Autumn view of the Roaring Fork river in the western slope area of Colorado. © Bill Grindle/TNC

A PRACTICAL GUIDE TO ENVIRONMENTAL FLOWS FOR POLICY AND PLANNING

WITH NINE CASE STUDIES IN THE UNITED STATES

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with selected case studies by Mark P. Smith and Alisa Richardson

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Acknowledgments

This compilation would have been impossible without the forward thinking and hard work of many dedicated individuals. LeRoy Poff, Angela Arthington, Brian Richter, Bob Naiman, Stuart Bunn, Mike Acreman, Brian Bledsoe, Mary Freeman, Ken Rogers, Julian Olden, Rebecca Tharme, Dave Merritt, Jay O'Keefe, Rob Jacobson, Jim Henriksen, Jonathan Kennen, and Andy Warner knew that environmental flow protection had to be accelerated, and had the vision to scale up what previously had been a river-by-river endeavor to a practical framework for nationwide protection. Many of them, along with Michele DePhilip, John Sanderson, Sally Palmer, Judy Dunscomb, John Stark, Kim Lutz, Julie Zimmerman, Thomas Wilding, Nicole Rowan, Dave Armstrong, Stacey Archfield, Rodney Knight, Stephanie Flack, Claire Buchanan, Heidi Moltz, Paul Seelbach, Troy Zorn, Rob Burgholzer, Carlton Haywood, Tara Moberg, Dave Hamilton, Josh Knight, Mark P. Smith, David Sutherland, Chris Konrad, Rick Palmer, Austin Polebitski, John Hickey, Chris Hatfield, Rich Bowman, Todd Richards, and more brave, trusting souls accepted their challenge and led the first applications of this framework on the ground. We want to thank them not only for having the courage, resourcefulness, diplomacy, and tenacity to see these ambitious projects through, but also for sharing with us the lessons they learned along the way. Most of all, we applaud their pivotal roles in protecting and restoring environmental flows at a geographic scale never before imaginable.

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Foreword

Freshwater scientists around the world acknowledge a crisis in biodiversity loss and diminished ecosystem function in streams, rivers, wetlands and lakes. One main culprit in this decline is human-caused change in the historical magnitude, frequency and timing of river flows that have supported key ecological processes and native species in diverse aquatic systems.

The Ecological Limits of Hydrologic Alteration (ELOHA) framework arose as a response to the recognition that the rate of global hydrologic change was outpacing science's ability to develop environmental flow guidelines one site at a time. A new scientific framework was needed, one to guide the development of environmental flow guidelines at a regional scale.

Regional environmental flow management is extremely challenging. Not only are data needs great for underlying hydro-ecological models, but translation of science into policy and management necessarily occurs in a complex societal context constrained by governance structures, regulatory authorities and competing political interests.

A comprehensive and scientifically sound framework was required, yet it had to be flexible enough to accommodate the inevitable "experiments" that will result from its application to real-world settings.

This guidebook presents nine case studies in regional environmental flow management in the United States. The successes described in these case studies clearly illustrate that innovative thinking and creative experimentation within the structured ELOHA framework have significantly advanced the development of flow standards at regional scale. The accomplishments are the fruit of the dedicated efforts of innumerable agency, academic and non-government scientists, engineers, water managers, and policy makers, all of whom were willing to think outside the box and take up the challenge of pushing the frontiers of sustainable environmental management of streams and rivers. Their stories are impressive and inspiring!

A key contribution of this guidebook is that it distills an excellent synthesis across the case studies and offers valuable insight into transferable lessons learned from individual studies. Importantly, numerous tips and extended discourse are offered on how to adapt the flexible ELOHA framework to streamline and strengthen the scientific process. While a more robust social framework may still be needed to effectively translate science into policy and regulations, the information presented in this guidebook serves as an indispensible resource for all those engaged in protection and management of freshwater ecosystems. The authors of the guidebook are to be commended for their outstanding product, and more generally for their dedication to the cause of science-based freshwater conservation.

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Executive Summary

Environmental flows are gaining broad recognition across the United States, and the underlying science is sufficiently developed to support regional planning and policy applications. This report explores how six states and three interstate river basins are effectively developing and applying regionalized environmental flow criteria to water resource planning, water withdrawal permitting, and multi-dam re-operation. The broad range of approaches they relate clearly demonstrates the feasibility of integrating science-based environmental flow needs into regional water management in the absence of site-specific assessments.

The case studies embrace the following principles:

- Regionalized environmental flow criteria apply to all the water bodies across a state or large river basin for which site-specific criteria have not yet been established.
- Flow criteria link explicitly to the health of the entire aquatic and riparian ecosystem, and are not limited to specific species.
- Flow regimes mimic natural inter- and intra-annual flow variability.
- The development of environmental flow criteria and the policies for their implementation are closely linked. Defining a clear path to policy implementation from the onset ensures that the ensuing science answers the right management questions.
- Flow criteria are developed through a transparent, inclusive social process informed by sound science. A structured social process for identifying, understanding, and negotiating tradeoffs is critical.

To varying degrees, the Ecological Limits of Hydrologic Alteration (ELOHA) framework influenced each of the case studies. ELOHA is a flexible framework for determining and implementing environmental flows at the regional scale using existing hydrologic and biological information. Major components of ELOHA include a hydrologic foundation of streamflow data, classification of natural river types, flow-ecology relationships associated with each river type, and river condition goals.

A **hydrologic foundation** of streamflow data informs water managers where, when, and how much water occurs in all water bodies across the region. These data are used to assess flow characteristics, classify river types, quantify flow alteration, relate ecological responses to flow alteration, and evaluate the status of sites relative to environmental flow standards. They should be estimated for every stream segment or sub-basin where environmental flows will be managed. Without this information, limits on flow alteration are very difficult to permit, measure, or enforce without expensive site-specific data collection.

Although a database of daily streamflow under naturalized and current conditions remains an ideal, the lack of these data need not hinder the determination of environmental flow needs. In practice, few places have such a dataset in place at the onset, and building it usually requires considerable time and thought. Many water managers have successfully advanced other parts of the ELOHA framework while the hydrologic foundation is being developed, rather than awaiting its completion before proceeding with successive steps.

The basic components of a hydrologic foundation of daily or monthly streamflow data are hydrologic simulation and water use accounting. Hydrologic simulation is used to estimate streamflow conditions, while water use accounting estimates the impact of water use on streamflow conditions. Two general approaches to hydrologic simulation are regression modeling and process modeling.

Regardless of the modeling approach, the hydrologic foundation can only be as accurate as the water-use (withdrawal and return flow) data that go into it. Accurate, spatially explicit water use reporting and improved water use estimation methods and decision support systems are greatly needed.

The treatment of interactions between groundwater and surface water depends on the type of hydrologic model used and on the hydrogeology. The approaches reported in our case studies range from assuming direct and immediate impacts of groundwater pumping on streamflow to using linked groundwater and surface-water models to calculate the time, place, and amount of depletion.

River Type classification can strengthen the statistical significance of flow-ecology relationships based on rivers that have been studied, and extends those relationships to other rivers that have not been studied. However, recent practice demonstrates that natural river type classification is not always needed for setting scientifically defensible environmental flow standards.

Where it has been used, river type classification tends to be iterative and based on pre-existing classifications. Using an existing classification system helps build trust among scientists who are familiar with it and accelerates the overall process. By treating natural river type classification and flow-ecology analyses as iterative processes, each one strengthens the explanatory power of the other. Parameters used to classify river types include hydrology, water temperature, ecoregion, and watershed and macrohabitat characteristics. Incorporating watershed and macrohabitat variables from the onset is useful for assigning river types to ungaged sites.

Flow-ecology relationships generalize the tradeoffs between flow alteration and ecological condition for different types of rivers. Successful projects follow a progression from hypothesis development to data assembly and analysis to build these relationships.

Several case studies used statistical analyses to isolate the influence of flow alteration from that of other environmental stressors, and then to identify the flow and ecological metrics that best describe ecological response to flow alteration. However, although strictly exploratory data analysis may result in robust statistical relationships, if the metrics used do not resonate with biologists and water managers, then the results may be ineffective in supporting environmental flow policy.

Even where large biological databases exist, rarely will quantitative flow-ecology analyses represent all flow-dependent taxonomic groups and ecological processes. A holistic approach requires a combination of quantitative and qualitative relationships to represent the ecosystems and natural flow regimes across a state or basin. Structured ecological literature review, historical streamflow analysis, and facilitated expert workshops can build scientific consensus around qualitative relationships of sufficient rigor to quantify flow criteria.

Condition goals, also known as desired future condition, underlie all environmental standards. Within any large region, people value different rivers for different purposes. They may strive to keep certain rivers nearly pristine, while accepting that other, more developed rivers simply maintain a basic level of ecological function. Stakeholder negotiations that focus on applying different standards to rivers with different ecological condition goals generally lead to successful implementation.

The environmental flow standard is the degree of allowable flow alteration associated with each condition goal, according to the flow-ecology relationships. An ecological risk-based framework associates ecological goals with allowable flow alteration, and accounts for scientific uncertainty by associating appropriate policy actions with different levels of ecological risk. Decision support systems greatly facilitate the integration of environmental flow standards into state water allocation programs and regional water resource planning.

Although ELOHA provides a useful framework to guide the development of environmental flow criteria, there is no one-size-fits-all approach. Regardless of the rigor of the scientific analyses, expert judgment calls are required to adapt the process and to interpret results. Facilitated expert workshops and advisory panels improve the outcomes and their credibility to the public. The level of sophistication needed depends ultimately on what policy makers want and stakeholders will accept. Early outreach to stakeholders, the definition of shared guiding principles, the formation of advisory committees, attention to political and economic drivers, and process transparency are all likely to pay dividends in environmental flows implementation.

1.0 Introduction

1.1 Background

After decades of complacency, water managers not only in the arid West, but increasingly in the humid eastern United States, face chronic water shortages. Irrigation is on the rise. Growing urban and suburban populations need secure water supplies. Demands for domestic energy herald hydropower intensification. Climate change, deteriorating infrastructure, and shortsighted land developments increase flood risk. At the same time, there is a rising expectation that water resource development should not degrade freshwater ecosystems (Acreman 2001, Postel and Richter 2003).

Globally, flow alteration is among the most serious threats to freshwater ecosystems. Natural, seasonal patterns of rising and falling water levels shape aquatic and riparian habitats, provide cues for migration and spawning, distribute seeds and foster their growth, and enable rivers, lakes, wetlands, and estuaries to function properly (Bunn and Arthington 2002, Poff et al. 1997). Altering the natural flow pattern—by damming, diverting or channeling water—takes a serious toll on the plants, animals, and people that depend on it. But how much change is too much? When does “change” become “degradation” or “unacceptable adverse impact”? These are the questions that have spawned the interdisciplinary fields of environmental flow science and management.

Environmental flows describe the timing and amount of water to be retained in lakes, rivers, streams, and estuaries to sustain seasonal patterns of high and low water levels needed for natural functions, processes and resilience to persist. While all natural flow provides some environmental benefit, the need to allocate a portion of this water to meet society’s needs for water supply, crop production, energy generation, and flood management requires careful evaluation and integration of competing uses.

For decades, environmental flow quantification has been conducted at the scale of individual river reaches, with a range of potential methodologies used to evaluate flow requirements. Holistic methodologies that account for all flow-dependent ecosystem needs are well-established (Tharme 2003), but can take years to complete for just one river reach. A more systematic approach applied at a watershed, region, or state-wide scale is required if freshwater ecosystem protection and recovery are to match the pace and extent of water resource development. Ultimately, this necessitates a scaling-up from site-by-site environmental flow provisions to the state, provincial, or national policy realm (Le Quesne et al. 2010). Only in this way will environmental flows become integral to all water management decisions from the onset, and not just as an inconvenient afterthought.

Regionalizing environmental flow management means making decisions that minimize ecological impacts of new water developments, direct water development to least-sensitive water bodies, and prioritize flow restoration efforts. These decisions hinge on a scientific understanding of how changes in the natural flow regime affect ecological conditions.

The Ecological Limits of Hydrologic Alteration framework (ELOHA; Poff et al. 2010) helps water managers meet this challenge. ELOHA is a flexible framework for determining and implementing environmental flows at the regional scale using existing hydrologic and biological information. ELOHA was developed specifically to meet the needs of managing environmental flows through state, provincial, basin, or national water policy: it addresses many rivers simultaneously; explicitly links flow and ecology; and applies across a spectrum of flow alteration, data availability, scientific capacity, and social and political contexts (Poff et al. 2010).

The ELOHA framework rests on the premise that although every river is unique, many exhibit similar ecological responses to flow alteration. Furthermore, within every river type, or group of ecologically similar rivers, there exist individual rivers under various degrees of hydrologic and resulting ecological alteration. If, for example, within a group of similar rivers, percent of water withdrawn in August is plotted against the ecological condition of the remaining fish populations, then a flow-fish ecology relationship can be quantified for that type of river. ELOHA assumes that this relationship holds for all rivers of that type.

The steps of ELOHA (Figure 1.1) may be carried out in a number of different ways, ranging from professional judgment to sophisticated statistical modelling, depending on the available data and technical capacity. Likewise, the sequence of steps is flexible. As later sections of this report will detail, hydrologic modeling is used to create a **hydrologic foundation** of streamflow data for every stream segment in the project region. **Stream classification** can be used to group the segments into ecologically similar natural **river types**. Hydro-ecological

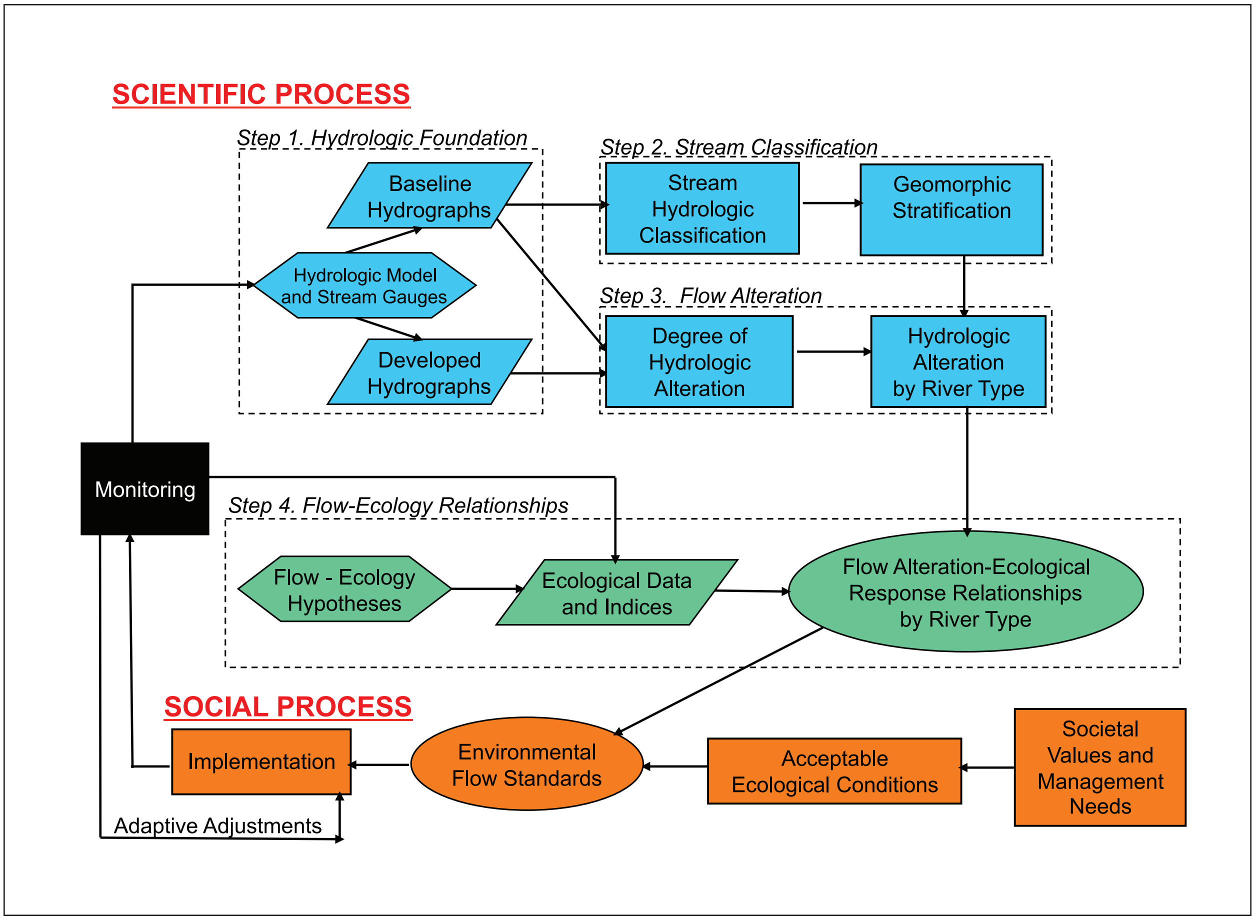

Figure 1.1. Steps of the ELOHA framework (Poff et al. 2010).

analyses and/or structured scientific workshops generate flow-ecology relationships (Figure 1.2) for different types of rivers. This scientific process is depicted by the blue and green boxes in Figure 1.1.

ELOHA's "social process" (orange boxes in Figure 1.1) is typically a policy-making effort driven by a new law, regulatory rulemaking, or policy guidance. Such a process is almost always led by a governmental authority and often closely involves stakeholders. The determination of "acceptable ecological conditions", or ecological condition goals, for river and stream segments has similarities to many state water quality programs that classify water bodies according to water quality attainment goals. This goal classification is distinct from the scientific classification of natural river types mentioned above.

Flow-ecology relationships link these socially-determined ecological condition goals to differing degrees of hydrologic alteration, enabling the establishment of streamflow standards or criteria to meet different goals. Thus, a river with a "good" ecological goal would be required to meet a higher standard (less hydrologic alteration) than the same type of river with a "fair" ecological goal. The terms "standards" and "criteria", as used in this document, mean limits on hydrologic alteration designed to achieve a set of management goals through a planning or regulatory structure.

1.2 Purpose

Several authors have proposed conceptual frameworks (Arthington et al. 2006, Poff et al. 2010, Richter et al. 2011) as outlined above for establishing environmental flow criteria for all waters across large jurisdictions, but stopped short of fully applying the concepts themselves. Instead, they challenged water managers to adapt the frameworks to their own states, provinces, countries, and transboundary river basins. River scientists and water managers from around the world have expressed interest in adopting these concepts, but most felt they needed more practical guidance and on-the-ground examples to proceed.

This report is intended to fill that gap. The title of this report notwithstanding, its main purpose is not to guide practitioners stepwise through a structured process, but rather to explain how others have adapted a general framework to different situations, and to provide references for obtaining more in-depth information. By recounting the experiences of nine states and river basins, this report demonstrates a broad range of approaches for establishing and implementing environmental flow criteria at the scale needed to support regional water resource planning, water withdrawal permitting, and multi-dam re-operation.

1.3 Structure and Scope of this Report

The main content of this report appears in the following two sections. Section 2 presents case studies that illustrate how six states and three interstate river basins are effectively developing and applying regionalized environmental flow criteria to water policy and planning. Because they are written with the intent of standing alone, each case study has its own, separate list of references and figure and table numbering. Section 3 walks through the fundamental steps of developing such a process. For each step, various options are presented, referring to examples from the case studies. Section 4 concludes with general guidelines, reflecting on lessons learned from the case studies.

Each case study first explains its legal context for environmental flow management, then outlines the project management structure, steps through the relevant scientific analyses conducted and tools developed, and culminates with an account of how the results are being or will be used for water management. While Poff et al. (2010) were moderately prescriptive about the scientific process supporting environmental flow management, they were rather vague about the social process. Several case studies begin to fill this gap by describing the sequence of negotiations and stakeholder input that translated the science into agreed-upon flow targets and institutional procedures for achieving them.

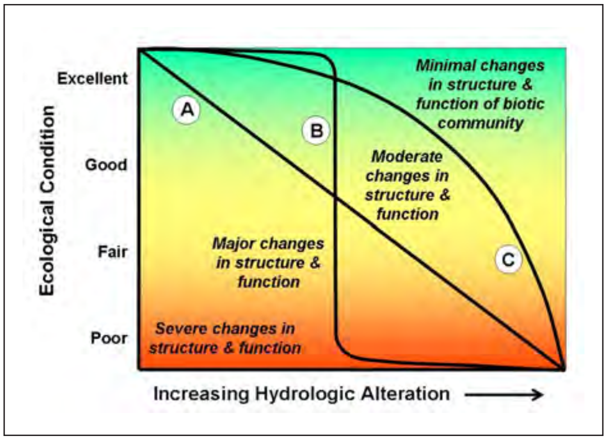

Figure 1.2 Conceptual flow-ecology curves showing possible forms of the relationship. A: linear, B: threshold, C: curvilinear. The graph represents one river type. After Davies and Jackson (2006).

2.0 Case Studies

The case studies described here span a broad range of regional-scale approaches to environmental flow management among completed or nearly completed projects. The intent of the case study descriptions is to convey the breadth of social and scientific processes undertaken, and to provide references for readers to pursue more detailed accounts of scientific methods and models.

We selected these case studies because to our knowledge they illustrate the most advanced integration of regionalized environmental flow science and policy in the United States. They represent diverse approaches applied over a range of geographic areas, from the 2,400-km^2 Fountain Creek pilot basin in Colorado to the entire 254,000-km^2 State of Michigan.

Of the case studies reported, however, only Michigan, Rhode Island and Connecticut have fully translated environmental flow criteria into statewide water management programs. Michigan began its process many years before the others. All of the case studies describe completed or nearly completed scientific assessments and some degree of implementation at the policy or planning level.

While reporting on partially completed projects is not ideal, the immediate need for practical guidance compels us to distribute this comprehensive report now. The broad range of approaches it relates clearly demonstrates the feasibility of integrating science-based environmental flow needs into regional water management in the absence of site-specific assessments. But the entire process from start to finish takes time, and this report provides ample guidance for new projects to launch while ongoing projects continue to lead the way to implementation.

Table 2.1 summarizes how each project built a hydrologic foundation, classified river types, related flow alteration to ecological response, and applied (or is applying) the science outcomes to water management policy. The ELOHA framework influenced all of these projects from the onset, except for Michigan, which evolved with the framework. Rhode Island and Connecticut adopted principles from ELOHA without systematically following the framework. Massachusetts; Colorado; Ohio; and the Susquehanna, Middle Potomac, and Connecticut River basin projects were designed explicitly around ELOHA.

Although other applications of the ELOHA framework are underway, the case studies profiled here were selected because of their successful positioning at the intersection between science and policy. In each case, scientists, stakeholders, and decision makers worked together to ensure that the scientific work supported a specific policy need. Consequently, these case studies trace selected environmental flow policy applications from their initiation to their implementation of environmental flow management across large geographic areas.

Most of our case studies describe the development of biologically-based flow criteria for managing water withdrawals. These applications take place in the eastern US, where a few state governments have set flow standards that reserve water for the environment; for example, by incorporating streamflow protection into new water withdrawal permit programs. In the eastern states where government lacks that authority, policy reform to grant it is feasible—if difficult—under the riparian doctrine of water management. In these states, water resources are relatively abundant and generally only over-allocated locally, but are increasingly pressured by population growth and climate change. Therefore, the focus of regional environmental flow management tends to be on streamflow protection, rather than on large-scale restoration, with notable exceptions (e.g., see Connecticut Basin case study).

Principles Guiding Selection of the Case Studies

- Development of environmental flow criteria and policies for their implementation are closely linked.
- Regionalized environmental flow criteria apply to all the water bodies across a state or large river basin for which site-specific criteria have not yet been established.
- Flow criteria link explicitly to the health of the entire aquatic and riparian ecosystem, and are not limited to specific species.
- Flow regimes mimic natural inter- and intra-annual flow variability.
- Flow criteria are developed through a transparent, inclusive social process informed by sound science.

Table 2.1. Comparison between major process components of five state and three interstate river basin case studies described in this report.

Case Study	Hydrologic Foundation	River Type Classification	Flow-Ecology Relationships	Application
Michigan (253,793 km^2)	Median August flow, based on multiple linear regression; streamflow depletion model (STRMDPL) estimates groundwater pumping delay	11 by water temperature, catchment area	Fish community-flow models based on large database of fish species occurrence	Online tool for screening proposed water withdrawals in relation to adverse impact standard
Ohio (116,096 km^2)	Mean September flow based on generalized least-squares regression	5 by Aquatic Life Use	Fish community-flow curves using quantile regression based on large fish and habitat databases	Future thresholds for permitting water withdrawals
Massachusetts (27,336 km^2)	Daily flow based on duration-curve regression model and water accounting (Sustainable Yield Estimator, SYE)	Not used to date	Fish community-flow alteration curves using quantile regression and generalized linear models based on large fish database	Environmental flow criteria for permitting new and existing water withdrawals
Colorado (3,700-km^2 and 2,400-km^2 pilot basins)	Daily water accounting (Colorado StateMod)	3 by ecoregion	Fish, invertebrates, vegetation, recreation response to various flow metrics using various approaches based on data found in literature	Risk-mapping tool for water use planning
Connecticut (14,357 km^2)	Daily flow based on duration-curve regression model and water accounting (SYE)	Not used	Flow needs of state river species by bioperiod per technical committee recommendation	Statewide reservoir release rules
Middle Potomac River interstate basin (11,500 km^2)	Daily flow based on process model (HSPF), channel morphology, flow routing, water accounting, and non-linear ground-water recession in a Watershed Online Object Oriented Meta-Model (WOOOMM)	Not used; flow and ecology metrics normalized to account for natural variability	Benthic invertebrate response to 18 flow metrics using quantile regression based on large invertebrates database	Interstate land and water use planning; potential to inform water withdrawal permitting in individual states
Susquehanna River interstate basin (71,000 km^2)	Daily flow from minimally-altered index gages; daily streamflow estimator tool based on duration-curve regression model and water accounting (SYE)	5 by water temperature, catchment area, hydrology	Nineteen hypotheses relating various taxa and ecological processes to flow components, based on literature review and expert workshops	Water withdrawal standards and dam operations regulated by Susquehanna River Basin Commission
Connecticut River interstate basin (19,288 km^2)	Daily flow based on duration-curve regression model and water accounting (SYE) and dam operations model	Not used	Conceptual models of full range of taxa and flow components, based on literature review and expert workshops	Collaborative decision support tool to integrate and optimize operations of >60 dams
Rhode Island (2,706 km^2)	Regression-based (for 7Q10)	Not used	Fish-flow relations from Georgia, supported by local data analyses	Wetland permitting and statewide planning

Western states, in contrast, manage water under the prior appropriation doctrine, and water users commonly have appropriated most of the natural streamflow during much of the year. In these states, it may be too late to reserve water for nature; instead, environmental flow policy initiatives focus on flow restoration by enabling and financing senior water right transfers from offstream to instream flows. These legal transactions require significant commitments of time and money. Regional environmental flow assessment helps prioritize these transactions.

