Susquehanna River Basin
Ecological Flow Management Study Phase I

Section 729 Watershed Assessment

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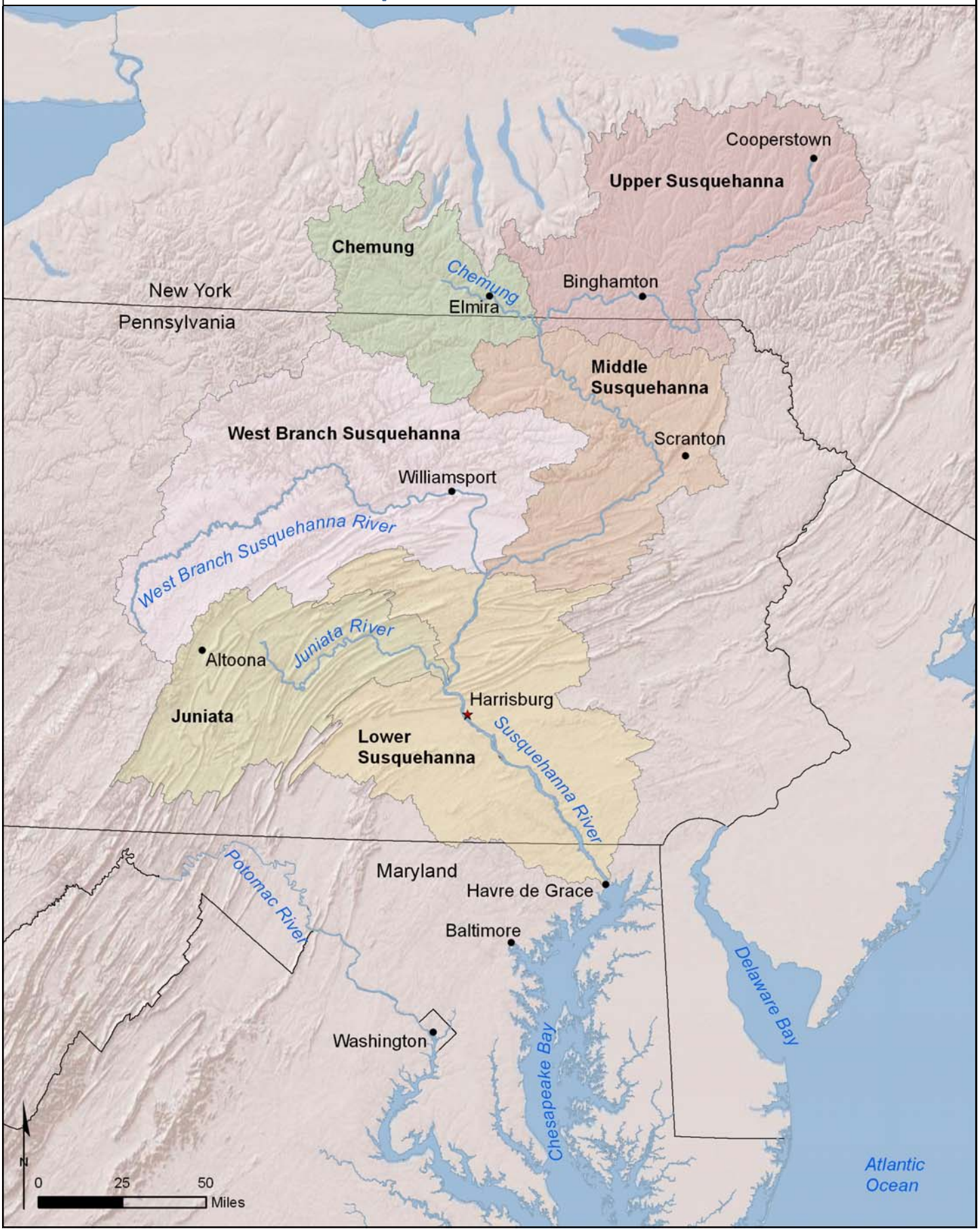
SRBC

US Army Corps of Engineers
Baltimore District

The Susquehanna River Basin



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Appendix A: Ecosystem Flow Recommendations for the Susquehanna River Basin
The Nature Conservancy, 2010

Cover Photograph: The mouth of the Susquehanna River near Havre de Grace, Maryland.
Ben Longstaff, IAN Image Library (www.ian.umces.edu/imagelibrary)

Executive Summary

The Susquehanna River has supported the regional culture and sustained a vibrant economy for generations. As the single largest freshwater input to the Chesapeake Bay, the Susquehanna River is a key tributary to one of the nation's most important estuaries. Natural hydrologic variability is a fundamental component of any river system's ecological health. Aquatic species and natural communities have evolved in concert with naturally variable flows, and the ecological health of a river system depends on an intact hydrologic regime. This study is focused on ecological flow needs, often called environmental flows, and other water resource needs are not explicitly considered.

This study is intended to synthesize the knowledge of an interdisciplinary group of experts, and to characterize the nature and significance of flow conditions in the Susquehanna River basin. Significant low flows — combined with current and projected water demands — may create critically low flow conditions in the basin. The overarching goal is to clearly establish the volume and timing of flows required to support aquatic species, and to minimize and avoid deleterious impacts. To begin the study process, researchers, managers, and other practitioners met at three workshops. Extensive literature reviews were then conducted to address data gaps and answer questions raised in the workshops.

This study is a partnership between the U.S. Army Corps of Engineers (USACE) and the Susquehanna River Basin Commission (SRBC). Under contract to SRBC, The Nature Conservancy (TNC) provided technical expertise as part of SRBC's study cost-share. Study activities were authorized by Congress under Section 729 of the Water Resources Development Act (WRDA) of 1986, as amended. Section 729 of WRDA 1986, as amended, authorizes watershed assessments for ecosystem protection and restoration, drought preparedness, and other factors. It requires intergovernmental coordination and results in holistic strategies for integrated water resources management. The reconnaissance phase of this study began in 2003 and a Feasibility Cost Sharing Agreement was signed in 2008 by USACE and SRBC. TNC conducted the technical analysis and facilitated the three workshops. Federal, state, and local agencies, in concert with non-governmental organizations and academic institutions, participated in this effort.

The study process generally followed the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al. 2010). Using stream and river classifications to establish ecosystem response relationships to flow alterations across a broad geographic area, the approach enables environmental flow needs to be assessed when in-depth studies are not possible for an entire watershed. The result is a set of stream flows that support ecosystem health. The range of stream flows were made without consideration of other competing water uses in the Susquehanna River basin such as water supply, power generation, recreation, and flood risk management. The flows are intended as guidelines to inform stakeholders and future studies.

This report summarizes the study team's technical findings and discusses the following major topics related to low flow in the Susquehanna River basin:

Chapter 1 provides an introduction and outlines the study methodology and coordination.

Chapter 2 discusses existing physical and hydrological conditions within the basin.

Chapter 3 summarizes the study results and describes general flow requirements.

Chapter 4 presents stream flows that support ecosystem health in the Susquehanna River and its tributaries.

Chapter 5 suggests various application options for achieving environmental flows.

Basinwide water management must account for a spectrum of problems, needs, and opportunities associated with water quantity, quality, availability, and regulation. Increasing demands strain water resources, especially during dry seasons. Demand is expected to increase in the future as population and consumptive uses (water used and not returned) are both predicted to grow. Consumptive use demands include increasing power production, municipal water use, and agricultural production. In addition, energy production associated with the development of natural gas wells in the Marcellus and other shales presents another consumptive use not previously contemplated by water management agencies for the basin prior to 2007.

Significant low flows, combined with water withdrawals and consumptive water use, may create critical low flow conditions in stream channels, impacting natural functions of the ecosystem and the species that depend on these functions and attributes. The complexity of the Susquehanna River system and the potential for changing conditions in the basin call for a better understanding of how to manage low flows. It is critical to maintain the current range of unaltered flow variability to sustain the full range of species and ecological processes throughout the basin. Chapter 4 details the timing, frequency, and duration of necessary flow conditions and the degree to which they can deviate relative to unregulated flows while still supporting ecosystems. There is special emphasis on headwater streams because their smaller size makes them more vulnerable and less adaptable to changes.

Chapter 5 identifies application strategies to preserve and restore flows necessary to support ecosystem health and resilience by USACE and SRBC; the two partners in this Phase I watershed assessment. The variable flows may be supported with reservoir operations by USACE and water resource management actions by SRBC to include consumptive use regulation, passby flows, water budget studies, and other related actions. Other mechanisms for managing ecosystem flows may be available and may be implemented by other agencies or groups.

With the highest average flow of any river in the eastern United States (PADEP, 2009), the Susquehanna River and its tributaries deliver flow to meet numerous water uses throughout the basin. Communities rely on streams for clean drinking water, agricultural irrigation, energy production, and recreation.

While challenges lie ahead with increasing population, changing land use, and climate uncertainties, there are still many ways to maintain ecological flow variability. Management and regulatory actions can help maintain and restore a flow regime that supports the characteristic natural habitats and characteristic species of the Susquehanna River basin and also provide benefits for all the basin's inhabitants.

Continuation of the Susquehanna River Basin Ecological Flow Management Study under Section 729 of WRDA 1986, as amended to a second phase (Phase II) is warranted and would allow the examination of a number of options to protect aquatic ecosystems and augment low flows.

Chapter 1: Introduction

The Susquehanna River basin drains an area exceeding 27,500 square miles, including about half the land area of Pennsylvania and portions of New York and Maryland. The Susquehanna River basin has six major subbasins: Chemung, West Branch, Juniata, Upper, Middle, and Lower Susquehanna (Figure 1.1). The mainstem of the Susquehanna River begins in southern New York state, flows through central Pennsylvania, and empties to the Chesapeake Bay at Havre de Grace, Maryland. Flowing at an average rate of more than 40,000 cubic feet per second (cfs) at the Conowingo Dam near the river's mouth, the Susquehanna River delivers half of the freshwater inflow sustaining the Bay.

Figure 1.1. The Susquehanna River flows from Lake Otsego near Cooperstown, NY to Havre de Grace, MD. Six major subbasins are defined: Upper Susquehanna, Chemung, Middle Susquehanna, West Branch Susquehanna, Juniata, and the Lower Susquehanna.

Basinwide water resources management must address the full spectrum of problems, needs, and opportunities associated with water quantity, quality, availability, and regulation. The spectrum ranges from flooding to extreme low flow and drought; from degraded streams to pristine areas warranting protection; and from problems related to agricultural and urban runoff to a remarkable diversity of wildlife, abundant recreation, significant public utilities and infrastructure, and historic communities.

Water demands come from within and outside of the basin, and the demand for water is expected to increase as the current population of more than 4.1 million people continues to grow. In the Lower Susquehanna Subbasin, census estimates predict population will increase more than 16 percent over the next 20 years. Consumptive water use (water that is used and not returned to the basin) continues to increase with power production, municipal water supplies, and agriculture among the largest demand sectors. The extraction and production of natural gas in the basin present new consumptive uses in the basin not contemplated by water managers prior to 2007.

Droughts are a concern in the Susquehanna River Basin with thirteen droughts occurring over the past century (SRBC 2010a). The drought of record occurred in 1964 and the river stage at Harrisburg was less than 1 ft. Droughts are important in the evolutionary history of Susquehanna River ecological communities but prolonged droughts and low flow conditions have the potential to negatively impact community health, particularly if these communities are already under stress from water quality or other factors. Droughts also affect water supply and other water uses; therefore, plans are in place to manage water during droughts to ensure continued water supply (SRBC 2000).

The Susquehanna River basin is one of the most flood prone basins in the United States. Aquatic organism and natural communities have evolved with periodic flooding in the basin. Multiple reservoirs in the basin address the risk of flooding to human communities. Flood risk management may present a challenge for environmental flow management in the basin due to reservoirs that may interrupt the natural flow regime of rivers.

As the technical report included as Appendix A elucidates, significant low flow conditions combined with current and projected water demands have the potential to create critically low flows in the basin, impacting natural ecosystems in the Susquehanna River basin under current conditions and in the future. As land use changes, with more open fields and forests being developed and as demand for water increases, there is a clear need to address how all stream flows will be managed (low flows, seasonal flows, and high flows). Developing goals and standards for stream flows is a management priority of the U.S. Army Corps of Engineers (USACE) Baltimore District, the Susquehanna River Basin Commission (SRBC), The Nature Conservancy (TNC), the states of Maryland, New York and Pennsylvania, and many other partners.

This report presents a collaborative effort to determine ecological flow requirements that will protect the species, natural communities, and key ecological processes throughout the basin. Information is presented regarding the timing, frequency, and duration of necessary flow conditions and the degree to which these conditions can deviate relative to unregulated flows while still supporting basin ecosystems.

1.1 Goals and Objectives

The goal of the Susquehanna River Basin Ecological Flow Management Study is to understand ecological flow needs for the Susquehanna River and its tributaries, particularly for low flows. With an understanding of the basin's ecological flow needs, we can identify management options, and the agencies and process to meet these needs while meeting other competing water resource needs. Several premises provide the study foundation:

- Flow affects 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 streams.
- Streams provide water for public supply, energy production, recreation, industry, and other, sometimes competing, demands and activities.
- Negative ecological impacts can be minimized by incorporating ecological needs into water management and planning.

The primary objective of the study is to develop a range of environmental flows based on existing information, data, and expert opinion that have application to existing water management programs. Only ecosystem health and sustainability objectives were evaluated in deriving flow regimes—other resource needs were not considered in this study.

1.2 Study Methodology

While it is intuitive that altered flow conditions could stress natural processes in aquatic ecosystems, there has been insufficient study to determine what level of flow causes adverse impacts and how these impacts vary spatially, temporally (duration and frequency of drought conditions), and in severity within the basin. With the exception of an in-stream flow study developed for coldwater streams in small drainage basins (<100 square miles) in the Pennsylvania and Maryland portions of the basin, no comprehensive study has investigated the need to maintain certain low flow parameters to sustain aquatic ecosystems in other stream systems (large rivers, large subbasins, and warmwater streams).

In order to characterize the nature and significance of potential altered flow conditions in specific reaches in the Susquehanna River system, the in-stream flow requirements of aquatic species must be clearly established. Determining species-specific requirements was the necessary first step in identifying various mechanisms to reduce the impacts of low flow in sensitive areas.

The study generally followed the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al. 2010). ELOHA uses stream and river classification to help extend the application of flow alteration and ecological response relationships to streams and rivers in a broad geographic area (for example, a state or large basin as opposed to specific reaches). This approach broadly assesses environmental flow needs when in-depth studies cannot be performed for all rivers in a region. The elements of ELOHA used for the Susquehanna River basin included stream and river classification, identification of flow statistics, calculations of flow alteration, and development of flow alteration and ecological response relationships.

Five major habitat types were used in this study as the basis for developing sustainable flows. A set of flow statistics was chosen to represent the magnitude, timing, frequency, and duration of low, seasonal, and high flow conditions. These statistics were used in this study to define recommended ecological flows through an iterative workshop and study process. These statistics can also be used to quantify existing or projected hydrologic changes associated with water withdrawals, reservoir releases, and water management changes.

The study process, flow needs, and flow alteration and ecological response relationships were developed through a collaborative workshop process informed by published literature and existing studies. During three workshops, participants were encouraged to identify and gather relevant information about flow-sensitive species, natural communities, and physical processes. The best professional judgment of regional and national experts was incorporated throughout, and the result was a set of ecosystem flows for the range of aquatic habitat types found in the basin.

The first 1-day workshop focused on collecting preliminary species information and needs. Based on the results of that meeting, TNC conducted a literature review and met with experts on the aquatic ecology of the Susquehanna River basin. After this investigation, participants at a 2-day workshop defined and refined flow needs for species that may respond to flow variability. Based on the recommendations from this workshop, expert consultation, and literature review, flow alteration and ecological response relationships were developed. Finally, a third 2-day workshop was convened to develop ecosystem flows for the Susquehanna River and its tributaries based on the flow alteration and ecological response relationships. TNC produced a technical report detailing the study process, literature review, and flow regime for the Susquehanna River basin (TNC 2010).

1.3 Study Process

In 2005, a reconnaissance report was prepared in response to specific language contained in Section 202 of the Water Resources Development Act (WRDA) of 2000, which amended Section 729 of WRDA 1986 that directed USACE to conduct a comprehensive assessment of the water resources needs in the Susquehanna River. The report recommended, in part, the development of a watershed investigation for the Susquehanna River basin focused on ecosystem restoration, watershed protection, and water supply. Water resource solutions were recommended to be pursued through four methodologies: (1) changes in the operations of and/or storage reallocation at Federal reservoirs with consideration of changed operations at state and local reservoirs; (2) preservation of critical groundwater recharge areas; (3) water conservation efforts; and (4) acid mine drainage abatement.

After several years during which a project management plan was prepared and the scope of the study defined, Phase I of the Susquehanna River Basin Ecological Flow Management Study began with the signing of a Feasibility Cost Sharing Agreement in 2008 between USACE and SRBC. The study has been conducted under Section 729 of WRDA 1986, as amended, which allows for a 75 percent federal (USACE)/ 25 percent non-federal (SRBC) cost share for watershed planning. Watershed planning addresses problems, needs, and opportunities within a watershed or regional context; strives to achieve integrated water resources management (IWRM); and, results in general, non-project specific, holistic plans or strategies to address those watershed needs. The result of the study process is a watershed

planning document that may be a watershed plan, or it may provide information that can inform subsequent watershed management planning efforts. The Susquehanna River Basin Ecological Flow Management Study, while undertaken in the context of watershed planning is not itself a watershed plan. This study was a technical study undertaken to support ecosystem flows that may be used in future watershed planning efforts.

As part of the project cost-sharing, SRBC engaged TNC to lead the collaborative technical study process. An orientation workshop was convened in March 2009 and two additional workshops were held in October 2009 and April 2010. The technical study team, led by TNC, also contacted experts for advice and coordinated with numerous scientists from the academic community, state and federal agencies, and other interested organizations and groups. A complete listing of meeting and workshop participants is provided in the technical report prepared by TNC (2010). This report summarizes the TNC technical report completed in 2010. Participating agencies included the U.S. Geological Survey (USGS), the U.S. Fish and Wildlife Service (USFWS), USACE, the Maryland Department of the Environment (MDE), the Pennsylvania Department of Environmental Protection (PADEP), Pennsylvania Fish and Boat Commission (PFBC), the Pennsylvania Natural Heritage Program (PNHP), New York State Department of Environmental Conservation (NYSDEC), SRBC, Interstate Commission on the Potomac River Basin (ICPRB), Delaware River Basin Commission (DRBC), and TNC.

