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Proctor Creek Ecological Model (PCEM)

Phase 1- Site Screening

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Cheryl Hughes, Allan Annaert, Meredith Ladart,
and Justin McDonald

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Abstract

In partnership with the City of Atlanta and thirteen federal agencies, the Mobile District (SAM) of the U.S. Army Corps of Engineers (USACE) 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 phase one of model development (PCEM1), a rapidly applicable site-screening tool for informing preliminary project decisions. PCEM1 contains four modules related to instream condition, riparian condition, hydrologic change, and watershed connectivity, these are combined into an overarching assessment of stream ecosystem integrity at the watershed-scale. The model was applied to the Proctor Creek watershed to screen 46 potential sites to 17 sites, these were continued forward at the alternatives milestone of the planning process. While developed in the context of Proctor Creek, PCEM1 provides a simple screening level model for comparing site-specific alternatives at a watershed scale, this could be adapted to other stream restoration sites or watershed studies. While developed for rapid application, the PCEM toolkit also represents a state-of-the-science approach for conducting watershed assessment and is deeply grounded in peer-reviewed approaches to stream restoration prioritization.

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Preface

This study was conducted for, and funded by, the U.S. Army Corps of Engineers (USACE), Mobile District (SAM), Proctor Creek feasibility study under Environmental Laboratory Scope of Work #16-14. Ms. Cheryl Hrabovsky was the SAM project manager, Mr. Peter F. Taylor was the Deputy District Engineer for Programs and Project Management, and Colonel James A. DeLapp was the District commander.

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

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman 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

Acronyms and Abbreviations

CE-ICA	Cost-Effectiveness and Incremental Cost Analyses
DoD	Department of Defense
EL	Environmental Laboratory
ERDC	Engineer Research Development Center
FWP	Future With Project
FWOP	Future Without Project Conditions
GIS	Geographic Information System
GUI	Graphical User Interface
HEC-HMS	Hydrologic Engineering Center's-Hydrologic Modeling System
IEI	Index of Ecosystem Integrity
IWRM	Integrated Water Resources Management
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
PCEM	Proctor Creek Ecological Model
PDT	Project Development Team
SAM	USACE Mobile District
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

1 Introduction

1.1 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 storm water and wastewater (e.g., “flashy” 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). Integrated water resources management (IWRM) in these ecosystems will require not only proactive management and preservation, but in some cases, ecosystem restoration to return these systems to less impacted, more natural conditions.

Stream restoration provides a potential mechanism for returning ecological functional of urban waters. 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 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). Furthermore, the drivers and stressors associated with urban areas have often shifted the underlying mechanisms associated with stream functions, this requires a team to examine projects from a “process-based” view of restoration (Beechie et al. 2010; Palmer and Febria 2012). In some cases, restoration projects inadequately address the underlying reasons for degradation, and have not resulted in the ecological improvements that were originally anticipated (See September 2011 Special Issue of Ecological Applications). To avoid these problems, Palmer et al. (2005) and Jansson et al. (2005) propose the following six standards for ecologically successful river restoration: (1) use a guiding image of a dynamic state, (2) improve ecosystems, (3) increase resilience, (4) do no

lasting harm, (5) complete an ecological assessment, and (6) construct conceptual model to guide restoration.

1.2 Proctor Creek ecosystem restoration

Proctor Creek in Atlanta, Georgia presents a classic example of the ecological degradation common in urban streams. The headwaters of this watershed drain the most urbanized portions of downtown Atlanta as the stream flows west into the Chattahoochee River (Figure 1). Common drivers and stressors in this watershed include combined sewer overflows, extremely high impervious surface coverage (> 30% on average) (Figure 2), and other industrial and residential sources of pollution (Horowitz et al. 2008; Peters 2009; Wright et al. 2012). Additionally, this watershed contains areas with high rates of poverty, crime, property abandonment, illegal dumping, and interior flooding (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.

Figure 1. Map of the Proctor Creek watershed showing downtown Atlanta in the southeast, the Atlanta rail yard to the north, and major interstates (I-20 and I-285) bracketing the south and western edges of the watershed.

Figure 2. Proctor Creek watershed land use map (National Land Cover Database (NLCD) 2011) showing the large extent of high intensity development within the watershed and riparian corridors.

1.3 Objectives

In planning the Proctor Creek project, the USACE team followed a basic structured decision making model known as the “ProACT” framework, in which Problems are identified, Objectives are developed and refined, Alternatives are identified, Consequences of alternatives are assessed relative to the 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). As a result of this process, the team identified three overarching goals for the Proctor Creek ecosystem restoration study along with project objectives and quantifiable sub-objectives (Table 1).

Given these objectives, the project development team (PDT) identified a menu of potential restoration alternatives that could be appropriate at multiple sites in the Proctor Creek watershed (e.g., riparian planting, flow attenuation, fish passage improvement, streambank protection). Restoration of the Proctor Creek watershed has been highlighted by a variety of federal, state, local, private, and non-governmental groups (ARC

2011; Ecological Solutions 2011; Park Pride 2011; EPA 2016), and all restoration planning drew from the ideas, proposals, and potential measures identified in these prior studies.¹

Table 1. Planning goals, objectives, and sub-objectives for the Proctor Creek ecosystem restoration study.

Goal 1: Make Proctor Creek a vibrant, sustainable ecosystem full of native species.	
1.1	<p>Improve in-channel conditions suitable for a diversity of aquatic organisms (e.g., fish, crayfish, salamanders, benthic macroinvertebrates, turtles)</p> <ul style="list-style-type: none"> • 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	<p>Improve riparian conditions supportive of a diverse aquatic and riparian community</p> <ul style="list-style-type: none"> • 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	<p>Restore flow regimes to best attainable conditions achievable in altered urban environments</p> <ul style="list-style-type: none"> • Decrease peak flows induced by high levels of impervious areas • Increase baseflows through increased watershed infiltration and shallow groundwater • Decrease flashiness of the “peaky” urban hydrograph • Minimize the difference between altered and unaltered hydrographs
1.4	<p>Promote an interconnected system resilient to foreseen and unforeseen disturbances</p> <ul style="list-style-type: none"> • Increase connectivity of movement corridors for aquatic and riparian species • Increase the capacity to absorb natural and anthropogenic disturbance
Goal 2: Make Proctor Creek an asset and source of pride for the community.	
2.1	<p>Reconnect residents to aquatic and historic landscapes</p> <ul style="list-style-type: none"> • Increase recreational access
2.2	<p>Make the creek a living laboratory for learning about local waters</p> <ul style="list-style-type: none"> • Provide educational opportunities for both residents and tourists
Goal 3: Make Proctor Creek a safe place to work and play.	
3.1	<p>Maintain or decrease existing levels of flood risk</p>
3.2	<p>Reduce health risks to neighboring communities</p> <ul style="list-style-type: none"> • Reduce exposure to contaminated water • Decrease mosquito breeding areas to reduce vector borne disease transmission

¹ <http://www.proctorcreek.org/plans--studies.html>.

1.4 Purpose

The USACE team required a scientifically defensible, analytical approach for forecasting the ecological benefits of multiple restoration actions at many sites throughout the Proctor Creek watershed. A two-phase modeling framework was developed to meet the needs of the feasibility planning milestones. Phase 1 (presented here) informs the screening of potential restoration actions at many sites in the watershed to reach the “Alternatives Milestone.” This phase emphasizes a static view of futures with and without projects, time-dependent forecasts are not used. Furthermore, this phase uses general descriptions of alternatives and preliminary costs. In later planning, Phase 2 modeling (presented in an accompanying technical report) informed selection of the Tentatively Selected Plan, this included site-specific restoration designs, temporal forecasts of restoration benefits, and refined cost estimates.

1.5 Approach

The site-selection (Phase 1) model presented here provides the basis for quantifying environmental benefits of different combinations of restoration actions. This report documents the development of a numerical modeling framework for the Proctor Creek ecosystem restoration study.

1.6 Scope

A common ecological modeling process of conceptualization, quantification, evaluation, and application is followed (Grant and Swannack 2008; Swannack et al. 2012) (Figure 3). Notably, model development was constrained by the need for rapid development and application under the USACE SMART planning paradigm, this required less than four months for field study, model development, and project application. As such, many components of the model rely on existing data, professional judgment, or rapid field assays. This model framework was designed to be applied under these constraints, but also be adaptable for future applications, where additional data or modeling inputs may be available.

Figure 3. Ecological model development process.

2 Model Conceptualization

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). 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).

The Proctor Creek conceptual ecological model (Figure 4) was iteratively developed by project team members during early project planning in conjunction with the identification of problem and opportunities, metrics, and potential alternatives. 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 2 presents the generalized conceptual ecological modeling process along with its application to Proctor Creek.

Figure 4. Conceptual ecological model for Proctor Creek stream restoration.

The model was iteratively developed during and after team meetings, preliminary site investigations, and quantitative model development. The team opted for a simplified representation of the model due to the clarity of presentation relative to a complex urban system with many simultaneous ecological processes, feedback mechanisms, and drivers and stressors. Notably, the model includes drivers and stressors outside of the USACE authority and consideration (e.g., management of combined sewer overflows). These actions were included in the model to facilitate coordination with the local sponsor (the City of Atlanta), other federal agencies (an intimate part of the Urban Waters Partnership), and stakeholder groups. Although these actions are not being pursued in this project, they have the potential to influence project outcomes.

