Ecosystem Flow Recommendations for the Delaware River Basin

Report to the Delaware River Basin Commission

Upper Delaware River
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Report prepared by The Nature Conservancy

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Acknowledgments

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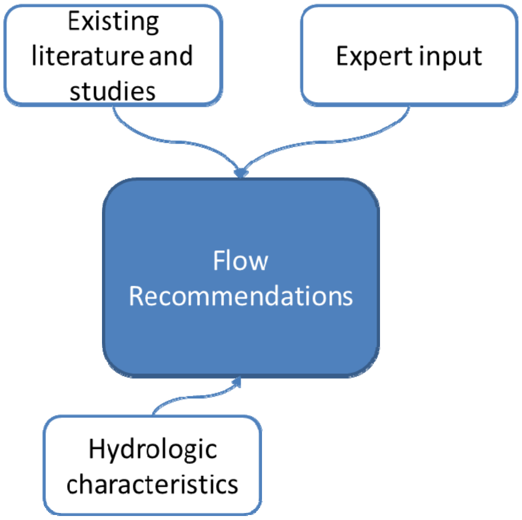
We thank all who generously contributed their time, invaluable expertise and resources through each of our technical workshops, in-person meetings, phone calls and other means of consultation. We especially thank Bob Tudor, Dave Kovach, Eric Engle, Bob Limbeck, Greg Cavallo, Hernan Quniodoz (Delaware River Basin Commission); Mark Hartle, Daryl Pierce, and Doug Fischer (Pennsylvania Fish and Boat Commission); Mary Ann Furedi and Greg Podniesinski (Pennsylvania Department of Conservation and Natural Resources, Pennsylvania Natural Heritage Program); Hoss Liaghat and Tony Shaw (Pennsylvania Department of Environmental Protection); Brian Henning, John Vile, Robert Somes, Jeanette Bowers-Altman, Jeff Hoffman, Leslie McGeorge, Ian Snook, Shawn Crouse, Pat Hamilton, Vic Poretti, Chris Smith (New Jersey Department of Environmental Protection); Mark Woythal, Jeff Loukmas, Bob Angyal, Mike Flaherty, Kathy Hattala, Chris Van Maaren, Brenan Terrier, Fred Henson, Andy Kahnle (New York State Department of Environmental Conservation); Greg Wacik (US Army Corps of Engineers – Philadelphia District); Matt Fisher (Delaware Department of Natural Resources and Environmental Control); Jonathan Kennen, Heather Galbraith, Carrie Blakeslee, Jeff Cole, Kelly Maloney, and Kirk White (U.S. Geological Survey); Rich Evans and Don Hamilton (US National Park Service); Jim Kurtenbach (U.S. Environmental Protection Agency); Angela Padeletti (Partnership for the Delaware Estuary); Laura Craig (American Rivers); Dave Strayer (Cary Institute of Ecosystem Studies); Rich Horwitz (Academy of Natural Sciences); Dave Arscott and Willy Eldridge (Stroud Water Research Center); and Jason Taylor (Cornell University).

We thank our colleagues from The Nature Conservancy, Colin Apse, Su Fanok, and George Schuler, who helped facilitate workshops and provided regional expertise.

We customized **the Ecological Limits of Hydrological Alteration (ELOHA) framework to develop flow recommendations** for the Delaware River basin. Our approach is cost-effective, relatively fast, and addresses multiple taxonomic groups over a large geographic area. This project followed the general model of other projects that developed flow recommendations for large rivers, most specifically the Susquehanna River, the Upper Ohio River in Western Pennsylvania, and the Great Lakes in New York and Pennsylvania. The ELOHA framework has been used to improve the ecological basis for water management throughout the U.S., including in Michigan, Rhode Island, Connecticut, the Colorado River basin.

Staff from **many agencies and research institutions contributed** by providing input throughout the process. In addition to the Delaware River Basin Commission, key agencies provided technical expertise and will be involved in the implementation of these recommendations: Pennsylvania Fish & Boat Commission, Pennsylvania Department of Environmental Protection, New York State Department of Environmental Conservation, New Jersey Department of Environmental Protection, U.S. Geological Survey, U.S. Fish & Wildlife Service, and U.S. Army Corps of Engineers.

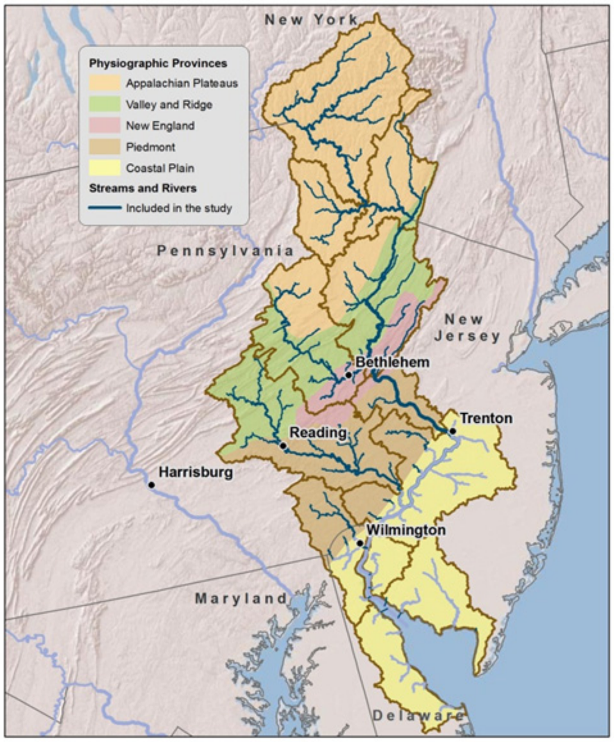
Recommendations were developed through a **series of three workshops** with technical experts on the biology, water quality, and hydrology in the project area. We used the workshops to get input on flow-sensitive species and natural communities, develop hypotheses about ecological responses to flow alteration, and review draft recommendations.



We also **synthesized over 200 publications and reports** on ecological responses to flow alteration and incorporated this information **into a weight-of-evidence based summary of the degree of support for each recommendation.** Lastly, we used daily flow data from 34 index gages within the study area to **characterize long-term hydrologic characteristics of major habitat types** within the basin.

Brook trout © Freshwater Institute

The project area includes **all tributary rivers and streams in the Appalachian Plateau, Ridge and Valley, New England, and Piedmont** Provinces and the non-tidal portion of the mainstem. The study did not address streams in the Coastal Plain Province.

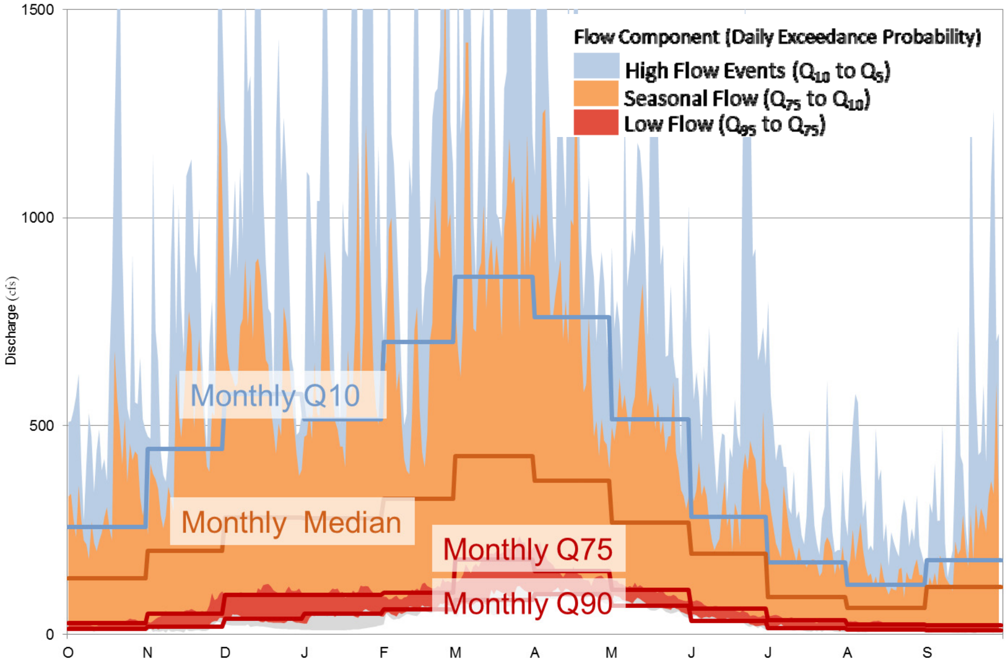


We identified groups of **fish, mussels, aquatic insects, reptiles, amphibians, birds, mammals, and vegetation** that are expected to be sensitive to changes in the flow regime. We also incorporated information on how streamflow affects **water quality and floodplain and channel maintenance.** These species groups are associated with one or more of **twelve habitat types** ranging from headwaters to large rivers.

By overlaying key life history requirements for each group on representative hydrographs for each habitat type, **we identified relationships between species groups and seasonal and interannual streamflow patterns**.

Pond Run Creek, Pike County, Pennsylvania © G. Gress

We used flow components to highlight specific portions of the hydrograph and discuss the **ecological importance of low flows, typical seasonal flows, and high flows.** We used monthly flow exceedance values (Qex) to divide flows into three components. Recommendations address the entire flow regime, even though some flows are likely to be affected by water withdrawals, diversions, reservoir operations, and other water management and others are primarily influenced by climate and precipitation. We calculated a suite of flow statistics for minimally-altered gages in the basin and used this **hydrologic characterization to describe the naturally-occurring range of variability** within and among years. Flow Recommendations are expressed as recommended limits to alteration a suite of flow statistics that are indicators of ecologically-important flows.



Recommendations account for differences in sensitivity among watershed sizes. They also account for seasonal differences in streamflow patterns.

These **recommendations can be applied to water withdrawal policy,** including setting passby flows and water withdrawal limits. They can also guide site-specific reservoir operations.

Flow Recommendations for all Habitat Types – Delaware River Basin

		Summer	Fall	Winter	Spring
High flows	**All habitat types**	Maintain magnitude and frequency of **20-year (large) flood**; and Maintain magnitude and frequency of **5-year (small) flood**; and Maintain magnitude and frequency of **bankfull (1 to 2-year) high flow event**			
	All habitat types	< 10% change to magnitude of **monthly Q10**			
			Maintain **frequency of high flow pulses > Q10** during fall		Maintain **frequency of high flow pulses >** Q10 during spring
Seasonal flows	**All habitat types**	Less than 20% change to **seasonal flow range (monthly Q10 to Q50)**			
	Headwaters	**No change to monthly median**; and **No change to seasonal flow range (monthly Q50-Q75)**			
	Creeks	**Less than 10% change to monthly median**; and **Less than 10% change to seasonal flow range (monthly Q50-Q75)**			
	Small Rivers	**Less than 10% change to monthly median**; and **Less than 10% change to seasonal flow range (monthly Q50-Q75)**			
	Medium Tributaries and Large Rivers	**Less than 15% change to monthly median**; and **Less than 15% change to seasonal flow range (monthly Q50-Q75)**			
Low flows	Headwaters	**No change to monthly Q75**; and **No change to low flow range (monthly Q75 to Q99)**			
	Creeks	**No change to monthly Q90**; and **Less than 10% change to low flow range (monthly Q75 to Q99)**			
	Small Rivers	***Summer and Fall*** **No change to monthly Q90**; and **Less than 10% change to low flow range**		***Winter and Spring*** **Less than 10% change to monthly Q90**; and **Less than 10% change to low flow range**	
	Medium Tributaries and Large Rivers	**Less than 10% change to monthly Q90**; and **Less than 10% change to low flow range (monthly Q75 to Q99)**			

For more information about this project and applications for these recommendations please contact

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Section 1: Introduction

1.1 Project Description and Goals

The Delaware River Basin Commission (DRBC) seeks to increase the amount of scientific information that they incorporate into basin-wide goals and standards for river flow management. Taking advantage of recent research and studies that address ecological responses to flow alteration is of particular interest. The Nature Conservancy (Conservancy) and other partners share the Commission's interest.

The project purpose was to produce flow recommendations based on ecological responses to flow alteration that DRBC can incorporate into water management planning and permitting, while meeting demands for water use. The project was funded by DRBC and the workplan was developed to address several elements of the Commission's Compact (Compact), Comprehensive Plan, Water Code, Water Quality Regulations (WQR), and Water Resources Program, specifically:

- Section 3.6 of the Compact, which authorizes the Commission to establish standards of planning, design and operation of all projects and facilities in the Basin that affect its water resources;
- the Commission's WQR, which currently include numerical stream quality objectives for the protection of human health and aquatic life based on the consecutive 7-day flow with a 10-year recurrence interval (Q7-10) unless otherwise specified, and accordingly, the Commission generally requires docket holders to adhere to pass-by flow restrictions and conservation releases based on the Q7-10;
- an acknowledgment that since the Commission's water quality objectives were first established, scientific understanding of the relationship of streamflows to aquatic health has evolved to suggest that the Q7-10 may not provide adequate protection for the aquatic life of streams and rivers; and
- Commission recognition that a study of ecological flow requirements specific to the Delaware River Basin is needed in order for the Commission to effectively manage and plan to meet future water needs in the Basin.

With this foundation in mind, in September 2011, the Commissioners adopted Resolution 2011-11 to engage the Conservancy to lead a process to develop basinwide ecosystem flow recommendations for the subwatersheds of the Delaware Basin, following the general model of other basin-scale projects.

The study is based on several premises:

- Flow is considered a "master variable" because of its direct and indirect effects on the distribution, abundance, and condition of aquatic and riparian biota.
- Flow alteration can have ecological consequences.
- The *entire* flow regime, including natural variability, is important to maintaining the diversity of biological communities in rivers.
- Rivers provide water for public water supply, energy production, recreation, industry, and other needs.
- Negative ecological impacts can be minimized by incorporating ecological needs into water management planning.

We had several objectives when developing flow recommendations for the Delaware River basin. Specifically, we sought to:

- build on projects that produced flow recommendations for other river basins in the United States;
- provide information for all stream and river types in the basin (except Coastal Plain);
- represent as many taxonomic groups and aquatic habitats as possible;
- address the entire flow regime, including low, seasonal, and high flow components;
- use existing information, data, and consultation with scientists and managers;
- develop flow recommendations that are applicable to existing water management programs; and
- create a framework that can accommodate new information on ecological responses of flow-sensitive species and habitats.

1.2 Project Approach

This project implements the major objective described in the Ecological Limits of Hydrologic Alteration (ELOHA) framework: to broadly assess environmental flow needs when in-depth studies cannot be performed for all rivers in a region (Poff et al. 2010, See ***ELOHA in Practice***). Our approach incorporates several elements in the ELOHA framework, including river classification, identification of flow statistics and calculation of flow alteration, and development of flow alteration-ecological response relationships.

Given the available hydrologic and biological data and the timeframe for this project, we chose to develop flow recommendations based on hypotheses about relationships between flow alteration and ecological response that were developed through expert consultation and supported by published literature and existing studies. This is an alternative to focusing on novel quantitative analyses to relate degrees of flow alteration to degree of ecological change that is described in Poff et al. (2010). Apse et al. (2008) point out advantages to the approach we have taken: it is timely, cost-effective and can address multiple taxonomic groups over a large geographic area. It can also serve as a precursor to more quantitative analyses and produce flow recommendations based on existing information that can be implemented in the meantime. The

ELOHA in Practice. Since the ELOHA framework was first presented in 2010, case studies from around the world illustrate the flexibility and innovative thinking that has emerged within the structure of the framework. In 2012, A Practical Guide to Environmental Flows for Policy and Planning was published to summarize the range of regional-scale approaches to environmental flow management among nine complete or nearly complete projects. These case studies represent diverse approaches over a range of geographic areas – from a 2,400 km^2 pilot basin in Colorado to the entire 254,000 km^2 State of Michigan.

Within these cases, Michigan, Rhode Island, and Connecticut have translated environmental flow criteria into statewide water management programs.

A Practical Guide to Environmental Flows for Policy and Planning is available online: http://www.eflownet.org/viewinfo.cfm?linkcategoryid=1&id=280&linkid=44&siteid=1

resulting flow hypotheses can help direct future quantitative analyses to help confirm or revise flow recommendations.

This project followed the general model of other projects that developed flow recommendations for large river basins, most specifically the Susquehanna River, the Upper Ohio River in Western Pennsylvania, and the Great Lakes in New York and Pennsylvania (DePhilip and Moberg 2010, USACE 2012, DePhilip and Moberg 2013, Taylor et al. 2013). The first of these three studies, Ecosystem Flow Recommendations for the Susquehanna River Basin, was developed to support SRBC's water management programs and their collaborating agencies. The report was used to help develop the revised Low Flow Protection Policy (LFPP) adopted by SRBC in December 2012.

Our approach also applies principles that guided other projects that developed flow recommendations for large rivers, including the Savannah River, the Willamette River, the Rivanna River (Virginia), and the upper Colorado River (Bowler et al. 2006, Richter et al. 2006, Gregory et al. 2007, Wilding and Poff 2008). However, it differs from projects that focused on recommendations for specific reaches (e.g., Savannah River) and addressed operations of specific facilities (e.g., reservoir releases). Unlike reach-specific projects, our goal was to identify ecosystem flow needs that can be generally applied to the various stream and river types throughout the basin. The resultant recommendations are likely to be a key component in a subsequent policy development process for instream flow requirements. Such a policy would likely address pass-by requirements for water withdrawals, conservation release requirements for reservoirs, consumptive use mitigation triggers and flow targets. The recommendations will also help the Commission and other basin partners in the planning, design (location and size) and operation of future water supply storage facilities.

Throughout the basin, there are many reaches that are affected by storage and releases made for water quality, recreation, hydropower and other purposes. This study gathers and summarizes available information about how flow affects suitability of habitat for species that use or migrate through these regulated reaches, but defining reach-specific flow recommendations is beyond the scope of this project (See ***Releases from reservoirs in the Upper Delaware***).

Releases from reservoirs in the Upper Delaware. Since the New York City water supply reservoirs were completed, the four basin states and New York City have worked together to manage reservoir releases for multiple objectives. Interim implementation of the most recent program, the Flexible Flow Management Program (FFMP), began in 2007. FFMP is "a framework for managing diversions and releases for multiple objectives, including water supply, drought mitigation, flood mitigation, protection of the tailwaters fishery, a diverse array of habitat needs in the main stem, estuary and bay, recreation and salinity repulsion". Since interim implementation began, experimental adjustments have been made each year in an effort to balance human and ecosystem needs and adjust to changes in river conditions. More information about the history of apportionment of the basin's waters is available at http://www.nj.gov/drbc/programs/flow/

We synthesized existing literature and scientific reports, results of hydrologic analysis, and expert input to develop recommended limits to flow alteration based on best available science. Figure 1.1 illustrates how various sources of information were used to develop interim products and final recommendations.

The majority of the work on this project was completed between April 2012 and December 2013. The project centered on three workshops to review interim products. Because travel was difficult for many technical experts employed by state and federal agencies, Conservancy and DRBC staff also traveled to consult with staff from New Jersey Department of Environmental Protection (NJ DEP), New York State Department of Environmental Conservation (NYSDEC) and others whose schedules or travel restrictions prevented participation in the workshops. This was an efficient way to get input on specific aspects of the project and incorporate state-specific information.

April 2012	Project orientation WebEx
Sept 2012	Workshop I – Flow Hypotheses (at NJ School of Conservation, Branchville, NJ)
Mar 2013	Workshop II – Flow Recommendations (at Kirkridge Retreat Center, Bangor, PA)
Sept 2013	Circulate draft recommendations for comments and hold review workshop at DRBC
Dec 2013	Final report complete

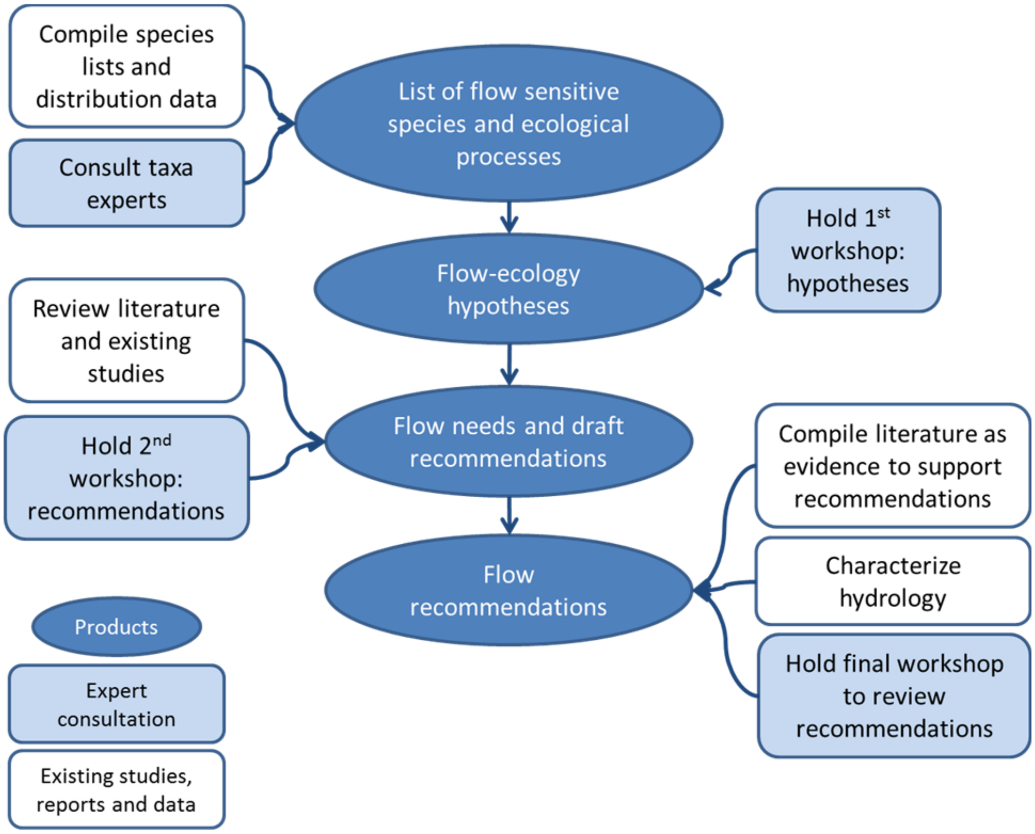

Figure 1.1 Process for developing flow recommendations. Multiple sources of information were integrated to support the recommendations. Interim and final products are within the ovals. Expert consultation occurred throughout and was organized around three workshops.

We reviewed peer-reviewed literature, research reports, and unpublished studies that either (a) provided qualitative confirmation of the importance of a particular magnitude or timing of flow for a group of species or an ecological process or (b) quantified an ecological response to flow alteration. In general, we prioritized information sources as follows: (1) data and literature for the Delaware River; (2) sources for the same species in mid-Atlantic U.S.; (3) sources for the same taxa in other temperate rivers; (4) sources for similar species and taxa in the mid-Atlantic U.S.; (5) sources for similar taxa in other temperate rivers. Most sources were either for the same taxa in other temperate rivers or for similar taxa in the mid-Atlantic U.S.

This report summarizes information on flow needs for key biological and physical processes and conditions and culminates with flow recommendations presented in Section 5. Specifically, this report and appendices include:

- life history summaries for flow-sensitive species and natural communities;
- flow needs, by season, based on life history information and physical processes and conditions;
- flow statistics that can be used to track changes to low flows, seasonal flows, and high flow events;
- flow recommendations for headwater, creeks, small rivers, medium tributaries, and large rivers; and
- a summary of literature and studies relevant to flow recommendations.

Section 2: Project Area and Basin Characteristics

Several reports provide detailed information on hydrologic characteristics, water quality, water use, infrastructure, and water resource management in the Delaware River basin. We drew from these documents to provide a very brief summary of basin physiography and its influence on hydrologic conditions. For more extensive descriptions of basin hydrologic conditions and current water management, please see

- State of the Delaware River Basin Report (DRBC 2008)
- Water Resources Plan for the Delaware River Basin (DRBC 2004)
- Estimated Ground-Water Availability in the Delaware River Basin, 1997-2000 (Sloto and Buxton 2006)

2.1 Project Area

The project area includes all tributary rivers and streams in the Appalachian Plateau, Ridge and Valley, New England, and Piedmont Physiographic Provinces (Figure 2.1). The study did not address streams in the Coastal Plain Province.

2.2 Physiography, Climate, and Vegetation

The Delaware River flows approximately 330 miles from the confluence of the East and West Branches to the Delaware Bay. From their confluence, the mainstem Delaware initially flows in a southeasterly direction, forming the border between New York and Pennsylvania. The topography is characterized by a relatively narrow floodplain as the Delaware River winds through a valley framed by steep mountains. River gradient is high compared to other mainstem reaches. The temperature in this reach is influenced by the tailwater releases from Cannonsville and Pepacton reservoirs. It is generally shallow, fast-flowing, and considered to be nutrient-poor (Santoro and Limbeck 2008; PFBC 2011).

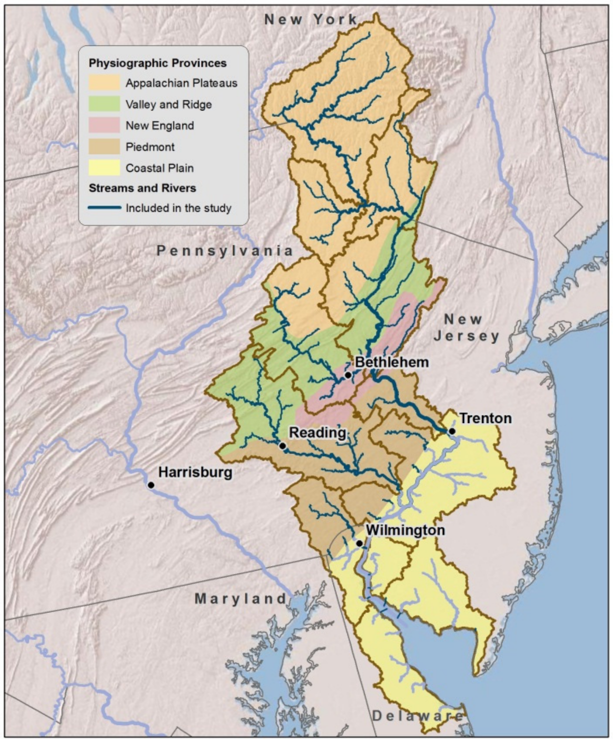

Figure 2.1 Map of Project Area

At Port Jervis, NY the river turns sharply and flows to the southwest, constrained by the Ridge-and-Valley topography, before crossing the Kittatinny Ridge at the Delaware Water Gap and cutting south toward Easton, PA. The floodplains along this reach tend to be relatively small and confined on the east and west banks by the Kittatinny, Godfrey, and Blue Mountain ridgelines. This reach has slightly higher nutrient concentrations than the upstream reach (Santoro and Limbeck 2008). Compared to the upstream reach, which is partially-influenced by releases to maintain a cool tailwater fishery, this reach is also warmer, with more extensive pools and shorter riffles (PFBC 2011).

The Lehigh River flows into the Delaware River at Easton, PA. From Easton, the Delaware River flows to the southeast toward Trenton, NJ. This reach of the river is a transition zone where both natural and anthropogenic changes to water quality occur. Limestone bands influence the water chemistry of the river and its tributaries. Compared to upstream reaches, this reach has higher nutrient concentrations and is warm, with very long pools and fewer riffles; islands are common (Santoro and Limbeck 2008; PFBC 2011).

The Delaware River basin occurs within two major physiographic divisions that influence stream hydrology: the Appalachian Highlands and the Atlantic Coastal Plain. The Appalachian Highlands includes four primary provinces: the Appalachian Plateau, Ridge and Valley, New England Province, and Piedmont (DRBC 2008).