Report Outline

This report summarizes the study team's technical findings and discusses the following major topics related to low flow in the Susquehanna River basin:

- Chapter 2 contains a summary of existing conditions within the basin including physical and hydrological conditions;
- Chapter 3 provides a summary of the flow needs investigation results including biota affected by flows and a description of general flow needs by season;
- Chapter 4 presents stream flows that support ecosystem health in the Susquehanna River and its tributaries;
- Chapter 5 presents application options for flow findings.

Following these chapters are references, a short glossary, and abbreviations used in this report.

Chapter 2: Existing Conditions

The Susquehanna River basin encompasses about 27,500 square miles with about 76 percent of the basin in Pennsylvania, about 23 percent in New York, and the remaining 1 percent in Maryland. The main stem of the Susquehanna River is 444 miles long, from the mouth at the Chesapeake Bay near Havre de Grace, Maryland, to its source at Lake Otsego near Cooperstown, New York.

Major tributaries include the Chemung River, West Branch Susquehanna River, and the Juniata River — they define three of the six subbasins, along with the Upper Susquehanna, Middle Susquehanna, and Lower Susquehanna (Figure 1.1).

Head-of-tide on the Susquehanna River is about 3 miles below the Conowingo Dam and 6 miles upstream from the mouth of the river and the Chesapeake Bay. The basin includes almost 45 percent of the Chesapeake Bay's drainage area and provides about 50 percent of its freshwater.

This chapter discusses existing conditions in the Susquehanna River basin, including hydrology and flow components, water management, impoundments and withdrawals, water quality, climate, physiography, and vegetation and land use.

2.1 Hydrology and Flow Components

Drawing on worldwide examples of environmental flow components and their application for setting ecosystem flow standards, Mathews and Richter (2007) describe a broad spectrum of hydro-climate regions: extreme low flows, low flows, high flow pulses, small floods, and large floods.

Flow components integrate the concepts of seasonal and inter-annual variability. This study considers three ecological flow components: low flows, seasonal flows (typical monthly range of flows), and high flows. The ecological importance of each is described below and the flow regime for the Susquehanna River is organized around these components. These flow conditions are discussed in greater detail in the TNC Technical Report (Appendix A).

Low Flows

During dry periods, low flows provide habitat for aquatic organisms. Low flows keep floodplain soil moist, connect the floodplain to the hyporheic zone (region along and underneath stream bed and bank), and help to maintain cooler water temperature minimizing fluctuations in dissolved oxygen concentrations. Extreme low flows enable recruitment of certain aquatic and floodplain plants that require exposed soil and rock substrates to grow. These periodic disturbances help maintain populations of a variety of species adapted to different conditions.

Seasonal Flows

Seasonal flows represent a typical range of flows for each month and are useful for describing typical variation between seasons (for example, summer and fall). They are also useful for describing variation among years (for example, a wet summer compared to a dry summer). Most of the time – in all but the wettest and driest portions of the flow record – flows are within this range.

Seasonal flows may dictate the reproductive behaviors of spring, summer, and fall spawning fishes. Seasonal flows are within the range required to ensure that eggs in nests (redds) remain submerged and a variety of aquatic substrates and habitats are available. Seasonal flows also provide habitat for overwintering species, prevent formation of anchor ice, maintain bank habitat for nesting mammals, and maintain a range of persistent habitat types. Naturally occurring variability within seasons ensures conditions suitable for multiple species and life stages.

High Flows and Floods

High flow events and floods are part of the natural history of the Susquehanna River and influence most components of the riverine ecosystem. High flows and floods provide cues for fish movement and migration, maintain channel and floodplain habitats, inundate submerged and floodplain vegetation, transport organic matter and fine sediments, and help maintain optimal temperature and dissolved oxygen concentrations. High flow events range from relatively small, flushing pulses of water (for example, after a typical summer rain) to extremely large events that reshape floodplains and occur more rarely (for example, extreme snowmelt or Nor'easter-driven spring floods).

Flood Probability

A flood is described by the probability of occurring in any given year. The *20 year flood,* for example, has a 1-in-20 (or 5 percent) chance of occurring in any given year.

Large and small floods

Depending on their magnitude, floods can change the size, shape, and location of a river. Larger floods usually cause more dramatic changes. In the Susquehanna River basin, the large, less-frequent, 20-year flood (5 percent probability) is associated with floodplain maintenance, which allows for various successional changes in riparian vegetation. During smaller 5-year (20 percent probability) floods, changes typically occur within the channel. Changes to the magnitude or frequency of these events will likely lead to channel and floodplain adjustments, changes in the distribution or availability of floodplain habitats, and alterations to floodplain and riparian vegetation.

Bankfull events

Bankfull discharge, when water just fills the channel and its surface is level with the floodplain, is commonly referred to as channel forming discharge. Bankfull events occur fairly frequently (about every 1-2 years); over time, channel forming discharge is responsible for moving the most sediment and defining specific channel morphologies.

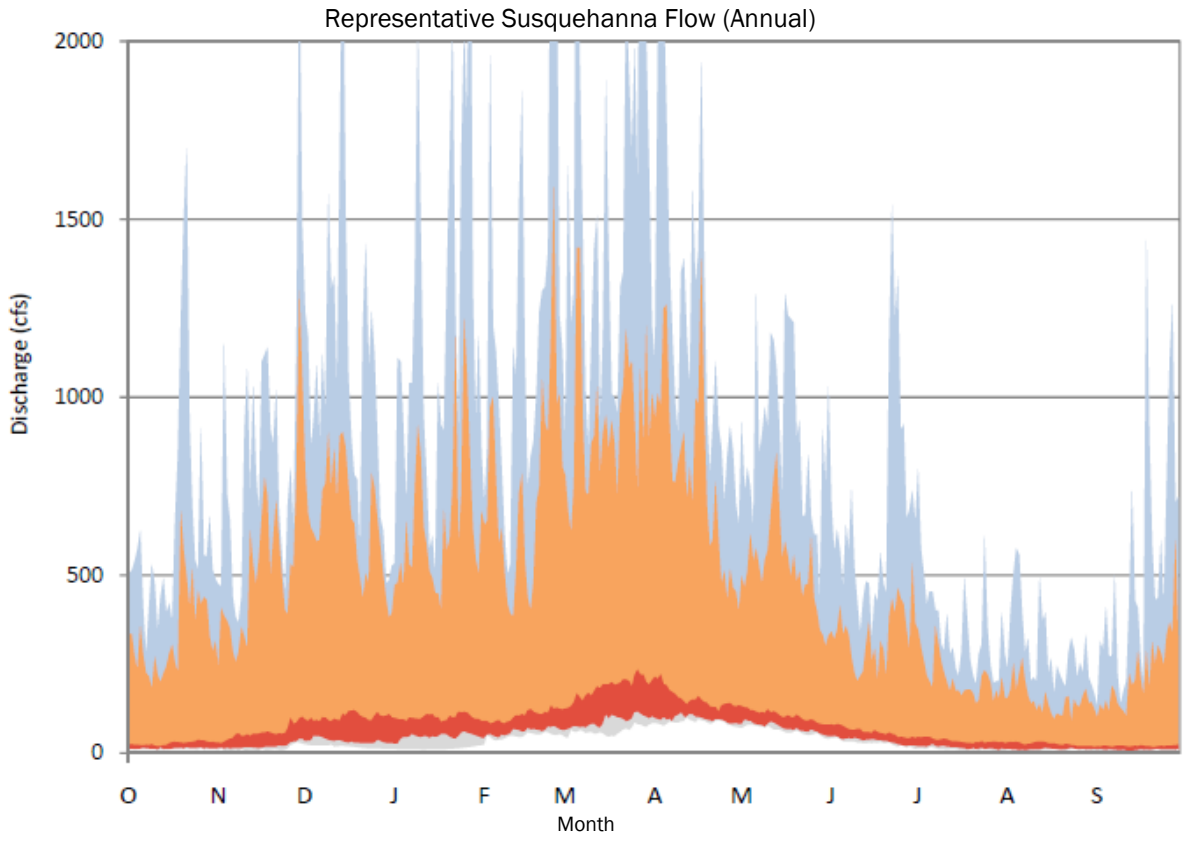
High flow pulses

High flow pulses (smaller than bankfull events) flush fine sediment, redistribute organic matter,

Defining Flow Components

Flow components (discharges, or Q, measured in cubic feet per second) are used to highlight specific portions of the hydrograph and discuss the ecological importance of each one. Flow exceedance values (Qex) 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. Each flow component is defined on a monthly basis (for example, using monthly flow exceedance values) to capture seasonal variation throughout the year.

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



and moderate stream temperature and water quality. 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 they occur. These events may be particularly important in summer and fall when flows are generally lower than in other seasons.

2.2 Existing Water Management Programs

The states of New York, Pennsylvania, and Maryland have primary responsibility for managing the waters of the Susquehanna River basin within their boundaries. SRBC closes any regulatory gaps within each state's water management program by assuming regulatory responsibility until a member state has the regulatory authority to implement a water management program consistent with the Susquehanna River Basin Compact.

The SRBC mission is to enhance public welfare through comprehensive planning, water supply allocation, and management of the basin's water resources. To accomplish this mission, SRBC works to: reduce damages caused by floods; provide for the reasonable and sustainable development and use of surface and groundwater for municipal, agricultural, recreational, commercial, and industrial purposes; protect and restore fisheries, wetlands, and aquatic habitat; protect and monitor water quality and in-stream uses; and ensure future availability of flows to the Chesapeake Bay.

SRBC regulates groundwater and surface water withdrawals and consumptive water uses. Ground and surface water withdrawals have the potential to impact wetlands, aquatic habitat, fish migration, recreation, and other water users. Consumptive use of water depletes the total volume of water available in streams and which reaches the Chesapeake Bay; posing severe problems during drought. SRBC has protective measures and guidance to protect the environment, while allowing for water use — including pass-by flows and consumptive use mitigation.

Pass-by flows protect streams and wetlands by requiring that water withdrawals cease when flows reach a specified low flow threshold. The thresholds are determined by stream classifications, such as special protection designations, the magnitude of the requested water withdrawal, existence of sensitive species within the withdrawal area, and the presence of other water users.

SRBC's consumptive use regulation, adopted in 1976, required project sponsors to provide mitigation for their consumptive use during low flow events. Sponsors were expected to comply with the regulation by providing compensatory water or discontinuing consumptive use during low flow events. While a few power companies were able to make the financial investments to secure water storage at large existing reservoirs for compensatory purposes, this option proved impractical for most sponsors, and discontinuation of consumptive use was largely unreasonable for facilities. In response, the Commission enacted a measure in 1993 to allow project sponsors to pay a consumptive use fee to the Commission in lieu of providing actual compensatory water. The payment of fees was intended to allow the Commission to undertake additional large-scale storage projects to provide low flow mitigation for consumptive use projects paying the fee.

SRBC coordinates closely to implement these and other programs with NYSDEC, PADEP, PAFBC, MDE, MDDNR, USACE, and other federal, state, local, and non-governmental agencies. These agencies also have numerous water resources programs and projects, many of which are summarized annually in the water resources program compiled and published by SRBC (www.srbc.net/planning).

The annual water resources program is the mechanism for implementing the "actions needed" listed in the basin Comprehensive Plan under six Priority Management Areas (Water Supply, Water Quality, Flooding, Ecosystems, Chesapeake Bay, and Coordination, Cooperation and Public Information). The

management areas serve as the foundation by which SRBC, USACE, federal, state, local, and non-governmental organizations identify and catalog their water resource programs and projects to help meet the water resource needs in the Susquehanna River basin.

For fiscal years 2012-2013, actions outlined in the water resources program constitute a broad range of actions to be undertaken by federal, state, local, and non-governmental organizations under six water resource needs: water supply, water quality, flooding, ecosystems, Chesapeake Bay, and coordination, cooperation, and public information. The following paragraphs provide a quick glance at state and federal water management programs in the Susquehanna River basin. It is not exhaustive nor deep. All agencies listed here, and others not listed, have extensive involvement in aspects of water management in the Susquehanna River basin.

State water management programs include the allocation of public water supplies by the NYSDEC. The NYSDEC is also actively investigating impacts to water resources from natural resource extraction activities, and climate change. Other New York state agencies are active in safeguarding water quality for human health, and encouraging conservation. In Pennsylvania, water use and allocation is considered by various agencies, such as PADEP and PFBC, when access and resource development of Commonwealth lands and waters is proposed. Pennsylvania agencies also assist with the management of water re-use from abandoned mine drainage (AMD) for quality and quantity Water management in Maryland is primarily overseen by MDE and the Maryland Department of Natural Resources (MDDNR). Water quantity and quality in the Susquehanna River from the Conowingo Dam to the Chesapeake Bay is impacted by upstream activities, and MDE and MDDNR, in addition to permitting and monitoring activities coordinate with upstream jurisdictions to ensure adequate water quantity and quality for ecosystem health and human use.

Multiple Federal agencies, including USACE, USGS, the U.S. Environmental Protection Agency (USEPA), USFWS, National Resource Conservation Service (NRCS), and National Weather Service (NWS) provide assistance and support for various facets of basin water management. USACE has water management responsibilities related to the operation of USACE reservoirs, which will be discussed in more detail in the next section of the report. USGS continues to provide expertise in hydrology, hydrologic modeling, and real-time gaging which supports water management decisions. USEPA provides guidance and guidelines on water quality as well as supporting decision making for flow and water quality impacts on ecosystems. USFWS provides expertise on aquatic and riparian resources, as well as water supply and demand . NRCS ensures that NRCS-assisted dams have proper local operation and maintenance. NWS provides multiple precipitation forecast and prediction services. Many other programs and policies within these and other federal agencies affect water quality and quantity within the Susquehanna River and influence the water management by state and local agencies.

2.3 Impoundments and Withdrawals

In addition to water management programs, flow is affected in the Susquehanna River basin by 4 large hydroelectric dams and a system of 15 reservoirs (other dams are within the basin but are not considered in this analysis). This section describes these impoundments and the role they play in the basin's flow regime.

The York Haven, Safe Harbor, Holtwood, and Conowingo Dams are located on the lower mainstem of the Susquehanna River (Figure 2.1). A fifth facility, the Muddy Run Pumped Storage Facility, uses Conowingo Pond as an afterbay for producing power during peak demand. These dams create multiple barriers to fish passage, restricting access to most of the historic diadromous fish spawning habitat in the basin. Fish passage facilities have been installed by dam operators to help alleviate this situation (Table 2.1). These dams also alter streamflow on a daily or sub-daily basis depending on the season, reservoir capacity, and operating schedule. They have operating requirements included in their Federal Energy Regulatory Commission (FERC) licenses, as well as other agreements and certifications (for example, Clean Water Act, Section 401 Water Quality Certification, as regulated by states). Safe Harbor Dam has no minimum flow requirement.

In addition to the major hydroelectric dams, there are 14 USACE-constructed reservoirs and one state-constructed reservoir (total storage capacity of 1.5 million acre-feet (AF)), operated primarily for flood risk management (Table 2.2). Several projects are also authorized for water supply purposes, low flow augmentation, recreation, and hydroelectric power. Releases from some dams are also made to dilute acid mine drainage (AMD) during low flow periods. The cumulative hydrologic impact on the magnitude of floods is tempered by the location of these dams in the watershed on small to medium-sized streams. Half of these reservoirs are on headwater and small streams, with upstream watersheds ranging from 6.5 to 122 square miles. The rest of the reservoirs are on medium-sized tributaries. The collective drainage upstream of these 14 reservoirs is about 3,416 square miles or 12 percent of the total Susquehanna River basin. Reservoir operating rules sometime result in reservoir outflows that are equal to or larger than inflows at a specific time. Optimally managed reservoir releases, such that the authorized or original purpose of the reservoir is not compromised, can be a component of ecologically sensitive water management when the effects of releases are thoroughly understood.

Table 2.1. Fish Passage Facilities on the Lower Susquehanna River

Dam	Year Installed	Facility Details
Conowingo	1970	West fish lift is originally constructed to enable fish passage but had limited success. This lift is currently used for shad egg production and research.
Conowingo	1991; 1997 operational	East fish lift was constructed to provide improved passage opportunities. Since 1997, more than 1.1 million shad have passed upstream.
Holtwood and Safe Harbor	1997	Fish elevators were installed at each dam to provide upstream passage for shad that have passed upstream from Conowingo.
York Haven	2000	A fish ladder was installed at Three Mile Island east channel dam, completing the opening of 435 miles of mainstem Susquehanna River to shad and other migratory fish.

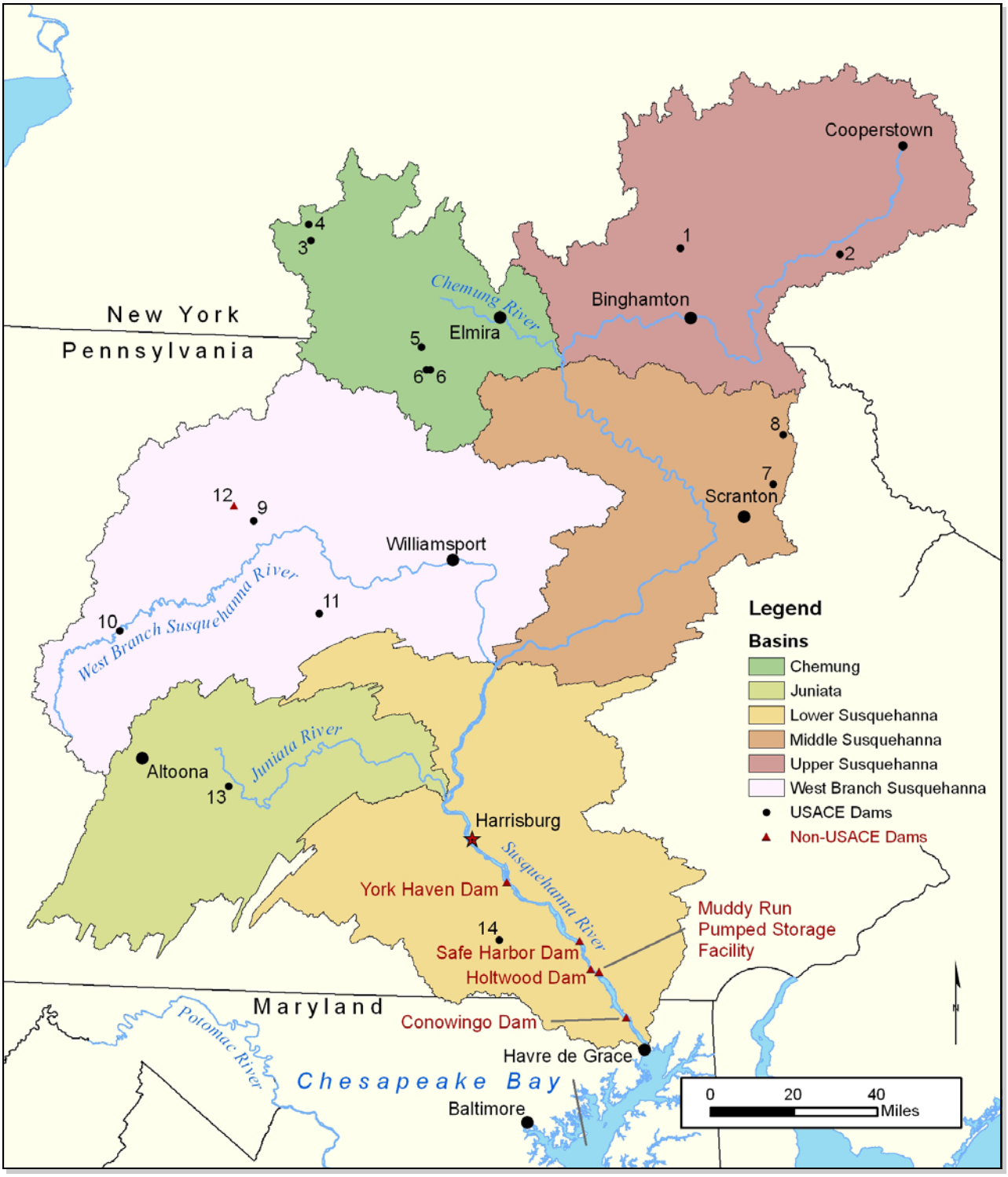


Figure 2.1. Major impoundments on the Susquehanna River include USACE dams (numbers correspond with Table 2.2 and major hydroelectric facilities on the Lower Susquehanna River).