Table 2. Stepwise development of the Proctor Creek conceptual ecological model.

Step	Proctor Creek Application
1. State the model objectives	This model provides a basic understanding of the interaction between existing drivers and stressors, ecological outcomes, and the associate points for restoration interventions. The model is intended as a communication tool for working with partners and stakeholders and informing quantitative model development.
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	Using a basic driver-stressor model framework, a list of model components was compiled starting with key ecological outcomes, then drivers and stressors, then “functional state conditions” linking the drivers and services. Although drivers and stressors can influence streams in numerous ways, stream condition within the Piedmont can be summarized by a relatively small number of “functional states” characterized by geomorphic condition, flow regime, nutrient and energy flows, and the degree of connectivity.
4. Articulate the relationships among the components of interest	Given the communication-driven purpose of the model, the only model relationships shown are connections between drivers and stressors, ecosystem states, ecological outcomes, and restoration actions. Development of a mechanistic conceptual model was not pursued due to the inability to translate processes into a quantitative model within required development timelines.
5. Represent the conceptual model	A simple graphic representation of the conceptual model (Figure 4) was developed to facilitate communication between project team members and other interested parties.
6. Describe the expected pattern of model behavior	The team qualitatively assessed flow of logic between model components (e.g., culverts can reduce connectivity, which impacts ecological movement corridors and reduces capacity for recovery after disturbances). The team also addressed the role of restoration actions on altering existing state conditions by addressing the drivers and stressor directly.
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 for input and revision.

3 Model Quantification

An enormous array of models has been developed for stream corridor assessment. 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, a common approach to ecological modeling based on quantity and quality of habitat was taken. 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) 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 general ecological functionality of the ecosystem. Four basic sub-models (or modules) are used in the assessment of habitat quality, each of which is directly related to one or more of the planning objectives for the restoration study (Table 3) and directly connects to the Proctor Creek conceptual ecological model (Figure 5).

The following sections detail the key components of the PCEM, including the combination of quantity and quality into an overarching index of ecosystem integrity (IEI), descriptions of each module, field, or remote sensing protocols, and the associated numerical toolkit for executing these analyses. The model is applied on a reach-by-reach basis, but the reach scores address the cumulative effects of upstream development (via hydrology) and downstream barriers (via connectivity). As such, this model represents a watershed scale model for assessing the cumulative benefits of multiple stream and riparian restoration actions in the Proctor Creek watershed. Importantly, all four modules are treated independently, although there are important interactions not captured by this assumption (e.g., hydrology influences instream habitat).

Table 3. Overview of the quality sub-models in the Proctor Creek Ecological Model (PCEM).

Module	Pertinent Planning Objective	Brief Description
Instream condition	1.1 Improve in-channel conditions suitable for a diversity of aquatic organisms	Instream conditions are crucial to the long-term success of the native aquatic organisms. This module assesses geomorphic condition, biogeochemical cycling of nutrients and carbon, and habitat needs of local fauna.
Riparian condition	1.2 Improve riparian conditions supportive of a diverse aquatic and riparian community	Local streams are directly related to the health of adjacent riparian zones due to their effects on stream temperatures (via shading), geomorphology (via bank stabilization), energy sources (via leaf and wood inputs), and nutrient cycling (via plant uptake). This module combines the effects of these process on overall stream health along with the benefits of the riparian zones as habitat themselves (e.g., for migratory songbirds).
Hydrology	1.3 Restore the flow regime to the best attainable condition	Urban development directly alters a river's flow regime (i.e., magnitude, frequency, timing, duration, and rate-of-change of discharge). This module addresses the degree of hydrologic change relative to an undeveloped, reference condition.
Connectivity	1.4 Promote an interconnected system resilient to disturbances	Watersheds with a high degree of longitudinal connectivity are capable of recovering and repopulating after disturbances such as floods or chemical spills. The resilience provided by connectivity is crucial in an urban area, where disturbances are likely to occur frequently. As such this module plays a prominent role in the assessment of quality by addressing the cumulative connectivity of a reach to its downstream terminus (the Chattahoochee River).

Figure 5. Modular breakdown of the Proctor Creek ecological modeling framework relative to the components of the conceptual ecological model.

Notably, the rapid development and application timeframes required that some methods be pseudo-quantitative (e.g., 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 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), this could be substituted for a more rigorous approach including field sampling or laboratory analyses.

3.1 Overarching model framework

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).

Habitat quality is computed as the combination of quality scores relative to instream condition, riparian condition, hydrologic change, and watershed connectivity. This 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.

$$IEI = \sqrt[4]{I_{ins} * I_{rip} * I_{hyd} * I_{con}} \quad (1)$$

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.

Reaches were delineated based on key infrastructure (e.g., major road crossings), fish passage barriers (e.g., sewer-crossings or perched culverts), confluence with major tributaries (e.g., Terrell Creek), or significant changes to instream or riparian conditions (e.g., bank stability, invasive species dominance, etc.). Appendix A describes each reach and locations defining breakpoints between reaches.

3.2 Instream module

Instream condition refers to the overall geomorphic state, degree of biogeochemical processing, and habitat provision associated with the inchannel environment. 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 1), variables were selected to emphasize the associated sub-objectives of the following:

- 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.

Seven variables were identified to characterize instream conditions for a given reach (Table 4). Field-based visual surveys were used to assess each variable on a pseudo-quantitative, 0 to 20 scoring scale. Appendix B provides the field assessment used in measuring these variables and examples of scores applied within the Proctor Creek watershed.

Qualitative surveys are a common approach to rapid assessment of stream conditions (Newton et al. 1998; Barbour et al. 1999; Rankin 2006; Boyer 2009), and variables and the associated scales drew heavily from existing approaches (Reviewed in Appendix B).

All stream reaches were visited during a rapid survey conducted 1–5 February 2016. The complete length of each reach was walked by USACE personnel and collaborators. The instream scoring system was then independently assessed by all present team members for the existing condition. Scores were discussed to ensure criteria were consistently applied. Potential restoration actions were then discussed by the team, and a future with project scenario was subsequently scored during the field survey. All reaches and restoration alternatives were scored by a minimum of two observers to minimize the role of subjectivity in the assessment (Barbour et al. 1999; Hughes et al. 2010). Appendix B also provides a summary of field surveys, observers, and the associated qualifications of the observers.

Table 4. Description of instream condition variables.

Variable	Description and Reason for Inclusion
Velocity and depth regime	Instream complexity is often indicative of the 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.
Instream substrate	Sediment types and sorting play an important role in benthic processes and the deposition and embeddedness of sediments is a common indicator of instream processing. This metric addresses the size and distribution of sediment types present and incorporates indicators of channel degradation such as increases in point and mid-channel bar formation.
Channel alteration	The degree 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.
Channel stability	Evidence of channel change such as bed degradation, channel widening, and head cutting are appropriate surrogates for ongoing degradation.
Bank stability	Bank erosion and undercutting are common sources of sediment input as well as a metric for channel evolution and associate instream degradation.
Habitat and available cover	Logs, snags, stable banks with root wads, and other stable habitats provide structure for aquatic organisms.
Large wood	Riparian loading of wood provides a structural component of habitat as well as a source of natural channel and bank stability.

For all analyses, variables were averaged across observers and normalized from 0 to 1. The total instream condition (I_{ins}) was assessed using a combination of arithmetic and geometric means (Equation 2). Correlated variables were combined with geometric means, and independent variables (or combinations) were combined with arithmetic means. Appendix C presents a brief statistical analysis of the current conditions for the in-stream variables, the associated correlations between variables, and the justification for this variable combination approach.

$$I_{ins} = \frac{\sqrt[4]{V_{vel}V_{sub}V_{alt}V_{hab}} + \sqrt[2]{V_{cstab}V_{bstab}} + V_{wood}}{3} \quad (2)$$

Where V_{vel} is velocity and depth regime score, V_{sub} is instream substrate score, V_{alt} is channel alteration score, V_{hab} is habitat and available cover score, V_{cstab} is channel stability score, V_{bstab} is bank stability score, and V_{wood} is the large wood score.

3.3 Riparian condition module

Riparian condition refers broadly to the overall health of the riparian zone, its influence on instream processes (e.g., temperature regulation, nutrient uptake, carbon loading), 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 1), and variables were selected to emphasize the following associated sub-objectives:

- 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.

Five variables were identified to characterize riparian conditions (Table 5). Four of these variables were assessed using field-based, visual surveys on a pseudo-quantitative, 0 to 20 scoring scale analogous to the instream system. Appendix B provides the field assessment used in measuring these variables and examples of scores applied within the Proctor Creek watershed. Qualitative surveys are a common approach to rapid assessment of the effects of riparian condition on stream health (Newton et al. 1998; Barbour et al. 1999; Rankin 2006), and variables and the associated scales drew heavily from existing approaches (Reviewed in Appendix B).

