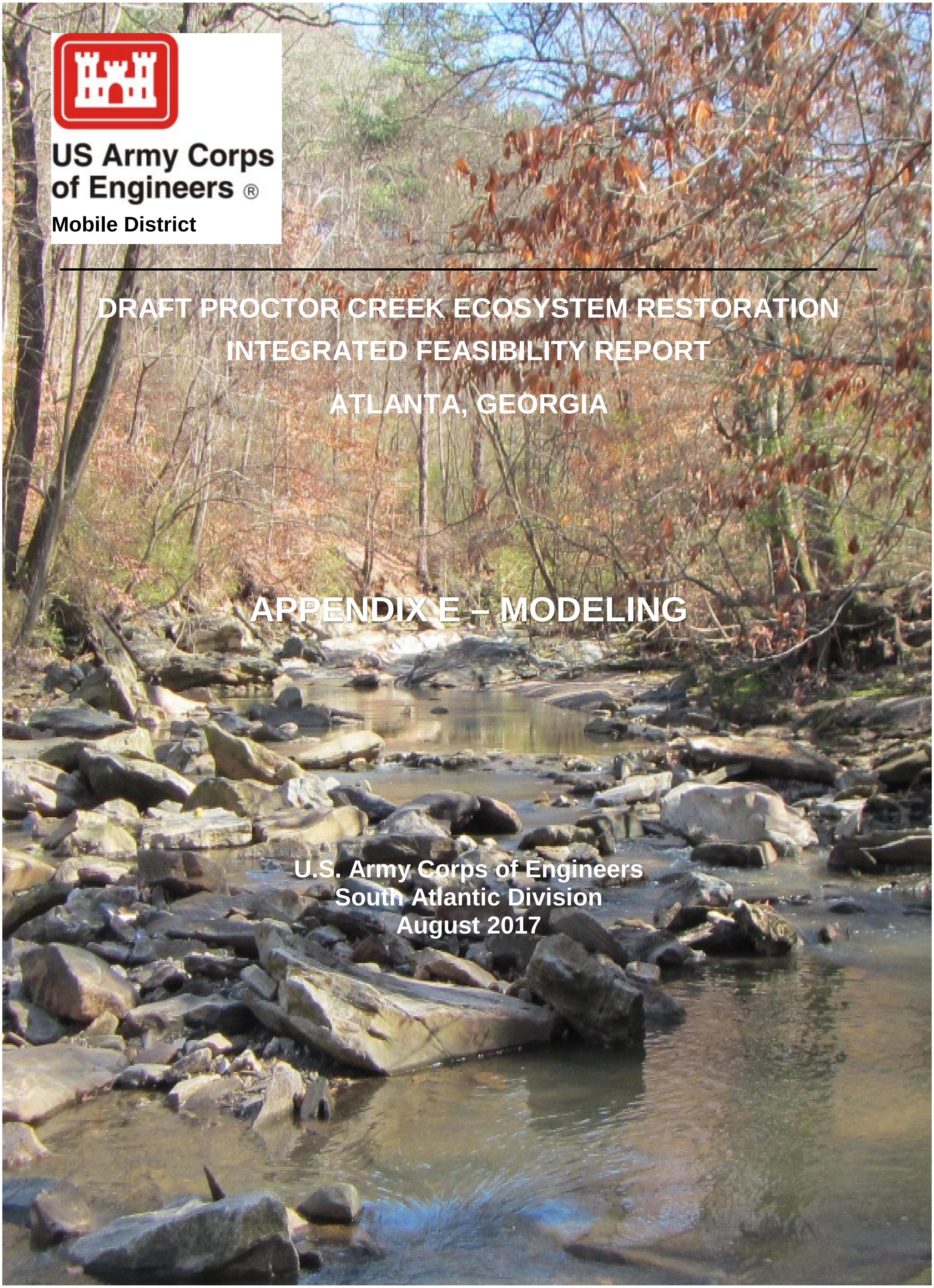


US Army Corps of Engineers®
Mobile District

DRAFT PROCTOR CREEK ECOSYSTEM RESTORATION INTEGRATED FEASIBILITY REPORT

ATLANTA, GEORGIA

APPENDIX E – MODELING

U.S. Army Corps of Engineers
South Atlantic Division
August 2017

APPENDIX E

MODELING

ERDC TR-XX-DRAFT

US Army Corps
of Engineers®
Engineer Research and
Development Center

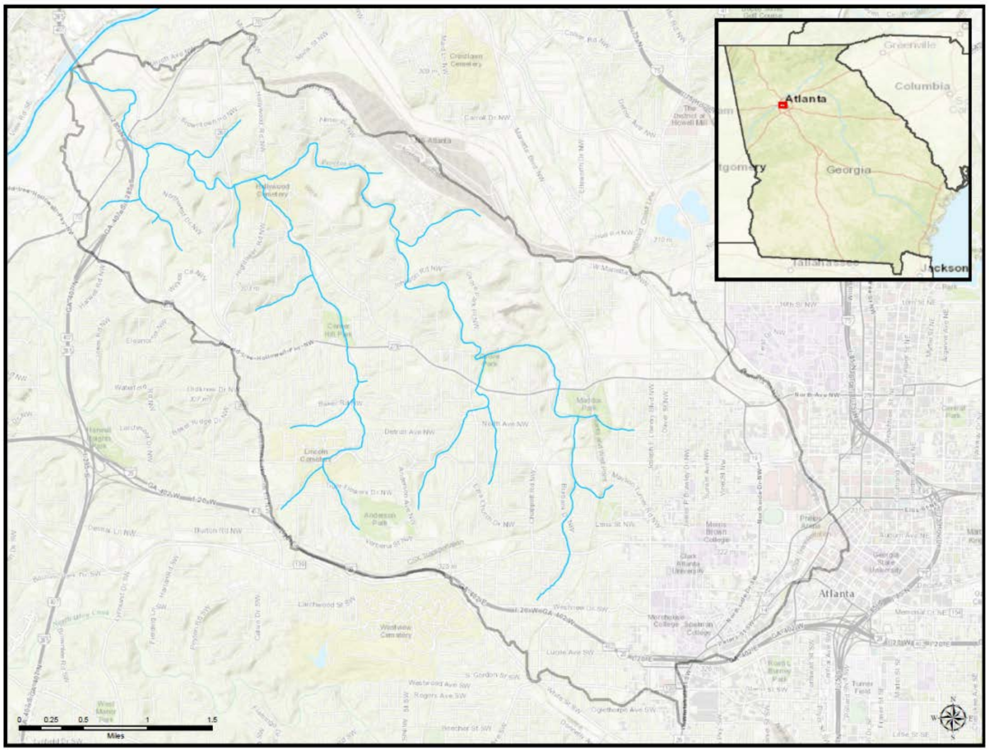
ERDC
INNOVATIVE SOLUTIONS
for a safer, better world

Ecosystem Management and Restoration Research Program

Proctor Creek Ecological Model (PCEM): Phase 2 Benefits Analysis

S. Kyle McKay, Bruce A. Pruitt, Brian A. Zettle, Niklas Hallberg,
Vince Moody, Allan Annaert, Meredith Ladart, Marshall
Hayden, and Justin McDonald

June 2017



Engineer Research and
Development Center

Ecosystem Management and Restoration
Research Program

ERDC TR-XX-DRAFT
June 2017

Proctor Creek Ecological Model (PCEM): Phase 2 Benefits Analysis

S. Kyle McKay

Environmental Lab
US Army Engineer Research and Development Center
26 Federal Plaza
New York, NY 10278

Bruce A. Pruitt

Environmental Lab
US Army Engineer Research and Development Center
960 College Station Road
Athens, GA 30605

Brian A. Zettle, Allan Annaert, Meredith Ladart, Marshall Hayden, and Justin McDonald

Mobile District
US Army Corps of Engineers
109 St. Joseph St.
Mobile, AL 36602

Niklas Hallberg

Norfolk District
US Army Corps of Engineers
803 Front St.
Norfolk, VA 23510

Vince Moody

Savannah District
US Army Corps of Engineers
149 W. York St.
Savannah, GA 31401

Final report

Prepared for US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

In partnership with the City of Atlanta and thirteen Federal agencies, the Mobile District of the U.S. Army Corps of Engineers is planning an urban stream restoration in Proctor Creek, Atlanta, Georgia. A two-part numerical modeling toolkit, the Proctor Creek Ecological Model (PCEM), was developed to support planning of this ecosystem restoration project. This report presents the second phase of model development (PCEM2), a detailed numerical tool for computing environmental benefits of restoration actions, informing feasibility-level design, and facilitating restoration decision-making. Following from PCEM1's structure, PCEM2 contains four modules related to instream condition, riparian condition, hydrologic change, and watershed connectivity, which are combined into an overarching assessment of stream ecosystem integrity at the watershed-scale. The model was applied to compute ecological benefits of restoration actions at eleven potential sites in the Proctor Creek Watershed. Benefits were computed for 8,192 plans, which represent every possible combination of site and restoration action. When coupled with cost estimates, these data were used to conduct cost-effectiveness and incremental cost analysis to inform the Tentatively Selected Plan Milestone of the SMART Planning Process. While parameterized for Proctor Creek, PCEM2 provides an adaptable, generic framework for computing watershed-scale benefits of stream restoration actions.

Contents

Illustrations

Figures

Tables

Preface

This study was conducted for and funded by the U.S. Army Corps of Engineers (USACE), Mobile District (SAM), Proctor Creek Feasibility Study. Cheryl Hrabovsky was the SAM Project Manager, Peter F. Taylor was the Deputy District Engineer for Programs & Project Management, and Colonel James A. DeLapp was the District Commander.

The development of this report and the associated model was led by Dr. Kyle McKay of the Ecological Resource Branch (EE-E) in the Ecosystem Evaluation and Engineering Division (EE), US Army Engineer Research and Development Center – Environmental Laboratory (ERDC-EL). At the time of publication, Dr. Jen Seiter was Chief, CEERD-EE-E and Mark Farr was Chief, CEERD-EE. The Director of ERDC-EL was Dr. Beth Fleming.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
hectares	1.0 E+04	square meters
miles (US statute)	1,609.347	meters
square feet	0.09290304	square meters

1 Background

With over 80% of the U.S. population residing in urban areas (Muir 2014), the management and protection of urban waterways is a crucial challenge facing land and water management agencies. Urban streams and rivers are often highly impacted by changes to land use (e.g., from forested to suburban), impervious area (e.g., parking lots, rooftops), inputs of stormwater and wastewater (e.g., "flashy" surface runoff, industrial inputs), pollutant loads (e.g., nutrients, metals), infrastructure crossings (e.g., roads, dams), and a variety of other stressors (Wenger et al. 2009). These drivers and stressors characterize an "urban stream syndrome" (Walsh et al. 2005) seen throughout the world associated with a multitude of ecosystem changes ranging from channel degradation and water quality problems to reduced biodiversity and shifts in ecosystem functions (Paul and Meyer 2006, Booth and Bledsoe 2009).

Stream restoration provides a potential mechanism for returning ecological functional of urban waters, and a stream restoration and mitigation industry of more than $1B annually has emerged to meet this need in the United States (Bernhardt et al. 2005). A challenge confronting this field of study and practice is the inherently interdisciplinary approach required to address the array of hydrologic, geomorphic, ecological, design, and engineering issues that arise in the course of a project (Fischenich 2006, Bennett et al. 2011). Owing to these obstacles, some restoration projects have inadequately addressed the underlying reasons for degradation and have not resulted in the ecological improvements originally anticipated (September 2011 Special Issue of *Ecological Applications*). These failures have led to a broad call for the discipline to embrace a "process-based" view of restoration, in which a multi-disciplinary perspective of the ongoing drivers and stressors is explicitly applied and a dynamic view of ecosystems is embraced (Palmer et al. 2005, Jansson et al. 2005, Beechie et al. 2010, Palmer and Febria 2012).

Structured decision-making has emerged as a family of techniques capable of increasing the transparency and repeatability of environmental management decisions (Gregory and Keeney 2002). In the context of stream restoration, these methods help project teams "tell the story" of restoration decisions by explicitly linking underlying motivations for restoration (i.e., the problems) with the outcomes of restoration (i.e., the environmental and social benefits). This “benefits quantification” process can be applied to: (1) distinguish between different restoration actions, (2) characterize the return on investment from restoration, (3) prioritize restoration projects, (4) maximize desired outcomes relative to different levels of expenditure, and/or (5) ensure mitigation requirements are met (Fischenich et al. 2013). Hydrogeomorphic, engineering, and ecological models often play a role central in these analyses by providing objective, scientifically based evidence used to inform decisions (Swannack et al. 2012).

1.1 Proctor Creek Ecosystem Restoration

Proctor Creek in Atlanta, Georgia presents a classic example of ecological degradation common in urban streams. The headwaters of this watershed drain the most urbanized portions of downtown Atlanta as the stream flows west to the Chattahoochee River (Figure 1). Common drivers and stressors in this watershed include combined sewer overflows, extremely high impervious surface coverage (> 30% on average), and other industrial and residential sources of pollution (Horowitz et al. 2008, Peters 2009, Wright et al. 2012). High rates of poverty, crime, property abandonment, illegal dumping, and interior flooding are also common within this watershed (EPA 2015). Owing to these challenges, this watershed was selected as one of nineteen nationwide sites for the urban waters federal partnership, in which a consortium of fourteen federal agencies are partnering with local communities to revitalize urban waters, restore stream ecosystems, and improve the lives of residents (Muir 2014, EPA 2016b). In partnership with the City of Atlanta (non-Federal sponsor), the U.S. Army Corps of Engineers (USACE), Mobile District (SAM) is leading a general investigation project associated with aquatic ecosystem restoration in this watershed.

In planning the Proctor Creek project, the USACE team iteratively applied a basic structured decision making model, the “PrOACT” framework, in which Problems are identified, Objectives are developed and refined, Alternatives are identified, Consequences of alternatives are assessed relative to objectives, and Trade-offs are made by decision-makers (Gregory and Keeney 2002). This process mirrors the USACE project planning process (ER-1105-2-100) and facilitates discussion of requisite planning steps (Fischenich et al. 2013).

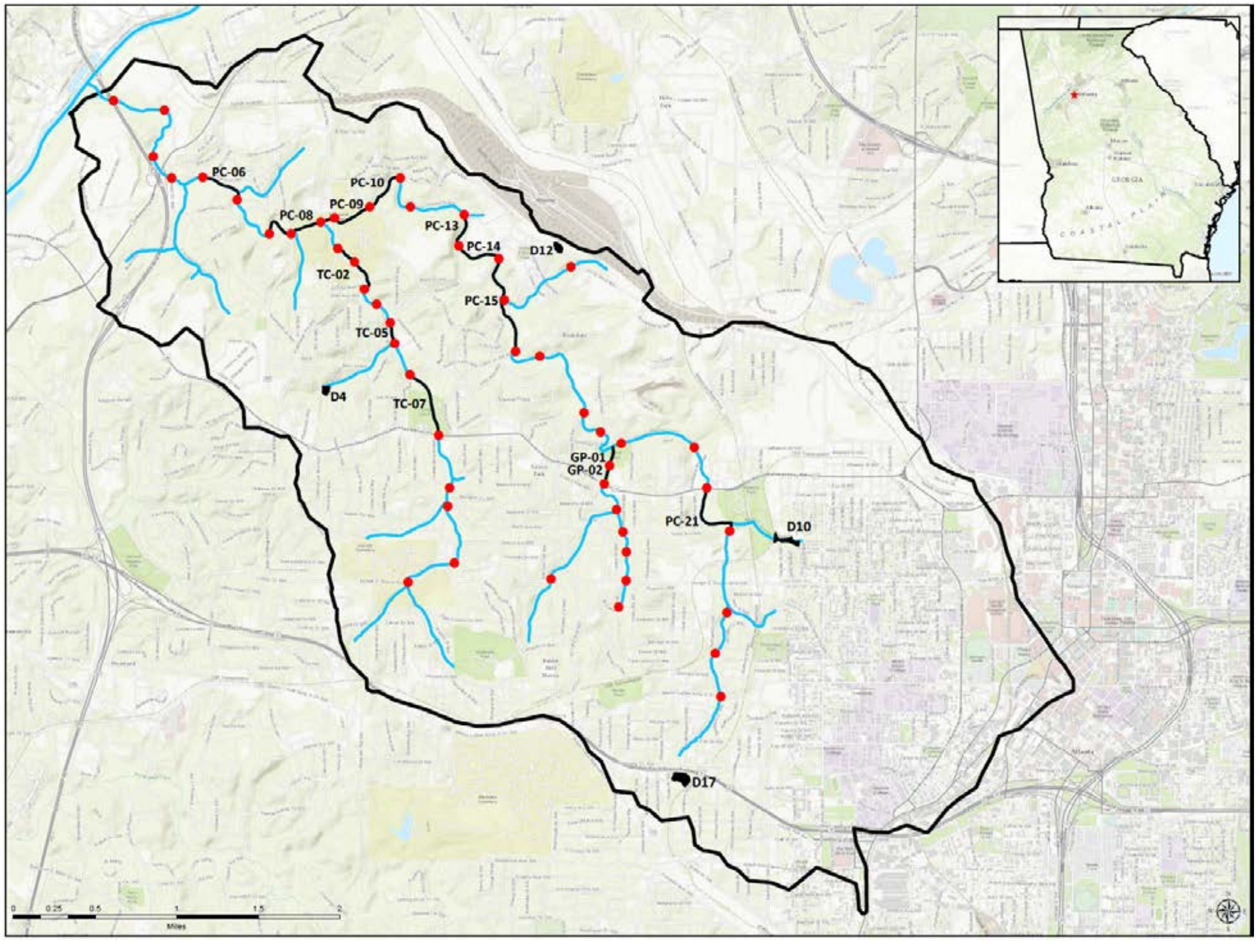


Figure 1. Proctor Creek watershed map with reach divisions shown as read points and potential restoration sites from Phase 1 analyses highlighted in black (See Table 1). Other notable features include the Chattahoochee River to the northwest, downtown Atlanta to the southeast, the Atlanta railyards to the north/northeast, and major interstates to the west (I-285) and south (I-20).

The project team iterated through the PrOACT framework in two primary phases. Phase 1 emphasized site selection and rapid screening in support of the USACE "Alternatives Milestone" of the SMART Planning Process[1] (See McKay et al. 2017). Phase 2 emphasized development of preliminary restoration designs and environmental benefits analysis of restoration alternatives in support of the USACE "Tentatively Selected Plan Milestone" of the SMART Planning Process.

In Phase 1, an objectives hierarchy was developed in coordination with the project sponsor, local stakeholders, and other federal agencies. These objectives guided the development of metrics for identifying high potential restoration sites. Given these objectives, a menu of potential restoration alternatives (e.g., riparian planting, flow attenuation, fish passage improvement, streambank protection) was identified that could be appropriate at multiple sites in the Proctor Creek watershed. These alternatives drew heavily from existing basin planning activities (ARC 2011, Ecological Solutions 2011, Park Pride 2011, EPA 2016)[2]. A simple ecological model and rapid field reconnaissance were applied to screen from 61 potential restoration sites (46 reach-scale actions + 15 flow attenuation locations) to 17 high potential sites. The feasibility, acceptability, and desirability of these 17 sites were subsequently screened in coordination with the project sponsor. From this analysis, 12 reach-scale restoration sites and 4 flow attenuation sites were preserved for future consideration (Table 1).

The PrOACT framework was again applied in Phase 2 to analyze what group of sites and restoration actions together would form the USACE's recommended action, i.e., the "tentatively selected plan" (TSP). Problems, opportunities, and objectives from Phase 1 were further clarified and refined through meetings with the USACE team, sponsor, stakeholder groups, and other agencies. This objectives hierarchy (Table 2) serves as the basis against which the USACE project success is measured.

---

[1] More information on SMART Planning may be found in the USACE Planning Community Toolbox: https://planning.erdc.dren.mil/.

[2] http://www.proctorcreek.org/plans--studies.html

Table 1. Potential restoration actions and sites identified in Phase 1 analyses. Reach definitions are shown in Figure 1 and presented Appendix A.

Site	Brief Description of Phase 1 Restoration Alternative
PC06	Channel realignment by moving in-channel bars to decrease width
PC08	Bank protection and invasive species removal
PC09	Barrier improvement at sewer crossing (rock ramp)
PC10	Bank protection, invasive species removal, riparian plantings, and bar shaping
PC13	Invasive species removal, riparian plantings, and minor bar reshaping
PC14	Addition of woody debris
PC15	Reshape in-channel bars and bank protection
PC21	Bank protection and right bank wetland complex
TC02	Right bank wetland, channel reshaping, invasive species removal, riparian plantings, and recreation access
TC05	Barrier improvement at sewer crossing (rock ramp), left bank wetland, in-channel bar realignment, and channel reshaping
TC07	Bank protection, floodplain reconnection, possible wetland, and removal of historic bank armoring
GP01/02	Daylighting piped segment of stream with minor bank protection and plantings downstream
D04	Tributary detention pond at Ridge Avenue on a tributary of Terrell Creek
D10	Off-line flow attenuation structure in the “Valley of the Hawks”
D12	Inline detention structure upstream of Perry Road on tributary
D17	Inline flow attenuation structure upstream of I-20

Table 2. Planning objectives and sub-objectives for the Proctor Creek restoration study.

Primary goal and focus of restoration plan formulation.

Make Proctor Creek a vibrant, sustainable ecosystem full of native species.

1.1 Improve in-channel conditions suitable for a diversity of aquatic organisms (e.g., fish, crayfish, salamanders, benthic macroinvertebrates, turtles)

- Restore channel geomorphic conditions to less disturbed conditions
- Reduce sediment loading from stream bed and banks
- Increase instream habitat for a diverse assemblage of local fauna

1.2 Improve riparian conditions supportive of a diverse aquatic and riparian community

- Restore natural sources of organic carbon (i.e., energy) within the system
- Increase nutrient uptake within the basin
- Improve temperature regimes
- Increase riparian habitat to support native biodiversity

1.3 Restore flow regimes to best attainable conditions achievable in altered urban environments

- Decrease peak flows
- Decrease hydrologic flashiness
- Improve the capacity of the watershed to attenuate flows

1.4 Promote an interconnected system resilient to foreseen and unforeseen disturbances

- Increase connectivity of movement corridors for aquatic and riparian species
- Increase the capacity to absorb natural and anthropogenic disturbance

Secondary goals potentially affected by the project.

Make Proctor Creek an asset and source of pride for the community.

2.1 Reconnect residents to aquatic and historic landscapes

- Increase recreational access

2.2 Make the creek a living laboratory for learning about local waters

- Provide educational opportunities for both residents and tourists

Make Proctor Creek a safe place to work and play.

3.1 Maintain or decrease existing levels of flood risk

3.2 Reduce health risks to neighboring communities

- Reduce exposure to contaminated water
- Decrease mosquito breeding areas to reduce vector borne disease transmission

1.2 Purpose

The USACE team required a scientifically defensible, analytical toolkit to inform Phase 2 planning in the Proctor Creek Ecosystem Restoration Study. In particular, planning needs for the tool included:

- Informing restoration designs effective at meeting the project objectives for a given site at the feasibility level (i.e., 10-20% design).
- Assessing cumulative, watershed-scale effects of many types of restoration actions (e.g., flow management, riparian planting, or channel modification) at many locations (e.g., reach-1, reach-2, etc.).
- Forecasting the ecological benefits of restoration actions over a 50 year planning horizon to inform federal return on investment analyses (i.e., cost-effectiveness and incremental cost analysis).

The objective for model development was to provide a tool sufficiently sensitive to potential USACE restoration actions to inform the specified planning needs. The model is intended to capture the effects of extremely diverse project objectives (Table 2), and thus, its development emphasized the relative change in the overarching ecosystem condition relative to those objectives.

This report documents the development of a numerical model to inform Phase 2 of the Proctor Creek ecosystem restoration study (PCEM2). This index-based model synthesizes multiple project objectives into a single habitat unit based on the overall quality and quantity of habitat in the watershed. The model is programmed in a scripting environment (i.e., the R statistical software language) and uses a variety of field, office, and judgment based parameters as inputs, all of which are stored in an accompanying spreadsheet database. This report is intended to provide documentation of the model's theoretical basis, quantitative framework, testing and evaluation, application in the Proctor Creek watershed, and relevant information for USACE model certification (EC 1105-2-412, PB 2013-02).

2 Model Development Process

A two-phase modeling framework was developed to meet the separate needs of the SMART planning milestones for the Proctor Creek study. The Phase 1 Proctor Creek Ecological Model (PCEM1) utilized a rapid data collection and analysis framework for screening potential restoration sites. Additional details on PCEM1 may be found in McKay et al. (2017). This report documents the development of a numerical model to inform Phase 2 of the Proctor Creek ecosystem restoration study. This model (PCEM2) was developed explicitly to meet the modeling needs identified above and provides a more detailed analysis over the PCEM1. However, the basic framework for PCEM1 and PCEM2 are identical (i.e., consistent four modules mapped to project objectives), and the tools were designed to provide continuity in analytical approach throughout the project. Table 3 summarizes a few key elements distinguishing the two phases of PCEM.