Table 2.2. Major Flood Risk Management Reservoirs in the Susquehanna River Basin

Subbasin	Reservoir Name (Map Location, Figure 2.1)	Year Completed	Tributary	Upstream area (sq mi)	Project Purposes	Total Storage Capacity * (AF)	Flood Storage Capacity * (AF)
Upper Susquehanna	Whitney Point Lake (1)	1942	Otselic River	257	Flood risk management, low flow augmentation, recreation	84,233	72,545
	East Sidney Lake (2)	1950	Ouleout Creek	102	Flood risk management, recreation	32,705	29,864
Chemung	Almond Lake (3)	1949	Canacadea Creek	56	Flood risk management, recreation	13,397	12,557
	Arkport Dam (4)	1940	Canisteo River	31	Flood risk management	7,000	7,000
	Cowanesque Lake (5)	1980*	Cowanesque River	298	Flood risk management, water quality, recreation, water supply	84,747	54,871
	Tioga-Hammond Lakes (6)	1980	Tioga River and Crooked Creek	280 122	Flood risk management, recreation, water quality	125,818	107,248
Middle Susquehanna	Aylesworth Lake (7)	1970	Aylesworth Creek	6.2	Flood risk management, recreation	1,842	1,780
	Stillwater Lake (8)	1960	Lackawanna River	37	Flood risk management, recreation	11,558	11,311
West Branch Susquehanna	Alvin R. Bush Dam (9)	1962	Kettle Creek	226	Flood risk management, recreation	74,941	73,077
	Curwensville Lake (10)	1965	West Branch	365	Flood risk management, water supply, recreation	119,467	111,984
	Foster J. Sayers Dam (11)	1969	Bald Eagle Creek	339	Flood risk management, recreation	100,505	71,290
	George B. Stevenson (12)	1955	First Fork Sinnemahoning	243	Flood risk management, recreation	75,800	73,500
Juniata	Raystown Lake (13)	1973	Raystown Branch Juniata	960	Flood risk management, recreation, hydroelectric power (non-federal)	762,000	248,000
Lower Susquehanna	Indian Rock Dam (14)	1942	Codorus Creek	94	Flood risk management	27,657	27,657

* Total storage capacity is the storage volume in acre-feet (AF) between the lakebed and the spillway, partly occupied by water in conservation storage and partly vacant to accept excess flood runoff during high water events. Flood storage capacity is the normally vacant storage volume between the top of conservation pool and the spillway. All storage capacities are based on computations using the latest available surveys.

Water withdrawn from a surface water or groundwater source and not returned to the waters of the basin undiminished in quantity is referred to as consumptive use. Major consumptive uses in the basin are water supply (55 percent of total consumptive use) and power generation (25 percent). Maximum approved daily consumptive use associated with water supply is 325 million gallons per day (mgd). Public water systems throughout the basin have more than 340 surface water intakes and 7,500 groundwater wells. More than 1.2 million people depend on self-supplied water sources (almost all groundwater wells). Demand varies with population density, and peaks in June through August.

Twenty major electric power generation plants (fossil-fueled, nuclear, and hydropower) rely on water from the basin. The 11 largest facilities withdraw more than 4.2 billion gallons of water per day, with about 4 percent (168 million gallons) consumed and 96 percent returned to the stream (PADEP 2009). Power generation demands peak during summer months when streamflow is typically lowest.

Industrial water use includes water for manufacturing and mining. Recently, water demand for hydraulic fracturing associated with natural gas drilling in the Marcellus shale formation has grown significantly. The Marcellus shale formation underlies about 75 percent of the basin, mostly in the Appalachian Plateau and portions of the Ridge and Valley Province. Associated consumptive water use accounted for more than 11 percent of the basin's reported consumptive use in 2011. Each gas well requires, on average, an estimated 4 to 7 million gallons of water (SRBC 2010b). Gas drilling in the Marcellus shale has increased water demand in the West Branch, Chemung and Upper Susquehanna Subbasins, including sensitive headwaters and small streams near drilling sites (Figure 2.2).

The timing of the maximum consumptive water use by irrigation generally coincides with low flow conditions in the basin. In the agricultural sector, at least 785 agricultural operations each use more than 20,000 gallons per day in the growing season during periods of peak demand (SRBC 2007). Golf course irrigation is estimated to consume 50 mgd, with demand concentrated on headwaters and tributaries in the Ridge and Valley and Piedmont Provinces (TNC 2010).

2.4 Water Quality

Localized water quality impairments are mostly attributable to industrial, agricultural, and urban development. The most recent National Water Quality Inventory Report to Congress, 305(b) report, indicates that 81 percent of assessed waters in Pennsylvania met water quality standards and associated designated uses. For non-attaining streams, the leading cause of impairment was AMD, which lowers pH and delivers elevated metals and sulfate concentrations to streams and rivers. AMD continues to be one of the basin's most prevalent water quality issues, with most of the impairment occurring in the Tioga River and West Branch Subbasin on the Appalachian Plateau. Decreased flow magnitude may reduce assimilative capacity and decrease the effectiveness of AMD remediation. In the Ridge and Valley and Piedmont Provinces, water quality impairments are associated with elevated sediment and nutrient concentrations caused by agricultural and urban development.

Watershed Implementation Plans (WIP) have been developed in response to the Chesapeake Bay Total Maximum Daily Load (TMDL). These plans identify sources of nutrient and sediment pollution and the loading reductions needed to meet the Bay TMDL but do not explicitly cover streamflow. WIPs also recommend practices and programs needed to meet the Bay TMDL reduction goals, which can also contribute to restoring locally impaired water bodies to their intended uses.

Figure 2.2. This montage represents a typical Marcellus shale drilling operation in Bradford County, Pennsylvania: (A) The drilling rig; (B&C) water intake and pumphouse for water needed for hydraulic fracturing; (D) tanker trucks transporting water to the drilling site; (E) constructed basin used to retain water before or after a fracturing operation. Photos: USACE.

2.5 Climate

The Susquehanna River basin's climate is mild, sub-temperate, and humid. Continental weather conditions include cold winters with snow and warm to hot summers. Within the basin, precipitation (annual average from 33 to 49 inches) and air temperature (annual average from 44° to 53°F) are largely influenced by latitude and elevation. Both precipitation and temperature increase from north to south and from west to east. About half of the region's precipitation occurs during storms from May through September. An estimated 52 percent of precipitation is lost to evapotranspiration, with the remaining 48 percent infiltrating to groundwater storage or resulting in overland flow and streamflow runoff.

Long-term climate analysis indicates that overall, temperatures in the region are increasing and will continue to do so. Future impacts of various climate events are uncertain, especially on a regional scale, but temperatures in the region are widely expected to warm throughout the 21st Century. Annual precipitation is also likely to increase, as will winter precipitation, with less precipitation in the form of snow. With warming temperatures, more precipitation may be rain on snow, which will cause snow to melt faster potentially changing stormwater regimes in the basin. By the late 21st Century, the region should see a 3 to 5 week longer growing season, with increased evapotranspiration. Overall, weather in

the basin may become more extreme, with longer dry periods and more intense storms. Research also suggests there will be fewer, more intense tropical storms (Shortle et al. 2009).

In the future, general streamflow is likely to increase during the summer months. Overall runoff may increase by 5 to 10 percent, be flashier due to increased urbanization, and would negatively impact stream water quality. Stream temperature is likely to increase, with potential negative effects for native aquatic organisms.

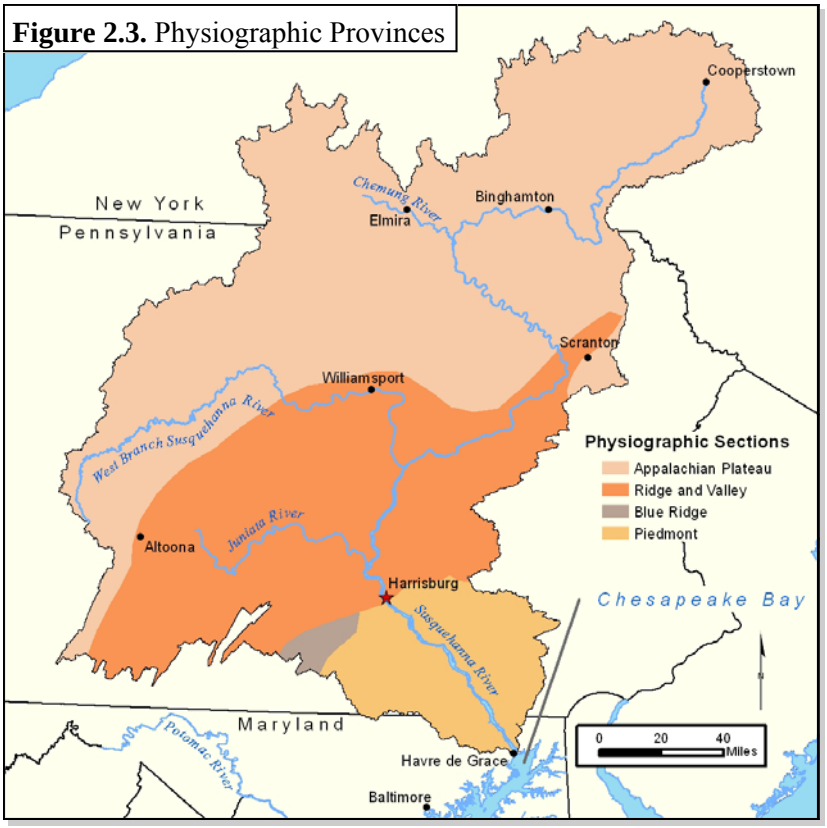
2.6 Physiography

The Susquehanna River basin spans three major physiographic provinces that provide the geomorphic context for rivers and streams: the Appalachian Plateau, the Ridge and Valley Province, and the Piedmont Province. This geomorphic context influences the hydrology of streams and therefore the ecosystem flows needed by aquatic communities.

The Appalachian Plateau underlies most of the basin, including the Upper Susquehanna, Chemung, and northern portion of the West Branch Subbasins. The Appalachian Plateau is characterized by steep slopes and deeply dissected valleys. Portions of the province were modified by Pleistocene glaciations, resulting in surficial glacial deposits 8 to 15 m thicks that influence surface water hydrology by creating heterogeneous gaining and losing reaches (Cushing et al. 2006)

The Ridge and Valley Province consists of a band of parallel ridges created by folded sandstone, shale, and limestone. Because of their subsurface water storage capacity, limestone formations have a significant influence on the hydrology of streams, yielding higher seasonal flows and a more stable hydrograph than streams in non-karstic (non-soluble bedrock) terrain. Subbasins within the Ridge and Valley Province include the southern portion of the West Branch, the Juniata, and mainstem and tributaries from the confluence with the Lackawanna River to the Conodoguinet confluence.

Figure 2.3. Physiographic Provinces



The Piedmont Province lies between the Appalachian Mountains and the coastal plain, and the basin's warm headwater

streams are concentrated in this low elevation province. Portions of the Lower Susquehanna Subbasin are within the Piedmont Province. The province is dominated by dendritic drainage patterns and channel forming processes are dominated by fluvial erosion (Fenneman 1938; Sevon 2000).

2.7 Vegetation and Land Use

Throughout the Susquehanna River basin, forest cover plays a major role in governing the distribution and timing of streamflows. The region is dominated by deciduous trees. Peak evapotranspiration occurs in the late summer and early fall, and it is minimal during winter. This pattern of evapotranspiration is reflected in seasonal flow trends.

An estimated 95 percent of the region was forested before European settlement; however by the early 1900s, only 30 percent of the forest cover remained after several centuries of deforestation and land use conversion. Since the early 1900s, forest cover has more than doubled, to about 70 percent of the basin, due to abandonment of agricultural land and the evolution of silvicultural practices. During periods of low forest cover, streams and rivers had higher seasonal flows during summer and fall. Seasonal flows were higher because fewer trees resulted in a decrease in evapotranspiration during the growing season.

Figure 2.4. Forest Cover (2000)

2.8 Existing Conditions Conclusion

The existing conditions in the Susquehanna River basin, and conditions in the foreseeable future demonstrate that the Susquehanna River system is highly variable and diverse in respect to stream flows, land use, and water needs. There are foreseeable challenges and likely threats to the system that are not foreseeable, yet there are opportunities among many water management partners to plan for future challenges and manage water resources accordingly. Elucidating ecosystem flows is one strategy in meeting these current needs and future challenges.

Chapter 3: Ecosystem Flow Needs

A diverse array of biota depend upon the Susquehanna River ecosystem. The aquatic biological community depends on, and is to a large degree determined by, the abiotic stream habitat in which the community is found. Flow regime is a characteristic component of any given stream habitat. The study identified (1) proxy species — species that are representative of the flow needs for other species, (2) vegetation community types that represent major successional stages, and (3) major geomorphologic states within the basin that are necessary for community health. Species groups and their flow needs were defined through literature review, expert consultation, and expert workshops led by TNC.

3.1 Species Groups

The following sections summarize key flow needs for fish, crayfish, aquatic insects, mussels, reptiles and amphibians, and birds and mammals. Key flow needs are based on the flow needs for selected species, which are outlined in the technical report (TNC 2010).

3.1.1 Fish

Surveys and collection records dating to the 1800s indicate that nearly 120 fish species in 26 families occur within the basin. Two species are thought to be extirpated from the basin. In this study, fish species were placed into five groups based on similar life histories, habitat niches, or other characteristics that make them sensitive to hydrologic alteration (Table 3.1). The flow needs of fish species within each group are similar.

Key Flow Needs For Fish

- **Extreme low flows** reduce the availability of high velocity habitats and may decrease the abundance of riffle-dwelling fishes and species with small home ranges.
- **Seasonal flows** maintain connectivity among stream habitats, especially during spring and fall spawning periods, and provide access to thermal refuge during summer.
- **A decrease in summer and early fall flows** may reduce access to shallow, slow velocity nursery habitats in margins and backwaters.
- **High seasonal flows** are needed to maintain habitat, keeping fish spawning areas sediment-free, but flows cannot be so high that they scour and flush eggs from spawning areas.
- **High seasonal flows** provide velocities sufficient for shad migration and spawning in the spring and facilitate juvenile out-migration in the fall; flows that are too high can inhibit migration.
- **Winter baseflows** provide thermal refuge for a variety of species.
- **Fall high flow pulses** cue adult out-migration of American eels, and summer baseflows provide lower velocities that facilitate juvenile eel (elver) migration upstream.

Table 3.1. Key traits and representative species within each group of fishes

Group	Key Traits	Representative Species
Cold Headwater	Similar needs defined by temperature thresholds	Brook trout, brown trout, sculpins
Riffle Obligates	Small bodied, flow-velocity specialists who spend most of their life in riffle/run habitat	Margined madtom, longnose dace, central stoneroller, fantail darter
Riffle Associates	Resident species with moderate-sized home range that migrate to spawn and need access to, and connectivity between, riffle habitats	White sucker, shorthead redhorse, northern hog sucker, walleye
Nest Builders	Similar timed flow needs (during nest building, spawning, and egg and larval development), but diverse in terms of nesting strategy (includes true nests, mound construction, and ledge spawners)	Fallfish, creek chub, river chub, redbreast sunfish, smallmouth bass
Diadromous	Large-bodied, large home range species need connectivity during in– and out–migration, and during spawning (alosids)	Alewife (Figure 3.5), American shad, American eel

3.1.2 Crayfish

A keystone species within the Susquehanna River basin, crayfish exert significant influence on periphyton and macrophyte composition and help regulate fine particulate organic matter. Crayfish are also an important food source for fish, reptiles, amphibians, birds, and mammals, including the queen snake, hellbender, and northern river otter. Flow regime is crucial to crayfish, which generally are reproductively active in the fall through spring, with young of the year emerging in the summer. Drought conditions can increase crayfish susceptibility to predation. In addition, riffle-dependent species are especially dependent on flows under cobbles and boulders and in the hyporheic zone during summer dormancy periods.

Figure 3.1. Crayfish like these are dependent on the flow regime to which they are adapted. Photos: Eric Engbretson, USFWS

3.1.3 Aquatic Insects

Aquatic insects are key indicators of ecosystem health. The chemistry and temperature of streams control macroinvertebrate functions such as ion regulation, growth, and reproduction. Flows also help to control food availability. Healthy streams have diverse, well-balanced, and functioning insect communities. Quantitative and qualitative responses of species that share functional traits and/or assemblage metrics in other river systems were sued to set expectations about flow needs for aquatic insects. Functional traits used to help set ecosystem flow needs included: life history, mobility, morphology, and ecology. The expected or reported response of assemblage metrics to changes in flow were also used to set ecosystem flow needs. Assemblage metrics used to define ecosystem flow needs included: abundance, species richness, Hilsenhoff Biotic Index (HBI), and EPT richness (Ephemeroptera, Plecoptera, and Trichoptera).

Key Flow Needs For Aquatic Insects

- **Groundwater flow** through hyporheic zones provide refuge for aquatic insects.
- **Winter baseflows** need to be maintained for winter emerging species.
- **Flow depletion** can reduce macroinvertebrate density and richness; the abundance of sessile, rheophilic, large-bodied, filter feeding, and grazing taxa, and shift communities to pollution tolerant taxa.
- **Rapid wetting and drying** reduces benthic biomass.
- **Summer baseflows** provide thermal refuge for cold-water dependent taxa.