The fifth variable, riparian buffer extent, was measured remotely using GIS. Riparian buffer width (i.e., distance extending perpendicular to the stream bank) affects the degree to which associated riparian processes occur. For instance, nutrient uptake and sediment retention increase as buffer width increases (Wenger and Fowler 2000). Although riparian buffer extent could be considered a measure of habitat quantity, this module treats buffer width as a component of quality due to increases in overall stream health as a result of increased width. In recognition of the importance of riparian buffers, Georgia requires a minimum of 25 foot buffers on all streams, and the City of Atlanta extends this requirement to 100 feet on all streams in the Proctor Creek watershed. Riparian buffer width can, however, be less than the 100 feet in narrow valleys or highly developed zones, so delineated buffer areas were corrected accordingly. Buffers can also be partially developed as a result of variances to local policy (e.g., road construction exemptions) and development prior to ordinances (i.e., grandfathered

parcels). As such, the variable for riparian condition is the proportion of the area within the corrected 100 foot riparian corridor that is undeveloped (i.e., a continuous variable where 0 is fully developed and 1 is undeveloped). The area of buffer with impervious cover in the 2011 National Land Cover Database (NLCD) was used as a surrogate for overall development pressure.

Table 5. Description of riparian condition variables. All variables were separately assessed for the left and right riparian zones and combined as an average score.

Variable	Description and Reason for Inclusion
Bank vegetation and condition	The extent and vigor of streambank vegetation provides a metric for the overall impact of riparian function on instream processes such as nutrient uptake, channel stability, and temperature regulation through shading. Furthermore, near-channel ecosystems often have important exchange or subsidy of organisms and energy between the two ecosystem types (e.g., terrestrial insects consumed by fishes and aquatic insect consumed by birds) (Nakano and Murakami 2001).
Invasive species	Invasive riparian plants are common throughout the Piedmont (e.g., privet, English ivy, kudzu), and can alter not only the current condition of the system but also the long-term trajectory of riparian function. This metric summarizes the overall extent and role of invasive riparian species in long-term ecosystem integrity.
Canopy complexity	In unaltered conditions, streams have multiple sources of organic carbon inputs from a variety of riparian and upland trees. This carbon input serves as the energetic basis for the instream food web. Riparian tree canopy structure is indicative of multiple carbon inputs as well as the degree of channel shading and temperature regulation.
Floodplain connectivity	Connectivity between instream and riparian ecosystem provides ecological benefits such as nutrient uptake in riparian wetland environments, flood attenuation via riparian storage, opportunities for fishes to utilize riparian food sources, and input of riparian litter to downstream systems.
Riparian buffer extent	The overall health of a riparian ecosystem and its role in habitat provision is not only dependent upon the quality of the ecosystem (as described in the previous four variables), but also the quantity available. This metric uses riparian buffer development as an overarching metric for the role of riparian zones on instream ecosystem function.

Following the approach for instream condition assessment, all stream reaches were visited during a rapid survey conducted 1–5 February, 2016. All reaches and restoration alternatives were scored by a minimum of two observers to minimize the role of subjectivity in the assessment. Each variable was independently assessed for both left and right riparian zones (relative to an observer looking downstream), these were then subsequently averaged. Analogous to the instream module, all field survey variables were normalized from 0 to 1, and the overall riparian index (I_{rip}) was calculated using a combination of arithmetic and geometric means dependent upon the correlation between variables (Appendix C).

$$I_{rip} = \frac{\sqrt[3]{V_{veg} V_{inv} V_{can}} + V_{fp} + V_{ex}}{3} \quad (3)$$

Where V_{veg} is bank vegetation and condition score, V_{inv} is relative composition of native and invasive riparian species score, V_{can} is canopy complexity score, V_{fp} is floodplain connectivity score, and V_{ex} is buffer extent measured in GIS.

3.4 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 1), and variables were selected to emphasize the following associated sub-objectives of:

- Decrease peak flows induced by high levels of impervious areas.
- Increase baseflows through increased watershed infiltration and shallow groundwater.
- Decrease flashiness of hydrographs.
- Minimize the difference between altered and unaltered hydro-graphs.

Ideally, hydrologic condition would be assessed with site-specific, watershed-scale hydrologic models incorporating basin characteristics (e.g., drainage area, basin slope, geology), multiple land use types (e.g., urban vs. forested), and a variety of management options (e.g., detention basins, rain gardens, stormwater control). However, sophisticated hydrologic models (e.g., Hydrologic Engineering Center's Hydrologic Modeling System, HEC-HMS) were deemed unnecessary to screen alternative management actions for this project. This analysis used available hydrologic models, which could be rapidly adapted and applied to distinguish flow management actions (e.g., detention ponds, reductions in impervious cover, rain gardens, etc.) over a large spatial domain.

Three hydrologic metrics were used to distinguish effects of restoration actions. All variables were assessed as a percentage difference between current hydrologic conditions and a pre-development condition with no impervious cover. A pre-development condition is not attainable in the

Proctor Creek watershed. However, this condition serves as a consistent benchmark against which hydrologic conditions can be assessed.

All three variables summarize hydrologic conditions relative to floods of a specified magnitude. Gotvald and Knaak (2011) developed regional regressions for computing 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year peak discharge for the Piedmont region of North Georgia. These regressions were developed using 50 urban, and over 200 rural stream gages throughout the state of Georgia. The regression models have been applied successfully throughout the Piedmont of the southeastern United States (Feaster et al. 2014). Users input watershed drainage area and percent impervious cover to compute each of the specified peak flows. Three peak flows were selected for this analysis. First, a 5-year (i.e., 20 percent annual exceedance probability event) was selected as a flood of relatively high magnitude for design. Second, a 2-year (i.e., 50 percent annual exceedance probability) was selected as a relatively frequent flood, which is often correlated with geomorphically significant events (Wilkerson 2008). Third, one-half of the 2-year flood was used as a reasonable proxy for a frequent high flow event.

For each peak flow, a runoff hydrograph was estimated using the unit hydrograph of Inman (2000), which was also developed for application in the Georgia Piedmont. Basin lagtime was calculated using a regression proposed by Inman (2000). In reality, lag times are different for pre-development and post-development conditions. However, a consistent basin lag time was applied for both conditions in this analysis to allow for easy comparison of the volume under the hydrographs. As such, a hydrograph was computed for current development and pre-development conditions (e.g., Figure 6). Percent change in the total runoff volume (i.e., the area between the two hydrographs) was used as a metric of hydrologic similarity for all three return intervals.

Figure 6. Sample hydrographs generated using peak flow estimates from Gotvald and Knaak (2011) and Inman (2000). Storm volume was computed using current levels of impervious cover and pre-development impervious cover (i.e., 0%). The average percent increase in storm volume over pre-development conditions for three storms ($0.5Q_2$, Q_2 , and Q_5) was used as the summary metric for hydrologic similarity.

Each of the three variables represents a percentage change relative to the current (or restored) condition and a pre-development condition. All variables were scaled from 0 to 1, where 1 is identical to pre-development hydrology and 0 represents a 100% change in hydrology. A total hydrologic index was calculated as the arithmetic mean of all three variables.

$$I_{hyd} = \frac{V_5 + V_2 + V_{0.5}}{3} \quad (3)$$

Where, V_5 is percent volumetric change in the 5-year storm, V_2 is percent volumetric change in the 2-year storm, and $V_{0.5}$ is percent volumetric change in one-half of the 2-year storm.

Potential hydrologic restoration actions were identified by field surveys, watershed site scouting, and desktop analysis of aerial photographs and digital elevation models. Multiple forms of flow management were considered, including: in-line detention ponds, overbank detention areas (e.g., ponds and wetlands), and reductions in impervious cover (e.g.,

through brownfield restoration, rain gardens). Water storage options were assessed by reducing runoff volume associated with model outcomes.

3.5 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 2001). 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 1), and the variables were selected to emphasize the following 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). This approach is adopted here (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. Barrier locations were collected during field surveys, and a categorical visual assessment of passability was assessed by multiple

observers (Table 6). 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. The categorical assessment was de-rived using the general findings of studies of fish movement in the Piedmont region (Coffman 2005; Anderson et al. 2012). This ecoregion 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. Cumulative passage rates were computed in all focal reaches by combining barrier passage rates with a summary of watershed structure and topology (i.e., an adjacency matrix) using matrix algebra (McKay et al. 2013).

Table 6. Categorical barrier passability scores.

Barrier Passability	Description
Completely passable (1.0)	Passable at all discharges. This generally implies a lack of perched conditions, sufficiently low velocities (or complexity of velocity fields), or a sufficiently small distance not to provide a movement barrier (e.g., a short piped section).
Minor barrier (0.9)	Passable at most discharges. Perched less than 2 feet under baseflow conditions. Passable at higher discharges by flanking or “drowning” of the structure.
Significant barrier (0.5)	Passable at few discharges. Perched 2-6 feet. Only passable to the strongest swimming species and rarely passable for them. High velocity areas or long sections of piping are common.
Completely impassable (0.0)	Rarely passable to any fishes. Complete movement barrier at all discharges.

3.6 Numerical toolkit

The PCEM 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. Table 7 summarizes the diverse set of model inputs and sub-models used within this modeling framework.

A spreadsheet database was developed to compile field survey variables related to instream condition, riparian condition, barrier location, and

barrier passability for futures without and with restoration. This database also compiled watershed variables from a GIS, these were required for hydrologic and connectivity analyses. As described, pseudo-quantitative field survey data were assessed by multiple observers. Prior to executing the model, the mean observation was computed for each reach and observation type.

The PCEM combines all modules into a script-based environment 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 3.1.1, R Development Core Team 2007). Numerical model code is available from the authors upon request.

Table 7. Summary of tools and methods used in the Proctor Creek Ecological Model (PCEM).