The Appalachian Plateau includes the Catskill and Pocono Mountains. Rivers within this province are characterized by deep, narrow valleys through shales and sandstone. The upper basin watersheds – including the East and West Branches, the Lackawaxen, the upper Lehigh, and several tributaries to the mainstem are almost entirely within this province. The Appalachian plateau has some of the highest baseflow yields of anywhere in the basin (DRBC 2008, Sloto and Buxton 2006). The wetland-dependent streams that are characteristic of the Pocono plateau are within this province.

The Ridge and Valley province is a series of narrow, shale and sandstone ridges oriented from southwest to northeast. This province underlies major portions of the upper Schuylkill and Lehigh Rivers in Pennsylvania, the mainstem through the Delaware Water Gap, and the northernmost tributaries in New Jersey. Baseflows in the streams of the Valley and Ridge province provide yields comparable to the Appalachian plateau (DRBC 2008).

The New England province comprises less than 5% of the basin; streams are steep and rocky. This area is known as the Reading Prong in Pennsylvania and the Highlands in New Jersey and has been declared a landscape of national significance for its forested habitats and biodiversity. In 2006 New Jersey enacted legislation to protect the Highlands as an area of statewide significance, especially for water resources (DRBC 2008).

The Piedmont includes extensive stream networks through agricultural lands, rolling hills and sedimentary and crystalline rock. Nearly half of the basin population lives here and surface waters account for 90% of drinking water.

The Atlantic Coastal Plain is comprised of alternating layers of sand, clay and gravel. These unconsolidated sediments store and transmit more water than the consolidated bedrock in other provinces. Because the stream hydrology is quite different than other provinces and the ecological responses to changes in streamflow are likely to be quite different – and because groundwater is the primary water source and is subject to different management requirements – this study did not address streams in the coastal plain.

2.3 Major Habitat Types

Within the ELOHA framework, stream and river classification helps extend the application of flow alteration-ecological response relationships to streams and rivers in a broad geographic area (e.g., a state or large basin). In other words, classification allows us to aggregate data and observed responses from places that have been studied and transfer that information to similar streams for which less information exists. We used a relatively simple classification system to organize information about flow needs for various species and communities. This helps accomplish the objective of applying flow recommendations to all streams and rivers within the project area.

We defined major habitat types based primarily on drainage area, temperature and source of flow/flow stability (Figure 2.2). These variables are known to influence both hydrological and biological characteristics.

Size. Watershed size is one of the major influences on hydrologic characteristics and drainage area is often one of the most significant predictors in models that estimate streamflow. Drainage area is preferred to other commonly used measures of stream size – including stream order, stream link (i.e., the number of first order streams in the network above a given segment) or bankfull width. It is easy to calculate, independent of the scale of the hydrography layer, and relationships between stream size and drainage area are broadly understood (Olivero and Anderson 2008).

In the Northeast Aquatic Habitat Classification System (NAHCS), thresholds for size classes were evaluated by analyzing distributions of freshwater species across size classes. Various size class breaks were tested using cluster analysis on a regional database of fish, mussels, snails, amphibians, and aquatic insect species. The results highlight large differences between rivers with drainage areas less than 200 square miles (mi^2) and those greater than 200 mi^2 (Olivero and Anderson 2008)[1]. Based on these results, we incorporated size breaks at 200 and 1000 mi^2 into the classification. We also used a break at 40 mi^2 to represent a creek setting (rounded up from 38 mi^2 used in the NACHS). We combined all rivers greater than 1000 mi^2 into one class.

Small headwater streams differ both hydrologically and biologically from larger streams. In the NAHCS, headwater streams are defined as streams with drainage areas less than 3.8 mi^2 and have many of the characteristics listed below. Participants at the first workshop emphasized that these characteristics often occur in streams with drainage areas up to about 10 mi^2 and encouraged us to have a flexible upper limit to drainage area to define headwater streams. Based on this input, we define headwaters as: *all streams < 4 mi^2* ***and*** *streams between 4 and 10 mi^2 that have the characteristics listed below will be considered headwater streams.*

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[1] Also as part of the development of the NAHCS, a separate analysis used fish data and measures of classification strength to test potential size breaks in the Atlantic and Ohio basins in Pennsylvania. The following size classes had relatively high classification strength for fish communities in both the Ohio-Great Lakes and the Atlantic basins: 0-29 mi^2, 30-199 mi^2, 200-999 mi^2, 1000-6999 mi^2, 7000+ mi^2 (Walsh et al. 2007).

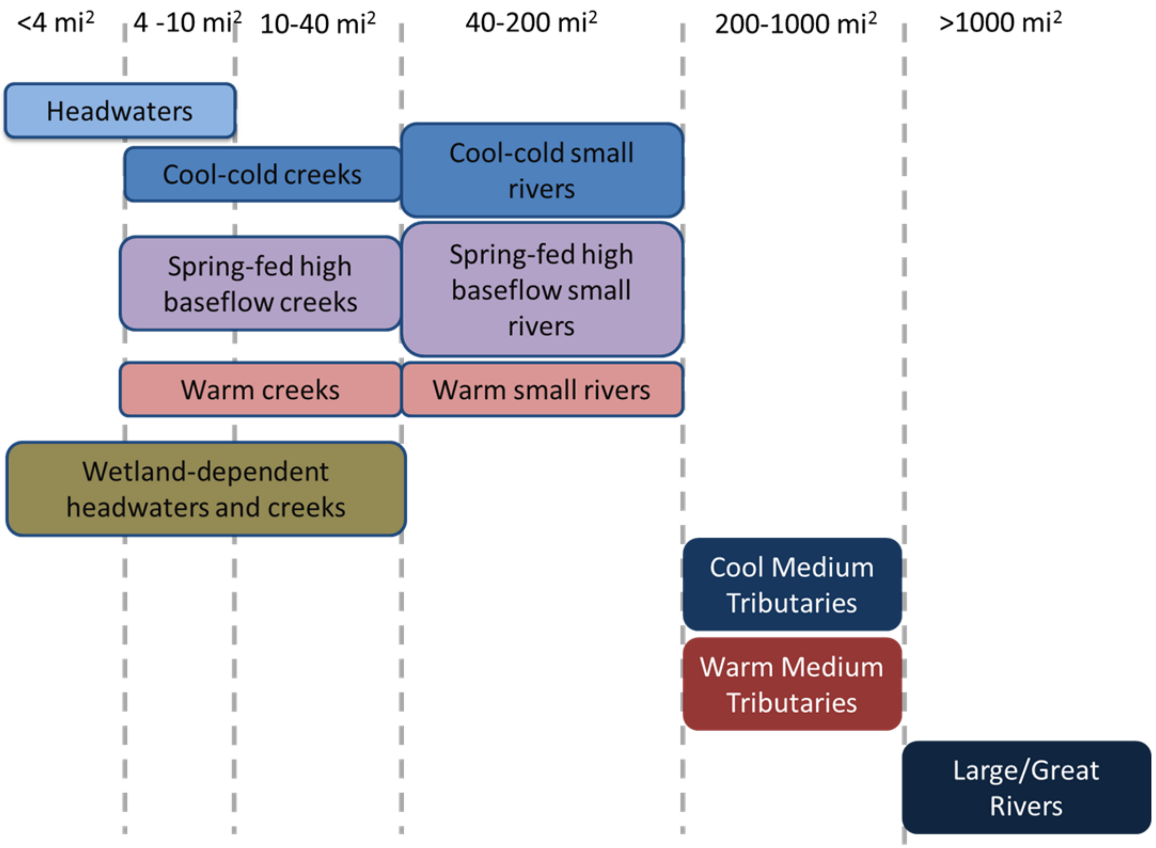

Figure 2.2 Habitat types for the Delaware Ecosystem Flow Study. Within each size class, additional types are defined by temperature and flow stability. The Northeast Aquatic Habitat Classification System was used to define and map size classes. http://rcngrants.org/content/northeastern-aquatic-habitat-classification-project

Below we summarize biological and hydrological characteristics for each size class.

Headwaters (< 4, 4-10 mi²)

- May be ephemeral or intermittent ("zero" flow days may occur in dry seasons and years)
- Stream channels are often poorly defined
- Stream network is highly dynamic and expands and contracts with precipitation
- Include macroinvertebrate species that are characteristic of headwater streams and seldom found in larger streams
- Amphibians may be top predator. If fish are present, the species and life stages are likely to feed on insects and alga, rather than being piscivorous
- Withdrawals may impact all parts of the flow regime and could increase intermittent conditions
- Increased intermittent conditions may affect processing of organic material and delivery to downstream network
- Streamflow estimates have high uncertainty
- A subset of headwater streams are defined as wetland-dependent, meaning that they are hydrologically connected to and typically fed by waters seeping through extensive wetlands

Creeks (4-10 to 40 mi^2)

- Typically perennial conditions
- Stream channels are usually well defined
- Fish are typically top predator
- Few mussels
- Species in bedrock reaches may be sensitive to drought conditions and flow depletion due to lack of hyporheic zones
- Withdrawals could lead to flow depletion in dry seasons/years
- Streamflow estimates may have high uncertainty during low flow conditions
- Creeks are subdivided into cool-cold, wetland-dependent, spring-fed high baseflow, and warm types

Small Rivers (40 to200 mi^2)

- Perennial conditions
- Stream channels are well defined and have higher morphological complexity than smaller streams
- Higher fish and mussel diversity
- Some floodplain development
- Flow likely to be sufficient to support water withdrawal proportional to streamflow
- Small rivers are subdivided into cool-cold, spring-fed high baseflow, and warm types

Medium Tributaries (200 to1000 mi^2)

- Perennial conditions
- High fish and mussel diversity
- Stream channels are complex and may include complex margins, islands and backwater habitats
- Floodplains are more expansive than on smaller-sized rivers
- Flow regime may be influenced by flood control and hydropower operations
- Flow likely to be sufficient to support water withdrawal proportional to streamflow
- Medium tributaries are subdivided into warm and cool types

Large/Great Rivers (> 1000 mi^2)

- Perennial conditions
- Stream channels are complex and may include islands, complex shorelines, backwaters and oxbows
- Flow regime may be influenced by flood control and hydropower operations
- Flow likely to be sufficient to support water withdrawal proportional to streamflow
- Include migratory fishes
- Large rivers are not further subdivided by temperature or other characteristics

Temperature. Stream temperature affects species distributions, growth rates, and biological productivity and is influenced by climate, elevation, and groundwater contributions (Allan 1995, Olivero and Anderson 2008). Thermal regimes can be altered by loss of riparian vegetation, increases in watershed impervious surfaces – both of which tend to increase stream temperature – as well as by the presence and operation of dams, which may either raise or lower expected temperatures (Allan 1995, Olivero and Anderson 2008, Stranko et al. 2007). Within creeks, small rivers, and medium tributaries, we distinguished cool (or cool-cold) from warm streams and rivers. In the Delaware basin, all medium tributaries are influenced by upstream reservoir releases, which may also influence temperature characteristics.

Source of flow and flow stability. We made two additional subdivisions for some size classes to capture differences in their hydrologic characteristics and potential response to changes in streamflow. For headwaters and creeks, we distinguished those that arise from wetland complexes from those that arise as concentrated overland or shallow subsurface flow in other landscape settings. Based on input at the first workshop, we defined 40 mi^2 as the upper limit at which these systems typically occur. Rivers larger than this (i.e., downstream of wetland-dependent headwaters and creeks), may have dark staining due to tannic inputs and may have higher flow stability than other rivers in the same size class, but experts generally agreed that once these rivers reach drainage areas near 40 mi^2, they should be considered with other small rivers.

Wetland-dependent headwaters and creeks typically have these characteristics:

- Sluggish, low gradient, naturally acidic systems
- Hydrologically connected to and typically fed by waters seeping through extensive wetlands
- Biodiversity is typically low, limited to organisms tolerant of naturally acidic conditions
- Occurs in the Pocono Plateau region of the basin and adjacent areas of southern New York and western New Jersey (although not mapped in any existing classification)[2]

Because high baseflow streams are also widely recognized to be hydrologically distinct from other streams, we distinguished them from other streams within the creek and small river size classes. These streams are not mapped throughout the basin, but they are concentrated primarily within the Ridge and Valley and Piedmont provinces and are often associated with high proportions of limestone in the drainage basin. They are typically classified as coldwater streams within the Pennsylvania classification, but are distinguished by extremely stable flows relative to other coldwater streams.

Spring-fed, high-baseflow creeks and small rivers typically have these characteristics:

- Typically have fairly stable and high baseflows throughout the year, even during dry periods
- Often have extensive hyporheic zones that provide refugia during dry periods
- Temperature variability is often moderated by groundwater contributions
- Occur in limestone and glaciated regions; may also occur in bedrock due to joint/fracture patterns. Chemical signatures vary and may be related to underlying geology
- May have cool or warm water fish assemblages

The classification used in this study creates a structure for organizing information about species, communities, and physical processes commonly associated with each habitat type. It helps ensure that the recommendations for each habitat type address all critical flow needs. We recognize that these types could be further subdivided using other variables and that there is considerable variability among

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[2] Neither the wetland-dependent nor spring-fed, high baseflow types are mapped comprehensively in this classification. Once the size class has been determined, these types will likely have to be assigned based on other sources of information when a project is proposed (including influence of wetlands on hydrology, presence of characteristic wetland species, influence of limestone on hydrology, and flow stability).

streams and rivers assigned to a given type. Our goal was not to develop – or redevelop – a definitive classification, but rather to use relevant variables from existing classifications to guide development and implementation of flow recommendations throughout the basin.

Section 3: Flow Components and Hydrologic Characterization

The discussion of flow components and flow statistics in Sections 3.1 and 3.2 was originally presented in Ecosystem Flow Recommendations for the Susquehanna River Basin (DePhilip and Moberg 2010) and adapted for this report and previous reports for the Upper Ohio River basin and the Great Lakes basin in New York and Pennsylvania.

3.1 Flow Components

Mathews and Richter (2007) discuss the concept of environmental flow components and their application to environmental flow standard setting. Drawing on examples from around the world, they describe the major flow components that are often considered ecologically important in a broad spectrum of hydro-climatic regions: extreme low flows, low flows, high flow pulses, small floods, and large floods. They also introduce a function within the Indicators of Hydrologic Alteration (IHA) software that can be used to assign daily flows to various flow components.

Flow components integrate the concepts of seasonal and interannual variability. Building on Postel and Richter (2003) and Mathews and Richter (2007), we define three ecological flow components: high flows[3], "typical" seasonal flows, and low flows. This section briefly describes the ecological importance of each flow component. We also define and illustrate these flow components for the Delaware River using flow exceedance values (See ***Defining Flow Components***). Throughout the rest of the document, we refer to these flow components and how they relate to ecosystem flow needs. We also organize our flow recommendations, which are presented in Section 5, around these components.

High flows and floods. In the Delaware River, high flow events and floods provide cues for fish migration, maintain channel and floodplain habitats, inundate submerged and floodplain vegetation, transport organic matter and fine sediment, and help maintain temperature and dissolved oxygen (DO) concentrations. These events range from relatively small, flushing pulses of water (e.g., after a summer rain) to extremely large events that reshape floodplains and only happen every few years (e.g., large snowmelt-driven or rain-on-snow events).

Increases in magnitude and/or frequency of these events could lead to channel instability, floodplain and riparian disturbance, and prolonged floodplain inundation. Loss of these events could result in channel aggradations, loss of floodplain inundation, and favor certain vegetation communities. Although the bankfull and overbank events that provide channel and floodplain maintenance commonly occur in winter and spring, these events could occur in any season.

Seasonal flows. Seasonal flows provide habitat for spring, summer, and fall spawning fishes; ensure that eggs in nests, redds, and various substrates are wetted; provide overwinter habitat and prevent formation of anchor ice; maintain bank habitat for nesting mammals; and maintain a range of persistent

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[3] Within the high flow component, we include high flow pulses (below bankfull), bankfull events, and flood events with 5- and 20-year recurrence intervals. Therefore we are effectively representing all of the components defined by Mathews and Richter (2007).

habitat types. Naturally-occurring variability within seasons helps maintain a variety of habitats and provides conditions suitable for multiple species and life stages.

Seasonal flows – often represented by median daily and monthly flows – are correlated with area and persistence of critical fish habitat, juvenile abundance and year-class strength, juvenile and adult growth, and overwinter survival. In summer, fall, and winter, studies in other rivers have shown that decreases in median monthly flow correspond to reduced macroinvertebrate density and richness, reduction of sensitive taxa, increase in tolerant taxa, and decrease in mussel density. Many studies cited tie ecological response to change in median monthly flows in a specific month or throughout a season.

These flows represent a "typical" range of flows in each month and are useful for describing variation between seasons (e.g., summer and fall). Most of the time – in all but the wettest and driest portions of the flow record – flows are within this range.

Low flows. Low flows provide habitat for aquatic organisms during dry periods, maintain floodplain soil moisture and connection to the hyporheic zone, and maintain water temperature and DO. Although low flow events naturally occur, decreases in flow magnitude and increases in frequency or duration of low flow events affect species abundance and diversity, habitat persistence and connectivity, water quality, increase competition for refugia and food resources, and decrease individual species' fitness. When they do occur, extreme low flows enable recruitment of certain aquatic and floodplain plants; these periodic disturbances help maintain populations of a variety of species adapted to different conditions.

Decreases in low flow magnitude have been correlated with changes to abundance and diversity of aquatic insects, mussels, and fish. Low flows also influence habitat persistence and connectivity, including riffle, pool, backwater and hyporheic habitats critical for fish, aquatic insect, crayfish, mussel, and reptile reproduction and juvenile and adult growth. Water quality, specifically DO concentrations, is directly correlated to low flow magnitudes.

3.2 Flow Statistics

Once we defined flow components, we needed to select a set of flow statistics that would be representative of each component. We adopted criteria for selecting flow statistics from Apse et al. (2008), which states that flow statistics should:

- represent natural variability in the flow regime;
- be sensitive to change and have explainable behavior;
- be easy to calculate and be replicable;
- have limited redundancy;
- have linkages to ecological responses; and
- facilitate communication among scientists, water managers, and water users.

In Table 3.2, we list the ten flow statistics we chose to represent the high, seasonal and low flow components. We chose these statistics because they are easy to calculate, commonly used, and integrate several aspects of the flow regime, including frequency, duration, and magnitude. Several statistics are based on monthly exceedance values and monthly flow duration curves. By using monthly – instead of annual – curves, we also represent the timing of various flow magnitudes within a year.

Defining Flow Components

We used flow components to highlight specific portions of the hydrograph and discuss the ecological importance of each portion. We used flow exceedance values (Qex) to divide flows into three components. For example, a 10-percent exceedance probability (Q10) represents a high flow that has been exceeded only 10 percent of all days in the flow period. Conversely, a 99-percent exceedance probability (Q99) represents a low flow, because 99 percent of daily mean flows in the period are greater than that magnitude. We defined each flow component on a monthly basis (i.e., using monthly flow exceedance values) to capture seasonal variation throughout the year.

Flow Component	**Definition**
High flows and floods	Flows > monthly Q10
Seasonal flows	Flows between the monthly the Q75 and Q10
Low flows	Flows < monthly Q75

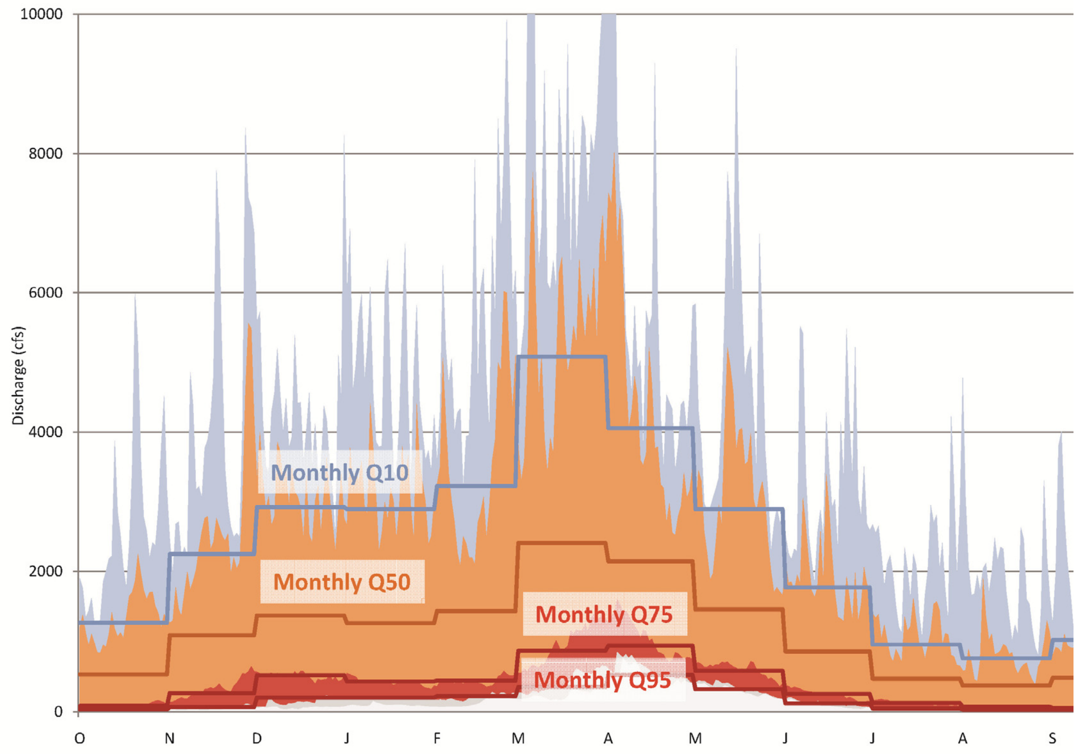

Table 3.2 Flow statistics used to track changes to high, seasonal, and low flow components

Flow Component	Flow Statistic
High flows	
Annual / Interannual (>= bankfull)	
Large flood	Magnitude and frequency of 20-year flood
Small flood	Magnitude and frequency of 5-year flood
Bankfull	Magnitude and frequency of 1 to 2-year high flow event
High flow pulses (< bankfull)	
Frequency of high flow pulses	Number of events > monthly Q10 in spring and fall
High pulse magnitude	Monthly Q10
Seasonal flows	
Monthly magnitude	Monthly median
Typical monthly range	Area under monthly flow duration curve between Q75 and Q10 (or some part of this range)
Low flows	
Monthly low flow range	Area under monthly flow duration curve between Q75 and Q99
Monthly low flow magnitude	Monthly Q75 Monthly Q90

As a group, these statistics help track (a) magnitude and frequency of annual and interannual events; (b) changes to the distribution of flows (i.e., changes to the shape of a flow duration curve); and (c) changes to four monthly flow exceedance frequencies: Q10, Q50, Q75, and Q95.

We define large and small floods as the **20-year and 5-year floods**, respectively, based on studies within the basin and in similar systems that indicate these events are commonly associated with floodplain maintenance and channel maintenance, bank and island morphology and maintaining various successional stages of floodplain vegetation (Burns and Honkala 1990, Auble et al. 1994, Abbe and Montgomery 1996, Walters and Williams 1999, Zimmerman and Podniesinski 2008). Changes to the magnitude or frequency of these events will likely lead to channel and floodplain adjustments, changes in distribution or availability of floodplain habitats, and alterations to floodplain and riparian vegetation.

Bankfull events are commonly referred to as the channel forming discharge. This event occurs fairly frequently and, over time, is responsible for moving the most sediment and defining channel morphology. Chaplin (2005) published recurrence intervals and regression equations for bankfull events within the basin. Based on this study, we selected the **1 to 2-year event** to represent the bankfull flow.

High flow pulses that are less than bankfull flows flush fine sediment, redistribute organic matter, moderate stream temperature and water quality, maintain aquatic and riparian vegetation, and promote ice scour during winter (Nanson and Croke 1992, Abbe and Montgomery 1996, Fortney et al. 2001, Hakala and Hartman 2004, Chaplin 2005, Dewson 2007b). These pulses have different magnitudes – and different ecological functions – in different seasons. They usually occur in response to precipitation events or snowmelt. Part of what makes these events important is their magnitude relative to typical seasonal flows. In other words, the exact magnitude of the high flow pulse may be less important than the fact that these events occur. These events may be particularly important in summer and fall when flows are generally lower than in other seasons. We selected the **monthly Q10** magnitude to represent high flow pulses. Most of the high flow pulses occur as peak events above the monthly Q10. In the Delaware basin, the frequency of these events (that is, the number of pulses above the monthly Q10) is particularly important in fall when these flows maintain water quality and temperature and transport organic matter and fine sediment. The frequency of these events is also important in spring, when they cue spawning fish, help maintain access to and quality of shallow-slow spawning and nursery habitat; and support vegetation growth. During spring and fall we count the frequency of events above the monthly Q10 (in addition to monthly Q10 magnitude).

We use the **median monthly flow (Q50)** to as one of the statistics that represents seasonal flows. Many studies cited in this report describe ecological responses to changes in median monthly flow. Describing flows relative to the long-term median monthly flow is useful for describing variation among years (e.g., a wet summer compared to a dry summer).

The median is a measure of central tendency, but it does not reveal much about the distribution of flows around the median. Therefore, we also propose to use a statistic that tracks the amount of change to the middle portion of each monthly flow duration curve; this statistic is modified from flow duration curve approaches described by Vogel et al. (2007) and Gao et al. (2009).

Because we defined the seasonal flows as flow between the monthly Q75 and Q10, we also defined a **seasonal flow range** as the area under monthly flow duration curve between Q75 and Q10 (or some part of this range) (Figure 3.1). This statistic helps quantify changes to a specific portion of a long-term monthly flow duration curve. Expressing flow recommendations in terms of change to the area under the curve allows for flexibility in water management as long as the overall shape of the curve, or a portion thereof, does not change dramatically. This statistic (and the monthly low flow range described below) build on the nondimensional metrics of ecodeficit and ecosurplus[4], which are flow duration curve-based indies used to evaluate overall impact of streamflow regulation on flow regimes (Vogel et al. 2007, Gao et al. 2009). Flow duration curve-based approaches are also good graphical approaches to assessing alteration to the frequency of a particular flow magnitude and are best described by Acreman (2005) and Vogel et al. (2007).

Monthly low flow magnitude can be represented using either the **monthly Q90 or monthly Q75**, depending on drainage area. We recommend using the Q75 in headwater streams with drainage areas less than 50 mi^2 and Q90 for larger streams and rivers. For headwater streams, we propose the Q75 because there are several studies in small streams that document ecological impacts when flows are reduced to below the Q75 and/or extreme sensitivity of taxa within headwater habitats (e.g., Hakala and Hartman 2004, Walters and Post 2008, Haag and Warren 2008, Walters and Post 2011a). Also, our

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[4] Vogel et al. (2007) defines ecodeficit as the ratio of the area between a regulated and unregulated flow duration curve to the total area under the unregulated flow duration curve. This ratio represents the fraction of streamflow no longer available to the river during that period. Conversely, ecosurplus is the area above the unregulated flow duration curve and below the regulated flow duration divided by the total area under the unregulated flow duration curve. The ecodeficit and ecosurplus can be computed over any time period of interest (month, season, or year) and reflect the overall loss or gain, respectively, in streamflow due to flow regulation during that period (Vogel et al. 2007).

analysis of streamflow at index (minimally-altered) gages in the basin showed that monthly Q90 values in headwater streams and creeks were often less than 1 cfs, especially in summer and fall months. Therefore, we concluded that a higher flow exceedence value (Q75) is needed to ensure that these flow values are outside of the measurement error of the streamflow gage.