3.1.4 Mussels

At least a dozen native mussel species occur in the Susquehanna River basin. Native mussels have a variety of traits related to habitat and velocity preference, body size, longevity, length of brooding, timing of spawning, glochidia (larval) release, and use of host fish. In general, mussel species have been undersampled in the Susquehanna River watershed compared to other basins, and as a result, little is known about them. Extreme low flow events increase the risk of exposure and predation of mussel beds. Significantly reduced flows may cause local extirpation or reduced growth. Changes to the timing and amount of high flows can lead to habitat degradation and may reduce opportunities for mussel species to interact with migrating fish, which disperse mussel larva and eggs throughout the watershed. Mussels were grouped into three categories to define their flow needs: primarily riverine species, facultative riverine species, and primarily lentic species (Table 3.2).

Key Flow Needs For Mussels

- **Extreme low flows** increase the risk of exposure and predation of mussel beds.
- **Significantly reduced flow magnitudes** may cause local extirpation or reduced growth.
- **Drought** can reduce individual fitness of mussels, even though some mussel species may be drought tolerant.
- **Increased magnitude and frequency of high flow events** can lead to habitat instability, reduced recruitment, and reduced carrying capacity of mussel habitat.
- **Decreased magnitude or frequency of high flows** can lead to habitat degradation, including embeddedness, lack of appropriate substrate size, and aggrading channel morphology.
- **Flows** are needed to facilitate host fish interaction and glochidia distribution during the spawning season.
- **Increased high flows** in spring or **decreased low flows** in summer may reduce host fish availability.
- **Natural flow regimes** can reduce the risk of infestation and establishment of non-native mussel species.

Table 3.2. Key traits and representative species within each group of mussels

Group	Key Traits	Representative Species
Primarily Riverine	Most associated with river habitats. Representative species are long-term brooders sensitive to changes in hydraulic habitat associated with reductions in streamflow magnitude.	Green floater, elktoe, brook floater, creeper
Facultative Riverine	Found in wide range of habitats from small streams to large rivers and lakes. Generally use slow to moderate current. Host fish include lotic and lentic species.	Yellow lampmussel, triangle floater, eastern lampmussel, eastern elliptio
Primarily Lentic	Use slow-moving river habitats and a range of hostfishes. Generally most tolerant of silt, mud, and nutrient rish water. Most tolerant of disturbed conditions and impoundments.	White heelsplitter, eastern floater, cylindrical papershell

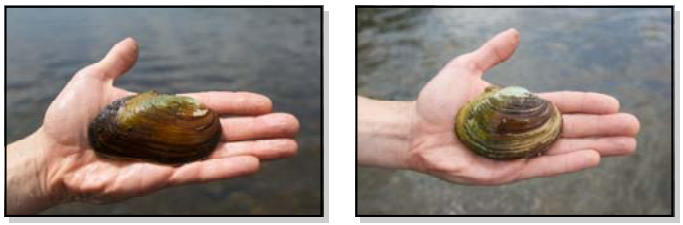


Figure 3.2. Two species of facultative riverine mussel species found in the Susquehanna River basin: Eastern elliptio (*Elliptio complanata*) is on the left and a lampmussel (*Lampsilis* sp.) is on the right. Photos: Phillip Westcott, USFWS

3.1.5 Reptiles and Amphibians

At least 35 species of reptiles and amphibians, including 12 species of salamanders, 2 toads, 9 frogs, 8 turtles, and 4 snakes use riverine and riparian habitats in the basin during various life stages. Fourteen species were selected to represent reptile and amphibian life history traits, and these species were organized into three groups: aquatic-lotic species, semi-aquatic lotic species, and riparian and floodplain-terrestrial and vernal habitat species (Table 3.3). Aquatic-lotic species are expected to be the most sensitive to changes in flow regime because they depend on flowing waters for all of their life stages.

Key Flow Needs For Reptiles and Amphibians

- **Winter and spring high flows** fill vernal pools and intermittent streambeds used for amphibian breeding and egg and larval development.
- **Increased frequency and duration of low flow events**, which can increase temperature and sediment concentrations and decrease dissolved oxygen levels, create conditions that several species are particularly sensitive to.
- **Decreases in winter flows or increased flashiness** could expose or destabilize stream beds, banks, and channel margins that several turtle and amphibian species use for overwintering habitat.
- **Small and large flood events** maintain floodplain habitats (especially regarding sediment texture and vegetation communities) for turtle nesting and amphibian and reptile burrowing sites.

Table 3.3. Key traits and representative species within each group of reptiles and amphibians

Group	Key Traits	Representative Species
Aquatic Lotic	Depend on flowing waters. Reptile and amphibian group expected to be most sensitive to changes in instream conditions, including water quality, flow velocity and depth, instream habitat availability, and abundance of specific food items.	Northern map turtle, common musk turtle, northern water snake, eastern hellbender, northern dusky salamander
Semi-aquatic Lotic	Rely on flowing waters or habitats within the active channel for one or more life stages, but spend part of their life cycle in floodplain or upland habitats. May only be sensitive to instream conditions uring particular life stages.	Wood turtle, bog turtle, eastern ribbon snake, northern leopard frog
Riparian and Floodplain Terrestrial and Vernal Habitat	Species do not use the stream channel for any life stage, but they do rely on overbank hydrologic processes to maintain floodplain habitats.	Eastern hognose snake, eastern gray treefrog, fowler's toad, eastern spadefoot, mole salamanders

3.1.6 Birds and Mammals

Birds and mammals rely on floodplains and riparian forests for food and habitat (Table 3.4). Many of the bird species found throughout the Susquehanna River basin use these areas for nesting and breeding. As such, these species may respond directly or indirectly to the availability of food sources or vegetation caused by streamflow changes. For example, several species depend on seasonal high flows to reduce predator access to dens or nest sites, and flow changes could allow predator access. Many bird and mammal species also rely on seasonal riparian and floodplain inundation to maintain their habitats, and flow changes could affect their normal reproduction, development, and survival (for example, osprey, Figure 3.3).

Key Flow Needs For Birds and Mammals

- **Seasonal flooding** maintains floodplain and riparian habitats that many bird and mammal species require.
- **Seasonal high flows**, during winter and early spring, reduce exposure of mammal dens (for example, muskrat).
- **Seasonal high flows** limit connectivity or land bridges between mainland and island habitats to avoid predatory access to bird rookeries.

Table 3.4. Key traits and representative species for birds and mammals

Group	Key Traits	Representative Species
Birds	Riparian and floodplain habitats used for nesting in breeding. In general, birds are sensitive to streamflow alterations that lead to a reduction of available food resources and/or reduction in the quality of foraging or breeding habitats.	Great egret, great blue heron, black-crowned nigh heron, bald eagle, osprey, belted kingfisher, bank swallow, Acadian flycatcher
Mammals	Rely upon access to stream-derived food resources and availability of bank, floodplain, and island habitats. May responds to shifts in food availability or vegetation composition and structure caused by streamflow alteration.	Northern water shrew, muskrat, northern river otter, bats

Figure 3.3. The osprey (*Pandion haliaetus*) is a fish-eating bird that requires access to an abundance of fish during nesting and rearing. Photo: Steve Hillebrand, USFWS

3.1.7 Vegetation

The distribution and structure of aquatic, riparian, and floodplain vegetation are driven by river flows and associated geomorphology, soil and water chemistry. Other factors affected by streamflows include seed dispersal and soil moisture. Juvenile fish and macroinvertebrates depend on submerged aquatic vegetation as nursery sites and for refuge. High flow pulses help to maintain wetland vegetation in headwaters and small streams, while decreased flow can desiccate plants. Ice scour associated with high winter flows can promote early succession of vegetation, and spring high flows can control encroachment of woody vegetation. Vegetation was grouped into four successional states for evaluation of ecosystem flow needs: submerged and emergent bed, herbaceous, scrub-shrub, and floodplain forest (Figure 3.4).

	Submerged and Emergent Bed	Herbaceous Community	Scrub-Shrub Community	Floodplain Forest
Elevation Gradient Lateral Position and Distance from Active Channel				
Disturbance Gradient Severity of Flood and Ice Scour	**Severe**	**Severe to Moderate**	**Moderate**	**Moderate to Low**
Inundation Gradient Inundation Duration	**Semi-permanent**	**Seasonal to Temporary Flooding**	**Seasonal to Temporary Flooding**	**Temporary Flooding**
Example Communities	River weed (*Podosternum ceratophyllum*)	Indian grass (willow) riverine shrubland (*Sorghastrum nutans*)	Speckled alder – dogwood riverine shrubland (*Alnus rugosa, Cornus florida*)	Sycamore floodplain forest (*Plantanus occidentalis*)
	Water willow emergent bed (*Justicia americana*)	Sedge-spotted joe-pye weed riverine herbaceous vegetation	Mixed hardwood riverine shrubland (*Plantanus* spp., *Acer* spp., *Betula* spp.)	Sycamore mixed hardwood floodplain forest (*Betula nigra*)
	Lizard's tail emergent bed (*Saururus cemuus*)	Riverside scour vegetation	Black willow slackwater shrubland (*Salix nigra*)	Silver maple floodplain forest (*Acer saccharinum*)

Figure 3.4. Examples of aquatic, riparian, and floodplain communities of the Susquehanna River basin along elevation, disturbance, and inundation gradients.

Key Flow Needs For Vegetation

- **Small and large floods** maintain habitat structure and diversity.
- **Increases or decreases in inundation duration** may encourage community transition along the inundation gradient.
- **Decreased flow magnitude** can desiccate submerged, emergent, and riparian vegetation.
- **High flow pulses** maintain wetland vegetation in headwaters and small streams.
- **Winter high flow events** and associated ice scour promote early successional vegetation.
- **Spring high flows** reduce encroachment of woody vegetation and maintain riparian zone characteristics.

3.2 Geomorphology

The geomorphology of streams is directly related to the frequency and magnitude of high flow events. Seasonal high flow pulses, bankfull flows, and small and large floods maintain geomorphic disturbance patterns by transporting large woody debris, moving rocks along the stream bed, forming islands, ice scouring, inundating floodplains, and maintaining in-channel and floodplain habitat structure and diversity. Channel and floodplain maintenance provides habitat availability for reptiles, amphibians, birds, mammals, and vegetation communities.

Key Flow Needs For Geomorphology

- **High flow events** during winter months catalyze ice scour processes, which maintain sites for early successional vegetation.
- **Spring high flow pulses** are needed to transport stream bottom material.
- **Bankfull flows** maintain active channel shape, form, and carrying capacity.
- **Small floods**, defined with a 5-year recurrence interval, provide connectivity between the active channel and low terrace riparian areas, and they maintain island geomorphology and riparian habitat structure and diversity.
- **Large floods**, defined with a 20- to 25-year recurrence interval, provide connectivity between the channel and floodplain, and they drive disturbance-dependent processes.
- **High flow pulses** during summer flush fine sediments and transport and break down coarse particulate organic matter.

3.3 Ecosystem Flow Needs Summary

The flow needs previously described for species groups were formulated as hypotheses that assume an anticipated response of a species, group of species, or habitat to a change in flow during a particular season. These hypotheses were then consolidated into flow need statements which are summarized here by season. Tables 3.5 through 3.8 summarize ecosystem flow needs in fall, winter, spring, and summer respectively.

Table 3.5. Fall (September to November) ecosystem flow needs.
The primary needs for each season are listed in bold; needs that continue from previous seasons are presented in gray font.

	Flow Component			
Flow Need	High Flows	Seasonal Flows	Low Flows	**Habitat Type**
Maintain channel morphology, island formation, and floodplain habitat	●			All habitat types
Transport organic matter and fine sediment	●	●	●	All habitat types
Promote vegetation growth	●	●		All habitat types
Cue diadromous fish out-migration	●	●		**Mainstem and major tributaries**
Support winter emergence of aquatic insects and maintain overwintering habitat for macroinvertebrates		●		All habitat types
Maintain connectivity between habitats and refuges for resident and migratory fishes		●		All habitat types
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals		●		All habitat types
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	**Cool and coldwater streams; high baseflow streams**
Maintain stable hibernation habitat for reptiles, amphibians, and nesting habitat for small mammals		●	●	**All habitat types**
Promote/support development and growth of fishes, reptiles, and amphibians		●	●	All habitat types
Support mussel spawning, glochidia release, and growth		●	●	All habitat types
Promote macroinvertebrate growth and insect emergence		●	●	All habitat types
Maintain water quality	●	●	●	All habitat types
Maintain hyporheic habitat			●	All habitat types

Table 3.6. Winter (December to February) ecosystem flow needs.
The primary needs for each season are listed in bold; needs that continue from previous seasons are presented in gray font.

Flow Need	Flow Component: High Flows	Flow Component: Seasonal Flows	Flow Component: Low Flows	Habitat Type
Maintain ice scour events and floodplain connectivity	●			**Mainstem and major tributaries**
Cue diadromous fish out-migration	●	●		Mainstem and major tributaries
Support winter emergence of aquatic insects and maintain overwintering habitat for macroinvertebrates		●		**All habitat types**
Maintain overwintering habitat for resident fish		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Maintain stable hibernation habitat for reptiles, amphibians, and nesting habitat for small mammals		●	●	All habitat types

Figure 3.5. Alewife (*Alosa pseudoharengus*) migrate from salt water to freshwater in early spring to spawn. Egg and larval survival is closely associated with stream velocity during spring and summer. Illustration: Duane Raver, USFWS

Table 3.7. Spring (March to May) ecosystem flow needs.
The primary needs for each season are listed in bold; needs that continue from previous seasons are presented in gray font.

Flow Need	Flow Component: High Flows	Flow Component: Seasonal Flows	Flow Component: Low Flows	Habitat Type
Maintain channel morphology, island formation, and floodplain habitat	●			**All habitat types**
Promote vegetation growth	●	●	●	All habitat types
Cue alosid spawning migration and promote egg and larval development		●		**Mainstem and major tributaries**
Support spring emergence of aquatic insects and maintain habitats for mating and egg laying		●		**All habitat types**
Support resident fish spawning		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Maintain stable hibernation habitat for reptiles, amphibians, and nesting habitat for small mammals		●	●	All habitat types
Cue and direct upstream migration of juvenile American eel		●		Mainstem and major tributaries
Promote/support development and growth of fishes, reptiles, and amphibians		●	●	All habitat types

Table 3.8. Summer (June to August) ecosystem flow needs.
The primary needs for each season are listed in bold; needs that continue from previous seasons are presented in gray text.

Flow Need	Flow Component: High Flows	Flow Component: Seasonal Flows	Flow Component: Low Flows	Habitat Type
Transport organic matter and fine sediment	●			**All habitat types**
Maintain channel morphology, island formation, and floodplain habitat	●			All habitat types
Promote vegetation growth	●	●	●	**All habitat types**
Cue and direct upstream migration of juvenile American eel		●		**Mainstem and major tributaries**
Maintain connectivity between habitats and refuges for resident and diadromous fishes		●		**All habitat types**
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals		●		**All habitat types**
Cue alosid spawning migration and promote egg and larval development		●		Mainstem and major tributaries
Support spring emergence of aquatic insects and maintain habitats for mating and egg laying		●		All habitat types
Promote/support development and growth of fishes, reptiles, and amphibians		●	●	**All habitat types**
Support mussel spawning, glochidia release, and growth		●	●	**All habitat types**
Promote macroinvertebrate growth and insect emergence		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Support resident fish spawning		●	●	All habitat types
Maintain water quality	●		●	**All habitat types**
Maintain hyporheic habitat			●	**All habitat types**

Chapter 4: Stream Flow Findings

Flow regimes for streams in the Susquehanna River basin were developed through an iterative collaborative process of literature review, expert workshops and discussion, sensitivity testing, and feedback on draft recommendations from experts. The information and analyses here and in the technical report (TNC 2010) support maintaining the range of flow variability that sustains the full range of taxonomic groups and ecological processes in the basin.

Flow regimes were developed for three stream classes and are based on literature review and analysis of stream gages in the basin. Statistics were selected that allow changes to be tracked to the flow needs that were previously defined. A sensitivity analysis was conducted to ensure the ability of these statistics to detect meaningful changes in flow over time.

Flows are organized by flow component (low flow, seasonal flow, and high flow), and for each flow component, flow statistics are presented. Finally, each flow regime is related to when it is applicable (seasonally, annually, inter-annually). These results are expressed as values for a flow statistic or as acceptable deviation in flow magnitude from reference conditions for a particular site. Rather than citing a specific flow magnitude (for example, in cubic feet per second), this approach allows flow regimes to be applied across a broad array of streams in the basin. Annotations to "maintain" or "limit" change to a given statistic are in reference to the long-term variability of these statistics during the 1960 -2008 water years at index gages.

4.1 Flow Regime Development

Stream Size

Flow regimes are organized by stream size (drainage area) as follows:

- Headwater streams (less than 50 sq mi)
- Streams and small rivers (50 to 200 sq mi)
- Major tributaries and mainstem (greater than 200 sq mi)

Flows for the Susquehanna River basin incorporate naturally occurring variability and are expressed in terms of acceptable variation from baseline values for any particular stream, flow regimes may be applied to multiple types of streams. Therefore, stream habitat types, used to organize information about flow-sensitive organisms and stream physical processes, were not needed for headwater and small streams.

Headwater streams were treated separately from streams and small rivers because they are characterized by low median monthly flow, especially in summer and fall months, and high flow variability relative to larger streams. About one-third of the index gages used for this study are on headwater streams. Monthly Q50 for these index gages is less than 10 cfs in August and October, and monthly Q95 is often less than 0.1 cfs. Because streamflows can be so low in these headwater streams, small changes to flow can result in zero streamflow. Similarly, water withdrawal

scenarios show that high flows (Q10) often decreased by 10 to 50 percent in response to water withdrawals (particularly during summer and fall months). Therefore, headwater streams are treated as a class separate from streams and small rivers, and specific flow regimes were developed for them. Furthermore, different statistics (for example Q75 rather than Q95) are used because they are more protective for low flows in headwater streams.

Literature Review

Most of the flow regimes are based on quantitative relationships between flow and ecology and other information found in published literature. In general, topics of the literature reviewed by TNC can be classified into four categories:

- Studies that describe (but may not quantify) an ecological response to hydrologic conditions;
- Studies on extreme low flow conditions, either observed (for example, during extreme droughts) or simulated (using experimental diversion);
- Studies that use a model to predict how species or communities respond to simulated withdrawals; and
- Studies that document the effects of loss of high flow events.