Module	Variables	Data Source
Quantity	Stream length (miles)	GIS-derived via the National Hydrography Dataset
Instream condition	Velocity and Depth Regime Instream substrate Channel Alteration Habitat and Available Cover Channel Stability Bank Stability Large Wood	Field visual assessment scoring protocol with a minimum of two observers for all scores
Riparian condition	Bank Vegetation and Condition Invasive Species Canopy Complexity Floodplain Connectivity Riparian Buffer Extent (percent undeveloped within buffer area)	Field visual assessment scoring protocol with a minimum of two observers for all scores GIS-derived based on 2011 U.S. Geological Survey (USGS) Land Use / Land Cover and City of Atlanta riparian buffer width ordinance
Hydrology	Percent difference in volume of peak flows for three storms (0.5Q2, Q2, and Q5) between current (or restored) condition and a pre-development condition with 0% impervious cover	Ad hoc numerical model in R based on Inman (2000) unit hydrograph model and Gotvald and Knaak (2011) peak flow regressions
Connectivity	Barrier location Barrier passability Cumulative passability between a focal reach and the Chattahoochee River	GPS data from field survey Assessed categorically by visual survey by a minimum of two observers Cumulative passability computed in R by an ad-hoc model adapted from McKay et al. (2013)

4 Model evaluation

Ecological models such as PCEM, commonly rely on multiple variables, ecological processes, and in many cases present a variety of ecological outcomes. As such, models can quickly become complex system representations with many components, inputs, assumptions, and modules. Model evaluation is the process for ensuring that numerical tools are scientifically defensible and transparently developed. Evaluation is often referred to as verification or validation, but it in fact includes a family of methods ranging from peer review to model testing to error checking (Schmolke et al. 2010). In this more general sense, evaluation should include the following (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. These generally consist of evaluating tools relative to the three following categories: technical quality, system quality, and usability (EC 1105-2-412, PB 2013-02).

4.1 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, PCEM was developed with a variety of novel ecological modeling methods for analyzing stream ecosystem integrity. The overarching quantity/quality framework has been applied extensively to assess outcomes ranging from the species to ecosystem levels of hierarchy (e.g., Habitat Evaluation Procedures and the Hydrogeomorphic Methods, respectively). Furthermore, each sub-model is supported by peer reviewed algorithms developed elsewhere to include the following: instream condition (Newton et al. 1998; Barbour et al. 1999; Rankin 2006; Boyer 2009), riparian condition (Newton et al. 1998; Barbour et al. 1999; Rankin 2006; Boyer 2009), hydrology (Inman 2000; Gotvald and Knaak 2011), and connectivity (McKay et al. 2013). Although qualitative, field based judgments are used in the instream and riparian 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. Model variables were combined, based not only on theoretical knowledge of stream processes, but also on the statistical properties of the field data set (Appendix C).

4.2 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 the following:

- Code checking: All code was error-checked during and after development by the primary programmer, and was also inspected by team members throughout the process. Error checking considered consistent variable naming, investigated outputs from each individual line of code, and blocks of code (e.g., functions and loops).
- Verification: Portions of the model were verified against other published models. The peak flow component of the hydrology model was checked against outcomes from an Excel tool provided by the U.S. Geological Survey (Gotvald and Knaak 2011). Furthermore, the broader hydrology model, including both peak flows and hydrograph development, was first written in Excel, error checked by the team, and then R code was verified against this independent model. Connectivity calculations drew from code published by McKay et al. (2013), and outcomes were tested against this script.
- Testing model outcomes: Model simulations were examined thoroughly as test cases for model functionality. For instance, if a barrier is completely impassable, all subsequent upstream reaches should have a zero connectivity score and a zero IEI. These logical interpretations were examined as site specific alternatives were manually turned on and off in the model.

4.3 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. The 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 by other USACE Districts. As such, there is currently no graphical user interface (GUI) for the model beyond the script itself.

To this end, the current form of the model has maintained usability through two key mechanisms. First, PCEM is designed in a simple input-output workflow. All inputs are stored in a single Excel file structured where each sheet is converted to a *.csv and imported directly into the PCEM. The model selects these *.csv files based on user specifications and provides all results in a separate *.csv file. Second, input data and files were checked extensively by the team to ensure accuracy of data entry and manipulation in Excel.

4.4 Future evaluation

Basic model evaluation has been pursued to check the validity of PCEM outcomes. However, additional evaluation could be pursued in future applications of the model, including the following:

- Sensitivity analysis of model inputs and structure.
- Qualitative comparison, verification, and validation against available data from urban streams (e.g., local adopt-a-stream data, U.S. Environmental Protection Agency (USEPA) monitoring sites, city monitoring data, state data, etc.).
- Qualitative comparison against the general observations of other urban stream models for the Appalachian Piedmont (e.g., Sterling et al. 2016 model of macroinvertebrate biomass relative to urban land use coverage).
- Verification of individual model components (e.g., hydrologic predictions relative to U.S. Geological Survey (USGS) streamflow gages).

5 Model Application

The PCEM was developed to examine the effects of multiple and diverse restoration actions distributed throughout an urban watershed. The PCEM was applied to inform multiple aspects of the Proctor Creek ecosystem restoration study, including the examination of future without project conditions and preliminary cost-effectiveness, and incremental cost analyses to inform site screening.

5.1 Future without project (FWOP) conditions

The 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 preliminary site screening, the following assumptions were made about the FWOP:

- Land use change is static. Due to the long history of development in the area, it was assumed that no additional development beyond current levels of imperviousness will occur. This assumption could be reexamined during future modeling of restoration benefits.
- No climate change is considered due to variable forecasts in the region ($< +0.5$ to $> +4$ °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 species currently occur in every reach of Proctor Creek with some reaches dominated. The team assumed expansion beyond the current extent will be minimal.

From these assumptions, the FWOP is assumed to be the existing condition. The FWOP condition (Figure 7) provides further insight into the individual modules of the PCEM and the overarching index of ecosystem integrity. The instream condition in Proctor Creek ranges from extremely poor to reasonably high quality, 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. The current hydrology module emphasizes impervious areas as a key

hydrologic driver, and thus, upper reaches of the Proctor Creek mainstem have low quality (due to high impervious cover), Terrell Creek and Grove Park tributaries have fair quality, and mainstem quality improves as tributaries provide a dilution effect on the mainstem. Connectivity in Proctor Creek is relatively high due to few fish barriers, but piped and channelized segments, and utility crossings serve as full and partial barriers disconnecting the mainstem from headwater reaches. Overall, the IEI indicates that headwaters are the most impacted portions of Proctor Creek, and the subsequent improvement of those headwater reaches would likely benefit downstream areas via hydrologic enhancements. Likewise, fish passage improvement would enhance connectivity to headwaters upstream and increases the IEI for these reaches.

Figure 7. Future without project condition.

5.2 Future with project (FWP) conditions

Prior to the February 2016 field investigation, the team conducted a review of common urban stream restoration actions (FISRWG 1998; NRCS 2007). The review resulted in ten general categories of measures with some (not all) examples shown of each type of measure. This list is not exhaustive, but instead provided to characterize the general breadth of restoration measures considered. Not all of these measures are appropriate for the USACE restoration missions. However, given the breadth of the Urban Waters Federal Partnership, opportunities related to all of these alternatives were carried forward to field investigation.

- Streambank protection: local erosion control (e.g., rootwads, plantings, etc.), bank reshaping, structural measures (e.g., deflectors), bank armoring (e.g., riprap, walls).
- In-channel actions: daylighting, dechannelization (e.g., removing concrete or riprap lining), dredging sediment deposits.
- Riparian buffer management: tree planting, federally led invasive species management, citizen-led invasive species management.
- Fish passage: culvert repair, barrier removal, passage structures
- Floodplain connectivity: low benches accessing riparian zones, wetland creation, flow diversion.
- Flow attenuation: culvert modification, inline detention, offline detention, infiltration measure (e.g., pervious surfaces, rain gardens, etc.), floodplain buy-outs coupled with reforestation.
- Recreational improvement: signage, trails, access points, shelters, amphitheaters.
- Nutrient management: fertilizer education, fecal control programs (e.g., dog disposal bags), nutrient trading programs.
- Litter control: education campaigns, trash pickup or pricing programs, trashracks, tire pickup programs.

On 1–5 February 2016, field teams walked 13.0 miles of the Proctor Creek watershed to collect data on the existing conditions and identify potential restoration actions. In each reach, team members proposed competing plans and ideas for restoration and developed a site-specific alternative composed of one or more of the above measures (Table 8).

Table 8. Potential non-detention restoration actions in Proctor Creek presented by reach.