Understanding environmental flow needs at a regional scale opens up opportunities for efficiency by identifying a suite of flow re-allocation, reservoir re-operation, and conjunctive management strategies, and helps target limited resources on acquiring the right amount of water at the right times of year in the right places to gain the most ecological benefit. The Colorado case study describes the development of a decision support tool that starts stakeholders down this path. The Connecticut River case study, though not Western, also produced a decision support tool for regional water management—in this case, it is the integration of dam operations throughout the basin to optimize both social and ecological outcomes.

2.1 Michigan's Water Withdrawal Assessment Process

The Michigan Water Withdrawal Assessment process demonstrates an effective science-policy process with user-friendly decision tools developed to support it. Michigan's process was established and fully implemented before Poff et al. (2010) published their paper, yet in many ways parallels the ELOHA framework. Hamilton and Seelbach (2011), Ruswick et al. (2010) and Steinman et al. (2011) provide detailed overviews of the entire scientific and policy development.

A series of interstate compacts and Michigan water management laws initially spawned the process. Annex 2001 to the Great Lakes Charter, ratified in 2008 in the Great Lakes Compact, stipulates that signatory states may cause no significant *adverse individual or cumulative impacts* on the quantity and quality of the Waters and Water-Dependent Natural Resources of the Great Lakes Basin. Signatory states further commit to:

- establish programs to manage and regulate new or increased withdrawals;
- implement effective mechanisms for decision making and dispute resolution;
- develop mechanisms by which individual and cumulative impacts of water withdrawals can be assessed; and
- improve the sources and applications of scientific information regarding Waters of the Great Lakes Basin and the impacts of withdrawals from various locations and water sources on the ecosystems.

Michigan's 2006 water law defined "Adverse Resource Impact" as one that functionally impairs the ability of a stream to support characteristic fish populations. Occupying the top of the food chain, these fish are seen as biological indicators of the overall health of Michigan's rivers and streams. The law also committed the state to create an integrated assessment model to determine the potential for any proposed water withdrawal to adversely impact the state's waters and water-dependent resources.

An Advisory Council composed of industry, advocacy, NGO, agency, and academic stakeholders was convened and given a 1-year timeline and strong bipartisan support to recommend a process to the Michigan legislature to carry out this mandate. The Council developed and operated under Guiding Principles (see box), to which its success is largely attributed. These Principles focused Council members on their common interests, regardless of their other differences. The process recommended by the Council (Michigan Groundwater Conservation Advisory Council 2007) ultimately was adopted into state law (2008 Public Act 189). The Michigan Department of Environmental Quality was the primary implementing agency.

The first technical step was to delineate stream segments for subsequent analysis and management of environmental flows. Michigan's 30,000 National Hydrography Database Plus (NHD+) river reaches were grouped into about 6,800 segments believed to have characteristic and relatively homogeneous hydrology, geomorphology, hydraulics, water quality, water temperature, and biological attributes with fish assemblages that are distinct from neighboring segments (Brenden et al. 2008). Reviews by field scientists further aggregated the number of stream segments to about 5,400 for subsequent analysis.

Michigan's hydrologic foundation is a database of the median daily flow for the month of lowest summer flow (typically August) for each stream segment. This can be thought of as the typical low flow during the relatively dry summer months. This "Index Flow" was chosen because it represents the most ecologically stressful period of the year. The amount of water that can be withdrawn is expressed as a percent of Index Flow, as suggested by Richter (2009). Multiple linear regression using landscape and climate characteristics (aquifer transmissivity, forest cover, average annual precipitation, and soil permeability) was used to estimate the Index Flow for all ungaged stream segments (Hamilton et al. 2008). Acknowledging model uncertainty, these estimates were then adjusted by a "safety factor" to ensure that estimated flow exceeds actual flow only 10% of the time, further protecting rivers from Adverse Resource Impacts due to excessive withdrawals.

In Michigan, groundwater discharge plays a significant role in determining fish species assemblage. During the summer low flow period, groundwater discharge into Michigan's rivers provides most of their flow, and regulates their temperature and dissolved oxygen levels. Groundwater withdrawals by pumping wells reduce natural groundwater discharge to rivers. To account for groundwater withdrawals, a computer model estimates streamflow depletion from the nearest stream segments for any proposed withdrawal based on well location, depth, aquifer and riverbed characteristics, and the timing and quantity of withdrawal (Reeves 2008, Reeves et al. 2009).

Michigan's stream segments were classified according to catchment size (streams, small rivers, large rivers) and

Michigan Guiding Principles

March 20, 2007

1. Michigan has an abundance of water resources. There is no overall shortage of water in the State. Currently, water withdrawals in Michigan do not present a crisis.
2. Not all water withdrawals are alike, and have differing levels and types of impacts. Certain water sources can support a large amount of withdrawal without harm to other users or to the ecosystem. Other water sources are more vulnerable to large withdrawals.
3. Some areas of the state have been identified as sensitive to groundwater withdrawals. Current and future withdrawals in these areas require a higher degree of monitoring, scientific research, and understanding.
4. Water is a valuable asset, and if used efficiently, can provide the basis of a strong economy and high quality of life in Michigan.
5. Ground and surface water are strongly interrelated and cannot be viewed as separate and distinct.
6. In order to protect basic ecological function, adequate stream base flow must be maintained.
7. Water use by type of user or by purpose of use is not prioritized.
8. The amount of water withdrawn from a hydrologic system must be sustainable. Water resource sustainability involves the use of scientific analysis to balance the economic, social and environmental demands placed on the resource to ensure that the needs of current and future generations are not compromised by current usage.
9. Indicators of sustainability are important to assessing Michigan's water use.
10. The accuracy and effectiveness of water management is an evolutionary, long-term process that must be continually enhanced with scientific information. Additional monitoring of stream flows, water levels, aquatic ecosystems, and related mapping and analysis is essential to protecting water resources.
11. Any water management process must be consistent with applicable statutory and common law in Michigan, neither abrogating nor expanding the law absent specific legislative action.
12. Consistency of regulation and predictability between state and local units of government are essential to managing the resource.
13. Education is critical for all water users, private and public, to understand their responsibilities for water conservation and efficient use.
14. Local, voluntary problem-solving approaches for resolving water use disputes and withdrawal impacts are the desirable starting point for conflict resolution. Michigan has a role in disputes involving impacts on environmentally sensitive areas. Legal action by any party should be seen as the last option.
15. Withdrawals presenting the greatest risk of causing an adverse impact to natural resources should be the primary focus of a water management process.
16. Information gathered and provided for the purpose of preliminary evaluation of water withdrawal projects must be simple and understandable in the most accurate and represented manner possible.
17. Mitigation of adverse resource impacts is a reasonable alternative for new and expanding water withdrawals where deemed appropriate.
18. Conservation of water resources includes the efficient use and protection of quality.
19. Preliminary evaluation of potential adverse resource impacts on fish populations and other existing water users caused by new water withdrawal must have value to new and existing water users, is important prior to significant economic investment and is critical to determining the need for further analysis.
20. The goals of a water use assessment tool are to provide a better understanding of withdrawal impacts, to minimize water use conflicts, to facilitate water planning among stakeholders, and to assess long-term conservation strategies.

thermal regime (cold, cold transitional, warm transitional and warm)—the dominant variables previously shown to influence fish assemblages in Michigan (Lyons et al. 2009, Wehrly et al. 2003, Zorn et al. 2008). This classification yielded 11 river types (Brenden et al. 2008, Seelbach et al. 2006), which were mapped onto the Michigan NHD+ stream segment data layer.

For each of the 11 river types, Zorn et al. (2009) modeled fish response curves that relate population and density changes in fish communities to percentage reductions in Index Flow (Figure 1). The curves are based on a representative subset of samples collected from about 1,700 locations over 30 years (about one sample per year per site from about 20 sites per river type) and housed in three databases. Curves for *thriving* species (those expected to be especially abundant) can be considered "early warning flags" of Adverse Resource Impact, which the legislature defined in terms of *characteristic* species (expected to be more abundant than the state mean abundance). Michigan's ecological response curves are unique because they summarize in a single model the response of the entire fish community to flow alteration in a given river type. Other taxonomic groups (invertebrates, vegetation, etc.) were not assessed.

To compensate for uncertainties in the models, the 2008 Michigan law created "management zones" representing increasing levels of risk to the environment (Figure 1), and prescribed a suite of water management actions for each level. Because the curve for each river type is different, the flow removal associated with a given change in fish assemblage—and therefore the boundaries between management zones—differs by river type (Figure 2).

Prospective water users employ an online Water Withdrawal Assessment Tool (WWAT; Michigan Department of Environmental Quality 2009) to determine the level of risk associated with their proposed withdrawals. Users enter the location, timing, quantity, and if relevant, the screen depth of their proposed groundwater or surface water withdrawals. Using the hydrologic foundation and groundwater model, the WWAT calculates flow depletion of the nearest stream segment during summer low flow due to the proposed withdrawal, added to the cumulative withdrawals from upstream segments. Using the stream types and fish response curves, the WWAT associates that depletion with its risk level for that type of river. If the risk level is low, then the withdrawal may be registered online with no further analysis. If the risk level is high, meaning the withdrawal would likely cause an Adverse Resource Impact, then site-specific review by Department of Environmental Quality staff is required, using local flow and fish data and expert opinion instead of the less accurate statewide model. After site review, the withdrawal will be registered, registered with modifications, or rejected.

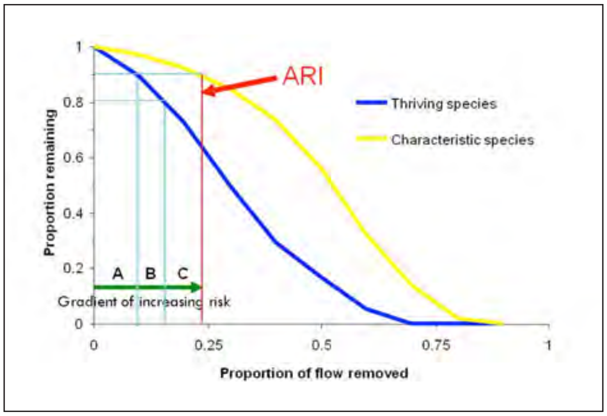

Figure 1. Typical fish-response curves. ARI indicates Adverse Resource Impact, depicted here as 90% of characteristic fish species remaining, as recommended by the Advisory Committee. Light lines indicate thresholds between water management zones associated with different degrees of ecological change. A = register water use, B = notify local water users, C = form a water user committee.

Outcomes of the process are:

- Withdrawals are capped at the volume that risks adversely impacting fish communities during the most-sensitive time of year. This volume applies all year long. Therefore, flow variability is maintained and low-flow thresholds are avoided.
- New withdrawals registration is expedited when environmental risk is low.
- Government staff time focuses on withdrawals that pose the most risk and stream segments that are most highly valued by society (because anyone can request a site review).
- Future water withdrawals will likely be taken from least-sensitive rivers.

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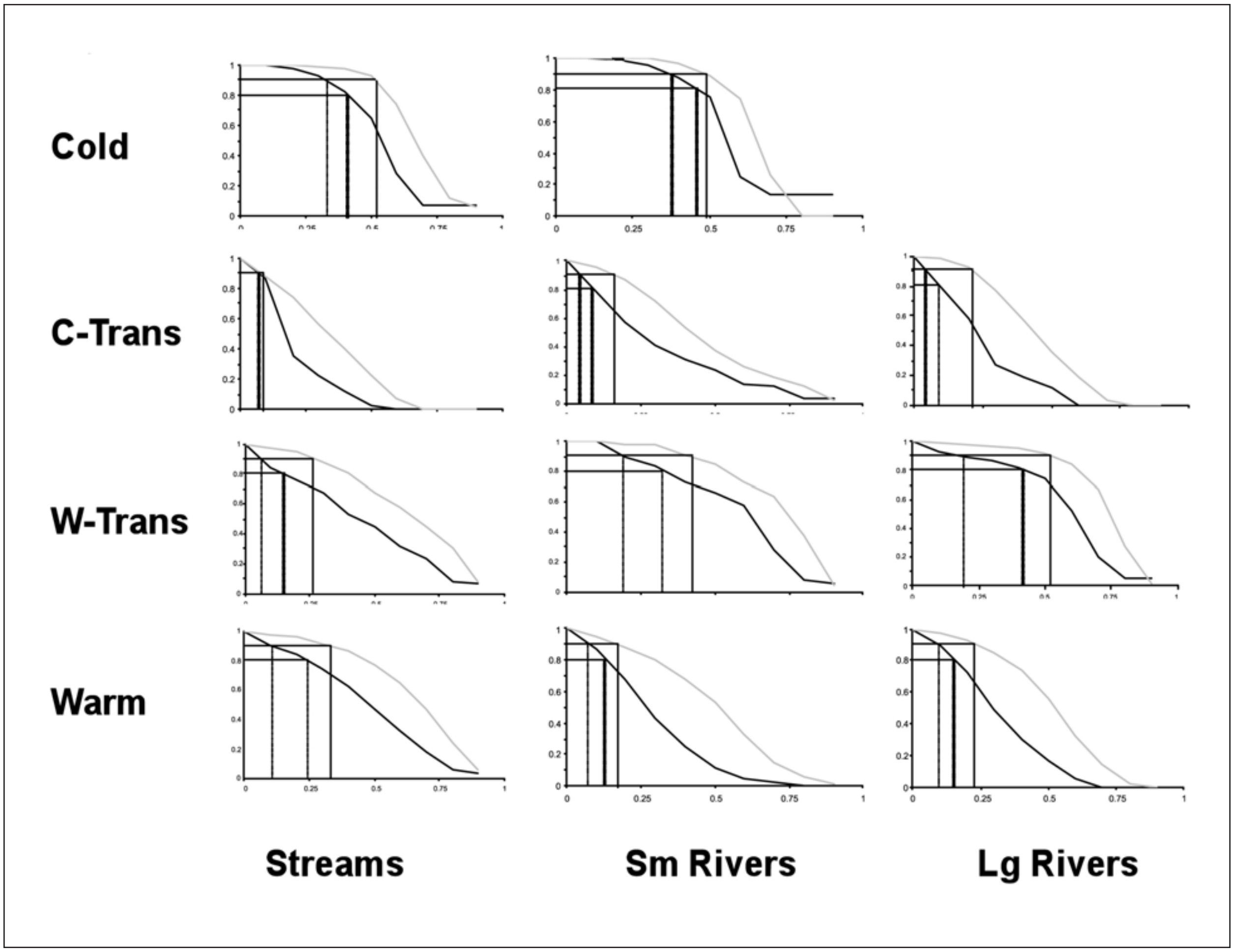

Figure 2. Michigan's fish response curves, showing how each type of river has different curves, and therefore different water withdrawals associated with each management zone. X- and y-axis labels are as shown in Figure 1. From Zorn et al. (2008).

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2.2 Massachusetts Sustainable Water Management Initiative

The Massachusetts Sustainable Water Management Initiative demonstrates the use of (1) a duration-curve regression approach to build a hydrologic foundation, (2) bioperiods as a temporal basis for setting flow criteria, (3) quantitative flow-ecology response curves to inform decision-making, and (4) a management framework that associates implementation actions with different condition goals. It is a work in progress.

Responding to water quality and quantity concerns, the 1987 Massachusetts Water Management Act (WMA) established a water withdrawal permitting system. Twenty years later, implementation of the Act was falling short of its objectives, as evidenced by persistent impacts from stream depletion. Consequently, environmental groups appealed permit decisions for not adequately protecting rivers and streams from excessive water withdrawals, and filed legislation requiring the development of environmental flow protection standards. In 2009, responding to continuing controversy, the state[1] launched the Massachusetts Sustainable Water Management Initiative (SWMI). Both the social and scientific processes of SWMI closely follow the ELOHA framework.

An Advisory Committee representing water suppliers, conservationists, agriculture, state agencies, and other stakeholders was established to develop a comprehensive approach to water management, including water withdrawals. A Technical Committee representing the same stakeholders and state and Federal agencies was formed to help inform and scientifically ground this effort. To date, these committees have met formally many dozens of times over the course of two years to design and carry out the criteria development process.

The hydrologic foundation is the Massachusetts Sustainable-Yield Estimator (SYE), a statewide, interactive decision-support tool developed by the U.S. Geological Survey (USGS) (Archfield et al. 2010). SYE first estimates the 1960-2004 series of unregulated (baseline), daily streamflow at ungaged sites using a duration-curve regression approach (Figure 1). Quantile regression is used to estimate the flow-duration curve for the ungaged site, based on climate and physical parameters. A minimally altered reference gage is then selected systematically as described by Archfield et al. (2010) and used to transform the flow-duration curve into a daily time series of baseline flows. Armstrong et al.'s (2004) analyses of streamflow and fish populations at the reference sites confirmed that they are minimally altered.

Current-condition flows are calculated by adding and subtracting water withdrawal and return flow data provided by the Massachusetts Department of Environmental Protection (DEP) for the period 2000-2004. Monthly water use data are divided evenly by the number of days in the

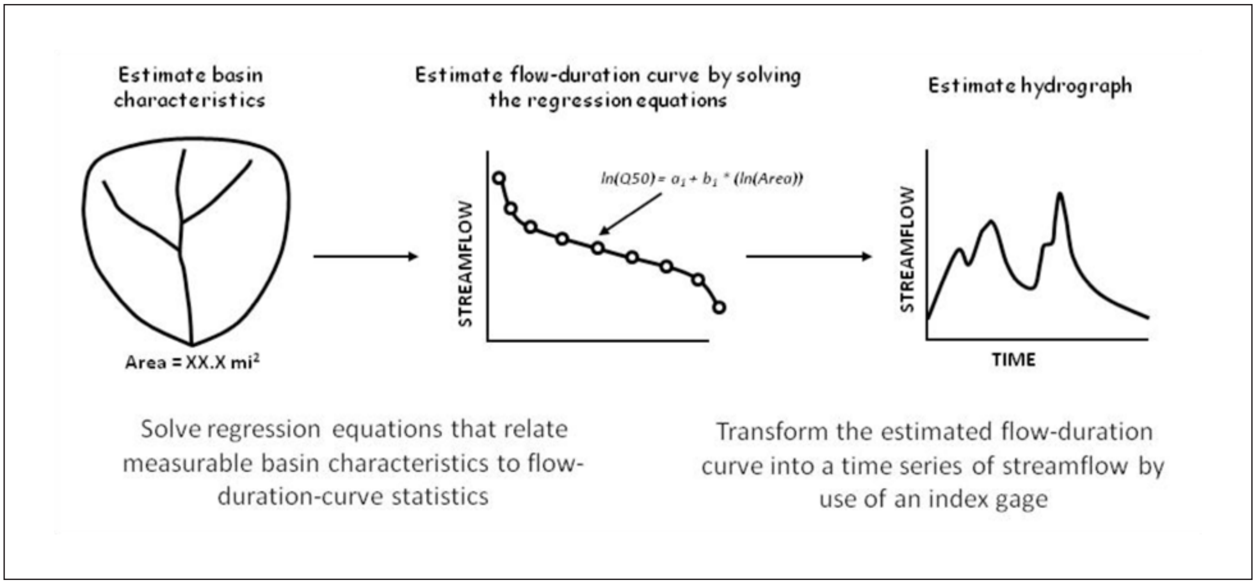

Figure 1. Duration-curve regression approach used to estimate baseline daily flow series in the Massachusetts Sustainable Yield Estimator (SYE). From Massachusetts Executive Office of Energy and Environmental Affairs (2012).

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[1] Massachusetts Department of Conservation and Recreation (MDCR), Massachusetts Department of Environmental Protection (MDEP), and the Massachusetts Department of Fish and Game (MDFG)

month; however, the user has the option of substituting more accurate information. Stream depletion due to groundwater withdrawals is assumed to occur instantaneously with the withdrawal. Alternatively, STRMDEPL (Barlow 2000) may be used to distribute the depletion over time, given well locations and basic aquifer characteristics. Weiskel et al. (2010) added several enhancements to SYE, including distributed flow models to simulate groundwater discharge into rivers in certain parts of the state. Additional, detailed dam operation data are needed to simulate reservoir storage (Archfield et al. 2010).

The Technical Committee of stakeholders, guided by state resource agencies, identified four seasonal bioperiods necessary to support life histories and biological needs of resident fish communities and fluvial-dependent diadromous species: overwintering and salmonid egg development, spring flooding, rearing and growth, and fall salmonid spawning. The Technical Committee confirmed that January, April, August, and October adequately represent the four bioperiods to allow for simplified criteria development.

Weiskel et al. (2010) delineated 1,395 nested, topographically defined sub-basins draining to National Hydrography Database (NHD) stream reaches. For each sub-basin, current-condition flows were calculated as described above, adding back in estimated domestic well withdrawals and septic system discharges. This allowed for the calculation of a range of flow statistics, including the baseline and current-condition median flow during January, April, August, and October. Flow alteration was calculated by comparing baseline to current-condition data.

Flow-ecology relations are described in two USGS Scientific Investigation Reports by Armstrong et al. (2010. 2011), the more recent of which used data from 669 fish-sampling sites in the Massachusetts Division of Fisheries and Wildlife fish-community database. Literature review guided the selection of a set of flow-sensitive fish metrics, including species richness, abundance of individual indicator species, and abundance of species grouped based on life history. A set of environmental variables was calculated for the contributed watershed area for fish sampling sites, including land cover (e.g., % buffer in wetland), land use (e.g., % impervious cover), and fragmentation (e.g., dam density) variables. In addition, dozens of streamflow alteration variables were calculated for all the fish sampling sites, using the general approach of Weiskel et al (2010).

Most of the streamflow alteration variables are monthly median flow statistics, and a subset of those was calculated by separating out different types of withdrawals and return flows. For example, a variable was created for the percent alteration of August median flow due to groundwater withdrawals (excluding return flows and other types of withdrawals). Estimated indicators of flow alteration were found to be highly correlated among the twelve months of the year. Ordination and cluster analysis facilitated the grouping of fish species into habitat use classifications such as fluvial specialist.

The number of environmental variables in the study was reduced using principal components analysis and Spearman rank correlation. It was found that estimated August median flow alteration resulting from groundwater withdrawals was both significant and not highly correlated with other non-streamflow variables in the model. Once this step was completed, quantile regression (Cade and Richards 2005) and generalized linear modeling were used to quantify the response of stream fish to the reduced set of environmental variables.

As illustrated in Figure 2, quantile regression revealed that increases in the percent alteration of August median flow from groundwater withdrawal was associated with decreases in the 90th quantile for relative abundance of brook trout and blacknose dace (both classified as "fluvial fish"). A similar declining pattern relative to increasing flow alteration was seen for fluvial fish relative abundance and fluvial fish species richness.

The generalized linear modeling (GLM) approach led to a small set of somewhat strong models for describing the relations between fish-response and environmental/anthropogenic variables. The study found that, relative to eight chemical and physical covariates, diminished flow magnitudes are primary predictors of biological integrity for fish and wildlife communities. The August median flow alteration due to groundwater withdrawals variable is significant in the subset of GLM equations describing the relationship between fluvial-fish relative abundance (as measured by catch per unit effort) and environmental factors. In other words, the key resulting equation revealed that a "1 percent increase in percent alteration of August median streamflow from groundwater withdrawals is associated with a 0.9 percent decrease in fluvial-fish relative abundance" if other variables in the model, such as impervious surface, are held constant (Armstrong et al. 2011). A graphic of this relationship is shown in Figure 3.

As part of the Massachusetts Sustainable Water Management Initiative Technical Committee process, the Massachusetts Department of Fish and Game (DFG) led a process of categorizing the current condition of the state's flowing waters using fish community metrics as a surrogate for ecological integrity. More specifically, DFG used the GLM and quantile regression results to assign ranges of alteration in fluvial fish relative abundance values to five condition classes, or "Biological Categories." This approach

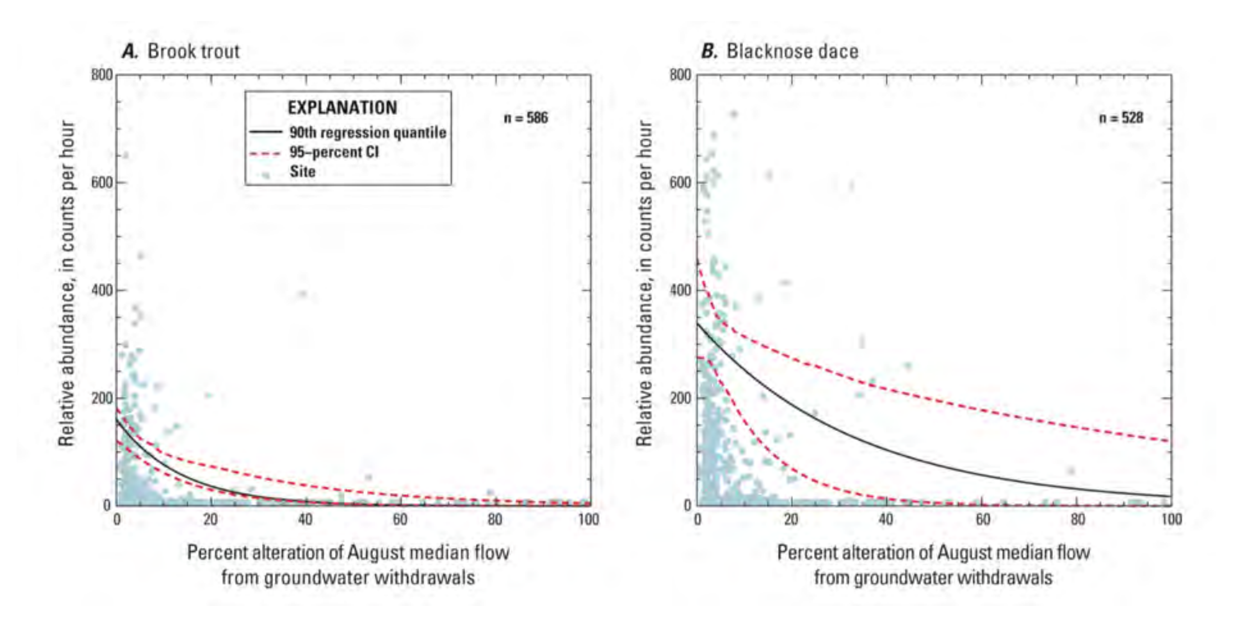

Figure 2. Examples of flow-ecology curves for Massachusetts showing quantile-regression relationships between fish-community metrics and August flow depletion. From Armstrong et al. (2011).

required use of the analyses described above, along with best professional judgment, and was built upon the biological condition gradient concept (Davies and Jackson 2006). These condition classes were designed to reflect the combined effects of withdrawals and impervious surfaces on fluvial fish relative abundance, and are in tiers. As a result, all sub-basins in the state can be placed into a Biological Category based on known natural watershed characteristics along with estimates of impervious surface and percent alteration of the August median flow due to groundwater withdrawals.