Development of PCEM2 followed a common ecological modeling process of conceptualization, quantification, evaluation, and application (Grant and Swannack 2008, Swannack et al. 2012). PCEM1 also followed this process, and thus, PCEM2 represents a second more detailed iteration through the modeling process. The model was developed iteratively with the model development team (i.e., authors of this document) and the larger project development team. An outline of model structure was presented prior to field data collection, refined by the field team, further refined during team meetings, coded as a numerical model, tested and reviewed, and subsequently documented. The team avoided errors by documenting code thoroughly, checking input data sources, and manually checking code during development. These processes cannot guarantee error-free analyses; however, best practices can minimize the occurrence of errors. Notably, Phase 2 model development was constrained by the need for rapid development and application under the USACE Smart Planning paradigm, which required eight months for field study, model development, and project application. This model framework was designed to be applied under these constraints, but also be adaptable for future uses, where additional data or time may be available.

Table 3. Phased modeling approach for the Proctor Creek Ecological Model (PCEM).

Model Element	Phase 1 (PCEM1)	Phase 2 (PCEM2)
Primary Use	Informed site-selection and prioritization leading into the Alternatives Milestone	Informed the Tentatively Selected Plan (TSP) recommendation and feasibility-level design
Data Sources	Remotely sensed data Rapid, field survey at the stream segment and watershed scales	Remotely sensed data Field measurement at down-selected set of high potential restoration sites
Cost	Rapid, relative cost estimates for purely comparative purposes	Site-specific, rough order of magnitude (ROM) cost engineering analyses
Treatment of Time	Snapshot of futures with and without projects	Temporal trajectories over 50-year horizon based on restoration recovery rates
Treatment of Uncertainty	None	Rapid examination of expected, worst, and best case scenarios and stochastic simulation across a range of model inputs
Actions by Others	Neglected	Examined through scenario analysis of the recommended plan
Quantity	Length of stream from NHD	Length of stream from NHD
Quality Sub-Model: Instream Condition	Simple visual surveys of generalized condition	Field-based measurements and targeted visual surveys explicitly associated with project sub-objectives
Quality Sub-Model: Riparian Condition	Simple visual surveys of generalized condition	Field-based measurements and targeted visual surveys explicitly associated with project sub-objectives
Quality Sub-Model: Hydrology	Ad hoc unit hydrograph model based on Gotvald and Knaak (2011) and Inman (2000). Crude measurement of storm volume only.	Spatially explicit watershed model based on land use and rainfall data (i.e., HEC-HMS). Addresses multiple aspects of the hydrologic flow regime and hydrologic function of the watershed.
Quality Sub-Model: Connectivity	Network-scale model of cumulative passability from the Chattahoochee River based on qualitative passability scores	Network-scale model of cumulative passability from the Chattahoochee River based on quantitative barrier passability estimates from Coffman (2004) and Collins (2016)

3 Model Conceptualization

An enormous array of models has been developed for stream corridor assessment (e.g., FISRWG 1997, Appendix B). In addition to differing in technical complexity and application time, these models also vary based on factors such as the disciplinary perspective (e.g., hydrologic, geomorphic, ecological), the level of ecological hierarchy addressed (e.g., individuals, populations, communities, ecosystems), the basic approach to modeling (e.g., statistical, theoretical), input requirements (e.g., few parameters vs. extensive geospatial layers), the treatment of time and space (e.g., lumped vs. distributed), and the degree of development (e.g., long history vs. ad hoc). Here, we take a common approach to ecological modeling based on quantity and quality of habitat. These "index" models (Swannack et al. 2012) were originally developed for species-specific applications (e.g., slider turtle, *Pseudemys scripta*, Morreale and Gibbons 1986), but the general approach has also been adapted to guilds (e.g., salmon), communities (e.g., floodplain vegetation), and ecosystem processes (e.g., the Hydrogeomorphic Method, Brinson 1993).

The Proctor Creek Ecological Model (PCEM, pronounced "P-Sim") combines habitat quantity and quality for a given segment of river. Quantity assesses the size of the ecosystem (e.g., area or linear feet along a stream), and quality provides a numerical assessment of the general ecological functionality of the ecosystem. For Proctor Creek, four basic sub-models (or modules) are used in the assessment of habitat quality: instream condition, riparian condition, hydrology, and watershed connectivity. Each of these modules is directly related to the primary planning objectives for the restoration study (Table 2) and forms the central structure for PCEM.

Conceptual ecological models are required for all USACE ecosystem restoration projects due to their utility to increase understanding, identify potential alternatives, and facilitate team dialog (Fischenich 2008, USACE 2011). A generalized conceptual model of Proctor Creek (Figure 2) was iteratively developed by project team members during Phase 1 project planning in conjunction with the identification of problem and opportunities, objectives and metrics, and potential alternatives. McKay et al. (2017) provide additional detail on the development and scope of this model.

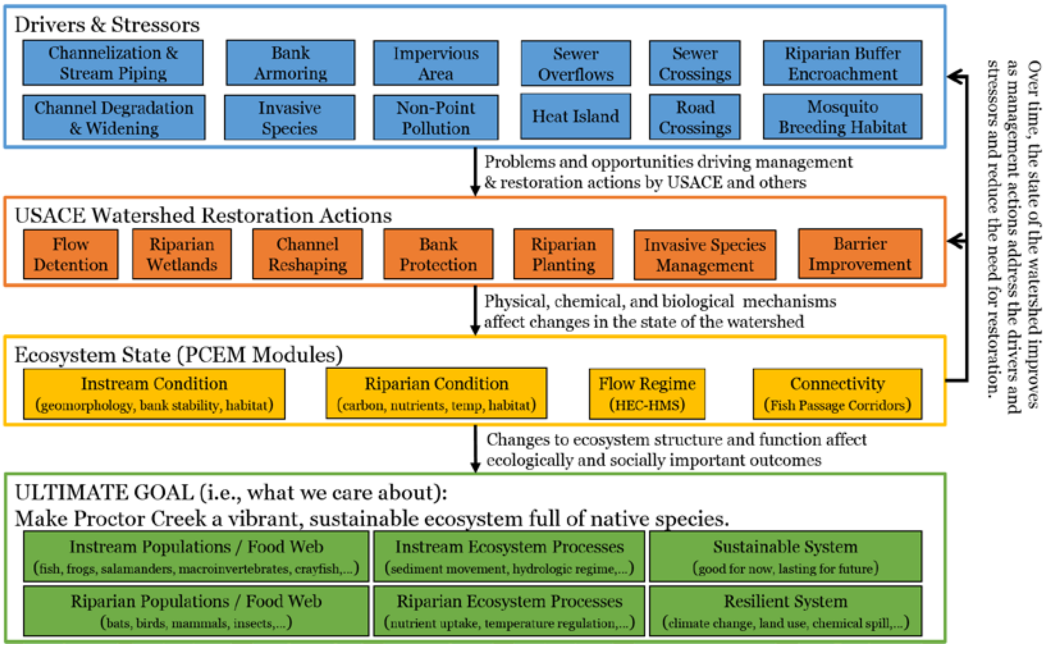


Figure 2. General conceptual ecological model for Proctor Creek stream restoration intended to facilitate communication among team members, stakeholders, the project sponsor, and agency partners (adapted from McKay et al. 2017).

Conceptual models also inform the development of quantitative ecological models used in the assessment of the environmental benefits of restoration (Grant and Swannack 2008, Swannack et al. 2012). A more detailed conceptual model was created to inform PCEM2 development (Figure 3). This model emphasizes a more mechanistic view of how proposed restoration actions alter key elements of the ecosystem and subsequently roll into model variables. A seven step conceptual model development process was followed (Fischenich 2008, Grant and Swannack 2008), drawing heavily from existing conceptual models addressing general stream processes (e.g., Channel Evolution Model, Simon 1989), urban streams (Wenger et al. 2009), and Appalachian Piedmont streams (McKay et al. 2011, McKay and Pruitt 2012). Table 4 presents the generalized conceptual modeling process along with its application to informing PCEM2.

The model was iteratively developed following the Phase 1 model structure (Figure 2), site investigations, and quantitative model development. The model does not provide a complete mechanistic description of all ongoing physical, chemical, and biological processes. For instance, bank erosion is influenced by a complex set of state conditions such as bank height and sediment material (clay v. sand) and processes such as helical flow and seepage. Furthermore, bank protection practices ranging from bank shaping to crib walls uniquely act upon these conditions (FISRWG 1997).

However, the general notion of many bank protection actions is to reduce near bank shear stress, which is presented in our diagram. Following this example, Figure 3 provides insight into some key mechanisms and emphasizes the logic of how a particular family of restoration methods (orange boxes) is intended to influence key project outcomes (yellow boxes). The model also explicitly acknowledges the 11 model variables (grey boxes), which are combined to assess habitat quality in the quantitative phase of model development (Chapter 3). Notably, the model does not explicitly include boundary conditions of the watershed (e.g., geology, climate, land use), specific ecological outcomes stemming from improvement in the four focal outcomes (e.g., the increase in abundance of Fish-X is not shown), or restoration and management actions outside of the USACE authority and consideration (e.g., management of combined sewer overflows). The generalized conceptual model (Figure 2) is intended to provide this context, whereas this model (Figure 3) is intended to guide detailed numerical model development.

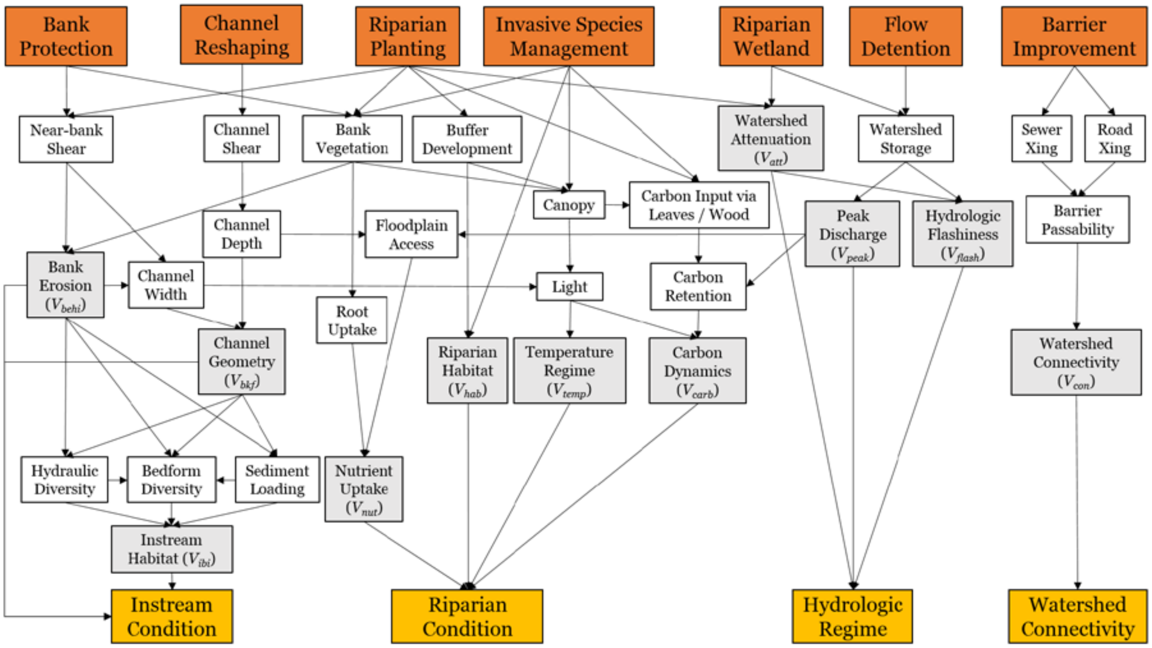


Figure 3. Detailed conceptual model for Proctor Creek stream restoration intended to inform numerical model development. Boxes are color-coded relative to: potential USACE restoration actions (orange), model variables (grey), intermediate aspects of ecosystem structure and function (white), and ecosystem state conditions captured by PCEM modules (yellow).

Table 4. Stepwise development of the detailed conceptual model for Proctor Creek to guide numerical model development (Figure 3).

Step	Proctor Creek Application
1. State the model objectives	This model provides sufficient detail linking families of restoration actions to focal project outcomes, which may then be used to guide numerical model development. The model is intended as a tool for communicating the basic structure of the PCEM2 numerical model within the model development team as well as to interested technical groups.
2. Bound the system of interest	The model was developed specifically for the Proctor Creek watershed in Atlanta, Georgia. However, the model is relatively general and could likely be applied or adapted to other urban or Appalachian Piedmont streams. The model was designed to address stream corridors including the instream, riparian, and associated wetlands environments.
3. Identify critical model components within the system of interest	Model components were compiled in both “bottom-up” and “top-down” formats. First, ecological outcomes were derived from project objectives and sub-objectives. Physical, chemical, and biological processes leading to these outcomes were then assembled. Second, a menu of potential restoration actions was compiled from existing literature (e.g., FISRWG 1997, EMRRP Technical Notes collection, etc.). Associated elements of ecosystem structure and function were then collected, which are directly affected by these restoration measures. Duplicate or redundant processes and model elements were then removed.
4. Articulate the relationships among the components of interest	The general flow of the model was intended to capture the relationship of each family of restoration method to the project-specific, ecological outcomes of interest. Accordingly, model relationships were identified based on prior conceptual models (e.g., Wenger et al. 2009), peer-reviewed literature (e.g., McKay et al. 2016), grey literature and project reports (e.g., Rosgen 2001), and professional judgment and experience.
5. Represent the conceptual model	A box-and-arrow flow diagram of the conceptual model (Figure 3) was developed to articulate relationships between restoration actions, ecological processes, model variables, and project outcomes. In this process, some model elements were removed to simplify the diagram.
6. Describe the expected pattern of model behavior	The team qualitatively assessed flow of logic between model components (e.g., culverts can reduce passability, which affects watershed connectivity and reduces capacity for recovery after disturbances).
7. Test, review, and revise as needed	The model was informed by current views of urban stream function (e.g., Wenger et al. 2009), developed by the team in isolation of other groups, and then subsequently presented to the local sponsor and interagency working group for input and revision.

4 Model Quantification

The second phase of ecological model development quantifies some or all of the conceptual model in terms of mathematical relationships, model parameters, a simulation environment, and ultimately quantitative outputs (Grant and Swannack 2008). This chapter articulates the general structure of PCEM2, the functional form of each of the sub-models (i.e., modules), protocols for collecting model parameters, and the numerical toolkit for executing the model.

As described above, PCEM2 is an “index” model based on assessing the quantity and quality of habitat for a given segment of river. The model is applied on a reach-by-reach basis, but the reach scores address the cumulative effects of upstream drainage areas (via hydrology) and downstream barriers (via connectivity). As such, this model represents a fully integrated, watershed scale model for assessing the cumulative benefits of multiple stream and riparian restoration actions in the Proctor Creek watershed. Notably, project timelines required that some methods include rapid assays (e.g., pseudo-quantitative scoring systems) or rely on professional judgment. However, if the model were applied under different planning circumstances, these components could easily be substituted for more sophisticated, direct analyses. For instance, the instream condition module includes a rapid scoring system for measuring embeddedness of stream substrates (i.e., a 0-20 pick-list), which could be substituted for a more rigorous approach including field sampling or laboratory analyses (e.g., “depth of embeddedness”, MacDonald et al. 1991).

The basis for the model is the combination of habitat quantity and quality into a single variable, a quality-weighted stream mile. Length of stream is used as the primary metric of habitat quantity. Stream length was assessed using a Geographic Information System (GIS) as all mapped segments in the National Hydrography Dataset (NHD).

For Proctor Creek, four basic sub-models (or modules) are used in the assessment of habitat quality: instream condition, riparian condition, hydrology, and watershed connectivity. Each module is directly related to the primary planning objectives for the restoration study (Table 2) and forms the central structure for PCEM. The modules are summarized in indices scaled from 0 to 1, where 0 indicates no ecological value and 1 indicates perfect ecological condition. The modules are described in detail in subsequent sections of this document, but briefly, each index is composed of multiple model variables (Table 5), which directly correspond to project sub-objectives and are themselves often composed of multiple field measurements.

Habitat quality is computed as the combination of quality scores for each module. This "Index of Ecosystem Integrity" (*IEI*) is then combined with habitat quantity and summed at the watershed scale as an overarching metric of watershed condition. The *IEI* is computed as the geometric mean of the four modules with the assumption that ecosystem quality is dependent upon a balance of all four components and degradation is likely when any single component is degraded.

$$IEI = \sqrt[4]{I_{ins} * I_{rip} * I_{hyd} * I_{con}}$$

Where *IEI* is the Index of Ecosystem Integrity, I_{ins} is an index of quality from the instream module (0 to 1), I_{rip} is an index of quality from the riparian module (0 to 1), I_{hyd} is an index of quality from the hydrologic module (0 to 1), and I_{con} is an index of quality from the watershed connectivity module (0 to 1).

The final model output is a quality-weighted stream mile. The maximum possible output for the Proctor Creek watershed would occur if all stream segments in the watershed (i.e., 13.0 miles in the NHD+) had perfect quality (i.e., *IEI*=1). However, this outcome is not realistic given the highly developed watershed, consequently, is not considered attainable in the PC watershed.

Table 5. Overview of the quality sub-models in the Proctor Creek Ecological Model (PCEM).

Module	Objective	Sub-Objective	Metric / Model Variable
Instream condition (I_{ins})	1.1 Improve in-channel conditions suitable for a diversity of aquatic organisms	Restore channel geomorphic conditions to less disturbed conditions.	V_{bkf} – Percent difference in bankfull channel area relative to a regional hydraulic geometry curve.
		Reduce sediment loading from stream bed and banks.	V_{behi} – Bank Erosion Hazard Index scoring system for assessing bank stability (Rosgen 2001).
		Increase instream habitat for a diverse assemblage of local fauna.	V_{ibi} – State-wide visual fish habitat assessment for measuring biotic integrity (GA DNR 2005).
Riparian condition (I_{rip})	1.2 Improve riparian conditions supportive of a diverse aquatic and riparian community	Restore natural sources of organic carbon (i.e., energy) within the system.	V_{carb} – Visual assessment protocol reflecting carbon sources and the basis of the food web.
		Increase nutrient uptake within the basin.	V_{nut} – Combination of variables assessing lateral connectivity of the river and floodplain and potential for root uptake by riparian plants.
		Improve temperature regimes.	V_{temp} – Ratio of riparian canopy height to bankfull channel width as a proxy for temperature regulation.
		Increase riparian habitat to support native biodiversity.	V_{hab} – Extent of invasive species in riparian areas.
Hydrology (I_{hyd})	1.3 Restore the flow regime to the best attainable condition	Decrease peak flows.	V_{peak} – Peak discharge from 2-year rainfall.
		Decrease hydrologic flashiness.	V_{flash} – Hydrograph width for 2-year rainfall.
		Improve the capacity of the watershed to attenuate flows.	V_{att} – Visual assessment of the capacity of a reach to attenuate floods primarily via hydraulic roughness.
Connectivity (I_{con})	1.4 Promote an interconnected system resilient to disturbances	Increase connectivity of movement corridors for aquatic and riparian species.	V_{con} – Watershed connectivity to the Chattahoochee River for small-bodied native fishes. This single metric is used to reflect both objectives as the resilience of an urban stream often depends on its ability to recolonize following disturbance (e.g., repopulate following chemical spill).
		Increase the capacity to absorb natural and anthropogenic disturbance.	

PCEM2 was explicitly developed to measure the success of USACE restoration actions in the Proctor Creek watershed. While the approach is scientifically based and defensible, there are a number of key assumptions and limitations regarding the overall approach to model quantification.

- The index model structure of a quantity-quality assessment is standard of practice within USACE restoration planning. However, other modeling approaches could have captured different aspects of ecosystem structure and function (e.g., a simulation model of fish metapopulation dynamics). This model assumes an index approach sufficiently captures changes in ecosystem structure and function, and variables were intentionally designed to incorporate functional processes where possible.

- PCEM2 was designed to measure the ecological objectives for the Proctor Creek ecosystem restoration study. These objectives are commonly expressed stream restoration objectives, but the model is not intended to capture all potential ecologically relevant aspects of stream ecosystem structure and function (e.g., mass of nutrient uptake or abundance of salamanders).

- The four primary objectives for the project and associated indices are assumed to be of equal importance (i.e., they are not weighted). Likewise, model variables are assumed to be of equal importance when combined into the indices.

- Model variables were rigorously screened based on their sensitivity to restoration actions. Variables are developed to emphasize outcomes affected by USACE restoration actions. For instance, stream temperatures are strongly correlated with air temperature and surface runoff from impervious areas (e.g., hot runoff from a summer parking lot). However, impervious area was not included in the assessment of temperature regimes due to small changes associated with USACE actions (i.e., the percent change in imperviousness at the watershed scale would be small relative to project footprints).

- All variables and data collection had to be possible within the project timeline, which included one week of field data collection by two teams and eight months for all analyses.

4.1 Instream Module

The instream module addresses the overall geomorphic state, ongoing geomorphic processes, and habitat provision associated with the in-channel environment. Specifically, this module directly addresses the primary planning objective of “improve in-channel conditions suitable for a diversity of aquatic organisms” (i.e., Objective 1.1 in Table 2), and variables were selected to emphasize the associated sub-objectives. The variable associated with each sub-objective is presented below along with the combination of these variables into an index of instream condition.

4.1.1.1 Restore channel geomorphic conditions to less disturbed conditions

As a result of urbanization, stream geomorphology undergoes a predictable process of channel evolution (Simon 1989). As impervious area increases, the magnitude and timing of runoff events tends to induce dramatic or “peaky” hydrographs. The erosive force of these events leads to a common pattern of channel degradation (i.e., downcutting), widening (i.e., bank failure with associated loss of riparian vegetation), and eventually arrives at a new stable equilibrium. The stage of the stream along this continuum can inform restoration decisions and guide actions (Watson et al. 2002). This metric uses the shape and dimensions of a channel (i.e., its geometry) as a proxy for current and future geomorphic condition.

Geomorphologists have long used the bankfull dimensions of a channel as a surrogate for geomorphic condition and ongoing processes. In an unaltered stream, the bankfull condition generally refers to the incipient point of flooding, which is indicative of the long-term channel shape in response to the watershed’s hydrologic regime and geologic factors (Figure 4).

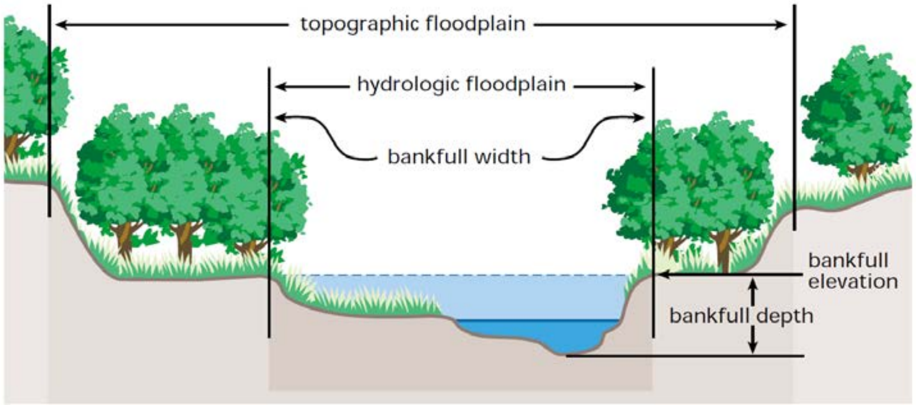


Figure 4. Bankfull channel geometry definitions (Figure 2.16 from FISRWG 1997).

Bankfull geometry (i.e., depth, width, and cross-sectional area) may be measured at many sites in a region to develop a regional hydraulic geometry curve. These regressions typically relate geometric properties with drainage area or bankfull discharge in an effort to characterize “typical” channel shape in the region. Regardless of data set size, these regressions often display a significant amount of scatter due to the simplistic assumption of a single independent and dependent variable to define a complex system (NRCS 2007, Ch 7).

As a reference condition for the Proctor Creek study, bankfull geometry data were assembled from three existing studies of Appalachian Piedmont streams in (Figure 5): Georgia (Pruitt 2001), North Carolina (Doll et al. 2002), and Maryland (McCandless and Everett 2002). These studies provided bankfull dimensions across a land use gradient, which were compiled to developed regional hydraulic geometry curves for high and low levels of impervious area (i.e., greater than and less than 10%, respectively). For Proctor Creek, we use the deviation from the low imperviousness regional curve as our primary metric of geomorphic condition (V_{bkf})

$$V_{bkf} = \frac{\left|A_{bkf,ref} - A_{bkf,site}\right|}{A_{bkf,ref}}$$

Where V_{bkf} is the metric for geomorphic conditions, $A_{bkf,ref}$ is the cross-sectional area predicted by the low imperviousness regional curve, and $A_{bkf,site}$ is the cross-sectional area of the stream at a proposed Proctor Creek restoration site (either without or with the restoration project).

Cross-sectional surveys of existing condition in Proctor Creek were conducted in June 2016. Channel cross-sections were obtained at representative sites in each reach. Bankfull elevations were identified based on field indicators such as wrested vegetation, depositional zones or breaks in topography, tops of point bars, and leaf and debris markers (Harrelson et al. 1994). Regional curves were also used to inform design decisions (e.g., channel widths), and the design drawings were then used to extract channel geometry for the restoration conditions.