Reach ID	Restoration Alternative
PC02	Channel reshaping, bank protection, invasive removal
PC03	Channel reshaping, bank protection
PC05	Stabilize right bank, create point bars, woody debris features
PC06	Move bars to decrease width
PC07	Move mid-channel bars and stabilize
PC08	Bank protection, invasive removal
PC09	Barrier improvement (rock ramp)
PC10	Bank protection, invasive removal, plantings, bar shaping
PC12	Cross vanes, channel redesign, invasive removal, plantings
PC13	Invasive removal, plantings, minor bar reshaping
PC14	Add woody debris
PC15	Reshape bars, bank protection
PC16	Channel reshaping, bank protection, plantings
PC17	Bar reshaping, bank protection
PC18	Improve left bank/bar
PC19	Bank protection, channel reshaping
PC20	Bank protection, invasive removal
PC20A	Bank protection
PCU02	Left bank wetland area, bank protection (minimal)
TC01	Invasive removal, trash removal (local)
TC02	Right bank wetland, channel reshaping, invasive removal, plantings, recreation access
TC03	Left bank flood buyout, riparian wetland creation
TC05	Barrier improvement (rock ramp) at sewer, left bank wetland, channel reshaping
TC07	Bank protection, connect to floodplain, possible wetland detention, dechannelization
TC09	Barrier improvement at Baker Rd
TC10	Dechannelize and create natural channel
TC11	Right bank layback, plantings
GP01	Bank protection, plantings
GP02	Daylighting with plantings
GP03	Bank protection
GPT01	Fish barrier improvement
GPT02	Bank protection, invasive removal, plantings

Hydrologic modification is a common source of geomorphic and ecological degradation in urban waters (Bledsoe et al. 2012). Flow attenuation via riparian zones, rain gardens, inline detention, and offline detention provides a suite of actions to manage “peaky” urban hydrographs. In addition, to reach scale alternatives, the team examined aerial photographs of the watershed to identify potential detention locations. During field investigation, these sites were further assessed based on site conditions (e.g., nearby homes, feasibility, etc.). From these methods, 24 sites were identified as having potential for flow detention with meaningful downstream effects on hydrologic conditions and subsequent

ecological outcomes. Each site was then assessed relative to the detention basin properties (e.g., area, storage volume, excavation requirements, etc.) and the watershed hydrology (e.g., degree of urbanization, watershed area). This screening identified nine infeasible sites, and the remaining 15 sites were carried forward into the array of alternatives (Table 9). Each detention site was then assigned to the closest downstream reach for application in PCEM.

Table 9. Flow attenuation opportunities.

Reach ID	Detention Description	Volume Stored (ft ³)
PC10	Offline detention (D22) on right bank	262,400
PC20	Offline detention (D15) on right bank	110,539
PC20A	Offline detention (D7) on right bank	226,148
PC21	Offline in Valley of the Hawks (D10), Inline at Mosquito Hole (D11), Offline in English Ave (D16)	245,938
PCU03	Inline detention (D17) upstream of I-20	179,682
TC02	Hollywood Rd right bank wetland (D19)	33,868
TC03	Left bank flood buyout and wetland at Spring Rd (D20)	73,012
TC06	Tributary detention pond (D4) on Ridge Ave.	106,734
TC08	Tributary detention pond (D3) upstream of Hollowell Boulevard	113,373
TC11	Tributary detention pond (D1) upstream of cemetery	124,967
PCT02	Two inline ponds (D8+D21)	276,039
PCT01	Inline detention (D12) upstream of Perry Rd	94,399

5.3 Relative cost estimation

Site screening requires not only an estimate of the benefits of restoration, but also the costs. For instance, a site providing 1,000 linear feet of stream restoration may not be competitive for \$500k, but may be worthwhile for \$100k. Detailed cost estimation for the 38 proposed restoration reaches was infeasible given the rapid screening timeline, so a cost estimation technique was developed to provide relative cost differences between alternatives. These costs should not be construed as exact or comprehensive, and the remainder of this report will refer to these screening level estimates as “relative costs” rather than “cost (\$K).” The following key assumptions apply to all of these estimates:

- Estimates omit site preparation activities (e.g., access roads, land clearing) and economies of scale.
- Estimates omit real estate differences.
- Estimates assume recreational and educational costs are equivalent at each site and thus do not provide a relative measure of change to screen alternatives.
- Costs include subcontractor and prime contractor overhead and profit.
- Costs do not include any contingencies.
- All costs have been adjusted to account for location in Atlanta, Georgia.

Restoration alternatives often relied on similar recommended measures (e.g., bank protection), and costs were developed on a unit cost basis for uniform application across the watershed for bank protection, riparian planting, invasive species management, and channel shaping. The quantity of restoration within a given reach typically depends on the level of degradation. For instance, a severely degraded reach with high, failing banks would require more earth moving and planting than a segment with a couple of bank failure hot spots. As such, the instream and riparian assessment scores were used to estimate the quantity of restoration within each reach in feet, acres, or cubic yards as appropriate (Table 10). These quantities were then coupled with unit costs for each technique (Table 10) with the following assumptions:

- Bank protection and stabilization: initial and final bank slopes of $\frac{1}{2}$ H:1V and 3H:1V, riprap toe armoring, 50% off-site haul and 50% onsite haul, one rootwad every 100 linear feet, willow staking at three plants per square yard of bank slope, grass seeding and coir rolls.
- Riparian planting: adapted costs from other restoration projects.
- Invasive species management: manual herbicide application.
- Channel shaping: excavation and movement of 75 feet with a skid steer loader, mobilization and demobilization excluded.

Some sites did not conform to these unit cost rules and generalized estimates were made based on cost engineering judgment for the remainder of the restoration actions including detention sites, stream daylighting, dechannelization, and fish passage improvement (Table 11). The relative cost estimates including all proposed actions at each site are shown in Table 12.

Table 10. Summary of screening unit cost estimation methods.

Type of Cost	Quantity of Restoration	Unit Cost (\$)
Bank protection and stabilization	$L_e = L_{total} \%_{eroded}$ Where L_e is length to be protected, L_{total} is reach length, and $\%_{eroded}$ is the portion of the reach eroded. $\%_{eroded} = \begin{cases} V_{bstab} \leq 5 & -0.08 * V_{bstab} + 1 \\ 5 < V_{bstab} \leq 10 & -0.06 * V_{bstab} + 0.9 \\ 10 < V_{bstab} \leq 15 & -0.05 * V_{bstab} + 0.8 \\ 15 < V_{bstab} & -0.01 * V_{bstab} + 0.2 \end{cases}$	$C_L = L_e (0.556h^2 + 10.423h + 66.5)$ Where h is the approximate bank height and C_L is the relative cost (\$/ft).
Riparian planting	$P_{total} = \frac{V_{veg,FWP} - V_{veg,FWOP}}{20} A_{rip}$ Where P_{total} is total area of riparian planting (ac), FWP denotes restored condition, $FWOP$ denotes unrestored condition, and A_{rip} is riparian buffer area (ac). Right and left banks considered separately.	$C_P = 10,150 P_{total}$ Where C_P is the relative cost (\$/ac).
Invasive species removal	$I_{total} = \%_{inv} A_{rip}$ Where I_{total} is the total area of invasive species management (ac) and A_{rip} is the total area of riparian buffer (ac). Right and left banks considered separately. $\%_{inv} = \begin{cases} V_{inv} \leq 6 & -0.0567 * V_{inv} + 1.000 \\ V_{inv} > 6 & -0.0471 * V_{inv} + 0.943 \end{cases}$	$C_I = 560 I_{total}$ Where C_I is the relative cost (\$/ac).
Channel shaping	$V_{shaping} = \begin{cases} V_{ins} \leq 5 & 1 * \frac{2}{3} L_{total} * W \\ 5 < V_{ins} \leq 10 & 0.75 * \frac{1}{2} L_{total} * W \\ 10 < V_{ins} \leq 15 & 0.5 * \frac{1}{4} L_{total} * W \\ 15 < V_{ins} & 0 * L_{total} * W \end{cases}$ Where $V_{shaping}$ is the total volume of earth movement for channel shaping, V_{ins} is the instream substrate score, W is approximate channel width, and (1, 0.75, 0.5, and 0) are depth of sediment being moved.	$C_V = 2.77 V_{shaping}$ Where C_V is the relative cost (\$/yd ³).

Table 11. Summary of site-specific screening cost estimates.

Type of Cost	Applicable Sites	Description of Relative Cost Estimate
Detention Sites	PC10, PC20, PC21, PCU03, TC02, TC03, TC06, TC08, TC11, PCT01, PCT02	Proposed flow attenuation sites were analyzed in GIS to estimate excavation volumes, storage volumes, and pool areas. Relative cost assumed grading and compaction to 1/3 of excavation volume, seed and mulch for the pond footprint, installation of a 72 inch riser pipe, and cost is proportional to the excavation volume, number of riser units, pond footprint, and minor riprap protection.
Daylighting	GP02	The Grove Park stream daylighting effort assumes a two 10 ft X 5 ft existing culverts, 18 inches of existing fill above the culvert, final bank slope of 3H:1V, off-site haul of all spoils, no drainage structures will be affected, and no change to nearby infrastructure at Hollowell Road.
Dechannelization	TC10	Concrete-lined channel will be replaced by natural bottom channel. Assumes 9 inch thick concrete lining, off-site haul of spoils, and no impact to existing infrastructure (pedestrian bridge).
Rock Ramps	PC09, TC05, TC09, GPT01	Fish passage improvement by adding a rock ramp at each barrier. The volume of rock fill to overcome the barrier is computed as a rock wedge based on the height of the barrier, a 10:1 ramp slope, and the width of the stream at the barrier. The cost is then computed as $C = 10.3w_{stream}$, where w_{stream} is the width of the creek in feet. Assumes that a rock ramp is appropriate for all sites. Relative cost is proportional to the fill volume rather than placement.

Table 12. Restoration relative cost estimate by reach.

