

An Approach for Developing Regional Environmental Benefits Models

by S. Kyle McKay¹ and Bruce A. Pruitt²

OVERVIEW: Ecosystem restoration projects in a given region often have similar drivers, stressors, state conditions, and ecosystem services. Moreover, objectives and accompanying metrics may be similar enough to encourage regional model development. Regional approaches to environmental benefits analysis offer opportunities to streamline project evaluation by developing consistent understanding, metrics, and models. This technical note proposes a framework for developing regionally applicable environmental benefits models. The proposed framework is demonstrated for streams in the Appalachian Piedmont. This approach could serve as a basis for developing consistent restoration outputs that can be combined and compared at regional scales.

INTRODUCTION: Owing to the complexity and variability of natural systems, accounting for the benefits of ecosystem restoration, management, and mitigation efforts with scientifically based, repeatable, and transparent techniques can be challenging (Fischenich et al. in preparation). To overcome these obstacles, models of environmental effects have been developed in regions with similar hydrologic, geomorphic, and ecological processes (e.g., ecoregions or physiographic provinces). Some commonly applied regional models of environmental benefit and impact include indices of biotic integrity (Karr 1991, Smogor and Angermeier 2001, Georgia Department of Natural Resources ((GA-DNR) 2005), wetland assessments with hydrogeomorphic methods (Brinson 1993, Smith et al. 1995, Brinson and Rheinhardt 1996), and regional environmental flow standards (Poff et al. 2010, Snelder et al. 2011). Herein, these regional approaches are augmented with standard methods for conceptual and numerical model development. The result of this combined approach is a framework for developing regionally applicable models of environmental benefits. Although regional models have been developed for varying purposes (e.g., impact assessment, mitigation requirements), the focus of this technical note is on the regional approach as it pertains to the evaluation of proposed ecosystem restoration projects. The regional modeling approach outlined here may help USACE planners develop scientifically based models of environmental benefits and construct model documentation capable of addressing rigorous quality assurance standards typically highlighted during various internal and external peer review processes.

WHY DEVELOP A REGIONAL MODEL? Prior to examining the framework for regional model development, it is constructive to review strengths and weaknesses of regional models. The primary advantages of developing a regional model include:

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- *Consistency*: A regional model can transform regional scientific knowledge into a common framework for management decisions that minimizes intra-regional inconsistency in evaluation and assessment methods. In cases where natural resource managers can agree on how to assess ecosystems, regional models (or suites of models) can serve as standard tools for identifying and communicating probable impacts of management decisions. Consistent reporting of benefits at the project level can facilitate communication with decision makers and can aid attempts to aggregate benefits at the programmatic level (e.g., a comparison of projects is facilitated by similar outputs). A regional model can also provide a means of comparing and contrasting the benefits, costs, and return on investment during intra- and inter-study comparisons of plans being considered or recommended for further action.
- *Efficiency*: Development of a regional model can provide a source of efficiency if developed to be applied to a broad array of restoration activities in the area. Agreement upon a common ecosystem vision, a set of regional objectives, and associated metrics can lead to more robust models for forecasting of those metrics. Broadly applicable models are more likely to be adopted and improved by other agencies or entities. Regional model development could also contribute literature, data, and other information that might be worthy of documenting in a common database. Each of these factors yields information that can improve the efficiency of ecosystem evaluation activities, and thus improve the cost-effectiveness of regional restoration programs.
- *Collaboration*: Collaborators and partners in restoration projects may struggle to participate in project-by-project analyses due to budgetary and time constraints. However, developing a regional model can provide coordination, collaboration, and communication that spans multiple projects and gains buy-in from sponsors, resource agencies, partnering entities, and stakeholders.
- *Identification of Key Uncertainties*: The regional model development process provides an opportunity to identify key uncertainties in system structures, processes, and functions. As such, model development provides a foundation for identifying research needs and forming testable hypotheses in the region.