We also define the **monthly low flow range** as the area under the monthly flow duration curve between Q75 and Q99 (Figure 3.1). This statistic quantifies changes to the low flow tail of the monthly flow duration curve, specifically between the Q75 and Q99. This statistic is an indicator of changes to the frequency of low flow conditions.

All flow statistics described in this section can be easily calculated using readily available tools. ***Calculating Flow Statistics*** describes two tools we used in this study. We used these tools to calculate flow statistics for the analysis of natural range of variability used to support flow recommendations described in Section 5.

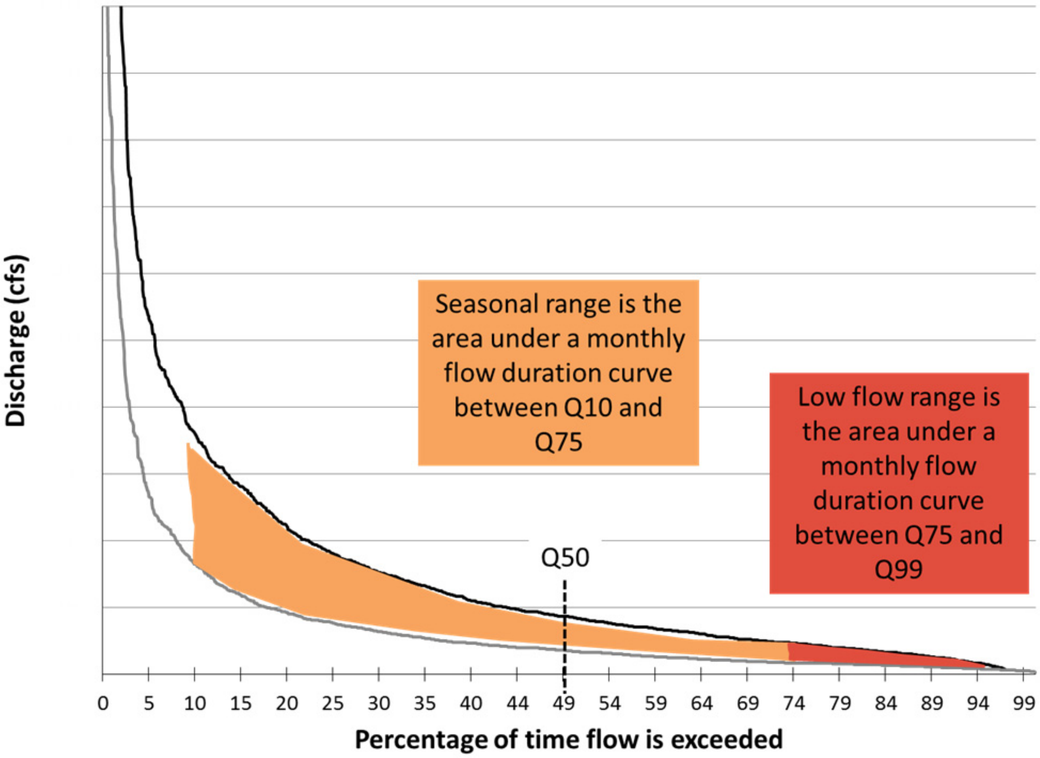


Figure 3.1 Seasonal range and monthly low flow range statistics. The black line represents unregulated conditions and the gray line represents regulated conditions. The colored area represents the difference in area between portions of the two curves.

Calculating Flow Statistics

Indicators of Hydrologic Alteration (IHA), version 7.1 calculates the median monthly flow (**Q50**) and monthly **Q10, Q75,** and **Q90** and produces monthly flow duration curves. The IHA also calculates the magnitude and frequency of various high flow events, including bankfull, small floods, and large floods. These events can be defined by recurrence interval (e.g., 5-year floods) or specific magnitude (in cfs or cms). The IHA will also return the frequency of high flow pulses, based on a user-defined threshold, during a specified season. The IHA was developed to compare values of flow statistics calculated for two different periods (e.g., pre- and post-alteration, which is referred to as a two-period analysis) or to evaluate trends in flow statistic (referred to as a single-period analysis). For this project, we ran single-period analyses to characterize flow variability at minimally-altered gages. The IHA software can be downloaded for free; it requires registration (also free) and agreement to a simple legal disclosure and terms of use. http://www.conservationgateway.org/ConservationPlanning/ToolsData/Tools/CommonlyUsedTools/Pages/commonly-used-tools.aspx#IHA

Calculating change to flow duration curves. Although the IHA 7.1 generates flow duration curves, calculating the **seasonal range** and **low flow range** changes to flow duration curves requires some additional processing. These two statistics require an additional, spreadsheet-based tool that calculates the ratio between the differences in area under two flow duration curves and compares it to the area under the reference curve. This tool builds on a flow duration curve calculator developed by Stacey Archfield (Research Hydrologist, USGS Massachusetts-Rhode Island Water Science Center) and uses the IHA output as input. It allows users to specify areas under *portions* of the curve; this customization allows us to calculate the area under the curve between Q10 and Q75 and also between Q75 and Q99 (or any portion of the curve). This tool can be obtained by contacting the study authors.

Daily flows for multi-year periods. All statistics should be calculated using multiple years of data. Richter et al. (1997) and Huh et al. (2005) suggest that using at least 20 years of data is sufficient to calculate interannual variability for most parameters, but to capture extreme high and low events 30 to 35 years may be needed.

Comparing values of these flow statistics requires (a) a sufficiently long period of record before and after (pre- and post-) alteration; (b) a sufficiently long pre-alteration (baseline) period of record and the ability to simulate a post-alteration time series; or (c) a sufficiently long post-alteration period of record and the ability to simulate a pre-alteration time series.

3.3 Hydrologic Characteristics of Major Habitat Types

We used flow data from 36 index gages within the study area to characterize the range of long-term monthly exceedence values within major habitat types. An index gage is a USGS stream gage where flows are not significantly affected by upstream regulation, diversions, mining, or development and therefore reflects minimally-altered hydrologic conditions. The set of 34 index gages includes at least one example of each stream and river type, although some types are better represented than others. For this analysis, we combined all types within each size class in order to increase the number of gages used to characterize each stream class.

We used water years 1960-2008 to define interannual variability of these statistics. This period is the best practical approximation of long-term variability within the basin and includes the drought and flood of record. This period was also used to develop the Baseline Streamflow Estimator (BaSE), which simulates minimally-altered flows for ungaged streams in Pennsylvania (Stuckey et al. 2012).

We used the Indicators of Hydrologic Alteration to calculate the monthly median flow (Q50) and two monthly low flow statistics (Q75 and Q90) for each index gage. The IHA provides these values for each month in each year of the period of record. Then, it calculates the median of the monthly values over the period of record (i.e., median Q50, median Q75, and median Q90 based on 48 years of record). Then, we summarized these values by the drainage areas used to define stream and river types (Figure 3.2). To facilitate comparisons among seasons and drainage areas, we assigned these values to three categories: < 10 cfs; between 10-50 cfs; and >50 cfs. These categories help estimate relative sensitivity to alteration and how much error is associated with measuring or estimating streamflows. The values for all median (Q50) monthly stream flow and monthly low flow statistics (Q75 and Q90) are included in Appendix 1.

Headwaters (< 10 mi^2) – values based on 9 gages

- 83% of summer and fall Q50 are < 10 cfs.
- 67% of the winter and spring Q50 are < 10 cfs.
- 91% of summer and fall Q75 are < 10 cfs. Over two-thirds are < 5 cfs; some are < 1 cfs.
- 76% of winter and spring Q75 are < 10 cfs.
- 10% change is within measurement error for many of these streams

Creeks (10 - 40 mi^2) – values based on 5 gages

- 33% of the summer and fall Q50 are < 10 cfs. 100% are less than 50 cfs.
- All winter and spring Q50 are >10 cfs. 77% are between 10 and 50 cfs.
- 90% of summer and fall Q90 values are below 10 cfs.
- In winter and spring, 38% of Q90 values are below 10 cfs and 62% are of winter and spring Q90 are between 10 and 50 cfs.

Small rivers (40 -200 mi^2) – values based on 15 gages

- In small rivers, 54% of the summer and fall Q50 are below 50 cfs; only 1% is below 10 cfs.
- Almost all (96%) winter and spring Q50 are above 50 cfs (the lowest value is 48 cfs)
- 91% of summer and fall Q90 in small rivers are below 50 cfs. In August and September, most Q90 values are below 20 cfs and 20% are below 10 cfs.

Medium tributaries (> 200 mi^2) and large rivers (>1000 mi^2) – values based on 5 gages

- In all seasons, monthly Q50 values are above 50 cfs.
- 33% of summer and fall Q90 in med tribs and large rivers are < 50 cfs.
- Almost all Q90 in winter and spring are > 50 cfs (only two values at the gage with the smallest drainage area – 211 sq mi - are 41 and 49 cfs in December and January)
- The gages used to represent medium tributaries are at the small end of the size range.

Tools for Estimating Streamflow at Ungaged Locations

Baseline Streamflow Estimator (BaSE) - Pennsylvania

In 2012, USGS, in cooperation with the Pennsylvania Department of Environmental Protection, Susquehanna River Basin Commission, and The Nature Conservancy, completed the Baseline Streamflow Estimator (BaSE), a tool to estimate minimally-altered streamflow at a daily time scale for ungaged streams in Pennsylvania using data collected during water years 1960–2008. The tool is free, publicly available, and allows estimation of a minimally-altered daily flow for any Pennsylvania stream using a point-and-click interface. The BaSE tool and accompanying report documenting the methods is available online http://pubs.usgs.gov/sir/2012/5142/.

New York Streamflow Estimation Tool (NYSET) – New York

USGS, in cooperation with New York State Energy Research and Development Authority (NYSERDA) and The Nature Conservancy, is developing the New York Streamflow Estimation tool (NYSET). NYSET will produce an estimated daily-mean streamflow each day for the period Oct. 1, 1960 – Sep. 30, 2010 at any user-selected point on nearly all streams in New York, excluding Long Island. For additional information visit New York Water Science Center Web site at: http://ny.water.usgs.gov

National Water Census – Delaware River Basin

The Delaware River Basin is one of three focus areas in the National Water Census. Two additional basinwide streamflow models will be developed through this effort. The **W**ater **A**vailability **T**ool for **E**nvironmental **R**esources (WATER) will be used to develop a streamflow model for the non-tidal Delaware River Basin. The model will be used as a decision support tool to evaluate how water stressors such as population growth, land-use change, climate variability, and climate change affect the availability of water resources in the basin. Model results will be published and the model will be available to the public.

The second model will use a similar approach (i.e., QPPQ) to what was used for Pennsylvania BaSE and New York SET to estimate daily mean streamflow for ungaged locations in the Delaware basin using map correlation to nearby gaged sites. Flows will be estimated from 1960 to 2011 and the model will be available to the public.

More information on both of these models is available online http://water.usgs.gov/watercensus/delaware.html

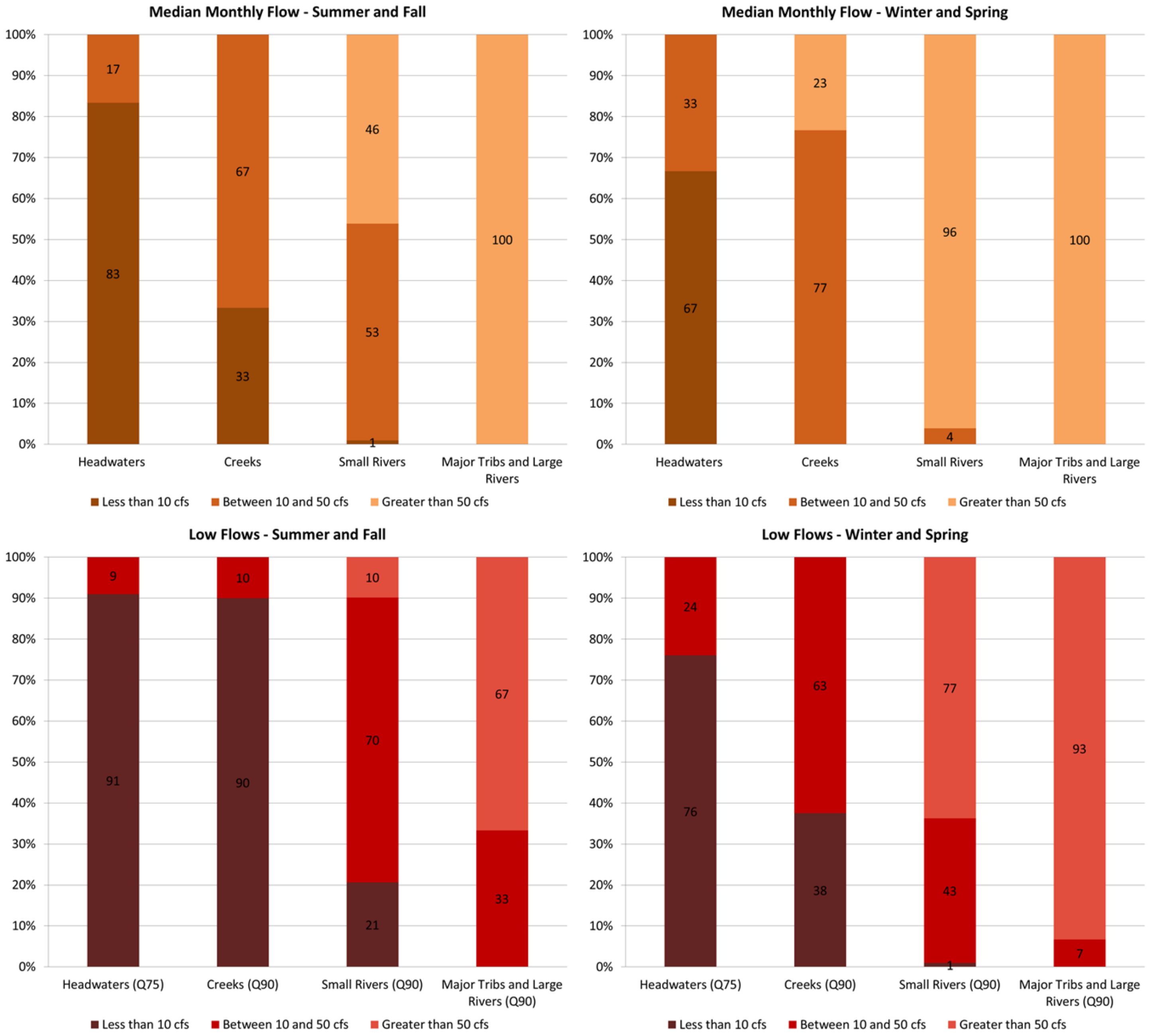


Figure 5. Distribution of monthly median and low flow statistics in each season based on minimally-altered gages

Section 4: Defining Ecosystem Flow Needs

In the Delaware River basin, hundreds of species depend on a mosaic of riverine habitats and fluvial processes to complete their life cycles. To define the flows needed to support these complex ecosystems, we organized species into groups that share a sensitivity to one or more aspects of the flow regime. Biological and ecological traits are commonly used to describe groups of species with similar life histories, physiological and morphological requirements and adaptations, thereby providing a mechanistic link to understanding or predicting responses to varying hydrologic conditions (Poff et al. 2006, Vieira et al. 2006, Merritt et al. 2010, Mims and Olden 2012). Information about how species respond in other river systems can help set expectations about the potential mechanisms and taxa response of species with similar functional traits in the Delaware River basin.

We identified 19 groups comprised of over 100 species to represent the characteristic biological communities of the Delaware River basin. We summarized critical life history stages and timing for species within each group and used species distribution data to associate groups with habitat types (Cooper 1983, Merrit 1987, Brauning 1992, Hulse et al. 2000, Walsh et al. 2007, Zimmerman and Podniesinski 2008).

By overlaying key life history requirements for each group on representative hydrographs for each habitat type, we highlight relationships between species groups and seasonal and interannual streamflow patterns (Figure 4.1).

Grouping species that share life history traits helps explain how and why multiple species may respond to environmental change, in this case flow alteration.

We identified 19 groups of species – including fish, mussels, aquatic insects, reptiles, amphibians, birds, mammals, and vegetation – that are expected to be sensitive to changes in the flow regime.

Expert input helped us state approximately 100 flow-ecology hypotheses that describe how specific taxa and ecological processes are expected to respond to changes to the flow regime. We aggregated related hypotheses by timing, flow-sensitive life stages and ecosystem function into a set of 20 flow needs that combine one or more responses of a group of taxa to a change in flow conditions.

In this section, we describe flow-dependent taxa and physical and chemical processes within the basin. For each taxa group, we summarize flow needs and key hydro-ecological relationships identified through workshops and literature review. Several appendices provide more detailed information:

- **Appendix 2. Life history diagrams and tables**, similar to Figure 4.1, illustrate the timing of life stages for taxa that occur in six major habitat types. The accompanying tables provide more detailed life history information for fish, mussels, vegetation and reptiles and amphibians.
- **Appendix 3. Distribution of flow-sensitive species groups among habitat types** indicate which species groups are expected to occur in each of the major habitat types
- **Appendix 4. Flow-ecology hypotheses** state how fish, mussels, vegetation, aquatic insects, crayfish, reptiles and amphibians, and physical and chemical processes are expected to change in responses to changes in streamflow
- **Appendix 5. Flow needs figures** summarize the flow needs in each season and indicate whether these needs are related to high, seasonal, or low flow components.

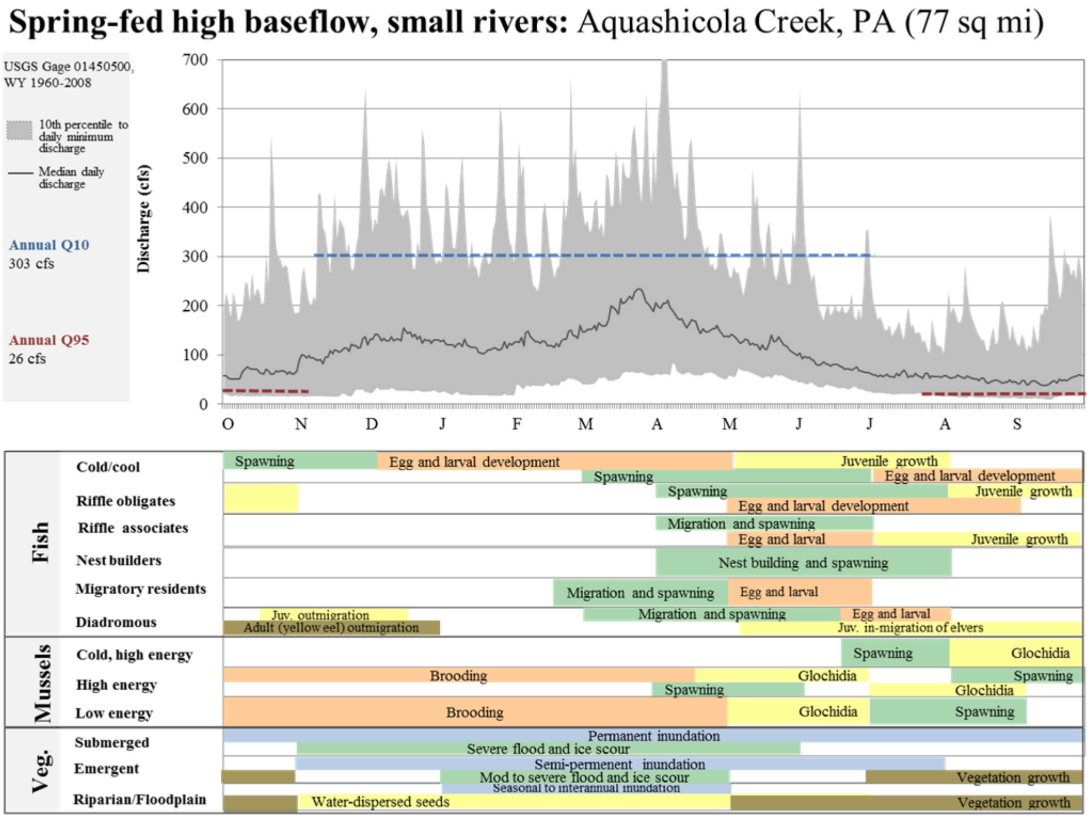


Figure 4.1 Example flow-ecology diagram for spring-fed, high baseflow small river

4.1 Fish

Key flow-related needs for Delaware River basin fish

- **Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes**
- **Maintain fall salmonid spawning habitat and promote egg, larval and juvenile development (brook and brown trout)**
- **Cue outmigration of diadromous fishes**
- **Maintain overwinter habitats for resident fish**
- **Support resident fish spawning**
- **Cue upstream migration and maintain access to riverine habitat**
- **Maintain access to and quality of shallow-slow margin and backwater habitats**

Records estimate that more than 90 fish species spend some portion of their life within rivers and wetlands of the Delaware River basin (Cooper 1983). Minnow (Cyprinidae) and sunfish (Centrarchidae) families account for almost half of the basin's fish diversity (Cooper 1983). These species represent diverse life strategies and range in body size from two inches to four feet. We used regional data, reports and expert input to organize fish into six groups representing 33 species (Cooper 1983, Argent 2000). Traits include body size, fecundity, home range, habitat associations, feeding habits and flow-velocity tolerances (Table 4. 1) (Cooper 1983, Winemiller and Rose 1992, Jenkins and Burkhead 1993, Vadas and Orth 2000, Frimpong and Angermeier 2009, Mims and Olden 2012).

Table 4.1 Fish groups in the Delaware River basin and shared life history traits

Group *example species*	**Life history traits**
Cold/cool fishes *mottled sculpin, slimy sculpin, brook and brown trout, pearl dace*	• thermal tolerance limits distribution to cool and cold habitats • sensitive to decreases in dissolved oxygen or increases in turbidity • across group, spawning occurs in all seasons
Vegetative obligates, slow margin and backwater species *bridle shiner, ironcolor shiner, golden shiner, eastern mudminnow, redfin pickerel, blackbanded sunfish, bluespotted sunfish*	• occur primarily in cool or warm sluggish headwater streams or backwaters and side channels of small and large rivers with aquatic vegetation • many of these species have eggs that adhere to vegetation
Riffle obligates *longnose dace, eastern blacknose dace, central stoneroller, margined madtom*	• small-bodied fishes • occur in all river types • require moderate to fast velocity habitats with coarse substrates • small home-range makes them sensitive to localized extreme conditions
Nest builders *river chub, creek chub, smallmouth bass, fallfish, redbreast sunfish, bluespotted sunfish*	• sensitive to flow conditions during spring and summer nest building • diverse nesting strategies within group • most require maintenance coarse substrate for nest building
Migratory residents *white sucker, northern hogsucker, walleye*	• moderate-sized home range • medium body size requiring moderately deep habitats, particularly during winter • spring spawners requiring connectivity between tributary and small river habitats • northern hogsucker and white sucker require connectivity during spring between overwinter habitats and upstream spawning riffles • upstream migration cued by temperature and rising water levels
Diadromous fish *American shad, hickory shad, blueback herring, alewife, striped bass, shortnose sturgeon, Atlantic sturgeon, American eel*	• long-lived, large-bodied fishes that move between the ocean and riverine habitats • migration typically cued by temperature and rising water levels • require connectivity to floodplain and backwater habitats as well as to upstream tributaries

Compared to other taxonomic groups, there is extensive literature documenting relationships between flow and fish species composition, population size, recruitment success, and habitat availability and quality. Flow is one of the main variables that influences fish habitat availability, creates habitat heterogeneity and maintains connectivity among essential habitats for various life stages. This is most often recognized during summer and fall, when flows are typically low compared to other seasons and low flows can reduce the amount of suitable hydraulic habitats or exacerbate high temperatures and low dissolved oxygen conditions. A national study of flow alteration and biological response found that diminished flow magnitudes were the primary predictors of biological integrity for both fish and macroinvertebrate communities (Carlisle et al 2010). In the southeastern U.S., estimated species richness and fish density were greatest under median seasonal discharge and lowest at 7Q10 discharge across all channel types and sizes (McCargo and Peterson 2010). 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 from 50 to 100% of 7Q10 (Freeman and Marcinek 2006). Other studies have estimated the changes to fish assemblages and documented fewer fluvial dependent fishes, benthic invertivores, and characteristic fish species when withdrawals were between 5 and 25% of the August median depending on the stream size and type (Zorn et al. 2008, Kanno and Vokoun 2010, Armstrong et al. 2011).

Small bodied fishes and riffle obligate fishes that have specific velocity preferences may be especially susceptible to hydraulic changes associated with flow depletion. Low stream discharge tends to reduce riffle area habitats to a greater extent than pool area habitats (Hakala and Hartman 2004, Armstrong et al. 2001). Using an IFIM model, weighted usable area for riffle obligates increased with increasing flow up to summer median flow values and then decreased due to velocity preferences (Leonard and Orth 1988). Reduction in available habitats can lead to resource depression, niche partitioning, and the competition for food between darter species (Schlosser and Toth 1984, Stauffer et al. 1986, Welsh and Perry 1998).

A decrease in flow magnitude may also expose stream margins and side-channel habitats reducing shallow-slow habitat for small-bodied and juvenile fishes, resulting in reduced abundance and assemblage shifts. Hydrologic models indicate shallow-slow backwaters dry with greater frequency and duration compared to similar in-channel habitat. Fish communities had a higher richness of rheophilic species where habitats remained connected (Flinn et al. 2008). Freeman et al. (2001) showed that young-of-year abundance was most highly correlated with shallow-slow habitat area and persistence and decreased daily flows reduced availability and persistence of shallow-slow habitat in summer. Bowen et al. (2003) demonstrated that the distribution, location, and extent of shallow-slow habitat in an unregulated river was tied to the spring and summer hydrograph. The side channels and tributary backwaters that were available during spring benefitted larval stages, which typically have poor swimming ability and rely on zooplankton and detritus as food sources. By the time spring flows recede to the main channel, these larvae have developed to juvenile stages that have better swimming and foraging ability. Availability of suitable habitat can also affect growth rates. Growth rates and survival of brassy minnows in backwaters were significantly lower in dry years than wet years (Falke et al.2010).

During summer, a decrease in magnitude and duration of low flows may increase temperature outside of thermal ranges for cool-coldwater fishes, leading to increased competition, stress, reduced body mass and possibly mortality. Cowx et al. (1984) observed salmonid year class failure during a summer when low flows contributed to extreme temperatures (26°C). Trout survival was negatively correlated to the amount of time that water temperature exceeded 20°C. Effects have been also seen on an individual level. Extreme low flow conditions resulted in individual brook trout having significant lower body condition during the drought relative to the post-drought period. Proportionally larger decreases in riffles and reduced flow velocity combined to limit food availability. Restricted habitat availability increased competition for limited food resources (Hakala and Hartman 2004). When flows where experimentally diverted to an estimated summer Q90 and 95, fish body length was 30 to 40% shorter for larger bodied fishes and 10% shorter for small bodied fishes (Walters and Post 2008). Alonso-Gonzalez et al. (2008) observed a negative correlation between age-1 trout mean fork length and the number of days flow was below the Q75 discharge during the late spring and early summer.

Fall marks the beginning of the spawning period for brook and brown trout and several studies describe the interrelationship of low and seasonal flows to spawning success and egg and larval development. A decrease in groundwater or surface flows may reduce access to and quality of redds during salmonid spawning, and several studies have found that localized groundwater contributions attract salmonids to habitats capable of supporting egg and larval development over winter and through the spring (Hazzard 1932, Raleigh 1982, Curry and Noakes 1995, Curry et al. 1994). Similarly, over a three year study on small streams in New York, all observed brook trout redds were constructed either immediately below springs or in places where seepage entered the redd through gravel (Hazzard 1932). In addition to groundwater contribution, depth and velocity are also critical to suitable spawning areas. A regional IFIM study predicted a loss of 10% of habitat loss for withdrawals of 11 to 14% of the November median (Denslinger et al. 1998). While extreme low flow conditions may reduce extent of spawning habitat in some systems, an analysis of brook and brown trout biomass before and after the 1991 drought showed that low flows during fall could actually increase brook trout spawning success and these periodic fall drought conditions may give brook trout a competitive advantage over brown trout where the two species coexist (Greene and Weber 1993).