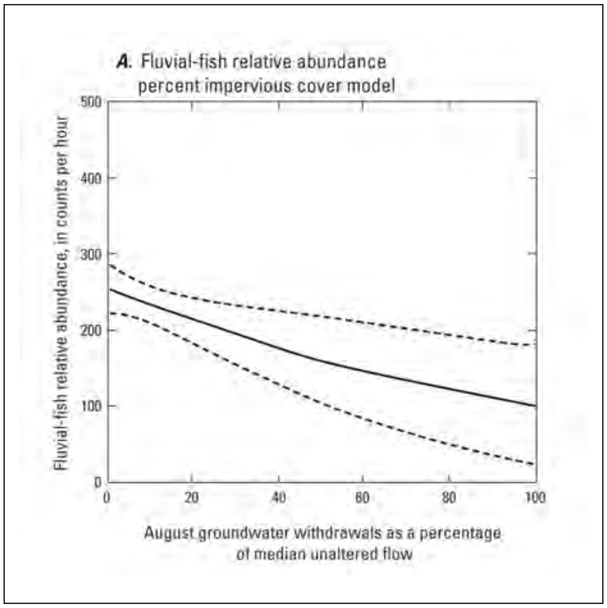

Figure 3. Generalized linear modeling result linking alteration in August median flow from groundwater withdrawal to fluvial fish relative abundance. From Armstrong et al. (2011).

A set of draft streamflow criteria (limits on hydrologic alteration) and a larger water management framework have been proposed by Massachusetts resource agencies for comment by participants in the SWMI process. The draft streamflow criteria (Table 1) were developed by using the GLM equation for fluvial-fish relative abundance in Armstrong et al (2011), defining the amount of flow alteration that corresponds with the boundaries between Biological Categories when impervious surface is held constant at 1% (as agreed to by the SWMI Technical Committee). Specifically:

- 3% alteration of August median flow leads to a shift from Biological Category 1 to 2;
- 10% alteration leads to a shift from Category 2 to 3;
- 25% alteration leads to a shift from Category 3 to 4; and
- 55% alteration leads to a shift from Category 4 to 5.

For any river or stream segment, the set of streamflow criteria that would apply is based on that water body's existing level of flow alteration due to groundwater withdrawal (i.e. "Flow Level"). Those water bodies with relatively low existing hydrologic alteration would have stricter criteria apply in August than those that have more significant current use of groundwater.

Table 1. Massachusetts draft streamflow criteria structure (February 3, 2012 version). Flow-ecology curves relating fluvial fish communities to percent flow alteration in August from groundwater withdrawal informed the development of these proposed criteria. From Massachusetts Executive Office of Energy and Environmental Affairs (2012).

		Seasonal Streamflow Criteria			
Flow Level	August Flow Level (Range of % alteration due to groundwater withdrawal)	% allowable alteration of estimated unimpacted median flow			
		Aug	Oct	Jan	April
1	0 to < 3%	3%	3%	3%	3%
2	3 to < 10%	10%	5%	3%	3%
3	10 to < 25%	25%	15%	10%	10%
4	25 to < 55%	feasible mitigation and improvement			
5	55% or greater				
Streamflow Criteria Narrative: Existing sources in subbasins with alteration levels higher than those shown will be required to minimize existing impacts to the greatest extent feasible and mitigate additional withdrawal commensurate with impact.					

Draft streamflow criteria also were proposed for October, January, and April, in order to protect the overall pattern of the natural flow regime across the year. Each of these months is linked to a biological need in Massachusetts rivers and streams through the bioperiod concept. Based on best professional judgment, and lacking a GLM equation for these months, the non-summer criteria were generally set at one "Flow Level" below (more stringent than) each of the August flow criteria. October's flow criteria are somewhat less strict, recognizing that flow alteration across the state during the fall is larger than during winter or spring. Given the relatively significant impacts to fluvial fish communities—and by proxy ecological integrity—from August alterations due to groundwater withdrawals greater than 25 percent, no quantitative criteria were proposed for Flow Levels 4 or 5. Withdrawals from rivers and streams within these sub-basins would be required to minimize existing impacts to the greatest extent possible and to conduct feasible mitigation and improvement in a way that is commensurate with their impact.

These draft streamflow criteria would be used to guide allowable withdrawals under the Massachusetts Water Management Act permitting process[2]. For high-quality streams, defined as either those with documented cold water fisheries or those in Biological Categories 1, 2 or 3, additional review and minimization of impacts would be required. The framework also is designed to prevent stream degradation from an existing to a lower Biological Category.

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[2] http://law.onecle.com/massachusetts/21g/index.html

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2.3 Connecticut River Basin Ecosystem Flow Restoration

The Connecticut River basin project demonstrates (1) coordinating diverse stakeholders to assess the costs and benefits of re-operating more than 70 dams within an interstate basin and (2) pursuing basin-wide environmental flow and water use objectives through collaborative simulation and optimization modeling.

This case study describes a major component of The Nature Conservancy's Connecticut River Program[3] to restore important river processes, thereby improving the health of declining native species and diverse habitats along the river and its tributaries. With 44 major tributaries, approximately 70 large dams, more than 2,600 smaller dams and 44,000 road-stream crossings spanning 4 states (Connecticut, Massachusetts, New Hampshire, and Vermont) within the 19,288-km^2 watershed, coordinated basin-scale planning and management clearly is needed. Currently, management of the 70 dams—including 14 owned and operated by the US Army Corps of Engineers (Corps)—is not integrated as a system.

The objective of the ecosystem flow restoration component is to modify management of dams and water supply systems to provide environmental benefits while continuing to supply water, reduce flood risk, and generate hydropower (Zimmerman et al. 2008). It is collaboratively managed and funded by the Corps New England District Office through a congressionally authorized (in the Water Resource Development Act, or WRDA) study budgeted at $3 million. The Nature Conservancy is a cost-share partner and has raised its $1.5 million share through a private donation.

Preliminary technical studies by The Nature Conservancy established the spatial extent, distribution, and scope of flow alteration. Zimmerman (2006a) documented how streamflow patterns influence physical processes and the native species and communities of the Connecticut River basin, based primarily on literature review. Zimmerman (2006b) rigorously analyzed hydrologic alteration downstream from flood-control dams on two tributary rivers. Zimmerman and Lester (2006) mapped the potential degree and extent of such alteration across the basin. Zimmerman et al. (2009) modelled sub-daily flows and analyzed hourly flow variability downstream of multiple dams across the basin. Additionally, Gannon (2007) inventoried permitted withdrawals and discharges to gain insight into each state's water resource management policies and their relative contributions to hydrologic alteration within the watershed. These studies laid a sound technical foundation and helped focus and engage stakeholders.

Local, state, and federal stakeholders were convened on numerous occasions and in a variety of formats, beginning with a 2008 kick-off meeting. In 2009, the non-profit Consensus Building Institute interviewed all key stakeholders across the four states. One constituency that was crucial to the project's success was the private large dam owners. A 2009 workshop and one-on-one onsite visits with dam owners over 1.5 years proved essential for understanding their operational constraints and for gaining their involvement in the process. A 2010 workshop introduced stakeholders to the modeling that was underway and a 2011 workshop made initial environmental flow recommendations for the basin.

The modeling team is building a hydrologic model and set of decision–support systems (DSS) (Figure 1) for integrated water resource management. Water managers and stakeholders will be able to use the system to evaluate environmental and economic outcomes of various water management and climate change scenarios. The DSS also will be useful for upcoming Federal Energy Regulatory Commission (FERC) relicensing actions, for setting individual dam operations in their regional context. Model construction began in 2009 and is nearing completion.

The DSS includes two simulation models, one built by University of Massachusetts Amherst (UMass) modelers and the other by the US Army Corps of Engineers (Corps). The UMass model uses STELLA system-dynamics software to directly represent current reservoir operations and economic outcomes in sub-basins. This model readily solicits and synthesizes feedback from stakeholders. The more operationally detailed Corps model generates essentially identical output to the UMass model, but in the Res-Sim format with which Corps dam engineers—who will attempt to implement the recommendations that result from the project—are most comfortable. Both models input a hydrologic foundation of unimpaired (baseline) daily streamflow hydrographs developed by the U.S. Geological Survey, using duration-curve regression modelling (see Massachusetts case study) for the middle 90 percent of flows, and a modified drainage area ratio method for extreme high flows. Resulting hydrographs are accessed through the new Connecticut River UnImpacted Streamflow Estimator[4] (CRUISE) tool.

The simulation models are linked to a multi-objective optimization model built by UMass modelers using Lingo programming language. The optimization challenge was to find daily releases from 70 reservoirs that meet flood

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[3] http://conserveonline.org/workspaces/ctriver

[4] http://webdmamrl.er.usgs.gov/s1/sarch/ctrtool/index.html

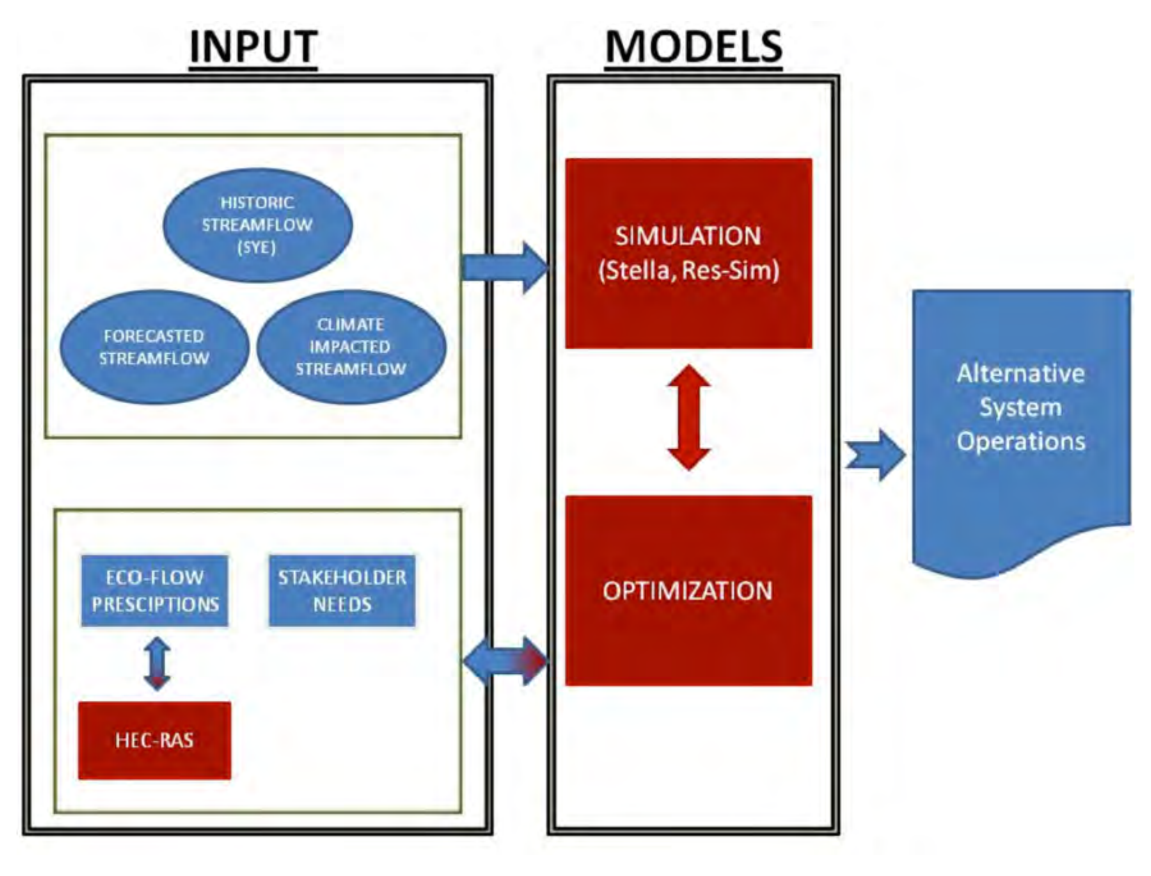

Figure 1. The basic structure of multi-agency water management decision support system for the Connecticut River basin, which includes an optimization routine with environmental flow targets.

control, hydropower, water supply, recreation and ecosystem requirements over time periods ranging from one season to many years. The Connecticut River Wiki[5] Page tracks model development progress.

The inclusion of environmental flow regime targets is novel to water resource optimization modeling. In 2010, environmental flow scientists convened a workshop with UMass modelers to better understand modeling constraints. Together, they devised a way to tailor the 2011 expert workshop to express flow needs in "model" language: environmental flows are modeled as optimization targets accompanied by penalty functions that describe their flexibility. A steep penalty function indicates that the target must be met; a shallow penalty function implies less urgency in meeting that target.

At the 2011 expert workshop, The Nature Conservancy provided participants with a list of preliminary flow recommendations organized by species and biological communities, based on extensive literature review. Each flow recommendation was expressed in terms of season, environmental flow component, flow range, and the underlying flow-ecology hypothesis. In breakout sessions, participants grouped according to their scientific disciplines to review and refine the preliminary flow recommendations. Then, all participants reconvened to resolve differences in recommendation terms and inconsistencies between the discipline-specific flow recommendations.

Although the workshop participants were comfortable recommending flow targets, they felt unprepared to define penalty functions needed for optimization modeling. The project team therefore has proposed environmental flow penalty functions based on the "presumptive standard" described by Richter et al. (2011).

The workshop attendees have agreed to reconvene to learn how the optimization and operations models represent the environmental flow recommendations, examine how their flow recommendations and associated penalty functions

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[5] http://ctriver.ecs.umass.edu/wiki/index.php/Main_Page
http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/connecticut/connecticutriver/index.htm

perform in terms of maintaining key aspects of unregulated hydrographs and flow duration curves, and show how often these recommendations can be achieved under various water management scenarios. HEC-RAS, a hydraulic model that calculates stage-discharge relations, will facilitate this conversation. Participants will be asked to refine their initial recommendations based on these results.

In 2012, project efforts will focus on refinement of environmental flow targets and use of the models for decision support. The Nature Conservancy will actively involve stakeholders in exploring opportunities for dam re-operation to provide environmental flows. At least one experimental environmental flow release from an Army Corps' dam is anticipated in 2013. Monitoring will document ecological conditions before and after flow implementation and strengthen flow-ecology relationships. Already, baseline mapping of vegetation at 91 floodplain sites and hydraulic modeling (in HEC-RAS) have been completed for the entire mainstem in Connecticut and the mainstem in the vicinity of Northampton (MA), and may be expanded to other upper mainstem or tributary reaches. This information will be used to assess future benefits of any dam re-operations.

Efforts to engage diverse stakeholders are paying off. Owners of one of the large dams plans to use the project models to support its FERC relicensing request, and the National Atmospheric and Oceanographic Administration has already been using the CRUISE tool to support its participation in upcoming relicensing reviews. Having all stakeholders agree on a common scientific foundation is essential for integrating dam operations across the basin.

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2.4 Colorado Watershed Flow Evaluation Tool

The Colorado ELOHA project demonstrates (1) using flexible approaches to develop flow-ecology curves based on studies reported in the literature and (2) using flow-ecology curves to inform basin-scale water-resource planning. Sanderson et al. (2011) provide a more detailed discussion of the project.

In 2005, the Colorado Legislature passed the Colorado Water for the 21st Century Act, launching a statewide water planning effort. The Act mandated that representatives of cities, farms, and other water users join conservation and recreation interests at "basin roundtables" to assess future water supply needs for their watersheds. These assessments are framing discussions about future water allocations and must address both consumptive and non-consumptive (recreation and environmental flows) water needs.

The Colorado Water Conservation Board funded this 1-year, approximately $200,000 project to help two pilot basin roundtables—the Roaring Fork watershed in western Colorado and the Fountain Creek watershed in eastern Colorado—understand tradeoffs between consumptive and non-consumptive water uses. In 2008, the consulting firm Camp Dresser & McKee (CDM) worked with scientists from Colorado State University and The Nature Conservancy, staff from the Colorado Water Conservation Board, and representatives of the Colorado Basin Roundtable to apply ELOHA to estimate flow-related ecological risk at the basin scale. The Watershed Flow Evaluation Tool (WFET) displays the results under various water management scenarios.

A hydrologic foundation existed for the Roaring Fork watershed before this project began. The State of Colorado's water supply model, StateMod (CDWR and CWCB 2009), is a monthly water accounting program that begins with gaged streamflow data under current conditions. Reservoir storage changes, water diversions, and return flows are added or subtracted to obtain baseline flows. Simple water accounting, weighted by drainage area and precipitation, is then used to calculate baseline flows at ungaged sites. Monthly flows are disaggregated into daily flows using one of several techniques, most commonly by emulating the daily flow patterns recorded at selected gages. Baseline flows at ungaged sites are calculated by apportioning flows across watersheds according to their drainage areas and mean annual precipitation rates. Current-condition flows at ungaged sites are calculated by adding or subtracting reservoir storage change, water diversions, and return flows to the baseline flows. Groundwater withdrawals and return flows are similarly added and subtracted from streamflow, allowing for an aquifer-dependent time delay. Several options are available for distributing monthly water use data to daily time steps. StateMod has not yet been calibrated for the Fountain Creek watershed, so analyses for that pilot were restricted to gaged sites.

Indicators of Hydrologic Alteration (IHA) software (The Nature Conservancy 2009) used output from StateMod to calculate changes in five ecologically relevant flow statistics—mean annual flow, mean August flow, mean September flow, mean January flow, and mean annual peak daily flow—after major water-supply projects had started. Because StateMod was developed for purposes other than ecological assessments, engineers analyzed its assumptions and output to determine that these particular IHA metrics could be calculated with sufficient accuracy.

River type classification was straightforward. As an informal framework for organizing information about flow and ecology, rivers were designated as Interior West, Rocky Mountains, or Great Plains, according to the Level-1 ecoregion (CEC 1997) in which they are located. Geomorphologic sub-classification limited the application of resulting flow-ecology relationships to appropriate river reaches. For example, relationships pertaining to floodplain function were not applied to steep canyon reaches.

A Colorado State University Ph.D. student, Thomas Wilding, developed relationships between streamflow and warmwater and coldwater fish, riparian vegetation, invertebrates, and white-water rafting and kayaking, based on his review of 108 studies reported in the literature. Quantitative approaches varied, depending on the form and abundance of relevant information, and ranged from statistical analysis using quantile regression (Cade and Noon 2003) to categorical relationships and expert consultation (Camp Dresser & McKee Inc. et al. 2009). Figure 1 shows some examples.

The technical team then identified 3-5 risk classes for each ecological attribute, based on expert opinion, if the flow-ecology relationships were not already categorical. Using the flow-ecology relationships, they determined the range of flow values associated with each ecological risk class. Then, using the StateMod and IHA output, they associated each river segment with its level of ecologic risk. For each river reach, the resulting map (Figure 2) indicates

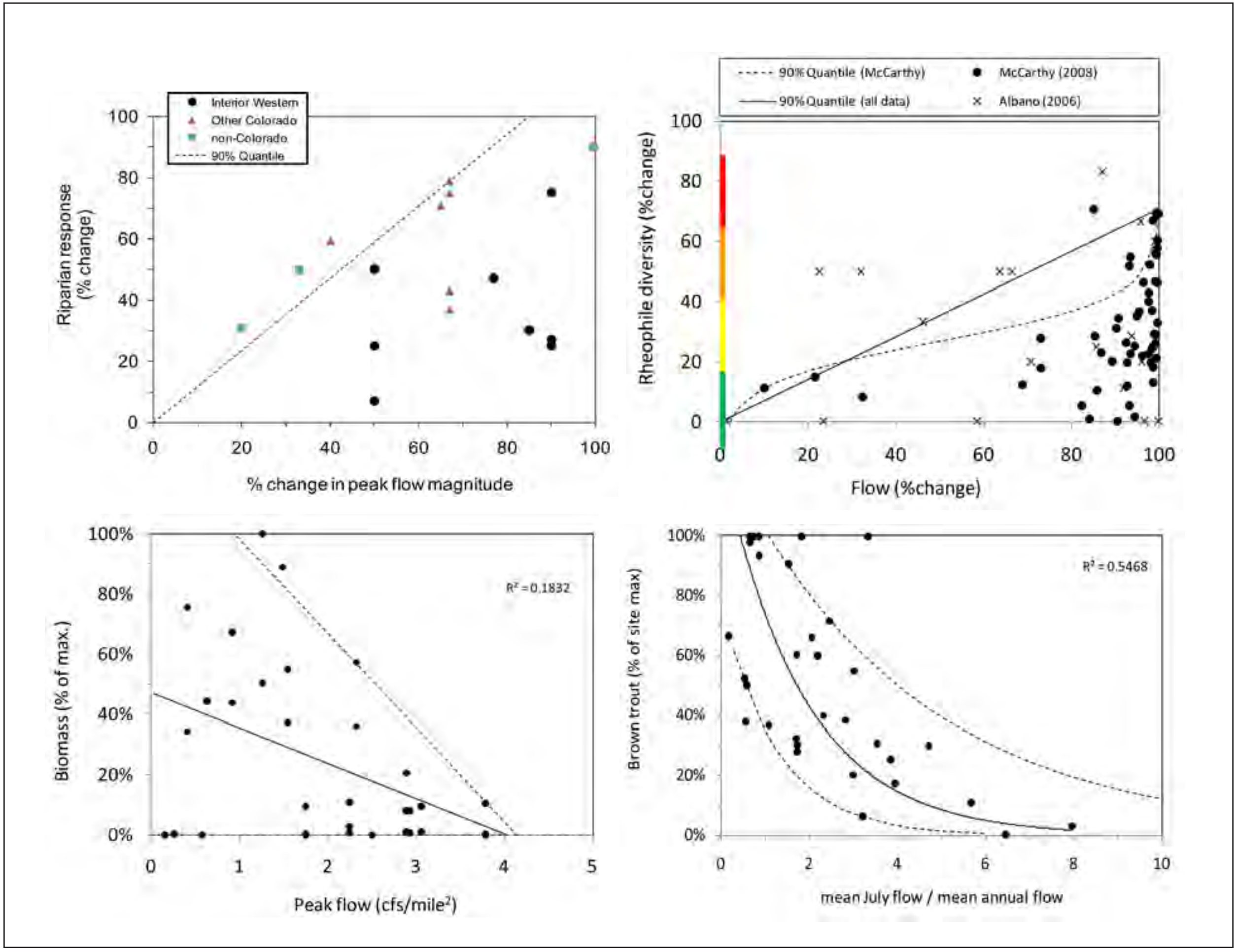

Figure 1. Selected flow-ecology relationships for Colorado (Camp Dresser & McKee Inc. et al. 2009). Upper left: Response of riparian plant communities to peak flow alteration. Upper right: Response of Rocky Mountain invertebrate species diversity to flow depletion on the day of sampling, using data from two studies. Lower left: Response of flannelmouth sucker, a warmwater fish, to peak flow. Flow data were divided by watershed area to compare different sized rivers. Lower right: Response of brown trout recruitment success to mean July flow. Regression lines indicate percentiles advised by expert committee.

the risk that flow alteration has compromised ecological values. The WFET allows basin roundtables to similarly analyze the spatial distribution of ecological risk associated with different potential future water use scenarios.

As mentioned earlier, unlike the Roaring Fork watershed, the Fountain Creek watershed lacks streamflow data for ungaged sites where biological data have been collected. The researchers found that without a hydrologic foundation, they were unable to formulate flow-ecology relationships with sufficient certainty to warrant the development of a WFET for that watershed.

Following the successful deployment of the Roaring Fork WFET, the Basin Roundtable chose to expand the WFET to the entire mainstem of the Colorado River within Colorado and its tributaries. Stakeholders are now using the results of the WFET to assess where flow restoration may be feasible, to estimate the quantities of flow that may be needed for restoration, to identify areas where additional study is needed, and to prioritize protection actions for areas with little flow-related ecological risk. The WFET is emerging as a valuable tool in the development of a basinwide plan for the protection and restoration of river health.

ACKNOWLEDGMENT

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Figure 2. Watershed Flow Evaluation Tool output detail, showing level of flow-related ecological risk for each river reach. Risk levels: red = high, orange = moderate, yellow = minimal, green = low. Blue = not modelled (no flow data).

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2.5 Connecticut Statewide Environmental Flow Regulations

By Mark P. Smith, The Nature Conservancy

This case study demonstrates the development of statewide regulations to protect environmental flows, including a process to establish condition goal classes for every river and stream in the state and the development of reservoir release rules based on their estimated natural inflows. These reservoir release rules feature several innovative approaches to mimic natural conditions, to ensure water reliability for communities, and to be flexible during drought events.

In 1971, the Connecticut legislature passed a law requiring the protection of environmental flows for the "stocked streams" of Connecticut—that is, those rivers and streams stocked with fish by the Division of Wildlife. In 2005, at the request of environmental advocates and with the concurrence of water users, the legislature updated this statute to require the Department of Environmental Protection (DEP) to develop environmental flow regulations for all rivers and streams in the state while also providing for the other uses of water.

The statute requires that these regulations be developed with the participation of an advisory group representing a broad range of stakeholders. The DEP Commissioner subsequently established three advisory groups—a technical advisory committee, a policy advisory committee, and a Commissioner's advisory committee—to inform the process. These groups met and negotiated for six years until final regulations were agreed to in November 2011. This process included a formal public comment process and high-visibility advocacy campaigns, both for and against the new regulations. In addition, in Connecticut all final regulations must be reviewed by the Regulations Review Committee of the legislature to ensure they comply with the legislative intent. The first of these committee reviews sent the initial regulations back for further negotiation and narrowing of the scope before the final regulations were produced. In the end, all sides advocated for approval of the regulations as something they could "live with."

The new regulations[6] contain three primary components: (1) a set of narrative streamflow standards that apply to all streams; (2) a goal classification process through which every stream segment in the state will be associated with one of four environmental flow standards it needs to meet; and (3) a detailed set of flow release requirements for reservoirs and impoundments, with different requirements for small and large reservoirs. Each of these three aspects introduces novel approaches to environmental flow management. The regulations also include the typical requirements related to rights of appeal, public participation, and due process.