Stream Gage Analysis

The research team analyzed long-term interannual variability in the streamflow statistics (water years 1960-2008) using index gage flow data. The period selected contains the drought and flood of record and is the best practical approximation of long-term flow variability in the basin. The index gages are the same as those being used in a concurrent project to simulate baseline (minimally-altered) flows for ungaged streams in Pennsylvania.

Index gages were selected based on the following criteria: (1) the stream at a gage is not significantly affected by upstream regulation, diversions, or mining; (2) less than 15 percent urban area in the watershed; and (3) a minimum 15 years of record, except where shorter periods of record improved spatial coverage and included major drought events. Forty-five gages met these criteria.

Flow Statistics

Appropriate flow statistics were chosen after flow components and flow needs were defined. Table 4.1 presents the statistics chosen to represent each flow component. The statistics are easy to calculate, commonly used, and integrate several aspects of the flow regime, including frequency, duration, and magnitude.

Table 4.1. Flow statistics used to track changes to low, seasonal, and high flow components.

Flow Component	Flow Statistic
Low Flows	
Monthly low flow range	Area under monthly flow duration curve between Q75 and Q99
Monthly low flow magnitude	Monthly Q75
	Monthly Q95
Seasonal Flows	
Monthly magnitude	Monthly median
Typical monthly range	Area under monthly flow duration curve between Q75 and Q10
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 summer and fall
High pulse magnitude	Monthly Q10

Sensitivity Analysis

A sensitivity analysis was conducted for the selected statistics to ensure that flow regimes are not constrained by the limitations of a statistic to detect change or by extreme sensitivity. Using the Indicators of Hydrologic Alteration (IHA) software program and a flow duration curve calculator, water withdrawal scenarios were evaluated for headwater, small streams, major tributaries, and the mainstem. Using eight water withdrawal scenarios representing various sectors of water use, values for each flow statistic could be calculated before and after a simulated water withdrawal. The change in each statistic was analyzed to see how these typical water withdrawals would affect each statistic. Review of the results indicated that the statistics selected appear to be at an appropriate level of sensitivity to determine the impact of water management scenarios on ecosystem flows.

Table 4.2. Flow regime for the Susquehanna River, based on flows recorded between 1960 and 2008 at 45 index gages .

Flow Component	Flow Statistic	Flow Regime		
		Headwater Streams (< 50 sq mi)	**Streams and Small Rivers (50 to 200 sq mi)**	**Major Tributaries and Mainstem (> 200 sq mi)**
Low Flows	Monthly Low Flow Range	No change to area under curve between Q75 and Q99	≤ 10% change to area under curve between Q75 and Q99	
	Monthly Q75[1]	No Change	*Not Applicable*[3]	
	Monthly Q95[2]	*Not Applicable*[3]	No Change	
Seasonal Flows	Monthly Median	Between 45th and 55th percentiles		
	Monthly Seasonal Range	≤ 20% change to area under curve between Q10 and Q75		
High Flows	Monthly Q10	< 10% change in magnitude of monthly Q10		
	Large Flood – Annual and Interannual Events	Maintain magnitude and frequency of 20-year flood		
	Small Flood – Annual and Interannual Events	Maintain magnitude and frequency of 5-year flood		
	Bankfull – Annual and Interannual Events	Maintain magnitude and frequency of 1- to 2-year high flow event		
	Frequency of Events > Monthly Q10 - Summer	Maintain 2 to 8 events		
	Frequency of Events > Monthly Q10 - Fall	*Not Applicable*[3]		Maintain 1 to 5 events

[1] Statistic is applied to headwater streams because of low water volumes during low flows.

[2] Statistic is applied to all streams with a drainage area greater than 50 mi^2.

[3] Statistic is not applicable for all streams.

4.2 Low Flow Findings

Low flows are a natural component of the hydrologic cycle. However, decreases in flow magnitude and increases in the frequency or duration of low flow events may affect many species. Low flows are based on studies or expert consultation that quantified or described ecological responses to changes in low flow magnitude, frequency, or duration. The focus is to maintain the naturally occurring variation in the distribution of flows in the low flow tail of flow duration curves. The flow regimes are presented below for headwater streams (< 50 square miles) and other streams (> 50 square miles).

Headwater Streams

Low Flow Finding 1 — No change to the long-term monthly Q75 based on the monthly flow exceedence curves.

This finding is based on the quantitative responses of mussels and macroinvertebrates to streamflow reduction in headwater streams (Rader and Belish 1999; Haag and Warren 2008; and Walters and Post 2010). Other studies have also documented the loss of habitat and decreased individual fitness in cold and coolwater species resulting from streamflow reduction during summer, fall, and winter (Hakala and Hartman 2004; Rashleigh and Grossman 2005; Letcher et al. 2007; Walters and Post 2008). Q75 is used as the low flow magnitude statistic for headwater streams because, unlike larger streams where Q95 is used, the absolute values of Q95 are very low (often less than 1 cfs).

Low Flow Finding 2 — No change to the monthly low flow range (the area under the flow duration curve between Q75 and Q99).

Logically, the finding for no change to the monthly Q75 results in the shape of the low flow tail (which begins at Q75) not changing. In small streams, the area under the low flow tail between the monthly flow duration curves is so small, and the absolute magnitudes of flow are so low, that small changes risk causing zero streamflow.

All Other Streams

Low Flow Finding 3 — No change to the long-term monthly Q95, based on the monthly flow exceedence curves.

The long-term monthly Q95 exceedence value recognizes that 5 percent of the streamflow observations in a month during the period of record will be less than Q95. If this statistic is calculated using a minimally-altered time series, flows below this level are assumed to be naturally occurring. A decrease to this statistic would indicate an increased magnitude or frequency of extreme low flow conditions while increases may reflect low flow augmentation. Stating no change to Q95 *does not imply a recommendation to maintain* minimum flows at Q95.

This finding is based on numerous studies demonstrating that extreme low flow conditions can be detrimental to organisms and habitats.

Low Flow Finding 4 — Less than 10 percent change to the monthly low flow range (the area under the flow duration curve between Q75 and Q99).

This finding is similar to Seasonal Flow Finding 2, below. More protection is recommended for low flows because more effects to organisms and habitats have been associated with increased frequency and duration of extreme low flow conditions than with changes to median monthly streamflow. Additionally, even small changes to monthly low flows may have big ecological impacts, and therefore, the margin of safety is reduced.

4.3 Seasonal Flow Findings

Seasonal flow variation supports nearly all fish, macroinvertebrates, reptiles and amphibians, birds, mammals, and floodplain, riparian, and aquatic vegetation. Ecological responses are often tied to changes in median monthly flows or flows around the central tendency. Seasonal flow findings are based on studies that have quantified ecological responses related to changes in median monthly flows, and are focused on maintaining the long-term variation in the distribution of flows around the median.

Seasonal Flow Finding 1 — Maintain the long-term monthly median flow within the 45th and 55th percentile for all monthly values.

Figure 4.2 shows the distribution of monthly median flows for water years 1960-2008 for one index gage. The 45th and 55th percentiles create a bracket around the 50th percentile in which the monthly median flow may vary. The width of the bracket varies depending on the distribution of annual monthly values. For example, the bracket is wider in April and May, when flows are higher and more variable, than in August and September, when flows are lower and less variable. By maintaining the long-term distribution of median flows in each month, seasonal differences in water availability are included.

This finding incorporates published responses for several taxonomic groups, and it limits alteration to less than threshold levels that have been published in several other studies.

Seasonal Flow Finding 2 — Less than 20 percent change to the seasonal flow monthly range (the area under the flow duration curve between Q75 and Q10).

The median flow (Q50) is a measure of central tendency, but it reveals little about the distribution of flows around it. Therefore, the amount of change to the middle portion of each monthly flow duration curve should be limited. Less than 20 percent change to the seasonal flow monthly range is based on the sensitivity analyses conducted for this statistic and best professional judgment. Quantitative relationships were not explicitly used and further research and analysis is needed.

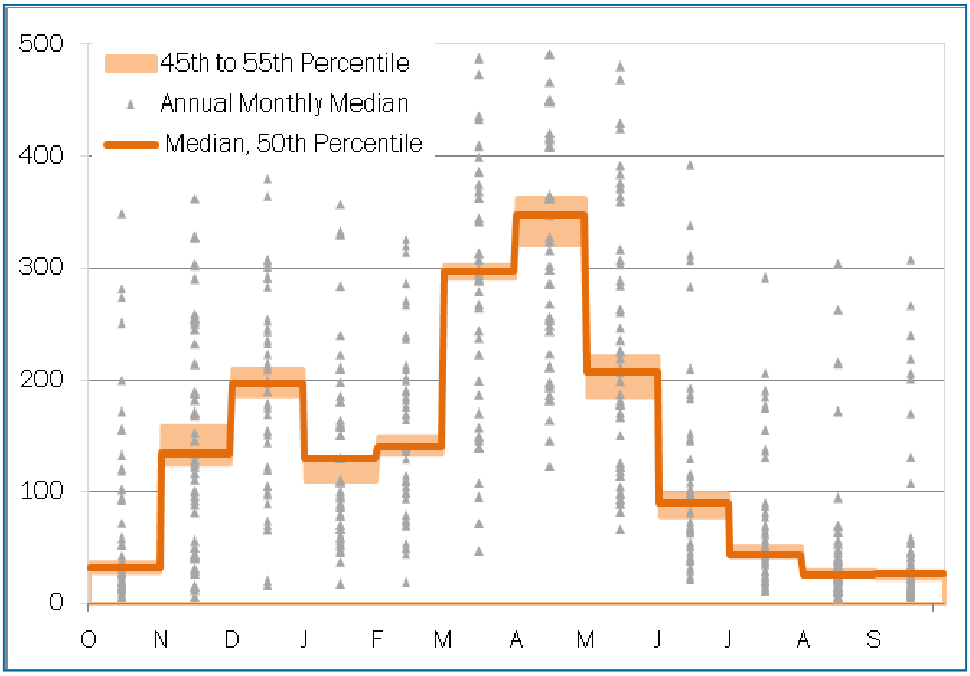


Figure 4.2. Illustration of the flow recommendation for monthly median flow. One index gage is used to illustrate the distribution of median monthly flows for WY 1960-2008, the long-term 50th percentile of all years, and the bracket created by the 45th and 55th percentile. Each triangular point represents the median of daily flows for one month of one year.

4.4 High Flow Findings

Small and large floods, and high flow pulses are included to emphasize their ecological importance, while recognizing that these flows are highly variable and affected by climate cycles, and only large flood risk management projects or diversions would likely alter the magnitude and frequency of the events. These high flow regimes are not anticipated to increase flood risk for Susquehanna River communities because they would not change the natural distribution and magnitude of flood events. The magnitude and frequency of bankfull events is affected by the same factors as overbank events, including landcover change, runoff, and channel modification. Detailed studies of flood risk were not performed as part of this study.

Annual and Interannual Events

High Flow Finding 1 — Maintain the magnitude and recurrence interval of the 20-year flood, 5-year flood, and 1-2 year high flow event.

This finding is based on expert opinion, regional studies of bankfull flows, and analysis of streamflow at index gages. Water management in the basin has a relatively small effect on bankfull to large flood events in most streams; therefore, flow regimes are not expressed in terms of allowable alteration to these flows.

Increases in the magnitude 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 could favor certain vegetation communities.

High Flow Pulses

High flow pulses are important for promoting ice scour during winter, maintaining riparian and floodplain vegetation, maintaining water quality, transporting organic matter and fine sediment, and cueing diadromous fish out-migration.

High Flow Finding 2 — Less than 10 percent change to the monthly Q10.

The long-term distribution of monthly Q10 is based on 49 years of values at index gages because very little information is available to quantify the degree to which high flow pulses can decrease without resulting in ecological impacts. The monthly Q10 was calculated for all index gages for every month between water year 1960 and 2008. The distribution of Q10 values was divided into quartiles, and the middle two quartiles (25th to the 75th percentiles of the distribution) were expressed as percentages of the median value. Across all index gages and months, the 25th to 75th percentiles were generally within 10 percent of median monthly Q10. Limiting any change to the long-term monthly Q10 to less than 10 percent should maintain high flow pulses within a naturally occurring distribution.

High Flow Finding 3 — Maintain 2 to 8 high flow pulse events during summer for all streams.

In 3 out of 4 years, at least two high pulse events occur during summer months. In 1 out of 4 years, there are as many as 8 high-pulse summer events. These estimates are based on analysis of index gages to estimate the frequency of high flow pulses. Summer high flow pulses maintain water quality, moderate temperature, support growth of vegetation, and transport sediment and organic matter during the growing season.

High Flow Finding 4 — Maintain 1 to 5 high flow pulse events during the fall season for major tributaries and the mainstem.

This flow is based on calculated high pulse frequencies at multiple streams. Fall high flow pulses cue diadromous fish out-migration. This regime only applies to major tributaries and the mainstem because in the Susquehanna River basin diadromous fish are most commonly associated with streams having greater than 200 square miles of drainage area.

Chapter 5: Application of Ecosystem Flows

Maintaining flow regimes is a holistic approach to conserving the ecological processes necessary to support freshwater ecosystems. Low flows have long been a concern in the Susquehanna River basin, and this study identifies flows that are necessary to support ecosystem health during low flow periods. The flow regime necessary for ecological health at seasonal and high flows is also identified. Application of these findings may be carried out through several distinct mechanisms, including the continuation of work under the authority of Section 729, WRDA 1986, as amended, largely under the authority of separate agencies: operations at USACE reservoirs, and regulations for water use and withdrawal managed by SRBC.

5.1 USACE and Other Reservoir Operations

Applying ecological flow regimes by modifying dam operations is outlined in several publications (Richter and Thomas 2007; Richter 2010; Le Quesne et al. 2010). Modifying operations at existing reservoirs in the Susquehanna River basin may have the potential to restore the flow regimes of altered streams, maintain flow regimes where the hydrograph exhibits natural behavior, or react to changes in the hydrograph resulting from a variety of causes. However, modified reservoir operations may have in -lake impacts and other unintended consequences that would need to be considered.

Water stored in reservoirs located in the basin (Table 2.2) may provide an opportunity to improve low flow conditions by modifying reservoir operations. Assessment of reservoir operations for ecological flows during low flow periods would need to evaluate:

- The timing, duration, frequency, and magnitude of releases;
- Beneficial and adverse impacts, both in-lake and downstream, that may occur as a result of operational changes;
- Impact modification features required;
- The funding mechanisms for all project phases; and
- Alternatives to modification of reservoir operations.

Figure 5.1. Cowanesque Lake, in Tioga County, Pennsylvania, in the Chemung subbasin, is authorized for flood risk management, water quality, recreation, and water supply. The total storage capacity of the reservoir is 84,747 AF with an upstream area of 298 square miles. Photo: USACE.

Several reservoirs operate with conservation releases that are typically greater than the inflow to their lakes, and thus greater than the flow that would naturally occur in the receiving streams. For example, Raystown Lake provides minimum seasonal releases of 200 cfs from May 15 to November 15 and 480 cfs from November 15 to May 15 to protect downstream habitats. These seasonal flow targets are greater than natural low flows in some years and may shift the monthly low flow range outside the ranges recommended in this report. Analysis may show that reservoirs in which conservation releases are greater than the natural flow regime could provide ecological flow opportunities through current or modified conservation releases during critical low flow periods.

During autumn some reservoirs are drawn down to a winter pool level, and there may be potential to use this storage during droughts for maintenance of ecological flows.

SRBC may also acquire water supply storage at selected reservoirs for the purpose of mitigating for the effects of downstream consumptive use of water thereby protecting downstream aquatic ecosystems.

In addition to using USACE reservoirs for ecological flows, SRBC has identified abandoned mines and reservoirs owned by the Commonwealth of Pennsylvania as other potential opportunities for low flow augmentation. Potential sources of flow augmentation include large abandoned coal mines. Opportunities to provide low flow augmentation at larger Commonwealth of Pennsylvania owned impoundments are being assessed by SRBC. While these facilities lack the storage of USACE reservoirs and often only provide recreation, they may nevertheless be able to provide short-term flow augmentation.

Altering existing operations at USACE reservoirs would require, at a minimum, an assessment to determine if modifications are warranted, and the local environmental, economic, and recreational impacts of those modifications. The funding mechanism and projected schedule for all project phases (preliminary assessment, NEPA, implementation/construction) for potential projects to alter existing operations at USACE reservoirs should be identified at the earliest opportunity in order to ensure a path to implementation.

This report and the TNC technical report have described existing flow conditions and environmental flow regimes for maintaining ecosystem health. Continuation of the Section 729 Susquehanna River Basin Ecological Flow Management Study to a second phase could allow the examination of a number of options available to continue the protection of aquatic ecosystems through operations at existing reservoirs and potential contributions of treated water from abandoned mines. Under Section 729, as amended, costs will be shared 75 percent Federal, 25 percent non-Federal.

5.2 SRBC Regulations

SRBC regulates groundwater and surface water withdrawals, consumptive water uses, and diversions in the Susquehanna basin under SRBC Regulation Subsection 806.4. The main goals of the regulation are as follows:

- Avoidance of conflicts among water users;
- Protection of public health, safety, and welfare;
- Protection of fisheries and aquatic habitat;
- Promotion of economic development and recreation;
- Regulation of flows and supplies of surface and groundwater; and
- Protection of the Chesapeake Bay.

Regulations limit water withdrawals to the amount (quantity and rate) required to meet the reasonably foreseeable needs of a project and that can be withdrawn without causing adverse impacts. Adverse impacts include excessive lowering of water levels; rendering competing supplies unreliable; causing permanent loss of aquifer storage capacity; degrading water quality that may be injurious to any existing or potential water use; adversely affecting fish, wildlife, or other living resources or their habitat; substantially impacting the low flow of perennial streams.

The SRBC consumptive water use regulation is designed to offset anthropogenic impact to streamflows that protect water supplies, in-stream uses such as fish and aquatic life, and recreation during periods of low streamflow. For water withdrawal projects, SRBC project review staff formulates specific recommendations that facilitate project operations without causing undesirable environmental effects. Water quantities and withdrawal rates can be reduced from those requested, or otherwise limited, as necessary, to protect other uses or avoid/minimize impacts. Many projects are conditioned with pass-by flow requirements. The intent is to protect streams during low flows by determining a prescribed quantity of water that must pass a specific point downstream from a water intake during water withdrawal.

With respect to low flow protection, the objective of the SRBC permitting process is to eliminate manmade impacts caused by withdrawals and consumptive uses during low flows. This approach ensures available water for downstream uses, including in-stream uses. Neither the pass-by flow or consumptive use mitigation effort is intended to provide more flow to waterways than would typically occur during a drought because native resident species are adapted to natural drought conditions. The species are not, however, adapted to more frequent and more severe low flow periods caused by increasing withdrawals and unmitigated consumptive use.