Regional modeling also has some limitations and potential pitfalls, including:

- *Over-extension of the model*: When a regional model exists, there may be a tendency to want to apply the model to all systems rather than just to those for which it was developed. Extension beyond the development or calibration range should proceed with caution.
- *Insufficient investment in model development*: Significant time, resources, and expertise are required to develop a scientifically robust model applicable to multiple projects across a broad geographic region. If the model is not adequately developed from the outset, a regional model could be a source of error applied to many projects.
- *Overlooking rare ecosystems*: Because regional models can be inherently general in treatment of ecosystems (i.e., from “lumping”), ecosystems of special concern or uniqueness can often be overlooked and their importance inadequately addressed.

- *Inadequate documentation or user training*: As is the case with all models, “usefulness of ecological [models] results as much from the process as from the product” (Grant and Swannack 2008). Effectively communicating the model development process, algorithms, and assumptions to those not involved becomes critical for *successful* regional adoption. If the model is not appropriately documented or users are not appropriately trained, inappropriate application of the tool beyond its limitations, assumptions, and ranges of applicability becomes possible (and likely).
- *Insufficient investment in model application*: Significant time, resources, and expertise are sometimes required to develop information necessary to correctly apply a model. In some instances, the costs of gathering or collecting information necessary to properly apply (or adapt) a regional model may exceed available resources.
- *Signal-to-Noise*: Natural variability within a region is common, and determining appropriate regional boundaries and scales of analysis to account for variability is critical. For instance, if a model were developed for *all* eastern U.S. streams, the model might be insensitive for distinguishing between two restoration alternatives at a particular site. Thus, the model is inappropriately scoped and the signal-to-noise ratio is too high for this application. However, if the intent of the model were to conduct a synoptic assessment of the collective condition of stream habitat in the eastern U.S., then uncertainty might be acceptably low to distinguish the relative condition of two streams.

A FRAMEWORK FOR DEVELOPING REGIONAL MODELS: Models supporting environmental decision making range in complexity and breadth from the very simple (e.g., a conceptual model depicting channel-floodplain interaction during floods) to very complex (e.g., a nitrogen dynamics model coupled to a three-dimensional hydrodynamic model quantifying rates of nitrogen exchange across the channel-floodplain interface). Swannack et al. (in preparation) provide a more comprehensive treatment of ecological modeling than can be addressed in this technical note. We propose a series of steps and guiding questions critical to regional model development (Table 1). These steps draw heavily from existing literature on development and application of conceptual and ecological models found in Fischenich (2008), Grant and Swannack (2008), Casper et al. (2010), Schmolke et al. (2010), Swannack et al. (in preparation), and USACE (2011). **However, this framework focuses on the unique aspects associated with developing models for regional application.** The framework follows four phases of model development proposed by Grant and Swannack (2008): (1) conceptualization, (2) quantification, (3) evaluation, and (4) application. The application phase will not be addressed in this document except to note that a well-developed model can easily be misapplied if users do not have access to requisite input data, are not appropriately trained, do not adhere to model limitations and assumptions, or do a poor job of applying the model (i.e., a model is only as good as its user).

This framework guides users through the process of regional model development. To begin, there are a few universal concepts that are applicable throughout the framework:

Iteration: Although the four phases of model development have been presented as sequential activities, modeling is a highly iterative process (Grant and Swannack 2008). Iteration can happen not only between phases, but also within a single phase. For instance, while in the conceptual phase, a team may not realize a model component (e.g.,

