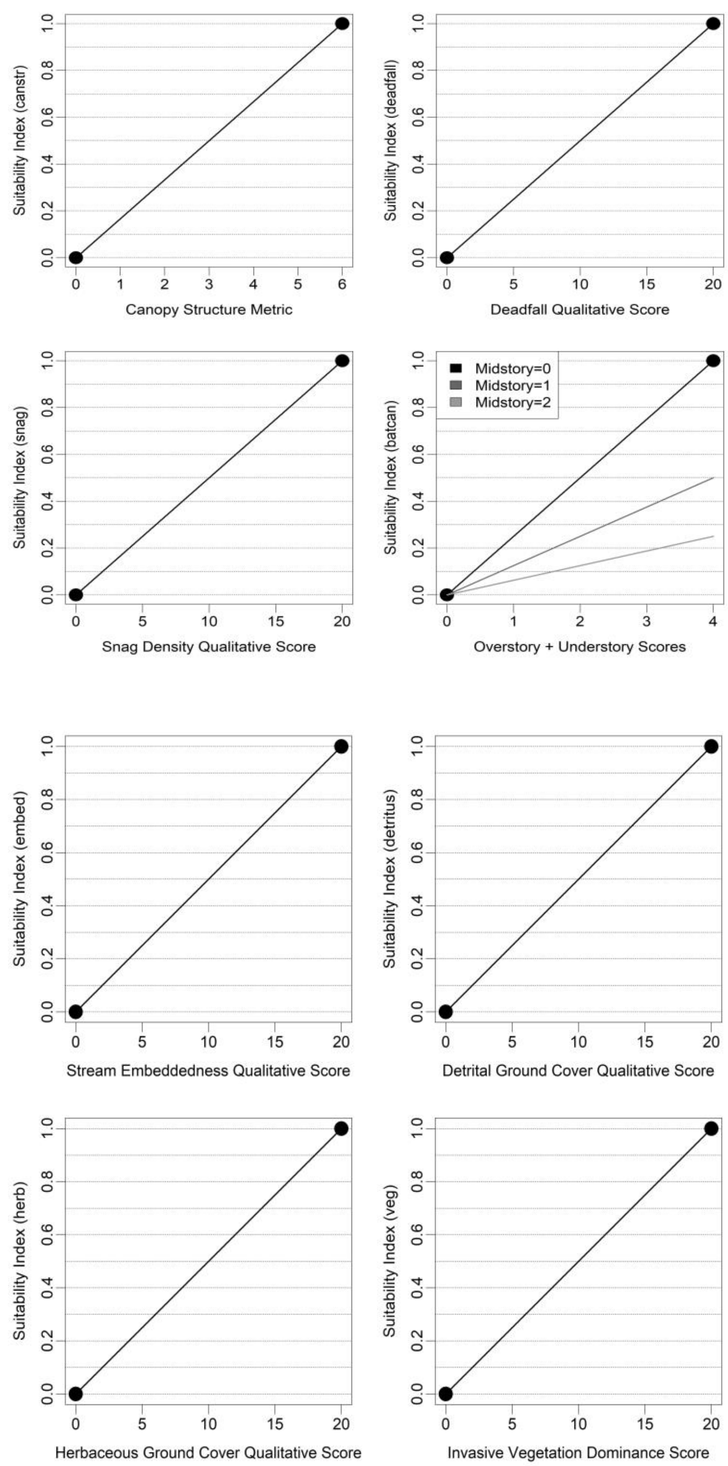

Figure 5. Suitability curves for the fauna module.

Avian Habitat ($birds$)

Avian species frequently utilize urban riparian forests as corridors throughout the year for foraging and nesting (Rottenborn 1999). Several factors affect how many species of bird can utilize a riparian forest for nesting, but canopy complexity can be rapidly assessed and is likely to have the greatest impact on biodiversity.

Forest canopy structure has been widely acknowledged as an important indicator of forest health and, generally, the more complex a canopy structure is, the greater the biodiversity found within the forest (MacArthur and MacArthur 1961, Kelly 2018, Storch et al. 2018). This is especially true concerning bird species, many of which rely on the presence of a relatively narrow niche to thrive (e.g. a certain food source or a certain layer of canopy required for nesting). The greater layering and species diversity a riparian forest exhibits, the more likely it is to possess habitat suitable to a given species.

Canopy structure was assessed using the basic quality and structure metrics described in the $carbon$ metric above.The quality of the overstory, midstory, and understory were each assessed visually as high, medium, or low. A “high quality” assessment is assumed to be a diverse native assemblage of trees for this particular vertical layer of the forest. These qualitative assessments were translated into quantitative scores of 2, 1, and 0 for high, medium, and low, respectively. The overall canopy structure is computed as the sum of the three layers. For instance, a high quality score for each layer gives as maximum score of 6. This canopy structure metric provides the overall metric for avian habitat (i.e., $birds = canstr$).

$$canstr = 0.1667 * (S_{overstory} + S_{midstory} + S_{understory})$$

Where $canstr$ is a suitability index for canopy structure of the riparian forest, $S_{overstory}$ is a 0, 1, or 2 score for overstory, $S_{midstory}$ is a 0, 1, or 2 score for midstory, and $S_{understory}$ is a 0, 1, or 2 score for understory, .

Small Mammal and Bat Habitat ($mammals$)

Two focal groups of mammals are assessed within SMURF: small mammals and bats. In urban and agricultural areas, it is thought that riparian forest corridors are an important refuge for small mammal species generally considered pests (e.g. mice, shrews, voles, etc.). Small mammal presence has been shown to be positively associated with the abundance of fallen logs (Miklos and Ziak 2002) and many species use deadwood as forest runways, for shelter, and for nesting (Bowman et al. 1999).

$$deadfall = 0.05 * S_{deadfall}$$

Where $deadfall$ is a suitability index for fallen logs in the riparian zone and $S_{deadfall}$ is a 0-20 qualitative scale defined in Appendix B.

Riparian corridors also provide essential habit to Kentucky's 14 resident bat species, 3 of which are federally endangered. Bat species are of special concern as white-nose syndrome moves across the U.S., resulting in the wide-scale decline of many bat species. In urbanized landscapes, natural maternity roosting habitat may be limited and maternity colonies are often unwelcome on man-made structures (Brittingham and Williams 2000). Snags in riparian corridors can provide this roosting habitat as well as a safe place for juveniles to learn to hunt and fly (Gardner et al. 1991, Britzke et al. 2003). The availability of standing deadwood (i.e., snags) was assessed on a 0-20 qualitative scale (Appendix B)

$$snags = 0.05 * S_{snags}$$

Where $snags$ is a suitability index for standing deadwood suitable for roosting habitat and S_{snags} is a 0-20 qualitative scale defined in App B.

Small forest openings or gaps in canopy layers increase the thermal suitability of snags and allow for flight. Ideally, bats have room to move between overstory and woody shrub layers, and the absence of a midstory facilitates flight. The canopy metrics described above were adapted to reflect a preference for the absence of a well-developed midstory as follows.

$$batcan = 0.25 * \frac{2 - S_{midstory}}{2} * (S_{overstory} + S_{understory})$$

Where $batcan$ is a suitability index for canopy structure of the riparian forest relative to bat flight needs, $S_{overstory}$ is a 0, 1, or 2 score for overstory, $S_{midstory}$ is a 0, 1, or 2 score for midstory, and $S_{understory}$ is a 0, 1, or 2 score for understory, .

These three simple metrics were combined to provide an overall index of the relative contribution of a riparian area to mammal habitat provision.

$$mammals = \frac{deadfall + snags + batcan}{3}$$

Where $mammals$ is a suitability index for small mammal and bat habitat.

Reptile and Amphibian Habitat ($herps$)

Herpetofaunal species diversity is often used itself as a metric of habitat health. As ectothermic species, both reptiles and amphibians are sensitive to the thermal conditions of streams and riparian forests. Amphibians are, in addition, susceptible to urban contaminants and must utilize both aquatic and terrestrial habitats within the riparian zone to complete their life cycle.

As aquatic larvae, amphibians in streams are susceptible to habitat reduction when potential cover objects (e.g. boulders, driftwood) are heavily embedded in silt or sand. Larvae use these sites to shelter from predators as well as to avoid fast-flowing stream waters. Lowe and Bolger (2002) found stream embeddedness to be negatively correlated with larval salamander abundance along with several other factors that increase fine particulate availability near streams. A qualitative embeddedness scale was adapted from the EPA's Rapid Bioassessment Protocol (Barbour et al. 1999) and the Qualitative Habitat Evaluation Index (QHEI, Rankin 2006), which is presented in Appendix B.

$$embed = 0.05 * S_{embed}$$

Where $embed$ is a suitability index for stream embeddedness and S_{embed} is a 0-20 qualitative scale defined in Appendix B.

In their terrestrial life stage, woody debris and leaf litter density provide moist, protected habitat to many species of salamanders and frogs (Whiles and Grubaugh 1996). Several salamander species even exhibit territorial defense of fallen logs, potentially making deadfall a limiting resource for these species (Mathis 1989, Chivers et al. 1994, Lang and Jaeger 2000). Herpetofauna also use leaf litter to move over the forest floor avoiding desiccation, actively foraging, or sheltering from predators (O'Donnell et al. 2014). Herbaceous vegetation also provides additional shelter and cover. All three metrics were assessed qualitatively with a simple scoring system and translated into a suitability index as follows:

$$deadfall = 0.05 * S_{deadfall}$$

$$detritus = 0.05 * S_{detritus}$$

$$herb = 0.05 * S_{herb}$$

Where $deadfall$ is a suitability index for fallen logs in the riparian zone, $S_{deadfall}$ is a 0-20 qualitative scale, $detritus$ is a suitability index for detrital leaf fall, $S_{detritus}$ is a 0-20 qualitative scale, $herb$ is a suitability index for herbaceous vegetation cover, and S_{herb} is a 0-20 qualitative scale. All qualitative scales are defined in Appendix B.

These four simple metrics were combined to provide an overall index of the relative contribution of a riparian area to reptile and amphibian habitat provision.

$$herps = \frac{embed + deadfall + detritus + herb}{4}$$

Where $herps$ is a suitability index for herpetofauna habitat.

Vegetation Community Composition (veg)

Invasive species such as kudzu, privet hedge, multiflora rose, Russian olive, and English ivy can rapidly homogenize riparian habitats if left unchecked (Cheng 2007, Fischer et al. 2012). This homogenization is of particular conservation concern, as it reduces the biodiversity of both flora and fauna. Because invasive species out-compete native plants, forests colonized by them typically become tightly packed and exhibit low canopy complexity and limited species diversity. The invasive species dominance of a plant community should therefore be taken into account when considering the health and potential of a riparian forest. A qualitative score was developed and translated into a suitability index as follows.

$$veg = 0.05 * S_{inv}$$

Where veg is a suitability index for vegetation community composition within the riparian zone and S_{inv} is a 0-20 qualitative scale defined in Appendix B.

4.3 *Ecological Corridor* ($I_{corridor}$)

Riparian zones serve as movement corridors for a variety of taxa, and their role as corridors is distinct from effects on instream processes or as habitat. Said differently, Wenger (1999) states, "Because there is general agreement that riparian buffers offer important high-quality habitat, there is little need to debate their merits as movement corridors at this time." Three categories of corridor impacts and functions are used within SMURF, namely: (1) the extent of development within the corridor, (2) the degree of "edge" habitat, and (3) the degree of confinement associated with the width of the riparian area. The variables associated with each of these processes are presented below along with proxy metrics used in the assessment. The corridor index ($I_{corridor}$), was assessed as the arithmetic mean of the three categories metrics.

$$I_{corridor} = \frac{bufdev + edge + confine}{3}$$

Where $I_{corridor}$ is an index of a riparian zone's function as an ecological corridor, $bufdev$ is a suitability index for buffer development, $edge$ is a suitability index for edge effects, and $confine$ is a suitability index describing the confinement of the zone relative to width. All variables are quality metrics scaled from 0 to 1, where 0 is unsuitable and 1 is ideal. Figure 6 summarizes all suitability curves associated with faunal function.