Outmigration of shad and river herring and American eel typically occurs in fall and winter and movement is cued, in part, by high flow events that are synchronized with other cues, like temperature and day length. A change to the timing or magnitude of high flow events could decouple cues for American eel outmigration, delaying or impeding movement. Cues for silver eel emigration include precipitation and high flow pulses, temperature decreases of > 1-4 °C, and the lunar cycle (Hildebrand and Welsh 2005, Greene et al. 2009). Without fall high flow cues, eels delayed outmigration from fall to winter on the Shenandoah River (Eyler et al. 2010). Juvenile shad outmigration is primarily cued by decreasing temperatures. Water temperature is a critical factor in juvenile survival and hydrologic conditions that cause temperatures to decrease below 6°C may cause sublethal effects (Chittenden 1972). Low flow conditions have also been documented to physically inhibit outmigration (Yako et al. 2002). Stier and Crance (1985) documented flows that support velocities between 0.5 and 3 ft/s as suitable for supporting juvenile shad emigration. High flow pulses may help push juvenile shad downstream (Greene et al 2009).

Compared to other seasons, there are relatively few studies in winter, but there is evidence that overwinter survival can be reduced when high flows increase bioenergetic costs. When fish have low energy reserves, an increase in high flow frequency, magnitude or rate of change may force fish to move to find refuge, (Facey and Grossman 1990, Brenden et al. 2006). Mottled sculpin population size has been shown to be regulated by overwinter population density due to intraspecific habitat competition between juveniles and adults (Rashleigh and Grossman 2005). Frazil ice poses direct physiological effects (attaching to gills) in addition to restricting available physical habitat (Brown et al. 1993).

Upstream migration – of both diadromous and resident migratory fishes – is cued by a complex interaction of external cues, including water temperature, discharge, and lunar cycle, depending on the species. Many species are known to use spring high flow events and conditions as partial cues for upstream spawning migration. Alosids, including American shad and river herring migrate from the mainstem to the tributaries and small rivers of the Delaware. While water temperature is the primary factor that cues spawning, higher river flows, coupled with temperature increases have been found to trigger large migrations (Orth and White 1993, Pace Environmental Services 2007). Under low flow conditions on the Delaware River, bottlenecks, or 'stacking up' has been observed during upstream migration (D. Pierce, personal communication, 2012). For alosids, discharge that supports suitable velocities (0.3-0.9 m/s) is a critical factor in providing suitable spawning habitat and successful egg and larval development – keeping silt-free oxygenated eggs (Williams and Bruger 1972, Steir and Crance 1985, Bilkovic 2000). Shortnose sturgeon also migrate up the mainstem in the spring. Their migration has been documented in association with increasing temperatures and the receding limb of a spring high flow event (Heise et al. 2004, LaHaye et al. 1992, Paragamian and Wakkinene 2011).

Doherty et al. (2010) showed that white sucker spawning activity increased following a spring high flow pulse. DiStefano and Hebert (2000) observed movement of walleye upstream during peaking discharges downstream of a dam. Walleye have been observed making a second spawning run after a second high flow pulse during the spawning season (Dustin and Jacobson 2003, Koel and Sparks 2002).

During spring, a change in the frequency, timing or magnitude of high flows may decouple flows from temperature, light, and other cues and may reduce spawning runs. Reid (2006) observed that sucker spawning migrations were delayed by a spring flood event. Spawning was initiated on the receding limb of this flood event in conjunction with rising temperatures. Currie and Spacie (1984) observed the interaction between temperature and discharge influenced the timing of sucker spawning runs and noted that stream alterations that affect temperature, flow regimes, substrate or connectivity may reduce niche diversity used by catostomid species.

In addition to cuing spawning migrations, high spring flows help maintain access to side channel and backwater habitats and between large rivers and smaller tributaries. During spring and early summer, a decrease in flow magnitude may reduce access to backwater and sidechannel spawning habitats, reducing successful larval development. These shallow-slow habitats are particularly critical for vegetation obligates. Janac et al. (2010) showed a positive linear relationship between juvenile phytophilic (vegetation obligates) species abundance and duration of flooded vegetation in floodplain backwaters. Within oxbow habitats, fish assemblage structure is associated with both macrohabitat features (depth, temperature, conductivity) and the frequency of floods that connected backwater habitats to the channel. Six species that were collected in oxbow lakes were never collected in river channel surveys and several species that were rare in river channel surveys were abundant in oxbows (Zeug et al. 2005).

Although flows are relatively high during spring compared to other seasons, and are important for migratory cues and maintaining connectivity among habitats, increases in high flow frequency or magnitude can decrease spawning success for other species. For example, increase in frequency or magnitude of high flows may flush nest builders from guarding nests or scour eggs and developing larvae, limiting recruitment of nest builders, riffle obligates and riffle associates. For smallmouth bass, June flow was more than 40% above the mean resulted in near year class failures (Smith et al. 2005). A high flow event was responsible for 85% of smallmouth bass nest failures in a Virginia stream (Lukas and Orth 1995). Other studies have also noted the relationship between high flows, nest scour and smallmouth bass recruitment (Graham and Orth 1986, Peterson and Kwak 1999). Survival of walleye larvae were directly related to the frequency of high flow events with low survival during years with multiple events during the spring (Mion et al. 1998).

4.2 Mussels

Key flow-related needs for Delaware River basin mussels

- **Support mussel spawning, glochidia transfer, juvenile colonization and growth**
- **Maintain overwinter thermal regimes and habitat for mussels**

As some of the least mobile and longest-living aquatic organisms in the basin, mussels provide a lens to evaluate long-term trends and conditions (Grabarkiewicz and Davis 2008). As filter-feeding bivalves, they are important links in the food chain, filtering bacteria and suspended materials from the water. Their reproduction is complex, relying on host fish for successful rearing of larval glochidia. At least a dozen species are native to the basin, most of which occur in the upper basin and have experienced a significant reduction in distribution and abundance. Nine of the twelve native species are listed as threatened or endangered in Pennsylvania (PFBC 2011).

In consultation with regional malacologists, we associated the 11 species known to occur in the basin into four groups based on traits including thermal preferences, substrate and velocity associations, longevity, length of brooding, timing of spawning and glochidia release and use of host fish (Table 4.2) (Bogan and Proch 1992, Anderson and Bier 1997, Strayer and Jirka 1997, Nedeau et al. 2000, Bogan 2008, Grabarkiewicz and Davis 2008). We then associated each species group with one or more representative habitat types.

Flows are important for maintaining suitable hydraulic habitats for spawning and juvenile colonization, to facilitate successful glochidia transfer with host fish, and to provide conditions suitable for growth. Persistent suitable habitat can be limited by both high flows, which increase shear stress, and low flows, which can restrict depth and velocity (Cole and White 2006, Cole et al. 2008, Maloney et al. 2012). Flows are also essential for maintaining water quality and temperature regimes, including during winter when mussels are typically inactive and their ability to move to avoid stressful conditions is limited.

During spawning and glochidia transfer, an increase in the frequency or magnitude of high flow events that mobilize bedload may result in scour of mussel beds. High flows and associated shear stress influences suitability of juvenile settlement and colonization (Hardison and Layzer 2001, Morales et al. 2006, Holland-Bartels 1990, Layzer and Madison 1995). High median flows in May and June and increased frequency of high flow events were also negatively correlated with long-term growth for some species (Rypel et al. 2009). Vaughn and Taylor (1999) also documented that increases in high flow frequency and magnitude were one factor in reducing mussel species diversity and abundance.

Conversely, during spring and summer, flows that are too low may restrict suitable hydraulic habitat in the channel and/or limit interactions between host fish and mussels. This can affect mussel species that use host fish with small home ranges if the suitable habitat for these fishes is limited. Low flows can also limit access to habitat for mussels that use migratory fish species as hosts (Layzer and Madison 1995). Schwalb et al. (2011) also found that rare mussels relied on host fish with short movement distances; mussels with a more secure conservation status had host fish that migrated over much larger distances. This suggests limited dispersal by host fish affects the abundance and distribution of unionid mussels, and supports the need to consider host-fish mobility to ensure connectivity between and maintenance of metapopulations.

Table 4.2 Mussel groups of the Delaware River basin and shared life history traits

Group *example species*	**Life history traits**
Species associated with cold, clear, flowing waters *Margaritifera margaritifera* (eastern pearlshell)	• Long-lived (may live more than 100 years) • Short-term brooder that spawns and releases glochidia in the same season • Require high quality cool-cold water streams, and use salmonids as a host fish.
Species associated with high energy, coarse substrates, flowing waters *Anodonta implicata (alewife floater) , Elliptio complanata (eastern elliptio), Lampsilis radiata (eastern lampmussel), Lampsilis cariosa (yellow lampmussel)*	• Found within high-energy environments in a variety of habitats, including small streams, large rivers, and lakes • Yellow lampmussel ,eastern elliptio and alewife floater are associated with larger-bodied, mobile host fish • Because host fish are highly mobile, longitudinal connectivity is essential for species recruitment
Species associated with moderate to low energy, stable substrate, flowing waters *Alasmidonta varicosa* (brook floater), *Strophitus undulatus* (creeper), *Alasmidonta heterodon* (dwarf wedgemussel), *Lasmigona subviridis* (green floater), *Alasmidonta undulata* (triangle floater)	• Long-term brooders • Require suitable spawning conditions in the summer and fall • Interact with host fish in spring and early summer. Host fish include darters, sculpin, and minnows.
Species associated with stagnant, vegetated backwaters *Pyganodon cataracta (*eastern floater)	• Primarily uses slow-moving habitats, including channel margins • Uses several fish as hosts, including mobile, large-bodied species and small-bodied localized species. • Long-term brooders that spawn in summer / early fall and release glochidia the following spring. • Of the three groups, these are the most tolerant of silt, mud, and nutrient-rich water and can tolerate impoundments

Flows that are too low during summer and fall may lead to increased water temperature and water quality that causes sublethal stress. Low flow events resulted in decreased velocity, disconnected habitats and increased water temperatures. In a study in the southeastern U.S., thermally sensitive species experience sublethal stress that affects respiration and causes mussels to catabolize glycogen. This can be especially stressful if these conditions occur during reproduction (Spooner et al. 2005, Spooner and Vaughn 2008). Thermal stress associated with low water levels was one of the proximate causes of decline in species density, abundance and diversity (Galbraith et al. 2010). Freshwater mussels generally have a slightly greater thermal tolerance then their host fish, therefore the effective thermal tolerance can also be limited by the obligate relationship with the host fish (Pandolfo et al. 2010, Pandolfo et al. 2012). A decrease in low flow magnitude may also decrease dissolved oxygen and increase ammonia concentrations outside of mussel tolerance (Strayer and Malcom 2012, Newton 2003, Augspurger et al. 2003, Wang et al. 2007). Juvenile mussels may be more sensitive than adults.

During late summer and early fall, a decrease in low flows may reduce depth or dewater shallow riffle or margin habitats exposing mussels to increased predation or desiccation. Dewatering of stream margin habitats have been observed in Pennsylvania when flows were close to the August Q90 (C. Bier, personal communication, 2012). Galbraith et al. (2010) also observed a significant negative relationship between water depth and mussel mortality during a summer low flow event. In the southeast U.S. during a record drought, reduced flows resulted in mussel emersion and increased predation. Emersion did not result in mortality in all mussels. Small-bodied mussels incurred higher mortality than large-bodied mussels (Johnson et al. 2001). Haag and Warren (2008) also found that when discharge was 50% less than median conditions in small streams, pools became disconnected from one another. On large river reaches, stream margins dried, but the stream remained hydrologically connected, suggesting that a decrease in low flow magnitude may have more significant impacts on mussel populations in creeks and small streams than on large rivers.

More extreme events can also influence distribution of mussel beds, shift assemblages, and reduce species abundance. An increase in the frequency or magnitude of small or large flood events may eliminate flow refuges, bury or physically scour (particularly thin-shelled) mussels. Strayer (1999) observed that a small flood event (i.e., 5 to 7 year return interval) redistributed bedload and mussels. Post-flood, mussels were five to fifteen times more likely to occur within flow refuges than outside of them. Species were abundant in areas where shear stresses during the 3 to 30 year floods are too low to displace them. Fraley and Simmons (2006) documented that a large flood event (e.g., > 50 year return interval) resulted in significant decreases in the abundance and distribution of mussels, especially in narrow, high gradient reaches that lacked flow refuges. Hastie et al. (2001) observed that a large flood event (> 100 year return interval) resulted in loss of 4 to 8% of the regional mussel population (>50,000 individuals). Increased frequency of this magnitude of flood puts many mussel species at risk (Hastie et al. 2001).

Although winter is a period of low activity, this is a period when gametogenesis begins, and a decrease in seasonal flow magnitude may reduce temperatures, shifting thermal regimes that cue gamete development and release. Reproductive success of long-term brooders may be influenced by overwinter flow magnitude (R. Villella, personal communication, 2010). Temperatures less than 10 C (and greater than 30 C) limit individual growth (Spooner and Vaughn 2008). Both field and lab studies suggest that thermal regimes are important cues for the timing of gamete development and potentially for gamete release. For all species, timing of reproduction was correlated with the number of accumulated degree days (Galbraith and Vaughn 2009).

While mussels have been documented to move under extreme high and low flow conditions, movements are slow, limited by substrate, and do not occur over long distances. They are not adapted to follow receding water levels when low flows quickly change (Layzer and Madison 1995). This is particularly true during the winter months when metabolic rates are extremely low (D. Strayer, personal communication, 2012). Some species have the ability to slowly migrate on the surface (e.g., *Strophitus undulatus* and *Alasmodanta varicosa*), but a sudden decrease in flow may strand mussels, particularly in margin and riffle habitats.

4.3 Aquatic Insects and Crayfish

Key flow-related needs for Delaware River aquatic insects and crayfish

- **Promote macroinvertebrate growth and emergence, abundance and diversity**
- **Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates**
- **Support spring emergence for aquatic insects and maintain habitats for mating and egg laying**

Macroinvertebrates including aquatic insects and crayfish are a critical component of all river types, especially headwaters, creeks, small rivers and medium tributaries. They are consumers at intermediate trophic levels –

grazers, predators, shredders – that serve as transmitters within the food chain. They influence nutrient cycles, primary productivity, decomposition and material transport and are an important source of food for fish, amphibians, reptiles, birds and mammals (Wallace and Webster 1996).

Aquatic insects are frequently used as indicators of ecological integrity. Although some studies are taxa-specific, more often, studies describe how multiple taxa that share functional traits respond to an environmental change. Poff et al. (2006) summarized 20 functional traits for 70 North American lotic insect families. In Table 4.3, we list a subset of species traits that are expected to be most sensitive to changes in hydrology within the Delaware River basin. In addition to functional traits, aquatic insect responses to hydrologic alteration have been measured using assemblage metrics such as the Hilsenhoff Biotic Index (HBI), Shannon-Wiener diversity Index, Ephemeroptera, Plecoptera and Trichoptera (EPT) diversity, community density and total biomass. While the direction of response varies among publications, the magnitude of flow alteration has been positively correlated with ecological change (Poff and Zimmerman 2009).

Table 4.3 Aquatic insect traits and responses to changes in low and high flow conditions

	Responsive Traits and Metrics		Response to a change in low and high flows	Citations
Low flow magnitude, timing and duration				
	Functional Trait Groups (from Poff et al 2006)			
	Life History	Voltinism	Increase in taxa that are multivoltine	Brittian and Salveit 1989
				Richards et al 1997
				Apse et al 2008
		Desiccation tolerance	Persistence or relative abundance of desiccation- adapted taxa (includes ability to diapause) and decrease in taxa not-adapted to desiccation	Boulton 2003
				Williams 1996
				Resh et al. 1998
				Lytle and Poff 2004
				Delucchi and Peckarsky 1989
	Mobility		Increase in diversity and abundance of highly mobile taxa	Boulton 2003
				Walters 2011
	Morphology	Size at Maturity	Increase in abundance of species with small-body size at maturity	Hinton 1960
				Rader and Belish 1999
				Richards et al. 1997
				Apse et al 2008
				Walters 2011
		Attachment	Increase in abundance of taxa that are free-ranging	Richards et al 1997
	Ecology	Rheophily	Increase in abundance and number obligate depositional taxa	Richards et al 1997
			Decrease in number and abundance of rheophilic taxa	Lake 2003
				Wills et al 2006
				Brooks et al. 2011
		Trophic Habit	Decrease diversity in grazers and shredders	McKay and King 2006
			Decrease in abundance of scrapers and shredders	Richards et al 1997
			Decrease in density and size of collector-filterer taxa (Simulidae)	Walters and Post 2011
			Decrease densities of filter feeding and grazing insect taxa	Wills et al 2006
			Increased predator densities	Miller et al 2007
				Walters and Post 2011
		Thermal Preference	Increase in eurythermal taxa (cool and warm water taxa)	Lake 2003
			Decrease in abundance of stenothermal (cold-water) taxa	Lake 2003
		Habit	Increase in abundance and number of burrowing taxa	Richards et al 1997
	General assemblage metrics			
		Abundance	Decrease in total number of individuals downstream of a withdrawal	Rader and Belish 1999
				McKay and King 2006
			Decrease in biomass	Walters and Post 2011
				Blinn et al 2005
		Species Richness	Decrease to taxonomic richness	Boulton and Suter 1986
				Englund and Malmqvist 1996
				Rader and Belish 1999
				Wood and Armitage 1999
				Kennen 2009
			No change to taxonomic richness	Wood and Armitage 2004
				Armitage and Petts 1992
				Cortes et al 2002
				Dewson et al 2003
		HBI	Increase in tolerant taxa	Rader and Belish 1999
				Apse et al 2008
				Walters 2010
		EPT Richness	Density of EPT taxa decreased	Wills et al 2006
High flow magnitude, timing and duration				
		Species richness	Mean April flow and duration of high flows explains assemblage variability	Kennen 2009
			High flow frequency explains richness of tolerant species	Kennen 2009

Hydrologic conditions and available habitat influence macroinvertebrate diversity, growth and productivity. Several studies have documented community shifts in response to decreased magnitude of low flows. A comparison of streams along a withdrawal gradient showed that assemblage change was proportional to the amount of water withdrawn. Changes included decreased relative abundance and shifts from collector-gatherer and filterer to predatory insects, non-insect taxa and scraping beetles (Miller et al. 2007). In headwater streams, Walters and Post (2011) used an experimental withdrawal to quantify changes in macroinvertebrate density, community composition and available habitat. A threshold seems to occur when withdrawals were reduced to between the summer Q75 and Q85. Decreases in low flow magnitude have resulted in many other documented community shifts including a transition from stenothermyl (cold-water specialist) to eurythermal (generalist) taxa, a reduction in taxa intolerant of desiccation, an increase in species with small body size at maturity and an increase in predator densities (Richards et al. 1997, Lake 2003, Boulton 2003, Miller et al. 2007, Apse et al. 2008, Walters and Post 2011a, Walters and Post 2011b).

In addition to shifting community composition, reductions in low flow magnitude have also resulted in a decrease in overall taxonomic richness (Boulton and Suter 1986, Englund and Malmqvist 1996, Wood and Armitage 1999, Wood and Armitage 2004). In a national study (approximately 250 sites) relating flow alteration to biological response, Carlisle et al. (2010) found that the likelihood of biological impairment, measured using macroinvertebrate indices, doubled with increasing severity of diminished stream flows. Other studies documented responses to extreme experimental reductions (up to 90% of baseflow), including a decrease in overall density, EPT taxa, filter feeding insects and grazing insects (Wills et al. 2006, Dewson et al. 2007a). During the drought of 1999 in the Delaware Basin, noninsect invertebrates with higher tolerance exhibited a higher relative richness during the drought year than during other low flow years (Fischer et al. 2004).

During the fall, macroinvertebrates convert allocthonous stream inputs, such as leaf fall and organic debris, into usable energy forms for downstream habitats. A decrease in flow magnitude could reduce macroinvertebrates in headwaters and small streams and reduce energy transformation and export. In an experiment where macroinvertebrate populations were eliminated from one catchment, the reduction significantly altered the magnitude of fine particulate organic matter (FPOM) exported during summer and fall storms, the seasonal pattern of export and the total annual export of FPOM (Wallace et al. 1991).

Streamflow reductions during fall and winter can reduce invertebrate density, richness, and community composition. For example, a withdrawal of > 90% of fall and winter baseflow resulted in a reduction in macroinvertebrate density (-51%) and richness (-16%), and an assemblage dominated by tolerant species (Rader and Belish 1999). Low winter flows have been correlated with anchor ice formation and reduction or elimination of (winter emerging) stonefly taxa (Flannagan and Cobb 1991, Clifford 1969).

Although aquatic insects are typically not considered to be the most sensitive taxanomic group in spring, spring flows must be appropriate to support spring emergence and maintain habitats for mating and egg laying. If high flow frequency or magnitude increases, the associated increased velocity and shear stress may scour aquatic insects from benthic habitats prior to emergence (Gore et al. 2011, Holomuzki 2000, Encalada and Peckarsky 2006, Kennen et al. 2009, Kennen et al. 2010, Konrad et al. 2008). Conversely, flows that are too low during spring could reduce availability of oviposition sites or cause gravel substrates to be armored with fine sediment.

Crayfish are a keystone species, having a significant influence on periphyton and macrophyte composition and regulation of fine particulate organic matter (Hart 1992, Kulmann and Hazelton 2007). They are also an important food source for basin fish, reptiles, amphibians, birds and mammals including the queen snake, eastern hellbender, and to some extent, northern river otter (Hulse et al. 2000).

Unlike aquatic insects, crayfish do not typically drift during extreme low flow disturbance; instead they burrow in the hyporheic zone. When conditions are extremely dry, they may undergo aestivation (Jones and Bergy 2007). Stressful conditions can result in reduced carapace growth and increase susceptibility to predation (Taylor 1982, Acosta and Perry 2001, Flinders and Magoulick 2003, Flinders and Magoulick 2007).

4.4 Reptiles and Amphibians

Key flow-related needs for Delaware River basin reptiles and amphibians

- **Promote/support the development and growth of reptiles and amphibians**
- **Maintain stable hibernation habitat for reptiles and amphibians**

Forty-seven species of reptiles and amphibians use the basin's riverine and riverine-dependent habitats during some or all of their life cycle. We organized reptiles and amphibians into three groups based on habitat association and timing of life stages including breeding, juvenile development, adult growth and hibernation (Table 4.4). At least one species from each group occurs in each habitat type.

Table 4.4 Reptile and amphibian groups of the Delaware River basin and shared life history traits

Group	Life history traits
Aquatic-lotic species *common map turtle, lungless salamanders, queen snake*	• some depend on specific hydraulic conditions, depth, velocity, width • use specialized stream-dependent feeding habits • sensitive to changes in water quality • require aquatic connectivity
Semi-aquatic lotic species *wood turtle, eastern ribbon snake, northern leopard frog*	• rely on flowing waters within the active channel for one or more life stages, typically hibernation • depend on access to and quality of floodplain and riparian habitats for migration, feeding, and reproduction
Riparian and floodplain-terrestrial and vernal habitat species *bog turtle, eastern gray treefrog, eastern hog-nosed snake, mole salamanders, fowler's toad*	• mating, egg and larval development may occur in vernal pools within the floodplain or in intermittent streambeds • terrestrial connectivity within riparian and floodplain habitats

Flow supports development and growth of reptiles and amphibians and helps maintain suitable hibernation habitat. Increased frequency of intermittency or extended dry conditions can reduce successful reproduction and growth, especially in headwater settings. Kinkead and Otis (2007) estimated that 90% of mole salamanders (genus Ambystoma) skipped a breeding year during dry conditions. Lungless salamanders (genus Desmognathus) use cascading waterfalls, streambeds, stream banks and seepage areas for nesting. Trauth (1988) documented that clutches were laid during flowing water but when drought conditions followed egg laying, brooding chambers became unsuitable because they lacked flowing water. This emphasizes the importance of maintaining suitable conditions during brooding. Trauth (1988) also found that the breadth of viable nesting habitat increased during years when precipitation is average or higher than average.

Extreme low flows during summer and early fall may also decrease suitability of mating and feeding habitats for reptiles and amphibians (Guimon and Hutchinson 1973, Hutchinson et al. 1973, Hopkins et al. 2001). A major drought in South Carolina provided opportunity to observe reproductive and emigration responses of freshwater turtle populations, including species that are present in the Delaware basin. Clutch numbers were significantly lower and emigrations were much higher than average in the years preceding the drought. The musk turtle (*Sternotherus odoratus*) did not emigrate and or reproduce under those conditions (Gibbons et al. 1983).

Sustained flow conditions are also important for maintaining stable hibernation habitat. Most species rely on hibernation sites capable of buffering winter air temperatures, such as flowing aquatic environments (Storey and Storey 1992). During hibernation, map and wood turtles need flowing waters (that generally do not freeze) and high DO concentrations (Graham and Forseberg 1991, Crocker et al. 2000). Hibernating species, such as wood turtles, are only capable of small and slow movements to avoid freezing or poor water quality conditions and are vulnerable if localized conditions such as temperature or DO change (Graham and Forseberg 1991). Greaves and Litzgus (2007) surveyed and radio-tagged wood turtles to monitor location of hibernacula and describe movement during the hibernation period. Wood turtles hibernated on the riverbed at a depth of approximately 1 m and approximately 1 m from the riverbank. Although air temperatures fluctuated between 10.5 and -40 °C, thermal buffering provided by flowing water helped turtles maintain relatively constant body temperatures between December and April.

4.5 Floodplain, Riparian, and Aquatic Vegetation

Key flow-related need for Delaware River basin floodplain, riparian, and aquatic vegetation

- **Support establishment and growth of floodplain, riparian and aquatic vegetation**

Within the Delaware River Basin, several assessments have been completed which identify more than a dozen riverine and floodplain vegetation communities that can be organized based on vertical zonation and dominant disturbance regimes: submerged aquatic vegetation, emergent vegetation, and floodplain and riparian vegetation (Table 4.5) (Fike 1999, Eichelberger et al. 2009, Fanok et al. 2009, PNHP 2012, TNC 1994, NatureServe 2012, Schuyler 1989). The disturbance regimes associated with this vegetation gradient sustain the diverse structure and associated niche habitats critical to the conservation of many of the basin's native birds, reptiles, amphibians, and mammals (PGC and PFBC 2005).

Throughout the year, a combination of high, seasonal and low flows help support establishment and growth of floodplain, riparian and aquatic vegetation by scouring riparian and floodplain areas, dispersing seeds and providing inundation and soil moisture. During the growing season, loss of high flow events and floods can shift plant communities and reduce abundance and diversity of many moist-soil species (Ahn et al. 2004). Reservoir operations and other diversions can reduce flood magnitude, frequency and duration, causing sharp declines in pioneer species that require frequent scour. Under new hydrologic regimes, these species may be replaced by later successional species and encroachment into the channel may occur (Johnson et al. 1998, Johnson et al. 1994, Cowell and Dyer 2002, Zimmerman and Podniesinski 2008, Eldred et al. 2003).