Reach	Restoration Alternative	Relative Cost
PC02	Channel reshaping, bank protection, invasive removal	170.8
PC03	Channel reshaping, bank protection	226.7
PC05	Stabilize right bank, create point bars, woody debris features	143.9
PC06	Move bars to decrease width	0.8
PC07	Move mid-channel bars and stabilize	1.7
PC08	Bank protection, invasive removal	221.8
PC09	Barrier improvement (rock ramp)	0.4
PC10	Bank protection, invasive removal, plantings, bar shaping, Offline detention (D22) on right bank	819.2
PC12	Cross vanes, channel redesign, invasive removal, plantings	307.2
PC13	Invasive removal, plantings, minor bar reshaping	8.9
PC14	Add woody debris	0.9
PC15	Reshape bars, bank protection	699.8
PC16	Channel reshaping, bank protection, plantings	111.8
PC17	Bar reshaping, bank protection	277.9
PC18	Improve left bank/bar	25.2
PC19	Bank protection, channel reshaping	255.8
PC20	Bank protection, invasive removal, Offline detention (D15) on right bank	94.5
PC20A	Bank protection, invasive removal	155.3
PC21	Bank protection, plantings, invasive removal, minor bar reshaping, Offline detention (D7) on right bank, Offline in Valley of the Hawks (D10), Inline at Mosquito Hole (D11), Offline in English Ave (D16)	1609.5
PCU02	Left bank wetland area, bank protection (minimal)	58.3
PCU03	Inline detention (D17) upstream of I-20	38.4
TC01	Invasive removal, trash removal (local)	12.8
TC02	Channel reshaping, invasive removal, plantings, recreation access, right bank wetland (D19)	234.9
TC03	Left bank flood buyout, riparian wetland creation Left bank flood buyout and wetland at Spring Rd (D20)	78.2
TC05	Barrier improvement (rock ramp), left bank wetland, channel reshaping	67.3
TC06	Tributary detention pond (D4) on Ridge Ave.	17.6
TC07	Bank protection, connect floodplain, wetland detention, dechannelization	140.4
TC08	Tributary detention pond (D3) upstream of Hollowell Blvd	204.8
TC09	Barrier improvement at Baker Rd	0.2
TC10	Dechannelize and create natural channel	206.5
TC11	Right bank shaping, plantings, Tributary detention pond (D1)	374.9
GP01	Bank protection, plantings	48.4
GP02	Daylighting with plantings	151.2
GP03	Bank protection	101.6
GPT01	Fish barrier improvement	0.1
GPT02	Bank protection, invasive removal, plantings	36.3
PCT02	Two inline ponds (D8+D21)	424.7
PCT01	Inline detention (D12) upstream of Perry Rd	22.4

5.4 Plan formulation and site screening

For a watershed scale project, site-specific alternatives may be combined into different plans. Ideally, the solution space would be 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 (or relative) costs of restoration (Robinson et al. 1995). Table 13 provides an example of this comprehensive search with three hypothetical sites.

Table 13. Example of plan formulation via combinations of restoration actions.

Plan	Site-A (Planting)	Site-B (Barrier Removal)	Site-C (Pond)	Number of Actions	Cost (\$K)	Benefits (IEI*length)
1				0	0	0
2	X			1	10	1000
3		X		1	10	2000
4			X	1	10	2000
5	X	X		2	20	2000
6	X		X	2	20	2000
7		X	X	2	20	3000
8	X	X	X	3	30	3000

However, exhaustive search of the solution space for Proctor Creek was numerically prohibitive with 38 proposed restoration sites (i.e., 38 sites provides 2^{38} possible plans or ~275 billion possible combinations). As such, plan formulation for Proctor Creek proceeded based on two phases. All combinations of zero to four alternatives were analyzed (i.e., 82,993 plans). Benefits and costs were computed for all plans with zero to four alternatives, and sites were screened based on this preliminary cost-effectiveness. Two criteria were applied in screening sites. First, if a site appeared in any of the cost-effective plans it was maintained. Second, a cost-effectiveness plot was developed highlighting each site, which provided a means of adding nearly cost-effective sites to the analysis. Figure 8 shows these basic steps in graphical format, (a) preliminary cost-effectiveness plot for all plans, (b) example of a site screened in from visual inspection, and (c) example of a site left out following visual inspection. Based on this screening, 19 sites were preserved for additional analysis (Table 14).

Figure 8. Preliminary cost-effectiveness analysis conducted to screen sites: (a) all computed plans, (b) example of visual site screening resulting in addition of Reach PC20A, and (c) example of visual site screening which left out Reach TC10. “Cost ineffective” is used here to characterize plans that are obviously not cost effective and can be screened out.

Table 14. Summary of sites maintained for development of additional plan combinations.

Reach	In cost effective plans	Visual Inspection	Maintained?
PC06	Y	Y	Y
PC07	Y	Y	Y
PC09	Y	Y	Y
PC13		Y	Y
PC14	Y	Y	Y
PC15	Y	Y	Y
PC20A		Y	Y
PC21	Y	Y	Y
PCU03	Y	Y	Y
TC01	Y	Y	Y
TC02		Y	Y
TC05	Y	Y	Y
TC06	Y	Y	Y
TC07		Y	Y
GP01		Y	Y
GP02	Y	Y	Y
GPT01	Y	Y	Y
GPT02	Y	Y	Y
PCT01	Y	Y	Y

5.5 Preliminary CE-ICA

Benefits and costs were computed for all combinations of 0–19 alternatives (i.e., 524,288 plans). The surveyed portion of 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 4.05 miles of quality-weighted habitat (21,369 feet). As a scale for potential habitat gain, the maximum obtainable habitat if all 38 proposed USACE actions were executed is 5.94 miles of quality-weighted habitat (31,384 feet).

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, 184 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) (Figures 9 and 10). These plans were then manually subjected to incremental cost analysis following existing methods (Robinson et al. 1995). Based on these analyses, 19 “best” plans were identified (Table 15).

These analyses represent a preliminary screening of restoration sites for the Proctor Creek ecosystem restoration study.* Based on these analyses, 19 watershed-scale restoration plans (Table 15), composed of 19 potential restoration sites are recommended for future analyses. These analyses indicate that actions at these sites could be highly effective relative to all potential actions considered in the watershed. For instance, relative to a plan with all 38 actions (31,384 feet, \$7,350k), 77% of the total lift above the future, without project, can be obtained with merely 44% of the total relative cost at these 19 sites. Future project planning should further screen sites based on logistical factors such as: acceptability to the City of Atlanta (the cost-share sponsor), real estate costs and willingness of land owners, acceptability to local organizations (e.g., the Proctor Creek Stewardship Council), and other ongoing work by agencies in the Urban Waters Federal Partnership and other interested parties (e.g., green space development initiatives).

* These are not USACE recommendations, additional details may be found in the feasibility report.

Figure 9. Screening level cost-effectiveness analysis.

Figure 10. Screening level cost-effectiveness analysis (higher-resolution view).

Table 15. Cost-effective and incrementally best plans.

Plan Number	Habitat (ft)	Habitat Lift (ft)	Relative Cost	Inc Cost / Unit	Number of Sites	PC06	PC07	PC09	PC13	PC14	PC15	PC20A	PC21	PCU03	TC01	TC02	TC05	TC06	TC07	GP01	GP02	GPT01	GPT02	PCT01
1	21,369	0	0	na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	21,605	237	0	0.00	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	21,669	300	1	0.01	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	21,708	340	2	0.02	3	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5,907	25,852	4,484	153	0.04	5	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0
16,855	25,895	4,527	155	0.04	6	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0
44,490	26,292	4,924	193	0.10	7	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0
96,300	26,742	5,374	261	0.15	8	1	1	1	0	1	0	0	0	1	0	0	1	0	0	0	1	1	0	0
174,459	26,854	5,486	278	0.16	9	1	1	1	0	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0
263,834	26,892	5,523	287	0.24	10	1	1	1	1	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0
357,129	26,942	5,574	300	0.25	11	1	1	1	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0
433,293	27,082	5,713	336	0.26	12	1	1	1	1	1	0	0	0	1	1	0	1	1	0	0	1	1	1	0
483,401	27,156	5,787	359	0.30	13	1	1	1	1	1	0	0	0	1	1	0	1	1	0	0	1	1	1	1
509,312	27,477	6,108	514	0.48	14	1	1	1	1	1	0	1	0	1	1	0	1	1	0	0	1	1	1	1
520,166	27,565	6,196	562	0.55	15	1	1	1	1	1	0	1	0	1	1	0	1	1	0	1	1	1	1	1
523,478	27,788	6,420	703	0.63	16	1	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	1	1	1
524,187	28,127	6,758	938	0.69	17	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
524,280	28,532	7,163	1,637	1.73	18	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
524,288	29,032	7,664	3,247	3.22	19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

6 Conclusions

Numerical models are needed to inform a variety of decision points within any urban stream restoration project. The model developed and presented here informed site selection at the basin scale for the Proctor Creek watershed restoration project. However, additional decisions will require other numerical tools after this preliminary screening, some of which may include the following: detailed analysis of the costs and benefits of restoration actions, forecasts of these benefits through time, and informing preliminary restoration designs. Because of this tiered set of needs, the PCEM is being developed in two-phases. This report has presented the first phase of model development (PCEM₁), which emphasized early project needs leading into the Alternatives Milestone of the SMART planning process. A second report and model is in development for the second phase (PCEM₂) to meet project needs related to the Tentatively Selected Plan Milestone of the SMART planning process. Table 16 provides a general comparison of these modeling phases and highlights key areas for improving predictions. Notably, this phased approach is proceeding with the same general model structure (e.g., quantity*quality, cumulative effects, four basic modules) with each algorithm improving accordingly.