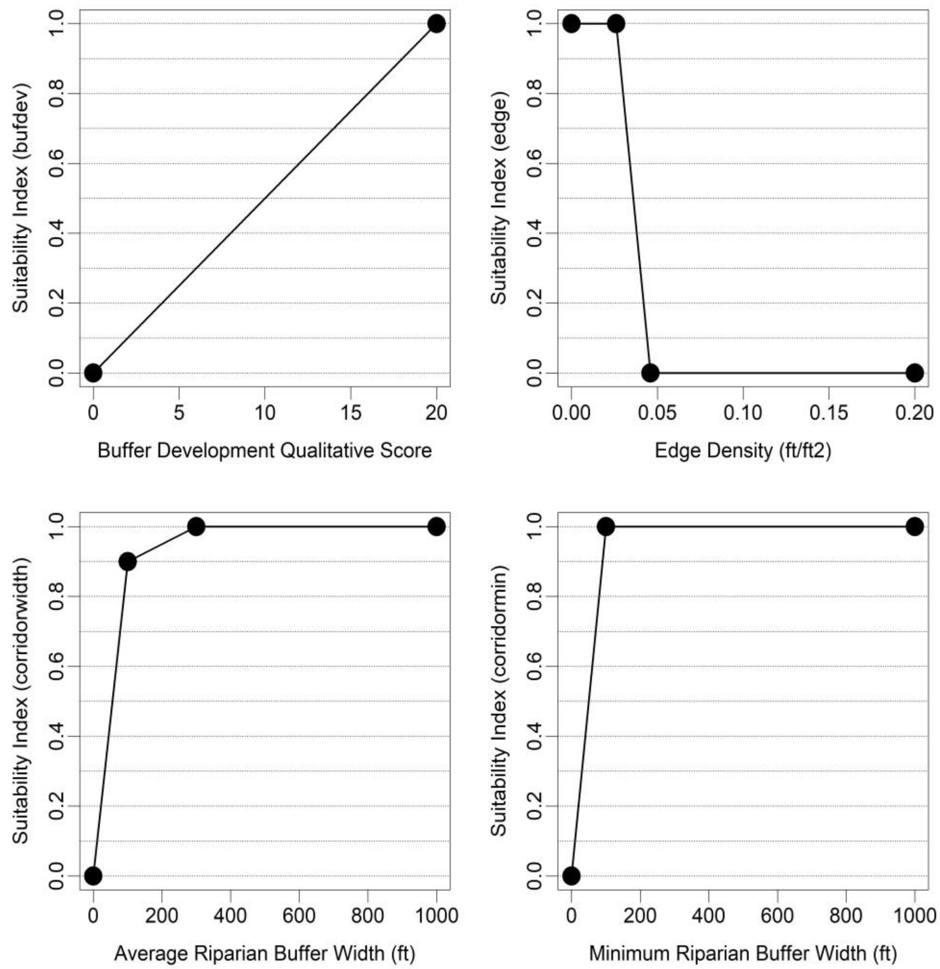

Figure 6. Suitability curves for the corridor module.

Buffer Development ($bufdev$)

Riparian zones are important ecotones between upland and aquatic systems, and their societal value is often high for uses ranging from recreational greenways to infrastructure rights-of-way to aesthetic benefits of viewing streams. Development and human use can disturb riparian zones and disrupt their functions as animal movement corridors. A qualitative scoring scale was used to assess the general level of development effects on buffer function (Appendix B).

$$bufdev = 0.05 * S_{bufdev}$$

Where $bufdev$ is a suitability index for buffer development and S_{bufdev} is a 0-20 qualitative scale defined in Appendix B.

Edge Effects ($edge$)

Animal movement and behavior can be impacted by development outside of the riparian zone. For instance, many bird species are sensitive to edge effect. Kelly (2018) found that both the overall Shannon Wiener Diversity Index for birds and percent presence of insectivores decreased in Kentucky wetlands as disturbance increased. By assessing the spatial structure of the edge of the riparian zone, bird species' sensitivity to disturbance can be taken into account. Edge density accounts for the relative proportion of edge length to interior habitat area. Rohde et al. (2005) report edge densities for regulated, restored, and "near-natural" rivers in Switzerland. We adopted this methodology and assume that the average edge density for their "near-natural" sites (~850 m/ha or 0.026 ft/ft^2) is a lower limit for the best possible habitat quality, and that suitability declines linearly as edge density increases. We then use their maximum observed edge density (~1,500 m/ha or 0.046 ft/ft^2) as an upper limit for the lowest habitat suitability.

$$edge = \begin{pmatrix} 1.0 & \frac{L_{buffer}}{A_{edge}} < 0.026 \\ 2.3 - 50 * \frac{L_{buffer}}{A_{edge}} & \frac{L_{buffer}}{A_{edge}} = 0.026 - 0.046 \\ 0.0 & \frac{L_{buffer}}{A_{edge}} > 0.046 \end{pmatrix}$$

Where $edge$ is a suitability index for the hydrologic and water quality benefits associated with a wide buffer strip, A_{buffer} is the area of the riparian buffer in a reach as delineated in GIS (in ft^2), and L_{edge} is the exterior length of the polygon defining the area (in ft).

Buffer Confinement ($confine$)

Corridor functions may be limited by the width of a riparian zone. Here, average and minimum width of a riparian zone are used as proxies for how animal movement may be limited along a corridor. Reach-averaged buffer width provides a general metric, and suitability thresholds are set based on meta-analyses by Fischer and Fischenich (2000) and Wenger (1999), who identify 100 ft (~30m) and 300 ft (~100m) as common recommendations from other studies.

$$corridorwidth = \begin{pmatrix} 0.009 * W_{buffer} & W_{buffer} = 0 - 100 \\ 0.85 + 0.0005 * W_{buffer} & W_{buffer} = 100 - 300 \\ 1.0 & W_{buffer} >= 300 \end{pmatrix}$$

Where $corridorwidth$ is a suitability index for the hydrologic and water quality benefits associated with a wide buffer strip and W_{buffer} is the average width of the riparian buffer in a reach as delineated in GIS (in ft).

Additionally, the most narrow riparian width of a given reach could provide a "pinch point" for movement. Impacts are conceptualized as width decreases below 100 ft (~30m), which is a common threshold as described above.

$$corridormin = \begin{pmatrix} 0.01 * W_{bufmin} & W_{bufmin} = 0 - 100 \\ 1.0 & W_{bufmin} >= 100 \end{pmatrix}$$

Where $corridormin$ is a suitability index representing local confinement of the riparian zone relative to movement corridors and W_{bufmin} is the minimum width of the riparian buffer in a sample reach as delineated in GIS (in ft).

These two metrics were combined to provide an overall index of the relative confinement of a riparian area.

$$confine = \frac{corridorwidth + corridormin}{2}$$

Where $confine$ is a suitability index for riparian corridor confinement.

4.4 *Numerical Model*

As described in Sections 4.1-4.3, SMURF is a tool for evaluating general riparian quality based on many separate lines of evidence. Input data to SMURF include a variety of field observations (e.g., bankfull channel dimensions) and desktop analyses (e.g., buffer width), which are assessed separately outside of the model. A single function was developed to combine inputs into suitability indices for each module as well as an overarching habitat suitability index and habitat units.

The `SMURF` function was programmed in the open-source, USACE-approved, R statistical software language. The model utilizes the ecorest package for conducting habitat suitability analyses. `ecorest` provides a suite of functions for computing suitability indices and habitat units, given a set of suitability index curves defined by breakpoints as shown in Figures 4-6. The package then allows for computation of an overarching habitat suitability index based on multiple suitability curves. Effectively, `SMURF` is an application-specific wrapper for `ecorest`. The `ecorest` package is being reviewed and certified for USACE use separately from `SMURF` (McKay et al. *draft*).

As presented below, `SMURF` has seven inputs: three sets of suitability curves corresponding to the modules (`instream`, `fauna`, `corridor`), three sets of application-specific inputs to the modules (`site.instream`, `site.fauna`, `site.corridor`), and an area associated with the assessed riparian zone (`site.area`). The application-specific inputs are vectors of input variables as described in Sections 4.1-4.3 and Appendix B. The `SMURF` subsequently outputs a simple data frame with six fields corresponding to the quality index for each module, an overarching habitat quality index, the site area, and the number of habitat units.

```
#Import and return suitability index curves for instream module
instream <- read.csv("SMURF_Parameters_2020-09-10_instream.csv", header=TRUE, dec=".")
instream

##   hydatt hydatt.SI stripwidth.ft stripwidth.SI flowpath.score flowpath.SI
## 1    0.0         1             0           0.0              0           0
## 2    1.5         1            30           0.5             20           1
## 3    3.0         0           100           0.9             NA          NA
## 4    5.0         0           300           1.0             NA          NA
## 5     NA        NA          1000           1.0             NA          NA
##   shading.ratio shading.SI cancov.score cancov.SI canstr.score canstr.SI
## 1             0          0            0         0            0         0
## 2             1          1           20         1            6         1
## 3            10          1           NA        NA           NA        NA
## 4            NA         NA           NA        NA           NA        NA
## 5            NA         NA           NA        NA           NA        NA
##   carbret.score carbret.SI
## 1             0          0
## 2            20          1
## 3            NA         NA
## 4            NA         NA
## 5            NA         NA

#Import and return suitability index curves for fauna module
fauna <- read.csv("SMURF_Parameters_2020-09-10_fauna.csv", header=TRUE, dec=".")
fauna

##   canstr.score canstr.SI deadfall.score deadfall.SI snag.score snag.SI
## 1            0         0              0           0          0       0
## 2            6         1             20           1         20       1
##   batcan.score batcan.SI embed.score embed.SI detritus.score detritus.SI
## 1            0         0           0        0              0           0
## 2            4         1          20        1             20           1
##   herb.score herb.SI inv.veg.score inv.veg.SI
## 1          0       0             0          0
## 2         20       1            20          1

#Import and return suitability index curves for corridor module
corridor <- read.csv("SMURF_Parameters_2020-09-10_corridor.csv", header=TRUE, dec=".")
corridor

##   buffer.dev.Score buffer.dev.SI edge.density.perft edge.density.SI
## 1                0             0              0.000               1
## 2               20             1              0.026               1
## 3               NA            NA              0.046               0
## 4               NA            NA              0.200               0
##   corridorwidth.ft corridorwidth.SI corridormin.ft corridormin.SI
## 1                0              0.0              0              0
## 2              100              0.9            100              1
## 3              300              1.0           1000              1
## 4             1000              1.0             NA             NA
```

```
#Describe inputs to SMURF

#ecorest suitability format is parameter columns followed by SI value columns. The paired
"breakpoints" define a suitability index curve.

#instream = data frame of suitability curves defining instream module (in ecorest format)
#site.instream = vector of site-specific inputs for the instream module
  #variables are: hyd.att, stripwidth.ft, flowpath.score, shading.ratio,
  #               cancov.score, canstr.score, and carbret.score

#fauna = data frame of suitability curves defining the fauna module (in ecorest format)
#site.fauna = vector of site-specific inputs for the fauna module
  #variables are: canstr.score, deadfall.score, snag.score, batcan.score,
  #               embed.score, detritus.score, herb.score, and inv.veg.score

#corridor = data frame of suitability curves defining the corridor module (in ecorest form
at)
#site.corridor = vector of site-specific inputs for the corridor module
  #variables are: buffer.dev.Score, edge.density.perft, corridorwidth.ft, & corridormin.ft

#site.area = area of riparian zone being assessed (typically acres)
##########
#Specify function for executing the SMURF model

SMURF <- function(instream, site.instream, fauna, site.fauna, corridor, site.corridor, sit
e.area){
  #Create empty matrices to store suitability outputs
  SI.instream <- c(); SI.fauna <- c(); SI.corridor <- c()

  #Calculate suitability indices for each input variable and module using SIcalc( ) from t
he ecorest package
  SI.instream <- SIcalc(instream, site.instream)
  SI.fauna <- SIcalc(fauna, site.fauna)
  SI.corridor <- SIcalc(corridor, site.corridor)

  #Create empty data frame to store outputs (Instream SI, Habitat SI, Corridor SI, HSI, Ar
ea, Habitat Units)
  SMURF.out <- as.data.frame(matrix(NA, nrow = 1, ncol = 6))
  colnames(SMURF.out) <- c("Instream.SI", "Fauna.SI", "Corridor.SI", "HSI", "Area", "HU")

  #If any input is NA, return NA
  if (sum(is.na(c(site.instream,site.fauna,site.corridor))) > 0){
    SMURF.out$Instream.SI <- NA
    SMURF.out$Fauna.SI <- NA
    SMURF.out$Corridor.SI <- NA
    SMURF.out$HSI <- NA
    SMURF.out$Area <- NA
    SMURF.out$HU <- NA
  }

  #Else compute all other outputs
  else{
    #Compute module-specific habitat suitability indices using HSIarimean( ) from the ecor
est package - ARITHMETIC MEAN
    SMURF.out$Instream.SI <- HSIarimean(SI.instream)
    SMURF.out$Fauna.SI <- HSIarimean(SI.fauna)
    SMURF.out$Corridor.SI <- HSIarimean(SI.corridor)

    #Compute overarching habitat suitability index and habitat units
    SMURF.out$HSI <- (SMURF.out$Instream.SI * SMURF.out$Fauna.SI * SMURF.out$Corridor.SI)
^ (1/3)
    SMURF.out$Area <- site.area
    SMURF.out$HU <- SMURF.out$HSI * SMURF.out$Area
  }
  #Send output from function
  SMURF.out
}
```

5 Evaluation

Ecological models typically rely on multiple variables, ecological processes, and in many cases present a variety of ecological outcomes. As such, models can quickly become complex system representations with many components, inputs, assumptions, and modules. Model evaluation is the process for ensuring that numerical tools are scientifically defensible and transparently developed. Evaluation is often referred to as verification or validation, but it in fact includes a family of methods ranging from peer review to model testing to error checking (Schmolke et al. 2010). The USACE has established an ecological model certification process to ensure that planning models are sound and functional. These generally consist of evaluating tools relative to the three following categories: system quality, technical quality, and usability (EC 1105-2-412).