Table 1. A framework for developing regional environmental benefits models (modified from common model development procedures).	
Development Phases	Guiding Questions for Regional Models
<i>Conceptualization</i>	
State the model objectives	What is the purpose of the model? What system attributes must the model simulate? How will it be used? Who is the user? What do you seek to accomplish (e.g., assessment, forecasting, restoration, mitigation)? What level of fidelity is sought? What level of precision and accuracy are necessary to inform decisions?
Bound the system of interest	What is the target region? What criteria are used to define the region (e.g., EPA ecoregions, physiographic provinces, community composition, etc.)? What is the regional extent and resolution (e.g., Ecoregion Level III or IV)? What social, economic, political, and jurisdictional boundaries are associated with the system? What ecosystem types (i.e., classes) are included (and excluded)? What are the spatial and temporal limits of the model?
Identify and categorize components of the system to be modeled	What are the pertinent ecological resources, environmental benefits, and/or ecosystem goods and services provided by ecosystems in the region? What drivers, stressors, and threats are acting on the ecosystem? Are there critical state conditions or classes connecting drivers/stressors to benefits/services?
Identify the relationships between the components of the modeled system	What physical, chemical, biological, or social processes link drivers/stressors, state conditions, and benefits/services? Which are the most relevant? Which are the most and least certain? Which literature or data support your observations?
Develop representation(s) of the conceptual model	What is the purpose of the conceptual model (i.e., communication, qualitative understanding, numerical model development)? What audiences will use the conceptual model (e.g., scientists, modelers, agencies, decision makers, public)? What conceptual model type most effectively communicates with these audiences (e.g., box-arrow, narrative, pictorial)?
Describe model behavior	Do the conceptualized components and relationships logically interact to reflect conditions that have been observed and/or might be encountered in the future (e.g., Do marsh types shift with sea level rise?)?
Document the range of applicability for model use	What are the model limitations with respect to geographic range, spatial and temporal scales, included processes, and scientific understanding? What assumptions were made in the development of the model and how do they affect interpretation of results? What key ecosystem processes were omitted? What knowledge do users need to understand and apply the model properly?
<i>Quantification</i>	
Choose modeling approach	What levels of complexity are appropriate for the applications under consideration? What type of model is most likely to satisfy the model objectives and represent the conceptual model (e.g., analytical, index, simulation, statistical, spatial)? Is there an existing model meeting these needs? What types of outputs are expected from the model? What data are available to calibrate, evaluate, or otherwise drive the model? What resources (e.g., time, funds, hardware, software) are intended users likely to have at their disposal? Who will operate and maintain the model?
Select the general quantitative structure for the model	Does the model need to simulate multiple types of processes/interactions (e.g., hydrologic, hydraulic, ecological)? Will multiple models need to be "linked"? Which data are passed between models? Are data of appropriate resolution? Will multiple models be used for the same process (i.e., different models representing different hypotheses about system function)? Does the proposed

	structure adequately represent the conceptual model or were additional assumptions and/or simplifications made? What analytical tools, computer languages, or software will be applied?
Identify the functional forms of model equations	For each process in the model, what analytical equations or formulae will be applied? What literature or data support these equations? For what circumstances are the equations valid? Are data available?
Develop protocols for estimating model inputs	What are the model inputs? Where can users derive input values? Are there standard procedures (e.g., data sources, field / statistical methods)?
Evaluation	
Review the technical quality	What are the technical quality, system quality, and usability of the model? Is model theory consistent with contemporary literature / knowledge? Does the model repeatedly produce outputs as expected based on its formulation? Are there errors in model formulas, coding, or computations? Is sufficient documentation available for users to become informed about and properly use the model?
Test the model	What data will be used to calibrate and verify the model? Does the model produce results that reasonably reflect the components of the system it was designed to characterize or otherwise emulate? Does the model behave and respond quantitatively as you would expect?
Validate	How does the model perform relative to observed data sets not used in calibration? Do model parameters or structure need to be adjusted based on validation results?
Assess model sensitivity and identify uncertainties	To which input parameters are outputs most sensitive based on systematic testing? What uncertainties are associated with the model? What is the cumulative error associated with application of multiple models in sequence?

a stressor) is missing until they begin depicting the model schematically or describing the qualitative response of the model (e.g., If imperviousness increases, do peak flows increase?). Alternatively, a model component could be maintained through conceptualization and removed during quantification due to a lack of available data. Significant set-backs and obstacles can be avoided by understanding the modeling framework and looking ahead to upcoming steps. Iteration may come in the form of short cycles as describe above, or long cycles such as evaluations of model applications and associated model updates after years of application to many projects.