Narrative Streamflow Standards: The streamflow regulations provide for four stream condition classes: Class 1 streams "shall exhibit, at all times, the depth, volume, velocity and variation of stream flow and water levels necessary to support and maintain habitat conditions supportive of an aquatic biological community characteristic of that *typically* present in free-flowing river or stream systems of similar size and geomorphic characteristics under the prevailing climatic conditions." Class 2 streams have conditions that can support an aquatic biological community minimally altered from a free-flowing stream of a similar type. Class 3 streams have conditions that support communities moderately altered from systems of a similar type.

Excerpt from the Connecticut Statute

"(1) Apply to all river and stream systems within this state (2) preserve and protect the natural aquatic life, including anadromous fish, contained within such waters; (3) preserve and protect the natural and stocked wildlife dependent upon the flow of such water; (4) promote and protect the usage of such water for public recreation; (5) be based, to the maximum extent practicable, on natural variation of flows and water levels while providing for the needs and requirements of public health, flood control, industry, public utilities, water supply, public safety, agriculture and other lawful uses of such waters; and (6) be based on the best available science, including, but not limited to, natural aquatic habitat, biota, subregional basin boundaries, areas of stratified drift, stream gages and flow data, locations of registered, permitted, and proposed diversions and withdrawal data reported pursuant to section 22a-368a, locations where any dams or other structures impound or divert the waters of a river or stream and any release made therefrom, and any other data for developing such regulations or individual management plans."

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[6] Connecticut Department of Energy and Environmental Protection Stream Flow Standards and Regulations Section 26-141b-1 to 26-141b-8, inclusive, of the Regulations of Connecticut State Agencies, Effective December 12, 2011, http://www.ct.gov/dep/lib/dep/regulations/26/26-141b-1throughb-8.pdf.

Finally, Class 4 streams allow for substantial alteration of flow conditions to meet human water needs, but must "exhibit to the *maximum extent practicable* the depth, volume, velocity and variation of stream flow and water levels *consistent with the narrative standard for Class 3* river and stream segments." This class was added in recognition that many existing dams and reservoirs will not be able to comply with class 3 standards but are required to meet them to the best of their ability. The detailed reservoir release requirements for such systems are covered below. The regulations do make it difficult (but not impossible) for any new reservoirs to be built to a class 4 standard.

An important feature of the classification system is that it does not require those biological communities to actually be present (because they could be affected by stressors other than flow), but rather that the flow conditions must be sufficient to support such communities. As discussed below, the level of alteration allowed within each condition class is based on fish and flow data that were available to the technical committee.

Stream Condition Goal Classification: The regulations prescribe a detailed public process by which the Department of Environmental Protection will assign a condition goal class to each stream or river reach. DEP must consult with the state Department of Public Health to ensure the classification accounts for both environment and public health needs.

The regulations stipulate 18 different considerations that the DEP will take into account when classifying streams. These range from environmental considerations like the presence of sensitive species, to the presence of existing water withdrawals, to existing and planned development upstream of the reach. They also provide that no river segment below an existing public water supply system (not all dams are for public water supplies) will be classified as the highest levels (class 1 or 2), which provides current water suppliers some assurance of continued use of their supplies.

The regulations also outline a public review process, including a public hearing, whereby the draft goal classification, by major basin, is released for public comment before a final classification is made. Additionally, the regulations provide for a process by which a classification can be changed in the future—based either on new information that may become available or based on future needs that cannot be anticipated. However, the burden of proof is higher for streams that petition to move to a lower class than to move to a higher class of protection.

Reservoir Release Rules: The regulations provide detailed release requirements for reservoirs and other waters impounded by a dam or diversion based on stream condition class and the size of the impoundment relative to its watershed or catchment.

The release requirements are based on existing studies that developed flow-response curves for fluvial-dependent species, as studied in Georgia (Freeman and Marcinek 2006) and subsequently confirmed for the northeastern United States (Vokoun and Kanno 2009, 2010; Armstrong et al. 2010, 2011). Building upon these and other environmental flow studies, the technical committee used a "weighted evidence" approach (Norris et al. 2012) to recommend stipulations that dams on class 1 streams cannot actively manipulate the storage of the reservoir (in effect making the dam "run of river") and dams on class 2 streams must release at least 75% of their reservoir inflows at all times. These were developed to meet the narrative standards for class 1 and 2 rivers, as discussed above.

An innovative approach was developed for the class 3 releases. Almost all dams of any significant size fall into this category (see below for more on reservoir size). For these structures, the release requirements include two additional factors to improve their ability to mimic natural flows.

First, the volume of the release required depends on the bioperiod in which it occurs. Bioperiods are biologically-based seasons lasting between one and four months. The regulations define six bioperiods based on the flow needs of the range of river species typically found in Connecticut (see Table 1). Varying the release requirements according to bioperiod improves their accuracy in mimicking natural seasonal flows.

Second, larger releases are required during high flows than during normal flows typical for the bioperiod. Although the technical committee discussed the application of this two-level release system year-round, the final regulation only applies it during the rearing and growth bioperiod (summer).

To implement this two-level release framework, the technical committee developed a system for defining flow levels based on average inflows over the preceding two weeks. If inflow to the reservoir during the preceding two weeks exceeded the bioperiod Q25 exceedance value, then the flow level is considered "high"; if inflow was less, then it is considered "normal." This was a practical compromise between aquatic ecologists, who would have preferred daily flow adjustments, and reservoir operators, who have operational and manpower issues to consider. This approach adequately addresses one of the difficult issues regarding release policies: how to account for wet and dry periods as they occur to prevent either overly augmenting streamflow that would naturally be low or unduly depleting streamflow that would naturally be high. By tying releases

Table 1. Effective dates and minimum release requirements by bioperiod, as stipulated by Connecticut's environmental flow regulations.

Bioperiod	Effective Dates	Minimum Required Release	
		Antecedent Period Dry	Antecedent Period Wet
Overwinter	Dec 1- Feb 28/29	Bioperiod Q99	
Habitat Forming	Mar 1 – Apr 30	Bioperiod Q99	
Clupeid Spawning	May 1 – May 31	Bioperiod Q95	
Resident Spawning	June 1 – June 30	Bioperiod Q90	
Rearing and Growth	July 1- Oct 31	Bioperiod Q80	Bioperiod Q50
Salmonid Spawning	Nov 1 – Nov 30	Bioperiod Q90	

to immediately preceding conditions, they mimic the natural flow regime.

Hydrologic Foundation: To quantify the daily unaltered flows for all streams in Connecticut, the DEP is investing in developing the hydrologic foundation component of the Safe Yield Estimator, which was originally constructed for Massachusetts (Archfield et al.2010), for the entire state. Once the baseline flows are determined, they will be used to calculate exceedance probabilities.

To ensure that releases are typical of the particular stream or river on which a dam occurs, the release requirements are expressed as bioperiod exceedance probabilities (Table 1). This addresses the challenge of using a consistent approach for the entire regulated community while acknowledging the different flow characteristics of different types of streams. The exceedance probability of any stream is based on the period of record of that particular stream or river; so, the Q95 flow (a flow rate that is exceeded 95% of the time) of a high-baseflow river differs substantially in volume from the Q95 of a flashy river. In addition, when reading Table 1 it is useful to take into account the seasonality of flow in Connecticut rivers and streams, since the relative size of releases associated with particular exceedance probability values may not be immediately obvious. For example, the required releases associated with a "habitat forming" (spring) bioperiod Q99 is always much larger than the discharge rate associated with a "rearing and growth" (summer) bioperiod Q80.

Balancing People and the Environment: The regulations also include several important provisions that ensure the reliability of public water supplies (but do not apply to dams used for other purposes). One is that during drought conditions, the release requirements can be reduced systematically (see Table 2). These reductions in releases are tied to the water suppliers' required drought contingency plans so that the reduced releases to streams occur somewhat simultaneously with the implementation of water-use restrictions that suppliers impose as they approach an emergency declaration. This includes a provision for zero releases during water supply drought emergencies, which ensures that the "last drop" of water goes to people rather than to the stream. These reduced releases during droughts significantly decrease the impact of the release requirements on the security of water supplies for human use.

The regulations also allow for extended, but time-limited, release reductions to ensure that public water suppliers maintain an adequate margin of safety. In Connecticut, the Department of Public Health strongly encourages public water suppliers to maintain 15% more water than their typical daily or monthly demand. Suppliers who cannot meet this margin of safety can reduce their reservoir releases as they undertake other measures—either conservation or development of new supplies—to ensure they have an adequate margin of safety under the new reservoir release requirements.

Negotiations of release requirements were substantially aided by the use of the Safe Yield Wizard tool that the Stockholm Environment Institute developed for the Water Evaluation and Planning (WEAP)[7] model (Vogel et al.2007). This tool calculates changes in the safe yield, or the amount of water consistently available for human use, that would result from different release requirements. Water suppliers and aquatic ecologists used the tool iteratively to design release requirements that would not unacceptably impact the amount of water available to supply customers.

Reservoir size: The regulations impose different release rules for the smallest impoundments. The technical committee recognized that very small impoundments (defined either by small volume relative to the catchment

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[7] http://www.weap21.org/

Table 2. Reduced release requirements for public water suppliers during drought.

Water Supply Plan Trigger	Percentage of Required Dry-Period Release	
	Rearing & Growth Bioperiod	All Other Bioperiods
Drought Advisory	100%	75%
Drought Watch	50%	50%
Drought Warning	25%	25%
Drought Emergency	No Release Required	No Release Required

area or by a very small catchment area) regulate flows less than larger reservoirs. This is primarily because small reservoirs are full for all but the driest times of the year and most of the river water spills over their dams; therefore, their natural hydrographs remain mostly intact. Also, for very small watersheds, the releases required would be so small that they would be difficult to implement or measure. Therefore, the rule requires only a single minimum release from most small reservoirs (the rearing and growth Q80) and exempts reservoirs whose calculated release would be less than 0.1 cubic feet per second.

The regulations include some important exemptions and exceptions. For example, water diverted for emergency purposes such as fire suppression is not explicitly exempt. Similarly, dams that are under Federal Energy Regulatory Commission (FERC) jurisdiction are not covered in order to avoid duplicate or potentially conflicting requirements (states have strong authority under the Clean Water Act's 401 certification process to provide conditions for FERC licensed facilities). Also, water diversions by agriculture and golf courses are included only in that the regulations require that they comply with other, existing best management practices for those uses. Finally, critical to the regulations' acceptance was the provision that those regulated by this rule have ten years from the time from which a stream is classified until they must fully comply with the regulations. This gives water managers, both public and private, the security of having sufficient time to make structural modifications to dams and/or to find additional supplies if necessary.

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2.6 Middle Potomac River Basin Environmentally Sustainable Flows

The Middle Potomac River basin project demonstrates (1) the determination of environmental flow needs for rivers and streams that are generally more impaired by land use change than by withdrawals or impoundments; (2) engagement of multiple water resource agencies and other stakeholders across jurisdictional boundaries; and (3) a structured, iterative approach for selecting flow and ecology metrics and refining river types to strengthen flow-ecology relationships.

The project began in May 2009 and is slated for completion in spring 2012. Its approximately $1 million ELOHA project budget is funded mainly by the U.S. Army Corps of Engineers (75% Federal cost-share through the Corps' Section 729 Watershed Assessment program) and The Nature Conservancy (25% non-Federal cost-share), with additional support from the National Park Service, the Interstate Commission on the Potomac River Basin (ICPRB), and other basin jurisdiction agencies. Boundaries of the 11,500-mi^2 Middle Potomac project area were determined by Congressional designation of the Corps' study authority, but the project analyses extended upstream to allow for system connectivity. The project area includes parts of Pennsylvania, Maryland, Virginia, West Virginia, and all of Washington, DC.

ICPRB is the project's technical lead. The Commission was created by interstate compact in 1940, primarily to provide technical support and expertise to the watershed jurisdictions. ICPRB lacks authority to regulate streamflow. Therefore, the project was designed to support efforts of the five watershed jurisdictions to protect and restore environmental flows.

The project team has informed and involved the watershed jurisdictions throughout the project development and analytical process. A seven-part webinar series, technical advisory group meetings, a technical workshop, agency consultative meetings, and a project website[8] have maintained watershed states' involvement throughout the project, from inception to completion. Through these interactions, stakeholders have reviewed the technical approach, discussed potential policy applications, and considered how to use the flow-ecology relationships to inform water and land use management decisions.

Because the Potomac River basin project area has few large dams and flow is relatively unimpaired by major impoundments, this assessment was not oriented towards changing dam operations. In fact, the analysis is finding that land use change is having a greater impact on the river's hydrologic regime than dams or impoundments. The project goals are to:

- Estimate current and future water withdrawals, given population, land use, and climate change projections;
- Determine impacts of water withdrawals, discharges, impoundments, land use, and climate change on flow;
- Characterize flows needed to support healthy biotic communities in smaller streams and rivers; and
- Provide data, information, and analyses to support water and land use planning and decision making at the state level.

A modified version of the site-specific "Savannah" process (Richter et al. 2006) was used to determine flow needs for selected segments of the Potomac River mainstem and selected large tributaries (Cummins et al. 2011), while the regional-scale ELOHA framework was used for smaller tributary streams and wadeable rivers. Here we describe only the ELOHA process.

Figure 1 shows how the project technical team modified the original ELOHA framework. The major modification is their exploratory approach to the biological data analyses, rather than first describing flow-ecology hypotheses based on available literature. They iteratively refined river types, flow metrics, and biometrics to determine flow-ecology relationships, which they then presented to watershed scientists for review. The project website—particularly the archived webinar series—documents the iterative analytical process in detail.

The project's hydrologic foundation consists of 21 years of daily flow data at biological monitoring sites under seven scenarios—modelled baseline (or relatively unaltered), modelled current, and five modelled future alternative flow scenarios—simulated by the Virginia Department of Environmental Quality's decision support system, WOOOMM[9] (Watershed Online Object Oriented Meta-Model). Input to WOOOMM includes edge-of-stream flows generated by the Chesapeake Bay Program's Phase 5.2 HSPF (Hydrological Simulation Program FORTRAN) model (enhanced to include non-linear groundwater recession and re-segmentation at major impoundments), a U.S. Geological Survey (USGS) channel morphology model, and a channel routing routine. The model was calibrated to measured flow at 56 USGS gages. The 747 subwatersheds in the final model capture 869 biological monitoring sites

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[8] http://www.potomacriver.org/2012/projects/middle-pot-assess

[9] http://sifn.bse.vt.edu/sifnwiki/index.php/WOOOMM_Modeling

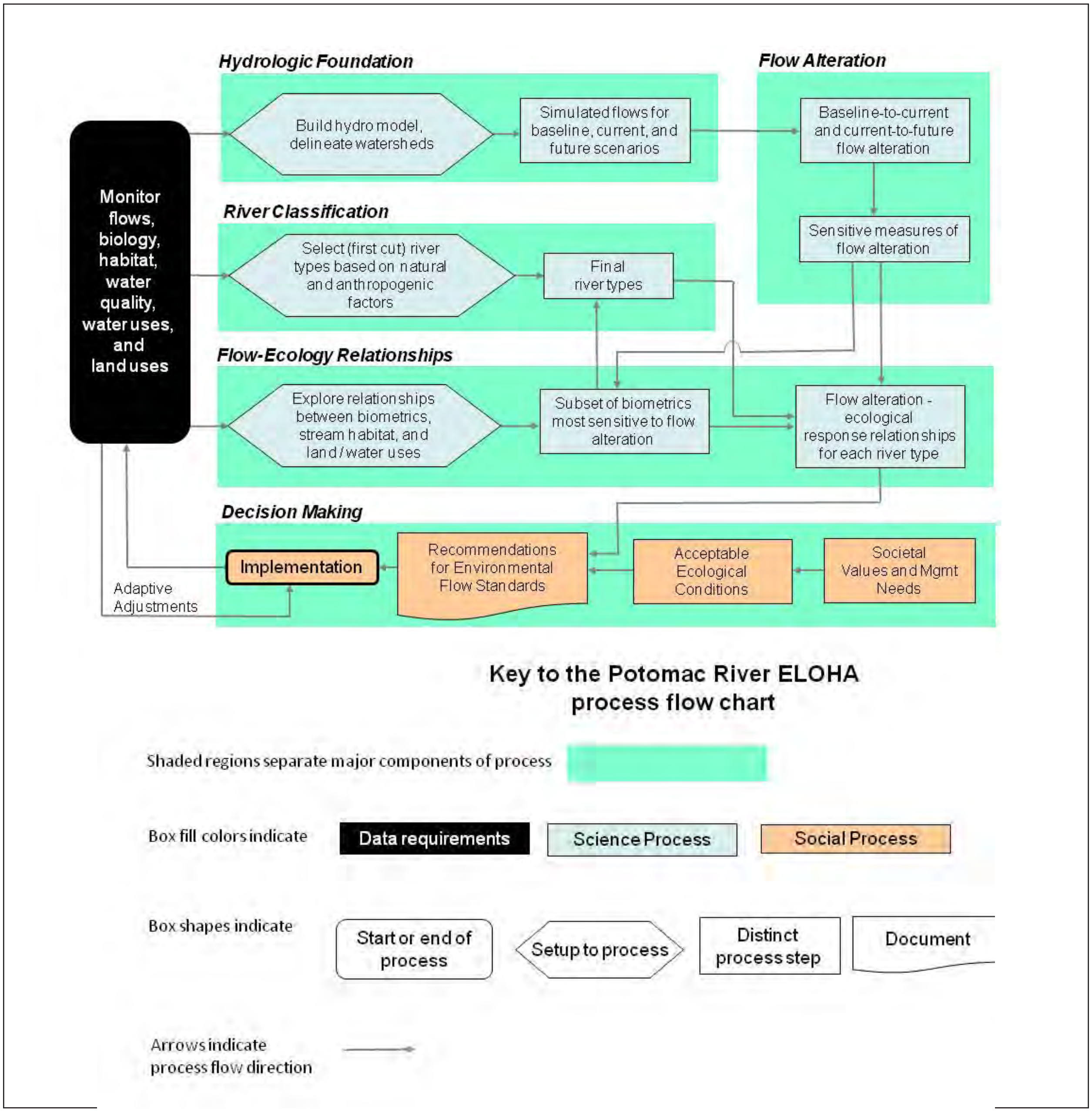

Figure 1 Modified ELOHA framework for the Middle Potomac River basin sustainable flows study.

and representative distributions of bioregions, land cover and catchment areas. Both baseline and current-condition flow series use 1984-2005 climate data.

To identify baseline flow conditions, modelers used a Category and Regression Tree (CART) analysis of 105 gaged watersheds in the Potomac and adjacent Susquehanna River basins. The CART analysis determined thresholds when flows were significantly impacted by anthropogenic land use, withdrawals, discharges, and impoundments. For each anthropogenic factor, thresholds were defined above or below which flows are considered altered. The analysis found that watersheds with greater than or equal to 78% forest cover and less than or equal to 0.35% impervious cover and no impoundments, withdrawals, or discharges have the least altered flows. Therefore, in the modeled baseline scenario, land use in every watershed was adjusted to have at least 78% forest, less than or equal to 0.35% impervious cover, and no withdrawals, impoundments, or discharges.

Current conditions were represented in the models using land use data for 2000, withdrawal and discharge data for 2005, and significant impoundments. Surface-water withdrawal data were obtained from the individual states. Groundwater withdrawals were not modeled due to incomplete data, insufficient understanding of complex groundwater flow systems, and limitations of the hydrologic foundation models. Permitted point-source discharge data were obtained from the Chesapeake Bay Program's discharge database. The Chesapeake Bay model simulates four large impoundments in the study area. Twelve smaller impoundments were added to the Middle Potomac project model because they are located near biological monitoring sites and contain significant storage or are used for hydropower production.

Eighteen flow metrics were selected for flow-ecology analysis from 256 metrics initially calculated by Indicators of Hydrologic Alteration (The Nature Conservancy 2009) and Hydrologic Integrity Tool (Henriksen et al. 2006) software (Figure 2). Analysis of flow alteration reduced the initial set to those that have changed the most from baseline to current conditions and are expected to change the most from current to future conditions. Metrics that correlate strongly with other metrics were then removed. The selected subset of hydrologic metrics represents all parts of the hydrograph (Table 1).

River type classification initially was based on watershed size and percent karst geology. This first-cut classification was later abandoned in favor of an iterative statistical approach aimed at increasing sample sizes and strengthening flow-ecology relationships. Ultimately,

Table 1. Subset of flow metrics selected for the Middle Potomac Sustainable Flows Project after screening. Italics indicate metrics exhibiting strong relationship to Chessie BIBI, a benthic index of biotic integrity.

Flow Range	Magnitude	Duration	Frequency	Other
High	*Mean high flow volume*	*High flow duration*	*High pulse count,* *High flow frequency,* *Flood frequency*	Skewness in annual maximum flows
Medium	Median annual flow volume	*Flood-free season*		*Fall rate,* *Flashiness*
Low	4-day harmonic mean low, Seasonal Q85, 7Q10	*Low pulse duration,* *Extreme low flow duration,* *Coefficient of variation in low flow pulse duration*	*Low pulse count,* *Extreme low flow frequency*	

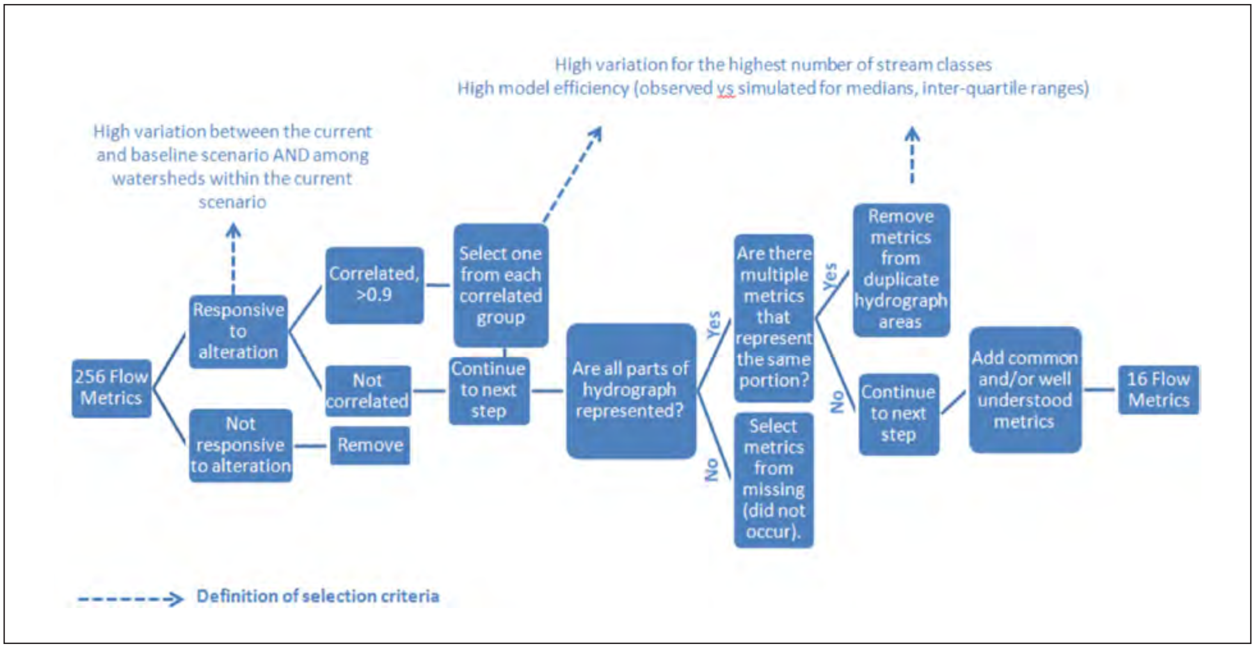

Figure 2. Process for selecting flow metrics for flow-ecology analysis.

selected hydrologic metrics were normalized by watershed area and biological metrics were normalized to a comparable scale, accounting for much of the basin's natural variability and thus obviating the need to classify rivers.

Biometric selection began with multiple exploratory analysis of an extensive basin-wide benthic invertebrate database to identify those metrics that are most responsive to anthropogenic stress and habitat degradation. Correlations between those biometrics and candidate flow metrics then were tested. Although a range of biometrics was examined, one particularly revealing metric was the Chesapeake Bay benthic index of biotic integrity database ("Chessie BIBI"). Chessie BIBI combines macroinvertebrate, habitat, and water quality data from 23 federal, state, local, and ICPRB monitoring programs in a uniform database structure. Starting with 50 family-level benthic invertebrate metrics, scientists selected the overall index metric (Buchanan et al. 2011) and 19 other metrics that indicate community status, are not correlated, and are expected to respond to flow alteration. These metrics represent taxonomic composition, pollution tolerance, functional habitat group, and functional feeding groups. Biological data for 2000-2008 were used.

Flow-ecology relationships were determined using quantile-regression. Examples are shown in Figure 3. The biological samples used represent status at a single point in time, but are being used to represent status over a longer time period. To account for uncertainty in the true biological status around the value calculated from a single point, flow-ecology curves were defined as the 90th percentile regression rather than as the maximum values of biological metrics reported. The regression curves (calculated with the Blossom program (Cade and Richards 2005)) represent the best possible biological score (with 10% allowance for uncertainty) for a given degree of flow alteration.