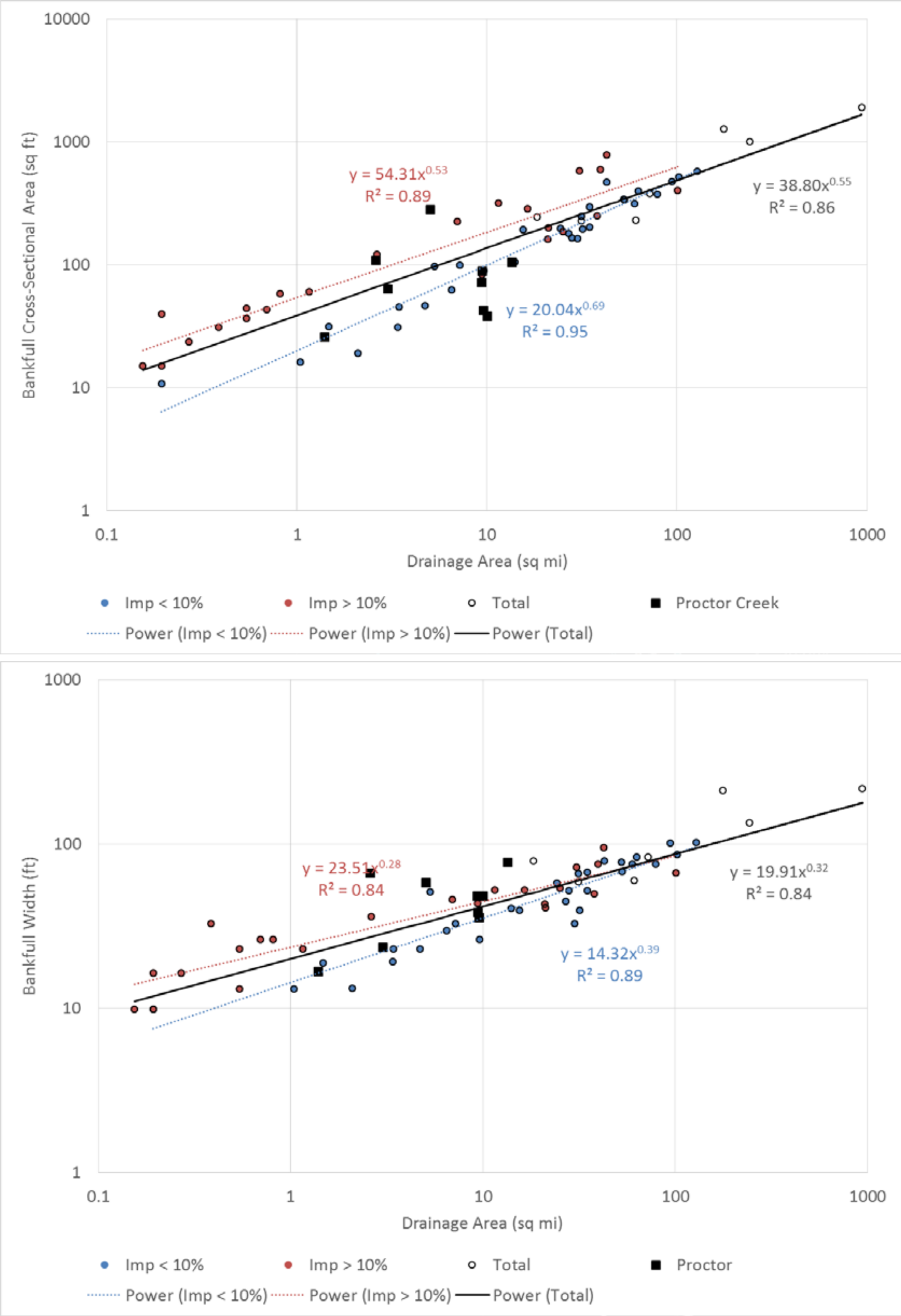


Figure 5. Region bankfull hydraulic geometry curves for the Appalachian Piedmont. Proctor Creek channel geometry is shown in black for relative comparison of the existing condition.

4.1.1.2 Reduce sediment loading from stream bed and banks

Urban runoff and accelerated erosion increase sediment supply from overland, bed, and bank sources. USACE actions are not intended to address overland introduction of sediment, and thus overland introduction is not considered here. However, sediment loading from the stream bed via degradation and stream banks via widening are problematic sources both for the Proctor Creek ecosystem (see embeddedness discussion below) and downstream rivers (e.g., reservoir sedimentation in the Chattahoochee River). The Proctor Creek watershed has been developed for many decades, and a majority of reaches have undergone downcutting and are now in the widening phase of channel evolution based on observations from a February 2016 field investigation. In addition, accelerated sediment deposition, results in formation of mid-channel and traverse bars which increases near bank shear stress and, ultimately, causes bank failure. As such, we neglect the influence of bed sediment and focus on the potential for sediment introduction from streambanks.

Rosgen (2001) proposed a semi-quantitative methodology for assessing potential for bank erosion. The Bank Erosion Hazard Index (BEHI) combines five basic variables into an overarching score on a 0 to 50 point scale: (1) a measure of entrenchment as the ratio of the height of the top of the bank to the bankfull depth, which diverges from 1 as a channel degrades, (2) the ratio of rooting depth to the height of the top of the bank, (3) a visual estimate of the root density in the bank zone, (4) the angle of the bank, and (5) a measure of the protection of bank surfaces by vegetation. For each variable, a categorical score is assigned based on a specified rubric (Table 6). For instance, a bank angle of 70 degrees would indicate a categorical score of 5.0. The scores are then summed across the five categories to reach an overall hazard score. We assumed linearity of scoring within a category, which is implied but not explicitly recommended by Rosgen. The BEHI approach also offers two correction factors for bank materials (e.g., bedrock v. silt) and stratification (i.e., layering of sediment types).

All data were collected for Proctor Creek in conjunction with channel cross-sectional measurements described above at representative locations in each reach. We disregard the correction factors to simplify application within the constrained time horizon of the project. BEHI scores were computed for both the left and right (descending) streambanks, and reach-wide scores were computed as the average of the values. To compute the overall sediment loading metric (V_{behi}), the 50-point scale was then normalized from 0 to 1.

Table 6. Bank Erosion Hazard Index (BEHI) scoring system.

Hazard Category (Range of Total Score)	Categorical Score	H_{bank} / H_{bkf}	H_{root} / H_{bank}	Root Density (%)	Bank Angle (deg)	Surface Protection (%)
Very Low (5-10)	1-2	1.0-1.1	1.00-0.90	100-80	0-20	100-80
Low (10-20)	2-4	1.1-1.2	0.90-0.50	80-55	20-60	80-55
Moderate (20-30)	4-6	1.2-1.5	0.50-0.30	55-30	60-80	55-30
High (30-40)	6-8	1.5-2.0	0.30-0.15	30-15	80-90	30-15
Very High (40-45)	8-9	2.0-2.8	0.15-0.05	15-5	91-120	15-10
Extreme (>45)	9-10	>2.8	< 0.05	< 5	> 120	< 10

4.1.1.3 Increase instream habitat for a diverse assemblage of local fauna

Urban waters commonly experience degradation and homogenization of instream habitat with an associated decline in biodiversity, although mechanisms are poorly understood (Paul and Meyer 2001). In Proctor Creek, pools have been filled due to accelerated sedimentation resulting in dominance of runs and reduction in bedform spacing and diversity. Diverse aquatic taxa (e.g., macroinvertebrates, fish, salamanders, and crayfish) often differentially experience these physical, chemical, and biological changes to the ecosystem. This metric uses a semi-quantitative scoring system design for Georgia's fish community to assess instream habitat (GA DNR 2004). While a more thorough taxa specific system is preferred (e.g., habitat suitability calculations for a diversity of taxa), the fish community's role as a high order consumer (i.e., often near the top of the aquatic food web) assumes that protecting fish habitat results in a concomitant protection of lower order taxa (e.g., benthic macroinvertebrates) that is they serve as an "umbrella species" (Lambeck 1997).

This assessment of instream habitat is based on two, well-vetted procedures: (1) the EPA's Rapid Bioassessment Protocol and (2) a state procedure for fish biomonitoring (GA DNR 2005). These procedures provide a 0 to 20 point scale for assessing ten variables indicative of habitat quality. This metric used a subset of the recommended ten variables (Table 7) because riparian condition and bank processes are assessed separately and bedform diversity is challenging to forecast. Qualitative descriptions of the 0 to 20 point scale were developed for each variable in the context of the Proctor Creek basin (Appendix B). The 20-point scale was viewed in the context of the Proctor Creek watershed with 20 representing the best attainable condition for this basin rather than a pristine, unaltered condition. Minor modifications to the scales were made in light of other qualitative stream survey methods (Newton et al. 1998, Barbour et al. 1999, Rankin 2006, Boyer 2009). The five habitat variables were averaged across observers and variables and subsequently normalized from 0 to 1 to obtain the instream habitat metric (V_{ibi}).

Table 7. Description of the importance of instream habitat variables.

Variable	Description and Reason for Inclusion
Epifaunal and Instream Cover	The presence and stability of diverse habitat types provides a variety of niches for aquatic organisms. Some possible stable habitat types include fallen trees, overhanging shrubbery, and diverse bedforms and substrates.
Embeddedness in Runs	Sediment types and sorting play an important role in benthic processes and the embeddedness of sediments is a common indicator of instream processing. This variable addresses the degree to which gaps around large substrates (e.g., gravels) are filled in with silts and clay.
Velocity and depth regime	Instream complexity is often indicative of habitat value for a variety of aquatic taxa, and diverse habitats (e.g., pools, riffles, runs, glides) are common to intact stream ecosystems. Four generalized depth and velocity regimes were addressed: slow-deep, fast-deep, slow-shallow, and fast-shallow.
Channel alteration	The degree and age of river engineering structures and alteration (e.g., piping, channelization, bank armoring) is a good surrogate for overall ecosystem impact experienced over long time scales.
Sediment Deposition	Sediment accumulation in pools reduces habitat diversity and negatively impacts benthic organisms. This variable assess the relative amount of deposition in an area as well as indicators of large-scale changes to the sediment environment (e.g., enlargement of bars).

Field-based visual surveys were used to assess the existing condition of each variable. All stream reaches with proposed restoration actions (Table 2) were visited during a rapid survey conducted June 13-17, 2016. The length of each reach was walked by a consistent team of USACE personnel.

The instream scoring system was then independently assessed by three team members for the existing and with project conditions. All surveys were conducted by a team including expertise in biology, geomorphology, stream ecology, water resource engineering, and USACE planning.

4.1.1.4 Instream index

Total instream condition (I_{ins}) was assessed as the arithmetic mean of the three instream metrics. Two assumptions are implicit in this equation: (1) equal weight among the variables and (2) independence of the variables.

$$I_{ins} = \frac{V_{bkf} + V_{behi} + V_{ibi}}{3}$$

Where I_{ins} is an index of instream condition, V_{bkf} is a metric of geomorphic condition, V_{behi} is a metric of sediment loading, and V_{ibi} is a metric of instream habitat.

4.2 Riparian Condition Module

Riparian condition refers broadly to the overall health of the riparian zone, its influence on instream processes, and its capacity to provide habitat. This module addresses the planning objective of “improve riparian conditions supportive of a diverse aquatic and riparian community” (i.e., Objective 1.2 in Table 2), with variables selected to emphasize associated sub-objectives. The variable associated with each sub-objective is presented below along with the combination of these variables into an index of riparian condition.

4.2.1.1 Restore natural sources of organic carbon within the system

Stream food webs obtain energy from inside of the stream (i.e., “autochthonous” sources such as algal growth) as well as 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 (Vannote et al. 1980). This metric assesses the contribution of different carbon sources as a proxy for energy input and its role in driving food web structure.

For PCEM2, the metric (V_{carb}) incorporates three components of carbon dynamics. All three elements were assessed visually using a procedure that follows the general form of the habitat assessment described above (i.e., EPA and GA-DNR's 0 to 20 point scale). First, primary carbon sources (e.g., algal v. leaf input) present in the system were coupled with an assessment of carbon retention within a reach (e.g., evidence of leaf packs and wood). Second, the complexity of the vertical structure of the riparian canopy was used as a proxy for the diversity of leaf inputs and relative effect of stream shading. Third, the diversity and vigor of bank vegetation was assessed from an adapted habitat assessment procedure (GA DNR 2005) as a second proxy for the diversity of leaf inputs and relative effect of stream shading. All three variables were assessed following the visual assessment procedure described above (i.e., stream walk, three observers, and averages of left and right banks). Qualitative descriptions of the 0 to 20 point scales for each variable in the context of the Proctor Creek basin are provided in Appendix B.

4.2.1.2 Increase nutrient uptake within the basin

Nutrient dynamics in urban streams are often highly altered from myriad factors such as increased loading (e.g., fertilizer runoff, sewer overflows), reduced uptake zones (e.g., impervious upland and riparian zones), and altered hydrology (e.g., reduced residence times). Watershed management actions such as stormwater control, installation of green infrastructure, wetland creation, or fertilizer control programs can reduce these effects significantly. However, proposed USACE restoration actions primarily influence the uptake capacity of the stream and associated floodplain and wetland complex, and thus are the focus of this metric.

First, lateral connectivity between the channel and floodplain contributes to the uptake of nutrients by increasing contact time with riparian vegetation and increasing the area of potential uptake. Floodplain connectivity is assessed in PCEM2 as the ratio of bankfull depth to the bank height of the lowest bank (to a maximum of one). Cross-sectional surveys described above are used in the assessment of these variables.

Second, vegetation along streambanks interacts with base flows through root zones, which can provide a source of nutrient reduction. Riparian zones can also uptake and transform nutrients from upland sources moving through these stream buffers (de Steven and Lowrance 2011). Uptake capacity of streambank vegetation is assessed as the average root density (%) from left and right bank measurements from the BEHI survey.

The overall nutrient uptake metric (V_{nut}) is the combination of the floodplain connectivity and bank vegetation variables.

4.2.1.3 Improve temperature regimes

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 (Kraseski 2015). This metric uses the relative level of canopy shading as a proxy for stream temperature regimes in a given reach. Specifically, the ratio of the canopy height within 25 feet of the top of bank to the bank-to-bank width (Figure 6) is used as a surrogate for light levels and associated temperature change. This ratio is assessed for both banks and averaged to a maximum value of one. Both parameters were assessed in the field during cross-sectional surveys.

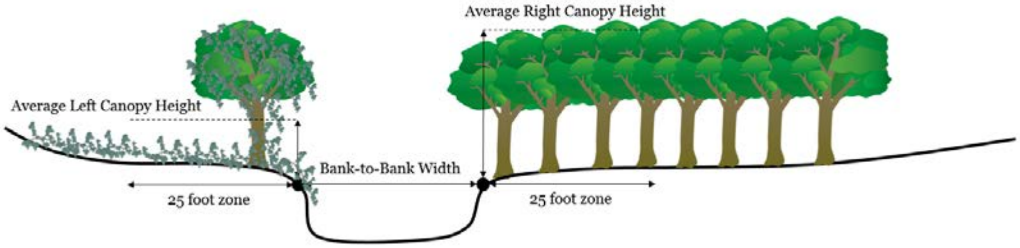


Figure 6. Schematic of stream shading zone (clip art from ian.umces.edu).

4.2.1.4 Increase riparian habitat to support native biodiversity

In addition to their influence on streams, riparian zones also serve as important habitats due to their role as an ecotone between the aquatic and terrestrial environments. In urban areas, riparian zones provide migratory corridors, refugia, and stopover habitat for a variety of birds, mammals, insects, and other organisms. Invasive species such as kudzu, privet hedge, multiflora rose, Russian olive, and English ivy dramatically alter habitats and overtake native species throughout the Proctor Creek watershed. This metric (V_{hab}) reflects the extent to which invasive species have compromised riparian habitat functions. This variable is computed as the average percent of native species in the left and right riparian zones from belt transect surveys conducted in conjunction with cross-sectional surveys.

4.2.1.5 Riparian index

The total riparian condition (I_{rip}) was assessed as the arithmetic mean of the four riparian metrics. Two assumptions are implicit: (1) equal weight among the variables and (2) independence of the variables.

$$I_{rip} = \frac{V_{carb} + V_{nut} + V_{temp} + V_{hab}}{4}$$

Where I_{ins} is an index of riparian condition, V_{carb} is a metric of carbon sources, V_{nut} is a metric of nutrient uptake, V_{temp} is a metric of temperature regimes, and V_{hab} is a metric of riparian habitat.

4.3 Hydrology Module

Hydrologic condition refers to the degree of similarity between an unaltered, pre-development hydrograph and the modified, current hydrograph. This module directly addresses the primary planning objective of "restore flow regimes to best attainable conditions achievable in altered urban environments" (i.e., Objective 1.3 in Table 2), and variables were selected to emphasize the associated sub-objectives. The variables associated with each sub-objective are presented below along with the combination of these variables into an index of hydrologic condition. Notably, the first two sub-objectives are presented together due to a single analytical approach.

4.3.1.1 Decrease peak flows and hydrographic flashiness

Hydrologic change due to increased impervious area in cities represents one of the most important changes in stream and riparian functions resulting from urbanization (Fischenich 2005). Piedmont streams provide a classic example of urban hydrologic change with watersheds generally exhibiting increased peak flows and reduced time of concentration (i.e., a "flashy" hydrograph; Inman 2000, Gotvald and Knaak 2011, Feaster et al. 2014). Flashy conditions result in a reduction in baseflow discharge and depth which adversely affects aquatic biota (e.g., suppressed dissolved oxygen, increased water temperature, reduction in "living space", limited access to habitat types). Two metrics are used to summarize these hydrologic changes in PCEM2, peak discharge (V_{peak}) and hydrograph width (V_{flash}), both of which are assessed via a hydrologic simulation model. Many other hydrologic metrics could be used to assess these objectives (e.g., Olden and Poff 2003, Baker et al. 2004), but these were selected in light of hydrologic model development burden and relevance to USACE actions.

The Hydrologic Engineer Center's Hydrologic Modeling System (HEC-HMS Version 4.2, Scharffenberg 2016) was applied to assess hydrologic change throughout the Proctor Creek watershed. Details of the hydrologic model development and calibration at local USGS gages are provided in Appendix C. To provide a reference point of comparison, the HMS model will be simulated for current levels of development and a hypothetical, undeveloped, forested condition. This is not to imply that this state is desirable or achievable, but merely provides a consistent frame of reference for comparison of hydrologic change. Each reach in the Proctor Creek watershed was assigned an associated "pour point" in the HMS domain, which provided HMS outputs for every reach and alternative.

HMS was executed in a storm simulation context (rather than a continuous simulation) for a 24-hour, 2-year recurrence interval rainfall event (3.72 in, NOAA 2017) uniformly applied over the entire watershed. The 2-year event was chosen for assessment of the benefits of restoration actions as a compromise between storm event frequency and magnitude. Furthermore, 2-year discharge events are often correlated with geomorphically significant events such as bankfull or effective discharge (Wilkerson 2008). For these simulations, hydrographs were generated, and peak discharge and hydrograph width were extracted for every reach in the watershed. Hydrograph width was assessed at 75% and 50% of the peak discharge following traditional methods for hydrograph characterization (Bedient et al. 2013), and the average width was applied as a metric of hydrologic flashiness. The relative change in these parameters from the forested condition was used as the metrics for PCEM2 (Figure 7), as follows:

$$V_{peak} = -\frac{Q_{peak}}{Q_{pre}} + 2 \qquad\qquad V_{time} = \frac{2w_{peak}}{w_{pre}} - 1$$

Where V_{peak} is the metric for peak discharge, Q_{peak} is the peak discharge for a given alternative, Q_{pre} is the pre-development, fully forested peak discharge, and V_{peak} is bracketed from a minimum of 0 when $Q_{peak} = 2^* Q_{pre}$ to a maximum of 1 when $Q_{peak} = Q_{pre}$. Also, V_{flash} is the metric for flashiness based on hydrograph width, w_{peak} is the average width of the hydrograph at 75% and 50% of peak discharge for a given alternative, w_{pre} is the pre-development, fully forested average width of the hydrograph at 75% and 50% of peak discharge, and V_{flash} is bracketed from a minimum of 0 when $w_{peak} = 0.5 * w_{pre}$ to a maximum of 1 when $w_{peak} = w_{pre}$ (Figure 7).

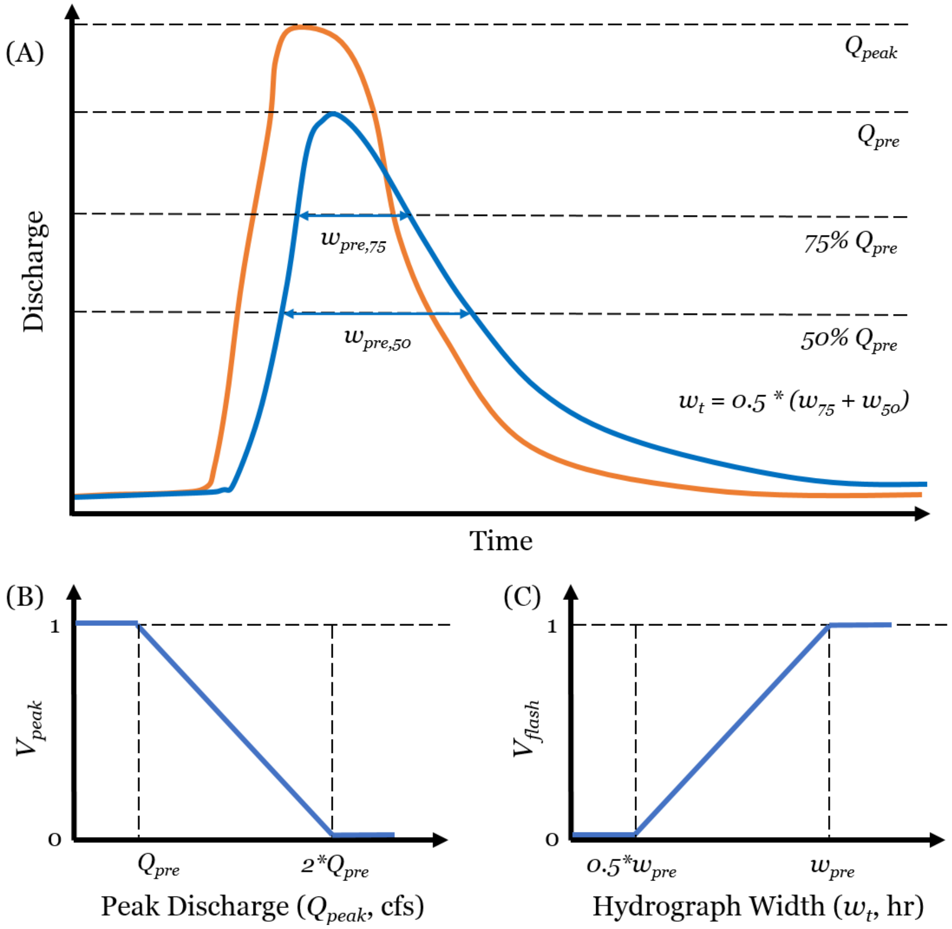


Figure 7. Summary of hydrologic metrics for peak discharge (V_{peak}) and flashiness (V_{flash}): (A) Schematic of storm hydrographs in undeveloped (blue) and developed (orange) watershed conditions with key hydrograph features as labeled. (B) Rescaling of peak discharge from 0 to 1. (C) Rescaling of flashiness metric from 0 to 1.

4.3.1.2 Improve the capacity of the watershed to attenuate flows

In addition to direct changes to hydrology, restoration actions can impact the hydrologic function of a watershed indirectly. For instance, a low floodplain environment with vigorous vegetation and a temporary wetland can alter flood routing via hydraulic roughness and surface storage. The degree of hydrologic impact is a function of the geomorphic conditions (e.g., accessibility of the floodplain), presence and health of riparian vegetation, degree of other roughness elements (e.g., large wood, meanders, etc.), and volume of floodplain storage areas. A visual assessment scale was developed to capture the relative effect of these factors on hydrologic function and attenuation within a reach (Table 8). The scale was designed following the 0 to 20 point scale used for other variables. Other hydrologic variables (V_{peak}, V_{flash}) were assessed cumulatively for every reach in the watershed, and thus, this variable was also applied watershed-wide. All assessments were conducted remotely by the team using information related to cross-sectional surveys (e.g., bankfull depth, bank height ratio), stream walks and photos, area / volume of known wetland features, and riparian vegetation scores. The scoring system was independently assessed by three team members for the existing and with project conditions. All surveys were conducted by a team including expertise in biology, hydrology, geomorphology, stream ecology, water resource engineering, and USACE planning. Scores were normalized from 0 to 1 to obtain the hydrologic attenuation metric (V_{att}).

Table 8. Semi-quantitative scoring system for assessing hydrologic attenuation.

Condition (Scoring Range)	Description
Optimal (20-16)	Low accessible floodplain environment with vigorous vegetation, little (if any) impervious area, significant storage, and likely presence of floodplain wetlands with significant residence time.
Suboptimal (15-11)	Vegetated floodplain with likely effect on flood routing due to frequency of events (e.g., accessible floodplain) or floodplain storage. Moderate residence times. High surface water- groundwater interaction.
Marginal (10-6)	Vegetated floodplain with minimal effect on flood routing due to frequency of events (e.g., perched floodplain) or floodplain storage. Low residence times. Low surface water- groundwater interaction.
Poor (5-0)	Perched floodplain with little vegetation, no surface storage, significant impervious cover, and little (if any) effect on flood routing.