The current standards for applying protective conditions are based on guidelines that are not necessarily specific to the needs of a particular waterway. This report may be used as a general framework for developing more targeted standards in SRBC's regulatory program that will be protective of the natural flow regime and the aquatic habitats, species, and natural functions the regime supports.

Using the results of this report, SRBC will consult technical advisors from member jurisdictions before recommending any changes to existing policies and procedures or new policies that offer protective criteria commensurate with the findings in this report. Application is likely to be completed in phases and would involve various SRBC policies. For example, restrictions on alteration of monthly low flows could be addressed by revising the existing Pass-by Flow Guidance, while seasonal and high flow patterns can be maintained through cumulative water use assessments and watershed-based water use regulations. SRBC staff expects that information presented in this report will be integrated into the Commissions's planning, management, and regulatory program.

5.3 Conclusion

This report summarized conditions in the Susquehanna River basin, the flow needs of several key groups of organisms, and a method for analyzing flows that will support these organisms. Multiple mechanisms are available for the application of the findings of this report. Management and regulatory actions can help maintain and restore a flow regime that supports the characteristic natural habitats of the Susquehanna River basin and the species that depend on them. Working together and aligning their complementary missions, Federal, state, and local agencies, as well as non-governmental organizations, can lead application of these findings to help balance competing water needs in the basin and maintain a system that provides benefits for all the basin's inhabitants.

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Glossary

Acid Mine Drainage (AMD): Outflow of acidic water from (usually abandoned) metal mines or coal mines.

Afterbay: A stream, conduit, pond, or reservoir of a hydroelectric power plant at the outlet of the turbines.

Anadromous: Fish that travel from salt water to fresh water to spawn.

Bankfull: Stream flow conditions that fill the channel to the top of its banks, just to the point where the water begins to overflow onto the floodplain.

Consumptive use: The portion of water withdrawn from a river or from groundwater that is not returned to its originating watershed.

Diadromous: Fish that travel between salt water and fresh water.

Evapotranspiration: The process by which water returns to the atmosphere by evaporation and by plants emitting water vapour from their leaves.

Glochidia: The microscopic larval stage of freshwater mussels. Glochidia have hooks used for attachment to fish.

Head-of-tide: Farthest upstream point where a river is affected by tidal fluctuations.

Hydrograph: A graph that shows changes in river discharge over time.

Hyporheic zone: The region underneath and along a stream bed and banks, where water in the channel mixes with shallow groundwater.

Intermittent stream: A stream that flows periodically.

Karst: Landforms created by solution of rock in which most of the drainage is by underground channels that may lead to the formation of caves. Normally refers to limestone karst but can occur in other rock types. Parts of Pennsylvania are characterized by karst geology.

Redd: Spawning nest made by fish.

Refuge or Refugia: Accessible microhabitats or regions within a stream reach or watershed where adequate conditions for organism survival are maintained.

Run-of-the-river: Hydroelectric generation where the natural flow and elevation drop of a river are used to generate electricity.

Succession: Process of ecosystem development brought about by changes in the populations of plant species in localized or geographic regions with particular characteristics.

Vernal pool: Temporary pool of surface water that provides breeding habitat for certain amphibian and invertebrate species, typically in the spring.

Water year: The annual cycle that is associated with the natural progression of the hydrologic seasons, generally 1 October to 30 September in the Northern Hemisphere.

Acronyms and Abbreviations

cfs	Cubic feet per second, a measure of streamflow.
DRBC	Delaware River Basin Commission
FERC	Federal Energy Regulatory Commission
ICPRB	Interstate Commission on the Potomac River Basin
MDE	Maryland Department of the Environment
MDDNR	Maryland Department of Natural Resources
mgd	Million gallons per day
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
NYOPRHP	New York State Office of Parks, Recreation and Historic Preservation
NYSDEC	New York State Department of Environmental Conservation
PADCNR	Pennsylvania Department of Conservation and Natural Resources
PADEP	Pennsylvania Department of Environmental Protection
PFBC	Pennsylvania Fish and Boat Commission
PNHP	Pennsylvania Natural Heritage Program
Qx	The streamflow that is exceeded x% of the time. For example, Q95 is the streamflow that is exceeded 95% of the time (low flow) while Q0.5 is streamflow exceeded 0.5% of the time (high flow).
SRBC	Susquehanna River Basin Commission
TNC	The Nature Conservancy
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Appendix A

The Nature Conservancy
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Ecosystem Flow Recommendations for the Susquehanna River Basin

Report to the Susquehanna River Basin Commission and U.S. Army Corps of Engineers

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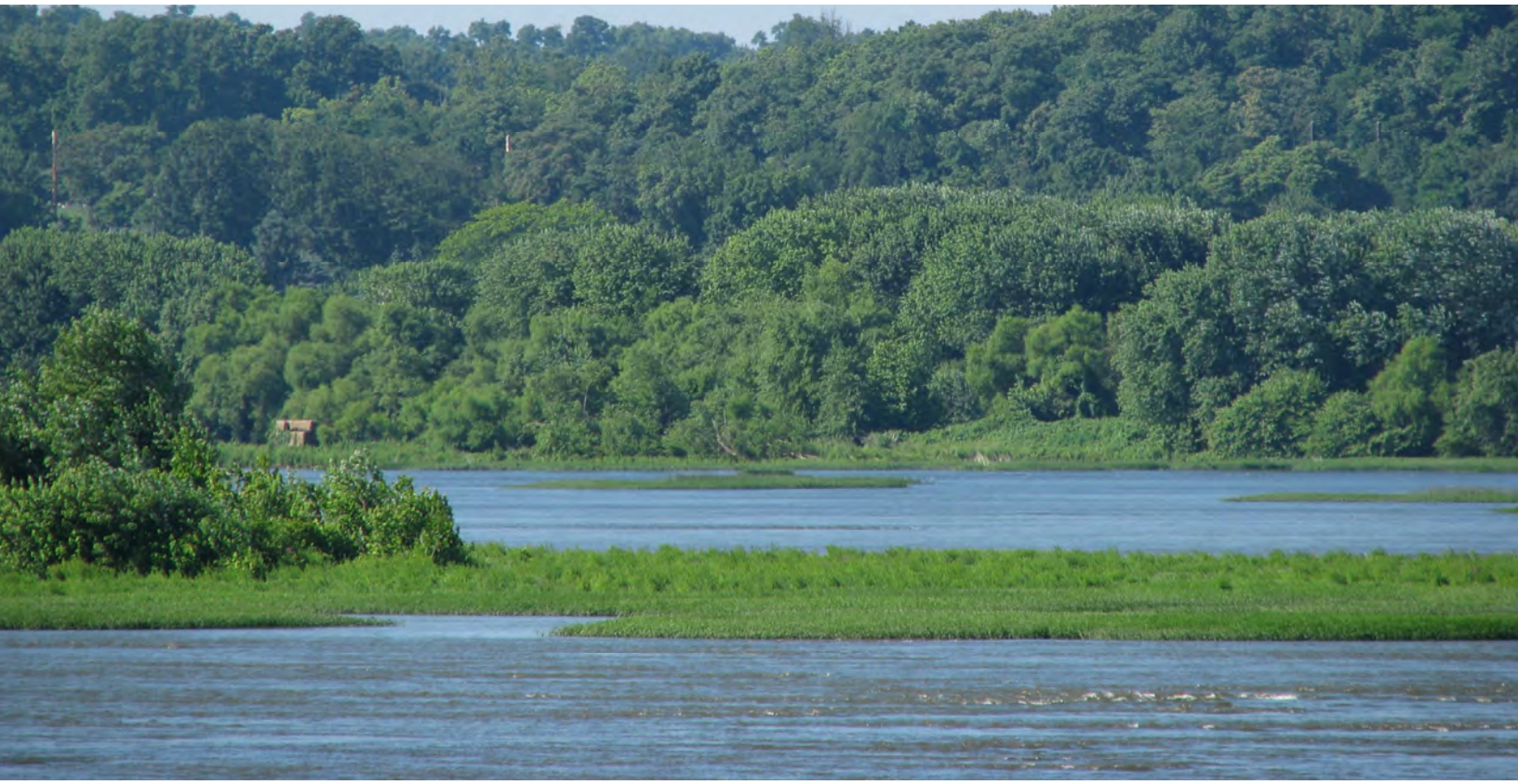
Submitted by The Nature Conservancy

November 2010

Ecosystem Flow Recommendations for the Susquehanna River Basin

Report to the Susquehanna River Basin Commission and U.S. Army Corps of Engineers



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Report prepared by The Nature Conservancy

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Executive Summary

The Nature Conservancy (Conservancy), the Susquehanna River Basin Commission (SRBC), and the U.S. Army Corps of Engineers, Baltimore District (Corps) collaborated to determine ecosystem flow needs for the Susquehanna River and its tributaries. The project outcome is a set of recommended flows to protect the species, natural communities, and key ecological processes within the various stream and river types in the Susquehanna River basin. The flow recommendations presented in this report address the range of flow conditions relevant to ecosystem protection, including extreme low and drought flows, seasonal (and monthly) flows, and high flows. Along with magnitude of these key flows, recommendations address timing, frequency, and duration of flow conditions.

Ecosystem-based flow recommendations will help inform important aspects of SRBC's water management program. Specifically, they will inform the establishment of appropriate conditions or limitations related to the issuance of water withdrawal approvals. They will also inform the management of water releases from upstream storage, which are made to minimize ecological impacts of consumptive water use during critical low flow periods. These recommendations also provide valuable information for future water management planning in the major subbasins.

Within approximately eighteen months, we developed flow recommendations based on published literature, existing studies, hydrologic analyses, and expert consultation. Using existing information rather than new field studies and analyses had several advantages: it was efficient, cost-effective and enabled us to address multiple taxonomic groups over a large geographic area. This project produced flow recommendations that can be immediately applied to water management programs. The flow needs identified through this project can also help direct future quantitative analyses to support or refine these recommendations.

We completed the following steps to develop flow recommendations:

- Consulted with experts to develop a list of flow-sensitive taxa, habitat types, and physical processes within the basin;
- Surveyed the literature to extract relationships between flow alteration and ecological response;
- Drafted flow hypotheses through expert workshops;
- Analyzed long-term variability of selected flow statistics using daily streamflow data at 45 minimally-altered (index) gages within the basin;
- Drafted flow recommendations based on published ecological responses, qualitative relationships, and maintenance of long-term flow variability; and
- Revised flow recommendations based on expert review and results of hypothetical water withdrawal scenarios.

We used a basic habitat classification to organize information about flows needed to protect the basin's species and natural communities. We defined five major habitat types based on watershed size,

temperature, and flow stability: cool and coldwater streams, warmwater streams, high baseflow streams, major tributaries, and the Susquehanna River mainstem.

We began by identifying taxa, habitats, and physical processes that are most likely to be sensitive to flow alteration in each major habitat type. We focused on fishes, aquatic insects, mussels, reptiles and amphibians, birds and mammals, and floodplain and aquatic vegetation. We also incorporated information on how streamflow influences floodplain and channel maintenance and water quality. Through expert workshops, we developed approximately 70 hypotheses that define anticipated responses of a species, group of species, or physical habitat to changing flow conditions. We consolidated these hypotheses into approximately 20 statements that describe the critical flow needs during fall, winter, spring, and summer for each habitat type. This approach confirmed the importance of high, seasonal, and low flows throughout the year and of natural variability between years.

We reviewed relevant literature that documented ecological responses to observed droughts, diversions or reservoir management, or experimental withdrawals. Published, quantitative responses to flow alteration were not available for most species. Many studies described qualitative ecological responses to flow alteration that were consistent with the hypotheses developed by experts. Although these studies do not provide quantitative thresholds, they support the need to protect low, seasonal, and high flow components.

We expressed ecosystem flow recommendations in terms of three primary flow components: high flows (including interannual and annual events and high flow pulses), seasonal flows, and low flows. We then identified a set of ten flow statistics that describe the magnitude and frequency of large and small floods, high flow pulses, median monthly flow, and monthly low flow conditions. Several statistics are based on monthly exceedance values (Qex) and monthly flow duration curves. Selected statistics include: magnitude and frequency of 20-year (large) flood, 5-year (small) flood, and bankfull (1-2 year high flow) events; frequency of high flow pulses in summer and fall; high pulse magnitude (monthly Q10); monthly median (Q50); typical monthly range (area under monthly flow duration curve between the Q75 and Q10); monthly low flow range (area under monthly flow duration curve between Q75 and Q99); monthly Q75 and monthly Q95.

As a group, these statistics help track changes to the entire flow regime. By using monthly (instead of annual) curves, we represent seasonal variation in streamflow. All statistics can be calculated using daily streamflow data and the Indicators of Hydrologic Alteration (IHA) software, spreadsheet-based flow duration curve calculators, or other easy-to-use available tools.

We present flow recommendations in Section 5 and Table 5.2. Most of our flow recommendations are expressed in terms of acceptable deviation (i.e., percent or absolute change to the long-term distribution) from reference values. We defined long-term variability of the selected flow statistics using daily flow data from water years 1960-2008 at 45 minimally-altered (index) gages within the basin. This period includes the flood and drought of record. Recommendations to “maintain” or “limit” change to a given statistic are in reference to the long-term variability of these statistics during this 48 year period.

In summary, we recommend:

High flows

For all streams and rivers

- Maintain magnitude and frequency of 20-yr (large) flood
- Maintain magnitude and frequency of 5-yr (small) flood
- Maintain magnitude and frequency of 1 to 2-yr high flow (bankfull) event
- Limit the change to the monthly Q10 to less than 10%
- Maintain the long-term frequency of high pulse events during summer and fall

Seasonal flows

For all streams and rivers

- Maintain the long-term monthly median between the 45th and 55th percentiles
- Limit change to "typical monthly range" to less than 20%

Low flows

For all streams and rivers with drainage areas greater than 50 square miles

- Limit change to "monthly low flow range" to less than 10%
- Maintain the long-term monthly Q95

For headwater streams with drainage areas less than 50 square miles

- Maintain the long-term "monthly low flow range"
- Maintain the long-term monthly Q75

By preserving the long-term distribution of flows in each month, we account for seasonal differences in water availability. For example, our recommended range around the monthly median flow is wider in April and May (when flows are higher and more variable) than in August and September (when flows are lower and less variable). We also recommend more protection for low flows in headwater streams due to their hydrologic characteristics and ecological sensitivity.

These recommendations supplement and complement previous instream flow studies by defining flows needed to sustain aquatic ecosystems in larger cold and coolwater streams and also in warmwater streams, major tributaries, and the Susquehanna mainstem. We emphasize that some streams may need site-specific considerations or have constraints due to existing water demands. Instream flow policy could also incorporate greater protection for high quality waters and habitats, streams containing rare species, and/or designated uses that warrant even greater protections. We anticipate that these recommendations will be strengthened and refined based on future studies that quantify ecological responses to flow alteration within and outside the basin.

Section 1: Introduction

1.1 Project Description

The Nature Conservancy (Conservancy), the Susquehanna River Basin Commission (SRBC), and the U.S. Army Corps of Engineers, Baltimore District (Corps) are collaborating to determine ecological flow needs for the Susquehanna River and its tributaries. The project outcome is a set of recommended flows to protect the species, natural communities, and key ecological processes throughout the Susquehanna River basin. These recommendations address the range of flow conditions relevant to ecosystem protection, such as extreme low and drought flows, seasonal (and monthly) flows, and high flows.

Through this project, SRBC specifically seeks to implement a key element of its Consumptive Use Mitigation Plan, which calls for an assessment of the flow needs of the aquatic ecosystem while allowing for water use demands to be met (SRBC 2008). Ecosystem-based flow goals will help important aspects of SRBC's water management program. Specifically, they will inform the establishment of appropriate conditions or limitations related to the issuance of water withdrawal approvals. They will also inform the management of water releases from upstream storage during critical low flow periods, which are made to minimize the ecological impacts of consumptive water use in the basin. These goals also provide valuable information for future water management planning in the major subbasins.

Providing basin-wide goals and standards for river flow management is a priority for the Corps, SRBC, the Conservancy, and other partners. In December 2008, the Corps and SRBC entered into a cost-share agreement to conduct a study of the Susquehanna River basin under the Section 729 authority of the Water Resource Development Act. This authority authorizes an assessment of water resource needs of river basins and is unique to the Corps in that it does not involve construction of new infrastructure. The Conservancy is not a signatory to the agreement but is a member of the Study Team and a contractor to SRBC. This phase of the study emphasizes ecological impacts of changes to low flow conditions, but addresses the entire flow regime. SRBC and the Corps are planning to pursue a second phase that focuses on implementation of these recommendations.

For the majority of the basin, there are information gaps related to the level of flow alteration that causes ecological impacts and how these problems vary spatially (at different reaches within the basin) and temporally (among seasons and with varying duration and frequency of drought conditions). One exception is the definition of instream flow needs for trout streams within small drainage basins (less than 100 square miles) (Instream Flow Studies: Pennsylvania and Maryland; Denslinger et al. 1998), which has been widely used throughout the basin to set conditions on water withdrawal permits. This project aims to supplement and complement this and other instream flow studies by defining flows needed to sustain aquatic ecosystems in larger cold and coolwater streams and also in warmwater streams, major tributaries, and the Susquehanna mainstem.

The project focuses on the mainstem and tributaries upstream of the four hydroelectric dams on the lower Susquehanna River. Several flow needs documented in this study may also be relevant to the lower mainstem that is directly affected by the presence and operation of the hydroelectric dams (e.g.,

flows to cue or facilitate diadromous fish migration, flows to maintain submerged aquatic vegetation). However, this project does not make specific recommendations for flow releases from these facilities. The Conservancy, SRBC and other partners are also collaborating to define flow needs for the upper Chesapeake Bay to help incorporate ecological considerations into water management of the lower Susquehanna River, including future operations of the hydropower facilities.

1.2 Goals and Objectives

The overall goal of the Susquehanna River Ecosystem Flow Study is to determine ecological flow needs for the Susquehanna River and its tributaries. 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 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 primary objectives when developing flow recommendations for the Susquehanna River basin. Specifically, we sought to:

- build on projects that produced flow recommendations for other river basins throughout the United States;
- provide information for all stream and river types in the basin;
- 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 immediately applicable to existing water management programs; and
- create a framework that can accommodate new information on ecological responses of flow-sensitive species and habitats.

This project followed the general model of other projects that developed flow recommendations for large rivers, including the Savannah River, the Willamette River, and the upper Colorado River (Richter et al. 2006, Gregory et al. 2007, Wilding and Poff 2008). However, it differs from other Ecologically Sustainable Water Management projects that focused on specific reaches (e.g., Savannah River) and produced recommendations that could be implemented through specific operational changes at individual 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. These flow recommendations can guide a variety of water management activities from a system perspective, potentially including limiting water withdrawals during critical periods, timing

withdrawals when water is abundant, and implementing reservoir releases in a way that mitigates impacts during extreme low flow conditions.