At the expert workshop in November 2011, local and regional scientists reviewed preliminary flow alteration-ecological response statistical relationships. The project technical team members explained that they chose to focus exclusively on benthic macroinvertebrates because of the availability of a basinwide dataset, and they gave an overview of their study design and initial findings. After reviewing the findings, the workshop participants recommended that the study team consider other taxa, particularly for evaluating ecological responses to low flow alteration—a primary management concern for which benthic macroinvertebrates proved to be poor indicators. The experts also questioned whether the relationships found for macroinvertebrates adequately captured flow-dependencies of other ecosystem components, such as fish and riparian vegetation. They also expressed a

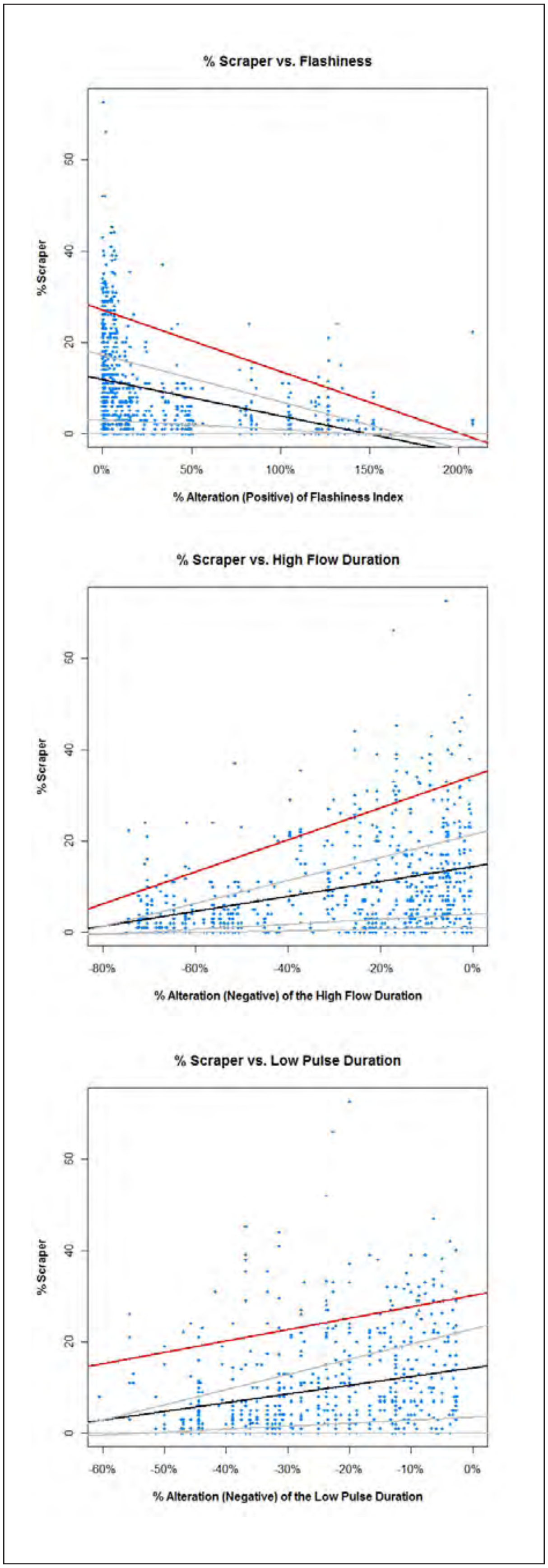

Figure 3. Quantile-regression plots of selected flow-ecology relationships in the Middle Potomac River basin project area. Red is 90th percentile. Additional quantile regressions at 10th, 25th, 50th, and 75th percentiles are also shown.

concern that water managers and users would have difficulty understanding the hydrologic metrics and relating to the biological metrics that were used, and they recommended providing alternative presentations of the study findings that would be more intuitive and understandable by resource managers.

The Potomac project was designed as a holistic, interstate environmental flow needs assessment for the entire watershed, using a shared hydrologic foundation and biological dataset. However, state agencies regulate water withdrawals in the Potomac watershed, and local authorities make land use decisions that affect flows. For this reason, flow recommendations emerging from this regional analysis will need to be implemented at the individual state or local level. The Potomac project team is sharing flow alteration-ecological response relationships with state-level resource managers and teams to support their technical assessments and recommendations for protecting and restoring environmental flows and stream health throughout the watershed.

ACKNOWLEDGMENT

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2.7 Susquehanna River Basin Ecosystem Flow Recommendations

The Susquehanna River basin project demonstrates (1) the systematic organization of relevant information sources, including published and gray literature and existing data, to facilitate expert input on flow-ecology relationships and environmental flow recommendations, and (2) a novel expression of environmental flows for maintaining long-term hydrologic variability.

The 1972 Susquehanna River Basin Compact between New York, Pennsylvania, Maryland, and the Federal government established the interstate Susquehanna River Basin Commission (SRBC). SRBC's mission is to manage the basin's water resources under comprehensive watershed management and planning principles, and it has authority to regulate water withdrawals within the three basin states. SRBC facilitated this science-based process to determine environmental flow needs throughout the basin. Because the SRBC has interstate regulatory authority, the resulting recommendations are expected to be used to revise water policy, inform basin planning, and improve water releases from reservoirs within the basin starting in 2012.

This project was completed under Section 729 authority of the Water Resource Development Act, which authorizes the U.S. Army Corps of Engineers (Corps) to assess water resource needs of river basins, including needs related to ecosystem protection and restoration and water supply. SRBC provided the non-federal cost share and contracted with The Nature Conservancy (TNC), which was the technical lead. The project began in early 2009 and was completed in 18 months.

The project's success hinged on the ability to synthesize diverse sources of information, to present it in formats that facilitate group discussion, and to convene and use expert knowledge effectively. Box 1 outlines the project schedule, organized around three pivotal meetings.

Through consultations with experts, the technical team assembled a broad list of ecological indicators, including flow-sensitive taxa groups, vegetation community types, and physical processes. The technical team then surveyed scientific literature to find dependencies between these indicators and specific flow components and, where possible, to extract relationships between flow alteration and ecological response. Using species distribution data and expert consultations, they associated species groups with major habitat types and described common traits and microhabitat preferences for each species group.

Box 1. Susquehanna River Basin Ecosystem Flows Study Outline

Orientation meeting (9 March 2009)

- **Meeting outcomes**
  - Engaged stakeholders
  - Nominated ecological indicators
  - Suggested information sources
  - Identified potential data gaps
- **Technical team work (Mar 2009-Oct 2009)**
  - Reviewed and synthesized literature
  - Identified functional species groups
  - Delineated preliminary river types

First expert workshop (14-15 Oct 2009)

- **Materials provided to participants before the meeting**
  - Hydrographs showing 1960-2008 inter- and intra-annual flow variability and the timing of life-history stages for each species group
  - Table of detailed information associated with each species and life stage
- **Meeting outcomes**
  - Drafted flow-ecology hypotheses by river type
  - Prioritized additional information for summary report
  - Suggested analyses to help develop flow recommendations
- **Technical team work (Oct 2009-Apr 2010)**
  - Reviewed literature and consulted experts to support hypotheses
  - Drafted flow recommendations
  - Drafted summary report

Second expert workshop (7-8 Apr 2010)

- **Materials provided to participants before the meeting**
  - Draft flow-needs diagram for each major habitat type (Figure 1)
  - Draft flow recommendations (Figure 2)
  - List of literature cited
- **Meeting outcomes**
  - Peer-reviewed major products
- **Technical team work (Apr 2010-Sept 2010)**
  - Analyzed effects of flow recommendations on streamflow under different water withdrawal scenarios; obtained further expert consultation
  - Finalized recommendations
- **Final report (Sept 2010)**
  - DePhilip and Moberg (2010)

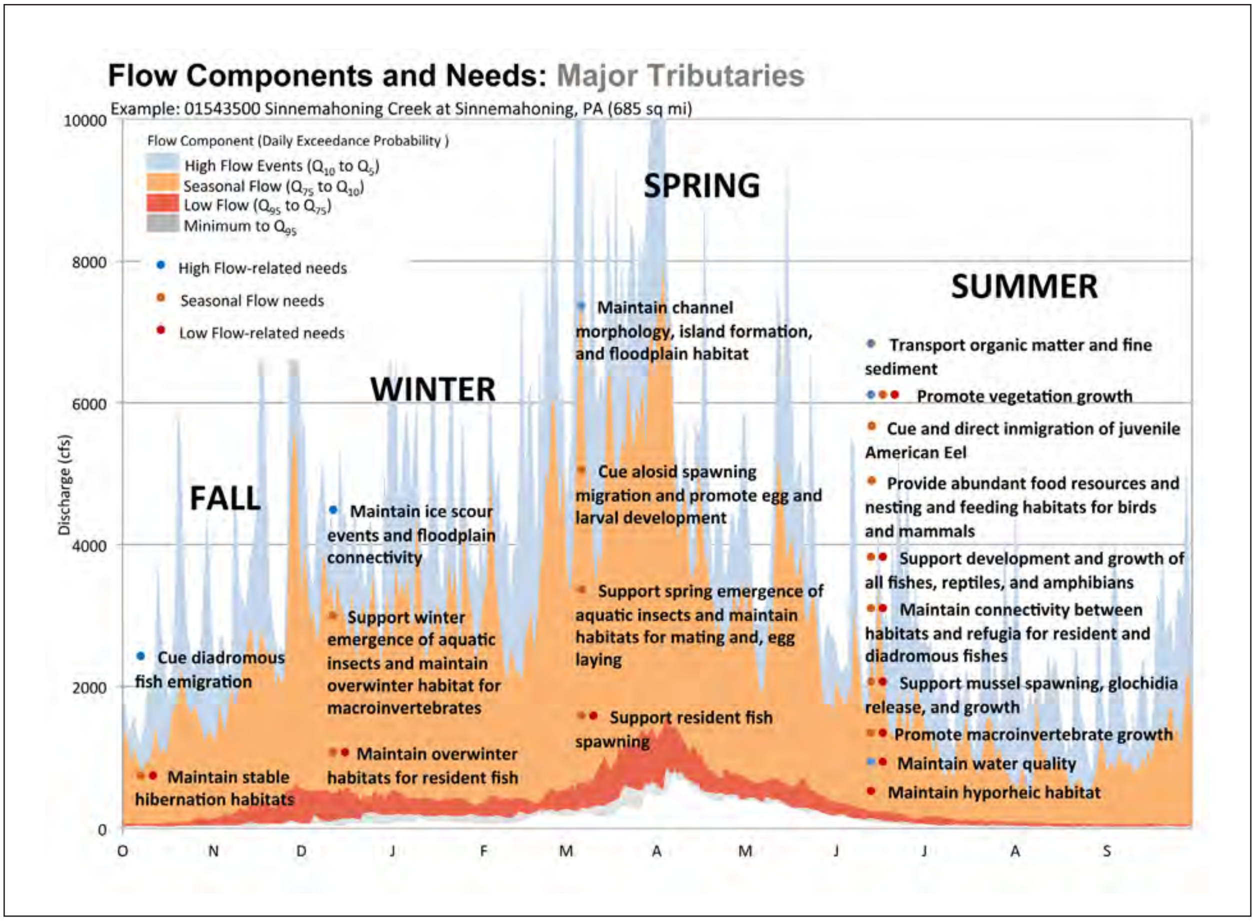

Figure 1. Graph showing ecological functions that depend on typical low, seasonal, and high flows during fall, winter, spring, and summer for one habitat type (Major Tributaries) in the Susquehanna River basin. A similar graph for each habitat type greatly facilitated development of flow recommendations in an expert workshop.

A basic habitat classification based on watershed size, temperature, and flow stability was developed for organizing and synthesizing information. Three existing classification systems were tapped to assign river reaches to five major habitat types. The Northeast Aquatic Habitat Classification (Olivero and Anderson 2008) defined "major tributaries" and "mainstems" as reaches with drainage areas exceeding 200 mi^2. Hydrologic classification using the USGS Hydrologic Integrity Process (HIP) software (Henriksen et al. 2006) defined "high-baseflow streams." Water-quality designations from state regulatory programs defined "cool and coldwater streams" and "warmwater streams."

Long-term data for 45 minimally-altered (baseline) stream-flow gages indicate that the flow volume on any day of the year varies considerably from year to year. To capture this variability, the technical team defined monthly high, seasonal, and low flow components for each major habitat type.

Representative hydrographs juxtaposing these flow components to life-history stages of native species prepared participants for the first expert workshop. Workshop participants used this information to identify the most sensitive periods and life stages for each habitat type, and to formulate flow-ecology hypotheses. Following the first workshop, the technical team further compiled and synthesized diverse information, using the flow-ecology hypotheses to focus their research.

Ecosystem flow needs were then summarized graphically by season in relation to high, seasonal, and low flows for each major habitat type (Figure 1). These graphs and supporting narratives describe the role of inter-annual as well as seasonal hydrologic variability in forming channels and floodplains; maintaining water quality; and supporting life stages of fish, aquatic insects, mussels, reptiles, amphibians, birds, and mammals.

The vast array of ecosystem flow needs convinced the project team that it needed to develop environmental flow recommendations for many different taxa for each major habitat type—even those that lack large databases. Rather than assume that a single species or group of species can represent all ecosystem needs, the team took a novel

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SUMMER		
Promote/support development and growth of all fishes, reptiles, and amphibians – Summer and fall flows needed to maintain high velocity riffles, low velocity pools, and backwaters and stream margins. *All habitat types*	**Seasonal Flow May-Oct** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Mar-July** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	In a large river, availability and persistence of shallow-slow water habitats were directly correlated with fish abundance, particularly percids, catostomids and cyprinids (Bowen et al. 1998). Reductions of streamflows during this period have had measurable impacts on size of adult brook trout (Hakala and Hartman 2004, Walters and Post 2008) On headwater and small streams, a simulated removal of 8% of Aug median (p50), predict 10% shift in fish assemblage; On large rivers removal of 10% in of the Aug median (p50) predict 10% shift in fish assemblage (Zorn et al. 2008). Baseflows in a large river were augmented by an estimated 100% under regulated conditions resulting in an estimated 40% reduction of shallow slow water habitat patch size during normal baseflow periods (summer-fall-early winter) (Bowen et al. 2003). Young-of-year abundance most correlated with shallow-slow habitat size and persistence. Suitable conditions predicted by statistics including seasonal median daily flow, high pulse magnitude, duration and rate of change (Freeman et al. 2001). A comparison of large warmwater streams along a withdrawal index gradient finds a shift in fish assemblages from fluvial specialists to habitat generalists as withdrawals increase above 50% of 7Q10 (Freeman and Marcinek 2006). Longitudinal connectivity is important as map turtles migrate to nesting locations. Stream migrations of 1-3 km have been documented on the lower Susquehanna River (Richards and Seigel 2009).
Maintain connectivity between habitats and refugia for resident and diadromous fishes – resident and diadromous fish need seasonal flows to maintain thermal refugia and maintain connectivity among habitats *All habitat types*	**Seasonal Flow - Jun-Oct** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Elimination of longitudinal connectivity (simulated barriers) prevented upstream migration of brook trout and led to extinction of local brook trout populations within 2 to 6 generations. Extinction of source populations increased the probability of metapopulation extinction (Letcher et al. 2007).

Figure 2. Format of Susquehanna River basin flow recommendations, associating ecological function with ranges of associated flow statistics, and information that supports the recommendation. Colors indicate flow components (low, seasonal, or high (not shown)).

approach. The resulting flow recommendations are based on (a) existing literature and studies that described and/or quantified relationships between flow alteration and ecological response, (b) expert input, (c) the analysis of long-term flow variability at minimally-altered gages, and (d) results of water withdrawal scenarios that tested the sensitivity of various flow statistics.

Ten types of flow statistics were selected to describe the magnitude and frequency of large and small floods, high flow pulses, median monthly flow, and monthly low flow conditions in the Susquehanna River basin: magnitude and frequency of 20-year (large) flood, 5-year (small) flood, and bankfull (1-2 year high flow) events; frequency of high flow pulses in summer and fall; high pulse magnitude (monthly

Q10); monthly median (Q50); typical monthly range (area under monthly flow duration curve between the Q75 and Q10); monthly low flow range (area under monthly flow duration curve between Q75 and Q99); monthly Q75 and monthly Q95. In addition, monthly range and monthly low-flow range statistics were used to quantify changes in flow-duration curve shape (Vogel et al. 2007), complementing analyses of changes in individual flow metrics to assess seasonal impacts of water use on ecological flow regimes. DePhilip and Moberg (2010) explain how to process output from Indicators of Hydrologic Alteration software (The Nature Conservancy 2009) to calculate flow alteration as differences between flow duration curves. Flow recommendations are expressed in terms of acceptable ranges of these flow statistics.

The team systematically documented the flow needs that each recommendation supports, and the literature and studies on which the recommendation is based (Figure 2). Structuring the flow recommendations in this way facilitated the review process and provides a framework for adding or refining flow needs, substituting flow statistics, revising flow recommendations, and documenting additional supporting information. This structure also focuses future research on relationships between specific types of flow alteration and specific ecological responses.

To further understand the sensitivity of each flow component and to help translate the flow recommendations into policy, the team analyzed a suite of future water withdrawal scenarios and compared alternative flow thresholds. In March 2012, SRBC released a draft Low Flow Protection Policy for public comment, based in part on the flow recommendations generated by this project.

TNC currently is extending the work described in this case study to the Ohio and Delaware River basins in Pennsylvania and adjoining states. At the same time, USGS is developing a Virtual Gage Tool similar to Massachusetts' Sustainable Yield Estimator (Archfield et al. 2010) to estimate minimally-altered (baseline) daily time series for ungaged sites in Pennsylvania. Adding water-use data to these time series will enable comparison between flows under baseline and current conditions. Pennsylvania Department of Environmental Protection (PA DEP) and SRBC plan to use this tool to help review proposed water withdrawals and to ensure that future water use maintains the environmental flows recommended in this and future studies.

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2.8 Ohio Thresholds for Ecological Flow Protection

This case study demonstrates (1) the integration of flow-ecology relationships and proposed streamflow protection standards with existing water quality standards using a tiered Aquatic Life Use (ALU) approach and (2) the development of flow-ecology response curves from statistical analysis of flow-habitat and habitat-ecology relationships using extensive habitat and biological databases.

This project is a work in progress. The process described here (Rankin et al. 2012) was carried out independently by a non-profit research institute, the Midwest Biodiversity Institute (MBI), with funding from The Nature Conservancy (TNC). A coalition of environmental groups is using the results to secure ecologically-based low flow protection in the ongoing Ohio Great Lakes Compact Implementation process. Additionally, the Ohio Department of Natural Resources (ODNR) has expressed interest in using the flow-ecology response curves developed during this process to evaluate proposed water withdrawals after a regulatory program is in place.

Ohio's development of ecological flow protection standards stems from Ohio's commitment to comply with the Great Lakes Compact (see Michigan case study). The Ohio Legislature's ratifying language and allotted time of one year to develop implementation language constrained the initial focus to low flows, which represent the most ecologically stressful period of the year. Given the time limit, water users' resistance to new regulatory programs, and the highly altered condition of many of Ohio's streams, the approach was designed to mesh with the Ohio Environmental Protection Agency's existing ecological monitoring and tiered ALU framework. Because the Compact drove the process, initially it was developed only for the Ohio streams that are tributary to the Great Lakes.

The hydrologic foundation is a database of mean daily flow for the month of lowest flow (historically September) over a 20-year period, housed in the U.S. Geological Survey StreamStats system (Koltun et al. 2006). Flow regression modeling (Koltun and Whitehead 2002) was used to estimate this flow statistic for ungaged sites. Because pre-development flows are not determined, the hydrologic foundation implicitly sets the current condition as the baseline. Groundwater-surface water interactions were not considered during this initial phase because almost all Ohio streams in the Lake Erie basin are runoff-dominated.

Table 1. Ohio's Aquatic Life Use Classes (Ohio EPA 2004).

Class	Description	% of Waters
Warmwater Habitat (WWH)	Principal restoration target for most of Ohio's rivers and streams in Ohio, with "typical" warmwater species assemblages.	77.4
Exceptional Warmwater Habitat (EWH)	Protection goal for Ohio's best water resources, which support "unusual and exceptional" assemblages of aquatic organisms, with a high diversity of species, particularly those which are highly intolerant and/or rare, threatened, endangered, or special status (i.e., declining species).	10.2
Modified Warmwater Habitat (MWH)	Streams and rivers that have been subjected to extensive, maintained, and essentially permanent hydromodifications such that the biocriteria for the WWH use are not attainable, with species that tolerate low dissolved oxygen, siltation, nutrient enrichment, and poor quality habitat.	3.8
Limited Resource Water (LRW)	Small streams (usually less than 3 mi^2 drainage area) and other water courses that have been irretrievably altered to the extent that no appreciable assemblage of aquatic life can be supported; includes small streams in extensively urbanized areas, those that lie in watersheds with extensive drainage modifications, those that completely lack water on a recurring annual basis (i.e., true ephemeral streams), and other irretrievably altered waterways.	6.2
Coldwater Habitat (CWH-N and CWH-F)	Waters that support assemblages of native coldwater organisms (CWH-N) and/or those that are stocked with salmonids with the intent of providing a put-and-take fishery on a year-round basis (CWH-F).	2.4

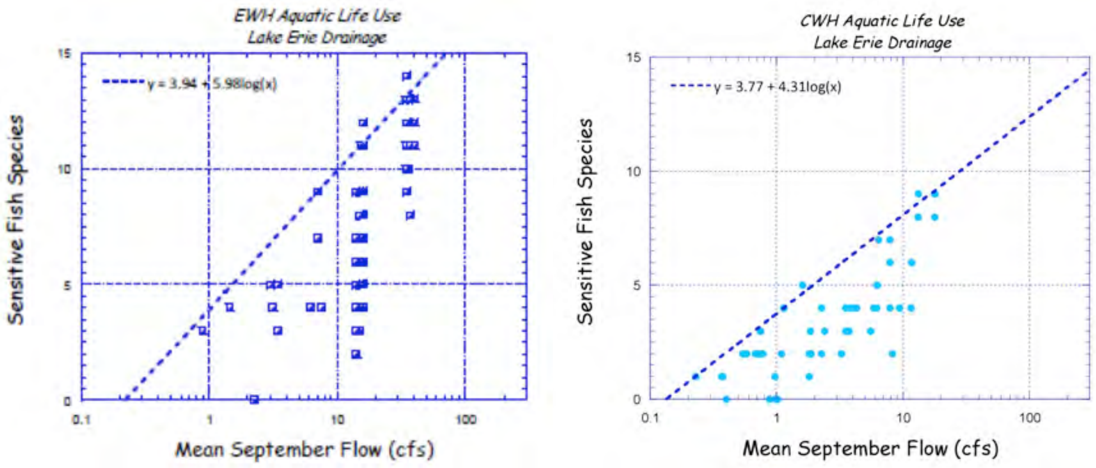

Figure 1. Flow-ecology relationships for two of Ohio's river types, EWH (exceptional warmwater habitat) and CWH (coldwater habitat). Dotted lines indicate 95-percent quantile regressions.

To classify river types, researchers considered base flow index, upstream catchment size, biotic assemblage, water quality, temperature, and other ecoregional characteristics. They found that none of these could better explain ecological response (number of sensitive fish species supported) than does the existing ALU classification (Table 1). Furthermore, adopting an existing classification avoids creating a new regulatory framework. The Ohio ALU classification stratifies on the basis of ecological condition, existing flow alteration, and thermal regime (coldwater or warmwater habitat). Note that the Ohio Aquatic Life Use classification is not a river type classification in the sense described in the ELOHA framework because it considers current ecological condition.

Ohio's flow-ecology curves (Figure 1) relate number of sensitive fish species to mean daily flow in September for each river type. These relationships are derived from fish-habitat and habitat-flow relationships, and are based on the premise that water withdrawals reduce available habitat niches, which reduces the number of sensitive fish species that a stream can support. The habitat portion of this relationship was developed from Ohio's Quantitative Habitat Evaluation Index (QHEI; Rankin 1989, 1995), which includes a measure of niche availability at ecological sampling locations.

Pollution-sensitive fish species were selected for use as a regulatory target for two reasons. First, Ohio maintains a list of pollution-sensitive fish which, according to expert opinion and literature review, are also sensitive to flow alteration. Second, responses of the species on this list to low-flow depletion are strongly related to those of other sensitive aquatic species such as freshwater mussels, macroinvertebrates, and other fish species. This was determined by analyzing long-term (1990-2009) ecological sampling data at the 3,070 sample points from the Ohio Ecological database (Ohio Environmental Protection Agency, Ecological Assessment Section) paired with corresponding gaged and synthesized low-flow data. Quantile regression (Cade and Noon 2003, Konrad et al. 2008), using USGS Blossom software, quantified the flow-ecology relationships at the 95th percentile (Figure 1).

Currently, ODNR registers but does not otherwise regulate large consumptive withdrawals. To comply with the Great Lakes Compact, withdrawals will need to be managed actively to prevent "adverse resource impact." Through a stakeholder small workgroup process, MBI and TNC proposed to representatives of regulated industries and the Ohio Chamber of Commerce that adverse impact be defined in terms of percent loss of sensitive fish species.

The proposal specifies allowable losses of sensitive fish species for each river type. For streams of highest ecological quality (EWH, CWH), which contain the largest number of sensitive fish species—including several that are rare in Ohio—MBI and TNC proposed an allowable loss of 2%. For warmwater streams (WWH), which generally have fewer sensitive species with less sensitivity to flow alteration, they proposed an allowable loss of 10%. For altered streams (MWH), which have few sensitive and no rare fish, they proposed a 50% species loss threshold. A proposed withdrawal rate that would approach the level at which adverse species loss occurs would trigger agency review of a water withdrawal application.

In this way, the flow-ecology curves allow the ODNR to determine the cumulative amount of low-flow depletion that would cause these predetermined unacceptable losses. Only withdrawals that maintain cumulative flows above threshold levels would be permitted automatically. Proposed withdrawals that trigger the permit process would be reviewed individually.

To calculate cumulative flow depletion, the ODNR, MBI, and TNC recommend modifying the existing Ohio Stream Withdrawal Evaluation Tool (OSWET). Currently, OSWET calculates streamflow depletion due to an individual withdrawal. In the future, OSWET also could calculate cumulative depletion during September due to all local and upstream withdrawals.

The proposed Ohio thresholds would provide the benefit of protecting ecologically sensitive freshwater ecosystems, while allowing future development in more resilient ecosystems. Because the process developed for Ohio uses existing river condition to classify river types and uses current conditions as the baseline, it “grandfathers in” existing water uses and sets no restoration goals at present. Moreover, future withdrawals that cause thresholds to be exceeded still could be approved after agency review. Even so, regulated interests rejected the proposal and sought alternative legislation to exempt most withdrawals from regulation. Although the legislature passed the industry-backed bill in spring 2011, Ohio’s Governor vetoed it due to technical and legal shortcomings. As of February 2012, it is not clear how the Ohio Department of Natural Resources will comply with the Great Lakes Compact.

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The authors thank John Stark of The Nature Conservancy for describing this project to us and reviewing this case study.

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2.9 Rhode Island Stream Depletion Method

By Alisa Richardson, Rhode Island Department of Environmental Management

This case study demonstrates (1) the use of flow-ecology relationships to determine groundwater withdrawal limits, (2) ecological goal setting through river basin classification, and (3) the adoption of an ecologically-based presumptive flow standard.