5.1 *System Quality*

System quality refers to the computational integrity of a tool and involves assessing the numerical accuracy of a model. System quality has three primary phases for avoiding errors (quality assurance), detecting errors through formal testing (quality control), and updating models based on review and use (model update) (McKay et al. 2020b).

Multiple quality assurance practices were followed throughout the development of SMURF. First, the simple workflow of a single function minimizes potential locations for errors. Second, code was written following a standard style used by the first author in more than a dozen prior models. Third, all code was documented extensively with in-line comments during development to articulate model logic, clarify naming conventions, and avoid editing errors. Fourth, model documentation was developed as functions were constructed using R Markdown. Fifth, model versions were controlled by date-stamping all input and model files.

Additionally, quality control procedures were applied to find and correct any errors. The first author used interim line-level checks of code to verify functionality. A colleague with R expertise subsequently inspected and verified the model. Finally, a test plan was devised to examine the overarching function as well as the computation of the instream, fauna, and corridor indices. Specifically, the test approach and results are as follows:

- Boundary conditions: A set of site-specific model inputs were derived, which represent the lowest and highest possible suitability values for SMURF. These “worst” and “best” case scenarios were then used to test the limits of the `SMURF`. For instance, a set of “worst” case inputs should result in 0 habitat suitability at both the module and overarching stages of computation. All combinations of worst and best case inputs were examined for each module. Table 4 summarizes these tests, all of which produce the expected outcome. **TEST RESULT = PASS**.

- Instream Suitability: Five input sets were developed for the instream module, to verify the computation of each suitability index. The data sets were pseudo random and intended to provide values that could be easily verified through manual calculations. Table 5 summarizes these tests, all of which produce the expected outcome. **TEST RESULT = PASS**.

- Fauna Suitability: Five input sets were developed for the fauna module, to verify the computation of each suitability index. The data sets were pseudo random and intended to provide values that could be easily verified through manual calculations. Table 6 summarizes these tests, all of which produce the expected outcome. **TEST RESULT = PASS**.

- Corridor Suitability: Five input sets were developed for the corridor module, to verify the computation of each suitability index. The data sets were pseudo random and intended to provide values that could be easily verified through manual calculations. Table 7 summarizes these tests, all of which produce the expected outcome. **TEST RESULT = PASS**.

Table 4. Model testing with extreme inputs for each module. Worst and Best indicate the worst and best possible input values, which should correspond to suitability indices of 0 and 1, respectively. Area is also varied to test sensitivity to input area values.

Instream Input	Fauna Input	Corridor Input	Instream SI	Fauna SI	Corridor SI	HSI	Area	HU
Worst	Worst	Worst	0	0	0	0	100	0
Best	Worst	Worst	1	0	0	0	100	0
Worst	Best	Worst	0	1	0	0	100	0
Worst	Worst	Best	0	0	1	0	100	0
Best	Best	Worst	1	1	0	0	100	0
Best	Worst	Best	1	0	1	0	100	0
Worst	Best	Best	0	1	1	0	100	0
Best	Best	Best	1	1	1	1	100	100
Best	Best	Best	1	1	1	1	0	0
Best	Best	Best	1	1	1	1	50	50

Table 5. Model testing for instream module.

hyd.att	stripwidth.ft	flowpath.score	shading.ratio	cancov.score	canstr.score	carbret.score	Instream.SI
1.5	120	12	5	20	1	10	0.74
0.5	25	6	2	5	6	4	0.60
2.0	250	18	4	15	3	20	0.83
6.0	250	14	3	10	2	16	0.62
3.0	75	2	1	10	4	12	0.52

Table 6. Model testing for fauna module.

canstr.score	deadfall.score	snag.score	batcan.score	embed.score	detritus.score	herb.score	inv.veg.score	Fauna.SI
6	20	2	0	2	15	17	8	0.52
0	11	5	1	12	18	1	9	0.38
1	3	10	2	20	10	15	5	0.48
4	6	15	3	5	8	11	14	0.55
2	17	20	4	15	17	18	19	0.83

Table 7. Model testing for corridor module.

buffer.dev.Score	edge.density.perft	corridorwidth.ft	corridormin.ft	Corridor.SI
0	0.005	25	20	0.36
20	0.040	750	100	0.82
5	0.010	85	60	0.65
10	0.020	125	100	0.85
15	0.030	245	200	0.88

Model errors are often uncovered during peer review and/or applications (i.e., "bugs"), which can be particularly important for large-scale or complex models. SMURF is a relatively simple tool and has been developed in the context of a single application in Beargrass Creek. However, the general framework may be easily adapted to other riparian zones and regions. As such, this report explicitly identifies the accompanying model as SMURF Version 1.0. The model and report were reviewed through USACE certification procedures, and review comments are archived here for future reference (Appendix C). This report will be published by ERDC, and the ERDC Knowledge Core will provide a means for archival of documents and associated code.

5.2 *Technical Quality*

The technical quality of a model is assessed relative to its reliance on contemporary theory, consistency with design objectives, and degree of verification and validation against independent field data. As described in Chapter 4, SMURF combines a variety of processes well-acknowledged as important to riparian ecosystem integrity. Where possible, model assessments were adopted or adapted from peer-reviewed resources. However, suitability curves and associated inputs are heavily based on professional judgment and hypothesized riparian function. Although qualitative, field-based judgments are used, these methods have been shown to provide significant utility and predictive power, and remain highly applied in stream assessment (Hughes et al. 2010). In addition to qualitative evidence of technical quality, two quantitative evaluation methods were applied: pseudo-verification with field judgments and sensitivity analysis.

Ideally, a riparian assessment procedure would be rigorously validated against empirical data for multiple ecological processes. However, validation data were not available in the Beargrass Creek system. Alternatively, field assessors were asked to provide an overall judgment of each site relative to their impression of the general riparian condition. These data provide a crude means of pseudo-verification of the SMURF framework, which is presented in Appendix D. The SMURF generally aligns with the overall professional judgment of field personnel. Interestingly, the fauna index and the overall habitat suitability index show the most agreement with the field teams, and the instream and corridor indices show the least. Faunal habitat provision could be easier to observe as a field scale than more complex off-site effects on instream processes or corridor functions. These data indicate that SMURF indices generally agree with professional judgment associated with the 104 samples in Beargrass Creek (i.e., independent left and right bank assessments at 52 access points). The general approach of pseudo-verification could provide a useful means of rapid model evaluation in future studies.

Sensitivity analysis "investigates how the variation in the output of a numerical model can be attributed to variations of its input factors" (Pianosi et al. 2016). Here, a global sensitivity analysis is undertaken using two approaches following the approaches described in Pianosi et al. (2016). First, a 'one-[factor]-at-a-time' method was applied by systematically inducing variation in each model input, while holding all other values constant at the "best case" scenario described in Section 5.1. Figure 7-9 show the effects of each parameter on the suitability index for a given module as well as the overall habitat suitability index. These analyses show that SMURF is more sensitive to inputs in the corridor module due to the lower number of suitability curves. Although the overall habitat suitability index is not dramatically altered relative to any one input, each variable can have noticeable effects on the overall index even when holding all other values at the "best case" scenario.

The second form of global sensitivity analysis used an all-[factors]-at-a-time method. The entire solution space for SMURF modules was explored comprehensively by examining inputs associated with every "breakpoint" in the model suitability curves. These combinations of inputs led to 960 input vectors for the instream module, 256 input vectors for the fauna module, and 96 input vectors for the corridor module. It was not numerically feasible to simulate the complete combination of all input vectors for SMURF as a whole (23,592,960 input data sets). Figures 10-12 present the results of the all-at-a-time analysis by showing the distribution of module indices relative to a given input. These analysis confirm the results from the one-at-a-time method and indicate that SMURF outputs are sensitive to inputs but any one input does not disproportionately dominate the analysis.

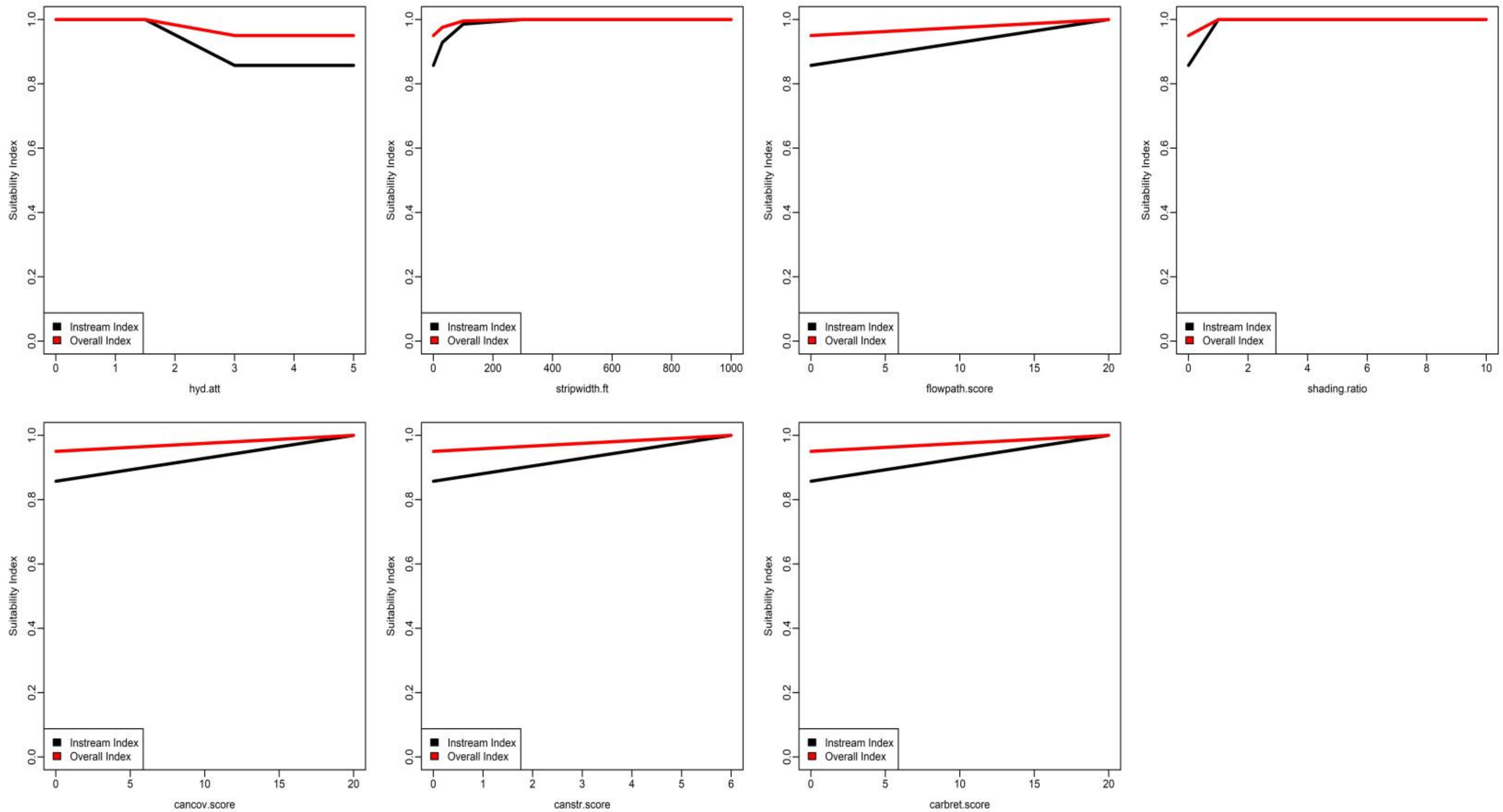

Figure 7. Local sensitivity analysis for the instream module.