- *Inclusion*: Given the complexity of socio-ecological systems, no single person, discipline, or entity is likely to develop an adequate regional model. Including others in the conceptualization, quantification, evaluation, and application of a model is vital for ensuring adequate scientific basis, technical quality, and buy-in of the user community (Schmolke et al. 2010). “Socializing” the model proceeds by including progressively larger groups and iteratively improving the tool. These groups should include the USACE project delivery team, colleagues familiar with the system, subject matter experts, cost-share sponsors, partnering agencies, local stakeholders, and others.
- *Peer-Review*: Although the end of each phase provides a logical point for critical peer input and review, peer review is an activity that can occur formally (e.g. independent external peer review) or informally (e.g., a “sanity check” by officemates) during any phase of development. In general, the development team is encouraged to develop, refine,

collaborate, and iterate throughout the modeling process. From this viewpoint, the iterative portion of the model development process can occur in a day, a week, or a month and should draw from informal comments and/or formal peer-review, as situationally appropriate.

- *Documentation*: Adequate and accurate model documentation is crucial to model success. Without good documentation (e.g., rationale for key components, model limitations), developers may forget critical assumptions, reviewers may not understand the model and its assumptions, users not involved in model development could misapply the tool, or a variety of other problems could arise (Schmolke et al. 2010, USACE 2011).

PIEDMONT STREAM CASE STUDY: Because of rapid land use change, high demand on freshwater ecosystem services, and a growing appreciation for the value of functioning ecosystems, a multi-million dollar stream restoration industry has developed within the Appalachian Piedmont. To this end, a regional model of Piedmont streams is currently being developed to inform stream restoration, water management, land use development, and other water resources decision making in the region. This tool seeks to build from an existing regional model (NGWRA 2007) and could be considered a second iteration of the entire modeling process. This discussion will only highlight the conceptual phase of regional model development. Additional information regarding the leap from conceptual to numerical models may be found in Grant and Swannack (2008) and Swannack et al. (in preparation). Table 2 presents the regional modeling framework and how each step in the conceptualization phase is being addressed through this process (See also McKay et al. 2011).

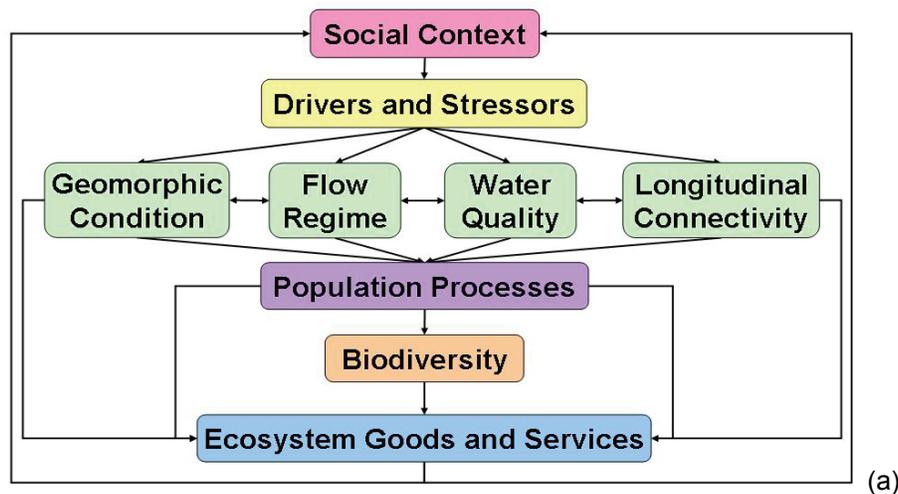
The regional conceptual model is being developed iteratively with different groups of subject matter experts. The first iteration was conducted by two team members with backgrounds in water resources engineering and ecology and knowledge of local stream restoration practice. Following a preliminary iteration through the steps in Table 2, a small team of eight subject matter experts representing a variety of disciplines (stream and riparian ecology, hydrology, biogeochemistry, geomorphology, engineering, and project planning) and agencies (EPA, USGS, four universities, USACE Mobile, and USACE-ERDC) was convened to discuss and improve upon the existing model. This preliminary version of the conceptual model underwent documentation and peer-review (Figure 1). Currently, the North Georgia Water Resources Agencies (NGWRA), an interagency working group supporting restoration projects in North Georgia, is providing input to the model.