The Rhode Island Stream Depletion Method (SDM) was developed in 2010 from a series of initiatives that began in 1999, driven by an increasing need for water supply in the state. In 1999, the RI General Assembly granted the Water Resources Board (WRB) sole authority to devise a fair and equitable allocation of water resources among users and uses to ensure that long-range considerations of water supply prevail over short-term considerations (Rhode Island Gen. Laws §46-15.7). In 2002, the Water Resources Board (WRB) formed the Water Allocation Program Advisory Committee (WAPAC) and launched an inclusive water allocation planning effort, which brought together 150 people from 66 participating organizations. The Committee recommended, and in March 2004 the Board approved, the establishment of the Streamflow Working Group, a partnership between WRB and the Rhode Island Department of Environmental Management (DEM) to address streamflow issues such as aquatic base flow and the further development of a statewide streamflow gaging network.

The SDM stemmed from this recommendation. At the time, most state instream flow methods in the Northeast were focused on releasing water from storage reservoirs to provide environmental flows. Very quickly it became clear that methods such as U.S. Fish and Wildlife Service's New England Aquatic Base Flow (ABF) (U.S. Fish and Wildlife Service 1981; Lang 1999) and the Rhode Island Aquatic Base Flow (Richardson 2005) approach could not work for groundwater withdrawal permitting, from a water supplier perspective, because it could prohibit groundwater withdrawals adjacent to a river with flows at or below natural August median (i.e. much of the summer).

Water suppliers needed a reliable and predictable amount of water to withdraw, particularly in summer, while the resource agencies needed to define environmentally sustainable limits on those withdrawals. Rhode Island has a large reservoir, the Scituate, which supplies 60% of the population; however, newer suburban development was occurring outside of Scituate's service area. Economic pressure to continue developing water sources was forcing water suppliers to find supplemental groundwater in places where water was already being withdrawn for agricultural needs, often at a substantial rate relative to the summer baseflow that these aquifers discharge to RI streams.

As DEM struggled to set environmentally protective withdrawal limits from permit to permit, criticism began mounting that water permits were unpredictable and costly and the process took too long. Under existing RI law, wetland permits are needed from DEM for any new or increased withdrawal of 10,000 gallons per day (gpd) or more. Additionally, the permit conditions might mandate water shutoffs during the lowest streamflow periods, which were concurrent with the highest demand periods, an unsupportable outcome for water suppliers. At the end of a long, expensive process, applicants might ultimately receive permits with limits that they did not anticipate or were infeasible to implement.

DEM began looking at various frameworks to improve their permitting process to meet the needs of both the water suppliers and the ecosystem. Two journal articles and an application concept by the Connecticut DEP (2009) played a major role in the development of the SDM. First, Freeman and Marcinek (2006) evaluated fishery response to surface and groundwater withdrawals. Second, the ELOHA framework (Poff et al. 2010) incorporated the concept of balancing human and ecological needs for water by differentiating the degree of flow alteration (i.e., allowable depletion) according to ecological condition goals.

The SDM was developed by DEM and a "Streamflow Subcommittee" of the Water Allocation Program Advisory Committee (WAPAC) as part of their eighteen-month public process. This Subcommittee included water suppliers, scientists, federal agency, and state agency representatives and outlived the WAPAC process. It was designed to answer the question of what is "sustainable" water use under Rhode Island law. In this way, DEM acted as a technical advisor to the Water Resource Board, which is the water allocation body.

METHODOLOGY

The SDM provides resource agencies with a withdrawal or streamflow depletion allowance that establishes the volume of water that can be extracted from a stream even during dry conditions (whether as direct stream withdrawals or as indirect groundwater withdrawals), while still leaving sufficient streamflow to maintain habitat conditions essential to a healthy aquatic ecosystem. This methodology is currently being applied to all new or increased groundwater withdrawals, and is being applied in the

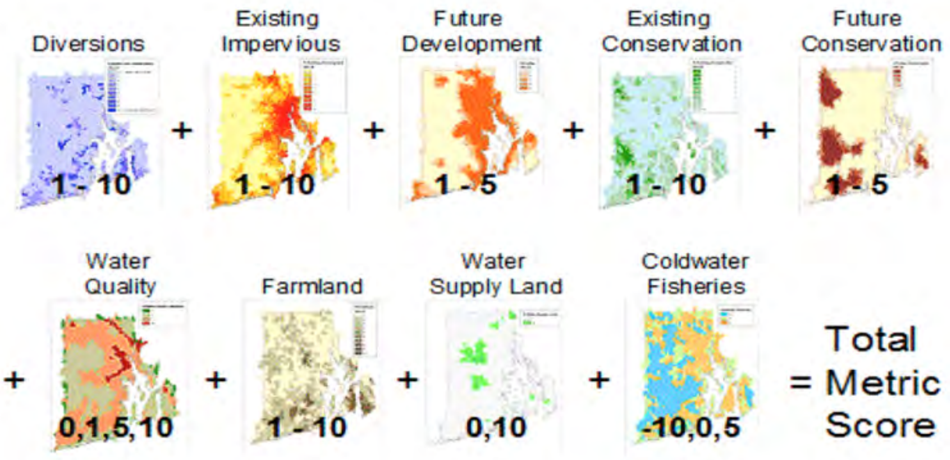

Figure 1. Representation of metrics and associated scores used in Watershed Goal Classification.

Rhode Island Water Resources Board's Statewide planning process to assess build-out scenarios and the potential for future water resource availability.

In order to arrive at a set of watershed condition goals for water management, RI watersheds were classified based on landscape and site characteristics (Figure 1). Each sub-watershed was scored using characteristics defined in a geographic information system. Higher scores were assigned to higher degrees of human alteration. By using a scoring approach, the state takes into consideration the fact that all watersheds are not of equal ecological value due to watershed characteristics and existing human influences that may alter habitat and/or natural streamflow characteristics within a watershed. Note that if a watershed contained a coldwater fishery, then 10 points were subtracted from the overall score, thereby allowing less water to be withdrawn and providing a higher level of protection via goal setting.

The total metric score was calculated for each sub-watershed and then grouped into larger watersheds to simplify management application. Each watershed was assigned to one of the goal classifications based on its total metric score, as shown in figure 2—the higher the score, the higher the class, and the higher the presumed degree of deviation from natural conditions. By applying the biological condition gradient (Davies and Jackson, 2006), appropriate management practices could be applied to each watershed.

The methodology allows for a fairly simple calculation of allowable streamflow depletion by considering existing withdrawals and returns, their locations within the watershed, the time of year, the watershed characteristics, and the natural low-flow conditions of the potentially affected river or stream. The allowable depletion calculation under the SDM takes into consideration the ecological importance of seasonal flow variations. Since it was well understood that the best management practices would maintain the natural flow regime (Poff and Zimmerman 2009; Poff et al. 1997), seasonal ecological needs were linked with natural streamflow patterns. Six hydroperiods were defined to represent the biological need for seasonal variability and four flow ranges were described to clarify the typical flow range in each hydroperiod (Figure 3).

The final step in the methodology is defining the specific streamflow depletion that is allowable and likely to maintain the natural streamflow variations described by the hydroperiods. The SDM is based upon studies conducted in the southern Piedmont area of Georgia by the U.S.

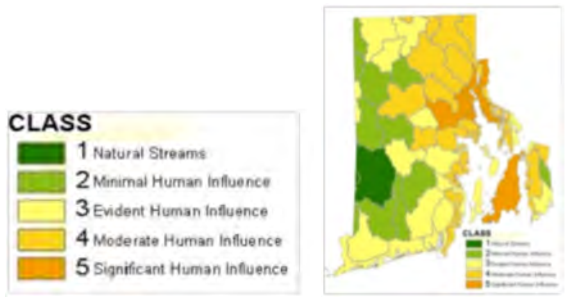

Figure 2. Final Watershed Goal Classification for each of the major watershed in Rhode Island.

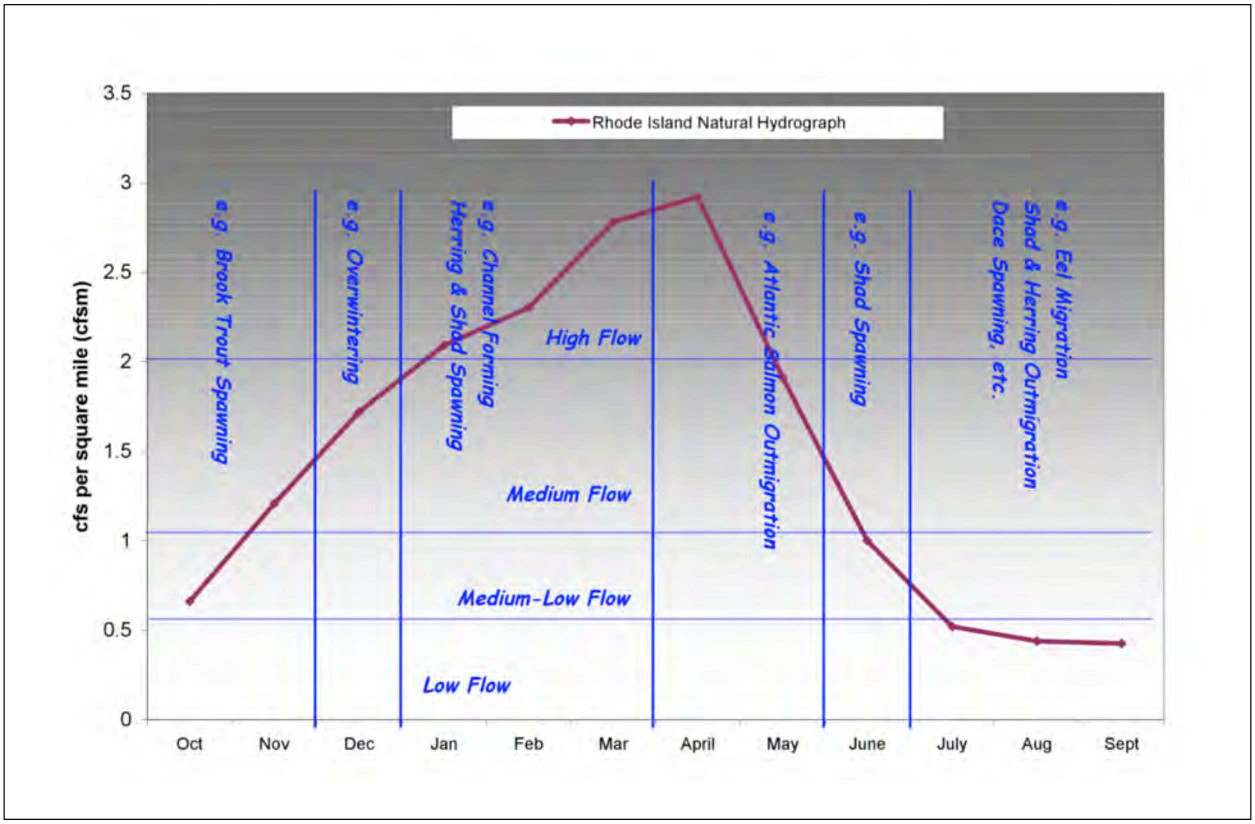

Figure 3. Annual Natural RI Hydrograph with associated hydroperiods and life stages of fish found in Rhode Island.

Geological Survey and the U.S. Fish and Wildlife Service. Freeman and Marcinek (2006) evaluated fish assemblage responses to surface water withdrawals and instream reservoirs, and documented that the richness of fluvial specialists declined as permitted monthly withdrawal rates increased above the volume equivalent to 50% of 7Q10. They also found that increasing withdrawal rates increased the odds that a site's Index of Biotic Integrity (a measure of the macroinvertebrate population health) score would fall below a regulatory threshold of biological impairment. They concluded that significant losses of river fish are associated with withdrawal rates greater than 50% of the 7Q10.

DEM gleaned from Freeman and Marcinek (2006) that 50% of the 7Q10 during the summer months (lowest flows) is the greatest depletion that could protect ecological function. DEM made the judgment that during non-summer months, more water could be depleted through withdrawals since there is almost always more water in the system. Yet it is important to note that summer low flows represent the major constraint to groundwater supply development.

Table 1 shows allowable streamflow depletions (as a percentage of 7Q10) linked to a set of Watershed Goal Classes that apply statewide. The largest depletion allowances apply to the highest classes. For example, watersheds that are the most heavily altered (e.g., greatest existing withdrawals, highly impervious, and no cold-water fisheries) were assigned a Class 5 protection goal (Figures 1 and 2) and are allowed a reliable depletion of 50% of the natural 7Q10 in summer months. Those watersheds that are the least altered (e.g., cold-water fisheries, low withdrawals, conservation land) were assigned a Class 1 protection goal and are allowed a reliable depletion of 10% of the natural 7Q10 (or a de minimus amount) in summer.

APPLICATION

When an applicant applies for a new wetlands permit, the SDM is used by the Rhode Island DEM wetlands permitting group as a presumptive approach. The DEM has prepared guidance for groundwater withdrawals (Richardson 2006) and fills out a worksheet by which DEM can quickly determine if the proposed depletion will be allowed without further study. If the proposed increased withdrawal is at or below the allowable depletion level (taking into account existing uses), then the withdrawal request is reviewed for other freshwater wetlands impacts and National Pollutant Discharge Elimination System (NPDES) flow needs.

Table 1. Allowable streamflow depletion as a percent of 7Q10.

MONTH	BIOPERIOD NEED	HYDROPERIOD	CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5
OCTOBER	Spawning & Outmigration	Medium - Low	20%	40%	60%	80%	100%
NOVEMBER DECEMBER	Overwinter	Medium	40%	80%	120%	160%	200%
JANUARY FEBRUARY	Overwinter & Channel Forming	High	60%	120%	180%	240%	300%
MARCH APRIL	Anadromous Spawning	High	60%	120%	180%	240%	300%
MAY	Anadromous Spawning	Medium	40%	80%	120%	160%	200%
JUNE	Peak Resident Spawning	Medium-Low	20%	40%	60%	80%	100%
JULY AUGUST SEPTEMBER	Resident Spawning Rearing & Growth Herring & Shad Out	Low	10%	20%	30%	40%	50%

Wetlands biologists evaluate the analysis, and if it is acceptable, then the permit is issued as requested. Impacts to wetlands are assessed and typically approved if there are no impacts to vernal pools and if the wetland vegetation is mostly surface-water driven. If the applicant's increased withdrawal exceeds the allowable depletion, or wetland impacts are unacceptable, then the applicant must conduct a site-specific study, reduce the request, or be subject to shutoffs. All decisions take into account cumulative impacts of existing use to the extent possible.

This method is also being applied at the statewide planning level. The WRB is evaluating future resources and projections of build-out demand by comparing future demand to the SDM for each watershed in Rhode Island. This method has helped to identify locations where water resources may constrain future development.

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3.0 Getting Environmental Flows to Scale: An Overview of the Process

Figure 1.1 reflects the original conceptualization of the ELOHA framework (Poff et al. 2010; Apse et al. 2008). This framework can be summarized in four not necessarily sequential steps:

- Building a Hydrologic Foundation and Assessing Flow Alteration
- Classifying River Types
- Developing Flow-Ecology Relationships
- Defining Goals and Setting Standards

In practice, as our case studies show, the up-scaling of environmental flows for policy and planning has taken many forms. The ELOHA framework has guided many of these processes, in others it has had less bearing, and in all cases the processes are adapted to local circumstances and data availability. This section of the report outlines each step of the framework, reviews how different users have adapted these steps to conform to their unique needs and constraints, and provides general observations regarding each step.

3.1 Understanding Water Availability: Building a Hydrologic Foundation

Informed regional water management decisions require knowledge of where, when, and how much water occurs in all water bodies across the landscape. Thus, the ELOHA framework is built on a "hydrologic foundation" of streamflow data[10] within a region. This information is used to assess flow characteristics, classify river types, quantify flow alteration, evaluate ecological responses to flow alteration, and evaluate the status of sites relative to environmental flow standards.

True to its name, the hydrologic foundation is indeed the foundation of ELOHA and as such its construction is considered the first step of the ELOHA framework. In practice, few if any places have such a dataset in place at the onset, and building it usually requires considerable time and thought. To maintain the momentum generated at the early stages of the project, many water managers have successfully advanced other parts of the framework while the hydrologic foundation is being developed, rather than awaiting its completion before proceeding with successive steps.

3.1.1 What is the Hydrologic Foundation?

The hydrologic foundation envisioned by Poff et al. (2010) consists of two databases of daily streamflow time series representing *baseline* and *current* conditions for every *analysis node* over a common time period of at least 20 years to represent climate variability. For planning purposes, databases of *future* streamflow scenarios also may be created.

Analysis nodes ideally are located where ecological data have been collected, where flow management actions such as water allocation may be taken, where streamflow will be monitored to ensure compliance with flow standards, and above and below major river confluences.

Baseline conditions typically refer to minimally altered conditions before major dams and diversions affected hydrology. Understanding baseline flow conditions and their natural range of variability is fundamental to understanding ecological flow needs and the response of ecosystems to hydrologic changes (Apse et al. 2008, Poff et al. 1997). Baseline conditions also may represent prior land cover and drainage conditions, depending on management and restoration goals, data availability, feasible restoration options, and political expediency.

Current conditions account for cumulative effects of dams, surface-water diversions, groundwater withdrawals, return flows, and other existing causes of flow alteration. Current-condition flow data can be compared with baseline flow data to calculate flow alteration at any analysis node.

Future conditions also may be modeled. For example, in the Middle Potomac River basin, scientists are modeling streamflow under five potential future scenarios, in addition to baseline and current conditions. This way, stakeholders can evaluate how different water management policies, population growth patterns, and climate change are likely to affect environmental flows.

Some adaptations of ELOHA use only current conditions, relying on spatial variation across watersheds to infer the range of potential conditions from least to most altered. This allows for development of flow-ecology curves, but limits the ability of researchers and decision makers to understand the degree to which flows have already been altered. Michigan and Ohio based their flow-ecology curves exclusively on current flow conditions.

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[10] This report refers to streamflow data and flow alteration. Although our case studies used flow data to assess rivers and streams, ELOHA is equally applicable to lakes and wetlands, in which case water level data would substitute or supplement flow data, and water-level and hydroperiod alteration would be assessed.

3.1.2 Criteria for Hydrologic Model Selection

Regardless of the application, developing a hydrologic foundation requires modeling. At many gaged sites, existing time series need to be extended and baseline conditions need to be simulated. At ungaged sites, the entire time series for both baseline and current conditions need to be simulated. Hydrologic modeling fills in these gaps and provides a powerful foundation for management.

Various approaches can be used to model hydrology. The model chosen depends on the project budget and schedule, data availability, hydrology, ecology, and modeler expertise.

The finer the temporal and spatial scale, the more flexible the model is likely to be for management. The databases generated by hydrologic modeling need to have enough spatial detail to resolve reaches with different streamflow characteristics (e.g., because of an intervening tributary) and small streams that nonetheless provide significant habitats. The reach scale of the U.S. Geological Survey's National Hydrography Dataset (NHD+) meets these criteria; moreover, the NHD+ provides a consistent spatial platform for routing flows and for compiling and processing other relevant data. Ideally, the model generates daily or even sub-daily flow data.

Daily flow data allow for the calculation of ecologically relevant flow statistics (Henriksen et al. 2006, Mathews and Richter 2007). Where daily flow synthesis is impractical, the model may generate weekly or monthly time series. If groundwater discharge provides significant baseflow to surface water, then it must be accounted for in the model. Likewise, if rivers discharge into estuaries, then estuarine inflows also should be modeled. As a general rule, the period of record modeled should be at least 20 years to account for normal climate variability. Kennard et al. (2009) provide more rigorous guidance on selecting a period of record for estimating hydrologic metrics for ecological studies.

Although a daily flow time series is ideal, many states and basins are having success using monthly or other time steps. In addition, in some applications (e.g., Michigan and Ohio), ecologically relevant flow statistics have substituted for time series; however, this approach limits the ability to analyze hydrologic alteration and to compare various management scenarios.

Individual and cumulative impacts on streamflow of surface-water diversions, groundwater withdrawals, and return flows should be included in the hydrologic foundation of current conditions. In states and basins with adequate reporting, this accounting is not particularly difficult or costly (e.g., Massachusetts). More difficult is the inclusion of dam operations and land-use changes into current condition hydrologic estimates. Both should be modeled if feasible, but it is worth noting than none of our case studies effectively incorporates both land use and dam operation impacts. Finally, the ability to simulate hydrologic impacts of climate change is useful for planning applications.

To summarize, an ideal hydrologic model creates a hydrologic foundation that will:

- be spatially comprehensive to capture regional-scale hydrologic variability and to include locations where water management decisions will be made and where ecological data have been collected;
- have the smallest time step possible for management needs;
- represent baseline (minimally altered), current, and potentially future streamflow conditions;
- address groundwater and estuarine flows where appropriate;
- be able to simulate new water uses and reservoir operations;
- allow for the calculation of the range of ecologically relevant flow characteristics; and
- simulate individual and cumulative effects of water use, reservoir operations, and potentially land use and climate change.

Every model has limitations: some excel at modeling high flows, others simulate low flows better, still others capture annual variability particularly well, and so on. The choice of hydrologic model depends largely on the flow components to which the subject ecosystems are most sensitive. For example, Michigan and Ohio modeled only August or September flows because those are the months when their aquatic ecosystems are most sensitive to water withdrawals, and their water withdrawal permitting programs are designed to address these sensitive periods. In contrast, for the Susquehanna and Connecticut River basins, the purpose of the hydrologic foundation is to evaluate the relative difference in flows between scenarios. In these cases, consistency and accurate water accounting may be more important than obtaining absolute flow values.

3.1.3 Components of the Hydrologic Foundation

The basic components of a hydrologic foundation of daily streamflow data are hydrologic simulation and water use accounting. Below we provide brief overviews of each component and examples of their application to ELOHA.

Hydrologic Simulation

Hydrologic simulation is used to estimate streamflow conditions. Three general approaches to hydrologic simulation are drainage area ratio method, regression modeling and process modeling. Drainage area ratio method and regression modeling tend to be faster, simpler, and therefore less expensive, whereas process modeling enables evaluation of land use and climate change scenarios.

Drainage Area Ratio Method

One of the simplest approaches to developing minimally altered streamflow data is the drainage area ratio method. This method derives a daily flow time series for an ungaged site by scaling the ratio of drainage area above that site to that above a gaged index site with minimally altered flows (Stedinger et al. 1992). This method is greatly limited by the spatial and temporal availability of gage data from minimally altered rivers that have similar watershed characteristics to the ungaged site of interest. However, this approach can be useful in areas of the country in which the density of stream gages on unregulated streams is relatively high and watershed characteristics do not vary greatly. Linking an ungaged site to a gaged index site can be as simple as using proximity and as complicated as kriging (Kitanidis 1992). Connecticut River basin modelers found the drainage area ratio method to estimate flood flows more accurately than regression techniques. StateMod, the hydrologic foundation for ELOHA in Colorado, also uses the drainage area ratio method, weighted by precipitation.

Regression Modeling

Various regression techniques have been used to estimate flow statistics and examples abound. For decades, USGS hydrologists have developed and published simple regression equations for estimating selected hydrologic statistics of local interest for water management. USGS StreamStats is an online application that computes flow statistics with regression equations for the user at any location. StreamStats is being developed on a state-by-state basis as funding becomes available. In Minnesota, for example, StreamStats uses regression equations (Lorenz et al. 2009) to estimate instantaneous peak flows with recurrence intervals of 1.5, 2, 5, 10, 25, 50, 100, and 500 years.

Sanborn and Bledsoe (2005) developed a modified regression approach that generates ecologically relevant flow statistics for highly heterogeneous regions under unaltered conditions. To account for heterogeneity, rivers are first stratified into similar hydrologic groups before developing regression equations specific to each group. Their regression parameters include climate and watershed characteristics. The method predicts flow magnitude, timing, and rate of change metrics better than streamflow variability metrics. This approach is being used to develop a hydrologic foundation for predicting risk of invasive species spread in river networks under various climate and dam management scenarios (LeRoy Poff, Colorado State University, written communication Feb.13, 2012).

Generally, regression modeling is a relatively inexpensive approach for reliably estimating baseline conditions statewide. It can generate a wide range of flow statistics, often with low standard errors of prediction. However, its versatility is limited. Apse et al. (2008) discuss caveats regarding simple regression models, including their limited ability to simulate extreme high and low flows and extremely large and small catchments. Furthermore, regression alone cannot generate daily flow series; regression only calculates certain statistics that characterize flow over a long time period. In contrast, with a time series of data, hundreds of flow statistics can be calculated and systematically reduced to those with the most ecological relevance for a particular river type.

To overcome this limitation, Archfield et al. (2010) developed a method that uses parameter-based regression to estimate flow-duration curves, which are then transformed into daily flow series for ungaged sites. A map correlation method (Archfield and Vogel 2010) is used to select reference gages for the regressions. The parameters used for regression include precipitation, air temperature, geologic substrate, percent of basin occupied by open water, and other basin characteristics. Because physical and climate processes affect portions of the flow-duration curve differently, different variables are used to estimate different streamflow quantiles. The Sustainable Yield Estimator (SYE) used this technique to generate baseline flow series for Massachusetts, Pennsylvania, and the Connecticut River basin. As mentioned above, current-condition flows are calculated by adding or subtracting water use and, in the case of the Connecticut River basin, reservoir release data to the baseline flows.

Michigan and Ohio used multiple linear regression and quantile regression, respectively, to estimate low-flow statistics for their flow-ecology models. Michigan added flow routing and a program that calculates time-varying streamflow depletion due to groundwater pumping (Barlow 2000), creating an online decision support system for water withdrawal permitting. Apse et al. (2008) describe other statistical approaches used to estimate ecologically relevant streamflow statistics in Pennsylvania, Tennessee, western United States, the United Kingdom, and elsewhere.

AFINCH (Analysis of Flows in Networks of CHannels) is a new computer application that uses regression and water accounting to generate monthly time series of current-condition flows at the National Hydrography Dataset Plus (NHD+) reach scale. Flows are accumulated and conserved downstream through the NHD+ streamflow network (Holtschlag 2009). Although AFINCH has not yet been used for flow-ecology analysis, its fine spatial resolution is amenable to coupling flow data with biological sampling sites. A model using the AFINCH application is currently being developed for the Great Lakes basin through Great Lakes Aquatic GAP[11]. Like all regression-based approaches, AFINCH is limited in its ability to model land-use and climate changes, to represent areas with karst or mined hydrogeology, and to simulate intermittent headwater streams.

Process Modeling

Physical process modeling, also known as rainfall-runoff, watershed, or hydrologic process modeling, tracks the flux of water through the entire hydrologic cycle, accounting for surface and subsurface watershed properties and weather. Although these models can be complicated to construct and calibrate, they can be used to simulate many different types of scenarios, including climate and land-use change. However, because of their complexity, process models typically are applied to sub-watersheds that are smaller than ELOHA's intended geographic scope or, when they are applied to large regions, their spatial discretization may be too coarse for ELOHA. Hydrological Simulation Program FORTRAN (HSPF), Precipitation Run-off Modeling System (PRMS), Soil and Water Assessment Tool (SWAT) and MIKE SHE[12] are commonly used hydrologic process models.