4.3.1.3 Hydrologic index

The total hydrologic condition (I_{hyd}) was assessed as the arithmetic mean of the three component metrics. Two assumptions are implicit: (1) equal weight among the three variables and (2) independence of the variables.

$$I_{hyd} = \frac{V_{peak} + V_{flash} + V_{att}}{3}$$

Where I_{ins} is an index of watershed hydrology, V_{peak} is a metric of peak flows, V_{flash} is a metric of hydrologic flashiness, and V_{att} is a metric of hydrologic attenuation in the watershed and riparian zone.

4.4 Connectivity Module

Hydrologic connectivity refers to the "water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle" (Pringle 2003). This module directly addresses the primary planning objective of "promote an interconnected system resilient to foreseen and unforeseen disturbances" (i.e., Objective 1.4 in Table 2), and the assessment approach emphasized the associated sub-objectives of:

- Increase connectivity of movement corridors for aquatic and riparian species.
- Increase the capacity to absorb natural and anthropogenic disturbance.

Connectivity between headwaters and large rivers is important for maintaining population dynamics and dispersal of both aquatic and riparian organisms (Freeman et al. 2007, Meyer et al. 2007, Fuller et al. 2015). Spatially connected systems are buffered against disturbances in urban environments (e.g., floods, chemical spills) and can repopulate or recover more quickly than isolated systems. This capacity to bounce back (i.e., resilience) represents an important mechanism for coping with urban stressors (Palmer et al. 2005).

In the PCEM, connectivity is assessed as a watershed-scale process and quantified as the cumulative probability of aquatic organism passage beyond a sequence of multiple potential barriers. For instance, two barriers in sequence create three unique reaches. If an organism has a 50% probability of passing each barrier, the cumulative probability of an organism passing in each reach is 100%, 50%, and 25% moving upstream. This general approach has been applied to more than 40 studies of barrier prioritization worldwide (McKay et al. 2016), and we adopt the approach of McKay et al. (2013), which uses network analyses to summarize the cumulative passage process.

In the Proctor Creek watershed, movement barriers arise primarily from road crossings, sewer crossings, piped or channelized streams, and natural waterfalls. While other organisms use aquatic and riparian corridors (e.g., amphibians, otter, song birds), all passage processes were assessed relative to fish movement. A multi-species framework would be preferable as a more holistic measure of connectivity, but fish were used as a surrogate with the assumption that they are generally more limited in movement ability than other taxa. Furthermore, this region possesses incredibly high fish biodiversity, and rather than a species-specific movement model, this approach is generalized for “small bodied fishes” of greatest conservation concern (Anderson et al. 2012).

Barrier passability was assessed using the methods of Collins (2016), which built from prior studies by Coffman (2005) and Anderson et al. (2012). In these studies, barrier properties (e.g., culvert perch height) are measured in the field, and these measurements are used to parameterize multiple passability models. From these models, a Bayesian belief network is used to predict the probability that a barrier is completely impassable, partially passable, or completely passable.

In Proctor Creek, potential barrier locations were compiled from existing dam databases, road-stream crossings, and other known crossings (e.g., sewers). The number of road-stream crossings were reduced by removing bridges from the National Bridge Inventory. This preliminary analysis resulted in 23 potential barriers, which were comprehensively surveyed in the summer of 2016 to collect needed physical parameters. Three potential barriers either were bridges or free spanning crossings, leaving 20 total barriers for the entire watershed. From field data, probabilities were estimated in group assignment relative to passable, partially passable, and impassable structure following the method of Collins (2016). An overall passage rate for each structure was assessed as the weighted average of group assignment and an estimate passage rate for the category as follows:

$$p_{total} = 0.0 * p_{impass} + 0.5 * p_{partial} + 1.0 * p_{pass}$$

Where p_{total} is the passage probability at a given structure, p_{impass} is the probability the barrier is completely impassable weighted by a passage rate of 0.0, $p_{partial}$ is the probability the barrier is partially passable weighted by a passage rate of 0.5, and p_{pass} is the probability the barrier is completely passable weighted by a passage rate of 1.0.

These structure-specific passage rates were combined with network analysis following the methods of McKay et al. (2013, 2016) to estimate the connectivity of a given reach to the Chattahoochee River (I_{con}).

4.5 Numerical Toolkit

The Phase 2 Proctor Creek Ecological Model (PCEM2) evaluates a variety of ecological processes addressing instream condition, riparian condition, hydrologic change, and watershed connectivity. This multi-metric, ecosystem-based approach requires a variety of input variables collected in both field and office settings. A spreadsheet database was developed to compile data from multiple field observations (e.g., visual assessments, cross-sectional surveys, barrier properties), office analyses (e.g., HMS outputs, connectivity assessments), and geospatial resources (e.g., reach lengths, watershed properties).

The PCEM2 combines all modules into a script-based environment, which the user can use to compute ecological outputs for futures without and with restoration actions. Potential restoration actions at any site throughout the watershed can be “turned on and off” by the user to analyze combinations of actions (e.g., riparian planting at site-1, barrier removal at site-2, and flow management at site-3). All analyses are conducted using the R statistical software package (version 3.3.2, R Development Core Team 2016). Numerical model code and associated project database are available from the authors upon request.

A generalized workflow was developed to track the execution of the quantitative model described in Chapter 4 (Figure 8). Generally, the workflow computes separately the variables related to reach-scale processes (V_{bkf}, V_{behi}, V_{ibi}, V_{carb}, V_{nut}, V_{temp}, V_{hab}, and V_{att}) and watershed-scale process (V_{peak}, V_{time}, and V_{con}) for the futures without and with restoration actions. The model then loops over every combination of restoration action and uses lookup tables to query the appropriate values and compute indices (I_{ins}, I_{rip}, I_{hyd}, and I_{con}). The overarching index (IEI) is then combined with habitat quantity as the benefits metric used in cost-effectiveness and incremental cost analyses. Model outputs are structured as a matrix with a unique plan identifier, the restoration status of every reach (i.e., 0=future without project, 1=future with project), the total habitat at all time points (i.e., years 0, 2, 10, and 50), and the average annual habitat units.

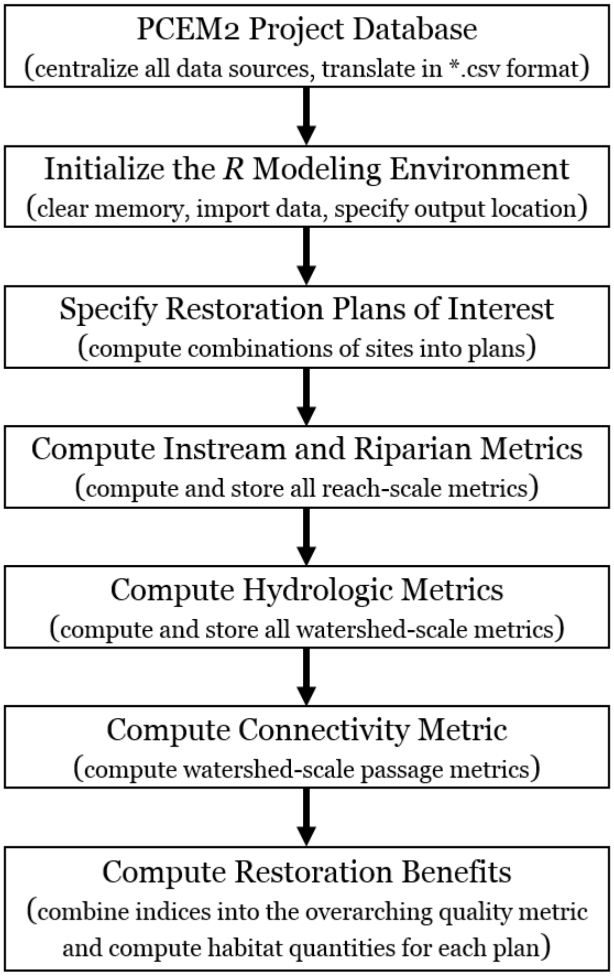


Figure 8. Numerical model workflow for PCEM2.

5 Model Evaluation

Ecological models, such as PCEM2, commonly address many ecological processes, rely on multiple variables, 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, transparently developed, and numerically sound. 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). In this more general sense, evaluation should include (Grant and Swannack 2008): (1) assessing the reasonableness of model structure, (2) assessing functional relationships and verifying code, (3) evaluating model behavior relative to expected patterns, (4) comparing outcomes to empirical data, if possible, and (5) analyzing uncertainty in predictions. The USACE has established an ecological model certification process to ensure that planning models used on ecosystem restoration projects are sound and functional, which generally consists of evaluating tools relative to three categories: technical quality, system quality, and usability (EC 1105-2-412, PB 2013-02).

5.1 Technical Quality

The technical quality of a model is assessed relative to its reliance on contemporary theory, consistency with design objectives, and degree of documentation and testing. As described in the conceptualization and quantification chapters, PCEM2 couples a variety of peer-reviewed ecological modeling methods for analyzing stream ecosystem integrity. The overarching quantity-quality framework has been applied extensively to assess restoration outcomes ranging from a single species to ecosystems (e.g., Habitat Evaluation Procedures and the Hydrogeomorphic Methods, respectively). Furthermore, the sub-models are supported by peer-reviewed algorithms described in Chapter 4. Although qualitative, field-based judgments are used in some sub-models, these methods have been shown to provide significant utility and predictive power and remain highly applied in stream assessment (Hughes et al. 2010). To minimize any potential bias from judgment, multiple observers assessed each judgment-based model input, and the mean judgment was used in analyses. In addition to qualitative evidence of technical quality, two quantitative evaluation methods were applied: calibration and sensitivity analysis.

5.1.1 Model Calibration

Calibration of the entire model is not feasible due to the lack of a single unifying metric of stream integrity. However, the hydrologic module was calibrated based on its ability to replicate observed stream discharge at a US Geological Survey stream gage (Gage #02336526 Proctor Creek at Jackson Parkway). The HMS model was deemed sufficiently accurate in calibration simulations relative to four unique storm events (Appendix C).

5.1.2 Global Sensitivity Analysis

Technical quality was also evaluated through a partial sensitivity analysis of the overall structure of the model. As described, the model is composed of 11 central variables, which are combined into four indices and one overarching quality index (Table 5). For this analysis, we examined the hypothetical change in the overarching index resulting from large changes in any one variable. We held all variables constant at a value of 1, and then systematically reduced one variable at a time by intervals of 0.05 to a value of zero. The change in IEI provides an indicator of the sensitivity of PCEM2 to any one variable in any given reach.

Figure 9 presents the change in IEI for each variable, with variables ranked from most to least sensitive (i.e., V_{con} to V_{hab}). The overarching index is highly sensitive to changes in the connectivity module due to the single variable influencing the connectivity index (i.e., $I_{con} = f(V_{con})$, whereas $I_{rip} = f(V_{carb}, V_{nut}, V_{temp}, V_{hab})$). Although sensitive, this index is derived from field measurements (rather than judgments) and a well-published set of quantitative techniques for estimating barrier passability and connectivity (Coffman 2005, Anderson et al. 2012, McKay et al. 2013, Collins 2016, McKay et al. 2016). Thus, index sensitivity is deemed satisfactory relative to the scientific support of this index. No other variable changes IEI values more than 10%, even under the extreme range of 0 to 1. Each variable could be subsequently broken down to examine the sensitivity of the components. For instance, the instream biotic integrity metric (V_{ibi}) is composed of five parameters assessed by professional judgment (Table 7). As such, PCEM2 is relatively insensitive to small change in any one of these parameters.

PCEM2 model structure is proposed in Chapter 4 as variables that are combined into indices using arithmetic means, and then subsequently combined into the IEI using a geometric mean. To examine the sensitivity to this formulation, we examined the inverse case as an extreme case of how model structure could influence sensitivity. In this formulation, variables are combined into indices using geometric means, and then subsequently combined into the IEI using an arithmetic mean. Even in this extreme scenario, the model shows similar sensitivity to connectivity and a maximum change in IEI of 25% for all variables.

From these analyses, we conclude that the model structure of PCEM2 is sensitive enough to capture ecological changes resulting from restoration actions, and that the most sensitive parameters are those relying on the strongest scientific evidence and the most commonly applied methods.

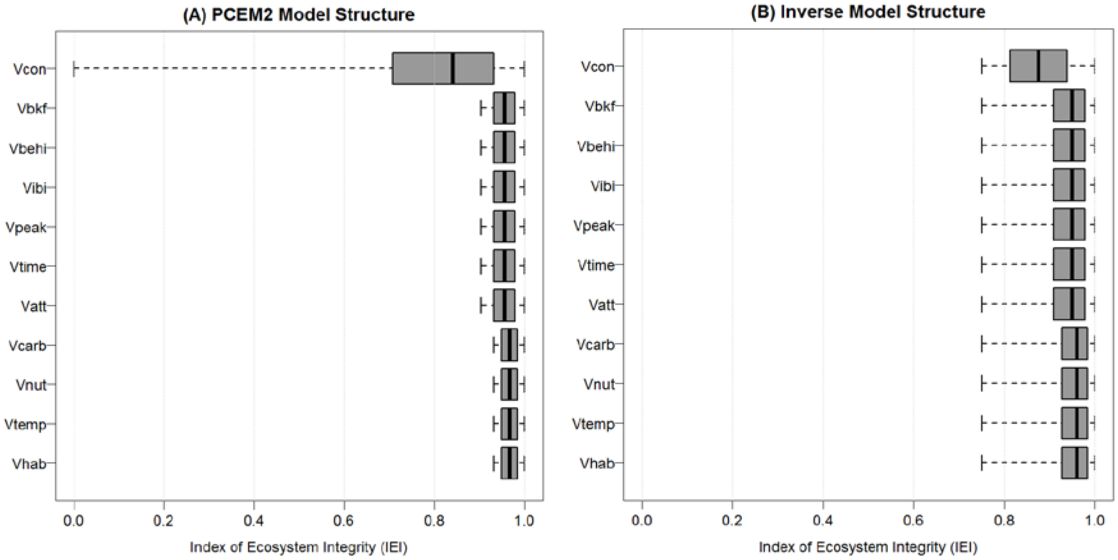


Figure 9. Global sensitivity analysis of major model variables.

5.2 System Quality

Ecological models must not only maintain an appropriate theoretical and technical basis, but also must be computationally accurate. System quality refers to the computational integrity of a model (or modeling system). For instance, is the tool appropriately programmed, has it been verified or stress-tested, and do outcomes behave in expected ways? The system quality of PCEM was evaluated in a variety of ways, including:

- Quality assurance practices: Errors were avoided to the extent practical by following common best practices for model development (Grant and Swannack 2008). First, a workflow was developed *a priori*. Second, all code was documented extensively with in-line comments during development to articulate model logic, clarify naming conventions, and avoid editing errors. Third, interim error checking was applied routinely during development. Fourth, input files are imported in one location with one naming convention to avoid version control problems. Fifth, old model code was stored in a separate directory to avoid version control issues.

- Code checking: All code was error-checked during and after development by the primary programmer (McKay) and was also inspected by team members periodically. Error checking considered consistent variable naming, investigated outputs from individual lines of code, and blocks of code (e.g., functions and loops).

- Model testing: An extensive post hoc test of model functionality was conducted on the final model version. Appendix D provides tabular results of individual tests run on all functions and large blocks of code, which include the purpose of the test, mechanism of testing, and result of the test. All model tests were deemed successful based on this testing procedure.

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. PCEM was developed for application by the USACE technical team of the Proctor Creek stream restoration study. The tool is not currently intended for broader application by local sponsors, other regional teams, or other USACE Districts. As such, there is currently no graphical user interface (GUI) for the model beyond the script itself. There is also no training on model use currently planned, given the small user community.

To this end, the current form of the model has maintained usability through four key mechanisms. First, PCEM is designed in a simple input-output workflow. All inputs are stored in a single Excel file, which is structured where each sheet is converted to a *.csv and imported directly into PCEM. The model selects these *.csv files based on user specifications and provides all results in a separate *.csv. Second, input data and files were checked extensively by the team to ensure accuracy of data entry and manipulation in Excel. Third, the R statistical language is open source, freeware that is approved for USACE usage. Fourth, the R language and *.csv inputs can function across operating platforms and with minimal computational burden, which makes the model flexible and transferrable to future applications.

6 Model Application

The Phase 2 Proctor Creek Ecological Model (PCEM2) was developed to examine the relative effects of multiple and diverse restoration actions distributed throughout an urban watershed. PCEM2 was applied to inform multiple aspects of the Proctor Creek ecosystem restoration study, in particular: examining current watershed condition (i.e., the future without project) and assessing cumulative effects of many types and locations of restoration actions (i.e., multiple futures with restoration projects). This chapter presents a preliminary demonstration of model application to inform USACE decision making for the Proctor Creek Restoration Study. However, these analyses do *not* represent all aspects of the feasibility study decision-making process, and therefore should not be construed as agency recommendations or decision documents.

6.1 Future Without Project (FWOP) Conditions

The future without project condition (FWOP) provides a baseline condition for the current status and future trajectory of the Proctor Creek watershed. The FWOP also provides the basis for comparing the ecological effects of restoration actions (ER 1150-2-100). For this analysis, we assume the following about the FWOP:

- Land use change is static. Due to the long history of development in the area, we assume no additional development will occur beyond current levels of imperviousness. Market trends within the basin indicate that land use may continue to change with redevelopment of portions of the basin, but there are not reliable forecasts of land use at the scale of the 50-year planning horizon.

- No climate change is considered due to extreme variability in forecasts in the region (< +0.5 to > +4 ^{0}C minimum and maximum temperature anomalies and < –10 to > +25 percent change in precipitation) based on statistically downscaled General Circulation Model projections for the Chattahoochee watershed in year 2090 (Lafontaine et al. 2015).

- No additional invasive species expansion. Invasive taxa currently occur in every reach of Proctor Creek with some reaches dominated. We assume expansion beyond the current extent will be minimal.

- As a focal watershed for the Urban Waters Federal Partnership, a variety of potentially relevant watershed management actions are being taken in the Proctor Creek basin (e.g., culvert repairs, stormwater programs, recreational development). However, to avoid dependence of USACE actions on these projects, we have assumed no other actions influence the USACE recommended plan.

Based on these uncertainties, the future without project condition is assumed to be the existing condition in the watershed, and future degradation or improvement cannot be substantiated without highly uncertain assumptions. As such, the existing condition is also assumed to persist for the duration of the 50-year planning horizon. In later stages of the feasibility study, alternative futures without project will be tested with scenario analyses of alternative land uses, climate conditions, and actions by others.

PCEM2 has been developed to assess the cumulative condition of the entire Proctor Creek watershed. Modules related to instream and riparian condition are assessed on a reach-scale, while modules for connectivity and hydrology are cumulative at the watershed-scale. For connectivity analyses, all known barriers in the watershed were surveyed and included in calculations. The hydrology model was developed basin-wide and outputs were obtained for each reach. All restoration reaches (Table 1) were examined using PCEM2 methods for instream and riparian condition. All non-restoration reaches assumed instream and riparian condition from prior data collection and modeling (i.e., PCEM Phase 1, McKay et al. 2017).

The future without project condition (Figure 10) provides further insight into the individual modules of the PCEM2 as well as the overarching index of ecosystem integrity (IEI). The instream condition in Proctor Creek ranges from extremely poor to reasonably high quality (0.04-0.82), often in conjunction with underlying geomorphology (i.e., bedrock grade controls and confined valley types). Riparian zones in the watershed are reasonably intact but often contain significant invasive species disturbance and resultantly have fair quality scores (0.13-0.80). The hydrology module emphasizes the departure of storm flows from a forested reference condition and accordingly shows extremely high alteration (0.01-0.57). The watershed is relatively well-connected (i.e., no large dams), but a few key barriers lead to significant areas of fragmentations. Examined in total, the IEI indicates that Proctor Creek is heavily impacted with 3.6 miles of total quality-weighted habitat out of a possible 13.0 miles.

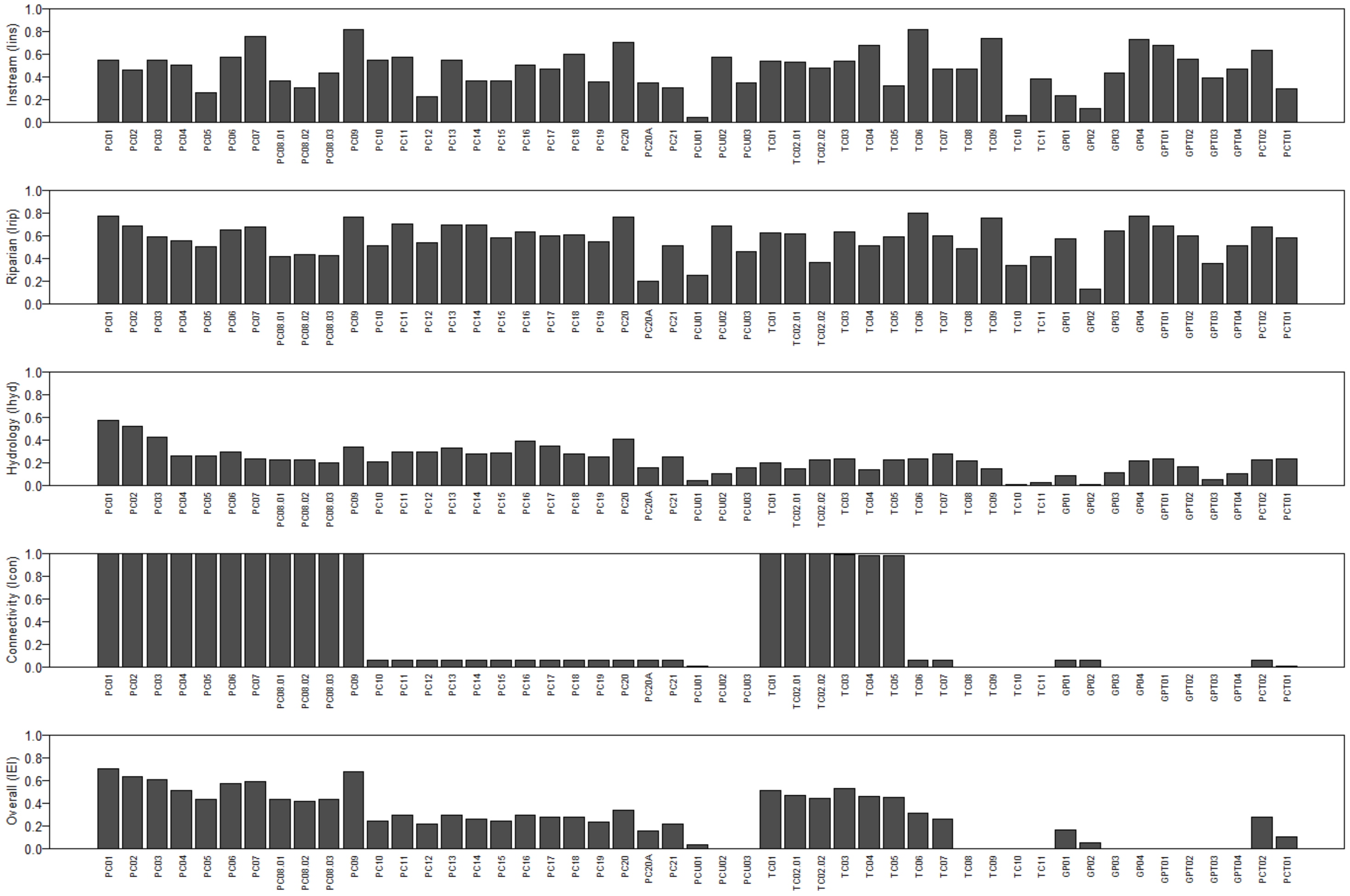


Figure 10. Future without project condition at year-0.

6.2 Future With Project (FWP) Conditions

As discussed in Chapter 1, prior project analyses identified 12 reaches with significant restoration opportunities and 4 potential flow attenuation sites (Table 1). All sites were investigated more thoroughly in the field, and as a result two reaches (PC06, TC07) and two detention features (D10, D12) were removed from additional consideration. The remaining reaches were walked by a consistent team with expertise in engineering, stream ecology, and project planning. The team noted specific restoration actions on aerial photographs and took extensive field notes to describe a restoration action for the site. From these notes, preliminary design drawings were developed describing each restoration site. An example drawing is provided for TC05 in Appendix E, but the project feasibility study should be consulted for more detailed design information. Two sites (PC08, TC02) were split into sub-reaches to distinguish the unique aspects of the restoration actions. For the flow detention sites, site investigation and survey were used to parameterize detention pond modeling software (PondPack™, Bentley Systems 2009). These simulations facilitated the screening of an additional detention site (D4) due to its minimal effect on hydrologic conditions downstream. Thus, fifteen sites were maintained for analysis in PCEM 2 (Table 9). Cost engineering methods were then applied to estimate costs associated with real estate, design, and construction of these actions (Appendix F).

Watershed conditions were assessed for the future with project at four time steps. Year-0 was assessed as the existing condition, unless a preliminary impact was anticipated from construction actions. Year-2 was assessed as an initial point of recovery with expectation of early riparian growth. Year-10 was forecasted as a point of vegetation establishment and identifies a key decision threshold based on policy and guidance surrounding monitoring and adaptive management (WRDA 2007 Section 2039). Year-50 was forecasted as the end of the planning horizon and a point of ecological maturity for any restoration actions.