The current conceptual model is flexible enough to be modified for a variety of ecosystem drivers and stressors. As is often the case with regional modeling, the balance between model flexibility and quantification is challenging. This first iteration of the modeling process merely sought to develop a conceptual model of “how Piedmont streams work.” Currently, this model is helping the USACE project delivery team communicate with interagency partners (i.e., the NGWRA) and refine an existing quantitative model. This conceptual model provides a transparent framework for telling the story of what will and will not be included in the quantitative model. Some components of this model will likely be removed as the process proceeds toward quantification (e.g., ecosystem services associated with air quality may be deemed outside of a particular agency’s mission area). Additionally, a quantitative model may

Table 2. Developing an approach to environmental benefits models in Appalachian Piedmont streams.	
Development Steps	Relevant Information for Piedmont Streams
State the model objectives	Stream restoration has become a major source of economic investment throughout the region. A comprehensive framework accounting for the monetary and non-monetary benefits of these efforts has not been developed. The objective is to develop a model for assessing the benefits of stream restoration projects in the Southern Piedmont.
Bound the system of interest	The Piedmont ecoregion (Level III Ecoregion, CEC 1997) extends from central Alabama northeast almost to the Virginia-Maryland border and is bound by the Appalachian Mountains and Blue Ridge to the northwest and the Atlantic Coastal Plain to the southeast. The southern Piedmont is the current focus, especially that of Georgia. This model focuses on stream corridor health including riparian areas, but will not address wetland environments. The model primarily addresses wadeable streams, but future versions may be expanded to include larger rivers.
Identify and categorize components of the system to be modeled	Using a basic driver-stressor model framework, the workshop team compiled a list of model components (Figure 1) starting with ecosystem services, then drivers and stressors, then “functional state conditions” linking the drivers and services. The team differentiated between drivers/stressors (e.g., urban land use / non-point runoff) and the social context leading to them (e.g., economic growth). Although drivers and stressors can influence streams in numerous ways, ecosystem condition within the Piedmont can be summarized by a relatively small number of “functional states” characterized by geomorphic condition, flow regime, water quality, and longitudinal connectivity. Ecosystem goods and services provide a logical means for measuring and trading-off benefits of a particular management action (e.g., stream restoration). Although the list of services may appear generic, the workshop team specifically omitted services not provided by Piedmont streams (e.g., waterborne transportation, pollination).
Identify the relationships among the components of the modeled system	Literature and data resources were identified to support each model component and the connections between them (e.g., effects of urban land use on flow regime and resulting effects on recreational fishing).
Develop representation(s) of the conceptual model	Multiple representations of the model were developed for different audiences. The simplest form of the model (Figure 1a) is a box-arrow diagram for communicating with broad audiences who may not be familiar with detailed system function. A more complex diagram is being developed for communication with scientists and modelers. This more complex diagram explicitly records the processes relating model components (e.g., reduced velocity induces sediment settling which induces channel aggradation).
Describe model behavior	The effect of each driver on each state condition and each state condition on each ecosystem service was assessed to ensure appropriate qualitative responses.
Document the range of applicability for model use	At this stage, the model was maintained in a very flexible format; however, future versions of the model are expected to eliminate some model components and more limitations may be imposed (see text below). At this juncture, physical, chemical, and biological processes linking drivers, states, and services are not fully explained.

require greater resolution in other parts of the model (e.g., physical processes leading to “flashy” urban hydrographs and resulting changes in channel form). This case study merely presents the conceptualization phase of regional model development. However, the product (i.e., the model) is being used as a basis for initiating numerical model development.