Scale issues notwithstanding, process models have generated hydrologic data for some ELOHA applications. The Middle Potomac River basin project and the Commonwealth of Virginia (see Commonwealth of Virginia Flow-Ecology website[13]) built their hydrologic foundations from an existing HSPF model, the Chesapeake Bay Program Watershed Hydrology Model. Kennen et al. (2008) used a process model called TOPMODEL to simulate daily streamflow under baseline and current conditions for 856 mostly ungaged biological monitoring sites in New Jersey. An empirically-based algorithm was added to improve simulation of runoff from impervious surfaces. The biological and hydrologic databases are now poised for analyzing flow-ecology relationships.

Water Use Accounting

A full hydrologic foundation that includes baseline and current-condition hydrographs employs water use accounting, regardless of the hydrologic simulation approach. By adding and subtracting water withdrawals and return flows to streamflow, water use accounting estimates the impact of water use on streamflow conditions.

The Middle Potomac River basin and Virginia[14] used process modeling to estimate current-condition flows, then added and subtracted withdrawals and discharges to generate baseline-condition hydrographs. Coming from the other direction, Massachusetts and the Susquehanna River basin used regression to estimate baseline flows, then subtracted and added withdrawals and discharges, respectively, to generate current-condition hydrographs. Moreover, the routing function of their water accounting module enables regression-based models to calculate cumulative effects of upstream water uses at any site.

Hydraulic flow routing and reservoir operation modeling improve model accuracy by accounting for the time delays of downstream water movement due to channel characteristics and dams, respectively. The WOOOMM model, which provides the hydrologic foundation for the Middle Potomac River basin, includes hydraulic flow routing. The Corps' HEC-ResSim model incorporates reservoir operations and flow routing into the Connecticut River basin model.

3.1.4 General Observations and Summary

Table 3.1 summarizes some of the main strengths and limitations of various approaches for developing a hydrologic foundation.

A hydrologic foundation need not be completed at the onset of the project. For the State of Connecticut and the Susquehanna and Connecticut River basins, scientists and managers recommended environmental flow ranges based on conceptual models extracted from literature, professional judgment, and analysis of flows at existing, minimally-altered gages to determine baseline flow variability. However, modeled daily flow data will be needed to implement their recommendations. In the Susquehanna River basin, proposed withdrawals and dam operations will be evaluated to determine whether they could alter streamflow beyond the recommended ranges. In the Connecticut River basin, streamflow and environmental flow targets feed into a model that compares different multi-dam operation scenarios. Therefore, both projects currently are building hydrologic foundations of baseline and current-condition daily streamflow series.

Regardless of the modeling approach ultimately selected, the hydrologic foundation can only be as accurate as the water-use (withdrawal and return flow) data that go into it. Ideally, all major surface and groundwater withdrawals are reported accurately. In practice, many states lack water use

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[11] http://cida.usgs.gov/glri/projects/accountability/watershed_modeling.html
[12] http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshemain.htm
[13] http://sifn.bse.vt.edu/sifnwiki/index.php/Commonwealth_of_Virginia_Flow-Ecology
[14] Ibid.

Table 3.1 Strengths and limitations of selected approaches for developing a hydrologic foundation, listed in approximate order of effort and expense. All approaches listed include water accounting. Case studies (section 2) elaborate on the examples listed.

Approach	Examples	Strengths	Limitations
Drainage-area ratio method	StateMod (Colorado), flood flows (Connecticut River basin)	Low cost, easy to generate.	Limited accuracy if index gages are sparsely located or do not represent the natural range of flow regimes.
Regression-generated monthly statistic	Median August flow (Michigan), mean September flow (Ohio)	Low cost, easy to generate, widely accepted.	Current-condition only. Not a time series. Represents only one environmental flow component.
Regression with water accounting and flow routing	U.S. Geological Survey (USGS) AFINCH (No ELOHA case study)	High spatial resolution; linked to NHD+.	Monthly time series only. Has not been tested outside Great Lakes basin.
Duration-curve regression plus water accounting	USGS Sustainable Yield Estimator (SYE) (Massachusetts, Pennsylvania)	Relatively low cost, easy to generate. Daily time step.	Difficult to simulate flows at hydrograph and basin-size extremes. Has not been applied outside eastern US.
Duration-curve regression plus dam operations model	USGS SYE plus US Army Corps of Engineers HEC-DSS (Connecticut River basin)	Same as above, with ability to model dam releases.	Relatively time-consuming (several years) to develop; example required two federal agencies.
Hydrologic process model plus water use accounting and channel routing	WOOOMM (Watershed Online Object Oriented Meta-Model) (Potomac River basin)	Can model land-use and climate change.	Resolution typically too coarse or area too small for regional application without modification.

reporting programs and many more have incomplete or inaccurate water use data. Withdrawal and discharge permits can be used as surrogates, but with caution because the difference between permitted and actual water use can be substantial. Therefore, there is a great need to develop and improve state water use reporting programs while also improving remote techniques for estimating the locations and timing of water withdrawals and return flows. Advocacy for state water use reporting laws along with federal and state investments in water use estimation continues to be necessary, particularly in states challenged by significant irrigation use or limited water management programs.

Periodic USGS water use reports (e.g., Kenny et al. 2009) are insufficient for these purposes, as they compile *reported* monthly or annual data at the county level, despite the lack of actual reporting requirements in many states. Furthermore, disaggregating these data by day and by stream reach requires assumptions about water use patterns. For regional policy and planning applications, one approach in the absence of accurate water use reporting is to research individual large water uses to obtain the most accurate data possible, and to estimate the smaller water uses.

Likewise, reservoir operation rules and actual releases can be obtained directly from willing dam owners and operators. Yet the time required to get this information can be considerable; in the case of the Connecticut River basin, researchers spent 1.5 years meeting with dam owners to understand their operations.

The treatment of interactions between groundwater and surface water depends on the type of hydrologic model and on the hydrogeology. Most process models incorporate groundwater flow, and do not require additional programming to simulate interaction with surface water. Regression-based and simple water-accounting models may warrant additional programming. In bedrock-dominated systems, where runoff is the main control on streamflow patterns and groundwater is not a significant water supply, groundwater may not need to be modeled. In narrow alluvial valleys, groundwater withdrawals may be assumed to deplete nearby streamflow directly and immediately. That is the default assumption of the Massachusetts SYE and of regression-transform approaches in Pennsylvania and the Connecticut River basin. Between these two extremes, the surface-water hydrologic model can be linked to a groundwater model as simple as the STRMDPL program used in Michigan or as comprehensive as MODFLOW (Harbaugh 2005). Massachusetts SYE users have the option of linking to existing STRMDPL models instead of using the default assumption in certain parts of the state.

3.2 Classifying River Types

This section summarizes a variety of river system classification approaches for regional environmental flow assessment, and defines the key parameters used for classification. We refer here to natural system classification (ELOHA's science process), rather than to goal classification for purposes of management or establishing standards (ELOHA's social process). Ideally, river type classification should result in a relatively small number of river types that capture the major dimensions of streamflow-related biological variability within a region. Section 3.4.1 covers goal classification.

3.2.1 Why Classify River Types?

Conceptually, river type classification extrapolates understanding of ecohydrologic conditions at sites that have been studied to similar sites that have not. The first reason to classify river types is to strengthen the statistical significance of flow-ecology relationships by combining available information from many rivers. The second reason is to extend those flow-ecology relationships to other rivers of the same type in order to define their environmental flow needs. A third reason is to direct future monitoring efforts to improve the strength of initial flow-ecology relationships or to extrapolate site-specific monitoring results. Apse et al (2008) covers classification for environmental flow standards in some detail.

Researchers have developed classification systems for Australia (Kennard et al. 2010, Pusey et al. 2009), Washington (Reidy Liermann et al. 2011), Canada (Monk et al. 2011), New Jersey (Hoffman and Rancan 2007, Kennen et al. 2007), Missouri (Kennen et al. 2009), Texas (Hersh and Maidment 2007), Pennsylvania (Apse et al. 2008), southeastern US[15], and elsewhere, all intended to meet the needs of ELOHA. In other places, such as South Africa, researchers have been classifying rivers for similar purposes since the 1980s.

Recent practice has demonstrated that river type classification is not always needed for setting scientifically-defensible environmental flow standards. In Massachusetts, for example, a statewide regression relationship links relative abundance of fluvial fish to watershed characteristics (area, gradient, etc.), obviating the need to classify aquatic system types according to those characteristics. In the Connecticut River basin, the project team decided that small differences between rivers within the project area did not warrant their being subdivided by type. Analyses by the Middle Potomac project team indicate that segregating rivers by type does not significantly strengthen their statistical relationships, and in fact could weaken them by reducing the number of data points per analysis. Classifying watersheds may help reduce variability, but classification also reduces sample size, which increases uncertainty.

Other researchers have found river type classification to be useful. In New Zealand, Snelder et al. (2011) report that flow-ecology relationships (represented by habitat availability) vary among major river types defined by morphology and flow regime. In Michigan, classifying rivers according to water temperature and catchment size protects the fish communities that are most sensitive to streamflow depletion.

3.2.2 General Approaches to Classification

Poff et al. (2010) envisioned rather sophisticated, time-intensive river classification systems being fully developed for ELOHA before being tested by flow-ecology analysis. For example, Reidy Liermann et al. (2011) used Bayesian-mixture modeling, a recursive partitioning algorithm, random forests, and a geomorphic classification to create a 14-tier hydrogeomorphic classification for Washington, in preparation for flow-ecology analysis, which is currently underway.

In practice, river type classification for ELOHA tends to be iterative or to use pre-existing classes. The iterative analytical approach is well-illustrated in the Middle Potomac River basin project. The first iteration, based on hydrologic analysis and habitat type, classified river reaches according to watershed size and karst geology. This informed the flow-ecology analyses, which in turn informed re-classification. In the end, biological and hydrologic metrics were normalized so that data from all sites could be combined, thereby maximizing the size of the datasets used to quantify flow-ecology relationships.

The Colorado project used a pre-existing classification. Rivers were classified by ecoregion, using a classification system that was already established. Literature review and flow-ecology analyses confirmed that this simple typology sufficiently captures eco-hydrologic variability of Colorado's river systems, especially considering the very limited databases with which the analysts had to work.

Using an existing classification system not only saves time, but also may help link streamflow management to regulatory programs that already are in place. By adopting Aquatic Life Use classes from an existing water quality program, the

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[15] http://sifn.bse.vt.edu/sifnwiki/index.php/Main_Page

Ohio project team deflected water users' concerns that biological flow criteria would create another layer of regulation. Moreover, the Ohio researchers were able to use extensive biological databases associated with the existing water quality program to develop flow-ecology relationships. Two of the river types for the Susquehanna River basin also borrowed from a water quality regulatory program.

3.2.3 Parameters Used for Classification

River classification for ecohydrologic analysis is becoming increasingly sophisticated, a trend apparently accelerated by publication of Poff et al. (2010). Olden et al. (2011) provide an excellent review of the full spectrum of approaches and their respective applications. Here, we focus on the parameters and approaches that these case studies have used to support flow-ecology analyses and flow criteria development.

Hydrology

As shown in Figure 1.1, Poff et al. (2010) suggested classifying rivers initially according to their hydrology. This is accomplished using hydrologic statistics calculated from daily streamflow data with Indicators of Hydrologic Alteration (IHA; The Nature Conservancy 2009), Hydroecological Integrity Assessment Process' (HIP) Hydrologic Index Tool (HIT; Henriksen et al. 2006), or similar software. The HIT software calculates statistics and the HIP process lays out an approach for using them to classify river types. Briefly, principal components analysis eliminates redundant statistics, and cluster analysis then groups the remaining data. In this way, the HIP process determines which hydrologic parameters are most appropriate for classifying river types.

A HIP classification was conducted for Pennsylvania (Apse et al. 2008). Of the five river types that HIP delineated, the Susquehanna project team incorporated one (baseflow-dominated streams) in the final classification because it represented an ecologically important hydrologic type that other classifications did not capture. In fact, none of our case studies adopted classifications based strictly on hydrology, although, like the Susquehanna project, preliminary hydrologic classifications did inform final river types in several.

Typically, hydrologic statistics that are used to classify river types differ from the metrics used to express environmental flow criteria, as described in section 3.3.2.

Water Temperature

Olden and Naiman (2010) argue for using water temperature in environmental flow assessments, especially where reservoir releases greatly alter natural temperature regimes. Water withdrawals, too, can affect water temperature to the extent that biological communities transform. This is certainly the case for coldwater streams in the upper Midwest; both Michigan and Ohio captured this phenomenon by incorporating water temperature into their river type classifications. Michigan's new water withdrawal permitting system is designed intentionally to keep coldwater streams cold by maintaining sufficient (cold) groundwater discharge into their channels. Many state water quality programs routinely monitor water temperature, so ample data may be readily available.

Ecoregion

Freshwater ecoregional classification seeks to identify critical areas for conservation by capturing representative components of freshwater biodiversity (Higgins et al. 2005). Although not developed expressly for flow management, ecoregional classification is based on many of the same factors that influence flow-ecology relationships. In Colorado, a coarse, high-level ecoregional classification (CEC 1997) proved adequate for distinguishing river types for flow-ecology relationships and accelerated the project timeline.

Watershed and Macrohabitat Characteristics

The influence of river size on flow-ecology relationships is well established (Higgins et al. 2005). Michigan, Susquehanna, and Middle Potomac River basin classifications incorporate catchment area, which strongly correlates with river size. Other useful watershed characteristics for defining river types include land cover, geology, climate, geomorphology, topography, water quality, and elevation. The value of using watershed characteristics to distinguish river types is determined by the ability of resulting river types to strengthen the statistical significance of flow-ecology relationships. In addition, watershed characteristics may be used to classify rivers for which flow data are unavailable.

In the Susquehanna River basin, the Northeast Aquatic Habitat Classification (Olivero and Anderson 2008) informed river type classification. This classification system incorporates watershed characteristics such as geology and river size, as well as macrohabitat variables such as modeled stream temperature and gradient. Using an established, credible classification system accelerated the Susquehanna project timeline by precluding the need to develop and defend a new system.

3.2.4 General Observations

In the literature and in our case studies, several aspects of river type classification differ in practice from the conceptual framework proposed by Poff et al. (2010). Some observations are:

- River type classification is intended to strengthen the statistical strength of flow-ecology relationships; therefore, it may be more effective if conducted in tandem with, rather than before, flow-ecology analyses.
- Natural river type classification is not always necessary to achieve management objectives, even if it may improve scientific defensibility of flow-ecology relationships. The Massachusetts case study illustrates this point.
- Given the goal of environmental flow standard development, hydrologic regime classification can clearly play an important role. But as the case studies demonstrate, other factors such as water temperature, stream geomorphology, ecoregion, and river size are important determinants of flow-dependent ecosystem composition and functions that should also be considered in classification.
- Incorporating watershed and macrohabitat variables from an existing framework such as the Northeast Aquatic Habitat Classification can improve the strength of flow-ecology relationships while building credibility among river science experts who recognize it.
- Many of the hydrologic classification applications that have been used to date lack a spatial extrapolation step for mapping hydrologic types to ungaged stream reaches. Integrating hydrologic classification within an aquatic habitat classification framework can enable such extrapolation and facilitate the classification's use in developing flow-ecology relationships, selecting monitoring sites, and managing water use.
- Regardless of the classification approach used, field scientists who are familiar with the rivers should review the resulting river types before the classification is finalized.

Overall, these variations on the ELOHA framework demonstrate the value of being flexible in how we approach natural system classification for developing flow-ecology relationships and setting environmental flow standards.

3.3 Describing Flow-Ecology Relationships

Relationships between flow alteration and ecological response are grounded in the biological condition gradient (Davies and Jackson 2006), which recognizes that increasing degrees of anthropogenic stress lead to decreasing ecological condition. Flow–ecology relationships may be expressed in various forms, depending on the information available and the results required: as an ecosystem attribute (E) as a function of the change in hydrologic condition (Q) from baseline ($\Delta Q/E$), as a change in ecosystem attribute from a reference condition as a function of change in hydrologic condition ($\Delta Q/\Delta E$), or as an expected status of an ecosystem attribute as a function of the value of a hydrologic metric (Q/E). Sanderson et al. (2011) used the latter two forms to build the Watershed Flow Evaluation Tool for Colorado. In some cases, these relationships include habitat as an intermediate variable, as seen in the site-specific DRIFT (King et al. 2003) and PHABSIM (Milhous et al. 1989) approaches and in the regional-scale Ohio case study.

Poff et al. (2010) envisioned a progression from hypothesis development to data assembly and analysis to build these relationships (Figure 1.1). In practice, successful projects appear to follow this progression, with the information available and the implementation mechanism influencing the relative emphasis on quantitative versus qualitative approaches.

3.3.1 Hypothesis Development

Regardless of the analytical approaches ultimately used, development of flow-ecology relationships begins with hypotheses derived from the literature and expert input about how each flow metric or environmental flow component (Mathews and Richter 2007) influences physical, chemical, and particularly biological processes within a river type. Subsequent quantitative analyses are then designed specifically to test these hypotheses.

Well-supported flow-ecology hypotheses also can lead directly to policy development if time, budget or data constraints prohibit the development of quantitative flow-ecology relationships. The State of Connecticut based statewide reservoir release criteria on best professional judgment and the extrapolation of quantitative relationships from another state.

The Susquehanna River basin project team introduced a structured approach for developing consistently worded hypotheses in an expert workshop setting (DePhilip and Moberg 2010). The Connecticut River basin project adopted a similar approach. The objective in both cases was to capture systematically the entire spectrum of taxonomic groups and physical processes across the entire flow regime. In each case, experts were asked to express hypotheses that answer the questions:

- Who (species or group of species)
- What (flow magnitude or event)
- When (month or season)
- Where (river type and habitat)
- Why/how (ecological response)

For example, “If summer *(when)* low-flow magnitude *(what)* decreases in baseflow-dominated streams *(where)*, then water temperature will increase *(why)* and salmonid populations *(who)* will decline *(how)*.” To facilitate hypothesis development, project scientists displayed flow-dependent life stages of native species for each river type superimposed on “typical” hydrographs. An example is shown in the Susquehanna case study.

In the Susquehanna, as in every large region, insufficient quantitative data were available to test every hypothesis. Yet, the literature conveyed that every ecosystem and flow component in the Susquehanna is important for maintaining ecological integrity, and no single data-rich species or guild could adequately represent the others. The experts agreed that to be scientifically defensible, their recommendations had to preserve both the inter- and intra-annual flow variability needed to protect the entire ecosystem. The only way to do that in the limited time allotted was to base environmental flow recommendations primarily on the literature review and their best professional judgment. The resulting recommendations are linked explicitly to their underlying hypotheses so that they may be tested quantitatively in the future.

In Massachusetts and in the Middle Potomac River basin, hypothesis development was not a formal part of the process. Yet, flow-ecology relationships developed for Massachusetts are directly informing environmental policy as intended. In the Middle Potomac, policy adoption of these relationships is yet to be seen. It appears that the main factor affecting policy adoption is whether a policy nexus exists and is seized upon from the onset, regardless of the hypotheses (or lack thereof) driving flow-ecology analyses.

3.3.2 Quantitative Analysis

The Michigan, Ohio, Massachusetts, and Middle Potomac project teams decided that scientific defensibility of their policy applications required quantitative analysis of extensive databases. All four had large biological databases with which to work, and carried out systematic processes for selecting the parameters that ultimately would define their flow-ecology relationships.

Our case studies support Apse et al.’s (2008) conclusion that to be useful for management ecological metrics selected for analysis should be:

- sensitive to flow;
- meaningful indicators of river health;
- broadly distributed spatially in a variety of watershed types and sizes, along a gradient of flow alteration; and
- recently sampled (to pair with current flow conditions).

Hydrologic metrics should:

- represent natural variability in the flow regime;
- be sensitive to change and have explainable behavior;
- be easy to calculate and replicable;
- have conceptual and empirical linkages to ecological response
- be easy for non-hydrologists to understand; and
- be non-redundant.

The Susquehanna River basin project developed an innovative set of hydrologic metrics to meet these criteria. Ten flow statistics to represent the frequency, duration, and magnitude of ecosystem-dependent flow components were based on monthly exceedance values and magnitude and frequency of high flow and events. Additional metrics to maintain the temporal distributions of flow were based on seasonal flow-duration curves.

Ecological condition of a river is the result of many factors, of which flow regime is only one. A focus of recent research is to isolate the influence of flow alteration from that of other environmental stressors, and then to identify the flow and ecological metrics that best describe ecological response to flow alteration. Several statistical techniques facilitate this analysis.

Multivariate statistical analysis can identify the environmental parameters that most strongly correlate with observed variation in ecological indicators. When indicators of hydrologic alteration are among the parameters analyzed, their importance relative to other stressors can be evaluated. This preliminary analysis greatly reduces the universe of flow statistics for subsequent flow-ecology analysis and builds confidence that these relationships will be minimally obscured by other factors. It also can be used to identify hydrologic metrics for defining environmental flow recommendations or standards. The Middle Potomac River basin scientists used multivariate statistical analyses to select non-redundant hydrologic and ecological metrics that define statistically significant flow-ecology relationships.

Kennen et al. (2010) used multivariate methods to identify a subset of eight ecologically relevant hydrologic variables describing streamflow magnitude, frequency, duration, timing, and rate of change to explaine variation in macroinvertebrate assemblage composition across the 339,290-km^2 northeastern United States. The study used physical, chemical, and biological data collected as part of the National Water-Quality Assessment Program and landscape characteristics from the National Land Cover Database. Principal component analysis (PCA) and partial collinearity assessment reduced 527 environmental and land-use variables initially analyzed to a subset of 52 variables that accounted for the most variance in macroinvertebrate assemblage, while minimizing redundancy and reducing the effects of natural variation. Conditional multiple linear regression was then used to quantify relationships between the remaining 52 variables. From this analysis, significant bivariate relationships were developed to depict relationship between macroinvertebrate assemblage structure and 8 hydrologic variables.

Several other studies have similarly used multivariate statistical analyses to select hydrologic statistics. Using generalized linear modeling, Armstrong et al. (2010) quantified fish response to several hydrologic statistics in Massachusetts. Using multiple regression analysis, Kanno and Vokoun (2010) showed that water withdrawal rate was more important than other natural and anthropogenic factors (e.g. land cover and stream size) in explaining several fish assemblage metrics. After using multivariate analysis to eliminate hydrologic parameters associated with anthropogenic disturbance, Kennen and Riskin (2010) found significant linear and curvilinear bivariate flow-ecology response relationships for fish and invertebrate assemblages in the New Jersey Pinelands. Kennen et al. (2007) combined watershed modeling and indirect ordination techniques to identify components of the hydrologic regime that most significantly affect aquatic-assemblage structure across a disturbance gradient. Important variables included the average number of annual storms producing runoff, ratio of 25% to 75% exceedance flows (flashiness), diversity of natural stream substrate, and the percentage of forested land near the stream channel (forest buffer). Knight et al. (2008) analyzed hydrologic time series to identify three hydrologic metrics essential to habitat suitability and food availability for insectivorous fish communities in streams of the Tennessee River Valley: constancy (flow stability or temporal invariance), frequency of moderate flooding (frequency of habitat disturbance), and rate of streamflow recession. Roy et al. (2005) quantified relationships among fish assemblage metric response, hydrologic variables, and imperviousness in small streams and their subcatchments in Georgia.

Classification and Regression Tree (CART) and **Boosted Regression Tree (BRT)** are statistical methods that identify threshold values for explanatory variables that separate groups of response variables. Carlisle et al. (2010) used CART to relate two indicators of altered hydrology—streamflow depletion and streamflow surcharge—and aquatic biological community impairment across the conterminous US compared to eight other covariates (water temperature, specific conductance, pH, total nitrogen, total phosphorus, channel gradient, agricultural land cover, and urban land cover of the riparian buffer). The degree of alteration (depletion and surcharge) was estimated based on regression models using landscape and watershed variables to predict flows at reference gages versus gages with highly modified upstream conditions.

Quantile-regression and other modeling can be used to quantify bivariate flow-ecology relationships from large datasets that represent sites affected by multiple stressors. The premise is that scattered flow-ecology data are bounded by “floors” and “ceilings” that represent the maximum ecological condition that could be achieved at any given flow value if all other stressors were absent (Cade and Noon 2003, Konrad et al. 2008). Regression is used to quantify the decline in maximum ecological condition as flow alteration increases. Using the 90th instead of the 100th percentile accounts for some uncertainty. Quantile-regression splines may be used to characterize changes along nonlinear response curves (Anderson 2008). The Colorado, Massachusetts, Middle Potomac, and Ohio case studies illustrate the use of quantile-regression modeling to define flow-ecology relationships.

In Michigan, scientists studied large fish and flow databases, along with other habitat suitability information (catchment size, base flow yield, July mean temperature), to develop predictive models of fish assemblage structure under a range of base flow reductions (Zorn et al. 2008). These models then generated flow-ecology curves for water withdrawal permitting.

3.3.3 Hybrid Approaches

Relying on existing biological databases limits flow-ecology analyses to a subset of a complex ecosystem. Likewise, relying on a single flow metric limits analyses to a subset of a complex hydrologic pattern. Conversely, basing flow recommendations on conceptual models may pose credibility issues in a controversial political milieu.

In Colorado, scientists blended the best of both. Lacking large ecological databases, the withdrawal thresholds that populate Colorado’s Watershed Flow Evaluation Tool are based on literature review and expert input. In this case, the experts not only helped develop flow-ecology hypotheses, but they also suggested how to use the very limited data found in the literature to test those hypotheses. Analytical approaches ranged from categorical threshold delineation to quantile regression, depending on the form and quantity of data available. Ultimately, flow-ecology relationships were quantified for warmwater and coldwater fish, invertebrates, riparian vegetation, and recreation. Many of those were based on only a handful of sites, which are assumed to represent their river type. Camp Dresser & McKee Inc. et al. (2009, Appendix B) document the specific approach used to quantify each flow-ecology relationship that they generated.