Table 4.5 Vegetation species groups

Vegetation species groups	Example species
Submerged Aquatic Vegetation (SAV)	
Submerged aquatic vegetation associated with riffles - occurs in relatively shallow (approx. 6-36”), fast moving waters of medium to large rivers. Vegetation tends to be sparse or absent with the exception of threadfoot.	threadfoot
Submerged aquatic vegetation associated with runs - occurs in moderately deep (approx. 12-48”), moderate currents of medium to large rivers. Vegetation is often most abundant and most diverse in these areas, and may form extensive submerged aquatic beds.	pondweeds, threadfoot, water-crowfoot, water-stargrass
Submerged aquatic vegetation associated with pools - occurs in relatively deep (usually > 36”), slow moving water of medium to large rivers. Diversity may be low, but abundance can be high. Often found along shorelines of deep pools.	waterweed, eel-grass
Emergent Vegetation	
Emergent vegetation – occurs in slow moving or stagnant areas of medium to large rivers. These areas include shorelines, side and back channels, and confluences with major tributaries. Water levels may fluctuate seasonally, but the substrate, typically fines and mucky soils, is seldom dry. Includes a mixture of submerged and free-floating aquatic species.	arrow-arum, common bladderwort, duckweed, fragrant water-lily, pickerel-weed, spatterdock
Floodplain and Riparian Vegetation	
Shoreline and scour vegetation – includes rock outcrops (including calcareous outcrops), flood scour communities, periodically exposed shorelines and stream margins maintained by severe flooding and scour. Includes various warm season grasses, ferns, and herbaceous species with scattered, often battered shrubs and trees.	blue vervain, chamisso's miners-lettuce, smartweed, st. johns wort, twisted sedge, water willow
Low floodplain vegetation - includes dwarf shrub and grassland communities maintained by seasonal to temporary flooding and severe scour. Located approximately 1-3 ft above shoreline scour communities.	hairy-fruit sedge, big bluestem, indian grass, switchgrass, stunted river birch, sycamore and willow, sand cherry
Mid-floodplain vegetation - includes riverine shrublands and forests maintained by seasonal to temporary flooding and moderate to severe scour.	bitternut hickory, ostrich fern, river birch, silver maple, sycamore
High floodplain vegetation - includes floodplain forests maintained by temporary flooding and low to moderate flood scour. These areas are topographically higher than the mid-floodplain.	green and red ash, red maple, sugar maple, sycamore, white pine
Backchannel vegetation - occurs along major rivers, often in old oxbows along the floodplain, in depressions behind natural levees, and on low floodplains. Ground water levels may be high during much of the growing season and surface water inputs may also come from surrounding uplands.	red maple, green ash, black walnut, sycamore, willows
Palustrine forest and wetland vegetation - includes wetlands and palustrine forests occurring within the riparian corridor of small rivers, creeks, and within headwater stream networks. These often occur on seasonally-saturated soils on the fringe of inundated areas, on flat-bottomed valleys of smaller tributaries, and within wetlands surrounding small streams.	red spruce, eastern hemlock, pin and swamp white oak, highbush blueberry, meadow-sweet, speckled and smooth alder

Flooding throughout the year, including during the dormant period, has been shown to affect the ability of plants to maintain the stored reserves essential for survival (Townsend 2001). During the growing season, lower flow magnitudes may also decrease groundwater storage and recharge, lowering the water table and resulting in stress to riparian plant and forest communities (Wilcox 1995, Poiani et al. 2000, Williams et al. 1999, Hanlon et al. 1998).

During late winter and early spring, a reduction of high flow magnitude and duration can reduce extent of water-dispersed seeds and scour and preparation of seed beds reducing availability and moisture of bare mineral soil. Riparian trees, including American sycamore, river birch and silver maple, depend on high flows for seed dispersal (Burns and Honkala 1990). Regulated high flows on the Allegheny River have altered the flow regime and led to failure in recruitment of silver maple and American sycamore along that portion of that river (Walters and Williams 1999). Comparing vascular plant species along free flowing and regulated river reaches has shown that regulated reaches had a higher proportion of wind-dispersed species and species with generalist dispersal mechanisms (Jansson et al. 2000). Winter high flows may be as or more important than spring for remobilizing and transporting propagules (Gurnell et al. 2008).

During summer and fall, increased duration of low flows may reduce water availability along channel margins, leading to a decrease in extent and condition of shoreline vegetation. Riparian vegetation assemblages in large rivers are particularly sensitive to changes to the minimum flow and high flow events (Auble et al. 1994).

4.6 Birds and Mammals

Key flow-related need for Delaware River basin birds and mammals

- **Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals**

As part of the Atlantic flyway, the habitats of the Delaware Basin are used by hundreds of resident and migratory bird species for feeding, nesting, and/or breeding (USNPS 1997). Major groups of birds include colonial nesting and wading birds, fish-eating raptors, and riparian and wetland breeders (Table 4.6). Species within these groups species rely upon (rather than merely use) stream-derived food resources and foraging and breeding habitats in riverine, wetland, riparian and floodplain areas. Birds and mammals are seldom, if ever, the taxa that are most sensitive to changes in streamflow, but they do respond to changes in riparian and floodplain habitats, and distribution and abundance of fish, aquatic insects and other riverine food sources.

From late winter through summer, a decrease in low flows may reduce the abundance of aquatic prey and feeding habitats for birds of prey and wading birds (Brauning 1992). Extreme low flows can create land bridges between mainland and island habitats, introducing predators that may threaten rookeries and breeding success (PGC and PFBC 2005).

Mammal species include the northern water shrew (*Sorex palustris albibarbis*), northern river otter (*Lutra canadensis*), mink (*Mustela vison*), muskrat (*Ondatra zibethicus*) and several species of bats. The northern water shrew is semi-aquatic and occurs in high quality cold headwater streams and bogs in the Upper basin. They are extremely sensitive to food availability, eating every three hours on macroinvertebrate larvae, small fish and fish eggs (Felbaum et al. 1995). Mink, muskrat and river otter construct dens within streambanks and prefer a diet of fish, frogs, crafish, snakes and turtles. They do best where water quality is good and prey is abundant (Fergus 2000).

Several species of bats occur in the basin. Their dependence on the basin's riverine habitats is highest during the spring and summer during the establishment of nursery colonies. With a high metabolic rate and need to store energy reserves during breeding, rearing and before hibernation, bats consume significant quantities of insects – up to one-third of their weight-during a particular feeding.

Table 4.6 Groups of birds and mammals that rely on Delaware River basin habitats

Group	Example species
Colonial Nesting and Wading Birds use a wide range of aquatic habitats, including lakes, wetlands, tidal marshes, and slow-moving reaches of large rivers. May nest in colonies in forested floodplains, estuaries, and on islands and hunt for prey by wading along the water's margins.	black-crowned night heron (*Nycticorax nycticorax*), great blue heron (*Ardea herodias*), tricolored heron (*Egretta tricolor)*, little blue heron (*Egretta caerulea)*, great egret (*Casmerodius albus*), snowy egret (*Egretta thula*), and yellow-crowned night heron (*Nyctanassa violacea*)
Fish-eating Raptors use Delaware mainstem and bay shores extensively during migratory stopovers and, more recently, as breeding habitat	bald eagle (*Haliaeetus leucocephalus*) and osprey (*Pandion haliaetus*)
Riparian and Wetland Breeders use the basin's riparian corridors and/or wetlands for breeding habitat. Species within this group use a range of habitats from bottomlands with a tall mature tree canopy, extensive wetlands, wooded swamps, hemlock-lined ravines, and narrow riparian corridors	American woodcock (*Scolopax minor*), belted kingfisher (*Megaceryle alcyon*), Louisiana waterthrush (*Parkesia motacilla*), winter wren (*Troglodytes hiemalis*), yellow-breasted chat (*Icteria virens*), cerulean warbler (*Dendroica cerulea*), Acadian flycatcher (*Empidonax virescens*), prothonotary warbler (*Protonotaria citrea*), red-shouldered hawk (*Buteo jamaicensis*), yellow-bellied flycatcher (*Empidonax flaviventris*), marsh wren (*Cistothorus palustris*)

4.7 Floodplain, Island and Channel Maintenance

Key flow-related needs for Delaware River basin geomorphology

- **Transport fine sediment**
- **Maintain ice scour events and floodplain connectivity**
- **Maintain valley and island formation, channel morphology, and substrate**

Geomorphic processes including floodplain, island and channel maintenance are driven by high flow events. Seasonal high flow pulses, bankfull flows, small floods and large floods create disturbances of varying intensities. These disturbances recruit and transport large woody debris, mobilize bedload, form islands, and redistribute sediment and materials onto the floodplain.

During winter, pulses are relatively frequent and promote ice scour along shorelines and rocky outcrops; this process is critical for early successional vegetation communities (Zimmerman and Podniesinski 2008). Spring high pulses generally have the highest magnitude relative to other seasons, with intensities capable of transporting bedload material. In summer and fall, the frequency and magnitude of high flow pulses is relatively low, however these flows are responsible for mobilizing fine sediment, reopening interstices in substrate and transporting and breaking down coarse particulate organic matter (Hakala and Hartman 2004, Dewson et al. 2007b).

The combination of frequency and magnitude of **bankfull flows** make these events responsible for moving the most sediment over time. Bankfull flows define channel morphology, including macrohabitat geometry, and substrate, bank and margin morphology (Wolman and Miller 1960, Dunne and Leopold 1978, Leopold 1994). In the region, recurrence intervals range from 1.4 to 1.7 years (Chaplin 2005).

Small and large flood events typically occur in the spring, although they can occur in any season. Flood magnitude influences sediment deposition, channel morphology and macrohabitat (McKenny 2001). Small flood events (5-year recurrence interval) provide connectivity between the active channel and low terrace riparian areas, facilitate exchange of materials between the channel and floodplain, and maintain shoreline habitat structure and diversity (Nanson and Croke 1992, MacBroom 2008, Zimmerman and Podniesinski 2008). Floods with 1- to 5-year return interval affect lateral point bar development and distribution of fine sediments in floodplain. Large floods occur at an estimated recurrence interval of 18 to 20 years. These events maintain floodplains and valleys, adjusting river profile and planform through lateral channel migrations (Shultz 1999).

4.8 Water Quality and Temperature

Key flow-related needs for Delaware River basin geomorphology

- **Maintain temperature and water quality**
- **Process and transport organic matter**

Most life stages of fish, insects, mussels and reptiles and amphibians are affected by temperature. This includes egg and larval development, growth rates, adult size and fecundity (Giller and Malmqvist 1998). Biological cues are often linked, not to instantaneous temperature, but to cumulative degree days (the number of days with temperatures above 0°F). Suitable flow conditions need to coincide with the timing of cumulative degree days in order for growth, emergence, migration, and other biological events to occur.

The effect of temperature on biota may also be indirect, through its influence on metabolic rates and oxygen concentration. Because air temperatures are high and flows are low compared to other months, flows to maintain water quality and temperature are often most critical – and potentially limiting – in August, September and October. Extended low flow conditions during these months can chronically stress organisms by increasing metabolic rates and decreasing DO. Increased temperatures can also promote excessive algal growth, increasing the biological oxygen demand. Specifically, large swings in DO can occur in response to subdaily patterns of photosynthesis and respiration. "Typical conditions" or seasonal flows can help to buffer the DO "sag" that occurs at night and is associated with respiration. Low flow conditions also concentrate solutes, which are commonly measured as specific conductance. High specific conductance (indicative of high inorganic salt concentrations) can significantly affect the ability of aquatic organisms to osmoregulate (Giller and Malmqvist 1998). Reduced velocities associated with extended low flow conditions may result in settling and deposition of fine sediments. Freshets associated with precipitation events can relieve chronic stresses associated with low flow conditions by flushing fine sediments, decreasing temperature and increasing DO.

During summer and fall, loss of high flow events may result in cumulative stress caused by temperature and dissolved oxygen conditions. Chaplin (2008) found that high flow pulses during summer relieved chronic high temperatures and DO sags.

Headwater stream biota may be especially sensitive to temperature and DO conditions (Angradi et al. 2001). In addition to effects on headwater biota, a loss of surface and groundwater flow from headwaters to has potential to decrease habitat suitability in downstream habitats by altering temperatures, potentially increasing temperatures in the summer and decreasing temperatures in the winter (Sloto and Buxton 2006, Walters and Post 2008). During summer and fall, a decrease in low flow magnitude in proximity to a point source discharge would reduce dilution capacity (effluent ratio) which may exacerbate existing water quality impairments or result in new impairments.

The combination of low flows and high temperatures in summer and fall can also increase the presence of algae and diel dissolved oxygen swings outside the range of tolerance for sensitive species. During the drought of July/August 1999, algal growth rates increased as a result of decreased streamflow and increased water temperatures and nutrient concentrations. At seven of the eight streams, tolerant diatom species made up higher percentages of the drought samples than in non-drought flow years (Fischer et al. 2004).

Table 4.7 Summary of Flow Needs in Each Season – Delaware River Basin

🟥 Low flow component

🟧 Seasonal flow component

🟦 High flow component

Flow Need - *and applicable habitat type(s)*	**Flow Component and Season (Month)**											
	Summer			**Fall**			**Winter**			**Spring**		
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**
Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes – *All types*	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥						🟧	🟧
Support mussel spawning, glochidia transfer, juvenile colonization and growth – *All types except headwaters*	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥							🟦 🟧	🟦 🟧 🟥
Promote macroinvertebrate diversity, growth, abundance and emergence – *All types except large rivers*	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥				🟪 🟥	🟪 🟥	🟪 🟥
Maintain temperature and water quality – *All types*		🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥							
Promote/support development and growth of reptiles and amphibians – *All types*					🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥		
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout) – *All cool-coldwater types*				🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥		
Cue outmigration of diadromous fishes – *Creeks, small rivers, major tributaries, large rivers*				🟦 🟧	🟦 🟧	🟦 🟧	🟦 🟧					
Process and transport organic matter – *All types*				🟦	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦	🟦	🟦
Maintain stable hibernation habitat for reptiles and amphibians – *All types*		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧		
Maintain overwinter habitats for resident fish – *All types* (salmonids in *cool-coldwater types* only)				🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥			
Maintain overwinter thermal regimes and habitat for mussels – *All types except headwaters*					🟦 🟧	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧		
Support winter emergence of aquatic insects and maintain overwinter habitat – *All types*							🟥	🟥	🟥			
Maintain ice scour events and floodplain connectivity – *All types except headwaters and creeks*							🟦 🟥	🟦 🟥	🟦 🟥			
Support resident fish spawning – *All types*	🟦 🟧 🟥						🟦	🟦	🟦	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥
Cue upstream migration and maintain access to riverine habitat – *All types except headwaters*	🟧 🟥									🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥
Maintain access to and quality of shallow-slow margin and backwater habitats – *All types*	🟦 🟧 🟥	🟦 🟧 🟥									🟦 🟧 🟥	🟦 🟧 🟥
Support spring emergence of aquatic insects and maintain habitats for mating and egg laying – *All types*	🟦 🟧 🟥	🟧 🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥

🟥	Low flow component	🟧	Seasonal flow component	🟦	High flow component

Flow Need - *and applicable habitat type(s)*	**Flow Component and Season (Month)**											
	Summer			**Fall**			**Winter**			**Spring**		
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**
Support establishment and growth of floodplain, riparian and aquatic vegetation – *All types*	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	🟧	🟧	🟧	🟧	🟧						🟧	🟧
	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals – *All types*							🟦	🟦	🟦	🟦	🟦	🟦
									🟧	🟧	🟧	🟧
	🟥	🟥	🟥						🟥	🟥	🟥	🟥
Maintain valley and island formation, channel morphology and substrate – *All types*	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	🟥	🟥	🟥	🟥	🟥	🟥						

Section 5: Flow Recommendations and Supporting Information

In this section, we present recommendations for limiting alteration to a suite of flow statistics presented in Section 3.2 in order to meet the ecosystem flow needs of the species and natural communities described in Section 4. The recommended limits to flow alteration are based on (a) literature that describes and/or quantifies relationships between flow alteration and ecological response; (b) an analysis of long-term flow variability at minimally-altered gages; and (c) feedback on draft flow recommendations from expert workshops and consultation. We begin by outlining several principles that guided the recommendations, followed by a discussion of how we synthesized literature and completed hydrologic analysis to support the recommendations. Then we present the recommendations by habitat type and discuss supporting information.

To frame the flow recommendations, we consulted experts to define approximately 100 working hypotheses that describe anticipated ecological responses to changes to the flow regime. Then, we aggregated related hypotheses into a set of 20 flow needs that combine one or more responses of a taxa group to a change in flow conditions. This provided the structure for using a weight-of-evidence approach to document the degree to which literature supports the flow hypothesis, flow needs and ultimately the recommendations (Figure 5.1). The key findings from literature are included in an annotated bibliography (Appendix 6).

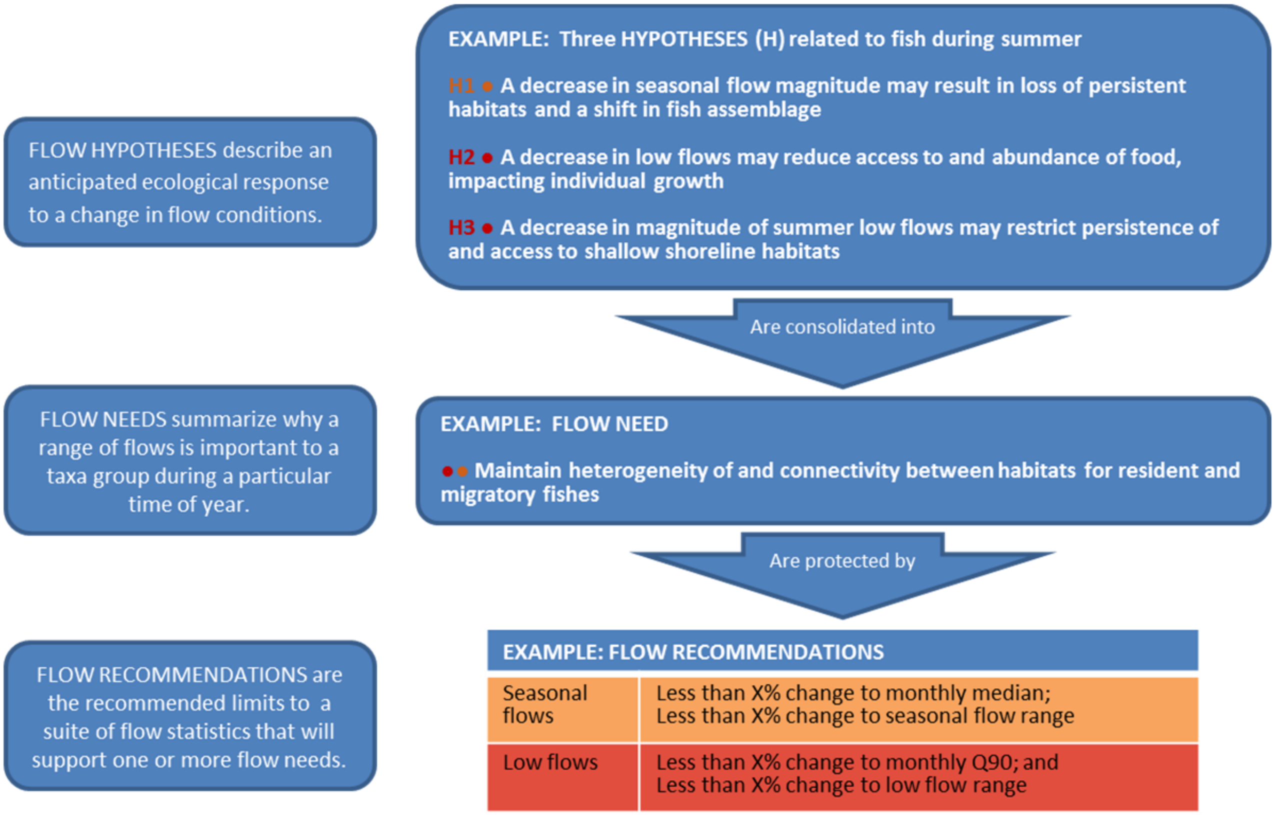


Figure 5.1 Illustration of the relationship between flow hypotheses, needs and recommendations

5.1 Structure and Principles for Flow Recommendations

We used several principles to guide the recommended limits to hydrologic alteration that would reduce risk of ecological changes. The first three principles are derived from the ELOHA framework. The last four emerged through workshops and consultation with technical advisors and DRBC staff.

1. **Flow recommendations address high, seasonal, and low flows for each season**. The flow needs summarized in Table 4.7 highlight the importance of all flow components in each season. For example, even though summer is typically considered a dry season and low flow conditions during summer may be limiting for many species, high flows during summer are also important for maintaining temperature and water quality and transporting fine sediment. Conversely, spring is a wet season, but low flow conditions during spring can limit access to fish spawning habitat.

2. **Flow recommendations for all the statistics, taken together, are intended to protect the entire flow regime.** We provide recommendations that limit alteration to the entire flow regime by using a suite of high flow, median, and low flow-related statistics. Individual recommendations will likely be applicable to a variety of water uses and water management and regulatory programs that affect different aspects of the flow regime. For example, water withdrawal permit programs may incorporate low flow recommendations since water withdrawals can lead to flow depletion. High flow recommendations may be incorporated into reservoir releases on regulated rivers or through stormwater management in watersheds where increased frequency and magnitude of high flow events could negatively affect instream habitat.

3. **Flow recommendations are expressed in terms of acceptable alteration from baseline values to capture naturally-occurring variability.** Recommendations related to flow magnitude are expressed in terms of acceptable deviation (i.e., percent or absolute change to distribution) from reference conditions for a particular site rather than prescribing a specific cfs or cfs/square mile. Because our flow recommendations are expressed in terms of acceptable variation from baseline values for a particular stream, we are able to apply the same recommendations to multiple habitat types. In other words, although the *relative* (percent) change to a particular statistic may be similar between two stream types, the absolute change may be different. For example, because groundwater-fed, high baseflow streams are generally less variable than cool-coldwater and warmwater streams, a 10% change to the typical monthly range will likely mean less *absolute* change in the high baseflow stream.

4. **Flow recommendations are more conservative (protective) for stream types, seasons, and flow components that are more likely to be sensitive to water withdrawals.** To reflect these differences in sensitivity, we apply higher levels of protection (i.e., more conservative limits to hydrologic alteration):

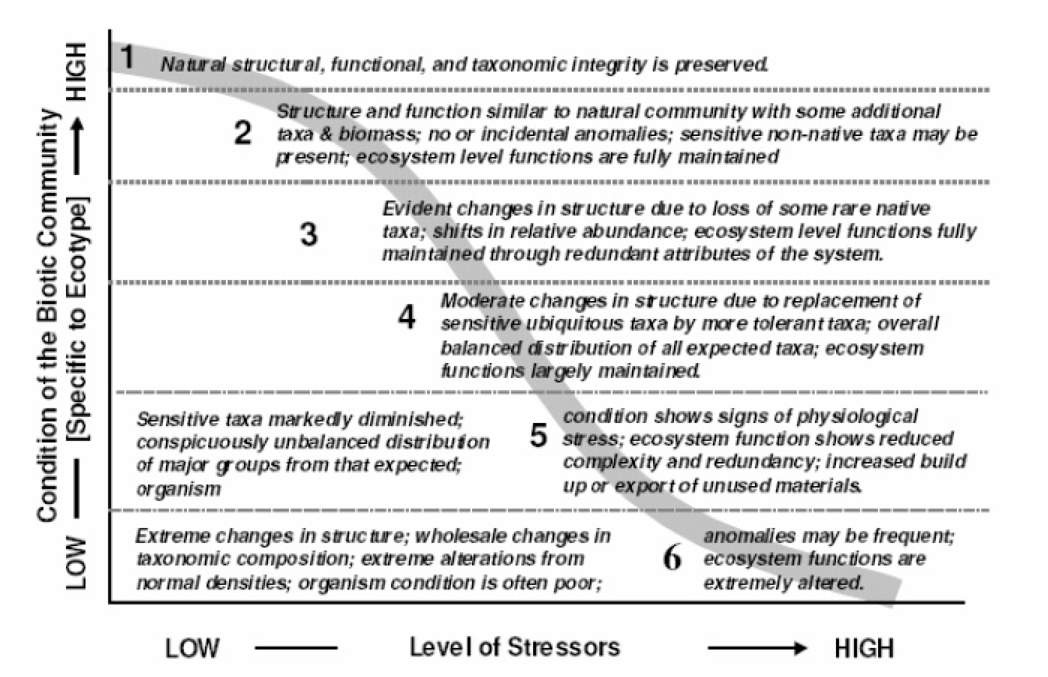
    a) To small streams as compared to large rivers (e.g., no change to monthly median in headwaters, < 10% change in small rivers, and < 15% change in medium tributaries and large rivers).
    b) In dry seasons compared to wet seasons (e.g., for medium tributaries and large rivers: no change to monthly Q90 in summer and fall and < 10% change to monthly Q90 in winter and spring).
    c) To low flow statistics compared to monthly median or high flow statistics. (e.g., for medium tributaries and large rivers: <15% change to monthly median and < 10% change to monthly Q90)

    Within a size class, some stream types may be more or less sensitive than other types.

5. **Flow recommendations protect the most sensitive taxa or processes in a season.** In most cases, there are many species and natural communities that benefit from a particular flow condition. In developing these recommendations, we considered the most sensitive taxa or ecological processes and used that information to establish the recommendation. For example, spring is an important season for emergence of aquatic insects. Spring is also a critical period for fish spawning and because of the importance of seasonal flows in maintaining access to and connectivity among spawning habitats. Experts indicated that fish will be more

likely than insects to be sensitive to changes in streamflow, and that a recommendation that protects flows for fish spawning would also be sufficient to protect insect emergence.

6. **We applied the concept presented in the Biological Condition Gradient to these recommendations (Figure 5.2).** The overall concept is that modifications to hydrology are limited so the level of stressor does not increase. For streams that are relatively unaltered (i.e., occur at the upper left in classes 1 and 2) we recommend limiting hydrologic alteration to an amount that *is less than where risk to ecosystem structure and functions have been documented.* Applying these limits to streams and rivers that have already been altered (classes 3 to 6), should help to prevent *any further negative changes to structure and function.*



1 Natural structural, functional, and taxonomic integrity is preserved.

2 Structure and function similar to natural community with some additional taxa & biomass; no or incidental anomalies; sensitive non-native taxa may be present; ecosystem level functions are fully maintained

3 Evident changes in structure due to loss of some rare native taxa; shifts in relative abundance; ecosystem level functions fully maintained through redundant attributes of the system.

4 Moderate changes in structure due to replacement of sensitive ubiquitous taxa by more tolerant taxa; overall balanced distribution of all expected taxa; ecosystem functions largely maintained.

5 Sensitive taxa markedly diminished; conspicuously unbalanced distribution of major groups from that expected; organism condition shows signs of physiological stress; ecosystem function shows reduced complexity and redundancy; increased build up or export of unused materials.

6 Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities; organism condition is often poor; anomalies may be frequent; ecosystem functions are extremely altered.

Figure 5.2. Conceptual model of the Biological Condition Gradient (Source: USEPA 2005)

7. **If at any given site, these recommendations are not sufficient to maintain existing water quality, they will need to be modified for that site.** Our goal is to recommend limits to hydrologic alteration that will protect existing water quality, including current assimilation capacity, which is typically calculated using the 7Q10 as the design flow condition. If these flow recommendations conflict with or are insufficient to protect water quality, then they should be modified and more protective limits to alteration should be set for that site.