PROGRAMMATIC APPLICATIONS: In addition to benefits at the project level, regional models can also reconcile obstacles at the programmatic scale. Application of a consistent tool across a region allows for side-by-side comparison of the benefits of two different projects both before and after implementation. A simplified version of a regional model could be developed for project prioritization, whereas a more complex version could be applied for benefit reporting. The metric categories might be the same (e.g., riparian health), while the metrics may be different (e.g.,



Drivers				
Urban land use	Land use type / intensity	Riparian zone condition	Temporary land uses	
	Channel alteration/piping	Bank treatment	Impoundments	
Agriculture land use	Wastewater discharge	Septic discharge	Industrial discharge	
	Power generation	Non-point runoff	Road crossings	
Resource extraction	Crop	Animal	Silviculture	
Ecosystem engineers	Mines	Sand and gravel	Timber	
Infrastructure	Beavers	Invasive species		
Climate change	Dams	Withdrawals	Transportation	
	Temperature	Precipitation		

State	Channel Form	Flow regime	Water quality	Connectivity
Services	Existence value			
	Heritage value			
	Cultural value	Aesthetics	Spiritual value	Historical value
		Educational	Ecotourism	Social cohesion
Recreation	Boating	Fishing	Hunting	
	Wildlife observation	Water contact		
Flow regime	Flood attenuation	Flood conveyance	Hydropower	
	Municipal withdrawal	Industrial withdrawal	Agricultural withdrawal	
	Reduced treatment cost	Waste assimilation		
Resource extraction	Mineral and ore	Sand and gravel	Timber	
Air quality	Micro-climate regulation	Carbon sequestration		
Public health	Disease regulation	Vector control		

Figure 1. (a) Generalized Piedmont stream conceptual model. (b) Examples of some of the Piedmont stream conceptual model components (McKay et al. 2011).

a simple scoring system for prioritization and forest modeling of stand properties to report benefits). Although benefit reporting would utilize similar metrics, cumulative or synergistic effects of numerous projects may not be captured by the models unless they are specifically designed to measure environmental benefit at multiple spatial scales (e.g., reach and watershed, Leibowitz et al. 1992). Moreover, a regional conceptual model could help standardize the science used throughout the region even if the quantitative models differed. For instance, if a regional conceptual model could clearly state the drivers and services the Corps is acting upon (e.g., USACE may address flood attenuation and existence value), other agencies may decide to act upon complementary drivers or services (e.g., EPA may address drinking water quality).

Herein, the discussion has focused on multiple applications of a project level model across a region or program. Some environmental benefits and ecosystem services may not be realized at the project level, but can only occur at regional levels through the cumulative effects of multiple actions. An alternative approach might focus on the development of regional models to capture synergistic or cumulative effects of multiple smaller projects. Although the application of the model is quite different, the proposed model development framework may still be applied.

SUMMARY: This technical note presents a framework for developing regional models for quantifying environmental benefits. This framework could be applied quickly to rapidly develop a simple set of project prioritization metrics for a particular ecosystem service, or it could be applied over the course of years to develop complex conceptual and numerical models to assess many ecosystem services. This deliberate and iterative framework is adaptable to the complexity and needs of the application at hand. If properly developed, regional models can provide a source of consistency and efficiency for project planning, but the model development team would do well to develop, refine, collaborate, and iterate.