PCEM2 was applied to each time step, and variables were forecast differently depending upon their basis. Any physical changes to the system (e.g., channel reshaping) were assumed static through time. Visual assessment were reassessed by the consistent team involved in field assessment. BEHI variables for root depth, root density, and surface protection were assessed as follows:

- Year-0 = Existing condition for root depth, root density, and surface protection
- Year-2 = Max of existing condition OR root depth=0.5*bankfull depth, root density=75%, and surface protection=75%
- Year-10 = Max of existing condition OR root depth=1.0* bankfull depth, root density=100%, and surface protection=100%
- Year-50 = Max of existing condition OR root depth=1.0* bankfull depth, root density=100%, and surface protection=100%

Table 9. Restoration site descriptions and preliminary cost estimates by reach. Appendix E presents an example of a detailed description of an alternative, and Appendix F presents an overview of cost estimation methods.

Reach ID	Brief description of restoration alternative	Project cost ($K)
PC08.01	In-channel structures accompanied by riparian planting and extensive right bank invasive species management	1,011
PC08.02	Right bank weir structures with bank reshaping, riparian planting, and extensive invasive species management accompanied by minor reshaping of the confluence with Terrell Creek	1,050
PC08.03	No action	0
PC09	Installation of a small rock ramp at a sewer crossing that is causing a fish movement barrier	394
PC10	Minor right bank structures with extensive invasive species management and riparian planting (right bank)	872
PC13	Installation of rock and wood weir structures with invasive species management and riparian planting on the left bank	512
PC14	Installation of rock and wood structures	366
PC15	Large reach with rock and wood weir structures, in-channel structures, and excavation and planting of a large left bank wetland complex	1,280
PC21	Rock and wood bank protection with extensive invasive species management and riparian planting along with excavation and planting of a large right bank wetland complex	2,179
PCU03	Excavation and installation of a flow retention pond (D17)	611
TC02.01	No action	0
TC02.02	Minor bank protection with extensive invasive species management and riparian planting along with excavation and planting of a large right bank wetland complex	953
TC05	Installation of a rock ramp fish passage structure at a sewer crossing along with bank protection, invasive species management, riparian planting, and installation of a small left bank wetland complex	635
GP01	Installation of log vane channel structures with minor riparian planting	526
GP02	Stream daylighting with extensive channel reshaping, in-channel structure construction, and riparian planting	821

6.3 Preliminary Cost-Effectiveness and Incremental Cost Analysis

For a watershed scale project, site-specific alternatives may be combined into different plans. Ideally, the solution space is explored by analyzing every possible combination of alternatives and calculating costs and benefits. Each of these plans could then be carried forward to cost-effectiveness and incremental cost analyses (CE-ICA) for comparing non-monetary benefits relative to the monetary restoration costs (Robinson et al. 1995).

For Proctor Creek, an exhaustive search of the solution space was conducted (i.e., 15 sites provides 2^{15} possible plans or 32,768 plans). From these, all plans were removed that contained "No Action" sub-reaches (PC08.03 and TC02.01), which left 8,192 plans (i.e., 2^{13}). Benefits and costs were computed for all plans, and average annual habitat units (AA-HUs) were computed for non-monetary benefits. All habitat units were converted to "lift" above the future without project condition (i.e., the net benefit of restoration actions) for CE-ICA.

Based on the forecasted costs and benefits, 60 plans were identified as cost-effective (i.e., maximum benefits for a given level of cost and/or minimum cost for a given level of benefit; Figure 11). These plans were then manually subjected to incremental cost analysis following existing methods (Robinson et al. 1995). Based on these analyses, 14 "best" plans were identified (Table 15), which represent the most efficient alternatives across a range of costs and benefits. These data can serve as an initial point for informing restoration decisions in Proctor Creek. However, these decisions are complex and depend on a variety of factors. Some preliminary observations that might also be taken into consideration, include:

- Proctor Creek is 13.02 miles long, and thus, if quality were perfect throughout the watershed, there could be 13.02 miles of habitat (68,746 feet). However, current levels of habitat degradation have significantly impacted quality in the study area, and there are only 3.6 miles of habitat (18,827 feet). The maximum obtainable habitat if all proposed USACE actions were executed is 6.0 miles of habitat (31,673 feet).

- Return on investment decreases with increasing investment (i.e., incremental cost per unit goes up). Initial investment provide the greatest return, but may not meet a given target or constraint. For instance, Plan-410 provides 81% of the potential benefit at 17% of the cost, but this plan only provides a net increase of 2.0 miles of habitat, which could be considered too small relative to an agreed upon target.

- Other criteria are often crucial for distinguishing between plans. For instance, the recreational value or connectivity to a recreational network (e.g., the Atlanta Beltline) could provide additional support for an action. Furthermore, an agency objective could be to demonstrate the application of multiple restoration techniques, and a plan offering multiple techniques could be justified (e.g., Plan 4,401).

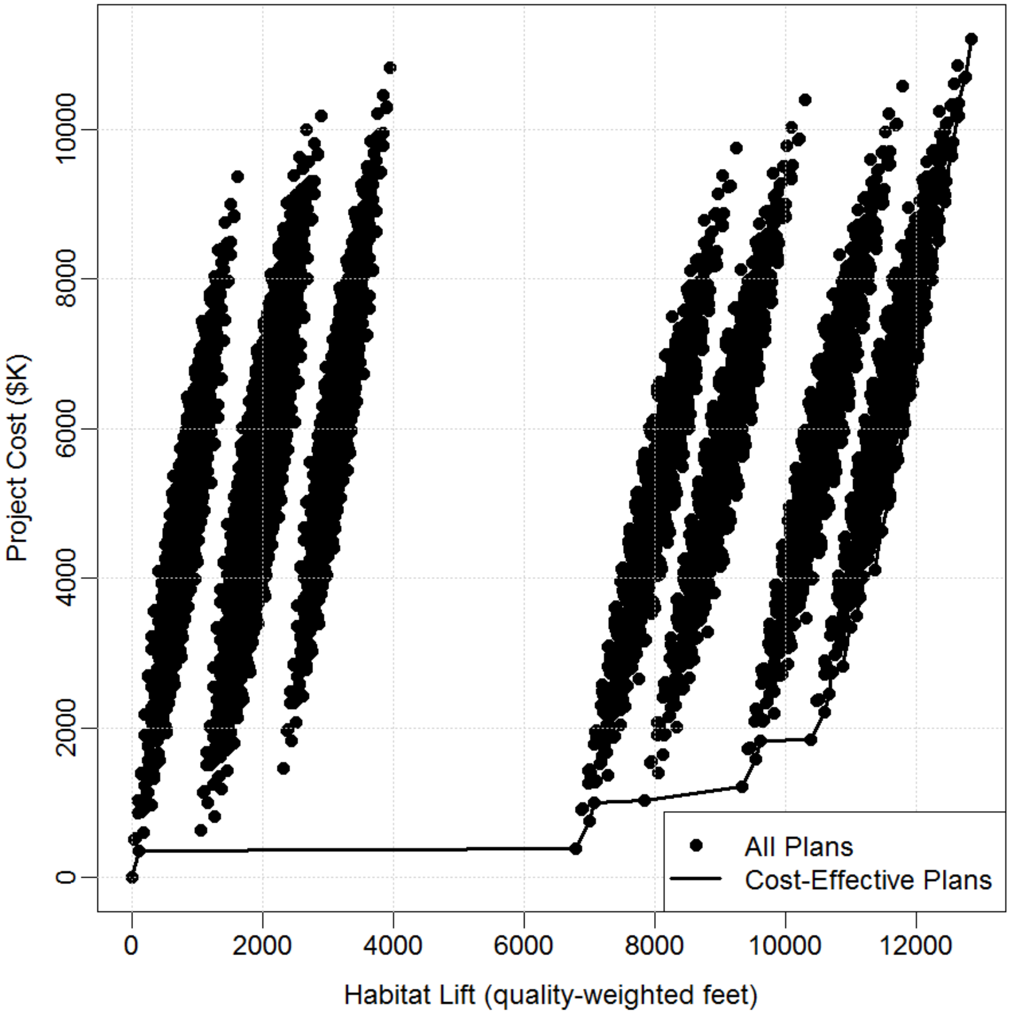


Figure 11. Preliminary cost-effectiveness analysis for model demonstration purposes only. Consult the feasibility study for final results.

Table 10. Cost-effective and incrementally best plans. Plan composition is indicated by 0 (no action) or 1 (restoration action).

Plan Number	AAHU (ft)	AAHU Lift (ft)	Cost ($K)	In Cost / AAHU ($K/ft)	Number of Actions	PC08.01	PC08.02	PC09	PC10	PC13	PC14	PC15	PC21	PCU03	TC02.02	TC05	GP01	GP02
1	18,827	0	0	na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	25,611	6,785	394	0.06	1	0	0	1	0	0	0	0	0	0	0	0	0	0
66	28,163	9,337	1,215	0.32	2	0	0	1	0	0	0	0	0	0	0	0	0	1
410	29,216	10,390	1,850	0.60	3	0	0	1	0	0	0	0	0	0	0	1	0	1
1,554	29,430	10,603	2,216	1.71	4	0	0	1	0	0	1	0	0	0	0	1	0	1
4,401	29,709	10,883	2,827	2.18	5	0	0	1	0	0	1	0	0	1	0	1	0	1
9,385	30,188	11,361	4,107	2.68	6	0	0	1	0	0	1	1	0	1	0	1	0	1
15,998	30,426	11,599	5,061	4.01	7	0	0	1	0	0	1	1	0	1	1	1	0	1
19,430	30,654	11,827	6,071	4.43	8	1	0	1	0	0	1	1	0	1	1	1	0	1
25,481	30,850	12,023	6,943	4.44	9	1	0	1	1	0	1	1	0	1	1	1	0	1
29,710	30,960	12,134	7,469	4.77	10	1	0	1	1	0	1	1	0	1	1	1	1	1
31,426	31,173	12,346	8,519	4.94	11	1	1	1	1	0	1	1	0	1	1	1	1	1
32,453	31,583	12,756	10,698	5.31	12	1	1	1	1	0	1	1	1	1	1	1	1	1
32,718	31,673	12,846	11,210	5.68	13	1	1	1	1	1	1	1	1	1	1	1	1	1

7 Conclusions

This report presents the development and application of the second phase of the Proctor Creek Ecological Model (PCEM2). The objective for model development was to provide a tool sufficiently sensitive to potential USACE restoration actions to inform the specified planning needs. The model is intended to capture the effects of extremely diverse project objectives, and thus, its development emphasized the relative change in the overarching ecosystem condition relative to those objectives. In particular, the tool needed to inform restoration designs at the feasibility level, assess the cumulative effect of many types of restoration actions at many locations, and forecast the ecological benefits of restoration actions over a 50-year planning horizon. This index-based model synthesizes multiple project objectives into a single ecological unit based on the overall quality and quantity of habitat in the watershed. The model is programmed in a scripting environment (i.e., the R statistical software language) and uses a variety of field, office, and judgment based parameters as inputs, all of which are stored in an accompanying spreadsheet database. This report is intended to provide documentation of the model's theoretical basis, quantitative framework, testing and evaluation, application in the Proctor Creek watershed, and relevant information for USACE model certification (EC 1105-2-412, PB 2013-02).

Applying this model, 60 watershed-scale restoration plans were identified as cost-effective (Figure 11) and 14 were identified as "best plans" that were incrementally efficient investments (Table 10). These data provide a numerical basis for informing restoration decisions in Proctor Creek. However, many additional decision criteria may affect the agency recommendation.

Overall, the PCEM framework has provided a basic structure for comparing the costs and benefits of diverse combinations of restoration actions spatially distributed throughout the Proctor Creek watershed. In Phase 1, a preliminary model was applied to rapidly screen potential restoration sites. In Phase 2, the model was refined and improved to inform restoration design and compute the environmental benefits of restoration actions. While the model met these needs, future improvements could address a variety of subjects, some of which may include:

- Novel applications within Proctor Creek: The PCEM framework uses a variety of parameters assessed by professional judgment, and the sensitivity of the model to alternative judgments could be examined. A variety of assumptions about the future watershed conditions (e.g., land use and climate) were also made during model application, which could be examined through model scenarios testing alternative assumptions regarding the future.

- Coupling with stakeholder values: PCEM1 and PCEM2 assume equal importance among the objectives. Multi-criteria decision analysis (MCDA) often examines the subjective importance different groups place on objectives, and this family of methods could be applied to better reflect local values.

- Additional variables: The PCEM framework was developed under the planning constraints of the Proctor Creek project. However, additional variables could be added to the model, or existing variables could be replaced by improved or more precise methods.

- Expanded scope: The model has been developed specifically for this application in an urban Appalachian Piedmont stream. However, the applicability to other streams in the region is high, and the basic structure could potentially be adapted for other watershed scale restoration projects.

- Verification: The PCEM framework assumes that many processes may be combined to reflect the overall condition of the watershed. These assumptions should be verified against other evidence of watershed condition (e.g., biological monitoring data; other data collection frameworks, e.g., Bledsoe et al. 2012; other models, e.g., Sterling et al. 2016).

Literature Cited

Anderson G.B., Freeman M.C., Freeman B.J., Straight C.A., Hagler M.M., and Peterson J.T. 2012. Dealing with uncertainty when assessing fish passage through culvert road crossings. Environmental Management. doi: 10.1007/s00267-012-9886-6.

Atlanta Regional Commission (ARC). 2011. Proctor Creek: Headwaters to Chattahoochee River. Watershed improvement plan.

Baker D.B., Richards R.P., Loftus T.T., and Kramer J.W. 2004. A new flashiness index: Characteristics and applications to Midwestern rivers and streams. Journal of the American Water Resources Association, 40 (2), 503-522.

Barbour M.T., Gerritsen J., Snyder B.D., and Stribling J.B. 1999. Rapid Bioassessment Protocols for use in streams and wadeable rivers. EPA 841-B-99-002. Office of Water, U.S. Environmental Protection Agency, Washington, D.C.

Bedient P.B., Huber W.C., and Vieux B.E. 2013. Hydrology and Floodplain Analysis. 5th Edition, Pearson, New York.

Beechie T.J., Sear D.A., Olden J.D., Pess G.R., Buffington J.M., Moir H., Roni P., and Pollock M.M. 2010. Process-based principles for restoring river ecosystems. Bioscience, 60 (3), 209-222.

Bennett S.J., Simon A., Castro J.M., Atkinson J.F., Bronner C.E., Blersch S.S., and Rabideau A.J. 2011. The evolving science of stream restoration. In Stream Restoration in Dynamic Fluvial Systems (Eds. Simon et al.). American Geophysical Union.

Bentley Systems. 2009. Product data sheet: PondPack® detention pond design and urban hydrology modeling. Accessed 31 March 2017. https://www.bentley.com/~/asset/14/1714.ashx.

Bernhardt E.S., Palmer M.A., Allan J.D., Alexander G., Brooks S., Carr J., Dahm C., Follstad-Shah J., Galat D.L., Gloss S., Goodwin P., Hart D., Hassett B., Jenkinson R., Kondolf G.M., Lake S., Lave R., Meyer J.L., O'Donnell T.K., Pagano L., Srivastava P., and Sudduth E. 2005. Restoration of U.S. Rivers: A national synthesis. Science, 308, 636–637.

Bjorkland R., Pringle C.M., and Newton B. 2001. A stream visual assessment protocol (SVAP) for riparian landowners. Environmental Monitoring and Assessment, 68, 99-125.

Bledsoe B.P., Stein E.D., Hawley R.J., and Booth D. 2012. Framework and tool for rapid assessment of stream susceptibility to hydromodification. Journal of the American Water Resources Association, 1-21, DOI: 10.1111/j.1752-1688.2012.00653.x.

Booth D.B. and Bledsoe B.P. 2009. Streams and urbanization. Chapter 6 in The Water Environment of Cities (Ed. L.A. Baker), Springer.

Boyer K. 2009. Stream visual assessment protocol Version 2. Part 614, Subpart B. USDA Natural Resources Conservation Service, Portland, Oregon.

Brinson M.M. 1993. A hydrogeomorphic classification for wetlands. WRP-DE-4. U.S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, Mississippi.

Coffman J.S. 2005. Evaluation of a predictive model for upstream fish passage through culverts. Master's Thesis. James Madison University, Harrisonburg, Virginia.

De Steven D. and Lowrance R. 2011. Agricultural conservation practices and wetland ecosystem services in the wetland-rich Piedmont-Coastal Plain region. Ecological Applications, 21 (3), S3-S11.

Doll B.A., Wide-Frederick D.E., Buckner C.M., Wilkerson S.D., Harman W.A., Smith R.E., and Spooner J. 2002. Hydraulic geometry relationships for urban stream throughout the piedmont of North Carolina. Journal of the American Water Resources Association, 38 (3), 641-651.

Ecological Solutions, Inc. 2012. Prospectus Emerald Corridor mitigation bank. Prepared for Emerald Corridor, LLC.

Environmental Protection Agency (EPA). 2015. Proctor Creek's Boone Boulevard Green Street Project Health Impact Assessment (HIA). Office of Research and Development and Region 4, U.S. Environmental Protection Agency, Atlanta, Georgia.

Environmental Protection Agency (EPA). 2016. Proctor Creek: Summary of Ongoing EPA Initiatives. Region 4, U.S. Environmental Protection Agency, Atlanta, Georgia.

Environmental Protection Agency (EPA). 2016b. Urban waters federal partnership: National strategic workplan 2016-2018. U.S. Environmental Protection Agency.

Feaster T.D., Gotvald A.J., and Weaver J.C. 2014. Methods for estimating the magnitude and frequency of floods for urban and small, rural streams in Georgia, South Carolina, and North Carolina, 2011. Scientific Investigations Report 2014–5030, U.S. Geological Survey, Reston, Virginia.

Fischenich J.C. 2006. Functional objectives for stream restoration. ERDC TN-EMRRP-SR-52, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Fischenich J.C. 2008. The application of conceptual models to ecosystem restoration. ERDC TN-EBA-TN-08-1. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Fischenich J.C., McKay S.K., Miller S.J., Price D., Pruitt B.A., Skaggs L.L., Suedel B.C., and Tazik D. 2013. Science-based framework for environmental benefits assessment. ERDC EL TR-13-4. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group (15 Federal agencies of the US government). GPO Item No. 0120-A.

Freeman M.C., Pringle C.M., and Jackson C.R. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association. American Water Resources Association, Vol. 43 (1), pp. 5-14.

Fuller M.R., Doyle M.W., and Strayer D.L. 2015. Causes and consequences of habitat fragmentation in river networks. Annals of the New York Academy of Sciences, 1-21.

Georgia Department of Natural Resources (GA DNR). 2004. Visual stream survey. Georgia Adopt-A-Stream, Georgia Department of Natural Resources, Environmental Protection Division, Atlanta, GA.

Georgia Department of Natural Resources (GA DNR). 2005. Standard operating procedures for conducting biomonitoring on fish communities in wadeable streams in Georgia. Wildlife Resources Division, Georgia Department of Natural Resources, Atlanta, GA.

Gotvald A.J. and Knaak A.E. 2011. Magnitude and frequency of floods for urban and small rural streams in Georgia, 2008. Scientific Investigations Report 2011– 5042. U.S. Geological Survey, Reston, Virginia.

Grant W.E. and Swannack T.M. 2008. Ecological modeling: A commonsense approach to theory and practice. Malden, MA: Blackwell Publishing.

Gregory R.S. and Keeney R.L. 2002. Making smarter environmental management decisions. Journal of the American Water Resources Association, 38 (6), 1601-1612.

Harrelson C.C., Rawlins C.L., and Potyondy J.P. 1994. Stream channel reference sites: An illustrated guide to field techniques. General Technical Report RM-245. USDA Forest Service, Fort Collins, CO.

Horowitz A.J., Elrick K.A., and Smith J.J. 2008. Monitoring urban impacts on suspended sediment, trace element, and nutrient fluxes within the City of Atlanta, Georgia, USA: Program design, methodological considerations, and initial results. Hydrological Processes, 22, 1473-1496.

Hughes R.M., Herlihy A.T., and Kaufmann P.R. 2010. An evaluation of qualitative indexes of physical habitat applied to agricultural streams in ten U.S. states. Journal of the American Water Resources Association, 46 (4), 792-806.

Inman E.J. 2000. Lagtime relations for urban streams in Georgia. Water-Resources Investigations Report 00-4049. U.S. Geological Survey, Atlanta, Georgia.

Jansson R., Backx H., Boulton A.J., Dixon M., Dudgeon D., Hughes F.M.R., Nakamura K., Stanley E.H., and Tockner K. 2005. Stating mechanisms and refining criteria for ecologically successful river restoration: A comment on Palmer et al. (2005). Journal of Applied Ecology, 42, 218-222.

Kaushal S.S., Likens G.E., Jaworski N.A., Pace M.L., Sides A.M., Seekell D., Belt K.T., Secor D.H. and Wingate R.L. 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment, 8 (9), 461-466.

Kraseski K.A. 2015. Damping of stream temperature time series by hyporheic exchange. University of Georgia, Athens, GA.

Lafontaine J.H., Hay L.E., Viger R.J., Regan R.S., and Markstrom S.L. 2015. Effects of climate and land cover on hydrology in the Southeastern U.S.: Potential impacts on watershed planning. Journal of the American Water Resources Association, 51 (5), 1235-1261.

Lambeck R.J. 1997. Focal species: A multi-species umbrella for nature conservation. Conservation Biology, 11 (4), 849-856.

McCandless T.L. and Everett R.A. 2002. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region. CBFO-S02-01. U.S. Fish and Wildlife Service.

MacDonald L.H., Smart A.S., and Wissmar R.C. 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA/910/9-91-001. U.S. Environmental Protection Agency, Water Division, Seattle, Washington.

McKay S.K. and Pruitt B.A. 2012. An approach for developing regional environmental benefits analysis models. ERDC TN-EMRRP-EBA-14. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

McKay S.K., Schramski J.R., Conyngham J.N., and Fischenich J.C. 2013. Assessing upstream fish passage connectivity with network analysis. Ecological Applications, 23 (6), 1396-1409.

McKay S.K., Pruitt B.A., Anderson C.J., Curran J., del Orca Archoa A., Freeman M.C., Rashleigh B., and Trawick E. 2011. Constructing a conceptual model linking drivers and ecosystem services in Piedmont streams. 2011 Georgia Water Resources Conference, Athens, Georgia.

McKay S.K., Cooper A., Diebel M., Elkins D., Oldford G., Roghair C., and Wieferich D. 2016. Informing watershed connectivity barrier prioritization decisions: A synthesis. Accepted at River Research and Applications.

Meyer J.L., Strayer D.L., Wallace J.B., Eggert S.L., Helfman G.S., and Leonard N.E. 2007. The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association. American Water Resources Association, Vol. 43 (1), 86-103.

Morreale S.J. and Gibbons J.W. 1986. Habitat suitability index models: Slider turtle. Biological Report 82 (10.125). U.S. Fish and Wildlife Service.

Muir R. 2014. The Urban Waters Federal Partnership: An emerging model for revitalizing urban rivers and communities. Proceedings of the 1st International Conference on Sustainable Infrastructure. American Society of Civil Engineers.

Newton B., Pringle C.M., and Bjorkland R. 1998. Stream visual assessment protocol. Technical Note 99-1, National Water and Climate Center, Natural Resources Conservation Service, U.S. Department of Agriculture.

National Oceanic and Atmospheric Administration (NOAA). 2017. Hydrometeorological design studies center: Precipitation frequency data server. National Weather Service. Accessed 31 March 2017. http://hdsc.nws.noaa.gov/hdsc/pfds/.

National Resources Conservation Service (NRCS). 2007. National Engineering Handbook, Part 654: Stream Restoration Design. U.S. Department of Agriculture, Washington, D.C.

Palmer M.A. and Febria C.M. 2012. The heartbeat of ecosystems. Science, 336, 1393-1394.

Palmer M.A., Bernhardt E.S., Allan J.D., Lake P.S., Alexander G., Brooks S., Carr J., Dahm C.M., Follstad Shah J., Galat D.L., Loss S.G., Goodwin P., Hart D.D., Hassett B., Jenkinson R., Kondolf G.M., Lave R., Meyer J.L., O'Donnell T.K., Pagano L., and Sudduth E. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology. British Ecological Society, Vol. 42 pp.208-217.

Olden J.D. and Poff N.L. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications, 19, 101-121.

Park Pride. 2011. Proctor Creek North Avenue Watershed basin: A green infrastructure vision. Park Pride. Atlanta, Georgia.

Paul M.J. and Meyer J.L. 2008. Streams in the urban landscape. Annual Review of Ecology and the Systematics, 32, 333-365.

Peters N.E. 2009. Effects of urbanization on stream water quality in the city of Atlanta, Georgia, USA. Hydrological Processes, 23, 2860-2878.

Pringle C. 2003. What is hydrologic connectivity and why is it ecologically important? Hydrological Processes, 17: 2685-2689.

Pruitt B.A. 2001. Hydrologic and soil conditions across hydrogeomorphic settings. Dissertation. University of Georgia, Athens, GA.

R Development Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.

Rankin E.T. 2006. Methods for assessing habitat in flow waters: Using the Qualitative Habitat Evaluation Index (QHEI). Technical Bulletin EAS/2006-06-1. Ohio Environmental Protection Agency, Columbus, Ohio.