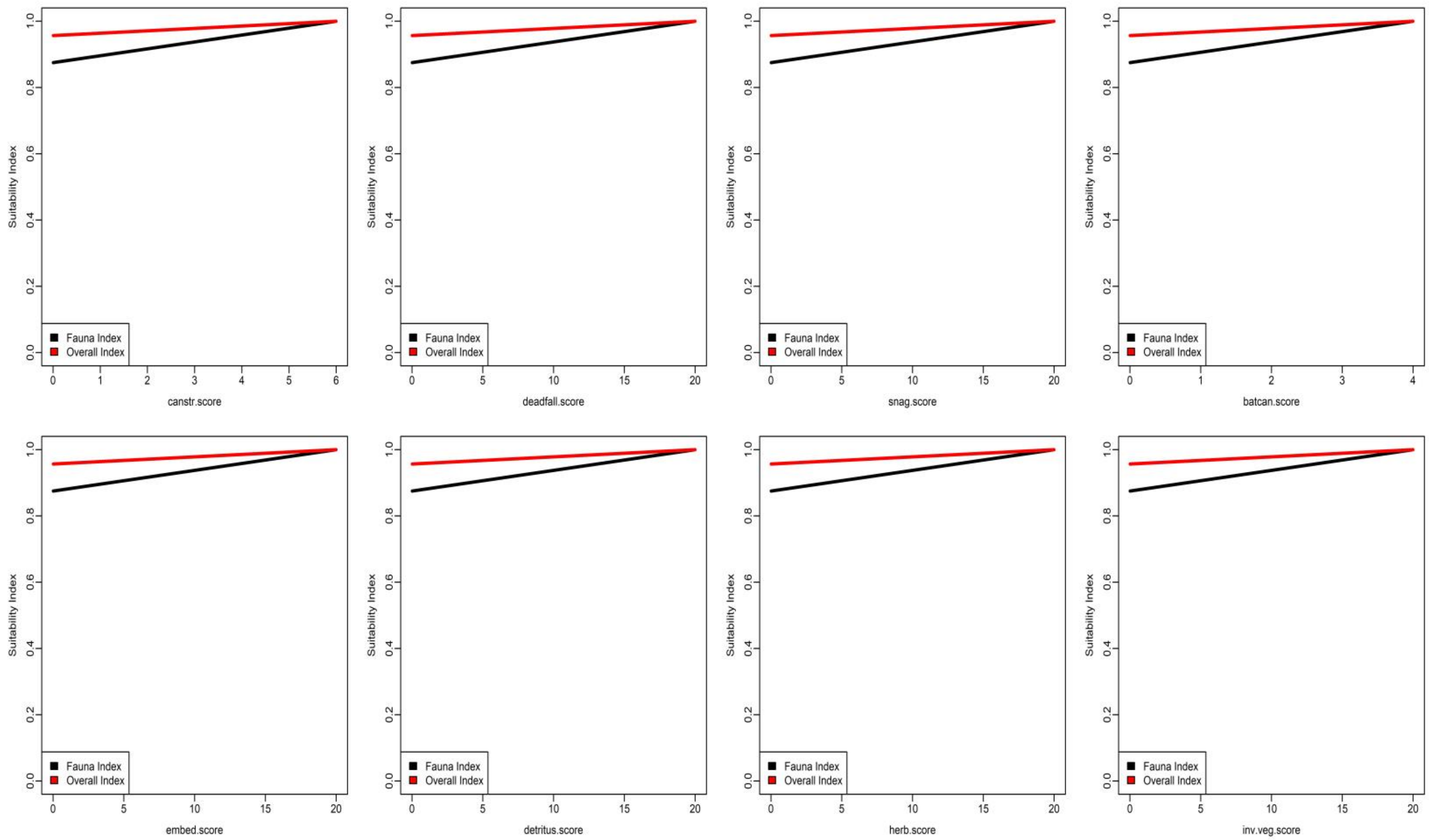

Figure 8. Local sensitivity analysis for the fauna module.

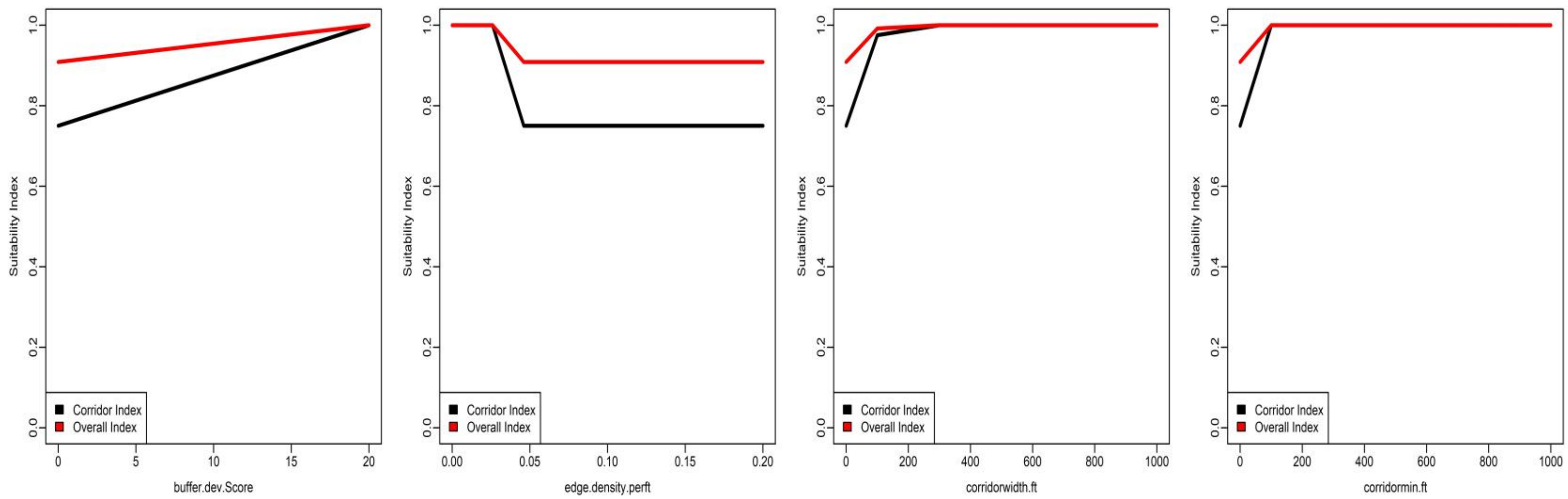

Figure 9. Local sensitivity analysis for the corridor module.

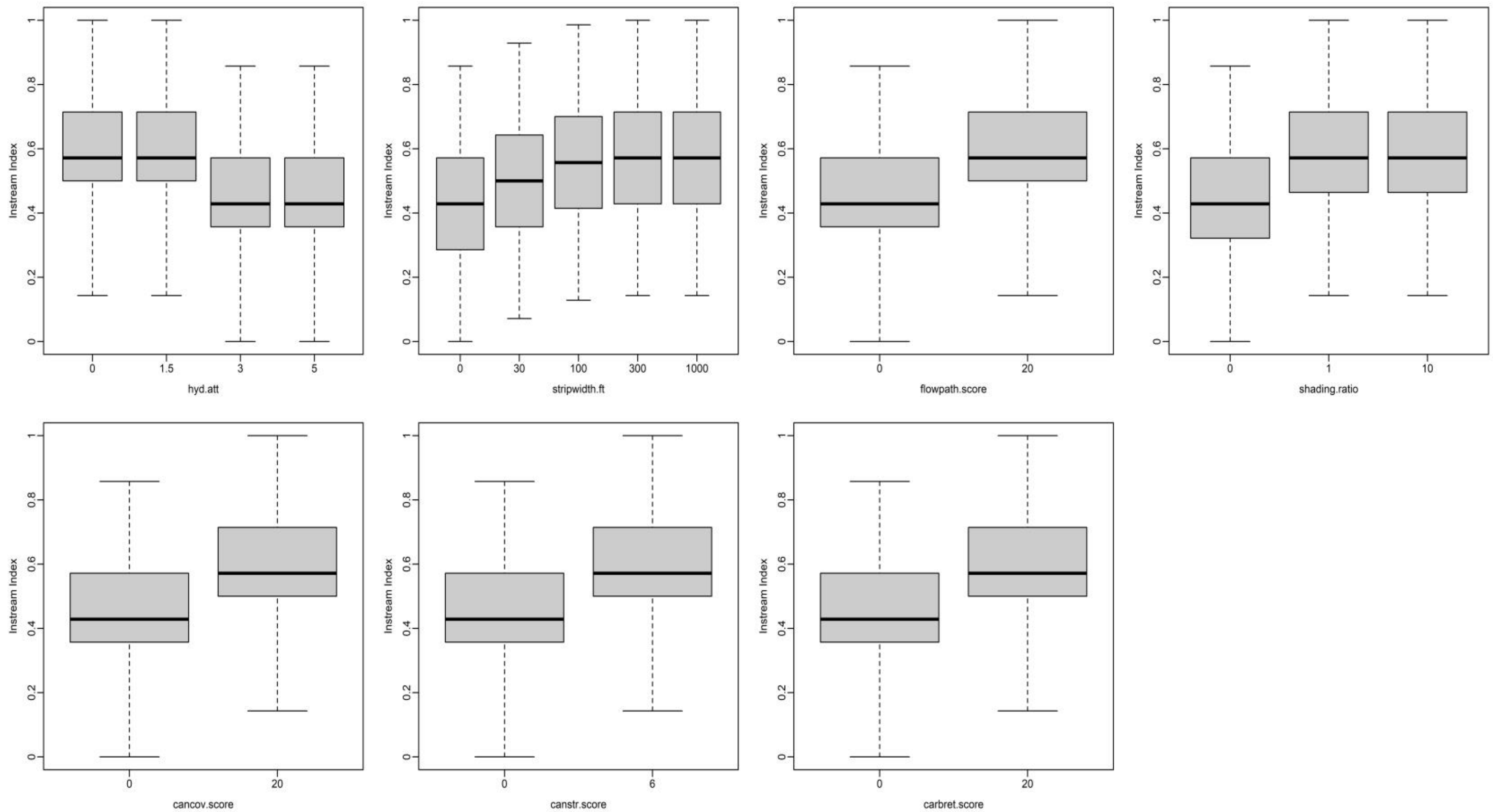

Figure 10. Global sensitivity analysis for the instream module.

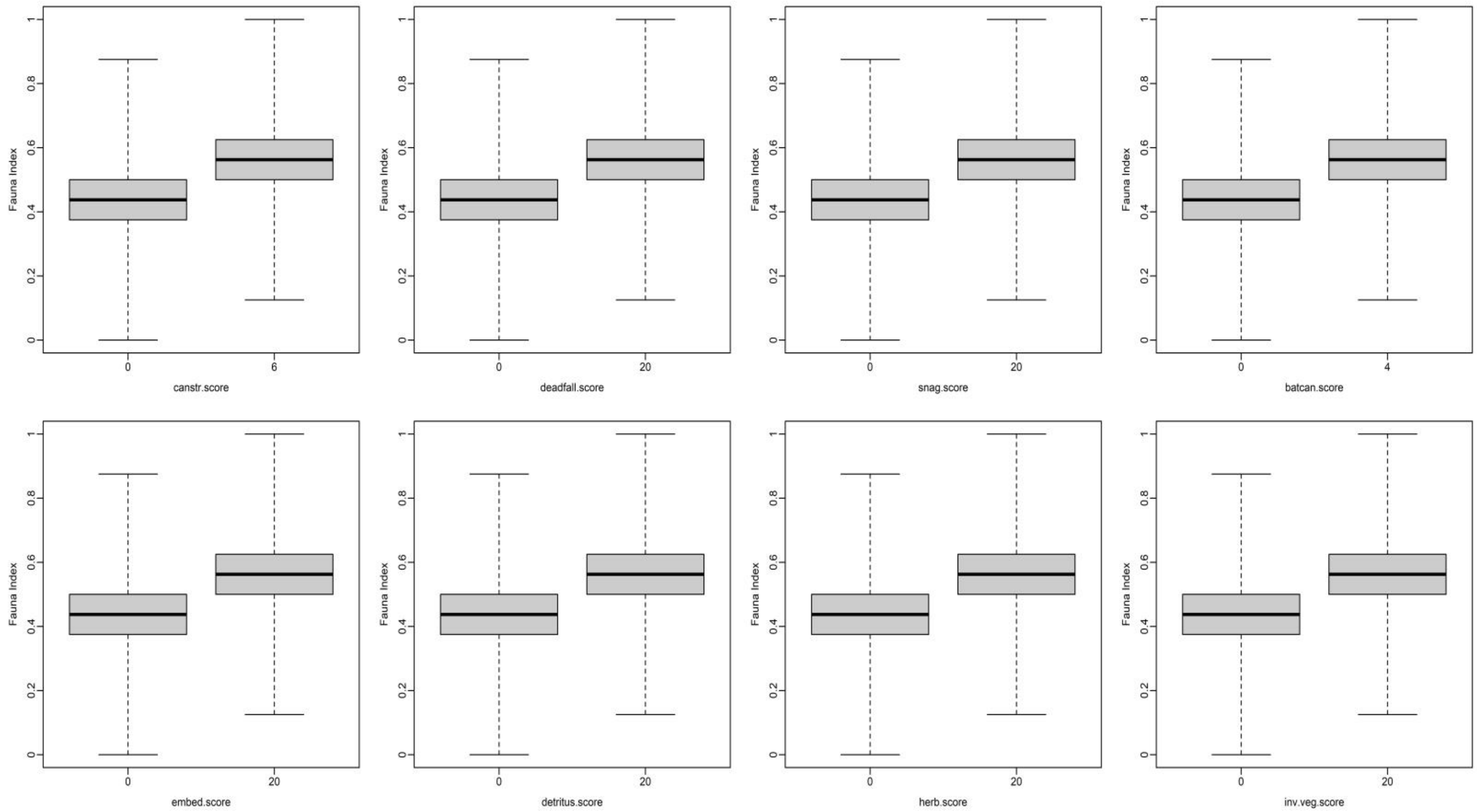

Figure 11. Global sensitivity analysis for the fauna module.