5.2 Using Literature to Support Recommendations

We synthesized existing literature and studies on relationships between flow alteration and ecological response and used this information as evidence to support environmental flow recommendations. Norris et al. (2012) emphasizes the need for a weight-of-evidence based approach to environmental research and management because of the difficulty establishing cause-effect relationships in natural systems. We used the Eco Evidence methods described by Norris et al. (2012) to systematically review the evidence for cause-effect hypotheses and to assess the strength of support for the flow recommendations. We applied evidence in two ways:

1. To support the need to protect a given flow component for a particular taxa (qualitative evidence). A paper was determined to support the *need to protect a flow component* if it described the relationship or response of

Delaware River basin species or processes to flow during a particular time of year (e.g., a paper indicating that winter flows are important for salmonid egg and larval development). In order to be relevant, the research had to be conducted in a temperate region ***or*** include an ecological response that is expected to occur independent of climatic region (e.g., reduction of EPT taxa in response to decreased velocities).

2. To support the recommended range of values for a particular flow statistic (quantitative evidence). In addition to supporting the need to protect a flow component, a paper was considered to support the *recommended limits of alteration for a flow statistic* if it (a) addressed taxa or processes that occur in the Delaware River basin; (b) was conducted either in the Delaware River basin or a similar temperate region; and (c) provided some quantitative flow-ecology relationship that was relevant to our recommendations (e.g., a study that shows changes in species composition when summer flows are reduced below the Q90). These criteria helped us make sure that we did not apply papers outside of their hydrogeographic context.

Each relevant paper provides evidence to support a hypothesis. In general, each paper is considered one piece of evidence. However, some papers document more than one flow-ecology relationship. For example, a paper may document responses of multiple taxa to hydrologic alteration or the response of a species in more than one season. In these cases, a paper may provide evidence for more than one cause-effect hypotheses. We summarized findings of more than 200 flow-ecology publications relevant to Delaware basin species groups and habitats. Figure 5.3 illustrates the distribution of relevant sources that support the needs and recommendations throughout the year. When evidence in all seasons was combined, there were over five times as many sources of qualitative evidence (N=460) than quantitative evidence (N=67).

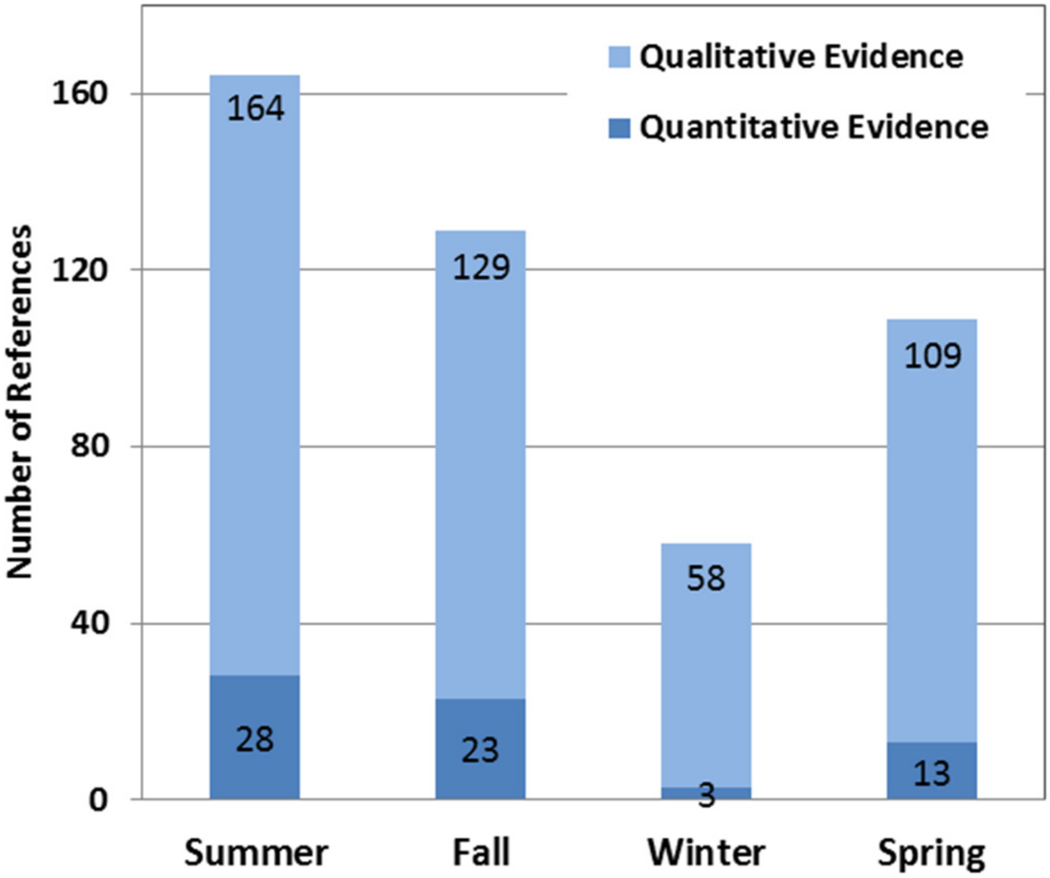


Figure 5.3 Distribution of evidence in literature that supports recommendations in each season

Qualitative evidence. There is more literature that documents or describes flow-ecology relationships in summer than in any other season. Overall, more publications focus on fish and mussels than on aquatic insects or vegetation. For these four taxa groups, papers document changes in growth, reproduction, individual fitness or survival, species composition and abundance and habitat availability. The effects of low flow or drought conditions are commonly addressed, including interactions between low flow conditions and algal growth, biological oxygen demand, dissolved oxygen and stream temperature.

Compared to summer, there are fewer published studies on ecological responses to streamflow changes in fall, but because fall is an extension of the low flow season, many of the publications that support the flow needs during summer are also applicable during fall. Fall also marks the beginning of the spawning period for brook and brown trout and several studies describe or quantify relationships between streamflow, spawning success and egg and larval development. Other papers describe conditions that cue outmigration of diadromous fish during fall.

Relatively few publications document flow-ecology relationships during winter. Of the studies that exist, the majority describe or provide evidence for winter as a resource-limited period when streamflow changes can increase stress due to increased bioenergetic demands. Other papers address the importance of winter flow conditions for maintaining physical habitat and thermal regimes. There are several papers and studies that focus on vegetation, specifically how physical processes (ice scour, overbank events, seed and sediment transport, energy export) sustain spring vegetation recruitment and establishment.

Literature supports several spring ecosystem needs, including vegetation establishment, fish spawning and egg and larval development, and mussel spawning and glochidia release. Because flows in this season are relatively high, few publications document flow-ecology relationships associated with low flow conditions. More commonly, literature addresses the importance of high flows for wetting channel margins and back channels used by spring-spawning fishes; other papers address the impacts when flows are too high and increase shear stress, scouring nests and destabilizing substrates. Although bankfull and channel-forming events can occur in all seasons, they frequently occur in spring. Literature addressing geomorphic processes – the magnitude and duration of high flow events, including bankfull and flood events – is summarized in spring.

Quantitative evidence. Quantitative evidence came from papers in several categories:

- studies on low flow conditions, either observed (e.g., extreme droughts) or simulated (e.g., using experimental diversions) (e.g., Haag and Warren 2008, Walters and Post 2011a);
- studies that use a regional model to predict how species or communities respond to incremental habitat loss (e.g., Denslinger et al. 1998);
- studies that document ecological responses to high flow events (e.g., Mion et al. 1998); or
- Delaware basin studies or observations that document ecological responses and were put into long-term hydrologic context (e.g., Munch 1993)

Figure 5.4 highlights some of the literature that provides quantitative evidence to support the recommendations. The colored numbers correspond to summaries of findings from some of the key papers, studies, and observations that document ecological responses to flow alterations. Many of these studies come from systems that can be manipulated experimentally, including headwaters and creeks where it is possible to divert large proportions of streamflow, or downstream of dams. These studies typically occur in the dry season. The majority of quantitative studies address median or low flow statistics during summer and early fall and document habitat loss and changes associated with reduced habitat extent and resource availability, including effects on species density and individual growth. Other studies (e.g., Zorn et al. 2008, Armstrong et al. 2011) use a model to create a continuum of flow conditions by using data from multiple sites, then fitting a curve to these points in order to estimate incremental responses to changes in streamflow.

The few papers that present quantitative evidence related to high flow recommendations document changes in species composition, reduced recruitment and reduced abundance, especially when these high flow disturbances occur during spawning events – whether spawning occurs in spring or fall. These papers provide support for not increasing the frequency of high flow events.

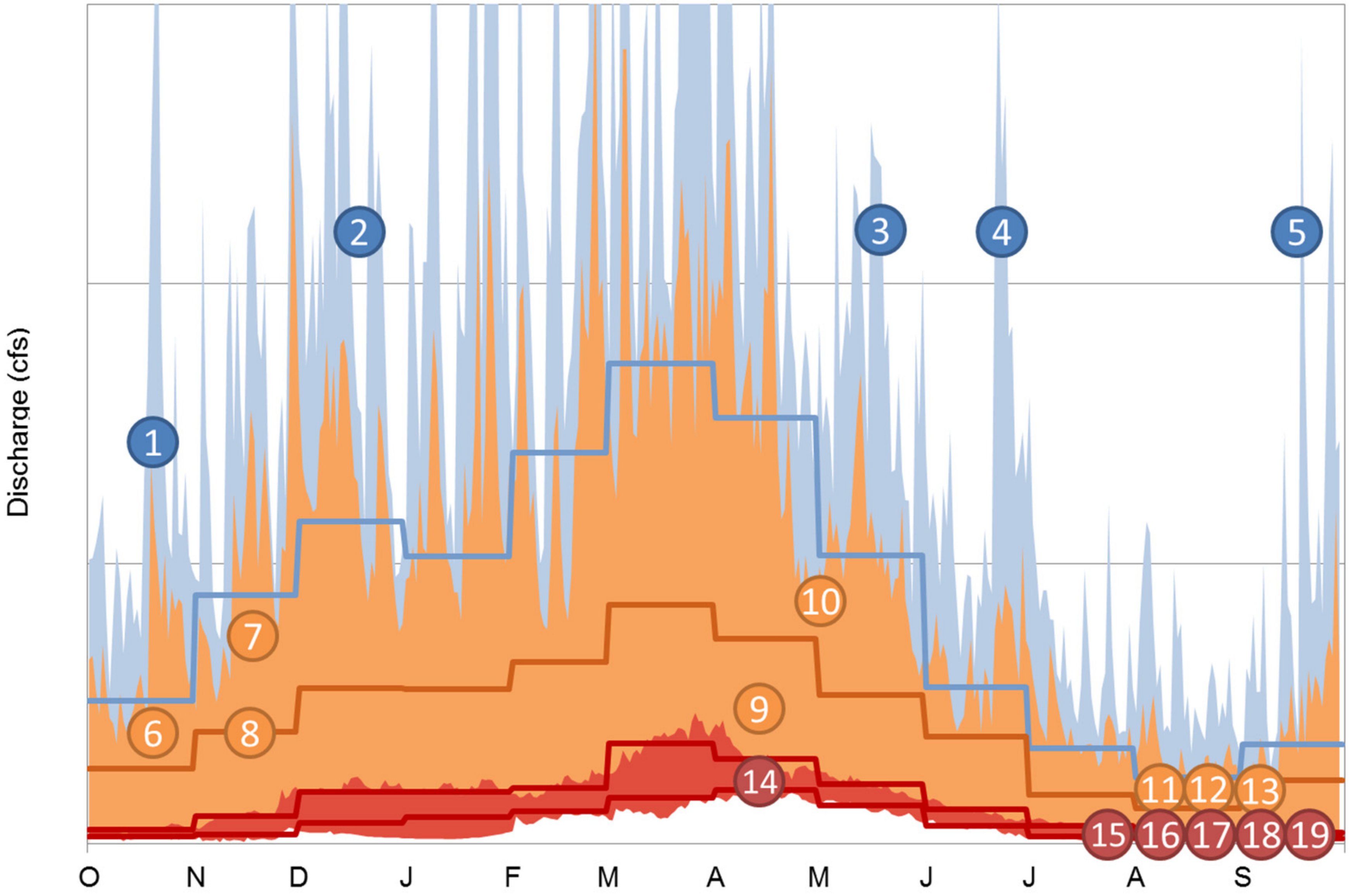


Figure 5.4. Quantitative relationships in the literature. Each numbered circle corresponds to an ecological response and one or more papers that document the response.

① **Fish recruitment decreased (fall spawners).** A post-spawning flood event (> 5-yr) reduced age-0 trout by 98% and age 1+ trout by 84% (Carline and McCullough 2003)

② **Change to fish species composition.** A large flood (> 20-yr) was followed by a shift in dominance from fall-spawning to spring-spawning trout (Warren et al. 2009)

③ **Fish recruitment decreased (spring spawners).** High flow events (as low as spring Q12) destroyed nests of rock bass and sunfish (Noltie and Keenleyside 1986, 1987; Lukas and Orth 1993; Jennings and Philipp 1994).

④ **Reduced mussel abundance.** A large flood (> 20-yr) resulted in decreases in abundance and distribution of mussels (Fraley and Simmons 2006, Cole and White 2006, Strayer 1999)

⑤ **Transport and breakdown of particulate matter** occurred during the 1-5 year flood (Neatrour et al. 2004)

⑥ **Fish recruitment increased.** Fall spawning salmonid recruitment was predicted to be twice as high during years when October median flows were above the long-term median as compared to years when October median flows were below the long-term median (Bishop et al. 2008)

⑦ **Fish recruitment decreased.** Densities of fall spawning salmonids have been negatively correlated with the number of days above Q25 during the incubation period (Spina 2001, Alonzo-Gonzolez et al. 2008).

⑧ **Fish habitat availability reduced.** When flows equivalent to the November median were reduced by 11-14%, trout habitat was reduced by approximately 10% (Denslinger et al. 1998)

⑨ **Fish habitat availability reduced**. During a low flow year (-64% of April median), available spawning habitat was reduced by approximately 50% compared to a more typical flow year (Bowman 1970)

⑩ **Fish recruitment reduced.** Year-class success of nest-building fishes was reduced by approximately 42% when spring median flows increased by 25% (Peterson and Kwak 1999). When mean June flows were >40% above the mean, near year-class failure occurred (Smith et al. 2005). When mean March flows increased by approximately 5%, fish recruitment was reduced; near year class failure occurred with a 45% decrease in spring mean flow (Lobon-Cervia 2004, 2007, 2009)

⑪ **Change to fish species composition and reduced abundance**. Benthic invertivores decreased by an estimated 10% when August median decreased by 5% and an estimated 15% when the August median decreased by 10% (Kanno and Vokoun 2010). In headwater and small streams, an 8-15% decrease to August median predicted a 10% change to fish assemblage. On large rivers, a 10-25% decrease to August median predicted a 10% change to fish assemblage. (Zorn et al. 2008). A 10% reduction of the August median reduced fluvial fish abundance by 9%. A 20% reduction reduced fluvial fish relative abundance by 17% (Armstrong et al. 2011). A 5-20% decrease in August median resulted in a shift in assemblage from fluvial specialists to habitat generalists (Freeman and Marcinek 2006)

⑫ **Mussel abundance reduced.** A 50% reduction in summer median flows resulted in a 60-85% decrease in mussel abundance (Haag and Warren 2008)

⑬ **Fish habitat availability reduced.** Salmonid habitat availability and number of distinct habitat types declined when summer flows fell below Q50 (Heggenes et al. 1996, Grossman et al. 2010)

⑭ **Fish movement occurs between side channel and mainstem habitat.** Fish movement between sidechannel and mainstem habitat was positively correlated with discharge and occurred when spring minimum discharge exceeded April Q90 (Kwak 1988)

⑮ **Fish growth decreased** when flows were artificially reduced to between the summer Q83-Q95 (Hakala and Hartman 2004) and between the Q90-Q95 (Walters and Post 2008)

⑯ **Submerged vegetation extent and condition decreased** when 7-day low flows were equivalent to the September Q77 (Munch 1993, S. Munch, personal communication, 2013)

⑰ **Habitat quality decreased.** When summer/fall monthly medians were reduced to flows comparable to summer Q_{83} to Q_{95}, fine sediments were deposited between spawning substrates in brook trout streams (Hakala and Hartman 2004)

⑱ **Macroinvertebrate density decreased and species composition changed** when flows were reduced to between the summer Q75-Q85 (Walters and Post 2011)

⑲ **Water quality decreased.** When flows reached summer Q87-Q93, phosphorous concentrations exceeded standards, temperature increased, and algal growth increased (Fischer et al 2004)

Figure 5.5 illustrates the quantitative stressor-response relationships listed above. Consistent with the concept of the biological condition gradient, we summarized responses that document a shift in ecosystem structure or function (moving from condition 1 or 2 to condition 3 in Figure 5.2) (US EPA 2005). This includes shifts in relative abundance of sensitive taxa and loss of rare taxa (US EPA 2005). We found no quantitative evidence of change to the structural, functional or taxonomic integrity of streams with alteration between -5 and +20% change to the monthly median.

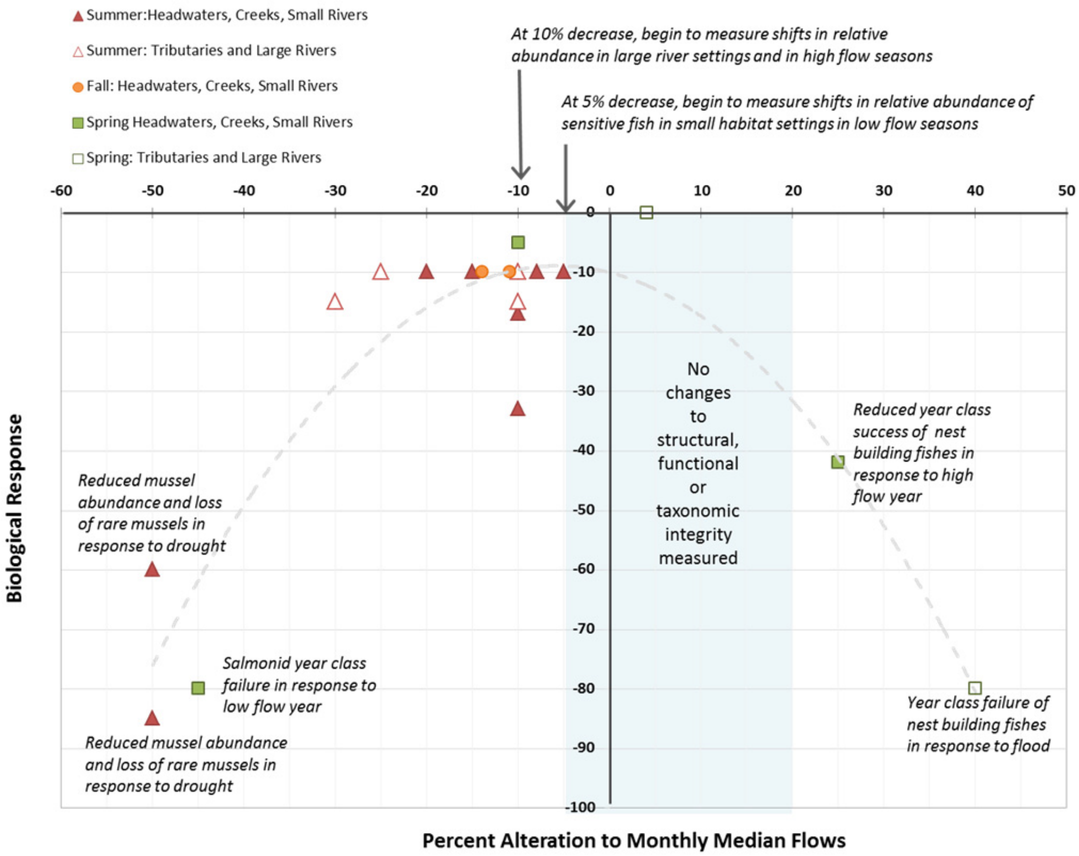


Figure 5.5 Relationships between flow alteration and biological condition. Quantitative biological responses to alteration of monthly median flows.

Quantitative studies confirm that smaller systems (headwaters, creeks and small rivers) are more sensitive to hydrologic alteration than larger systems (major tributaries and large rivers). In smaller systems, studies begin to document measurable shifts in relative abundance of sensitive fish species with a 5% decrease to the summer median. On large systems, shifts are measurable with a 10% decrease to the summer median. Quantitative studies also illustrate that percent alteration to the median during the summer season decreased biological condition more than the same percent alteration to the median during spring months.

Summarizing weight-of-evidence. In addition to the number of supporting references and the specific quantitative relationships in a subset of these sources, we also combined quantitative and qualitative evidence and evaluated the strength of support for each flow need. The weight-of-evidence for each source is calculated based on the rigor of study design including controls and replication. Support strength is categorized as **supported**, **moderate support** or **some support** (Table 5.1). The strength of support is the cumulative weight-of-evidence of relevant sources. Appendix 7 provides more detail on our methods for summarizing weight-of-evidence.

Table 5.1 Definitions for three levels of support for flow recommendations based on literature

Level of Support	Sources of evidence (#)	Weight of Evidence (score)	Explanation
Supported	3 to 20	> 20	• Supported by multiple sources • Rigorous study designs with high replication
Moderate Support	2 to 4	10 to 20	• Supported by a few sources • Studies range from observations to experimental designs
Some Support	1 to 3	1 to 10	• Identified as regionally relevant by experts • Few supporting sources, generally observations

Figure 5.6 shows the support scores for each flow need and flow component. For example, for the need **Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes**, which is concentrated in summer and fall, the scores for the seasonal and low flow components are both high (114 and 70, respectively). This indicates that there is a lot of evidence that protecting these flow components during summer and fall is important to maintain habitat heterogeneity and connectivity for fishes. In comparison, for the need **Support spring emergence of aquatic insects and maintain egg laying habitats**, which is concentrated in spring, the score for the high flow component is 19. This indicates that there is some evidence that protecting high flows in spring is important for aquatic insect emergence, but that (a) this taxa group may not be very sensitive to high flow changes; and/or (b) the interactions between spring emergence and high flows are not well documented in the literature that is applicable to the Delaware.

This weight-of-evidence summary provides additional basis for the importance of protecting each flow component throughout the year (Table 5.2). The flow needs listed below have the most support in the literature. We used the threshold score of 20 as **Supported**; this was the threshold proposed by Norris et al. (2012). This means that there are at least three sources of evidence with strong study designs **or** more than three sources with less rigorous designs. However, for these purposes, the relative length of the bar is a more important indicator of support than the absolute value.

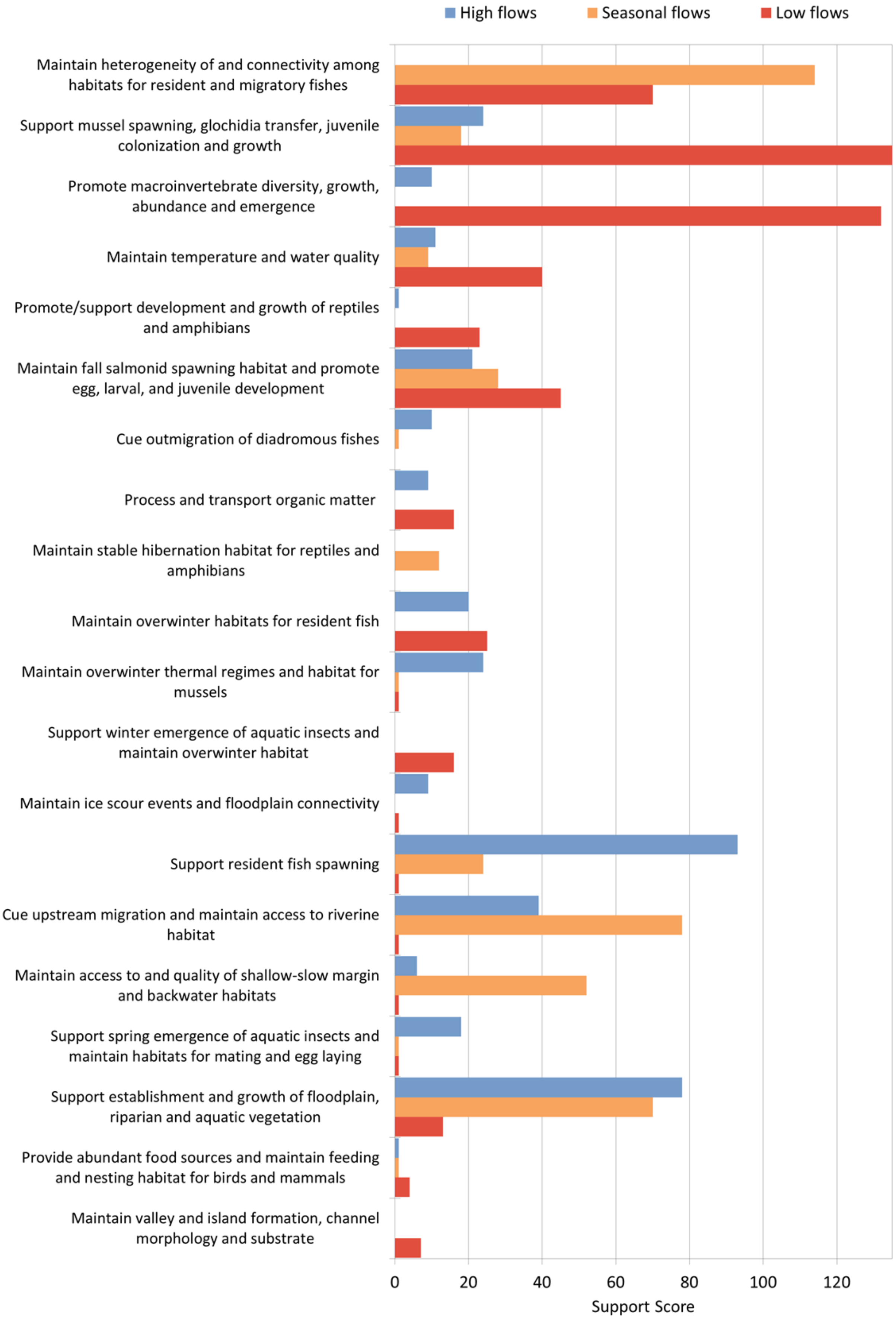


Figure 5.6 Summary of support for each flow need using weight-of-evidence approach.

Table 5.2 Timing of flow needs supported by weight-of-evidence analysis

Summer	Fall	Winter	Spring	Needs supported by Weight-of-Evidence Analysis
🟦	🟦		🟦	Support mussel spawning, glochidia transfer, juvenile colonization and growth
	🟦	🟦	🟦	Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development
	🟦	🟦		Maintain overwinter habitats for resident fish
	🟦	🟦	🟦	Maintain overwinter thermal regimes and habitat for mussels
🟦		🟦	🟦	Support resident fish spawning
🟦			🟦	Cue upstream migration and maintain access to riverine habitat
🟦	🟦		🟦	Support establishment and growth of floodplain, riparian and aquatic vegetation
🟦	🟦	🟦	🟦	Maintain valley and island formation, channel morphology and substrate
🟧	🟧		🟧	Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes
	🟧	🟧	🟧	Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development
🟧			🟧	Support resident fish spawning
🟧			🟧	Cue upstream migration and maintain access to riverine habitat
🟧			🟧	Maintain access to and quality of shallow-slow margin and backwater habitats
🟧	🟧		🟧	Support establishment and growth of floodplain, riparian and aquatic vegetation
🟥	🟥		🟥	Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes
🟥	🟥		🟥	Support mussel spawning, glochidia transfer, juvenile colonization and growth
🟥	🟥		🟥	Promote macroinvertebrate diversity, growth, abundance and emergence
🟥	🟥			Maintain temperature and water quality
	🟥	🟥	🟥	Promote/support development and growth of reptiles and amphibians
	🟥	🟥	🟥	Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development
	🟥	🟥		Maintain overwinter habitats for resident fish

5.3 Using Hydrologic Analysis to Support Recommendations

The weight-of-evidence analysis supports the need to protect the seasonal and interannual variability of flows for each habitat type in the Delaware River basin. By combining quantitative literature with feedback from expert workshops, we drafted recommended bounds of alteration around low, seasonal and high flow components. Here, we reviewed the draft recommendations to make sure the recommended limits to alteration met the following three criteria:

1. Recommended limits to alteration should **protect hydrologic regimes characteristic of each stream or river type**.
2. Recommended limits to alteration should **preserve variability associated with months and seasons.**
3. Recommended limits to alteration should **prevent major changes in the distribution of high, seasonal or low flows.**

We test the draft recommendations against these three criteria using an approach guided by McManamay et al (2013). The approach uses incremental withdrawals to assess when a stream becomes altered outside of the natural range of variability for each size class. Specifically, we altered flow statistics at 36 minimally altered gages by increments of -5, -10, -15 and -20%. We modified the approach by targeting the variables of interest (specifically, stream type, seasonality and interannual variability). We discuss methods and results for each test below using our small river recommendations as an example.