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). It includes 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.

ELOHA uses stream and river classification to help 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). We used five major habitat types as the basis for our flow recommendations. We also selected a set of flow statistics to represent magnitude, timing, frequency and duration of low, seasonal, and high flow conditions. These statistics can be used to quantify existing or projected hydrologic changes associated with water withdrawals, reservoir releases, and water management changes.

Given the available hydrologic and biological data and the timeframe for this project, we chose to develop flow recommendations based on flow alteration – ecological response hypotheses 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 resulting flow hypotheses can help direct future quantitative analyses to help confirm or revise flow recommendations.

1.3 Project Schedule

The majority of the work on this project was completed in approximately eighteen months between March 2009 and September 2010. This project represents a major portion of Phase I of the Susquehanna River Basin Low Flow Management Study.

March 2009	Project orientation meeting
October 2009	Workshop I – Flow Needs
April 2010	Workshop II – Flow Recommendations
July 2010	Circulate draft report for comments
September 2010	Final report to SRBC and the Corps

The Conservancy hosted three workshops to identify and gather relevant information on flow-sensitive species, natural communities, and physical processes and to incorporate best professional judgment into a set ecosystem flow goals for the range of habitats within the basin. Summaries of the March 2009 orientation meeting, October 2009 workshop, and the April 2010 workshop are included in Appendix 1.

We used a combination of peer-reviewed literature, research reports, unpublished studies, and professional input to draft flow needs and recommendations. Relevant literature and studies either provide qualitative information that confirms the flow need or quantifies an ecological response to flow alteration. In general, we prioritized information sources as follows: data and literature for the Susquehanna River, sources for the same species in mid-Atlantic U.S., sources for the same taxa in other temperate rivers, sources for similar species and taxa in the mid-Atlantic U.S., sources for similar taxa in the 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.

The report synthesizes background information on flow needs for key biological and physical processes and conditions and culminates with flow recommendations, which are 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 streams, small rivers, major tributaries, and the mainstem; and a
- summary of literature and studies relevant to flow recommendations.

Following receipt of this report, the Corps and SRBC will begin scoping Phase II of the Section 729 Study, which focuses on implementation. The Corps will also complete a final report for Phase I in accordance with their guidance. This report is scheduled to be completed in March 2011.

Section 2: Basin Characteristics and Hydrology

Key Elements

- Average annual precipitation ranges from approximately 33 to 49 inches.
- Forest covers more than 63% of the basin.
- Evapotranspiration losses account for 52% of total precipitation.
- Glaciated regions of the Appalachian Plateau are underlain by thick glacial deposits that result in losing and gaining river reaches.
- Subwatersheds underlain by limestone geology can have baseflows that are two to three times higher than other stream types.
- More than 50% of mean annual flow is delivered between March and May.
- Flows are lowest between July and October, when evapotranspiration rates are highest.
- The Susquehanna is one of the most flood-prone basins in the United States; historically, flood events have occurred in all seasons.
- Flow conditions can be highly variable from month to month; floods and droughts may occur in the same year.

The Susquehanna River is the longest river located entirely within the U.S. portion of the Atlantic drainage. Flowing 444 miles from Otsego Lake, New York to the Chesapeake Bay, the basin drains more than 27,500 square miles, covering half the land area of Pennsylvania and portions of New York and Maryland. There are six major subbasins: the Upper Susquehanna, Chemung, Middle Susquehanna, West Branch, Juniata, and Lower Susquehanna. Most of the basin's headwaters originate on the Appalachian Plateau, and the river crosses the Ridge and Valley and Piedmont provinces before reaching the Bay (Figure 2.1). The watershed encompasses over 43% of the Chesapeake Bay's total drainage area and provides about half of its freshwater inflow.

2.1 Hydrology

In this section, we describe seasonal and interannual flow variability in the basin. We also discuss hydrology as it relates to basin climate, vegetation, and physiography.

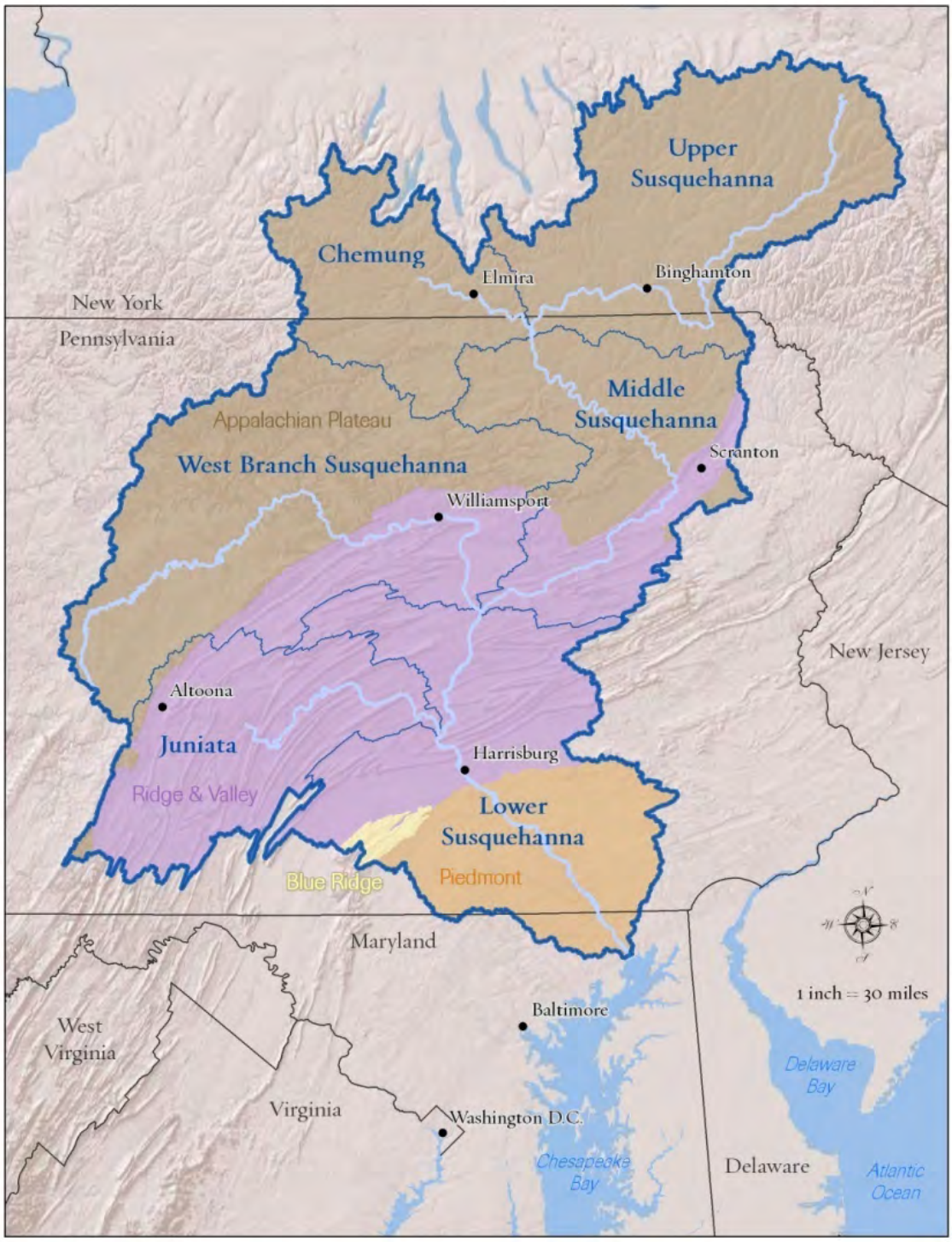

Figure 2.1 The Susquehanna River has six major subbasins and spans three major physiographic provinces.

2.1.1 Climate, Vegetation, and Physiography

In the eastern United States, climate, vegetation, geology and topography are the primary variables influencing river processes, particularly hydrology (Cushing et al. 2006). The basin's **climate** can be described as mild, subtemperate and humid. Continental weather conditions include cold winters with snow events and warm to hot summers. Within the basin, precipitation and temperature are largely influenced by latitude and elevation. Both precipitation and temperature increase from north to south and from west to east (Cushing et al. 2006). Average annual air temperatures are approximately 44°F in the northern portion of the basin and 53°F in the southern portion (SRBC 2010). Precipitation events can be severe, ranging from localized thunderstorms to regional hurricanes originating in the Atlantic Ocean. Average annual precipitation is approximately 40 inches, but has ranged from 33 to 49 inches. An estimated 52% of precipitation is lost to evapotranspiration, with the remaining 48% infiltrating to groundwater storage or resulting in overland flow and streamflow runoff (SRBC 2010). Climate trends in the last two decades have shown wetter conditions, on average, than in previous decades. Increased precipitation is reflected in higher annual minimum flows and slightly higher median flows during summer and fall (Zhang et al. 2009).

In the central and northeastern Atlantic Slope, **vegetation**, specifically forest cover, plays a major role in governing the distribution and timing of streamflows. The region is dominated by deciduous trees. Peak evapotranspiration occurs in the late summer and early fall, and evapotranspiration is minimal during winter. This pattern is reflected in seasonal baseflow trends. Land cover has changed significantly during the last centuries. It is estimated that 95% of the region was in forest cover before European settlement. Settlement was followed by large-scale deforestation and land use conversion due to increased agriculture, energy demands (charcoal wood), and industrial logging. Conversion and deforestation peaked in the early 1900s when only 30% forest cover remained. Since then, forest cover has more than doubled due to abandonment of agricultural lands and the evolution of silvicultural practices. Changes in forest cover directly influenced historic hydrology. During periods of low forest cover, streams and rivers had higher baseflows during the summer and fall months. Baseflows were higher because fewer trees resulted in a decrease in evapotranspiration during the growing season. Periods of low forest cover are also associated with flashier hydrographs.

Hydrologic characteristics also vary with basin **physiography**. A physiographic province is an area delineated according to similar terrain that has been shaped by a common geologic history (Fenneman 1938). They provide the geomorphic context for rivers and streams and influence valley form, elevation, slope, drainage pattern and dominant channel forming processes (Sevon 2000) (Appendix 2). The basin spans three major physiographic provinces: the Appalachian Plateau, the Ridge and Valley, and the Piedmont (Figure 2.1).

The **Appalachian Plateau** underlies most of the basin, including the Upper Susquehanna, Chemung and northern portion of the West Branch subbasins. It has the highest average elevation of all three provinces, ranging from 440 to 3210 ft, and is characterized by steep slopes and deeply dissected valleys (Shultz 1999). Portions of this province were modified by the Pleistocene glaciations, with dominant channel forming processes including fluvial and glacial erosion (Fenneman 1938, Sevon 2000). Surficial

glacial deposits can be 8 to 15 m thick. These deposits influence surface water hydrology by creating heterogeneous gaining and losing reaches (Cushing et al. 2006).

The **Ridge and Valley** province consists of a band of parallel ridges created by folded sandstone, shale and limestone ranging in elevation from 140 to 2775 ft. Depending on the underlying bedrock, dominant channel forming processes include fluvial erosion and solution of carbonate rocks (Fenneman 1938, Sevon 2000). More weather-resistant bedrock formations confine valley reaches and floodplains, while limestone valley reaches tend to be broad and less confined. Because of their subsurface water storage capacity, limestone formations also have a significant influence on the hydrology of Pennsylvania streams, yielding higher baseflows and a more stable hydrograph than in non-karstic terrain (Stuckey and Reed 2000, Chaplin 2005). Trellis and karst drainage patterns are very common. Headwaters and small streams typically flow north or south from the ridge tops to the valleys, then east or west along the valley floor to the mainstem. Subbasins within the Ridge and Valley include the southern portion of the West Branch, the Juniata, and mainstem and tributaries from the confluence with the Lackawanna River to the Conodoguinet confluence (Shultz 1999, Sevon 2000).

The **Piedmont** transition zone lies between the Appalachian Mountains and the coastal plain. It is characterized by low elevation rolling hills and moderate slopes between the elevations of 20 and 1355 ft. The Basin's lowest elevations and most southern latitudes occur within this province, resulting in a concentration of warm headwater streams. While trellis and karst drainage patterns occur, the province is dominated by dendritic drainage patterns and channel forming processes are dominated by fluvial erosion (Fenneman 1938, Sevon 2000). Portions of the Lower Susquehanna subbasin fall within this province (Shultz 1999).

2.1.2 Seasonal Variability

From the headwaters to mainstem, streamflow magnitude varies seasonally. The hydrograph in Figure 2.2 is from the Susquehanna River USGS gage at Harrisburg, PA. It is based on the daily median and 90th percentile of daily discharge between 1960 and 2008. Winter months have relatively high flows due to low evapotranspiration and snow melt delivering water to streams in moderately high pulse events. Stream flows peak during spring months as snowmelt increases. High pulse events are highest in magnitude and frequency during this season. The magnitude of median daily streamflow is significantly higher (approximately 10 times) in spring than in the summer and fall when flows are at their lowest because of evapotranspiration.

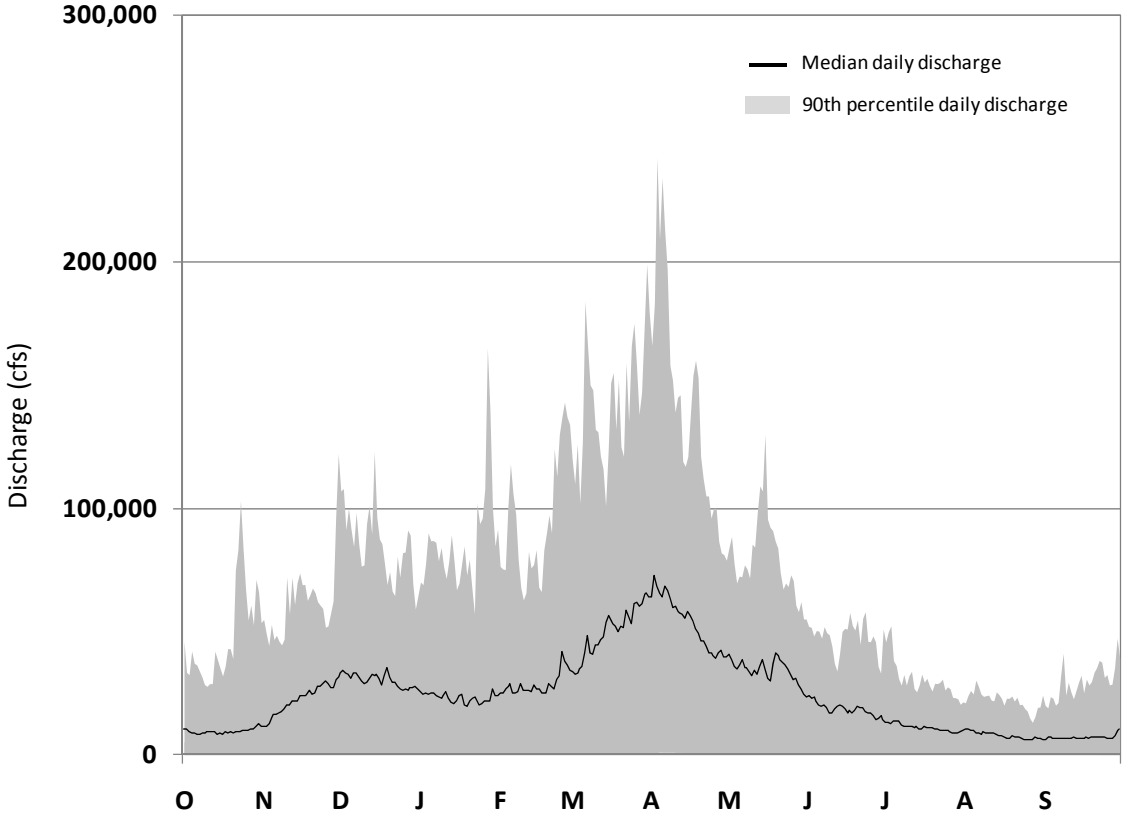

Figure 2.2 Hydrograph of the Susquehanna River at Harrisburg, PA (USGS gage 01570500).

The magnitude of monthly Q50 is closely correlated to watershed size in all seasons. Figure 2.3 compares monthly Q50 to watershed size for 45 minimally-altered basin gages. For all watershed sizes, the highest median flows occur in spring (April), followed by winter (December). The lowest median flows occur in late summer and early fall (represented by August and October, respectively). In these months, median flows for streams with drainage areas less than 50 square miles range from 0.3 to 10 cubic feet per second (cfs); for large tributaries with drainage areas greater than 400 square miles, median flows are greater than 100 cfs.

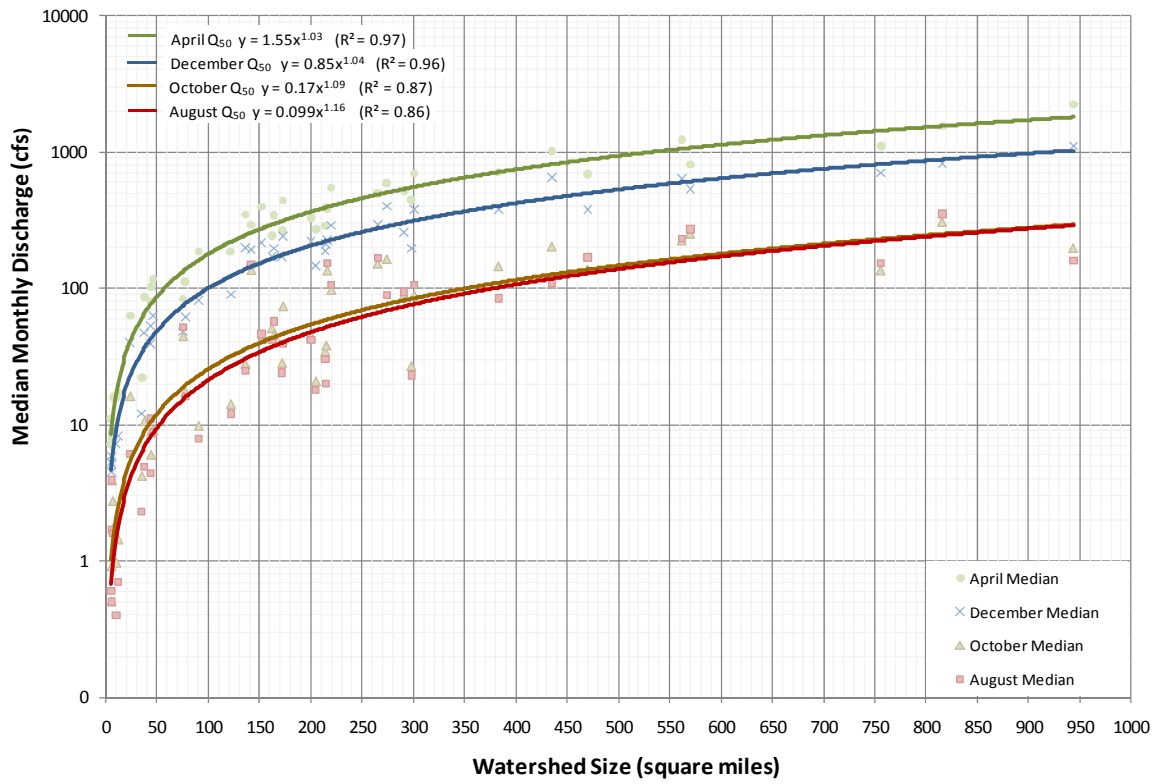

Figure 2.3 Relationship between median monthly (Q50) discharge and watershed size for gages (n=45) within the Susquehanna basin using a fall (Oct), winter (Dec), spring (Apr), and summer (Aug) month. Statistics were calculated using measured mean daily records for Water Years (WY) 1960-2008.