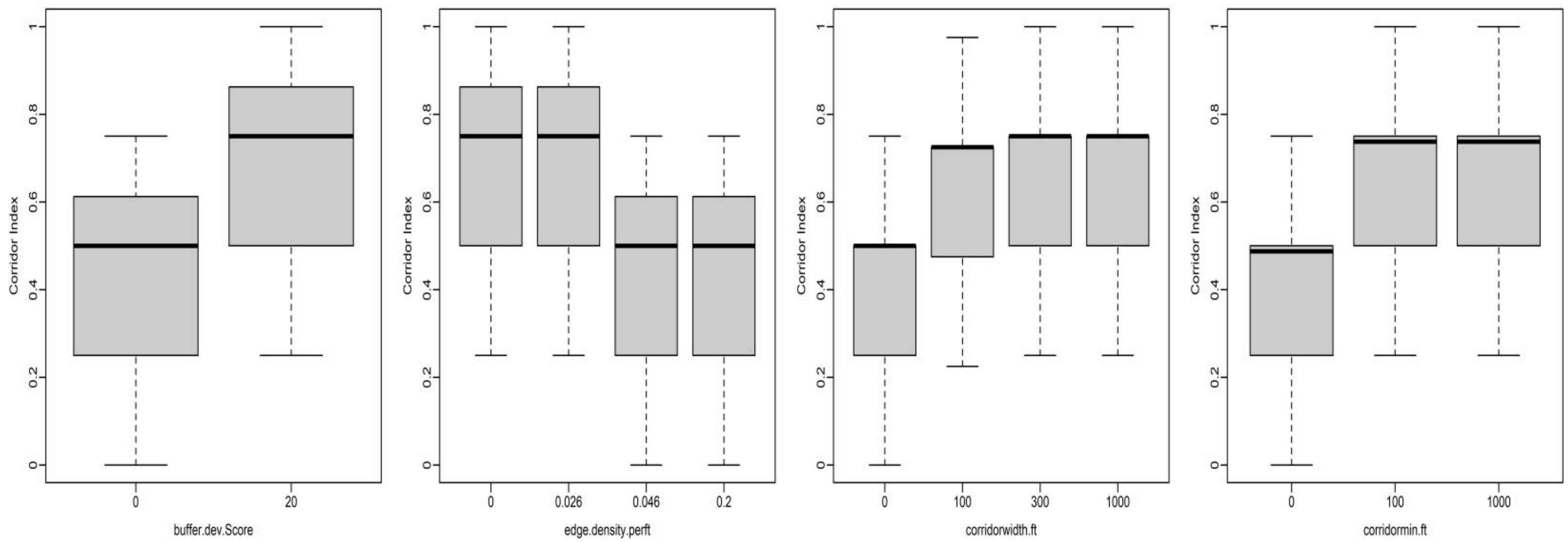

Figure 12. Global sensitivity analysis for the corridor module.

5.3 *Usability*

The usability of a model can influence the repeatable and transparent application of a tool. This type of evaluation typically examines the ease of use, availability of inputs, transparency, error potential, and education of the user. As such, defining the intended user(s) is a crucial component of assessing usability. SMURF was developed for application by the USACE technical team of the Beargrass Creek ecosystem restoration study. In its current form, the tool is not intended for broader application, and there is no associated graphical user interface beyond the script itself. However, the model is programmed in the widely available R Statistical Software language, and users familiar with R could likely apply the model easily, given its single functional form.

6 Application and Communication

SMURF could be used to assess riparian condition in a variety of applied restoration decision-making contexts (e.g., site screening, alternatives analysis, scenario planning). Here, a simple demonstration of SMURF is presented to assess existing conditions in the Beargrass Creek watershed. As described in Section 1.2, Beargrass Creek is a small urban watershed in Louisville, Kentucky. The USACE Louisville District (LRL) and Louisville Metropolitan Sewer District (MSD) are partnering to identify actions that could restore aquatic ecosystems in the watershed. The two primary objectives of the project are: (1) To reestablish quality and connectivity of *riverine* habitats and (2) To reestablish quality and connectivity of *riparian* habitats. An initial array of 50+ potential restoration sites was identified based on prior watershed assessments, local knowledge, preliminary field scouting, and desktop geospatial analyses. These sites were screened relative to technical, logistical, administrative, and policy factors, ultimately identifying 21 sites for detailed analysis.

SMURF is used here to assess existing conditions at these 21 potential restoration locations. SMURF assessments were conducted separately for left and right bank areas. Field data were collected through a coordinate campaign involving personnel from LRL and MSD from June-July 2020. Desktop geospatial analyses were conducted separately in December 2020. All data were compiled in a single Microsoft Excel spreadsheet for easy use and transfer. The assessments represent 42 independent applications of SMURF throughout the Beargrass Creek watershed (i.e., left and right bank assessments for 21 sites). The following code imports all data, compiles data into the input structure for the `SMURF` function, and executes the model. Data are archived in Appendix D (Tables D1-D8), and SMURF results are summarized in Tables 8 and 9 for the left and right bank riparian zones.

```
#Import Beargrass Data
Beargrass <- read.csv("Beargrass_Data_2021-02-11_SMURFonly_existing.csv", header=TRUE, dec=".")

#Compute the number of Beargrass Creek access point sites
nBG <- length(Beargrass$Rest_Name)

##########
#Compute derived variables and add as columns to data frame

#Shading ratio (shading)
Beargrass$Shading_Left <- Beargrass$Canopy_Height_25_Left_ft / Beargrass$Bankfull_Width_ft
Beargrass$Shading_Right <- Beargrass$Canopy_Height_25_Right_ft / Beargrass$Bankfull_Width_ft

#Canopy Structure (canstr)
Beargrass$Canstr_Left <- Beargrass$Overstory_Left + Beargrass$Midstory_Left + Beargrass$WoodyShrubs_Left
Beargrass$Canstr_Right <- Beargrass$Overstory_Right + Beargrass$Midstory_Right + Beargrass$WoodyShrubs_Right

#Bat Canopy Structure (batcan)
Beargrass$Batcan_Left <- ((2 - Beargrass$Midstory_Left) / 2) * (Beargrass$Overstory_Left + Beargrass$WoodyShrubs_Left)
Beargrass$Batcan_Right <- ((2 - Beargrass$Midstory_Right) / 2) * (Beargrass$Overstory_Right + Beargrass$WoodyShrubs_Righ
t)

##########
#Create an empty data frame to store LEFT bank inputs
BG.left <- data.frame(matrix(NA, nrow=nBG, ncol=19))
colnames(BG.left) <- c(instream.names, fauna.names, corridor.names)
rownames(BG.left) <- Beargrass$Rest_Num

#Specify inputs for instream module
BG.left[,1:7] <- cbind(Beargrass$Incision_Left, Beargrass$Buffer_Width_Mean_Left_ft,
                       Beargrass$Buffer_Flowpaths_Left, Beargrass$Shading_Left,
                       Beargrass$Stream_Canopy_Cover, Beargrass$Canstr_Left, Beargrass$OM_Retention)

#Specify inputs for fauna module
BG.left[,8:15] <- cbind(Beargrass$Canstr_Left, Beargrass$Deadfall_Left,
                        Beargrass$Snags_Left, Beargrass$Batcan_Left,
                        Beargrass$Embeddedness, Beargrass$Detritus_Left,
                        Beargrass$Herbaceous_Left, Beargrass$Invasive_Dominance_Left)

#Specify inputs for corridor module
BG.left[,16:19] <- cbind(Beargrass$Buffer_Development_Left, Beargrass$Edge_Density_Left_perft,
                         Beargrass$Buffer_Width_Mean_Left_ft, Beargrass$Buffer_Width_Min_Left_ft)

##########
#Create an empty data frame to store LEFT bank inputs
BG.right <- data.frame(matrix(NA, nrow=nBG, ncol=19))
colnames(BG.right) <- c(instream.names, fauna.names, corridor.names)
rownames(BG.right) <- Beargrass$Rest_Num

#Specify inputs for instream module
BG.right[,1:7] <- cbind(Beargrass$Incision_Right, Beargrass$Buffer_Width_Mean_Right_ft,
                        Beargrass$Buffer_Flowpaths_Right, Beargrass$Shading_Right,
                        Beargrass$Stream_Canopy_Cover, Beargrass$Canstr_Right, Beargrass$OM_Retention)

#Specify inputs for fauna module
BG.right[,8:15] <- cbind(Beargrass$Canstr_Right, Beargrass$Deadfall_Right,
                         Beargrass$Snags_Right, Beargrass$Batcan_Right,
                         Beargrass$Embeddedness, Beargrass$Detritus_Right,
                         Beargrass$Herbaceous_Right, Beargrass$Invasive_Dominance_Right)

#Specify inputs for corridor module
BG.right[,16:19] <- cbind(Beargrass$Buffer_Development_Right, Beargrass$Edge_Density_Right_perft,
                          Beargrass$Buffer_Width_Mean_Right_ft, Beargrass$Buffer_Width_Min_Right_ft)

##########
#Create empty matrix to store LEFT BANK outputs
BG.left.out <- as.data.frame(matrix(NA, nrow = nBG, ncol = 6))
colnames(BG.left.out) <- c("Instream.SI", "Fauna.SI", "Corridor.SI", "HSI", "Area", "HU")
rownames(BG.left.out) <- Beargrass$Rest_Num

#Create empty matrix to store RIGHT BANK outputs
BG.right.out <- as.data.frame(matrix(NA, nrow = nBG, ncol = 6))
colnames(BG.right.out) <- c("Instream.SI", "Fauna.SI", "Corridor.SI", "HSI", "Area", "HU")
rownames(BG.right.out) <- Beargrass$Rest_Num

#Execute SMURF for all sites
for(i in 1:nBG){
 BG.left.out[i,] <- SMURF(instream, BG.left[i,1:7], fauna, BG.left[i,8:15], corridor, BG.left[i,16:19], Beargrass$Ripari
an_Area_Left_ft2[i]/43560)
 BG.right.out[i,] <- SMURF(instream, BG.right[i,1:7], fauna, BG.right[i,8:15], corridor, BG.right[i,16:19], Beargrass$Ri
parian_Area_Right_ft2[i]/43560)
}
```

Table 8. Summary of SMURF riparian assessment at Beargrass Creek restoration site (LEFT BANK ONLY).

	Instream.SI	Fauna.SI	Corridor.SI	HSI	Area	HU
X2	0.64	0.48	0.44	0.51	13.3	6.8
X4	0.58	0.40	0.68	0.54	19.0	10.2
X5	0.64	0.42	0.60	0.54	37.4	20.4
X8	0.82	0.60	0.72	0.71	43.2	30.5
X9	0.81	0.56	0.75	0.70	7.9	5.5
X10	0.50	0.50	0.30	0.42	4.1	1.7
X11	0.69	0.49	0.59	0.58	30.0	17.5
X15	0.50	0.19	0.17	0.25	2.4	0.6
X19	0.44	0.33	0.61	0.44	8.3	3.7
X20	0.56	0.34	0.43	0.44	4.0	1.7
X21	0.61	0.45	0.25	0.41	5.6	2.3
X22	0.31	0.20	0.11	0.19	8.1	1.5
X24	0.19	0.22	0.22	0.21	3.5	0.7
X28	0.28	0.16	0.11	0.17	3.9	0.7
X29	0.74	0.41	0.70	0.59	39.2	23.3
X30	0.59	0.51	0.72	0.60	58.6	35.3
X31	0.36	0.22	0.18	0.24	3.7	0.9
X33	0.68	0.38	0.66	0.56	4.7	2.6
X34	0.65	0.46	0.54	0.54	47.2	25.7
X35	0.60	0.32	0.63	0.49	36.3	17.9
X38	0.43	0.37	0.24	0.33	3.4	1.1

Table 9. Summary of SMURF riparian assessment at Beargrass Creek restoration site (Right BANK ONLY).

	Instream.SI	Fauna.SI	Corridor.SI	HSI	Area	HU
X2	0.67	0.48	0.61	0.58	31.8	18.4
X4	0.59	0.38	0.69	0.53	32.8	17.5
X5	0.54	0.29	0.41	0.40	21.0	8.4
X8	0.81	0.57	0.69	0.68	48.3	33.0
X9	0.77	0.56	0.59	0.64	2.3	1.5
X10	0.60	0.51	0.70	0.60	14.6	8.7
X11	0.67	0.52	0.56	0.58	28.5	16.6
X15	0.49	0.19	0.14	0.24	2.3	0.5
X19	0.45	0.31	0.27	0.33	3.6	1.2
X20	0.55	0.40	0.23	0.37	2.0	0.7
X21	0.64	0.45	0.58	0.55	10.5	5.8
X22	0.29	0.21	0.09	0.17	5.9	1.0
X24	0.32	0.22	0.59	0.35	20.9	7.3
X28	0.23	0.14	0.06	0.13	0.9	0.1
X29	0.77	0.44	0.69	0.61	26.5	16.3
X30	0.46	0.25	0.26	0.31	3.3	1.0
X31	0.29	0.22	0.09	0.18	2.1	0.4
X33	0.60	0.40	0.27	0.40	1.3	0.5
X34	0.63	0.44	0.60	0.55	58.7	32.3
X35	0.62	0.49	0.66	0.59	38.6	22.7
X38	0.40	0.38	0.46	0.41	9.9	4.1

These results demonstrate how SMURF effectively distinguishes ecological outcomes in urban riparian zones. For instance, Site-X28 is a golf course with very little riparian forest, and the suitability indices and overall suitability are low (less than 0.28 for all indices). Conversely, Site-X8 is a reach with functioning riparian forests and significant wildlife observations during the site visits (all indices greater than 0.57). This analysis also shows the importance of distinguishing left and right riparian areas as unique ecosystems. For instance, Site-X2 is a location with significantly larger site area on the right bank, and thus, there are three-fold as many habitat units even though the quality assessments are similar.