Protect hydrologic regimes characteristic of each stream or river type. The recommendations should prevent alterations that would cause a stream within a given size class to have hydrologic characteristics of a smaller size class. We imposed incremental withdrawals on each stream type and compared the resulting range of flows for each stream type to the others. Figure 5.7 illustrates a comparison of impacts of incremental withdrawals on the range of winter low flows for small rivers compared to the range of low flows for creeks. In this example, a -15% alteration causes the range of low flows in small rivers to cross into the central tendency of creeks. This is not the case at -10% alteration. The recommendation is <10% alteration to winter low flows on small rivers and therefore meets the test of protecting the hydrologic regime characteristic of this stream type.

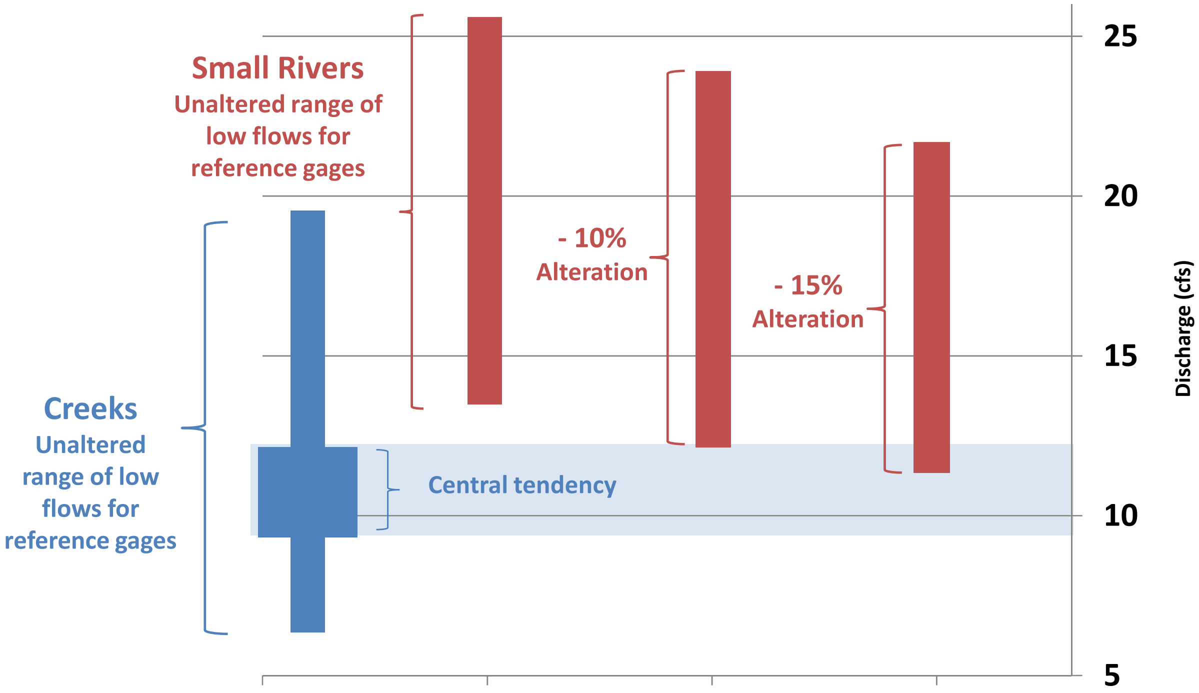


Figure 5.7 Comparison of winter low flows (Q90) between creeks and small rivers.

Preserve variability associated with months and seasons. Alteration to a statistic should not change magnitudes in one season to the extent that they become similar to typical magnitudes in another season. In Figure 5.8 we illustrate a comparison between mid-summer (July) and late fall (November) monthly medians on small streams. In this example, a -15% alteration to the November median (open purple squares) starts to resemble the magnitude of the July median (red diamonds). The recommendation to limit change to the monthly median on small rivers to <10% preserves the seasonal characteristics between mid-summer and late fall.

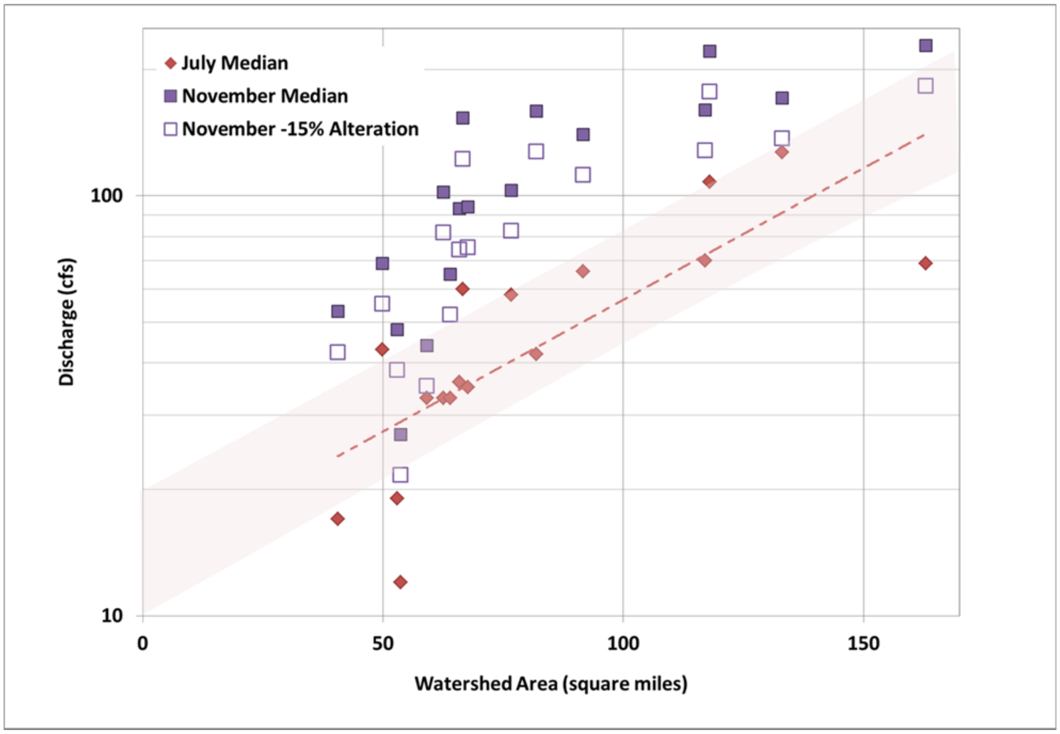


Figure 5.8 Comparison between July (Q50), November Q50 and November Q50 with -15% Alteration on representative small rivers. Pink illustrates a central tendency of July medians for small rivers.

Prevent major changes in the distribution of high, seasonal or low flows. For example, for a given stream, recommended limits should prevent monthly Q50 from decreasing to within the range of monthly Q75. In Figure 5.9 we illustrate a comparison July Q50 (seasonal component) and July Q75 (low flow component) on small rivers. In this example, a -15% alteration to the July Q50 (open red diamonds) starts to resemble the magnitude of the July Q75 (red circles). In this example, the recommendation to limit change to the monthly median on small rivers to <10% would preserve the distribution between seasonal and low flow components.

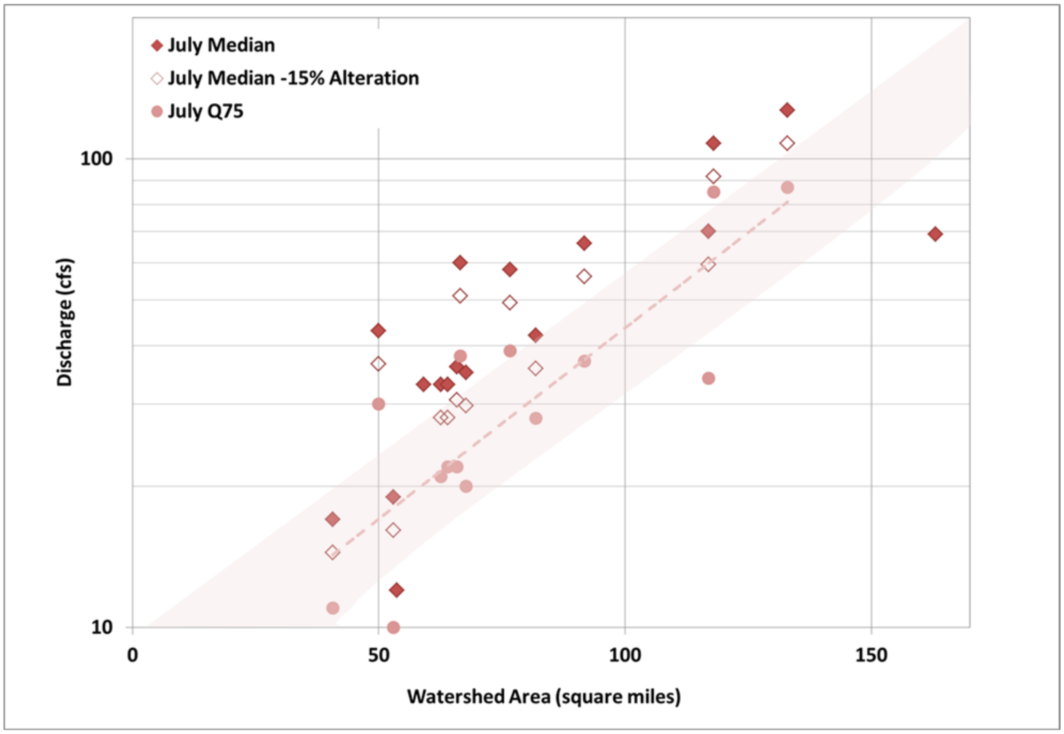


Figure 5.9 Comparison between July (Q50), July Q50 with -15% Alteration and July Q75 on representative small rivers. Pink band illustrates a central tendency of July Q75 for small rivers.

5.4 Flow Recommendations and Discussion of Supporting information

In Table 5.3, we present flow recommendations by habitat type and highlight studies and hydrologic characteristics that support the recommended limits to alteration of selected flow statistics. In the subsections that follow Table 5.3, we discuss differences among habitat types within streams and rivers of the same size class. These recommendations were reviewed by regional experts at a workshop in September 2013.

High Flow Recommendations for All Types

We include recommendations for small and large floods to emphasize their ecological importance, but we also recognize that these events are highly variable, affected by climatic cycles, and that only large flood control projects or diversions would likely affect the magnitude and frequency of these events.

The magnitude and frequency of bankfull events is affected by the same factors that affect overbank events, as well as by loss of forest cover, increased impervious surface, increased runoff, and channel modification. Because water management within the basin has a relatively small effect on these annual and interannual events in most streams, we are not expressing flow recommendations in terms of allowable alteration to these flows. Rather, we recommend maintaining the magnitude and recurrence interval based on (a) regional studies of bankfull flows; (b) analysis of streamflow at index gages between water years 1960-2008; (c) expert input; and (d) literature that documents ecological responses to changes in magnitude and frequency of these events in specific habitat types.

Many studies document the importance of high flow pulses (below bankfull) for promoting ice scour during winter, maintaining riparian and floodplain vegetation, maintaining water quality, transporting organic matter and fine sediment, and cueing fish migration. However, because of the limited amount of information to quantify the degree to which high flow pulses can decrease without ecological impacts, our recommendation of less than 10% change to the monthly Q10 is based on maintaining the long-term distribution of monthly Q10 based values at index gages.

We apply this recommendation to all stream types to emphasize the important function of high flow pulses throughout the basin. However, we recognize that in most streams larger than creeks, the magnitude or frequency of high flow events is unlikely to be affected by water withdrawals.

Table 5.3 Flow Recommendations for all Habitat Types – Delaware River Basin

		Summer	Fall	Winter	Spring
High flows	**All habitat types**	Maintain magnitude and frequency of **20-year (large) flood**; and Maintain magnitude and frequency of **5-year (small) flood**; and Maintain magnitude and frequency of **bankfull (1 to 2-year) high flow event**			
	All habitat types	< 10% change to magnitude of **monthly Q10**			
			Maintain **frequency of high flow pulses > Q10** during fall		Maintain **frequency of high flow pulses** > Q10 during spring
Seasonal flows	**All habitat types**	Less than 20% change to **seasonal flow range (monthly Q10 to Q50)**			
	Headwaters	No change to **monthly median**; and No change to **seasonal flow range (monthly Q50-Q75)**			
	Creeks	Less than 10% change to **monthly median**; and Less than 10% change to **seasonal flow range (monthly Q50-Q75)**			
	Small Rivers	Less than 10% change to **monthly median**; and Less than 10% change to **seasonal flow range (monthly Q50-Q75)**			
	Medium Tributaries and Large Rivers	Less than 15% change to **monthly median**; and Less than 15% change to seasonal **flow range (monthly Q50-Q75)**			
Low flows	Headwaters	No change to **monthly Q75**; and No change to **low flow range (monthly Q75 to Q99)**			
	Creeks	No change to **monthly Q90**; and **Less than 10% change to low flow range (monthly Q75 to Q99)**			
	Small Rivers	***Summer and Fall*** No change to **monthly Q90**; and **Less than 10% change to low flow range**		***Winter and Spring*** Less than 10% change to **monthly Q90**; and **Less than 10% change to low flow range**	
	Medium Tributaries and Large Rivers	Less than 10% change to **monthly Q90**; and **Less than 10% change to low flow range (monthly Q75 to Q99)**			

5.3.1 Flow recommendations for Headwaters (< 4 –10 mi^2)

Relevant subtypes in this class: Headwaters, Wetland-dependent headwaters

Recommendations for headwaters are based primarily on analysis of hydrology, expert input, literature that emphasizes the importance of ecological functions and potential sensitivity to flow alteration, and some studies that quantify responses to flow manipulation.

Headwaters may be ephemeral or seasonally intermittent, may have poorly defined stream channels and the stream network may be highly dynamic and expand and contract depending on season and precipitation (Gomi et al. 2002, Williams 2006, Fritz et al. 2008). Because of their relatively narrow channels and canopy cover, headwaters support vegetation, particularly bryophytes, that are seldom found in larger systems (Williams et al. 1999, Fritz et al. 2009). Allochthonous inputs from riparian vegetation support a macroinvertebrate assemblage dominated by shredders and grazers. These functional feeding groups play a critical role in energy conversion and export (Wallace and Webster 1996). The relatively shallow depths and coarse substrate in these settings also provide distinct habitat for streamside salamanders, fish spawning and nurseries for juvenile fish development (Trauth 1988, Fritz et al. 2009a, Hartman and Logan 2010).

In addition to supporting unique habitats and species, headwaters contribute significantly to downstream hydrologic and biogeochemical processes. This is documented extensively in literature and was confirmed by regional experts (Meyer et al. 2007, Lowe and Likens 2005, Morley et al. 2011, Keller et al. 2011). In headwaters, the high flow recommendations are intended to maintain flows that recruit and transport coarse and fine particulate organic matter and large woody debris. The importance of this recruitment and transport of organic matter in headwater streams is well supported in the literature (e.g., Wallace et al. 1991, Gomi et al. 2002, Neatrour et al. 2004) but there are few studies that document the threshold of flow alteration that would impair or eliminate this function. Therefore, for these streams we recommend maintaining the magnitude and frequency of high flow events based on their expected naturally-occurring range. In headwaters, and in some creeks, typical withdrawals may remove enough flow volume to reduce the magnitude of high flows (i.e., monthly Q10) during some seasons. Regional experts agreed that maintenance of the long-term monthly median should also help support these functions.

With a small contributing drainage area, headwaters have less groundwater recharge potential than larger systems, and therefore have a lower capacity for maintaining baseflows than larger systems. During low flow months or dry years, surface flow may disappear or occur only at groundwater discharge points. Although flows at an individual stream reach scale may be highly variable, cumulatively, headwaters contribute a significant proportion of baseflow to the downstream network (Alexander et al. 2007, Morley et al. 2007). This baseflow contribution influences downstream thermal regimes and may maintain connectivity to critical thermal refugia during winter and summer (Hartman and Logan 2010).

Experimental manipulation studies are more common in small systems – headwaters and creeks – than in other stream types because it is often possible to divert or otherwise manipulate large proportions of the flow volume and measure a biological response. These studies typically measure the response of macroinvertebrate and fish communities to hydrologic alteration in the summer season. We also applied results from experimental manipulation in creeks and small rivers (drainage areas between 10-40 mi^2 and 40-200 mi^2, respectively) to inform recommendations for headwaters and creeks when the taxa group studied occurs in both size classes. By doing so, we are making the assumption that if such responses can be documented in larger streams, similar responses would likely occur in smaller streams.

Several relevant studies quantify changes to species composition, abundance, reproduction, growth and habitat availability and quality (Figure 5.10). These studies are used to support the recommendation to maintain the long-term monthly median and Q75. Because we recommend no change to the monthly median in headwaters, we also recommend no change to the seasonal flow range (monthly Q50 to Q75) and low flow range (monthly Q75-Q99).

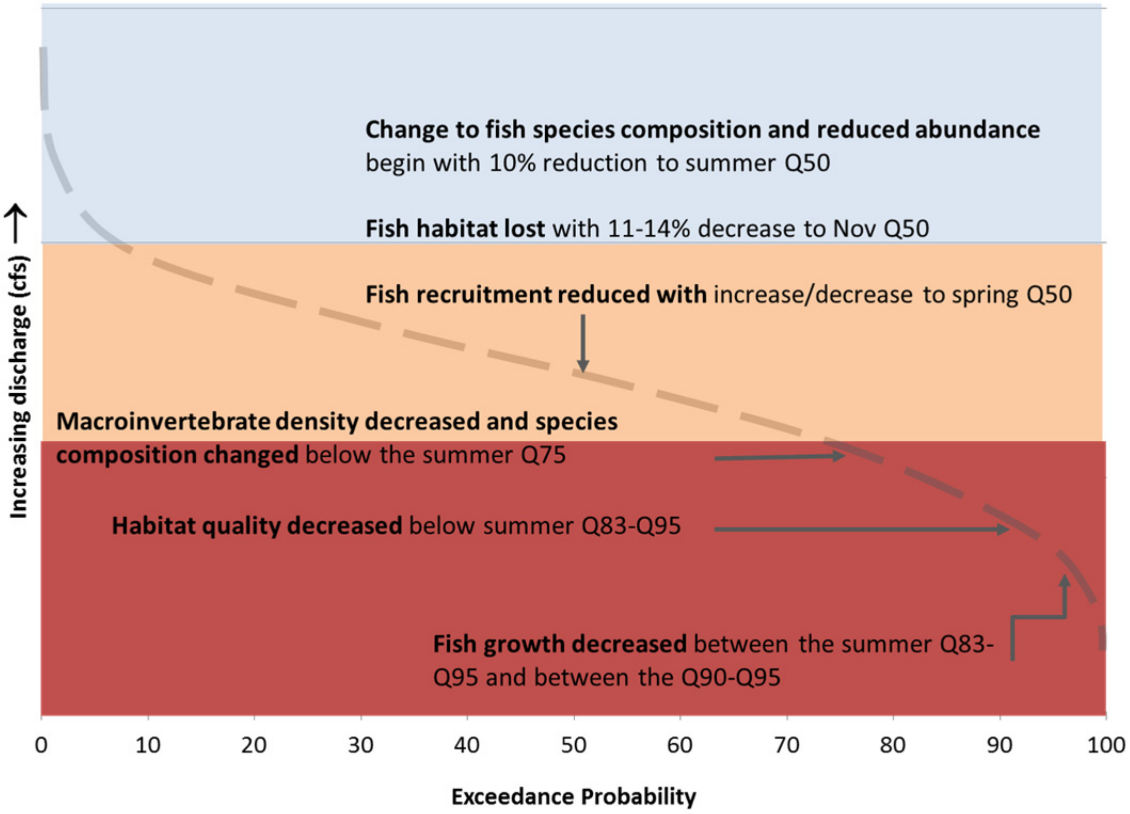


Figure 5.10. Summary of quantitative relationships between flow alteration and biological responses in headwaters and creeks

- **Change to fish species composition and reduced abundance** begin to occur with 10% change to August/September median (Kanno and Vokoun 2010, Zorn et al. 2008, Armstrong et al. 2011)
- **Fish habitat lost** at 11-14% decrease to November Q50 (Denslinger et al. 1998)
- **Fish recruitment reduced.** Year-class success of nest-building fishes was reduced by approximately 42% when spring median flows increased by 25% (Peterson and Kwak 1999). When mean June flows were >40% above the mean, near year-class failure occurred (Smith et al. 2005). When mean March flows increased by approximately 5%, fish recruitment was reduced; near year class failure occurred with a 45% decrease in spring mean flow (Lobon-Cervia 2004, 2007, 2009)
- **Macroinvertebrate density decreased and species composition changed** when flows were reduced below the summer Q75 (Walters and Post 2011)

- **Fish growth decreased** when flows were artificially reduced to between the summer Q83-Q95 (Hakala and Hartman 2004) and between the Q90-Q95 (Walters and Post 2008)
- **Habitat quality decreased.** When summer/fall monthly medians were reduced to flows comparable to summer Q_{83} to Q_{95}, fine sediments were deposited between spawning substrates in brook trout streams (Hakala and Hartman 2004)

In addition to literature that quantifies these relationships, many other flow needs are supported by literature and studies that address headwater streams. These flow recommendations are intended to reduce the following risks that could result from flow alteration:

Fish

- **Decreased fish species richness and density** (McCargo and Peterson 2010)
- **Change in fish species composition** (Carlisle et al 2010)
- **Loss of habitat for river obligate fishes** (Leonard and Orth 1988)
- **Competition between fish species** (darters) (Schlosser and Toth 1984, Welsh and Perry 1998)
- **Reduced young-of-year trout density** (Carline 2006)
- **Loss of thermal refugia/loss of access to thermal refugia** (Hakala and Hartman 2004, Walters and Post 2008, Baird and Krueger 2003)
- **Loss of riffle habitat** (Armstrong et al. 2001, Stauffer at al. 1996, Brewer et al. 2006, Freeman and Stouder 1989, Kessler et al. 1995, Roy et al. 2005)
- **Loss of habitat diversity** (Harvey et al. 2007)
- **Shifts to species assemblages** (multiple taxa groups) (Miller at al. 2007, Willis et al. 2006, Dewson et al. 2007, Boulton 2003, Richards et al. 1997, Apse et al. 2008, Lake 2003, Boulton and Suter 1986, Englund and Malmqvist 1996, Wood and Armitage 1999, Wood and Armitage 2004)
- **Decreased egg survival for fall spawners** (Curry and Noakes 1995)

Aquatic insects

- **Reduction in habitat for winter emerging mayflies** (Clifford 1969, Flanagan and Cobb 1991)

Reptiles and amphibians

- **Reduced reproduction of reptiles and amphibians** (due to loss of cues or poor conditions) (Kinkead and Otis 2007, Trauth 1988, Gibbons et al. 1983, Guimon and Hutchinson 1973, Hutchinson et al. 1973, Hopkins et al. 2001)
- **Loss of reptile and amphibian overwinter/hibernating habitat** (Crocker at al. 2000, Graham and Forseburg 1991, Greaves and Litzgus 2007, Storey and Storey 1992)

Water quality, temperature and geomorphology

- **Network contraction/contraction of hyporheic zone, species compression** (Boulton et al. 1998, Angradi et al. 2001, DiStefano et al. 2009)
- **Increased algal growth and decreased DO** (Fischer et al. 2004, Bartholow and Heasley 2005, Garvey et al. 2007)
- **Loss of groundwater, increased temp, increased bioenergetic costs, increased competition** (Rashleigh and Grossman 2005, Davidson et al. 2010, Murphy et al. 2006, Cunjak and Power 1986)
- **Loss of litter breakdown/processing** (Clare 1994, Benfield et al. 2000, Cummins et al. 1980, Meyer 1980, Webster and Benfield 1986)

Recommendations to maintain seasonal and low flow statistics are further supported by the hydrologic characteristics of headwaters. As discussed in Section 3.2, we recommend using Q75 (rather than Q90) as the low flow magnitude statistic for headwaters because the absolute values of Q90 are so low. In these small streams, the magnitude of the monthly median, monthly Q75 and the area under the monthly flow duration curves is so small – and the absolute magnitude of flows are so low – that even small changes risk creating zero-streamflow conditions.

Summary of hydrologic characteristics of headwaters

- 83% of summer and fall Q50 are < 10 cfs.
- 67% of the winter and spring medians are < 10 cfs.
- 93% of summer and fall Q75 are < 10 cfs. Over two-thirds are less than 5 cfs, some are less than 1 cfs.
- 76% of winter and spring Q75 are <10 cfs.
- 10% change is within measurement error for many of these streams

The headwater size class includes two types of headwater streams: **Headwaters** that arise from overland or shallow subsurface flow and **Wetland-dependent headwaters** that arise in wetland complexes. Wetland-dependent headwaters occur primarily Pocono Plateau region of the basin and adjacent areas of western NJ and southern NY; there are also wetland-dependent headwaters in the coastal plain outside the study area. Different hydrogeological processes support the two subtypes. Hydrology of headwaters that arise from overland or shallow subsurface flow is most commonly influenced by alterations at the transition between terrestrial and aquatic interface or by changes to groundwater elevation. Hydrology of wetland-dependent headwaters is also affected by surficial disturbance, wetland elevation and loss of recharge that may come from multiple sources. The connections between the emerging channel and adjacent wetland complexes are essential for maintaining characteristic vegetation, fish, macroinvertebrates, and other biota.

Based on the biological and hydrologic characteristics of headwaters, these recommendations would:

- **Limit risk of increased intermittency.** Because low flows are so low during summer, change to the monthly median or to the low flow range could increase the frequency and duration of extreme low flows and potentially increase intermittency.

- **Limit risk of alteration to seasonal variability.** With relatively low flows throughout the year, change to the monthly median statistic in most months, even by as little as 10%, could increase the duration of the dry season.

- **Limit risk where there is high uncertainty with measurement or estimation.** Monthly Q50 and Q75 values are so low that they are potentially affected by gage measurement error and/or error associated with estimating streamflow for small, ungaged sites.

- **Prevent changes to fish species composition, habitat loss, reduced recruitment, macroinvertebrate density, habitat quality, and fish growth** as documented in the literature.
    - For seasonal flows, these begin at approximately 10% change to the median.
    - For low flows, these begin when summer flows are reduced below Q75.

- **Reduce risk of other impacts to species composition and abundance, habitat availability and quality, temperature, and water quality** described in literature.