Robinson R. Hansen W., and Orth K. 1995. Evaluation of environmental investments procedures manual interim: Cost effectiveness and incremental cost analyses. IWR Report 95-R-1. Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, Virginia.

Rosgen D.L. 2001. A practical method of computing streambank erosion rate. Proceedings of the 7th Federal Interagency Sedimentation Confernce, Reno, NV. Vol. 2, pp. 9-15.

Rowe D.K., Parkyn S., Quinn J., Collier K., Hatton C., Joy M.K., Maxted J., and Moore S. 2009. A rapid method to score stream reaches based on the overall performance of their main ecological functions. Environmental Management, 43, 1287-1300.

Scharffenberg W. 2016. Hydrologic Modeling System (HEC-HMS): User's Manual. Version 4.2. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA.

Schmolke A., Thorbek P., DeAngelis D.L., and Grimm V. 2010. Ecological models supporting environmental decision making: A strategy for the future. Trends in Ecology and Evolution, 25: 479-486.

Simon A. 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms. John Wiley & Sons, Ltd., Vol. 14, pp. 11-26.

Sterling J.L., Rosemond A.D., and Wenger S.J. 2016. Watershed urbanization affects macroinvertebrate community structure and reduces biomass through similar pathways in Piedmont streams, Georgia, USA. Freshwater Science, 35 (2), 676-688.

Swannack T.M., Fischenich J.C., and Tazik D.J. 2012. Ecological Modeling Guide for Ecosystem Restoration and Management. ERDC/EL TR-12-18. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

U.S. Army Corps of Engineers (USACE). 2000. Planning Guidance Notebook. ER-1105-2-100. Washington, DC.

U.S. Army Corps of Engineers (USACE). 2011. Assuring quality of planning models. EC-1105-2-412. Washington, DC.

U.S. Army Corps of Engineers (USACE). 2014. Anacostia watershed assessment: Model procedures. Baltimore District, USACE, Baltimore, MD.

Vannote R.L., Minshall G.W., Cummins K.W., Sedell J.R., and Cushing C.E. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences, 37 (1), 130-137.

Walsh C.J., Roy A.H., Feminella J.W., Cottingham P.D., Groffman P.M., and Morgan R.P. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society, 24 (3), 706-723.

Wenger S.J., Roy A.H., Jackson C.R., Bernhardt E.S., Carter T.L., Filoso S., Marti E., Meyer J.L., Palmer M.A., Paul M.J., Purcell A.H., Ramirez A., Rosemond A.D., Schofield K.A., Sudduth E.B., and Walsh C.J. 2009. Twenty-six key research questions in urban stream ecology: An assessment of the state of the science. Journal of the North American Benthological Society. North American Benthological Society, Vol. 28 (4), pp. 1080-1098.

Wilkerson G.V. 2008. Improved bankfull discharge prediction using 2-year recurrence-period discharge. Journal of the American Water Resources Association, 44 (1), 243-258.

Wright D.B., Smith J.A., Villarini G., and Baeck M.L. 2012. Hydroclimatology of flash flooding in Atlanta. Water Resources Research, 48, doi: 10.1029/2011WR011371.

Acknowledgements

All analyses presented in this document were funded by the USACE Mobile District SMART planning study on Proctor Creek ecosystem restoration. Analyses were supported by the entire Mobile District planning and project management team, which also included supervision and guidance from Todd Boatman and Cheryl Hrabovsky.

Preliminary discussions of the Proctor Creek Ecological Model were informed by discussions with Krista Capps, Amy Rosemond, and Phillip Bumpers (University of Georgia), and their guidance is gratefully acknowledged. Technical reviews and comments by Craig Fischenich, Rachel Katz, Amy Rosemond, Seth Wenger, Phillip Bumpers, Krista Capps, and Brian Bledsoe are gratefully acknowledged. The team would also like to thank Nate Richards (USACE Ecosystem Restoration Planning Center of Expertise) for facilitating model certification reviews.

Appendix A: Proctor Creek Reach Delineation[1]

Table 11. Reach delineation points for Proctor Creek.

		Downstream Boundary		Upstream Boundary	
Reach ID	**Description**	**Latitude**	**Longitude**	**Latitude**	**Longitude**
PC-01	Chattahoochee River to I-285	33.807788	-84.495787	33.806248	-84.493255
PC-02	I-285 to Pipeline crossing at Parrott Rd	33.806248	-84.493255	33.805456	-84.487813
PC-03	Pipeline crossing at Parrott Rd to 200m DS of Bolton Rd	33.805456	-84.487813	33.801313	-84.488987
PC-04	200m DS of Bolton Rd to Northwest Dr.	33.801313	-84.488987	33.799396	-84.487008
PC-05	Northwest Dr. to Coordinate	33.799396	-84.487008	33.799450	-84.483733
PC-06	Coordinate to Coordinate	33.799450	-84.483733	33.797500	-84.480017
PC-07	Coordinate to Pet Cemetery Bridge	33.797500	-84.480017	33.794477	-84.474308
PC-08-01	Bar nr Pet Cemetery to Jackson Pkwy	33.794477	-84.474308	33.794448	-84.474308
PC-08-02	Jackson Pkwy to Terrell Creek confluence	33.794448	-84.474308	33.795535	-84.471138
PC-08-03	Terrell Creek confluence to Hollywood Rd	33.795535	-84.471138	33.795890	-84.469650
PC-09	Hollywood Rd to Coordinate	33.795890	-84.469650	33.796950	-84.465967
PC-10	Coordinate to Coordinate	33.796950	-84.465967	33.799517	-84.462633
PC-11	Coordinate to Coordinate	33.799517	-84.462633	33.797133	-84.461567
PC-12	Coordinate to Coordinate	33.797133	-84.461567	33.796283	-84.455800
PC-13	Coordinate to Coordinate	33.796283	-84.455800	33.793467	-84.456383
PC-14	Coordinate to Kerry Rd	33.793467	-84.456383	33.792325	-84.452173
PC-15	Kerry Circle to Johnson Rd	33.792325	-84.452173	33.784121	-84.450422

---

[1] PC indicates Proctor Creek Mainstem downstream of North Avenue, PCU indicates Proctor Creek mainstem upstream of North Avenue, TC indicates Terrell Creek (also known as Center Hill tributary), GP indicates the tributary through Grove Park, and PCT indicates the tributary draining the West Highlands neighborhood.

		Downstream Boundary		Upstream Boundary	
Reach ID	**Description**	**Latitude**	**Longitude**	**Latitude**	**Longitude**
PC-16	Johnson Rd to Coordinate	33.784121	-84.450422	33.783683	-84.447750
PC-17	Coordinate to Coordinate	33.783683	-84.447750	33.778650	-84.443000
PC-18	Coordinate to Coordinate	33.778650	-84.443000	33.776883	-84.441350
PC-19	Coordinate to Grove Park	33.776883	-84.441350	33.775867	-84.439033
PC-20	Grove Park to corner of industrial lots	33.775867	-84.439033	33.775530	-84.431395
PC-20A	Donald Lee Hollowell Rd to 1500 feet upstream	33.775530	-84.431395	33.771936	-84.429919
PC-21	Donald Lee Hollowell Rd to North Ave (Mosquito Hole)	33.771936	-84.429919	33.768110	-84.427418
PCU-01	North Ave to US end of concrete channel	33.768110	-84.427418	33.760923	-84.427852
PCU-02	US end of concrete channel to Burbank Rd	33.760923	-84.427852	33.757237	-84.428778
PCU-03	Burbank Rd to Martin Luther King Dr.	33.757237	-84.428778	33.753471	-84.428326
TC-01	Proctor Creek Confluence to Hollywood Rd	33.795462	-84.471468	33.793213	-84.469267
TC-02-01	Hollywood Rd to valley widening	33.793213	-84.469267	33.791976	-84.467504
TC-02-02	Valley widening to Hollywood Rd	33.791976	-84.467504	33.789556	-84.466304
TC-03	Hollywood Rd to 100m US of Spring Rd	33.789556	-84.466304	33.788148	-84.465192
TC-04	100m US of Spring Rd to US of church at Lotus	33.788148	-84.465192	33.786650	-84.463544
TC-05	US of church at Lotus to Sewer crossing DS of Brooks Ave	33.786650	-84.463544	33.784797	-84.463425
TC-06	Sewer crossing DS of Brooks Ave to 50m DS of Grand Ave	33.784797	-84.463425	33.781884	-84.461709
TC-07	50m DS of Grand Ave to Donald Lee Hollowell Rd	33.781884	-84.461709	33.776644	-84.458516
TC-08	Donald Lee Hollowell Rd to Ayrshire Cir	33.776644	-84.458516	33.771914	-84.457299
TC-09	Ayrshire Cir to Baker Rd	33.771914	-84.457299	33.770288	-84.457625
TC-10	Baker Rd to US end of concrete channel	33.770288	-84.457625	33.765281	-84.456810
TC-11	US end of concrete channel to J.E. Boone Blvd	33.765281	-84.456810	33.763544	-84.461853

Reach ID	Description	Downstream Boundary		Upstream Boundary	
		Latitude	Longitude	Latitude	Longitude
GP-01	Proctor Creek Confluence to Grove Park piping	33.775531	-84.440020	33.773902	-84.440367
GP-02	Grove Park piping to Donald Lee Hollowell Rd	33.773902	-84.440367	33.772270	-84.440859
GP-03	Donald Lee Hollowell Rd to Trib Confluence DS of Hasty Pl	33.772270	-84.440859	33.769993	-84.439517
GP-04	Trib Confluence DS of Hasty Pl to J.E. Boone Blvd	33.769993	-84.439517	33.763824	-84.446326
GPT-01	Trib Confluence DS of Hasty Pl to North Ave	33.769993	-84.439517	33.768043	-84.439038
GPT-02	North Ave to Carlisle St	33.768043	-84.439038	33.766276	-84.438512
GPT-03	Carlisle St to J.E. Boone Blvd	33.766276	-84.438512	33.763711	-84.438450
GPT-04	Boone Blvd to 241 West Lake Dr.	33.763711	-84.438450	33.761343	-84.439243
PCT-02	Perry Rd to piped section	33.791601	-84.444443	33.788615	-84.451535
PCT-01	Western Heights Trib at Proctor to Perry Rd	33.790485	-84.446920	33.791601	-84.444443

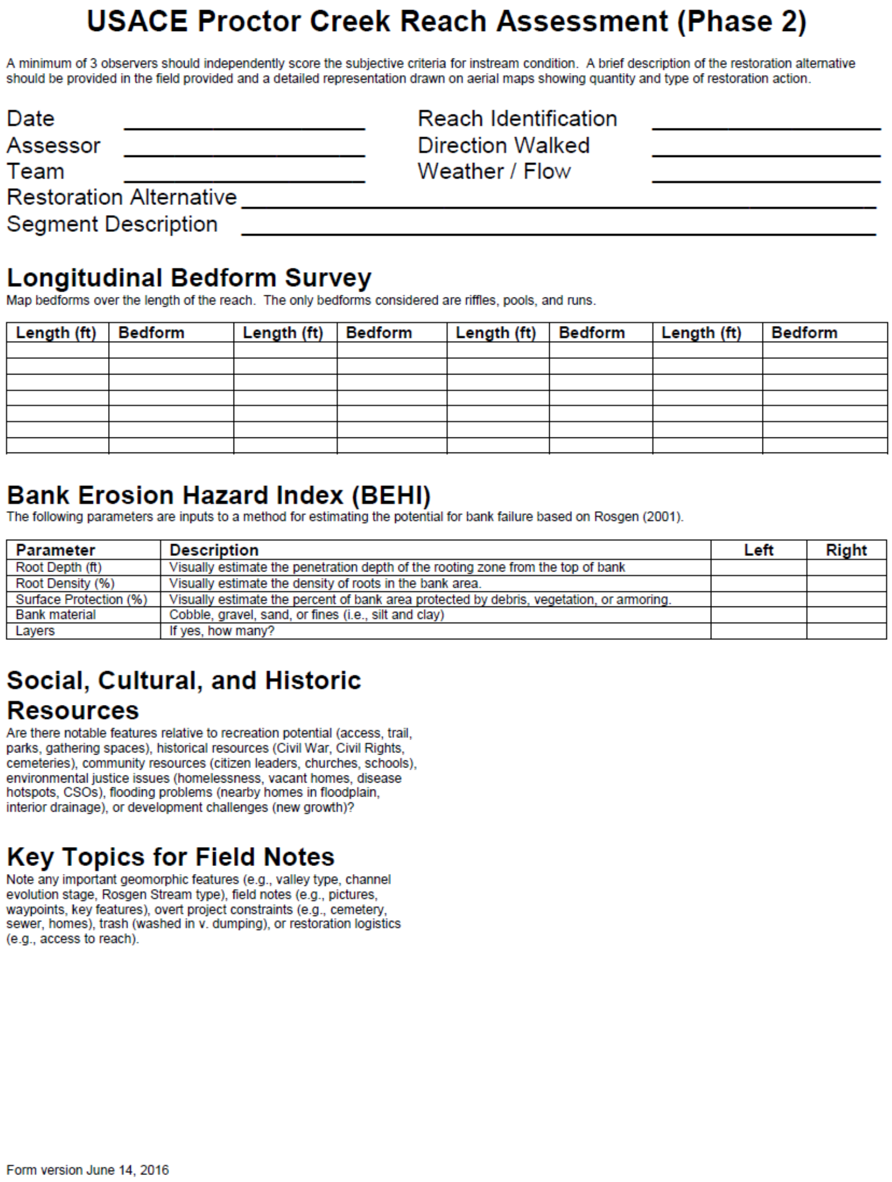
Appendix B: Field Data Collection

Many semi-quantitative and qualitative techniques exist for measuring the ecological, geomorphic, and hydrologic functions of stream corridors and riparian zones. Eight rapidly applicable data collection protocols provided the basis for the Proctor Creek visual assessments described in Chapter 4. Data collection forms (Figures 12-14) provided narrative descriptions of each variable. Most variables were scored on a 0 to 20 scale mirroring the EPA's Rapid Bioassessment Procotol (Barbour et al. 1999). In many cases, narrative descriptions were directly adopted or indirectly adapted from existing systems. The 20-point scale was viewed in the context of the Proctor Creek watershed with 20 representing the best attainable condition for this basin rather than a pristine, unaltered condition. Figures 15-23 provide visual examples of scores given in the Proctor Creek watershed for each variable used in PCEM2.

All data were collected during a single week by a consistent team (Hallberg, McKay, and Zettle), which included expertise in biology / ecology, water resource / design engineering, and USACE project planning. All cross-sectional surveys were completed by a consistent team (Hayden and Pruitt), which included expertise in survey methods, stream assessment, and civil engineering.

Table 12. Stream visual survey protocols used to create the instream and riparian condition surveys.

Description	Reference(s)
The Rapid Bioassessment Protocol (RBP) was developed by the U.S. Environmental Protection Agency to provide baseline information for stream management, including problem screening, site ranking, and trend monitoring. These protocols have broad national adoption and have served as the basis for many of the subsequent qualitative, semi-quantitative, and quantitative stream assessment methods.	Barbour et al. (1999)
The Stream Visual Assessment Procotol (SVAP) was developed by the Natural Resources Conservation Service to qualitatively evaluate the condition of wadeable streams.	Newton et al. (1998) Bjorkland et al. (2001) Boyer (2009)
The State of Georgia applied a consistent standard operating procedure for measuring the biological integrity of running waters. A semi-quantitative habitat assessment methodology is included in these procedures, which is similar to the RBP but altered specifically for application in Georgia.	GA DNR (2005)
Georgia's adopt-a-stream program engages citizens in the assessment and management of local streams. Through the state DNR, the program encourages use of a standardized, rapidly applicable visual stream survey methodology.	GA DNR (2004)
The Maryland Bioassessment Stream Survey (MBSS) developed a family of methods for rapid stream habitat assessment. These techniques were approved for USACE use by the Baltimore District and subsequently applied to the Anacostia River Watershed Study.	USACE (2014)
The Qualitative Habitat Evaluation Index (QHEI) is a qualitative method for general evaluation of macrohabitat for stream fishes. The technique was developed for the state of Ohio, but it has seen use throughout the Midwest.	Rankin (2006)
A qualitative scoring method was developed to assess the ecological condition of first- to third-order stream reaches in the context of compensatory mitigation in the Auckland region of New Zealand.	Rowe et al. (2009)
The Bank Erosion Hazard Index (BEHI) is a semi-quantitative scale for assessing the potential sediment contribution of eroding streambanks.	Rosgen (2001)



USACE Proctor Creek Reach Assessment (Phase 2)

A minimum of 3 observers should independently score the subjective criteria for instream condition. A brief description of the restoration alternative should be provided in the field provided and a detailed representation drawn on aerial maps showing quantity and type of restoration action.

Date ____________________
Assessor ____________________
Team ____________________
Reach Identification ____________________
Direction Walked ____________________
Weather / Flow ____________________
Restoration Alternative ____
Segment Description ____

Longitudinal Bedform Survey

Map bedforms over the length of the reach. The only bedforms considered are riffles, pools, and runs.

Length (ft)	Bedform	Length (ft)	Bedform	Length (ft)	Bedform	Length (ft)	Bedform

Bank Erosion Hazard Index (BEHI)

The following parameters are inputs to a method for estimating the potential for bank failure based on Rosgen (2001).

Parameter	Description	Left	Right
Root Depth (ft)	Visually estimate the penetration depth of the rooting zone from the top of bank		
Root Density (%)	Visually estimate the density of roots in the bank area.		
Surface Protection (%)	Visually estimate the percent of bank area protected by debris, vegetation, or armoring.		
Bank material	Cobble, gravel, sand, or fines (i.e., silt and clay)		
Layers	If yes, how many?		

Social, Cultural, and Historic Resources

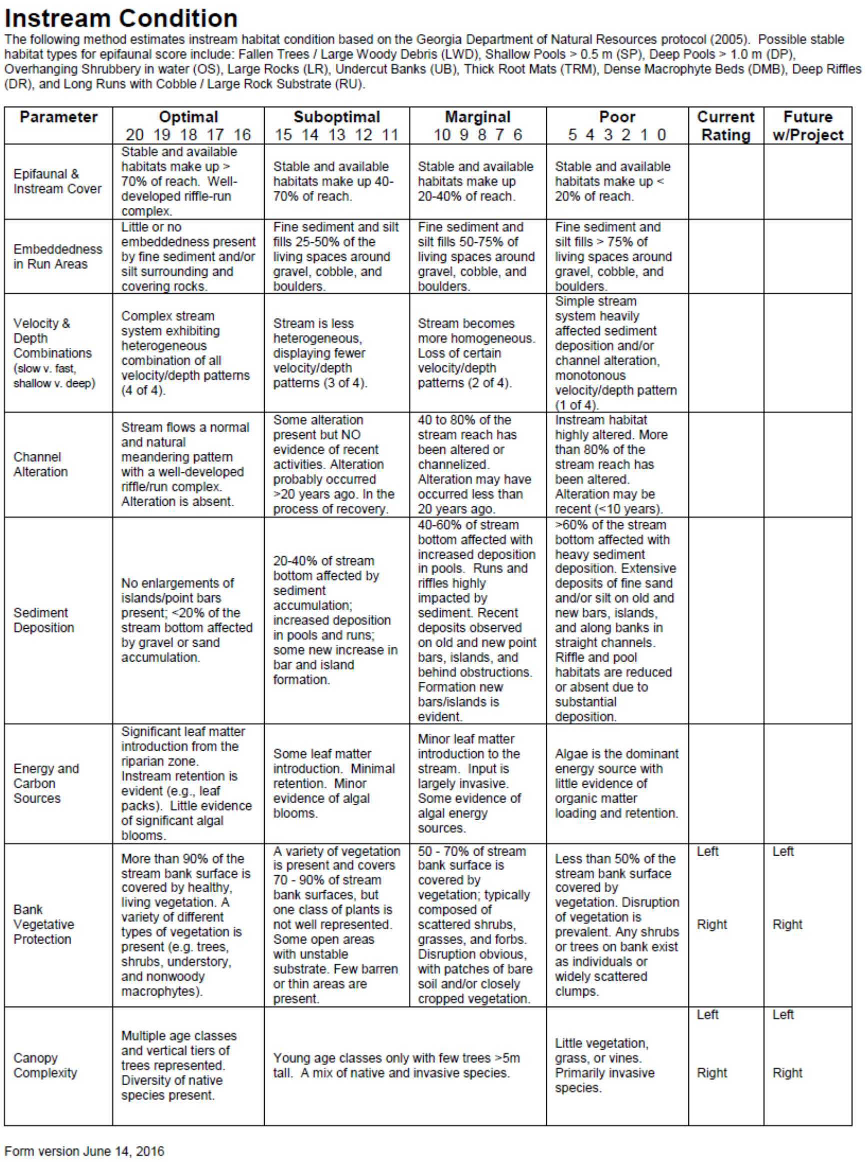
Are there notable features relative to recreation potential (access, trail, parks, gathering spaces), historical resources (Civil War, Civil Rights, cemeteries), community resources (citizen leaders, churches, schools), environmental justice issues (homelessness, vacant homes, disease hotspots, CSOs), flooding problems (nearby homes in floodplain, interior drainage), or development challenges (new growth)?

Key Topics for Field Notes

Note any important geomorphic features (e.g., valley type, channel evolution stage, Rosgen Stream type), field notes (e.g., pictures, waypoints, key features), overt project constraints (e.g., cemetery, sewer, homes), trash (washed in v. dumping), or restoration logistics (e.g., access to reach).

Form version June 14, 2016

Figure 12. Phase 2 field data collection form (1 of 3).



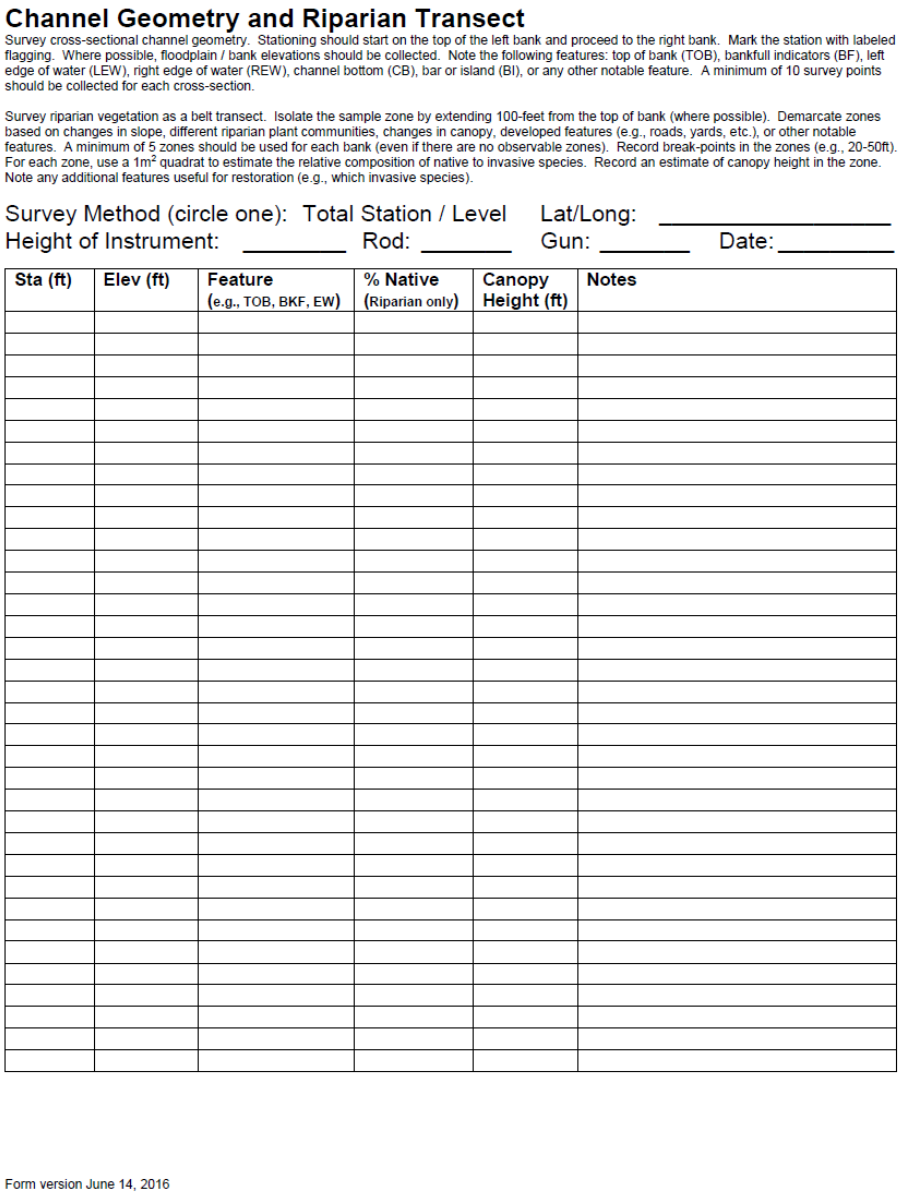
Instream Condition

The following method estimates instream habitat condition based on the Georgia Department of Natural Resources protocol (2005). Possible stable habitat types for epifaunal score include: Fallen Trees / Large Woody Debris (LWD), Shallow Pools > 0.5 m (SP), Deep Pools > 1.0 m (DP), Overhanging Shrubbery in water (OS), Large Rocks (LR), Undercut Banks (UB), Thick Root Mats (TRM), Dense Macrophyte Beds (DMB), Deep Riffles (DR), and Long Runs with Cobble / Large Rock Substrate (RU).