SMURF may be used to forecast management and restoration outcomes through multiple mechanisms. Ideally, each parameter would be linked to a process-oriented model, such as basing channel incision on geomorphic change tools. A second approach would be to develop a “rubric” for how inputs should be consistently varied across time and management alternatives. For instance, in Beargrass Creek project planning, a set of rules were used to modify each model input (e.g., a percent change in the deadfall parameter) in response to a specific alternative (e.g., riparian planting) at a specific point in time (e.g., Year-50); these guidelines facilitates consistent model application across many sites. A third approach would be to adjust model inputs based on professional judgment and knowledge.

7 Summary

This report has documented the development of a Simple Model for Urban Riparian Function (SMURF). The SMURF has been developed in the context of ongoing restoration planning in the Beargrass Creek watershed in Louisville, Kentucky. The model has been constructed and parameterized around local details, although the framework and approach may be applicable elsewhere. This report intended to document the technical details of this model and demonstrate its application in Beargrass Creek. Future improvements to this tool may include:

- Verification of model predictions relative to empirical observations of riparian function (e.g., bird occupancy, herpetofaunal density, vegetation community surveys, etc.),
- Incorporation of geospatial analyses and data processing algorithms within the model,
- Refinement of model parameters based on sites where additional data may be available,
- Modification of the model structure or parameterization based on additional research or literature support, or
- Refinement of suitability curves based on input from technical stakeholders.

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Appendix A: Glossary and Acronyms

- *ERDC*: U.S. Army Engineer Research and Development Center.
- *FWOP*: Future WithOut Project Conditions.
- *LRL*: USACE Louisville District.
- *MSD*: Louisville / Jefferson County Metropolitan Sewer District.
- *QHEI*: Qualitative Habitat Evaluation Index.
- *SMURF*: Simple Model for Urban Riparian Function.
- *USACE*: U.S. Army Corps of Engineers.
- *USFWS*: U.S. Fish and Wildlife Service.

Appendix B: Field Data Sheets

Simple Model for Urban Riparian Function (SMURF)

Reach ____________________
Date ____________________
Assessor ____________________
Lat/Long ____________________
Bankfull Depth (ft) __________
Bankfull Width (ft) __________

Dimensions (ft)	Left	Right
Bank Height		
Canopy Height (within 25 feet of bank)		

Parameter	Optimal 20 19 18 17 16	Suboptimal 15 14 13 12 11	Marginal 10 9 8 7 6	Poor 5 4 3 2 1 0	Left	Right
Buffer properties						
Buffer Development	Very minor evidence of human disturbance and no impact to corridor function.	Notable impacts within footprint (e.g., paths, lawns) but minor effect on animal movement.	Large scale impacts to buffer reducing migratory corridor function.	Significant major impacts inhibiting corridor functions.		
Buffer Flowpaths	Runoff flows through buffer evenly, in natural channels, or through wetlands.	Minor rills / channels are visible but mostly used during large events.	Major rills, flow paths, and channels used during small events.	Obvious short-circuiting of buffer by pipes and drainage at most events.		
Riparian habitat properties						
Multi-story Canopy Structure	Check all that are present and associated habitat quality in the LEFT riparian zone: Quality: High / Medium / Low Canopy / Overstory Midstory Woody Shrubs		Check all that are present and associated habitat quality in the RIGHT riparian zone: Quality: High / Medium / Low Canopy / Overstory Midstory Woody Shrubs			
Snag Density	Greater than 3 pieces of large, *standing* deadwood (4+in diameter, 36+in length) in 25'x100' area.	1-3 pieces of large, *standing* deadwood (4+in diameter, 36+in length) in 25'x100' area.	No large, *standing* deadwood, but large live trees for future snags.	No large, *standing* deadwood or large *live* trees.		
Deadfall Density	Greater than 10 pieces of large, down woody stems (4+in diameter, 36+in length) in 25'x100' area.	5-10 pieces of large, down woody stems (4+in diameter, 36+in length) in 25'x100' area.	0-5 pieces of large, down woody stems (4+in diameter, 36+in length) in 25'x100' area.	No large, down woody stems (4+in diameter, 36+in length).		
Detrital Ground Cover	Organic ground cover >70%. Mostly covered by thick detritus / woody debris layer.	Organic ground cover (detritus/woody debris) is 40-70%.	Organic ground cover (detritus/woody debris) is 20-40%.	Organic ground cover is <20%. Ground is mostly bare, lawn, or impervious.		
Herbaceous Vegetation Cover	Extensive and layered throughout reach.	Extensive, but lacks complexity and layering/	Patchy and lacks complexity or layers.	Minimal or absent throughout reach.		
Invasive Vegetation Dominance	Primarily native taxa. Little, if any, ecological effect of invasives.	Invasives notably present, but playing a minor ecological role.	Invasive species are dominant, but natives remain.	Invasive dominance in both composition and function.		
From the perspective of the stream						
Stream Canopy Cover	>85% cover with clear channel shading.	55-85% cover with stippled or time-dependent shading.	30-55% canopy cover. Temperature notably altered.	< 30% canopy cover. Temperature dramatically altered.		
Organic Matter Retention	Significant leaf matter introduction from riparian zone. Instream retention is evident (e.g., leaf packs).	Some leaf matter introduction. Retention affected by high flows.	Minor leaf matter introduction to stream. Little retention in reach.	Little evidence of organic matter loading and / or retention.		
Embeddedness	None. Less than 25% of the site has fine sediment surrounding and/or covering rocks.	Normal. Fine sediment fills 25-50% of the living spaces around gravel, cobble, and boulders.	Moderate. Fine sediment and silt fills 50-75% of living spaces around gravel, cobble, and boulders.	Extensive. Fine sediment and silt fills > 75% of living spaces around gravel, cobble, and boulders.		
Overall judgment of riparian condition						
Professional Opinion	**Highest quality habitat. Best attainable in watershed.**	**Good habitat. Minimal impact with significant levels of remaining ecological function.**	**Significantly impacted. Complete loss of some ecological functions.**	**Highly impacted. Little ecological value.**		

Figure B1. SMURF Field Data Sheet.

Simple Model for Urban Riparian Function (SMURF) Geospatial Analyses

Reach ______________________________
Date ______________________________
Assessor ______________________________
Lat/Long ______________________________
GIS Directory ______________________________

Parameter	Description	Units	Left	Right
Watershed Area	(*Recommended*) Watershed area is not required for SMURF. However, this parameter may be used in estimating bankfull dimensions from regional hydraulic geometry curves, and it may provide crucial contextual data (e.g., hydrologic metrics from regional streamflow regressions). Area calculations can be derived from manual delineation, the National Hydrography Dataset, ArcHydro, or online tools (e.g., Colorado State's eRAMS).			
Total Site Area	(*Recommended*) This field captures the total extent of riparian management actions including intact and degraded patches. This is generally a manually delineated polygon based on the assessor's professional judgment.			
Riparian Area	This is the area of functioning riparian zone associated with the SMURF assessment. This factor should be aligned with the quality assessment. Consistency can be found by intersecting the total site area (above) with locally available datasets for vegetation or riparian zones (often available through city planning). SMURF is agnostic to area units (e.g., km^2, ac, ft^2), but acres are the most common metric.			
Riparian Perimeter	This factor is the edge length of the entire riparian area on one bank. This is generally assessed as the polygon length associated with the riparian area described above.			
Channel Length	(*Recommended*) Channel length is not an explicit SMURF input, but it provides the simplest method for calculating mean buffer width (as well as important context on relative size of a site).			
Mean Buffer Width	Reach-averaged buffer width is most easily calculated as the riparian area divided by channel length. However, this may also be estimated from the average of multiple measurements of width along a riparian corridor. *SMURF requires this measurement in feet.*	ft		
Minimum Buffer Width	This factor is the lowest buffer width in a reach. This may be estimated from manual measurements and visual inspection of aerial photographs. *SMURF requires this measurement in feet.*	ft		
Edge Density	Edge density is calculated as riparian perimeter divided by riparian area. *SMURF requires this measurement in ft/ ft^2.*	ft/ft^2		

Figure B2. SMURF Desktop Geospatial Analysis Data Sheet.

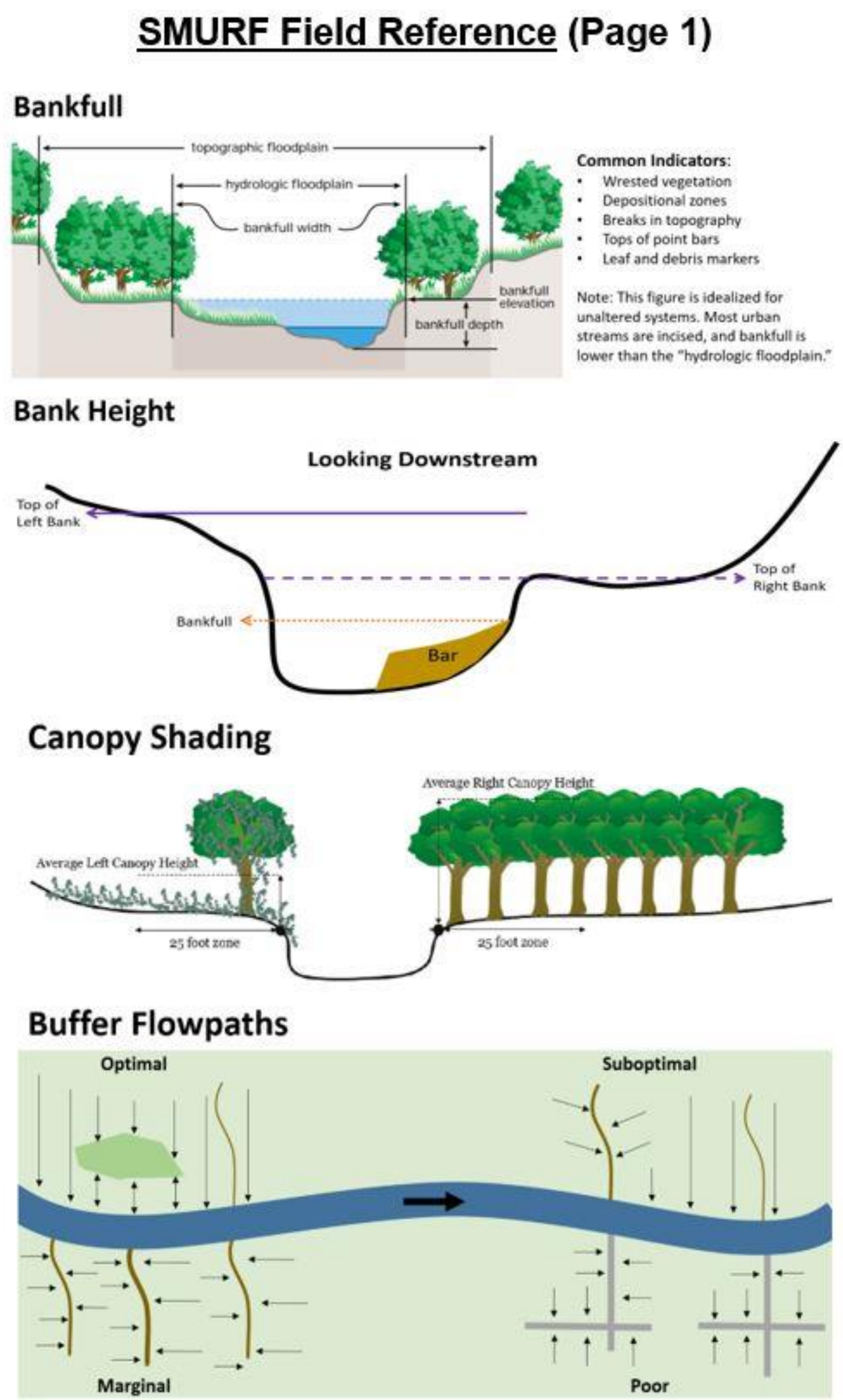
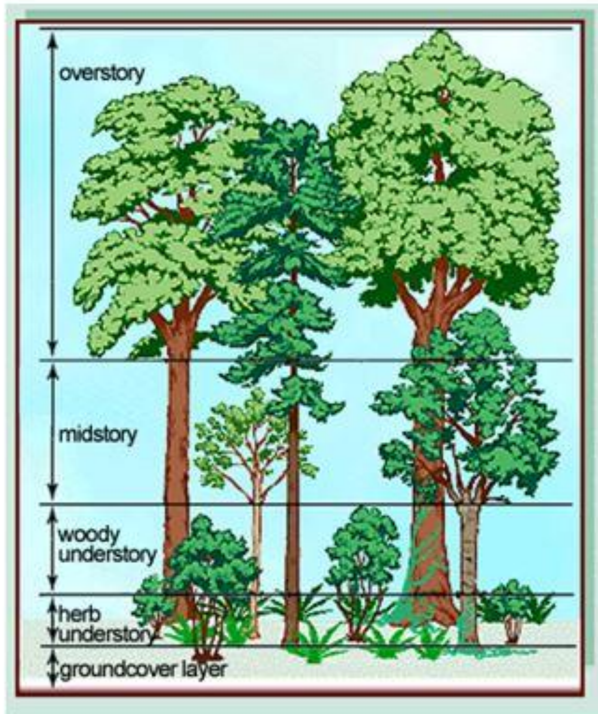


Figure B3. SMURF Field Reference (Page 1).