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. 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.

Table 16. Phased modeling approach for the PCEM.

Model Element	Phase 1 (PCEM1)	Phase 2 (PCEM2)
Primary Use	Informed site-selection and prioritization leading into the Alternatives Milestone	Inform Tentatively Selected Plan (TSP) recommendation and feasibility-level design
Environmental Benefits	Remotely sensed data Rapid, watershed survey Simple, desktop analyses	Remotely sensed data Field-based measurement at narrow set of sites More rigorous modeling approaches
Cost	Rapid, unit relative cost estimates	Site-specific cost analyses
Treatment of Time	Snapshot of futures with and without projects	Temporal trajectories based on restoration recovery rates
Treatment of Uncertainty	None	Rapid examination of expect, worst, and best case scenarios and stochastic simulation across a range of model inputs
Actions by Others	Neglected	Examined as a model scenario for the future without project condition
Quantity	Length of stream from NHD	Same data
Quality Sub-Model: Instream Condition	Field-based, visual surveys of multiple observers	Field-based measurements such as those used in Bledsoe et al. (2012), Rosgen (2001), Pfankuch (1975), and Pruitt (2001)
Quality Sub-Model: Riparian Condition	Field-based, visual surveys of multiple observers	Field-based measurements such as those used in Atkinson et al. (2010)
Quality Sub-Model: Hydrology	Ad hoc unit hydrograph model based on Gotvald and Knaak (2011) and Inman (2000). Addresses peak flows only.	Spatially explicit watershed model based on land use and rainfall data (e.g., HEC-HMS). Potential to address multiple aspects of the flow regime (Poff et al. 1997, Baker et al. 2004, McKay 2015).
Quality Sub-Model: Connectivity	Network-scale model of cumulative passability from the Chattahoochee based on qualitative passability	Same network model with improved barrier passability estimates based on Anderson et al. (2012) and Collins 2016.

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Appendix A: Proctor Creek Reach Delineation*

* 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.

Table A1. Reach delineation points for Proctor Creek.

Reach ID	Description	Downstream Boundary		Upstream Boundary	
		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	Bar nr Pet Cemetery to Hollywood Rd	33.794477	-84.474308	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
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

Reach ID	Description	Downstream Boundary		Upstream Boundary	
		Latitude	Longitude	Latitude	Longitude
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	Hollywood Rd to Hollywood Rd	33.793213	-84.469267	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
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

Reach ID	Description	Downstream Boundary		Upstream Boundary	
		Latitude	Longitude	Latitude	Longitude
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 qualitative techniques exist for measuring the ecological, geomorphic, and hydrologic functions of stream corridors and riparian zones. Nine rapidly applicable data collection protocols provided the basis for the Proctor Creek visual assessments (Table B1). Twelve primary variables were synthesized as the focal point for field data collection along with ancillary variables and other key field notes. Data collection forms (Figures B1 and B2) provided narrative descriptions of each variable. All variables were scored on a 0 to 20 scale mirroring the Environmental Protection Agency's (EPA) Rapid Bioassessment Protocol (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 B3–B13 provide visual examples of scores given in the Proctor Creek watershed for each variable used in PCEM1.

Prior to rapid data collection in sub-teams, the entire field team conducted three reach assessments together (PCo1, PCo2, PCo3) to ensure appropriate training in protocols, consistent use of terminology, and normative use of the qualitative scales. All data were collected during a single week by consistent teams for the main channel and tributary environments (Tables B2 and B3). Team division sought to have a range of backgrounds with expertise including a biology / ecology, water resource / design engineering, and USACE project planning (Table B4).

Table B1. 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 Protocol (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 Channel Stability Index (CSI) is a set of qualitative and quantitative methods for assessing geomorphic condition and sediment erosion potential, which were developed for mountain environments but have subsequently been applied nationwide.	Pfankuch (1975)
The Bank Erosion Hazard Index (BEHI) is a semi-quantitative scale for assessing the potential sediment contribution of eroding streambanks.	Rosgen (2001)

Figure B1. Field data collection form (front).

USACE Proctor Creek Reach Assessment						
Date			Latitude / Longitude			
Assessor			Direction Walked			
Team			Weather / Flow			
Reach Identification & Description _____ Reference site (Yes or No)? Describe Why. _____ Restoration Alternative & Description _____ Specific Conductance ($\mu\text{S}/\text{cm}$): _____ Other WQ Data _____						
Instream Condition						
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
Odor	None	Slight	Moderate	Severe / strong		
Trash & Litter	None	Small amount	Very common	Abundant		
Algae on Bed	None	In spots	Abundant	Everywhere		
Velocity & Depth Regime (slow v. fast, shallow v. deep)	Mostly riffles and pools (few runs); 4 of 4 velocity / depth regimes present	Equal distribution of riffles, pools, & runs; 3 of 4 velocity / depth regimes present	Occasional riffle, more than 25% runs; 2 of 4 velocity / depth regimes present	All runs with one depth-velocity pattern; 1 of 4 velocity / depth regimes present		
Instream Substrate, Deposition, & Embeddedness	Mixture of substrates; Firm sand deposits; Little or no enlargement of islands or bars; Coarse particles (gravel, cobble, and boulder) <10% surrounded by fine sediment	Mixture of sand & gravel with silt at margins; Minor increases in bar formation; Coarse particles 10-25% surrounded by fine sediment	Primarily sands & silts; Moderate increase in bar formation; Coarse particles 25-100% surrounded by fine sediment	Shifting fine sands, silts, & clays; Mostly runs; Large increase in bar development; No large particles to be embedded		
Channel Alteration	Channelization, piping, or river training absent	Minor evidence of channel alteration (often at bridges)	Significant channel alteration and bank armoring in 25-75% of reach	Over 75% altered, armored, piped, or channelized		
Channel Stability	Naturally stable; Evidence of incision or bank failure absent or minimal; Limited potential for future problems	Managed / stabilized; Evidence of incision or bank failure absent or minimal; Some potential for future problems	Moderately unstable; Some entrenchment (evident or possible); Long-term stability questionable; Impending bank instability	Unstable; Entrenched; Active headcuts or bank failures		
Bank Stability	Banks stable; Evidence of erosion or bank failure absent or minimal; Little potential for future problems; <5% of bank affected	Moderately stable; Infrequent, small areas of erosion; 5-30% of bank in reach with visible erosion	Moderately unstable; 30-60% of bank in reach with visible erosion; High erosion potential during floods	Unstable; Many eroded areas; "Raw" areas frequent; Obvious bank sloughing; 60-100% of bank contains erosional scars		
Habitat & Available Cover	Greater than 50% of bank habitat includes a mix of snags, submerged logs, undercut banks, and other stable habitat	5 to 50% of bank habitat includes stable habitat types, but not all types are present	Less than 5% usable habitat with substrates frequently disturbed or removed	Lack of habitat is obvious with unstable or no substrate		
Large Wood	Wood serves a significant structural role; Ample sources of future input	Wood is present, but not abundant; Source inputs remain	Patchy distribution; Future input source is uncertain	Wood not present; No future inputs available		

Form version 1/29/2016

Figure B2. Field data collection form (back).

Riparian Condition																								
Canopy cover based on densiometer																								
From a mid-channel location count the OPEN cells and divide by 24 (5 measurements)																								
Parameter	Excellent / Good					Marginal / Fair					Poor					Current Rating		Future w/Project						
	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Left	Right	Left
Bank Vegetative Diversity and Condition	More than 70% of the streambank surfaces covered by native vegetation, including trees, understory shrubs, and herbs; Vegetative disruption minimal or not evident					40-70% of the streambank surfaces covered by vegetation; At least two classes of vegetation present; Disruption obvious.					Less than 40% of the streambank surfaces covered by vegetation; Only one class of vegetation (if any)													
Invasive Species	Few invasive species present					Mix of native and invasive species					Largely or exclusively invasive species													
Canopy Complexity	Multiple age classes and vertical tiers of trees represented					Young age classes only with few trees >5m tall					Little vegetation, grass, or only vines													
Floodplain Connectivity	Evidence of recent events accessing floodplain					Perched floodplains likely experiencing overbank events during large storms					Little (if any) events capable of accessing floodplain													

Ecological Corridors

Barrier Type (culvert, dam, sewer, etc.): _____

Latitude / Longitude of Barrier (location of reach break): _____

Barrier Description: _____

Parameter	Optimal 1.0	Suboptimal 0.9	Marginal 0.5	Poor 0.0	Current Rating	Future w/Project
Barrier Passability	No passage barrier; Perched drop < 0.5 ft or at grade; Passable at all discharge	Occasionally impassable at low flows; Perched drop 0.5-1 feet	Rarely passable; Only passable when "drowned" or flanked; Perched 1-2 feet	Significant barrier under all flow conditions; Perched drop of > 2 feet		

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)?

Notes

Valley type, channel evolution model (stage I-V), valley type, Rosgen Stream type, pictures, waypoints, key features, restoration sketches, reach maps, overt constraints (cemetery, sewer), etc.