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	Current Rating	Future w/Project
Epifaunal & Instream Cover	Stable and available habitats make up > 70% of reach. Well-developed riffle-run complex.	Stable and available habitats make up 40-70% of reach.	Stable and available habitats make up 20-40% of reach.	Stable and available habitats make up < 20% of reach.		
Embeddedness in Run Areas	Little or no embeddedness present by fine sediment and/or silt surrounding and covering rocks.	Fine sediment and silt fills 25-50% of the living spaces around gravel, cobble, and boulders.	Fine sediment and silt fills 50-75% of living spaces around gravel, cobble, and boulders.	Fine sediment and silt fills > 75% of living spaces around gravel, cobble, and boulders.		
Velocity & Depth Combinations (slow v. fast, shallow v. deep)	Complex stream system exhibiting heterogeneous combination of all velocity/depth patterns (4 of 4).	Stream is less heterogeneous, displaying fewer velocity/depth patterns (3 of 4).	Stream becomes more homogeneous. Loss of certain velocity/depth patterns (2 of 4).	Simple stream system heavily affected sediment deposition and/or channel alteration, monotonous velocity/depth pattern (1 of 4).		
Channel Alteration	Stream flows a normal and natural meandering pattern with a well-developed riffle/run complex. Alteration is absent.	Some alteration present but NO evidence of recent activities. Alteration probably occurred >20 years ago. In the process of recovery.	40 to 80% of the stream reach has been altered or channelized. Alteration may have occurred less than 20 years ago.	Instream habitat highly altered. More than 80% of the stream reach has been altered. Alteration may be recent (<10 years).		
Sediment Deposition	No enlargements of islands/point bars present; <20% of the stream bottom affected by gravel or sand accumulation.	20-40% of stream bottom affected by sediment accumulation; increased deposition in pools and runs; some new increase in bar and island formation.	40-60% of stream bottom affected with increased deposition in pools. Runs and riffles highly impacted by sediment. Recent deposits observed on old and new point bars, islands, and behind obstructions. Formation new bars/islands is evident.	>60% of the stream bottom affected with heavy sediment deposition. Extensive deposits of fine sand and/or silt on old and new bars, islands, and along banks in straight channels. Riffle and pool habitats are reduced or absent due to substantial deposition.		
Energy and Carbon Sources	Significant leaf matter introduction from the riparian zone. Instream retention is evident (e.g., leaf packs). Little evidence of significant algal blooms.	Some leaf matter introduction. Minimal retention. Minor evidence of algal blooms.	Minor leaf matter introduction to the stream. Input is largely invasive. Some evidence of algal energy sources.	Algae is the dominant energy source with little evidence of organic matter loading and retention.		
Bank Vegetative Protection	More than 90% of the stream bank surface is covered by healthy, living vegetation. A variety of different types of vegetation is present (e.g. trees, shrubs, understory, and nonwoody macrophytes).	A variety of vegetation is present and covers 70 - 90% of stream bank surfaces, but one class of plants is not well represented. Some open areas with unstable substrate. Few barren or thin areas are present.	50 - 70% of stream bank surface is covered by vegetation; typically composed of scattered shrubs, grasses, and forbs. Disruption obvious, with patches of bare soil and/or closely cropped vegetation.	Less than 50% of the stream bank surface covered by vegetation. Disruption of vegetation is prevalent. Any shrubs or trees on bank exist as individuals or widely scattered clumps.	Left Right	Left Right
Canopy Complexity	Multiple age classes and vertical tiers of trees represented. Diversity of native species present.	Young age classes only with few trees >5m tall. A mix of native and invasive species.		Little vegetation, grass, or vines. Primarily invasive species.	Left Right	Left Right

Form version June 14, 2016

Figure 13. Phase 2 field data collection form (2of 3).



Channel Geometry and Riparian Transect

Survey cross-sectional channel geometry. Stationing should start on the top of the left bank and proceed to the right bank. Mark the station with labeled flagging. Where possible, floodplain / bank elevations should be collected. Note the following features: top of bank (TOB), bankfull indicators (BF), left edge of water (LEW), right edge of water (REW), channel bottom (CB), bar or island (BI), or any other notable feature. A minimum of 10 survey points should be collected for each cross-section.

Survey riparian vegetation as a belt transect. Isolate the sample zone by extending 100-feet from the top of bank (where possible). Demarcate zones based on changes in slope, different riparian plant communities, changes in canopy, developed features (e.g., roads, yards, etc.), or other notable features. A minimum of 5 zones should be used for each bank (even if there are no observable zones). Record break-points in the zones (e.g., 20-50ft). For each zone, use a 1m^2 quadrat to estimate the relative composition of native to invasive species. Record an estimate of canopy height in the zone. Note any additional features useful for restoration (e.g., which invasive species).

Survey Method (circle one): Total Station / Level Lat/Long: ____________________

Height of Instrument: _________ Rod: ________ Gun: ________ Date: __________

Sta (ft)	Elev (ft)	Feature (e.g., TOB, BKF, EW)	% Native (Riparian only)	Canopy Height (ft)	Notes

Form version June 14, 2016

Figure 14. Phase 2 field data collection form (3 of 3).

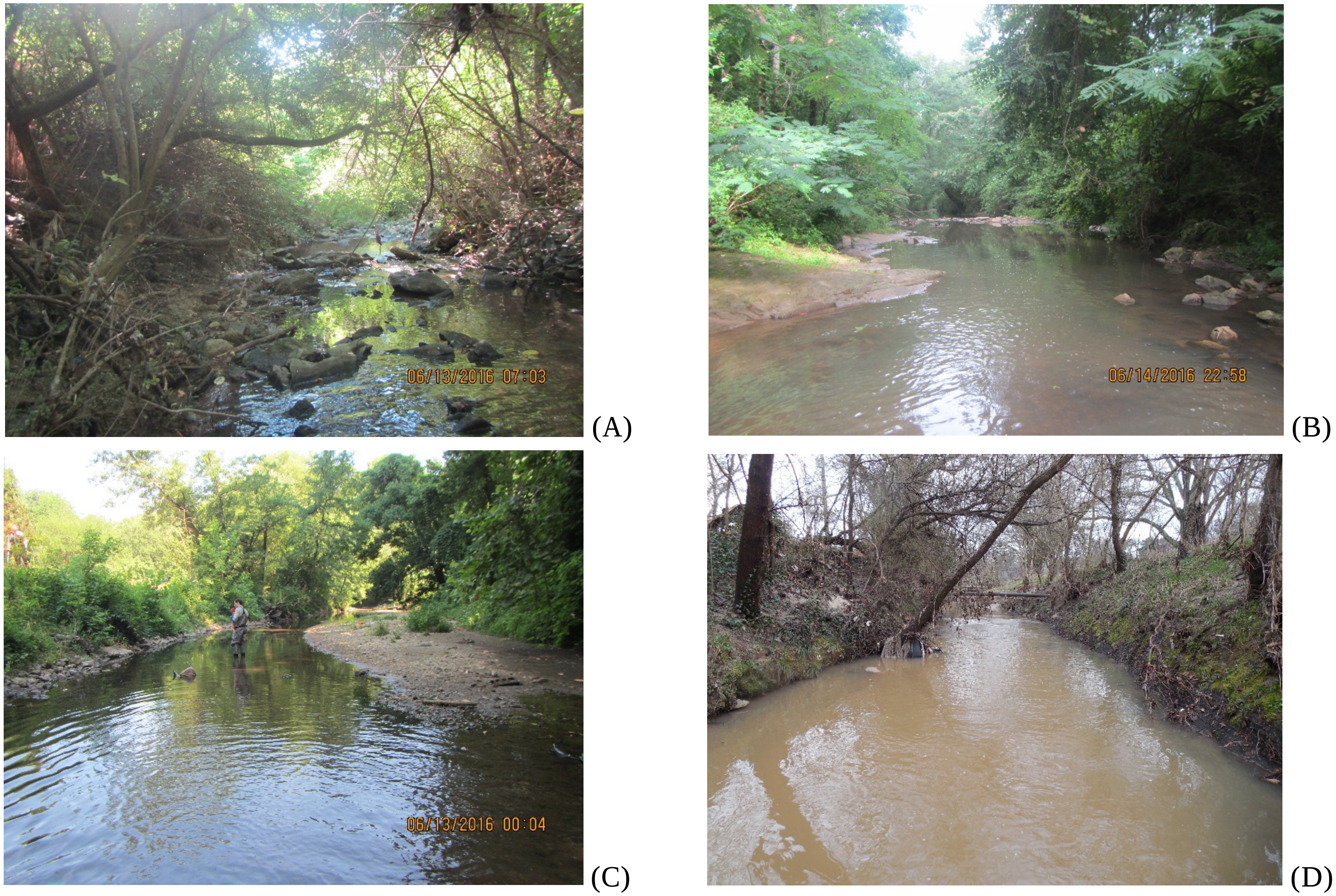


Figure 15. Examples of instream condition variable for epifaunal and instream cover: (A) optimal condition at TC02.01, (B) sub-optimal condition at PC13, (C) marginal condition at PC08.01, (D) poor condition at GP01.

Figure 16. Examples of instream condition variable for embeddedness: (A) optimal condition not observed in June 2016, (B) sub-optimal condition at TC02.01, (C) marginal condition at TC02.02, (D) poor condition at PC15.

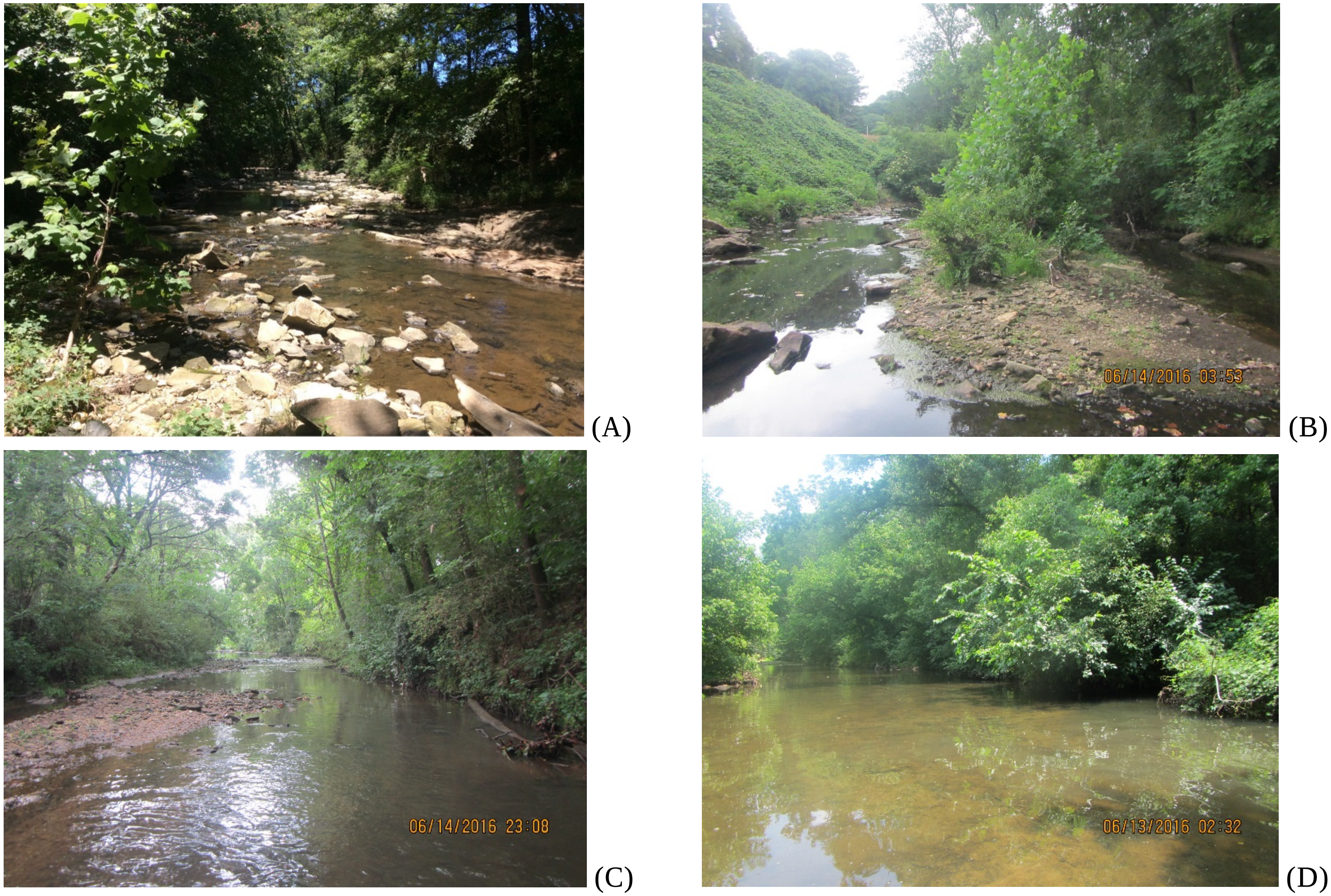


Figure 17. Examples of instream condition variable for velocity and depth combinations: (A) optimal condition at PC14, (B) sub-optimal condition at PC10, (C) marginal condition at PC13, (D) poor condition at PC08.02.

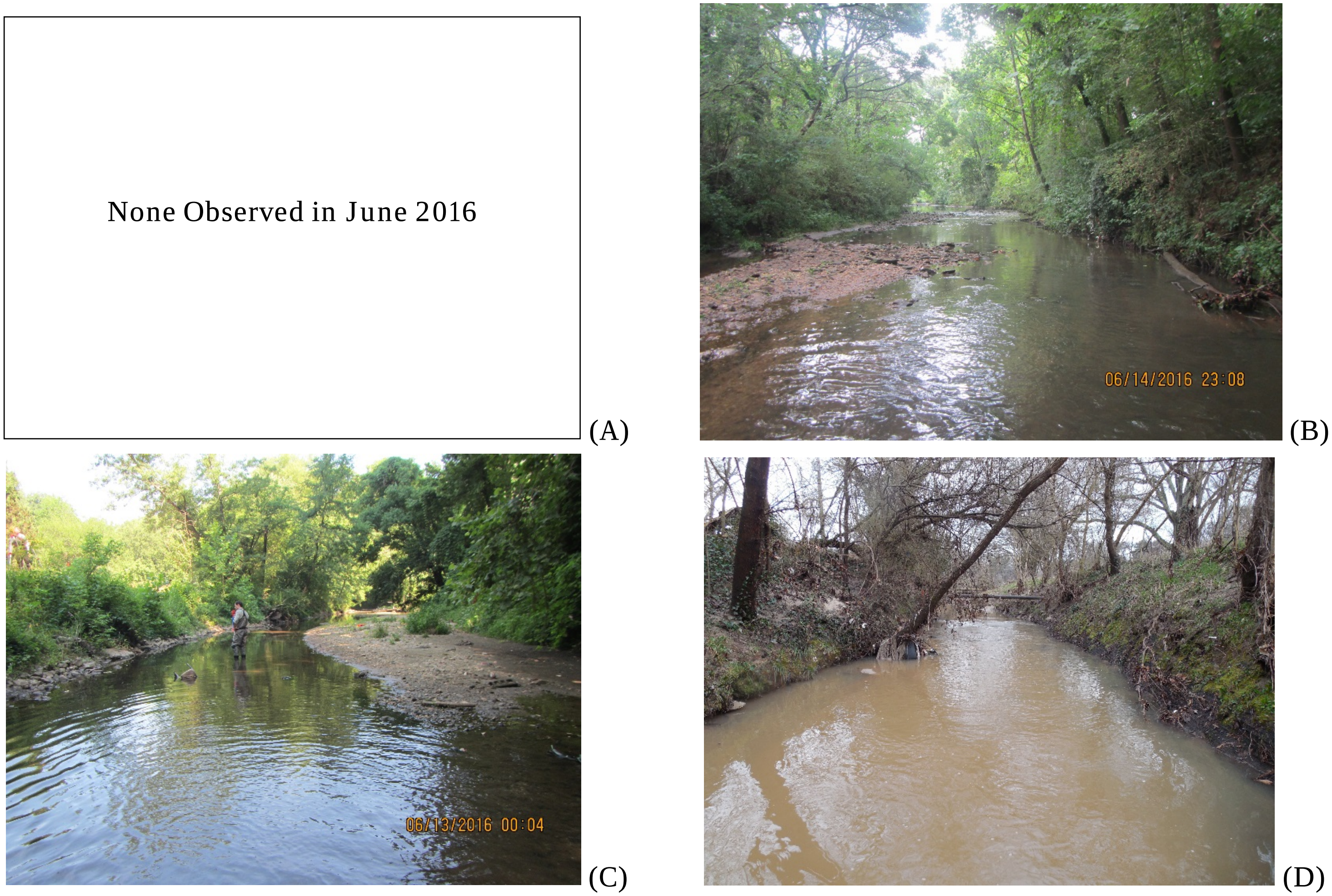


Figure 18. Examples of instream condition variable for channel alteration: (A) optimal condition not observed, (B) sub-optimal condition at PC13, (C) marginal condition at PC08.01, (D) poor condition at GP01.

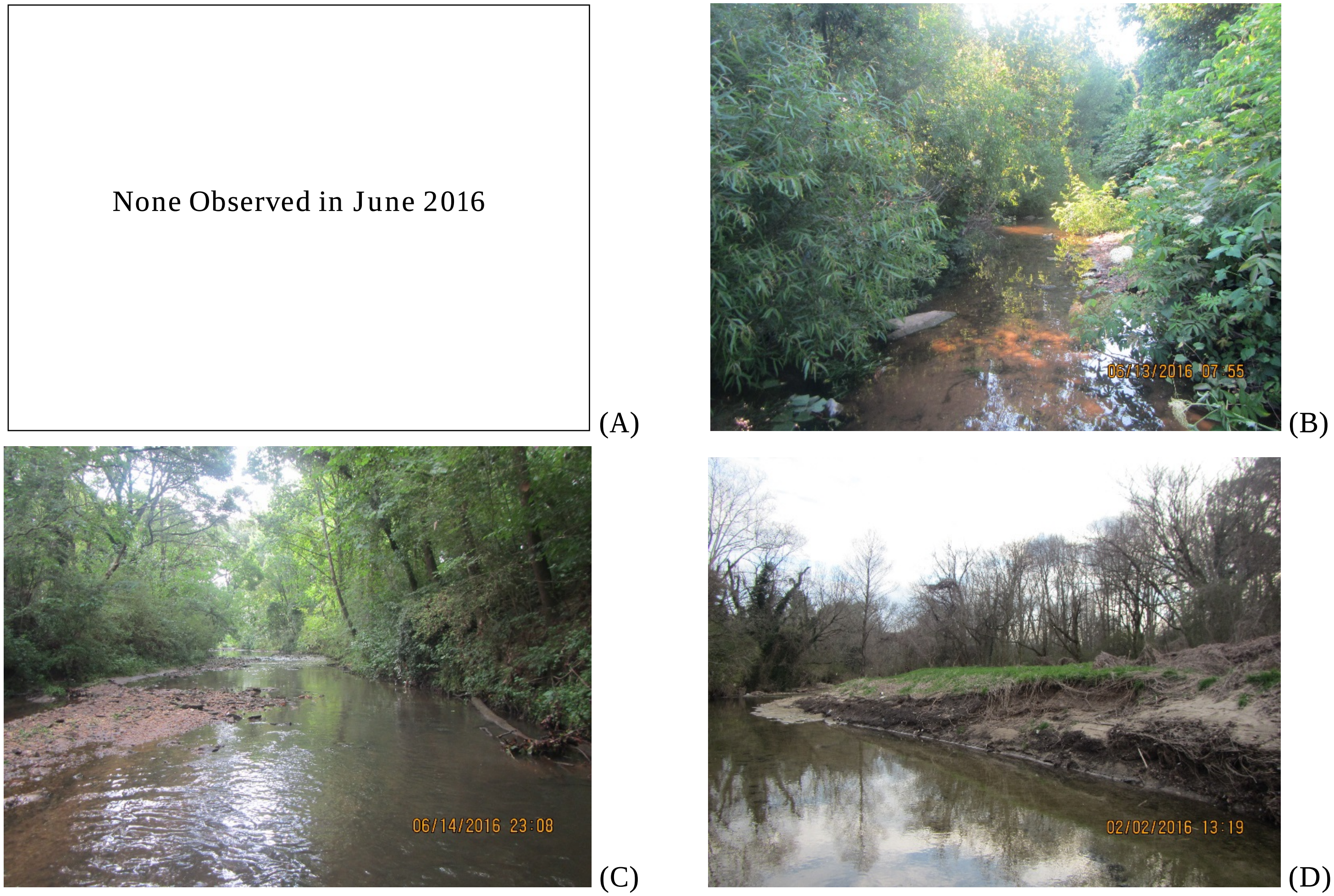


Figure 19. Examples of instream condition variable for sediment deposition: (A) optimal condition not observed, (B) sub-optimal condition at TC02.02, (C) marginal condition at PC13, (D) poor condition at PC15.

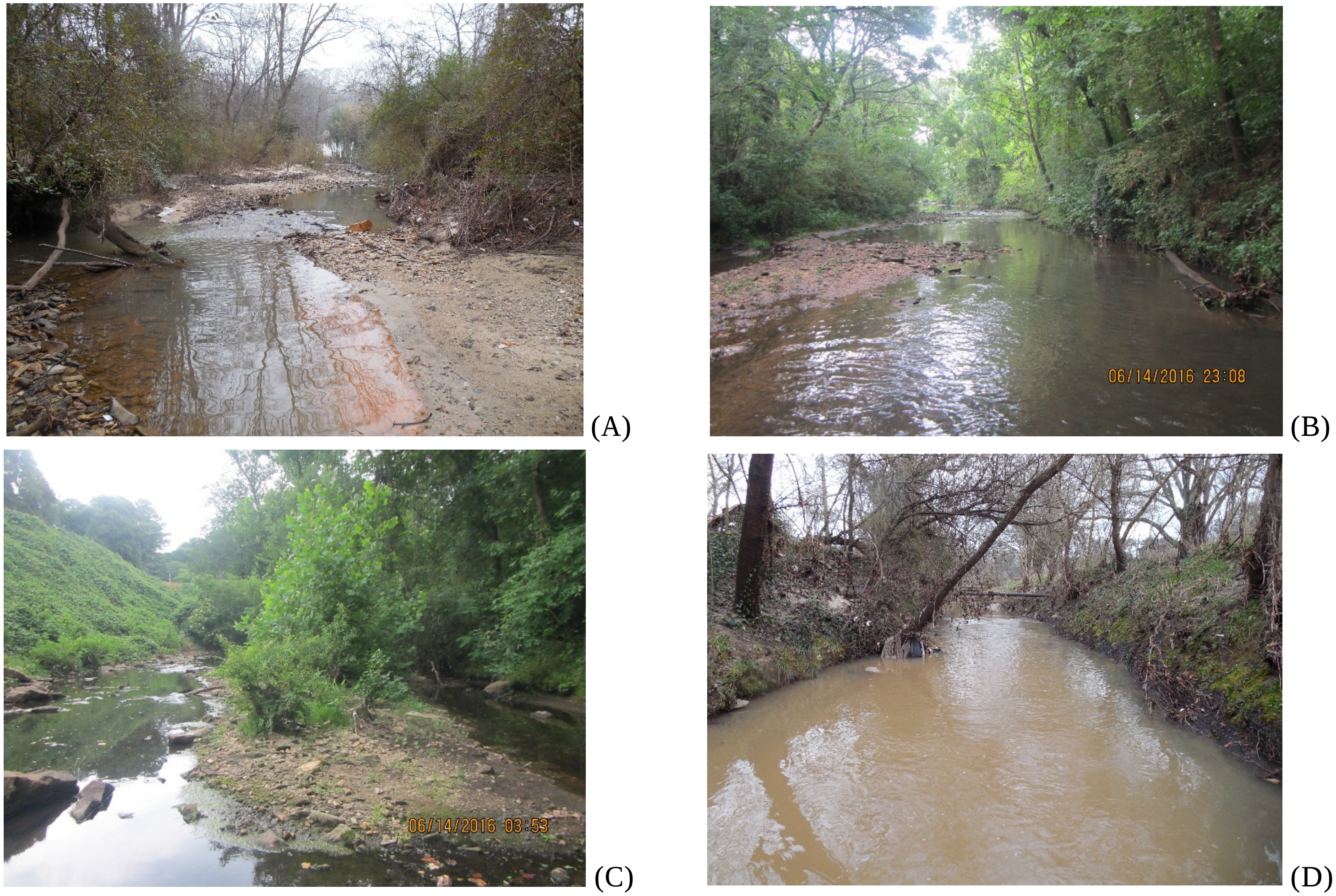


Figure 20. Examples of riparian condition variable for energy and carbon sources: (A) optimal condition at TC05, (B) sub-optimal condition at PC13, (C) marginal condition at PC10, (D) poor condition at GP01.