3.3.4 General Observations

Developing flow-ecology hypotheses (or conceptual models) is an important step in developing regionalized environmental flow standards or targets. Well-vetted flow-ecology hypotheses guide the selection of both hydrologic and ecological metrics. These hypotheses benefit subsequent data analyses by targeting the relationships that are examined and by increasing the transparency of the scientific process to stakeholders. The flow-ecology hypotheses themselves can be used in a structured expert workshop setting to arrive directly at environmental flow recommendations. For example, in the Susquehanna River basin, workshop leaders used qualitative flow-ecology hypotheses and quantitative analyses of the natural flow variability to facilitate expert-driven flow recommendations.

The scientific literature is replete with statistical analyses that relate flow alteration to ecological response. Yet very few of these have been used to support water management. Water managers and other stakeholders are more likely to respond to science that uses ecological and hydrologic metrics that they can explain and understand their causal links. A weighted-evidence approach (Norris et al. 2012) can help stakeholders understand the strength of causal links supporting different flow-ecology relationships. Environmental flow projects in the northeastern U.S. and Australia are piloting this approach to assess its application to watershed management.

The case studies demonstrate that because biological and hydrological databases are limited, a combination of quantitative and qualitative approaches is necessary to create flow-ecology relationships that are truly holistic. By holistic, we mean relationships that incorporate a range of environmental flow components (e.g., small floods as well as summer low flows) and ecological target groups (e.g., invertebrates and vegetation as well as fish). Collaborative and interdisciplinary teams, engaged from the start of the scientific process, enhance the likelihood that the information policymakers need is delivered through a balance of quantitative analysis and expert workshop-driven products informed by flow-ecology hypotheses.

3.4 Making Flow-Ecology Relationships Operational: Applying Environmental Flow Science at a Regional Scale

Sections 3.1 - 3.3 discussed the development of flow-ecology relationships. Figure 3.1 illustrates the use of such relationships to translate an ecological condition goal (y-axis) into an environmental flow criterion (x-axis). In this section, we discuss ways to establish those ecological condition goals, and then how such goals are being pursued in policy and on the ground.

Environmental flow criteria cannot be defined by science alone. Scientists can quantify the tradeoffs (flow-ecology relationships) that underlie their definition, but the criteria themselves are social decisions about the desired ecological condition of various water bodies.

Consider water quality standards as an analogy. Scientific analyses determine the concentration of a pollutant that has a risk of killing one in a million people who ingest it, the concentration with a risk of killing one in a thousand, and so forth. Statutes or rules state the allowable risk associated with ingesting pollutants based on societal tolerance, feasibility of removing the pollutant, economic costs, and other factors. The water quality standard is the allowable concentration associated with that socially determined risk.

Now consider environmental flow criteria. Scientific analyses determine the degrees of flow alteration associated with various levels of ecological degradation. These relationships are expressed as flow-ecology response curves. Statutes, rules, or perhaps guidelines state the allowable level of ecological degradation based on societal tolerance, existing water uses, and other factors. The environmental flow standard is the degree of flow alteration associated with that level.

Figure 3.1 depicts the social outcome with a simple flow-ecology curve that relates mid-summer water withdrawals (flow alteration) to fish community structure (ecological condition) for one type of river in Michigan. A technical advisory committee recommended, and the legislature then codified, a state map showing all the water bodies expected to achieve "acceptable" ecological condition, which they defined as maintaining a certain percentage (90% in Figure 3.1) of their native fish species. Based on the flow-ecology curve, the flow standard, or criterion, then, is 45% of natural mid-summer flow. Water managers tasked with achieving the ecological goal now manage water withdrawals and dam operations such that no more than 45% of natural mid-summer flows are diverted from these rivers. Scientists periodically monitor the fish community to ensure that the flow standard achieves its ecological goal.

Based on our case studies, two useful steps help put flow-ecology relationships into practice for environmental criteria. First, define ecological condition goals, or risk levels, in terms of the ecological metrics used in the flow-ecology response models. For example, what range of invertebrate richness indicates a high level of risk of ecological degradation? What range represents low risk? This decision could begin with ecologists proposing threshold levels. After public consultation, it could culminate with formal adoption through an appropriate legal process. In this conception, the flow-ecology curves act to translate ecological condition goals into environmental flow criteria. Hydrologists also may use models to help water users understand implications of the proposal on current or future water availability. As with water quality standards, plans can be made for monitoring, periodic review, and risk level revision as new information becomes available.

Second, determine policy actions associated with each ecological risk level. For example, if a proposed water withdrawal has a low risk of harming the ecosystem, can it be approved immediately? If its risk is high, will the proposed withdrawal automatically be denied? Or, if the risk is already high, will that river reach be prioritized for water right transactions?

Sections 3.4.1 and 3.4.2 further explain how these policy decisions are made, and how they are being implemented in various water management contexts.

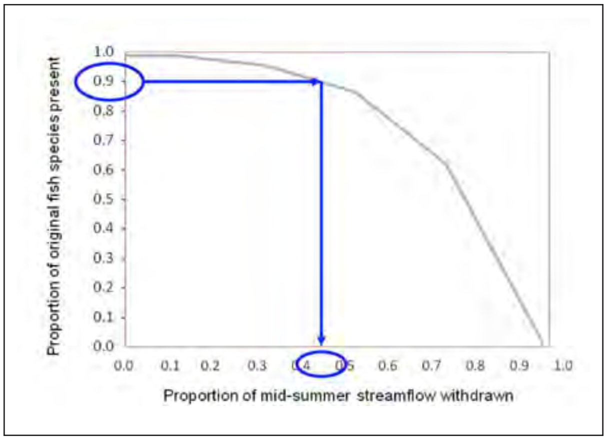

Figure 3.1. Using a simple flow-ecology curve to set an environmental flow standard. For an ecological goal of maintaining 90% of the original fish species, the environmental flow standard is that no more than 45% of the mid-summer streamflow may be withdrawn (or, conversely, 55% of the streamflow must remain in the stream). If withdrawals exceed that amount, then this model predicts that more than 10% of the original fish species will be extirpated from a stream of this river type.

3.4.1 Establishing Ecological Condition Goals and Defining Acceptable Risk

Underlying all environmental standards is the concept of condition goals, also known as desired future condition. Although some jurisdictions may choose to have a single goal and associated environmental flow standard, most will follow the example of most state water quality standards and have a tiered set of goals and standards. This is because, for practical reasons, not every aquatic system can be managed to maintain outstanding ecological qualities; for some heavily used water bodies, a simplified functioning ecosystem is the best condition attainable.

Some state flow management programs, such as Maine's, have adopted condition goal classes from existing water quality programs[16]. Others have defined new condition goals that apply explicitly to water quantity, based on existing conditions and stakeholder input. For example, Connecticut's 2011 streamflow protection regulations prescribe a condition goal class system for each of the state's river reaches. The implementing agency will map the state's water bodies by goal class, facilitate a formal public comment process, and revise the map accordingly. Rhode Island created a watershed goal classification based on natural characteristics (e.g., presence of cold water fish), land use condition (e.g., impervious surface), land use status (e.g., development zones, conservation land), water withdrawals, and water quality. The five resulting ecological condition goals range from "natural streams" to "significant human influence."

The process for defining condition goals, or "acceptable ecological conditions" (Figure 1), may depend on the form of the flow-ecology relationship (Figure 1.2). When a threshold response exists, the benchmarking approach of Arthington et al. (2006) can be used to establish an ecologically and societally acceptable level of risk. When the response is linear or curvilinear, "a consensus stakeholder process may be needed to determine acceptable risk. One possible process for setting such risk levels is to use expert panels to identify 'thresholds of potential concern' (Biggs and Rogers 2003; Acreman et al. 2008), which establish where along the flow alteration gradient there is agreement among stakeholders (including scientists and managers) that further hydrologic change carries with it unacceptably high ecological risk" (Poff et al. 2010).

In either conception, the ecological risk levels linked to condition classes can be informed by ecologists, who describe the specific ecosystem outcomes associated with each ecological condition class for each river type (if a natural river system classification is used). These ecological outcomes may describe key attributes of river ecosystem health, such as physical habitat, water quality, flow connectivity, biological composition and ecosystem services. If a natural river system classification is used, it is unlikely to overlap with the condition goal classes. For example, Figure 3.2 depicts four different condition goals for a single river type.

Figures 3.2 and 3.3 illustrate conceptually the translation from river condition classes to environmental flow criteria for one river type. In this example, a technical committee of

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[16] http://www.maine.gov/dep/water/swup/index.htm

scientists and water managers described the ecological outcomes associated with each river condition class (A-D) in terms of physical habitat, water quality, flow connectivity, biological composition, and ecosystem services (Figure 3.2, left). Some states, such as Connecticut, combine these ecological outcomes with human use goals into formal narrative standards.

From these descriptions, hydrologic and ecological indicators that are important to each river type can be defined, ideally ensuring that the indicators resonate with decision makers. As described above, a technical committee can develop flow-ecology functions that relate these indicators to each other, again by river type. Next, they assign each river condition class to a range of ecological indicator values along the y-axis (Figure 3.2, center). They obtain the environmental flow ranges for each river condition class from the x-axis of the flow alteration-ecological response functions (Figure 3.2, right). In this example, environmental flows are expressed as a percent alteration from baseline condition, and these percentages happen to be the same for high and low flows. Figure 3.3 shows the environmental flow ranges in hydrograph form for a particular river type and condition class. The blue line represents the baseline hydrograph. For the example shown, the environmental flow matrix indicates that both x and y = 50% for condition class C.

This clearly is not the only way to link flow-ecology relationships to ecological condition goals. Depending on political circumstances, quantitative flow-ecology analyses may not even be necessary to define environmental flow criteria. In the Susquehanna River basin, experts based quantitative flow recommendations primarily on conceptual models. In the Connecticut River basin, initial flow recommendations are based on a sustainability boundary approach (Richter 2009, Richter et al. 2011). In both cases, however, the flow metrics themselves (as opposed to their values) were rigorously identified as those that best represent flow variability and ecosystem dependence for their respective river types. This assists communication of results to water managers and water users, and facilitates adaptive management.

3.4.2 Implementation: Putting Flow Standards into Practice

The ability to estimate environmental flow needs for every water body in a large region unlocks a broad range of opportunities for implementation. Our case studies provide examples of integrating ecosystem health into water withdrawal permitting, multi-reservoir re-operation, and water supply planning at the policy level. Elsewhere, the ELOHA framework is guiding the estimation of environmental flow needs for integrated water resource management across large river basins. Although not all of our case studies have reached the implementation stage, some generalizations emerge regarding how to get there. The first two sub-sections below highlight the importance of having a structured, social process for defining implementation policy. The third highlights the value and use of decision support systems.

Setting Water Withdrawal Standards

Michigan used flow-ecology relationships and a well-defined social process to guide two major policy decisions regarding water withdrawals. First, the state legislature defined the threshold for "adverse resource impact," culminating a science-driven stakeholder process. Second, condition classes were reframed in terms of ecological risk levels, and water withdrawal permitting policies were designed to address each risk level. These policies were then

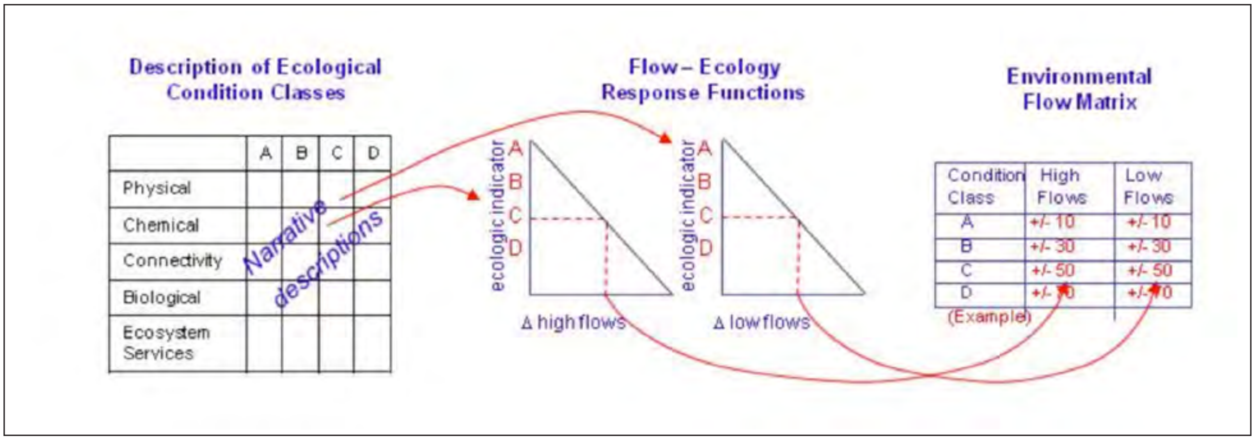

Figure 3.2. Process for translating condition classes (left) into environmental flow criteria expressed as degree of allowable flow alteration from baseline (right) for two flow components (high and low flows) for a hypothetical river type.

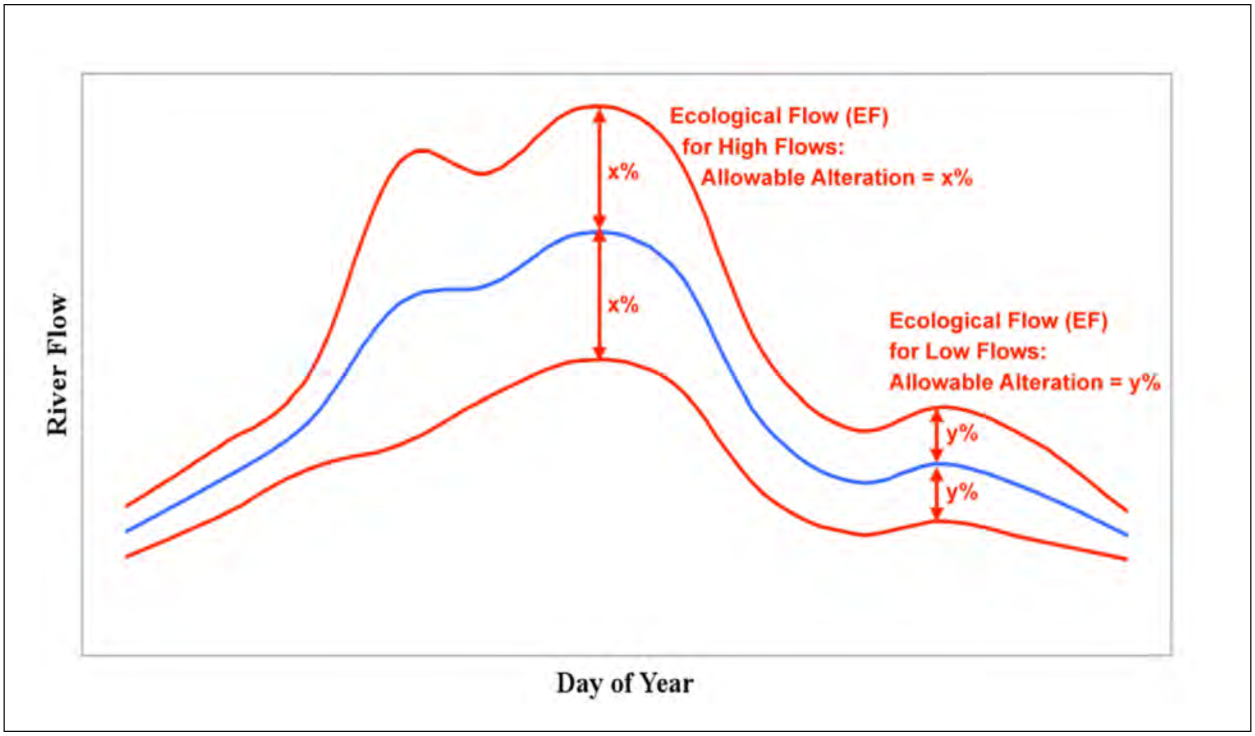

Figure 3.3. Sustainability boundaries (Richter 2009) shown in red, around natural hydrograph (blue) resulting from environmental flow criteria depicted in Figure 3.2 (right), where both x and y = 50% for condition class C.

incorporated into an online screening tool for prospective water users to determine which policy would apply to their proposed withdrawal. The Michigan Water Withdrawal Assessment process, as it is called, has won three national awards for streamlining government programs.

Beyond strong science, one of the key ingredients in Michigan's success was its clear, separate "social process" centered around a set of guiding principles that focused a diverse group of public, private, and non-profit stakeholders on common water management interests. The final water withdrawal standards were informed by a scientific assessment of ecological risk, but defined through a distinct political and social decision-making step that weighed social needs against ecological protection goals. The result is a set of standards that focuses water management agency effort on those rivers that are most vulnerable to impact and/or most valued by society, while steering future water development toward other systems.

Setting Dam Management Standards

Dams are designed, built, and operated to achieve specific objectives, including water supply, hydropower, recreation, and flood control. Only very recently have dam design and operation begun to consider downstream ecological health. Therefore, it is critical to work with dam owners and operators from the onset to find opportunities and understand constraints on re-operating existing dams to provide environmental benefits. This rings as true for regional dam management as it does for individual dam re-operations.

In Connecticut, a state-sponsored technical committee modeled numerous simulations to test and evolve a set of general dam operating rules that would protect natural flow variability (and presumably minimize ecological risk) at minimal cost to reservoir safe yield. Yet, despite these extensive analyses, it was critical to move from a technical phase to a socio-political phase in which the form and substance of the final reservoir release rules could be negotiated. This stakeholder negotiation allowed for trade-offs between ecological risk and socioeconomic costs. The resulting release rules will improve environmental flow releases to 156 river reaches.

Building a Decision Support System

A decision-support system (DSS) is an extremely useful tool for implementing environmental flow management and planning at the regional scale. According to Georgakakos (2004), DSSs are technical tools intended to provide valid and sufficient information to decision makers, comprised of five main components: data acquisition system, user-data-model interface, database, data analysis tools, and a set of interlinked models. A useful DSS makes the decision variables and results accessible to water managers and stakeholders, and hides the complex models, equations, and databases behind them.

DSSs for managing water withdrawals can readily incorporate environmental flow criteria. For any site, the Massachusetts SYE and Michigan WWAT can calculate the streamflow depletion that would result from a proposed new withdrawal, combined with the cumulative impacts of all upstream withdrawals and return flows, and compare it to environmental flow targets to determine the availability of water for additional withdrawals. Water managers use these tools to ensure that their water allocation decisions protect ecological values.

DSSs also can be designed to integrate environmental flows into regional water management. In the Connecticut River basin, federal and state agencies have come together to integrate operations of 70 large dams. One of the most significant challenges was to constructively involve individual dam owners. Through a series of workshops and one-on-one meetings, the dam owners themselves helped build a DSS to optimize basin-scale efficiency and provide environmental flows. With the owner of 14 of the largest dams playing a central role in the project, and at least one major dam owner committing to use the tool for federal relicensing, the likelihood of implementing a solution informed by the optimized scenario is high.

Colorado is building DSSs to integrate environmental flows into basin water planning. In the United States, water resource planning typically accounts for water supply and demand, hydropower, flood control, and perhaps other economically-driven factors. Only recently have environmental flows begun to be considered. Defining environmental flow needs and integrating them with other water demands at the large basin scale creates opportunities for efficiency; for example, the same water that sustains environmental flows upstream can be used for irrigation downstream. In Colorado, scientists created a pilot DSS that calculates cumulative streamflow depletion and associates it with ecological risk levels for any location. Color-coded basin maps indicate the degree of ecological risk to which each river segment would be subject under various scenarios, thus helping basin stakeholders understand tradeoffs between water management options. In this case, the majority of river reaches are already under some degree of stress due to flow alteration, so environmental objectives are geared toward flow restoration. Under Colorado water law, re-allocation of water to the environment is possible, but each re-allocation requires extensive research, relationship-building, and often a lot of money. The DSS helps target flow restoration to river reaches that would most benefit the basin overall.

In the interstate Middle Potomac River basin, water managers are analyzing how the combined impacts of land use change, water withdrawal, and impoundments affect low flows and stream health in small streams and rivers. A basin-scale DSS is being considered to inform each state's future land and water management and to benefit the basin overall. The DSS would be built from the existing process-model-based hydrologic foundation, so it could factor in future water use, land use, and climate change projections.

The next big challenge for all projects is to design DSSs that integrate information to support streamflow management decisions with other management actions. For example, decision tools that simultaneously assess both water quantity and water quality management are feasible. Likewise, if a DSS for environmental flows is built from a process-model-based hydrologic foundation, then options can be added to assess land use and drainage impacts. However, if development has drastically changed spatial drainage patterns and stream channel morphology, then it may be difficult to model impacts on ecosystem health.

3.4.3 General Observations

Implementation of science-based environmental flow policy and planning is still very much in its infancy. Nonetheless, there are lessons to glean from progress to date:

- Defining a clear path to policy implementation from the onset ensures that the ensuing science answers the right management questions.
- An ecological risk-based framework associates ecological goals with allowable flow alteration, and accounts for scientific uncertainty by associating appropriate policy actions with different levels of ecological risk.
- A distinct and structured social process for identifying, understanding, and negotiating tradeoffs is critical. To launch this process, a set of "guiding principles", or agreed-upon common objectives, focuses diverse stakeholders on common interests, and increases the likelihood of achieving implementable outcomes.
- Decision support systems greatly facilitate the integration of environmental flows into state water allocation programs, integrated dam management, and regional water resource planning.

4.0 Conclusions

Environmental flow protection is gaining broad acceptance in the United States, and the science is sufficiently developed to support regional planning and policy applications, including water withdrawal permitting, multi-reservoir operation, and regional water resource planning. Remarkable advances are being made in the use of structured scientific literature review, hydrologic modeling, river system classification, flow-ecology analysis, and condition goal designation to inform water management.

Hydrologic foundation development is a common goal of most, if not all, environmental flow management efforts. While a database of daily flow data under naturalized and current conditions remains an ideal for most applications, the lack of these data need not hinder the determination of environmental flow needs.

- If only current-condition hydrologic data are available, then flow-ecology relationships can still be discerned. However, without distinguishing altered from natural ranges of hydrologic and ecological conditions, flow restoration targets are more difficult to quantify.
- If only flow statistics are available—that is, if simple regression is used to generate the hydrologic foundation—then actionable flow-ecology relationships can still be determined if a limited set of statistics is deemed sufficiently protective of expected flow alteration. For example, Michigan decided to limit withdrawals all year to the amount needed to maintain fish communities during their most stressful (lowest flow) month. Given Michigan's hydrology, restricting water development in this way will prevent adverse impacts of withdrawals on river ecosystems all year.
- If only monthly (not daily) flow series are available, meaningful measures still can be taken to protect the magnitude of seasonal flows. However, monthly flow data do not capture freshets and other short-duration events that are important for maintaining certain ecological functions. Nevertheless, monthly flow data can be more than adequate in water bodies with very stable hydrologic regimes or for managing groundwater pumping, which generally does not impact short-duration flow events.
- No matter how estimates of unregulated hydrologic conditions are derived, a major constraint will almost always be accurate, spatially explicit water use data. Advocacy for state water use reporting laws along with federal and state investments in water use estimation and decision support systems is a high priority, particularly in states challenged by significant irrigation use or limited water management programs.

Regardless of the data or statistics used, they should be estimated for every stream segment or sub-basin where environmental flows will be managed. Without this information, limits on flow alteration are very difficult to permit, measure, or enforce without expensive site-specific data collection.

River type classification, as envisioned in Poff et al. (2010), is not being used in the majority of cases we reviewed. Where it has been used, it tends to be iterative and based on pre-existing classifications. By treating natural river type classification and flow-ecology analyses as iterative processes, each one strengthens the explanatory power of the other. Therefore, it makes sense to begin analyzing flow-ecology relationships before investing deeply in any detailed river type classification. Using an existing classification system helps build trust among scientists who are familiar with it. Moreover, incorporating watershed and macrohabitat variables from the onset is useful for assigning river types to ungaged sites.

Flow-ecology relations, whether in the form of hypotheses or the results of quantitative analyses, are also tremendously useful tools. They may be developed after or in tandem with the hydrologic foundation.

- Flow-ecology hypotheses guide quantitative analyses, focus expert workshops, and help engage stakeholders. These qualitative relationships typically are based on a combination of literature review and expert input. They can drive the selection of hydrologic and ecological metrics for subsequent analysis and flow management, and can also ensure that stakeholders have a common conception of the likely impacts of flow alteration.
- If large biological databases and a hydrologic foundation are available, then statistical analyses can be framed to test flow-ecology hypotheses. Strictly exploratory data analysis may result in robust statistical relationships, but if the metrics used do not resonate with biologists and water managers, then the results may be ineffective in supporting environmental flow policy.
- Even where large biological databases exist, rarely will the results of flow-ecology analyses represent all flow-dependent taxonomic groups and ecological processes. A holistic approach requires a combination of quantitative and qualitative relationships to represent the

ecosystems and natural flow regimes across a state or basin. In the Susquehanna River basin, scientists based flow recommendations on the historic natural variability of the flow components that flow-ecology hypotheses suggest are important. This approach can supplement biological data analyses to generate flow recommendations that protect the entire ecosystem.

Condition goal classification is proving extremely valuable for driving stakeholder negotiations that lead to policy implementation. Within any large region, people value different rivers for different purposes. They may strive to keep certain rivers nearly pristine, while accepting that other, more developed rivers simply maintain a basic level of ecological function. If stakeholders can agree to apply different flow standards to rivers with different tiers (i.e., classes) of ecological condition goals, then they will likely protect the most valuable ecosystems, while encouraging development of less sensitive ones. This approach has worked fairly well with water quality standards in the United States, and is emerging for water management. Condition goals may be linked to ecological risk levels resulting from flow alteration.

Implementation is still very much in its infancy, as is the ELOHA framework itself. Although ELOHA provides a useful framework to guide and describe the scientific process associated with environmental flow criteria development, there is no one-size-fits-all approach to either the scientific or the policy process. Regardless of the rigor of the scientific analyses, expert judgment calls are required to guide the process and to interpret results. Facilitated expert workshops and advisory panels improve the outcomes and their credibility to the public. The level of sophistication needed depends ultimately on what policy makers want and stakeholders will accept. No matter the situation, before developing scientific products, it is essential to consider the social and policy context in which environmental flow management would take place. Early outreach to stakeholders, the definition of shared guiding principles, the formation of advisory committees, attention to political and economic drivers, and process transparency are all likely to pay dividends in environmental flows implementation.

Although much of this report focuses on scientific tools and approaches, **social and policy processes,** as evidenced by the case studies, are becoming more sophisticated in their incorporation of scientific information and definition of ecological goals linked to water management. Poff et al.'s (2010) ELOHA framework lacks clear guidance on development and implementation of these processes. Given the importance of social and political drivers to environmental flow implementation, the most important advance needed to guide future environmental flow policy and planning is to build and test a robust social framework that complements ELOHA's scientific framework.

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