SMURF Field Reference (Page 2)

Canopy Structure



Organic Matter Retention

Suboptimal *Marginal* *Poor*

Figure B4. SMURF Field Reference (Page 2).

Appendix C: USACE Model Certification Review

USACE model certification review was provided by Dr. Michael Porter (USACE Albuquerque District, "Reviewer-1") and Mr. Mark Shafer (USACE Southwestern Division, "Reviewer-2"). All comments follow the four-part comment structure of: (1) identify the problem, (2) describe the technical basis for the comment, (3) rate the significance or impact of the problem, and (4) recommend a mechanism for resolution. Comments and author responses are provided for long-term archival purposes.

C.1. Reviewer-1

Comment 1.1: Application is missing inputs.

- Basis: I don't see the calculation for the edge metrics in this module. The code imports the arrays for buffer development, buffer average width, and buffer min width. Column 2 is populated with NA, and assigned the name edge.density.perft. Also see note at the end of line 1131.
- Significance: Low as it only affects this application.
- Resolution: Repair application.
- Author Response: Concur. The application was significantly revised to amend errors and clarify model application.

Comment 1.2: Automate edge calculations.

- Basis: In Section 4.3, the formula for the edge metric uses polygon area and perimeter length. The Beargrass dataset has unpopulated fields for the riparian buffer area or perimeter. The data has length and width for the buffer areas which can be used to estimate area and perimeter.
- Significance: Low as it only affects this application.
- Resolution: I suggest the following. Add code to read GIS file and extract perimeter and area values for polygons. Add a default option when data is unavailable from GIS. Add code to verify type of riparian buffer spatial data to support options below. Add calculation for edge using perimeter & area. Add alternate calculation for edge using buffer length and width.
- Author Response: Reject. The authors appreciate the goals of this comment, but geospatial analyses are beyond the current scope of SMURF. The protocol for the calculations has been clarified in the main body, but the calculations remain separate from this version of the model. Future versions of the model will consider adding geospatial assessment.

Comment 1.3: Improve description of organic matter scoring in field protocol.

- Basis: Descriptions for Organic Matter Retention categories in the Data Sheet would be better with example figure(s) in the Field Reference section (in Appendix B).
- Significance: Low.
- Resolution: Refine description.
- Author Response: Concur. Amended as suggested by adding example figures to the field reference.

Comment 1.4: Data compilation protocols do not adequately describe geospatial data.

- Basis: The Beargrass dataset includes many fields derived from GIS and other sources that are not on the field datasheets.
- Significance: Medium.
- Resolution: Suggest adding a GIS Data page describing the fields, other data sources, and metadata equivalent to the field data sheet. Include GIS filename and location.
- Author Response: Concur. A data form has been added for geospatial inputs.

Comment 1.5: Minor editorial issues in Section 4.2.

- Basis: Citation should be “Rankin 2006” not “Ranking 2006”. Also the 4th parameter in the herps formula should be “herb” not “her”. Note the hyperlink for Barbour et al. 1999 leads to broken links for acquiring the chapters. Suggest identifying a supported source or deleting the link.
- Significance: Low.
- Resolution: Edit accordingly.
- Author Response: Concur.

C.2. Reviewer-2

Comment 2.1: The index relationship for hydatt that relates incision ratio (bank height/ bankfull depth) is not sufficiently documented by either team discussions or by literature references.

- Basis: The scientific basis of each response curve should be provided in model documentation to assist model users in first determining if the curve is appropriate for their setting and second how to score their site.
- Significance: Low for one-time use authorization of model. Medium for regional/national use of model.
- Resolution: Provide either the logic used by the modeling team in setting the hydatt response cure and/or the literature that supports the curve.
- Author Response: Concur. The text was clarified and references added to provide the supporting logic (Harman and Jones 2016, IA DNR 2018).

Comment 2.2: Incision ration (bank height/bankfull depth) as a proxy does not appear to be the best available metric to utility for hydrologic connectivity.

- Basis: Where possible, the best available metrics should be used instead of a proxy particularly when attempting to predict with and without project conditions.
- Significance: Medium.
- Resolution: Recommend replacing this version of hydatt with one that relies on hydrologic model output (state/storm-event modeling) as mentioned in documentation since there will be better information to parameterize a hydatt function using predicted with and without project conditions for flood width divided by top width. (These type of projects will all require hydrologic modeling.).
- Author Response: Reject. The authors agree with that an assessment of top width may be preferrable in many circumstances. However, these analyses would have required both hydrologic models for rainfall-runoff processes (e.g., HEC-HMS) and hydraulic models to integrate streamflow with bathymetry (e.g., HEC-RAS). These tools are rarely available in early phases of project planning, and it was deemed infeasible to construct SMURF around these metrics. Similarly, SMURF is generally designed as a rapid assessment framework for restoration practitioners from multiple disciplines, so discipline-specific tools were not included. Future versions of SMURF may differentiate between rapid, coarse tools for relative comparison (like the present model) and fine-grained tools for detailed assessment (which could incorporate these types of analyses).

Comment 2.3: With respect to buffer width, there is insufficient documentation regarding how this function should be consistently scored by users who are not part of the model development team (once generally certified).

- Basis: Consistency in scoring across multiple users on a single team is important to the reliability of the model output.
- Significance: Medium. Consistency in model application is key to reliable output.
- Resolution: Provide a more robust description of the details considered when scoring this metric. Provide justification for 1 to 20 scoring system. Describe best practices for the scorers to use when potentially averaging flow path conditions across distinct sub-reach areas.
- Author Response: Concur. A data sheet and associated protocols were added for all geospatial inputs.

Comment 2.4: Buffer strip effectiveness is influenced by the slope of the buffer in addition to factors considered in the existing Buffer Width sub-factor. Slope may not be an important factor for Beargrass but if model is generally certified slope should be added to model parameters.

- Basis: Slope is a factor in the effectiveness of buffers in removing pollutants from overland flow.
- Significance: Medium.
- Resolution: Consider adding a slope factor to the buffer width sub-metric calculation to adjust effectiveness for steep slopes. If not added, then provide justification in the model documentation and/or discussion of limits of the buffer width calculation in terms of suitability for steep sloped terrain.
- Author Response: Concur. Slope is a crucial consideration. However, this factor was eliminated to minimize analytical burden. A discussion was added in section 4.1 (interflow) relative to the importance of slope in buffer performance and potential model limitations accompanying this omission.

Comment 2.5: In the temperature and light parameters, the documentation provides limited information on how this sub-matrix should be scored. This may lead to inconsistent scoring results when using multiple assessors.

- Basis: Uniform scoring assumptions are necessary for teams to consistently score model inputs.
- Significance: Low for one-time use. Medium for general certification use.
- Resolution: Provide additional discussion of scoring of the temperature and light regulation sub-indices.
- Author Response: Concur. Text in Section 4.1 was clarified to more adequately describe these metrics.

Comment 2.6: In the organic matter parameters, the scoring field sheet does not provide enough explanation of how these sub-indices should be rated. For instance, while a "diverse" assemblage of canopy species should be rated "high", no explanation of whether diversity in this case means, "more than one species", "50% of the number of species found at a reference site" or something else. Medium and low diversity scores are similarly not adequately described. The carbon retention scoring also could be better described using photo examples, for instance.

- Basis: Model should include sufficient documentation for use by users other than the developers.
- Significance: Low for one-time use. Medium for general certification of model.
- Resolution: Provide more information for scoring these sub indices.
- Author Response: Concur. Diversity is intended to be assessed based on regionally appropriate standards by the assessor. Additional language was added to clarify this reference based approach in Section 4.1, when the metric is first introduced. Carbon retention was clarified by adding figures to the field reference sheets.

Comment 2.7: With respect to overall system scoring, it appears that the model is designed to help estimate the habitat index score for individual reaches within a project study area. Several of the sub-indices, in particular "Ecological Corridor" appear to measure the connectivity between one reach and another. There does not seem to be any measurement of the continuity of the inter-connections between reaches within the study area. Presumably, the model allows users to estimate project related lift for each reach independently instead of interdependent units with scoring that reflects the habitat conditions of adjacent, and other upstream/downstream reaches. For example, one project alternative could provide great lift in the farthest upstream and downstream reaches but no lift in the middle reaches. A second alternative could provide similar overall average lift but geographically consistent lift across the entire stream corridor within the study areas. The model might predict equal lift, but ecologically it may actually be more preferable to select the more-uniform restoration alternative.

- Basis: It is unclear that in its current setup the model can provide a result that reflects upstream/downstream connectivity.
- Significance: Medium. The degree to which this issue is important may be stream and habitat/fauna specific.
- Resolution: Consider if it is important to provide a mechanism to address the interdependence of reaches with regards to acting independently/interdependently for ecological corridor function. Modify model if appropriate. Add section to model documentation to discuss interdependence/independence between reaches.

- Author Response: Reject. The authors agree that the importance of a riparian zone as a corridor is best measured through an approach addressing network dependencies. We have included proxy metrics for broader network connectivity, but a more comprehsnive approach (e.g., using network modeling) was considered beyond the scope of the present tool. This deficiency will be noted for future model improvements.

Comment 2.8: Methods to secure index curve inputs used to define ecorest function curves are not apparent since R package models don't have locked data inputs. For instance, accurate use of SMURF index functions require inputting the proper curve breakpoints into ecorest to define the curves. An incorrect dataset for these breakpoints may be used inadvertently or intentionally when a certified model is applied to a project application. This would be hard to detect unless reviewers use a prescribed process to test certified input files for curve breakpoints and compare that output to the output provided with the model application under review.

- Basis: Certified models should be either protected against incorrect input datasets or a verification system should be specified for reviewers to use certify that the model was properly used.
- Significance: High.
- Resolution: The Ecosystem Restoration Planning Center of Expertise and the developers of SMURF and ecorest should develop a "best practices" document for District Quality Control and Agency Technical Review reviewers that require them to check and test themselves whether the R package models they review are using the correct ecorest function curve datasets.
- Author Response: Concur. Incorrect user-specified suitability curves could impact the model significantly. To mitigate this issue, the suitability curves as explicitly displayed in the model document to avoid the issue and increase transparency.

Appendix D: Beargrass Creek Existing Condition Data

SMURF assessments were conducted for left and right bank areas at 52 sites in the Beargrass Creek watershed (24 South Fork, 22 Middle Fork, 6 Muddy Fork). Field data were collected through a coordinate campaign involving personnel from the USACE Louisville District and Louisville Metropolitan Sewer District from June-July 2020. Some sites were screened out and others grouped into logical sets for restoration planning. Desktop geospatial analyses were conducted for the remaining 21 sites in December 2020. Tables D1-D8 provide all data used in the SMURF analysis.