5.3.2 Flow Recommendations for Creeks (~4-10 to 40 mi²)

Relevant subtypes in this class: Wetland-dependent creeks, cool-cold creeks, spring-fed high baseflow creeks, warm creeks

Creeks share many biological, physical and hydrologic characteristics with headwater streams but several notable differences led us to make different recommendations for the two size classes. We acknowledge the transition between headwaters and creeks and have tried to account for it by defining the upper limit of headwater drainage area as between 4 and 10 mi^2 and emphasizing that the distinction between the two systems is better made by using the biological and hydrological characteristics discussed in Section 2.3 than a strict drainage area threshold. In general, creeks have greater channel definition and perennial conditions, although flows may still be very low in some seasons. Fish diversity is generally higher than in headwaters and mussels begin to appear in this size class, although diversity may be low. Like headwaters, creeks also have a role in energy conversion and downstream transport.

The differences in hydrologic characteristics are the main reason that we made different recommendations for headwaters and creeks. These differences are highlighted in Table 5.4. Because creeks generally have higher streamflows than headwaters, we recommend limiting the change to the seasonal flow statistics to less than 10% and using the monthly Q90 as the low flow statistic instead of the Q75. We also recommend limiting the change to the low flow range (flows between the monthly Q75 and Q99) to less than 10%. Since the flows in this range are generally higher in creeks than in headwaters, there is likely to be less risk of slight alterations to flows in this range.

Table 5.4. Comparison of recommendations for headwaters and creeks

	Headwaters	**Creeks**
Seasonal Flows	No change to monthly median and No change to seasonal flow range (monthly Q50-Q75)	**Less than 10% change** to monthly median and **Less than 10% change** to seasonal flow range (monthly Q50-Q75)
Low Flows	No change to monthly Q75 and No change to low flow range (monthly Q75 to Q99)	No change to monthly **Q90** and **Less than 10% change** to low flow range **(monthly Q75 to Q99)**

Figure 5.10 summarized quantitative relationships between flow alteration and biological responses that apply to both headwaters and creeks. In addition to these, several other studies were used to support the recommendations for creeks. These primarily focus on how mussels respond to changes in streamflow.

Haag and Warren (2008) observed a 60-85% decrease in mussel abundance when flows were approximately 50% lower than summer monthly median flows. In streams 4-105 mi^2, these drought conditions created disconnected pools. When seasonal and low flows are altered in creeks, other risks to mussels include loss of suitable mussel habitat (including habitat for host fish), which could limit interactions (Layzer and Madison 1995, Layzer 2009, Moles and Layzer 2008, Schwalb et al. 2011); increased sublethal stress to mussels due to increased temp, lower DO, and increase ammonia concentration (Spooner et al. 2005, Spooner and Vaughn 2008, Galbraith et al. 2010, Pandolfo et al. 2010, Pandolfo et al. 2012, Strayer and Malcom 2012, Newton 2003, Augspurger et al. 2003, Wang et al. 2007, Johnson et al. 2001, Golladay et al. 2004); and dewatering of shallow mussel habitats (Gough et al. 2012, C. Bier, personal communication, 2012, Johnson et al. 2001, Galbraith et al. 2010, Haag and Warren 2008).

Recommendations to maintain seasonal and low flow statistics are further supported by the hydrologic characteristics of creeks. Although streamflows are generally higher in creeks than in headwaters, flows can be very low during dry months.

Summary of hydrologic characteristics of creeks

- 33% of the summer and fall Q50 are < 10 cfs in creeks. 100% are less than 50 cfs.
- All winter and spring medians are >10 cfs. 77% are between 10 and 50 cfs.
- 90% of summer and fall Q90 values are below 10 cfs.
- In winter and spring, 38% of Q90 values are below 10 cfs and 62% are of winter and spring Q90 are between 10 and 50 cfs.
- 10% change is within measurement error for many of these streams

The creeks size class includes four subtypes: **Wetland-dependent creeks, cool-cold creeks, spring-fed high baseflow creeks, and warm creeks**. Compared to other types in this size class, the hydrology of wetland-dependent creeks is more likely to be affected by surficial disturbance, wetland elevation and loss of recharge that may come from multiple sources. When watershed drainage area exceeds about 40 mi^2, systems may retain the influence of headwater wetlands upstream, e.g., high flow stability and tannic staining, but these influences attenuate downstream as they transition to stream hydrology more similar to other small rivers.

Cool-cold creeks and spring-fed high baseflow creeks share many biological characteristics, including coolwater fish taxa and fall spawning salmonids. Compared to warm creeks, the biota in these two stream types may be more likely to be affected by extreme low flows in October and November, which could limit availability of suitable spawning areas. They may also be more likely to be affected if the relationship between fall flows and winter flows change, specifically if fall flows are higher than winter flows and the change in seasonality affects habitat suitability for egg and larval stages.

Compared to cool-cold creeks, spring-fed high baseflow creeks typically have higher and more stable baseflows throughout the year, even during dry periods. Temperature in both systems is often moderated by groundwater contributions and groundwater withdrawals can shift the natural balance between groundwater and surface water, changing temperatures. If the balance of ground to surface water changes during winter, these streams – which do not typically freeze – may be vulnerable to freezing.

Compared to cool-cold and spring-fed high baseflow creeks, warm creeks may naturally have lower flows during the dry season, but because they primarily occur in the Piedmont, their hydrology is also more likely to be affected by development and agriculture.

Based on the biological and hydrologic characteristics of creeks, these recommendations would:

- **Limit risk of increased intermittency during summer and fall.** Because low flows can be very low during July, August, September and October, change to the low flow range could increase the frequency and duration of extreme low flows and potentially increase intermittency.
- **Limit risk where there is high uncertainty with measurement or estimation, especially during summer and fall.** Monthly Q50 and Q90 values are so low that they are potentially affected by gage measurement error and/or error associated with estimating streamflow for small, ungaged sites.
- **Prevent changes to fish species composition, habitat loss, reduced recruitment, macroinvertebrate density, habitat quality, and fish growth** as documented in the literature, including in several quantitative studies.
- **Reduce risk of other impacts to species composition and abundance, mussel habitat availability and quality, temperature, and water quality** described in literature.

5.3.3 Flow recommendations for Small Rivers (40-200 mi^2)

Relevant subtypes in this class: Cool-cold small rivers, spring-fed high baseflow small rivers, warm small rivers

Compared to headwaters and creeks, small rivers have representatives of most flow-sensitive taxa groups, relatively high fish and mussel diversity and increased channel and floodplain complexity. This size class includes wadable streams, and data collected in these surveys are typically incorporated into biological condition assessments. These studies address multiple taxa groups and a variety of biological and habitat responses, including assemblage shifts, habitat loss, loss of assimilative capacity, and desiccation.

For small rivers, we recommend limiting the change to monthly median to less than ten percent. This is the same as the recommendation for creeks. Several studies that quantify biological responses to changes in streamflow that are applicable to headwaters and creeks also help support the recommendations for small rivers because they address the same taxa and the studies include rivers between 40-200 mi^2. These studies address fish species composition and reduced abundance (Kanno and Vokoun 2010, Zorn et al. 2008, Armstrong et al. 2011); fish habitat availability (Denslinger et al. 1998); fish recruitment (Peterson and Kwak 1999, Smith et al. 2005, Lobon-Cervia 2004, 2007, 2009); macroinvertebrate density and species composition (Walters and Post 2011); fish growth (Hakala and Hartman 2004, Walters and Post 2008); and habitat quality (Hakala and Hartman 2004).

Several additional studies presented quantitative relationships that support the recommendations for small rivers. These studies address fish habitat availability, connectivity among habitats, and vegetation growth. During a low flow year (-64% of April median), available spawning habitat was reduced by approximately 50% compared to a more typical flow year (Bowman 1970). Kwak (1988) observed fish movement between sidechannel and mainstem habitat was positively correlated with discharge and occurred when spring minimum discharge exceeded April Q90. In a study on submerged aquatic vegetation in the Delaware, the extent and condition of *Podostomum* beds decreased when 7-day low flows were equivalent to the September Q77 (Munch 1993, S. Munch, personal communication, 2013).

In addition to literature that quantifies these relationships, many other flow needs are supported by literature and studies that address taxa groups that occur in small rivers. These flow recommendations are intended to reduce the following risks that could result from flow alteration:

Fish

- **Loss of shallow, slow habitats and associated species** (Bowen et al. 2003, Freeman et al. 2001, Flinn et al. 2008, Travnichek et al. 1995)
- **Reduced connectivity to backwater and sidechannel habitats and decreased larval development** (Janac et al. 2010, Farrell 2010, Mingelbier et al. 2008, Farrell 2006, Gorski et al. 2011, Smith et al. 2005, Hudon et al. 2010, Bowen et al. 2003, Zeug et al. 2005)
- **Reduced growth rate** (for fish using backwaters e.g., brassy minnow) (Falke et al. 2010)
- **Reduce success of spring spawning fishes, partially attributed to decreased larval drift** (Jone 2003, Nilo 2007, Smith et al. 2005)

Mussels

- **Decreased unionid growth, diversity and abundance** with increasing spring/summer medians (Rypel et al. 2009, Vaughn and Taylor 1999)
- **Decreased reproductive success of mussels** (R.Vilella, personal communication, 2010, Spooner and Vaughn 2008, Galbraith and Vaughn 2009)

Vegetation

- **Reduced extent of aquatic vegetation** (Munch 1993, S. Munch, personal communication, 2013, Pahl 2009, Davis and Brinson 1980, Wilcox 1995)
- **Stress to riparian plants and forests** (Williams et al. 1999, Hanlon et al. 1998, Poiani et al. 2000, Wilcox 1995)
- **Decrease in extent and condition of vegetation in the scour zone** (Auble et al. 1994)

Birds and Mammals

- **Reduced abundance of aquatic food sources for birds and mammals** (Merrit 1987, PNHP 2009)

Recommendations for maintaining flood magnitude and frequency in small rivers are supported by studies that document responses of mussels and transport of organic matter during flood events (Hastie et al. 2001, Fraley and Simmons 2006, Strayer 1999, Neatrour et al. 2004). As with other size classes, we recommend maintaining the magnitude and frequency of high flow events based on their expected naturally-occurring range.

Summary of hydrologic characteristics of small rivers

- 54% of the summer and fall Q50 are below 50 cfs; only 1% is below 10 cfs.
- Almost all (96%) winter and spring Q50 are above 50 cfs (the lowest value is 48 cfs)
- 91% of summer and fall Q90 in small rivers are below 50 cfs.
- In August and September, most Q90 values are below 20 cfs and 20% are below 10 cfs

Because the values of the monthly Q90 in small rivers can be very low in summer and fall, we recommend no change to the long term monthly Q90 during these seasons. The monthly Q90 values are higher in winter and spring, and therefore we recommend limiting the change to these statistics to less than 10%. The differences in these recommendations are based on (a) the hydrologic characteristics and (b) the fact that most studies that exist are during dry seasons. In all seasons, we recommend less than 10% change to the low flow range between the Q75 and Q99.

The recommendations for creeks and small rivers are the same with respect to the median and the low flow in the summer and fall (the winter and spring low flow recommendations differ). In other words, during the dry season, the same recommendations apply to systems between 4-10 mi^2 and 200 mi^2. We recognize that systems are likely to be very different at the extreme ends of this range, however, we made the same recommendation because at the transition between the two size classes – between about 40 and 70 mi^2, the values of median and low flow statistics are very similar.

Based on the biological and hydrologic characteristics of small rivers, these recommendations would:

- **Reduce risk of extending summer critical low flow period** and exacerbating temperature and water quality conditions during low flow
- **Maintain quality and availability of shallow-slow habitats** and backwaters, and channel margins, which are critical habitats for many species, including migratory and spring spawning fishes
- **Reduce risk of sublethal stress to mussels**, including loss and/or dewatering of mussel habitat
- **Prevent changes to species composition, habitat loss, reduced recruitment, habitat quality, and growth of multiple taxonomic groups** as documented in the literature

5.3.4 Flow recommendations for Medium Tributaries and Large Rivers (>200 mi^2)

Relevant subtypes in this class: Cool medium tributaries, Warm medium tributaries

In medium tributaries and large rivers, flows are influenced primarily by precipitation, large infrastructure, cumulative impacts of water withdrawals and discharges and land cover changes that affect water budgets on a basinwide scale. In the Delaware River watershed, streamflow in nearly all medium tributaries and large rivers are affected by upstream reservoir releases. These habitat types are also affected by cumulative effects of multiple withdrawals and discharges and by point and non-point source pollution. Because the releases from these reservoirs are used to meet multiple objectives – water supply, flood risk reduction, recreation, maintenance of salinity conditions in the tidal area – flow recommendations for these types will need to be balanced with other management objectives on a site-by-site basis. These recommendations provide additional information about potential ecological impacts of existing or future operations that may not have been considered previously.

> In the Delaware River watershed, streamflow in nearly all medium tributaries and large rivers are affected by upstream reservoir releases. Because the releases from these reservoirs are used to meet multiple objectives, flow recommendations for these types will need to be balanced with other management objectives on a site-by-site basis.

Recommendations for medium tributaries and large rivers are based primarily on studies of (a) how similar taxa have responded to streamflow changes in other river systems and (b) studies within the Delaware basin that document ecological conditions at various streamflows, especially during extreme conditions (Figure 5.11).

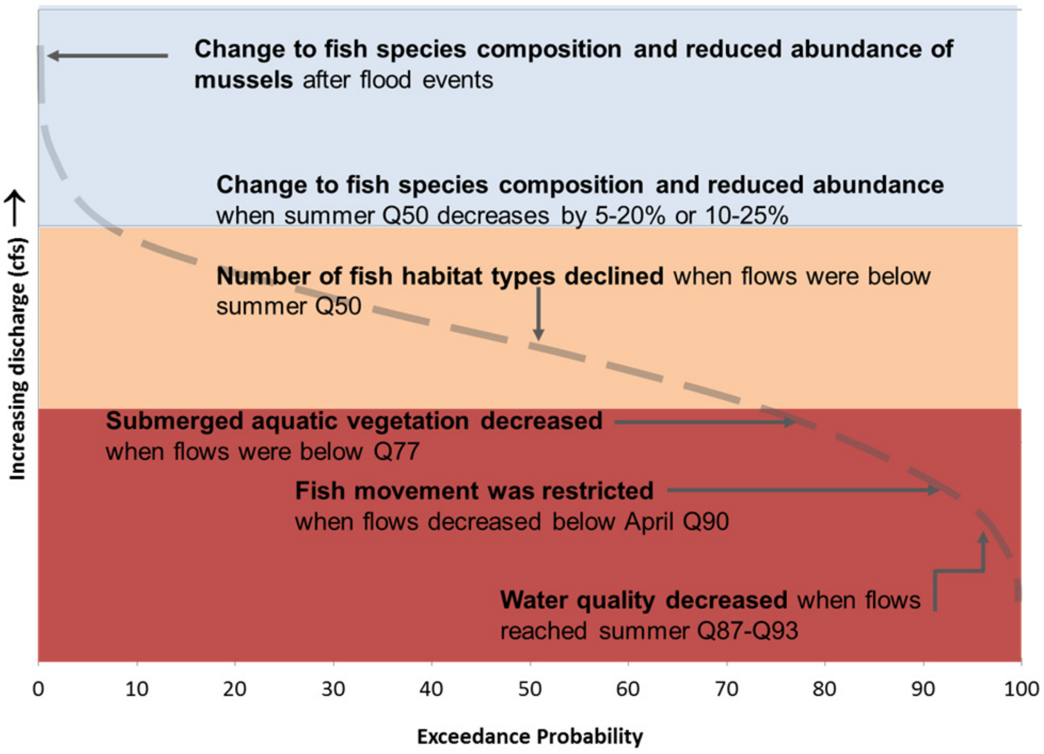


Figure 5.11. Summary of quantitative relationships between flow alteration and biological responses in small rivers, medium tributaries and large rivers

Fish

- **Change to fish species composition.** A large flood (> 20-yr) was followed by a shift in dominance from fall-spawning to spring-spawning trout (Warren et al. 2009)
- **Change to fish species composition and reduced abundance** begin to occur with 10-25% change to August/September median (Zorn et al. 2008) or 5-20% of summer Q50 (Freeman and Marcinek 2006)
- **Fish movement was restricted.** Fish movement between sidechannel and mainstem habitat was positively correlated with discharge and occurred when spring minimum discharge exceeded April Q90 (Kwak 1988)

Mussels

- **Reduced mussel abundance.** A large flood (> 20-yr) resulted in decreases in abundance and distribution of mussels (Fraley and Simmons 2006, Cole and White 2006, Strayer 1999)

Vegetation

- **Submerged vegetation extent and condition decreased** when 7-day low flows were equivalent to the September Q77 (Munch 1993, S. Munch, personal communication, 2013)

Water quality, temperature and geomorphology

- **Water quality decreased.** When flows reached summer Q87-Q93, phosphorous concentrations exceeded standards, temperature increased, and algal growth increased (Fischer et al. 2004)

Several studies that quantify biological responses to changes in streamflow that are applicable to other habitat types also help support these recommendations because they address the same taxa and the studies include rivers with drainage areas greater than 200 mi^2. These studies address fish habitat availability (Bowman 1970, Denslinger et al. 1998); fish species composition and abundance (Kanno and

Vokoun 2010, Armstrong et al. 2011); and fish recruitment (Peterson and Kwak 1999, Smith et al. 2005, Lobon-Cervia 2004, 2007, 2009).

Summary of hydrologic characteristics of medium tributaries and large rivers

- In all seasons, monthly Q50 are above 50 cfs.
- 33% of summer and fall Q90 in med tribs and large rivers are < 50 cfs.
- Almost all Q90 in winter and spring are > 50 cfs.

Compared to other habitat types, there are relatively few minimally-altered gages on medium tributaries. The analysis of hydrologic characteristics for these size classes are based on hydrologic characteristics from a few gages on medium tributaries. Compared to other habitat types, flows are relatively high.

This size class includes relatively few examples, and almost all are influenced by upstream reservoir operations. The temperature differences that distinguish **cool and warm medium tributaries** are mostly due to differences in latitude and the influences of reservoir operations that affect downstream temperature. The prevalence of discharges, multiple withdrawals, point and non-point source impacts, and management for multiple objectives make rivers within these classes more likely than other types to require site-by-site considerations, especially when assimilative capacity may be affected.

Based on the biological and hydrologic characteristics of medium tributaries and large rivers, these recommendations would:

- **Reduce risk of biological changes** to fish species composition, habitat loss, reduced fish and mussel abundances, habitat quality, and reduced growth and condition of submerged aquatic vegetation
- **Reduce risk of other impacts to quality and availability of habitats**, including of shallow-slow, channel margin, and backwater habitats and maintain connectivity among these habitats
- **Reduce risk of exacerbating temperature and water quality conditions** during low flow

Section 6: Conclusion

Maintaining flow regimes has been emphasized as a holistic approach to conserving the various ecological processes necessary to support freshwater ecosystems (Richter et al. 1997, Poff et al. 1997, Bunn and Arthington 2002, Richter et al. 2011). In this study, we began by identifying the species, natural communities, and physical processes that are most likely to be sensitive to flow alteration within the Delaware River basin. Through literature review and expert consultation, we identified critical periods and flow conditions for each taxa group and summarized ecological flow needs for all seasons. This "bottom up" approach confirmed the importance of high, seasonal, and low flows throughout the year and of natural variability among years. The emerging set of recommendations focuses on limiting alteration to a key set of flow statistics that represent high, typical seasonal, and low flows.

We structured these flow recommendations to accommodate additional information. We listed 20 ecological flow needs related to high, seasonal, or low flows, recommended a range of values for a relevant flow statistic, and documented the level of support for the recommendations based on existing literature and studies. This structure provides a framework for (a) adding or refining flow needs; (b) substituting flow statistics and revising flow recommendations if future research or management suggests that revisions are necessary to ensure ecological protection; and (c) incorporating additional supporting information, including results of basin-specific studies. The hypotheses presented can help focus additional studies that quantify relationships between specific types of flow alteration and specific ecological responses. Results of future studies can be incorporated into the framework and used to revise recommendations as appropriate.

The study follows the approach used previously to develop ecosystem flow recommendations for the Susquehanna River, the Upper Ohio River in Western Pennsylvania, and the Great Lakes in New York and Pennsylvania (DePhilip and Moberg 2010, USACE 2012, DePhilip and Moberg 2013, Taylor et al. 2013). There are many similarities among the projects and the recommendations that resulted from each, specifically:

- Low, seasonal, and high flow components were used to address ecological needs and monthly statistics were used to capture within-year variability.
- Flow recommendations are based on synthesis of existing literature and studies, hydrologic analysis of minimally-altered stream gauges, and expert input.
- Flow recommendations are expressed as recommended limits to alteration of a set of flow statistics that serve as indicators for each flow component.

Because this project timeline overlapped with the studies for the Upper Ohio River and Great Lakes basin, we benefitted from collaboration with the Conservancy staff and a Cornell post-doctoral research associate who led the technical aspects of Great Lakes basin project. We collaborated closely to identify representative species and species groups, to develop the weight-of-evidence methods for evaluating strength of support, and to engage technical advisors with expertise relevant to both projects. As a result, the amount of literature reviewed for this study exceeds any of the previous three studies for other basins.

We applied the concept presented in the Biological Condition Gradient to these recommendations (USEPA 2005). The overall concept is that limiting modifications to hydrology reduces stressor levels and reduces risk of change to ecosystem structure and function. For streams that are relatively unaltered, we recommend limiting the amount of change to an amount that is less than where risk to ecosystem structure and functions have been documented in literature or existing studies. This concept was extremely useful for framing the recommendations and communicating with technical experts what we are trying to achieve with these recommendations. We believe this could continue to be a useful framework to guide future studies that would help establish more points or thresholds along the curve for various flow conditions and taxa groups.

We also anticipate that the goals of this project – and the recommendations herein – will benefit greatly from current work under the WaterSMART initiative to characterize basin hydrology and establish relationships between hydrologic alteration and ecological responses using biological data from the Delaware River basin.

6.1 Potential Applications

These flow recommendations have applications to management of water withdrawals and reservoir operations. They can also help frame expectations for ecological changes that could result from hydrologic changes attributable to climate change and land cover changes in the watershed.

Water withdrawal policy. The *Ecosystem Flow Recommendations for the Susquehanna River Basin* were developed to provide one source of technical information for potential revisions to SRBC's water management programs. The report was used to help develop the revised Low Flow Protection Policy (LFPP) and technical guidance for establishing conditions on water withdrawal permits that SRBC adopted in December 2012.

With the LFPP and technical guidance, SRBC (1) changed the method for determining passby flows from one based on an annual value to one based on monthly exceedence values; (2) established the use of a percent-of-flow-based withdrawal limit to preserve natural flow variability and meet seasonal flow protection; and (3) revised the aquatic resources classes used to determine the applicable passby. The LFPP was accompanied by a proposed regulation change that would limit surface and groundwater withdrawals in headwater areas to prevent significant adverse impacts to the areas that are most sensitive to water withdrawals.

Upon completion of the flow recommendations – analogous to those presented here – SRBC initiated a policy development process that lasted nearly two years. During this time, SRBC staff engaged water management agencies and stakeholders in reviewing policy alternatives before proposing a package that included proposed regulation, revised policy and new technical guidance. This process could be replicated in the Delaware River basin.

Application in systems with existing hydrologic alterations. Our project goal was to develop a set of flow recommendations that generally apply to all streams and rivers within the project area. As stated above in the discussion of the Biological Condition Gradient, the recommendations are based largely on limiting alterations that would increase risk to ecosystem structure and functions in minimally-altered systems. It is important to recognize that some streams and rivers in the Delaware basin already have hydrologic alterations that exceed these recommendations. These reaches may need more site-specific considerations due to constraints from existing water demands, reservoir operations, and landscape changes.

Understanding the naturally-occurring variability of high, seasonal, and low flows can provide a starting point for developing site-specific flow recommendations in systems with known alterations. The flow needs of species in this report could help frame which species might benefit from flow regime restoration. In other words, they can help define the biological potential if some aspects of stream hydrology were restored. Applying these recommendations in systems with known hydrologic alterations will require additional steps:

- **Confirm presence or potential presence of flow-sensitive species** that would be expected in the given habitat type. If these species are not currently present, are the other conditions (e.g., water quality, temperature, habitat, substrate) suitable for these species?
- **Identify other purposes that might conflict with flow recommendations and their influence on flow conditions.** These may include reservoir operations for hydropower, flood control, maintaining water quality or salinity targets.
- **Determine what flexibility might exist in existing operations while still meeting project purposes.** If alterations are due to landscape changes – what potential exists to restore aspects of the flow regime that would support these species groups?

6.2 Limitations

This project approach has a number of advantages. It is efficient and relatively inexpensive compared to approaches that use novel quantitative analyses to relate degrees of flow alteration to degree of ecological change. It maximizes use of existing information and expertise in the Delaware River basin. It has the added advantage of being familiar to many of the technical advisors and water management agencies in the basin since it has recently been applied in other basins in Pennsylvania and New York.

However, we acknowledge several limitations:

Limitations of the stream gage network used for hydrologic characterization.

- Even the minimally-altered gages used have been impacted by historical land conversion, including past forest clearing.
- We tried to use a 40-year period of record to calculate hydrologic statistics, and this limited the number of gages we could use. The Indicators of Hydrologic Alteration helps evaluate the long-term distribution of hydrologic statistics based on annual values. Because our criteria were strict, we had relatively few gages for each size class and we did not have enough data to characterize hydrology of subtypes within each class (e.g., to distinguish spring-fed, high baseflow types from cool and warm types).
- Because there were so few gages with a 40-year record in headwaters, we summarized data from a shorter period of record (at least 15 years).
- We used the least altered gages possible for medium tributaries and large rivers, but even these gages have known hydrologic alterations.

Limitations of applicable studies.

- The quantitative studies that exist primarily address fish and macroinvertebrates and are mostly limited to headwaters, creeks, and small rivers. For the most part, they focus on impacts to species composition and abundance. Relatively little information exists on more complex effects (e.g., trophic interactions, competition for resources).
- There are few studies during winter, even though this is considered to be a stressful period when resources may be limited.
- Many of the studies were from outside the Delaware River basin. We strove to include as much information as possible from within the basin, and we applied criteria to ensure that studies from outside the basin were applicable here. Still, most of the sources were from outside the basin.
- The Biological Condition Gradient is conceptually relevant, but there is relatively little information to establish the thresholds between classes.

6.3 Future Analysis and Research

- During the study, we identified some data on shad and eel migration that could be used to look at timing and flow conditions for cues. We had hoped to incorporate this information during the study, but we did not have enough time.
- We hope to use the soon-to-be-completed Delaware mainstem Decision Support System to evaluate habitat availability for some of the target species represented in our groups in the upper mainstem. We have discussed this with USGS and plan to work with them on this after the report is complete.
- Conduct additional research during winter, which is known to be a resource-limited period but when relatively little information is available.
- Improve/expand models relating streamflow and temperature.
- Initiate additional research to define differences in sensitivity among river types (e.g., between high baseflow, wetland-dependent, and cool and warm creeks and rivers)
- Expand research on headwater systems, including on relationships between flow and headwater processes such as energy processing and transport. Also research on potentially sensitive (but undersampled) taxa groups, including streamside salamanders and wetland plants.
- Initiate/expand biological and other monitoring downstream of withdrawals to establish stressor-response relationships based on local data.
- Prior to/concurrent with development of draft policy, complete more extensive analysis of existing withdrawals and how they do/have potential to affect streamflow statistics. Evaluate whether or not resulting alteration is consistent with recommendations.
- Provide some guidance on how to track changes to hydrologic statistics on a short-term basis.

We look forward to collaborating with water management agencies and other organizations to apply these recommendations in the Delaware River basin; to use them as a starting point for site-specific operations; to increase the amount of research on how flow alteration affects riverine ecosystems; and to help apply this research to improve instream flow management in the Delaware and other northeastern U.S. rivers.

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