Form version 1/29/2016

Figure B3. Examples of instream condition variable for velocity and depth regime: (top left) optimal condition at PC20, (top right) sub-optimal condition at PC13, (bottom left) marginal condition at PCU03, (bottom right) poor condition at TC10.

Figure B4. Examples of instream condition variable for substrate, deposition, and embeddedness: (top left) optimal condition at TC04, (top right) sub-optimal condition at PC13, (Bottom left) marginal condition at TC07, (bottom right) poor condition at PC12.

Figure B5. Examples of instream condition variable for channel alteration: (top left) optimal condition at PC09, (top right) sub-optimal condition at GPT01, (bottom left) marginal condition at PC05, (bottom right) poor condition at PCU01.

Figure B6. Examples of instream condition variable for channel stability: (top left) optimal condition at TC06, (top right) sub-optimal condition at PC04, (bottom left) marginal condition at TC05, (bottom right) poor condition at PC12.

Figure B7. Examples of instream condition variable for bank stability: (top left) optimal condition at PC20, (top right) sub-optimal condition at PC11, (bottom left) marginal condition at TC05, (bottom right) poor condition at PC15.

Figure B8. Examples of instream condition variable for large wood: (top left) optimal condition at TC06, (top right) sub-optimal condition at PC08, (bottom left) marginal condition at PC13, (bottom right) poor condition at TC10.

Figure B9. Examples of riparian condition variable for bank vegetative diversity and condition: (top left) excellent / good condition at TC09, (top right) marginal / fair condition at GPT01, (bottom center) poor condition at PC20A.

Figure B10. Examples of riparian condition variable for invasive species: (top left) excellent / good condition at TC04, (top right) marginal / fair condition at PCT02, (bottom center) poor condition at PC10.

Figure B11. Examples of riparian condition variable for canopy complexity: (top left) excellent / good condition at TC06, (top right) marginal / fair condition at TC02, (bottom center) poor condition at PCU01.

Figure B12. Examples of riparian condition variable for floodplain connectivity: (top left) excellent / good condition at PCU02, (top right) marginal / fair condition at PC07, (bottom center) poor condition at TC04.

Figure B13. Examples of instream condition variable for barrier passability: (top left) optimal condition culvert at Hollywood Road in TC01, (top right) sub-optimal condition sewer crossing in PC09, (bottom left) marginal condition sewer crossing in TC05, (bottom right) poor condition culvert at Hollowell Pkwy in TC07.

Table B2. Summary of 2016 Proctor Creek field data collection. Proctor Creek mainstem.

Reach ID	Date	Team
PC01	2/1/2016	BAP, BAZ, JM, NUH, CB, SKM
PC02	2/1/2016	BAP, BAZ, JM, NUH, CB, SKM
PC03	2/1/2016	BAP, BAZ, JM, NUH, CB, SKM
PC04	2/1/2016	BAP, BAZ, JM
PC05	2/1/2016	BAP, BAZ, JM
PC06	2/1/2016	BAP, BAZ, JM
PC07	2/1/2016	BAP, BAZ, JM
PC08	2/2/2016	BAP, BAZ, JM
PC09	2/2/2016	BAP, BAZ, JM
PC10	2/2/2016	BAP, BAZ, JM
PC11	2/2/2016	BAP, BAZ, JM
PC12	2/2/2016	BAP, BAZ, JM
PC13	2/2/2016	BAP, BAZ, JM
PC14	2/2/2016	BAP, BAZ, JM
PC15	2/2/2016	BAP, BAZ, JM
PC16	2/4/2016	BAP, BAZ, JM, NT
PC17	2/4/2016	BAP, BAZ, JM, NT
PC18	2/4/2016	BAP, BAZ, JM, NT
PC19	2/4/2016	BAP, BAZ, JM, NT
PC20	2/4/2016	BAP, BAZ, JM, NT
PC20A	2/4/2016	BAP, BAZ, JM, NT
PC21	2/4/2016	BAP, BAZ, JM, NT
PCU01	2/4/2016	NUH, CB, KC, SKM
PCU02	2/4/2016	NUH, CB, KC, SKM
PCU03	2/4/2016	NUH, CB, KC, SKM

Table B3. Summary of 2016 Proctor Creek field data collection. Tributary streams.

Reach ID	Date	Team
TC01	2/1/2016	NUH, CB, SKM
TC02	2/1/2016	NUH, CB, SKM
TC03	2/1/2016	NUH, CB, SKM
TC04	2/1/2016	NUH, CB, SKM
TC05	2/2/2016	NUH, CB, SKM
TC06	2/2/2016	NUH, CB, SKM
TC07	2/2/2016	NUH, CB, SKM
TC08	2/2/2016	NUH, CB, SKM
TC09	2/2/2016	NUH, CB, SKM
TC10	2/2/2016	NUH, CB, SKM
TC11	2/2/2016	NUH, CB, SKM
GP01	2/3/2016	NUH, CB, SKM, KC
GP02	2/3/2016	NUH, CB, SKM, KC
GP03	2/3/2016	NUH, CB, SKM, KC
GP04	2/4/2016	NUH, CB, SKM, KC
GPT01	2/3/2016	NUH, CB, SKM, KC
GPT02	2/4/2016	NUH, CB, SKM, KC
GPT03	2/4/2016	NUH, CB, SKM, KC
GPT04	2/4/2016	NUH, CB, SKM, KC
PCT02	2/5/2016	CB, BAZ
PCT01	2/5/2016	CB, BAZ

Table B4. Field observers making qualitative assessments used in model.

Name (Initials)	Affiliation	Disciplinary Background
Hughes, Cheryl (CB)	USACE Mobile District	Geospatial specialist
Capps, Krista (KC)	University of Georgia	Stream ecologist (Ph.D.)
Hallberg, Niklas (NUH)	USACE Mobile District	Water resources engineer (P.E.)
McDonald, Justin (JM)	USACE Mobile District	Water resources engineer (P.E.)
McKay, Kyle (SKM)	USACE Environmental Laboratory	Water resources engineer (P.E.), Stream ecologist (Ph.D.)
Pruitt, Bruce (BAP)	USACE Environmental Laboratory	Stream and wetland ecologist (Ph.D.), Hydrologist (P.H.)
Tomczyk, Nate (NT)	University of Georgia	Stream ecologist
Zettle, Brian (BAZ)	USACE Mobile District	Biologist, Planner

Appendix C: Preliminary Statistical Analysis

This appendix presents a statistical analysis of the data collected during the February 2016 intensive field survey which characterized 15 environmental factors across 46 unique stream segments within the Proctor Creek watershed.

Initially, the complete dataset collected during the February intensive field survey was subjected to Principal Components Analysis (PCA). PCA is a mathematic procedure that converts a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. Consequently, variables that are more closely correlated group together. The objective of conducting this analysis was to determine which variables were and were not correlated. Based on the first PCA treatment, barrier passage, odor, algae and litter were not correlated to the other eleven parameters (Figures B1 and B2). However, flood connectivity, large woody debris, and channel alteration were fairly correlated and somewhat correlated to canopy complexity. This is noteworthy, in that these parameters are associated with the riparian zone. With the exception of canopy complexity, the remaining eight in-channel variables were generally moderate to highly correlated.

In addition to the aforementioned observations, note that substrate is highly correlated with velocity and depth regime and channel stability which is moderately correlated with velocity (Figure B2). Consequently, if channel stability is improved, it can be assumed that substrate and depth diversity will improve as well. Also noteworthy, cover (available habitat) is enhanced by improvements in velocity, substrate, channel alteration and stability, and bank stability.

A scatter plot showing the relationship between Axis 1 and Axis 2 for various environmental variables. The plot includes two clusters: a large blue circle containing Substrate, BankStab, ChanStab, Velocity, Cover, Invsp, BankVeg, and CanComplex; and a smaller red circle containing FloodCon, LWD, and ChanAlt. Other variables like BarPass, Odor, Litter, and Algae are plotted outside these clusters.

Variable	Axis 1 (approx.)	Axis 2 (approx.)
BarPass	0.12	0.30
Odor	0.13	-0.13
Litter	0.20	-0.18
Algae	0.14	-0.58
FloodCon	0.24	-0.27
LWD	0.26	-0.27
ChanAlt	0.28	-0.30
Substrate	0.28	0.32
BankStab	0.29	0.25
ChanStab	0.30	0.27
Velocity	0.28	0.18
Cover	0.32	0.08
Invsp	0.28	0.08
BankVeg	0.32	-0.02
CanComplex	0.29	-0.12

[illegible]

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14. ABSTRACT In partnership with the City of Atlanta and thirteen federal agencies, the Mobile District (SAM) of the U.S. Army Corps of Engineers (USACE) 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 phase one of model development (PCEM1), a rapidly applicable site-screening tool for informing preliminary project decisions. PCEM1 contains four modules related to instream condition, riparian condition, hydrologic change, and watershed connectivity, these are combined into an overarching assessment of stream ecosystem integrity at the watershed-scale. The model was applied to the Proctor Creek watershed to screen 46 potential sites to 17 sites, these were continued forward at the alternatives milestone of the planning process. While developed in the context of Proctor Creek, PCEM1 provides a simple screening level model for comparing site-specific alternatives at a watershed scale, this could be adapted to other stream restoration sites or watershed studies. While developed for rapid application, the PCEM toolkit also represents a state-of-the-science approach for conducting watershed assessment and is deeply grounded in peer-reviewed approaches to stream restoration prioritization.						
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