Table D1. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Rest_Name	Fork	Assessment_Points	Latitude	Longitude
X2	Confluence	South	SF.13 / SF.17	38.26153	-85.71690
X4	Shelby Campus	Middle	MF.29	38.25986	-85.58524
X5	Oxmoor Farm	Middle	MF.11	38.24065	-85.61851
X8	Houston Acre’s Farm	South	SF.38 / SF.41	38.21009	-85.61202
X9	Clark Park	South	SF.20	38.21545	-85.72654
X10	Alpaca Farm / Zoo	South	SF.22	38.20838	-85.70068
X11	Collegiate	Muddy	MU.14	38.27748	-85.69217
X15	Buechel Park	South	SF.43	38.19595	-85.62192
X19	South Fork / Newburg Rd	South	SF.26 / SF.42	38.18709	-85.65851
X20	Brown Park	Middle	MF.08US / MF.08DS	38.23940	-85.63495
X21	Arthur Draut Park	Middle	MF.09US / MF.09DS	38.24402	-85.62870
X22	Concrete Channel	South	SF.18 / SF.19A / SF.35	38.23444	-85.73027
X24	Oxmoor Country Club	Middle	MF.34	38.22907	-85.61478
X28	Hurstbourne Country Club	Middle	MF.12	38.24098	-85.58708
X29	Eastern / Creason Connector	South	SF.19B	38.21872	-85.72135
X30	Joe Creason Park	South	SF.21	38.21452	-85.71016
X31	Champions Trace	South	SF.24	38.20330	-85.67659
X33	MSD Basin	South	SF.39	38.21115	-85.62910
X34	Cherokee / Seneca Parks	Middle	MF.04US / MF.04DS / MF.05 / MF.06US / MF.06DS	38.24164	-85.69549
X35	Muddy Fork and Tribs	Muddy	MU.15	38.27966	-85.66859
X38	Cave Hill Corridor	Middle	MF.02 / MF.03	38.25018	-85.71695

Table D2. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Bankfull_Depth_ft	Bankfull_Width_ft	Bank_Height_Left_ft	Bank_Height_Right_ft
X2	4.7	60.0	3.5	2.5
X4	2.0	30.5	3.0	3.0
X5	1.8	34.0	2.2	2.2
X8	1.6	20.5	2.8	2.8
X9	3.5	13.0	6.0	6.0
X10	2.9	39.0	10.0	15.0
X11	2.2	22.0	5.5	5.5
X15	2.2	6.0	2.2	2.2
X19	1.8	23.0	9.0	6.0
X20	2.7	41.0	4.0	3.8
X21	2.7	32.2	3.1	3.1
X22	3.4	30.0	15.0	15.0
X24	2.0	34.0	6.0	5.0
X28	1.8	35.0	2.8	2.3
X29	3.2	20.0	4.0	4.0
X30	3.1	37.0	20.0	20.0
X31	2.6	55.0	10.0	10.0
X33	3.0	29.0	3.0	6.0
X34	3.3	34.6	4.4	4.6
X35	1.8	23.0	5.3	7.3
X38	3.4	39.9	6.6	12.8

Table D3. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Canopy Height w/in 25 ft Left_ft	Canopy Height w/in 25 ft Right_ft	Buffer Dev Left	Buffer Dev Right	Buffer Flowpaths Left	Buffer Flowpaths Right
X2	60	52	10	10	12	12
X4	50	50	12	12	14	14
X5	20	30	8	5	16	4
X8	75	72	16	13	16	16
X9	60	60	11	11	13	13
X10	100	100	11	15	5	11
X11	40	40	13	9	15	7
X15	60	60	6	6	11	11
X19	45	30	10	10	7	2
X20	40	45	10	11	11	11
X21	45	45	13	13	16	16
X22	47	52	3	3	3	3
X24	10	10	3	3	5	5
X28	0	0	4	4	4	3
X29	50	80	11	11	8	12
X30	80	80	13	8	3	11
X31	50	40	4	2	4	2
X33	35	45	12	12	8	8
X34	44	52	12	11	13	9
X35	40	40	11	13	12	14
X38	35	40	8	7	10	6

Table D4. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Overstory Left	Midstory Left	WoodyShrubs Left	Overstory Right	Midstory Right	WoodyShrubs Right
X2	1	1	1	1	1	1
X4	1	0	0	1	0	0
X5	1	0	0	0	0	0
X8	2	1	1	2	1	1
X9	2	1	1	2	1	1
X10	1	1	1	1	1	1
X11	1	0	0	1	1	1
X15	0	0	0	0	0	0
X19	1	0	0	1	0	0
X20	1	1	0	1	1	0
X21	1	0	0	1	0	0
X22	1	0	0	1	0	0
X24	0	0	0	0	0	0
X28	0	0	0	0	0	0
X29	2	1	0	2	1	0
X30	2	2	1	0	0	0
X31	0	0	0	0	0	0
X33	0	0	0	1	0	0
X34	1	1	1	1	1	1
X35	0	0	0	1	1	1
X38	1	1	0	1	0	0

Table D5. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Snags Left	Snags Right	Deadfall Left	Deadfall Right	Detritus Left	Detritus Right	Herb Left	Herb Right
X2	13	13	12	12	12	12	11	11
X4	12	12	8	9	11	10	11	9
X5	6	6	6	3	10	5	13	11
X8	16	14	14	12	12	12	10	10
X9	11	11	7	7	13	13	18	18
X10	18	18	13	13	10	10	10	10
X11	11	11	15	15	16	16	14	12
X15	6	6	0	0	3	3	13	13
X19	10	7	8	8	5	5	8	8
X20	8	13	2	4	5	6	11	12
X21	12	12	10	10	12	12	10	10
X22	8	9	4	4	2	2	4	5
X24	4	4	4	4	4	4	11	11
X28	6	3	0	0	3	3	11	11
X29	13	13	13	13	3	3	3	8
X30	12	15	6	3	13	3	13	3
X31	8	8	5	5	5	5	8	8
X33	13	8	8	8	11	11	8	8
X34	10	12	9	9	10	8	11	10
X35	11	13	8	8	5	11	8	13
X38	12	10	6	9	9	10	9	10

Table D6. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Invasive Dominance Left	Invasive Dominance Right	Stream Canopy Cover	OM Retention	Embeddedness	Overall Left	Overall Right
X2	10.0	10.0	7.5	7.5	4.0	10.0	10.0
X4	6.0	5.0	7.0	4.0	7.0	7.0	7.0
X5	8.0	6.0	16.0	4.0	16.0	10.0	10.0
X8	11.0	11.0	14.5	12.0	11.5	14.0	12.0
X9	15.0	15.0	18.0	13.0	5.0	13.0	13.0
X10	8.0	9.0	14.0	11.0	6.0	13.0	13.0
X11	13.0	13.0	10.0	13.0	1.0	10.0	9.0
X15	3.0	3.0	2.0	6.0	5.0	8.0	8.0
X19	7.0	7.0	5.0	8.0	6.5	8.5	8.0
X20	8.5	8.5	7.0	7.0	11.0	10.5	10.5
X21	12.0	12.0	10.5	6.5	7.5	9.5	10.0
X22	4.3	4.3	7.3	1.3	0.7	3.0	2.0
X24	7.0	7.0	4.0	5.0	6.0	5.0	5.0
X28	3.0	3.0	2.0	5.0	3.0	4.0	5.0
X29	8.0	8.0	14.0	13.0	10.0	11.0	14.0
X30	13.0	8.0	10.0	13.0	8.0	16.0	10.0
X31	8.0	8.0	11.0	8.0	2.0	3.0	3.0
X33	8.0	8.0	16.0	13.0	13.0	8.0	8.0
X34	10.0	9.8	11.4	8.2	7.2	11.2	9.4
X35	11.0	11.0	8.0	12.0	8.0	11.0	12.0
X38	6.5	6.5	6.0	9.0	7.0	8.5	7.5

Table D7. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Total Site Area_ft2	Riparian Area Left_ft2	Riparian Area Right_ft2	Riparian Perimeter Left_ft	Riparian Perimeter Right_ft
X2	7432938	578031	1384409	17726	23471
X4	3560369	826663	1429638	11963	16985
X5	9694538	1629401	913972	27403	28240
X8	5680621	1880479	2103996	32871	33815
X9	1598978	342979	100039	4349	2641
X10	3452381	176658	635077	7455	15395
X11	4295026	1307096	1242605	32503	32257
X15	1213163	106692	98428	4778	5719
X19	1936982	360573	157926	6144	6874
X20	1325175	173059	87629	5872	5752
X21	1741770	243083	457463	12028	11853
X22	2051402	354190	254979	23841	20629
X24	2658974	153803	911084	5761	7958
X28	637414	170930	38210	7821	2017
X29	4258276	1705439	1154652	22562	20829
X30	5285708	2554496	144338	11695	6292
X31	2102471	159317	92999	10774	10349
X33	514820	205213	54635	3981	3369
X34	11632832	2055032	2556929	58840	53987
X35	5571659	1581578	1682320	37162	25152
X38	2271040	148176	430825	5923	12388

Table D8. Existing condition data for Beargrass Creek restoration sites.

Rest_Num	Buffer Width Mean Left_ft	Buffer Width Mean Right_ft	Buffer Width Min Left_ft	Buffer Width Min Right_ft
X2	58	139	0	0
X4	125	217	20	20
X5	109	61	10	10
X8	126	141	20	20
X9	207	60	50	30
X10	33	119	15	15
X11	81	77	0	10
X15	34	31	0	0
X19	105	46	0	0
X20	59	30	10	10
X21	30	56	10	15
X22	25	18	5	5
X24	21	122	10	30
X28	27	6	0	0
X29	189	128	30	30
X30	543	31	25	25
X31	29	17	25	10
X33	114	30	15	20
X34	73	90	5	5
X35	95	101	10	10
X38	16	46	10	20

Ideally, a riparian assessment procedure would be rigorously validated against empirical data for multiple ecological processes. However, validation data were not available in the Beargrass Creek system. Alternatively, field assessors were asked to provide an overall judgment of each site relative to their impression of the general riparian condition. These data provide a crude means of pseudo-verification of the SMURF framework. The SMURF generally aligns with the overall professional judgment of field personnel. Interestingly, the fauna index and the overall habitat suitability index show the most agreement with the field teams, and the instream and corridor indices show the least (i.e., greater variability in assessments). Faunal habitat provision could be easier to observe at a field scale than more complex off-site effects on instream processes or corridor functions. These data indicate that SMURF indices generally agree with professional judgment associated with the 42 samples in Beargrass Creek (i.e., independent left and right bank assessments at 21 restoration sites).

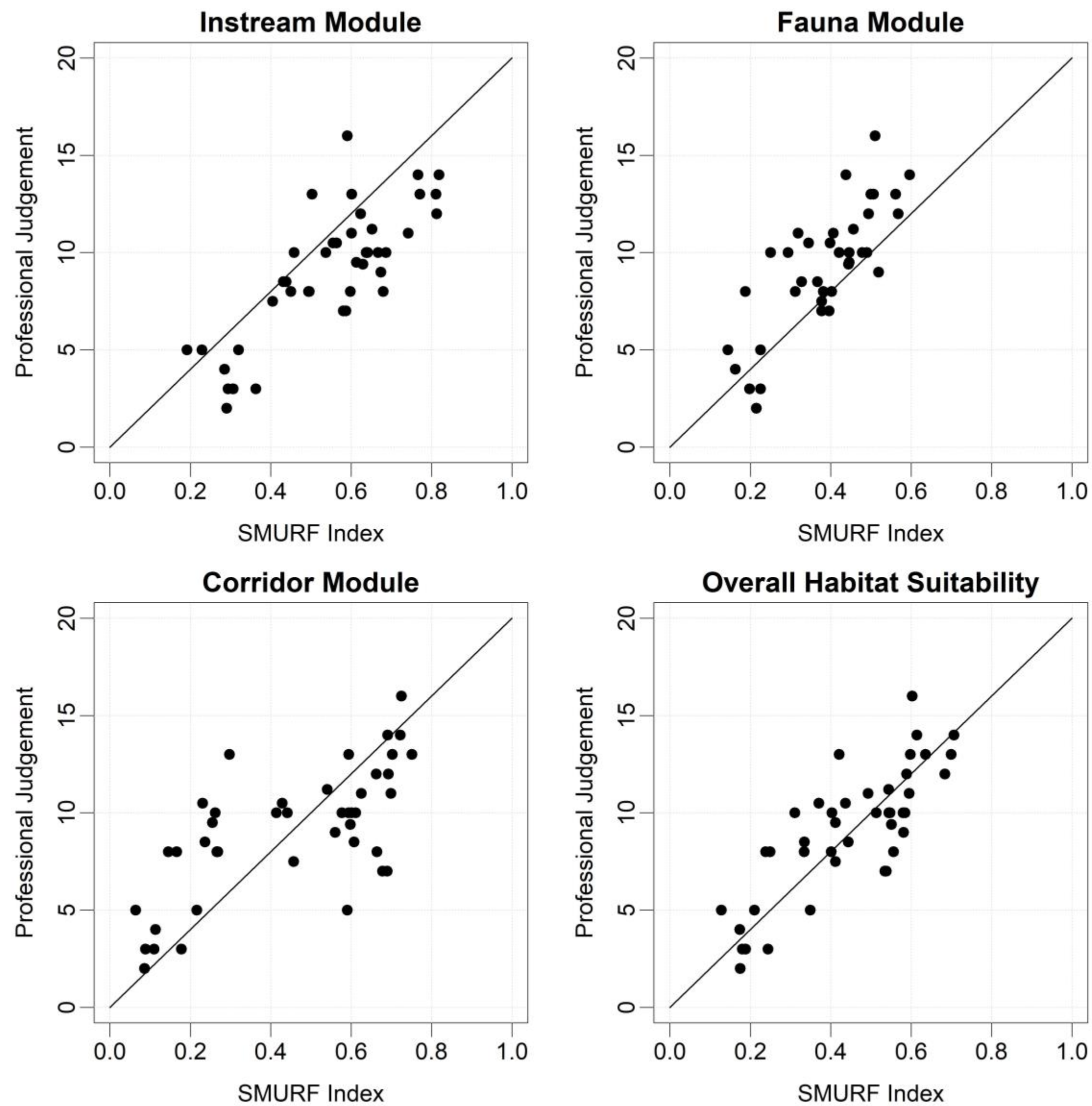


Figure D1. Pseudo-verification of SMURF relative to professional judgment of field assessors.