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REFERENCES

- Brinson, M. M. 1993. *A hydrogeomorphic classification for wetlands*. WRP-DE-4. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station.
- Brinson, M. M., and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. *Ecological Applications* 6 (1): 69-76.
- Casper, A. F., R. A. Efroymson, S. M. Davis, G. Steyer, and B. Zettle. 2010. *Improving conceptual model development: Avoiding underperformance due to project uncertainties*. EBA Technical Notes Collection. ERDC TN-EMRRP-EBA-5. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Commission for Environmental Cooperation (CEC). 1997. Ecological Regions of North America. www.epa.gov/wed/pages/ecoregions/na_eco.htm (accessed June 2010).
- Fischenich, J. C. 2008. *The application of conceptual models to ecosystem restoration*. EBA Technical Notes Collection. ERDC TN-EBA-TN-08-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Fischenich, J. C., S. K. McKay, S. J. Miller, D. Price, B. A. Pruitt, L. L. Skaggs, B. C. Suedel, and D. J. Tazik. *A framework for science-based environmental benefits assessment*. EBA Technical Notes Collection. In preparation. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Georgia Department of Natural Resources (GA-DNR). 2005. Part II: Scoring criteria for the index of biotic integrity and the index of well-being to monitor fish communities in wadeable streams in the Piedmont ecoregion of Georgia. GA-DNR, Wildlife Resource Division, Fisheries Management Section.
- Grant, W. E., and T. M. Swannack 2008. *Ecological modeling: A common-sense approach to theory and practice*. Malden, MA: Blackwell Publishing.
- Headquarters, U.S. Army Corps of Engineers (USACE). 2011. *Assuring quality of planning models*. Engineer Circular-1105-2-412. Washington, DC: Headquarters, U.S. Army Corps of Engineers.
- Karr, J. R. 1991. Biological integrity: A long-neglected aspect of water resources management. *Ecological Applications* 1 (1): 66-84.
- Leibowitz, S. G., B. Appruzzese, P. R. Adamus, L. E. Hughes, and J. T. Irish. 1992. *A synoptic approach to cumulative impacts assessment: A proposed methodology*. EPA/600/R-92/167. Eds. S.G. McCannell and A.R. Hairston. Corvallis, OR: U.S. Environmental Protection Agency.
- McKay, S. K., B. A. Pruitt., C. J. Anderson, J. Curran, A. del Orca Archoa, M. C. Freeman, B. Rashliegh, and E. Trawick. 2011. Constructing a conceptual model linking drivers and ecosystem services in Piedmont streams. *2011 Georgia Water Resources Conference, Athens, Georgia*.

- North Georgia Water Resources Agencies (NGWRA). 2007. *Ecosystem response model for use in north Georgia watersheds in the Metro-Atlanta area*. U.S. Army Corps of Engineers, Mobile District.
- Poff, N. L., B. D. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, M. Acreman, C. Apse, B. Bledsoe, M. C. Freeman, J. Henriksen, R. B. Jacobson, J. G. Kennen, D. M. Merritt, J. H. O’Keeffe, J. D. Olden, K. Rogers, R. E. Tharme, and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology* 55: 147-170.
- Schmolke A., P. Thorbek, D. L. DeAngelis, and V. Grimm. 2010. Ecological models supporting environmental decision making: A strategy for the future. *Trends in Ecology and Evolution*. 25: 479-486.
- Smogor, R. A., and P. L. Angermeier. 2001. Determining a regional framework for assessing biotic integrity of Virginia streams. *Transactions of the American Fisheries Society* 130: 18-35.
- Snelder, T., D. Booker, and N. Lamouroux. 2011. A method to assess and define environmental flow rules for large jurisdictional regions. *Journal of the American Water Resources Association* 47 (4): 828-840.
- Smith, R. D., A. Ammann, C. Bartoldus, and M. M. Brinson. 1995. *An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices*. WRP-DE-9. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station..
- Swannack, T. M., D. J. Tazik, J. C. Fischenich, et al. Modeling for environmental benefits analysis. EBA Technical Notes Collection. In preparation. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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