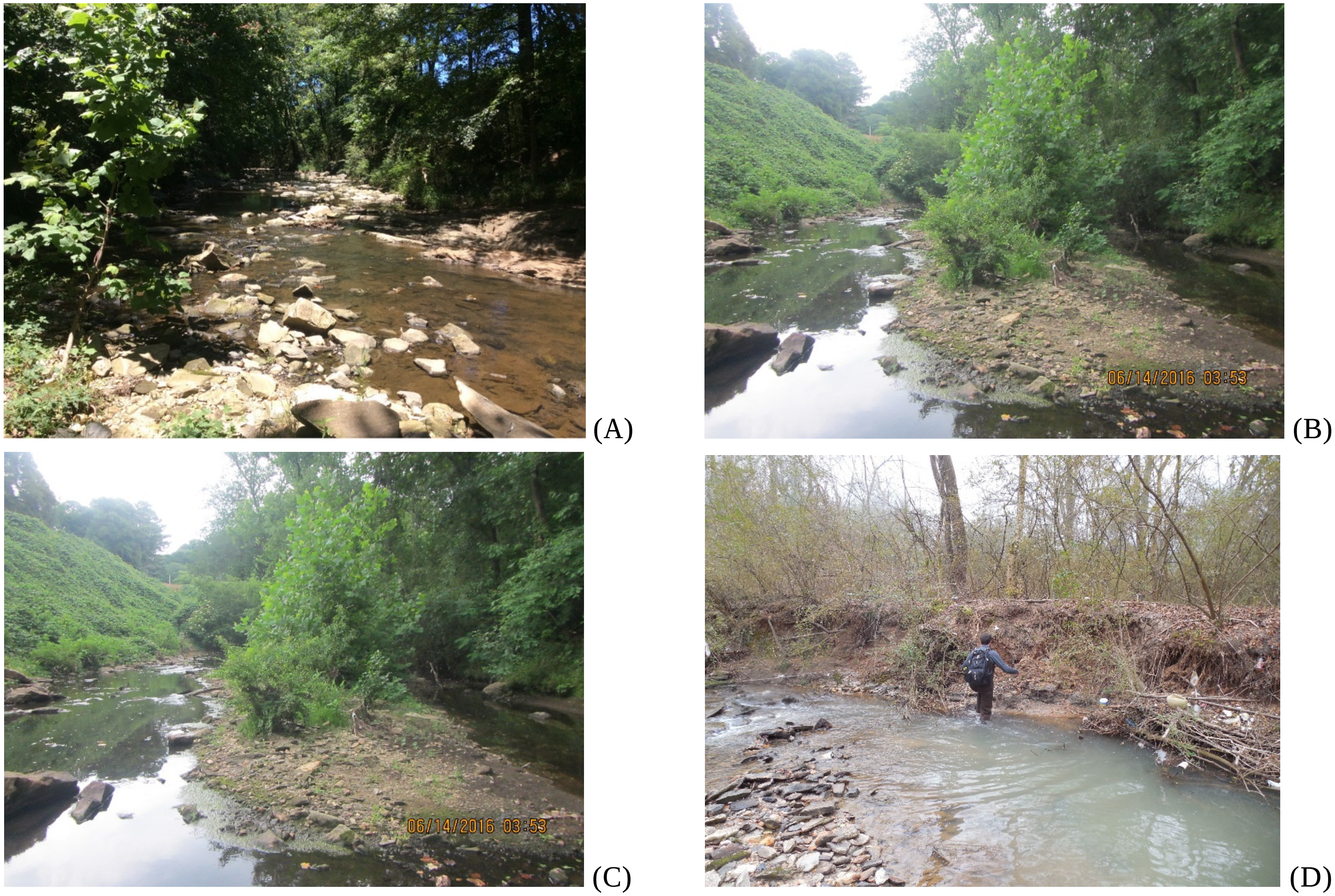


Figure 21. Examples of riparian condition variable for bank vegetation: (A) optimal condition at PC14, (B) sub-optimal condition at PC10 (right side of photo on river left bank), (C) marginal condition at PC10 (left side of photo on river right bank), (D) poor condition at TC05.

06/13/2016 00:04

06/13/2016 07:55

Figure 22. Examples of riparian condition variable for canopy complexity: (A) optimal condition at PC14, (B) suboptimal / marginal condition at PC08.01, (C) poor condition at TC02.02.

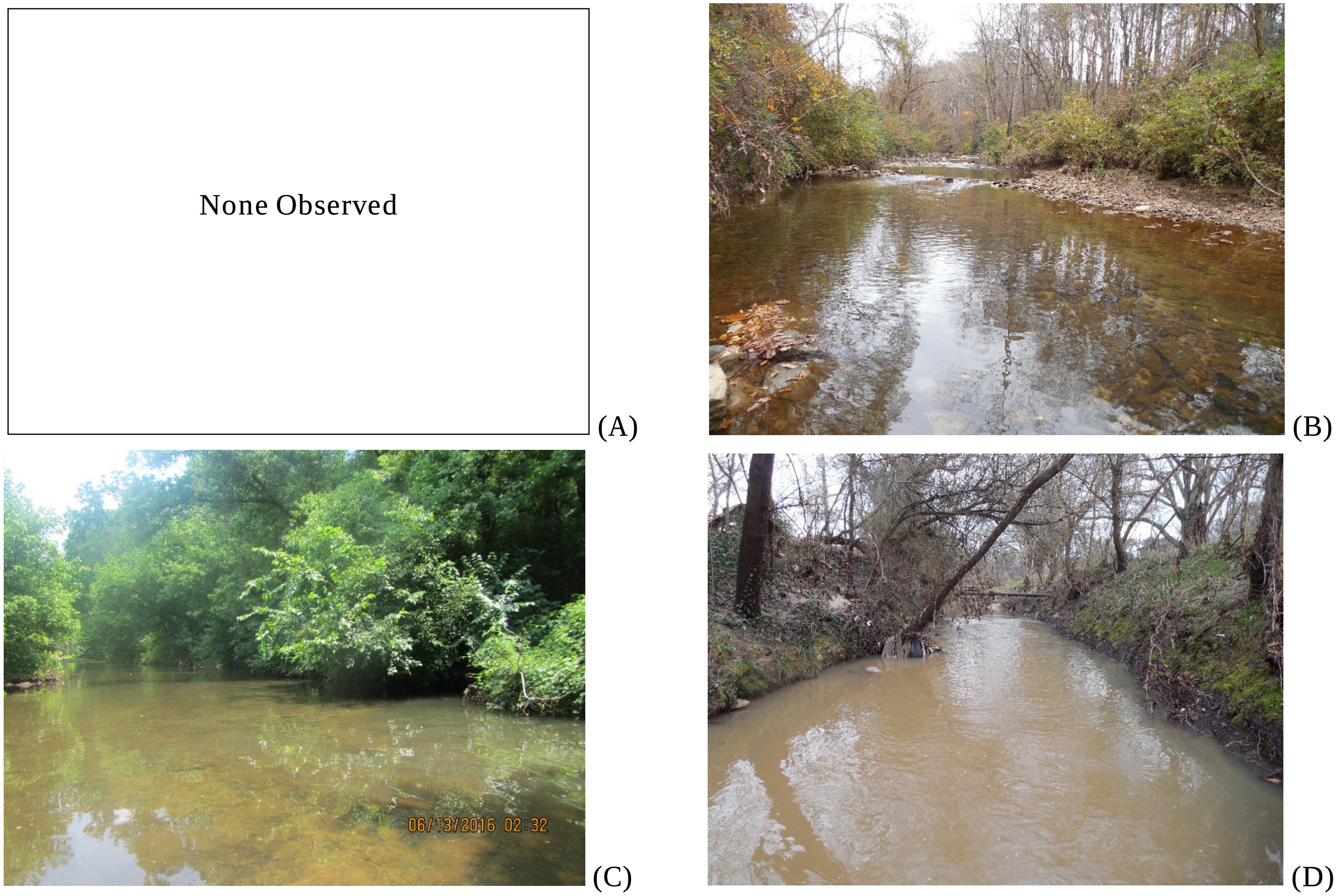


Figure 23. Examples of hydrologic condition variable for flow attenuation: (A) optimal condition not observed, (B) sub-optimal condition at PC09, (C) marginal condition at PC08.02, (D) poor condition at GP01.

Appendix C: Hydrologic Model Development

A HEC-HMS hydrologic model was applied for all hydrologic simulations in the Proctor Creek watershed (Scharffenberg 2016)[1]. An existing model was developed prior to the study for use in a Federal Emergency Management Administration Flood Insurance Study, which was obtained from the primary contractor and used as the principal basis for the existing model (Monica S. Urisko, Atkins Global, personal communication).

Prior to application in the Proctor Creek ecosystem restoration study, three storms were used to calibrate and verify the model, which occurred on 7-8 April 2014, 8-9 August 2014, and 8-9 November 2015. Storms were selected to bracket a range of peak discharges surrounding the two-year runoff event while addressing seasonal variation. Gridded rainfall data were obtained for each storm from the Southeastern River Forecast Center (National Weather Service), and data were resampled from a resolution of 4,762.5m to 500m using the HEC-GridInterp software. Curve numbers and lag times were adjusted based on land cover, soil type, and basin properties to minimize model error to the extent practicable (Figure 24). HMS simulations were calibrated and verified relative to two US Geological Survey gages on Proctor Creek at James Jackson Parkway (#02336526) and at Hortense Way (#02336517). The model was evaluated relative to peak discharge, runoff volume, and Nash-Sutcliffe efficiency indices (magnitude of residual variance compared to measured data variance; Table 13) as well as visual fit of observed hydrographs (Figure 25).

Table 13. HEC-HMS model verification following calibration.

USGS Gage	Storm	Peak flow Obs (cfs)	Peak Flow Sim (cfs)	Volume Obs (ac-ft)	Volume Sim (ac-ft)	Nash-Sutcliffe Index
02336526	7-8 Apr 2014	3790	3206	1339	1341	0.958
02336526	8-9 August 2014	1090	1441	231	336	-0.046
02336526	7-8 Nov 2015	1750	1383	551	405	0.900
02336517	7-8 Nov 2015	1160	1201	283	260	0.892

---

[1] Additional details may be found in the engineering appendix of the feasibility study report.

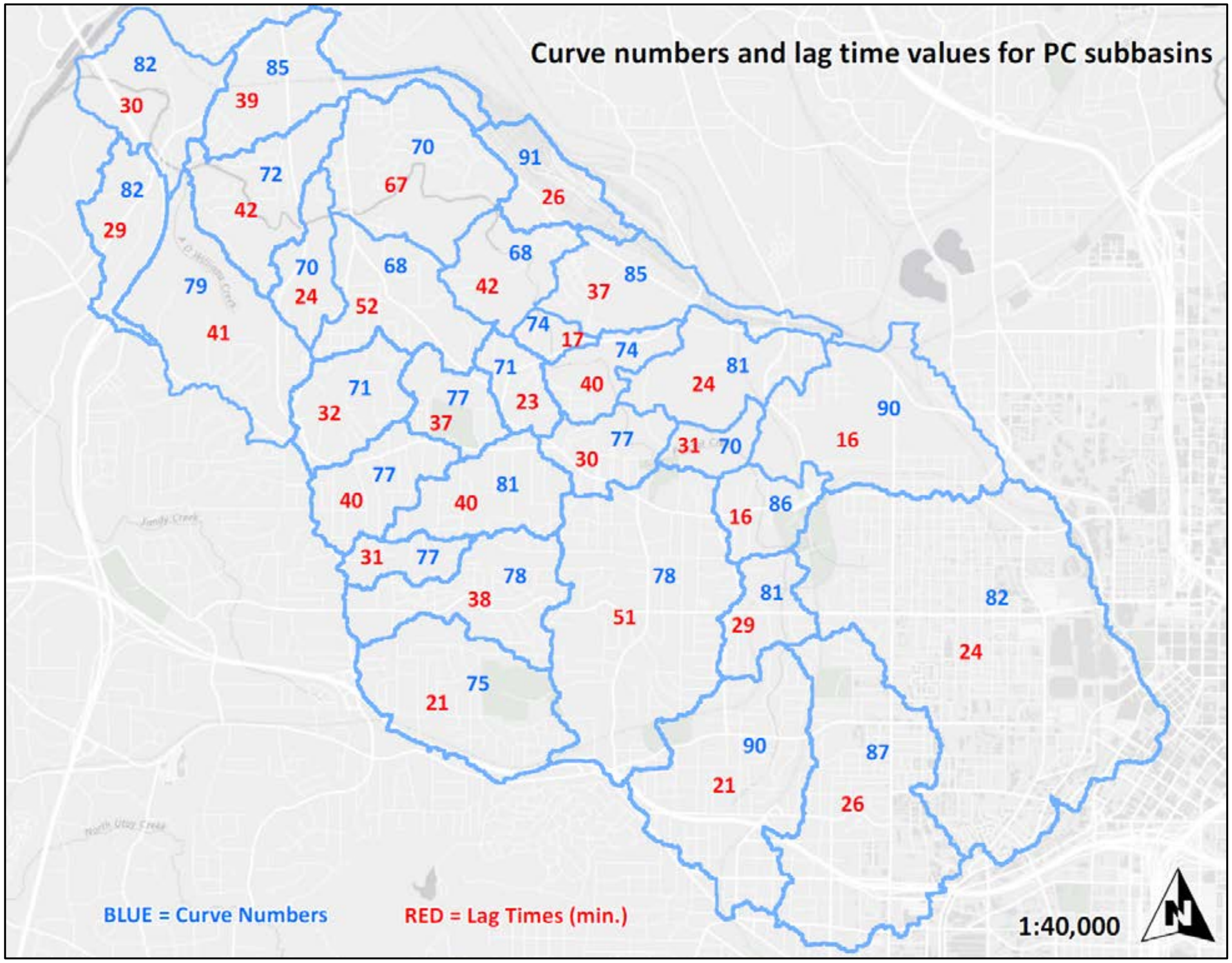


Figure 24. Primary HEC-HMS model parameters by sub-basin: basin lag time (red) and curve number (blue).

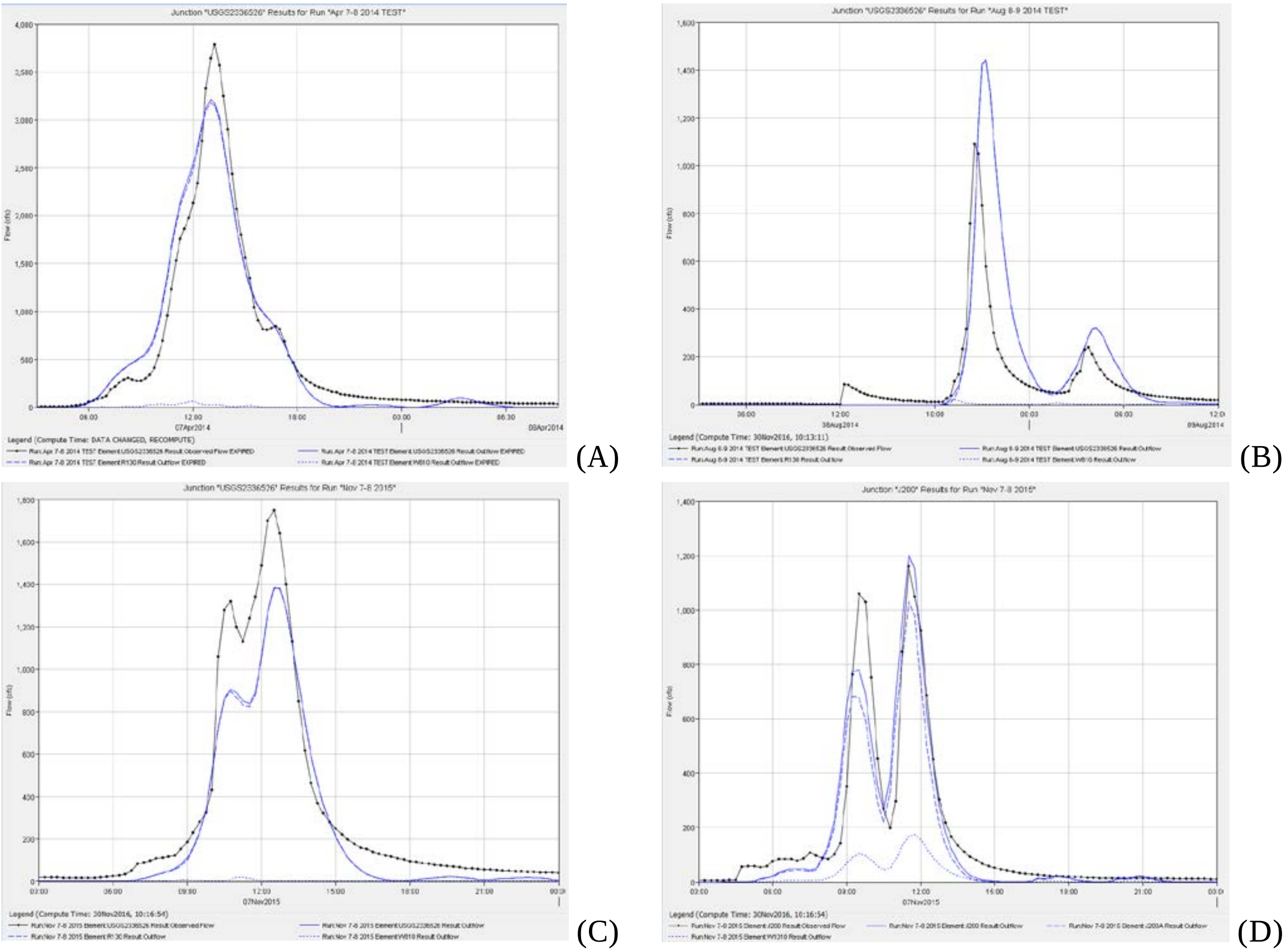


Figure 25. HMS model verification of three storms at two location: (A) 8-9 April 2014 at USGS #02336526, (B) 8-9 August 2014 at USGS #02336526, (C) 7-8 November 2015 at USGS #02336526, and (D) 7-8 November 2015 at USGS #02336517.

Appendix D: Model Test Plan

Following model development, an extensive post hoc test of model functionality was conducted on the final model version. The purpose of model testing was to ensure the numerical accuracy of the tool (i.e., its system quality). Table 14 provides a summary of all tests conducted and the rationale for the test. Overall, the tests were intended to ensure the numerical accuracy of successively larger blocks of code with the assumptions that if the parts work, the code as a whole is accurately producing results. All trials were conducted by the primary programmer (McKay) on February 24, 2017. Any test failures were repeated with code modification until successful. At the conclusion of testing, all tests were deemed successful due to their capacity to exactly replicate the validating calculations described.

Table 14. PCEM2 testing trials.

Component Tested	Test Rationale	Test Procedure	Test Result
Function for geometric mean	Function used in the combination of indices into the overarching index (IEI)	Compared function output to temporary Excel computation.	Success
Function for combining judgment based scores	Function used in the combination of any judgment based scores used in the model	Compared function output to temporary Excel computation.	Success
Data import	Verify data are imported correctly	Manually verified file names, imported data files, and examined variables in R relative to the original database.	Success
Restoration plan combination	All possible combinations of restoration sites are computed and stored in a matrix	The matrix of plans was manually examined for logical consistency (i.e., did the pattern of site combinations "make sense"). The total number of plan combinations for 15 sites (Table 9) is theoretically 32, 768, and the algorithm produced this number of plans.	Success
Computation of visual scores	Scores from individual observers are combined into an overall assessment score for each site, year, and alternative	Variable combinations were "spot checked" manually against a calculator for more than 15 random sets of scores.	Success
V_{bkf}	One of 13 model variables	Model values compared against Excel computations	Success
V_{behi}	One of 13 model variables	Model values compared against Excel computations	Success
V_{ibi}	One of 13 model variables	Model values compared against Excel computations	Success
V_{carb}	One of 13 model variables	Model values compared against Excel computations	Success
V_{nut}	One of 13 model variables	Model values compared against manual calculations	Success
V_{temp}	One of 13 model variables	Model values compared against Excel computations	FAILED
V_{temp}	Prior test failed. Code checked, bug found, and code repaired	Model values compared against Excel computations	Success
V_{hab}	One of 13 model variables	Model values compared against Excel computations	Success
V_{att}	One of 13 model variables	Model values compared against Excel computations	Success

Component Tested	Test Rationale	Test Procedure	Test Result
V_{peak}	One of 13 model variables	Model values compared against Excel computations	Success
V_{flash}	One of 13 model variables	Model values compared against Excel computations	Success
V_{con}	One of 13 model variables	Model values compared against manual calculations of cumulative passage rates	Success
I_{ins}	One of 4 model indices	Calculated through a lookup process. Lookup values verified and variable combination was spot-checked against manual calculations for FWOP and FWP conditions.	Success
I_{rip}	One of 4 model indices	Calculated through a lookup process. Lookup values verified and variable combination checked against manual calculations.	Success
I_{hyd}	One of 4 model indices	Calculated through a lookup process. Lookup values verified and variable combination checked against manual calculations.	Success
I_{con}	One of 4 model indices	Calculated through a lookup process. Verified lookup.	Success
IEI	Combination of 4 indices	Verified against manual calculations.	Success
habitat	Combination of quality and quantity for each time step	Verified against manual calculations.	Success

Appendix E: Example Restoration Design

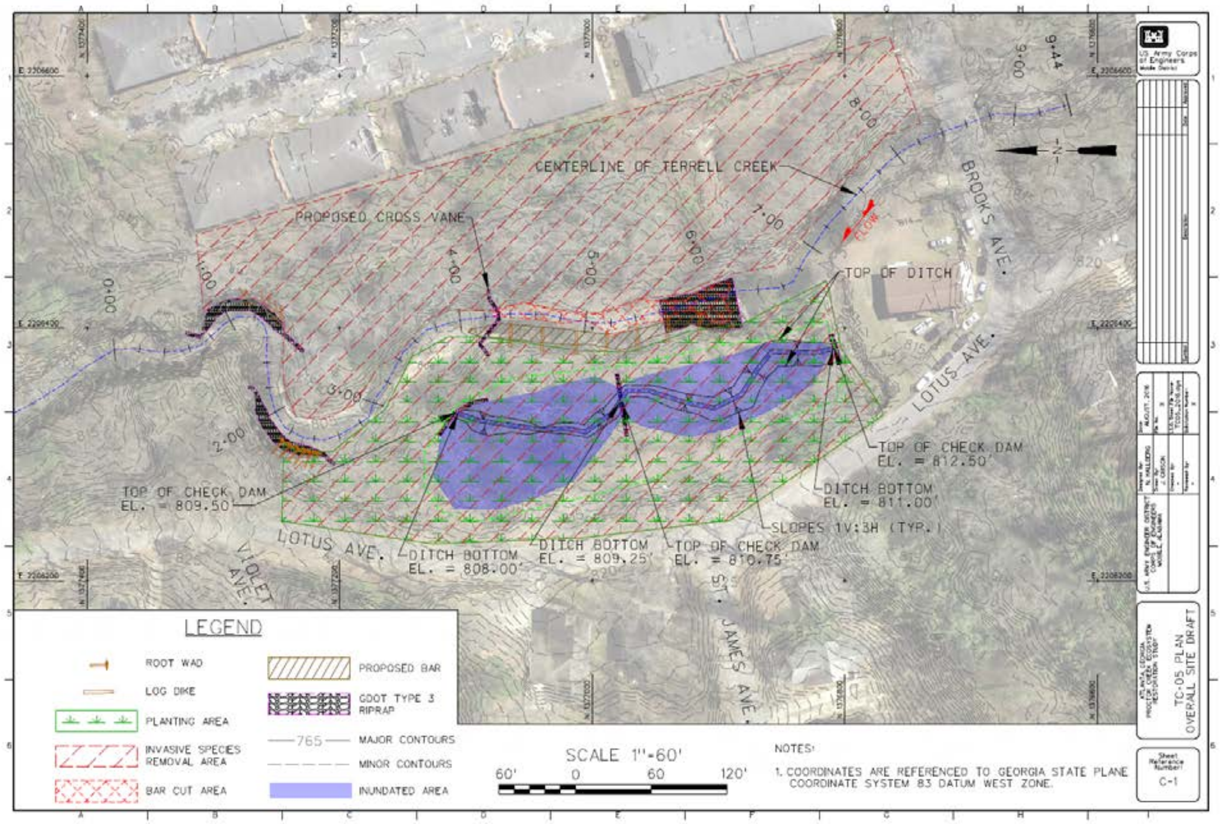


Figure 26. Example of preliminary design mock-up for TC05.

Appendix F: Cost Estimation

The cost estimate for each reach was developed using the Quantity Take-off method. Initially each reach was analyzed to determine the appropriate quantities for construction activities. The conceptual level plans, such as in Figure 26, along with the concept narratives provided the basis for the permanent works. The temporary activities, such as construction entrances, dewatering, and mobilization were primarily based on the estimator's judgement and discussion with PDT members. Planning, Engineering, and Design (PED), as well as Construction Management (CM) costs were determined as a percentage of the construction costs. Pre-and Post-Construction Monitoring were estimated as a level of effort and are identical for each reach.

Contingency amounts for the various reaches were developed using the Abbreviated Risk Analysis method as required by ER 1110-2-1302. The construction contingency amounts for each reach varied slightly depending on the mix of features of work included. The contingency amounts for PED and CM were consistent throughout. Real Estate costs and contingencies provided by the Mobile Real Estate division and escalation were included to calculate the total Project Cost shown in Table 9.

The cost estimates are budgetary and serve the sole purpose of comparing the alternatives. Each reach was priced separately from all of the other reaches, this would omit any savings that could be incurred from an economy of scale in alternatives including multiple reaches.