2.1.3 Flood and Drought History

In general, the seasonal patterns of relatively high winter baseflows, high spring baseflows, and low summer and fall baseflows are consistent from year to year, but extreme conditions also occur. Hydrologic conditions vary from year to year, and within years, and floods and droughts may occur in the same year.

Figure 2.4 illustrates the timing and relative magnitude of several large floods over the period of record in relation to the median daily discharge at Harrisburg, PA. **Floods** can occur in any month, but are most frequent in the spring months in response to rain-on-snow events or rain on saturated soils. Floods occurring in winter months are typically in response to rain-on-snow events, combined with ice jams (as in January 1996), while summer floods are typically driven by coastal storms or severe hurricanes (Shultz 1999, SRBC 2010). Hurricane Agnes (June 1972) was the most severe flood in recent history. Flow was nearly 1 million cfs at the Harrisburg gage, which is more than 60 times median daily streamflow. The estimated river stage for this event was 32 feet, almost twice the official flood stage of 17 ft.

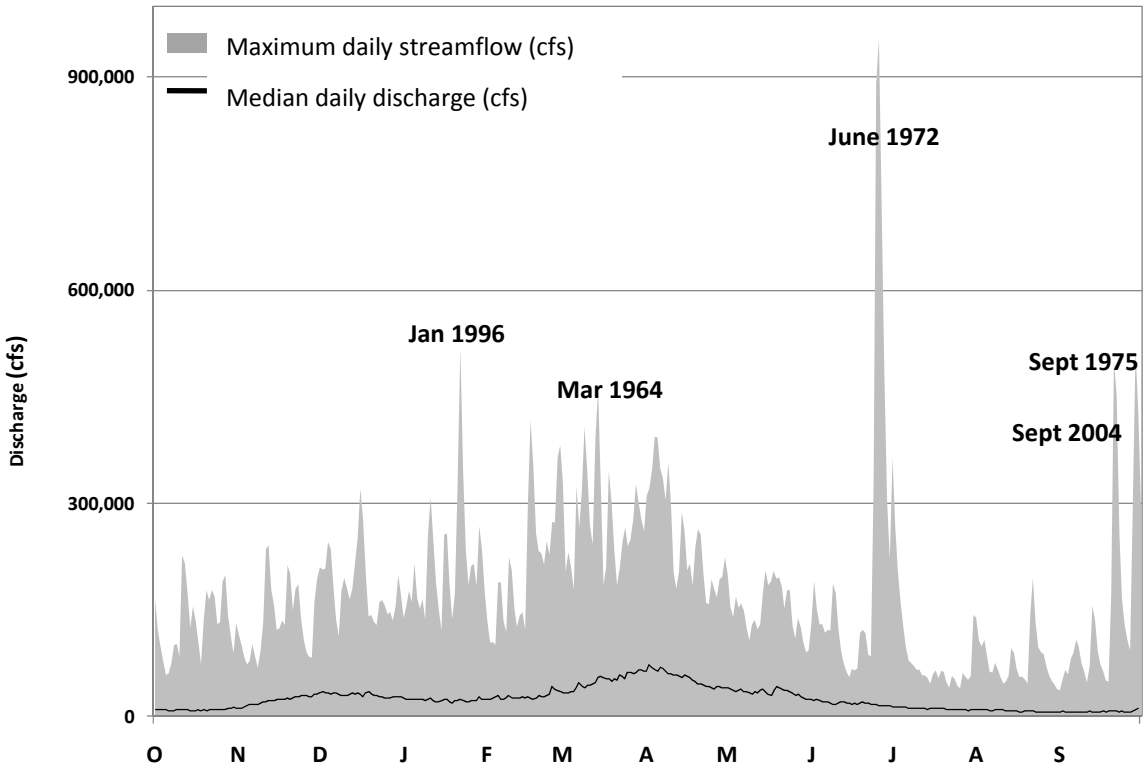

Figure 2.4 Flood events and maximum daily flow on the Susquehanna River at Harrisburg (1960-2008)

Major **droughts**[1] occurred in the early 1930s and the early 1960s, with thirteen droughts occurring over the past century (SRBC 2010). The lowest recorded daily discharge at Harrisburg during the drought of record (September 1964) was approximately 1,750 cfs, with a corresponding river stage of less than 1ft. This event occurred only a few months after a March 1964 high flow event. Recent drought periods include 1980, 1991-1992, 1995 and 2002.

2.1.4 Defining Flow Components

Mathews and Richter (2007) discuss the concept of environmental flow components and their application to environmental flow standard setting. Drawing 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.

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[1] SRBC defines a water supply drought as a period when actual or expected supply is insufficient to meet demands (SRBC 2000). This condition is estimated using indicators including precipitation deficits, ground-water levels, streamflows, the Palmer Drought Severity Index and reservoir levels.

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[2], "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 Susquehanna River using flow exceedance values in Box 1. 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 Susquehanna River, high flow events and floods provide cues for diadromous fish migration, maintain channel and floodplain habitats, inundate submerged and floodplain vegetation, transport organic matter and fine sediments, and help maintain temperature and dissolved oxygen 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., extreme snowmelt or Nor'easter-driven spring floods).

Large and small floods. In the Susquehanna basin, the 20-year flood and the 5-year flood are associated with floodplain maintenance and channel maintenance respectively, and maintain various successional stages of floodplain vegetation. 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. Bankfull events are commonly referred to as the channel forming discharge. This event occurs fairly frequently (approximately every 1-2 years) and, over time, is responsible for moving the most sediment and defining channel morphology.

High flow pulses. High flow pulses (smaller than bankfull events) flush fine sediment, redistribute organic matter, and moderate stream temperature and water quality. 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 they occur. These events may be particularly important in summer and fall when flows are generally lower than in other seasons.

Seasonal flows. These flows represent a "typical" range of flows in each month and are useful for describing variation between seasons (e.g., summer and fall). They are also useful for describing variation among years (e.g., a wet summer compared to a dry summer). Most of the time – in all but the wettest and driest portions of the flow record – flows are within this range. These flows are sometimes referred to as "baseflows," but we chose not to use this term because it is potentially confused with the groundwater component of streamflow.

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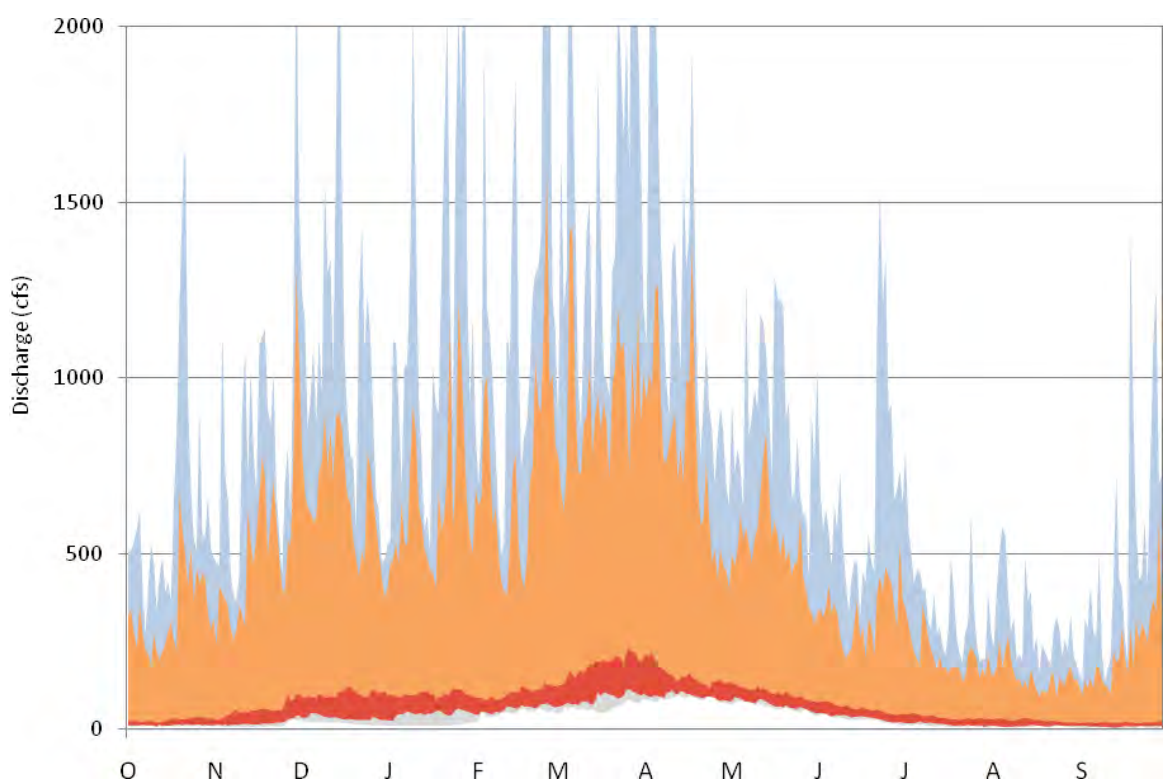
[2] For the Susquehanna, high flows include high flow pulses, bankfull flows and small floods, so we are effectively representing all of the components defined by Mathews and Richter (2007).

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

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 dissolved oxygen conditions. 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.

Box 1. 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



2.2 Major Habitat Types

Stream and river classification can help extend the application of flow alteration-ecological response relationships to streams and rivers in a broad geographic area (Poff et al. 2010). We used a relatively simple classification system to organize information about flow needs for various species and communities so that flow recommendations can be applied to all streams and rivers in the basin.

We defined five major habitat types:

Headwaters and small streams (less than 200 sq mi)

1. **Cool and coldwater streams** are primarily found within the Appalachian Plateau and Ridge and Valley province. They include glaciated and unglaciated streams. These streams support trout and coolwater assemblages.
2. **Warmwater streams** are primarily found within the Ridge and Valley and Piedmont provinces, although they are present in all provinces.
3. **High baseflow streams** have higher baseflow and lower peakflows than other streams of similar size (most are less than 200 sq mi, with a few exceptions). They are groundwater-dominated systems influenced by limestone geology. They occur primarily within the Ridge and Valley province and support cold and coolwater assemblages.

Major tributaries and mainstem (more than 200 sq mi)

4. **Major tributaries** include the mainstem of the Chemung, Upper Susquehanna, West Branch, and Juniata Rivers and all associated tributaries more than 200 sq mi.
5. The **Mainstem** includes the Middle Susquehanna (between the confluence of the Chemung and the confluence of the West Branch) and the Lower Susquehanna (from confluence with West Branch to backwaters of York Haven reservoir).

To assign habitat types to stream reaches, we combined information from several existing classifications. Sources include state water quality classifications from Pennsylvania, New York and Maryland; a regional aquatic biophysical classification (Northeast Aquatic Habitat Classification, Olivero and Anderson 2008); and a hydrologic classification developed for Pennsylvania by USGS using the Hydroecological Integrity Assessment Process (HIP; Apse et al. 2008).

Olivero and Anderson (2008) highlight differences in rare species associations between rivers with drainage areas less than 200 square miles and those greater than 200 square miles. We used 200 square miles to distinguish headwaters and small streams from major tributaries and mainstem habitats. Within headwaters and small streams, we further subdivided into three types based on size, temperature and flow stability. Table 2.1 lists the habitat types within existing classifications that we combined to create a basinwide classification.

Figure 2.5 illustrates the distribution of cool and coldwater streams throughout the basin. Maps of the remaining four stream types are included in Appendix 3. Pennsylvania and Maryland include coldwater stream types within their state water quality standards and use designations. Pennsylvania also includes a warmwater designated use. New York does not use a temperature designation in its water quality standards, but considers streams with trout (T) or trout-spawning (TS) designated use to be the types most analogous to Pennsylvania's cold water fishery (CWF) designation (M. Woythal and D. Lemon, Personal Communication, 2009).

Table 2.1 Source classes and designations combined into basinwide stream classification.

Headwater and Small Stream type	Source Classification and Class or Designation
Cool and coldwater streams	Pennsylvania - all streams designated as cold water fisheries (CWF) (25 Pa Code § 93) New York – all streams with designated use T (trout) or TS (trout-spawning) (NYCRR Part 701) Maryland – any streams with designated use III (Nontidal Cold Water) or III-P: (Nontidal Cold Water and Public Water Supply) (COMAR 26.08.02)
Warmwater streams	Pennsylvania – all streams designated as warm water fisheries (WWF) New York – all streams (Class A, B, C, D) and not designated as T or TS Maryland – all warmwater streams in Olivero and Anderson (2008) and not designated III or III-P
High baseflow streams	All "Class 2" streams in USGS HIP classification for Pennsylvania (described in Apse et al. 2008)

High baseflow streams are not specifically designated in any of the three state water quality standards, but they are widely recognized to be hydrologically distinct from other streams. We chose the pilot hydrologic classification developed by USGS using the Hydroecological Integrity Process (HIP, described in Apse et al. 2008) as our best approximation of the location of high baseflow streams within the basin. The HIP classification clustered stream gages based on similar values of hydrologic statistics related to flow magnitude, flow variability, and flood frequency. Within the HIP classification, Class 2 streams appear to be stable groundwater as indicated by their relatively low overall flow volumes, low variability of daily flows, and low flood frequency. 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 primarily classified as coldwater streams within the Pennsylvania classification, but are

distinguished by extremely stable flows relative to other coldwater streams. They generally have cold and coolwater fauna.

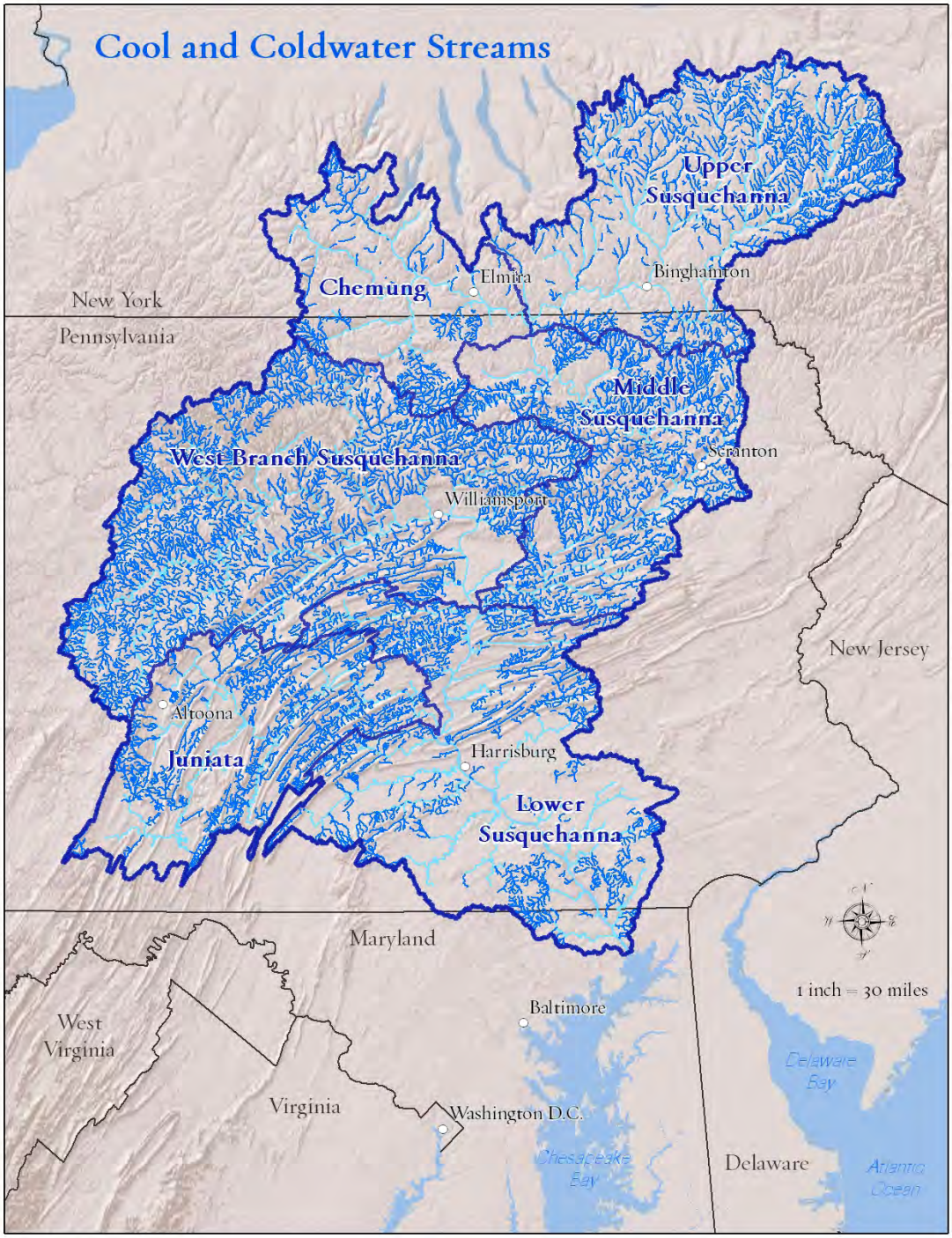


Figure 2.5 Cool and coldwater streams in the Susquehanna basin based on New York, Pennsylvania, and Maryland state water quality classifications.

Figure 2.6 compares flow duration curves (normalized to watershed area) for representative warm, cold, and high baseflow headwater streams within the basin. For the high baseflow stream (dashed line), the magnitude of high flow events (indicated by Q10) is lower than warm or cold water types. This relationship reverses during low flow events, as subsurface water stored during peak flows is released to the stream, resulting in low flow magnitudes (indicated by Q90) that are two to three times higher than those in warm or cold water types.

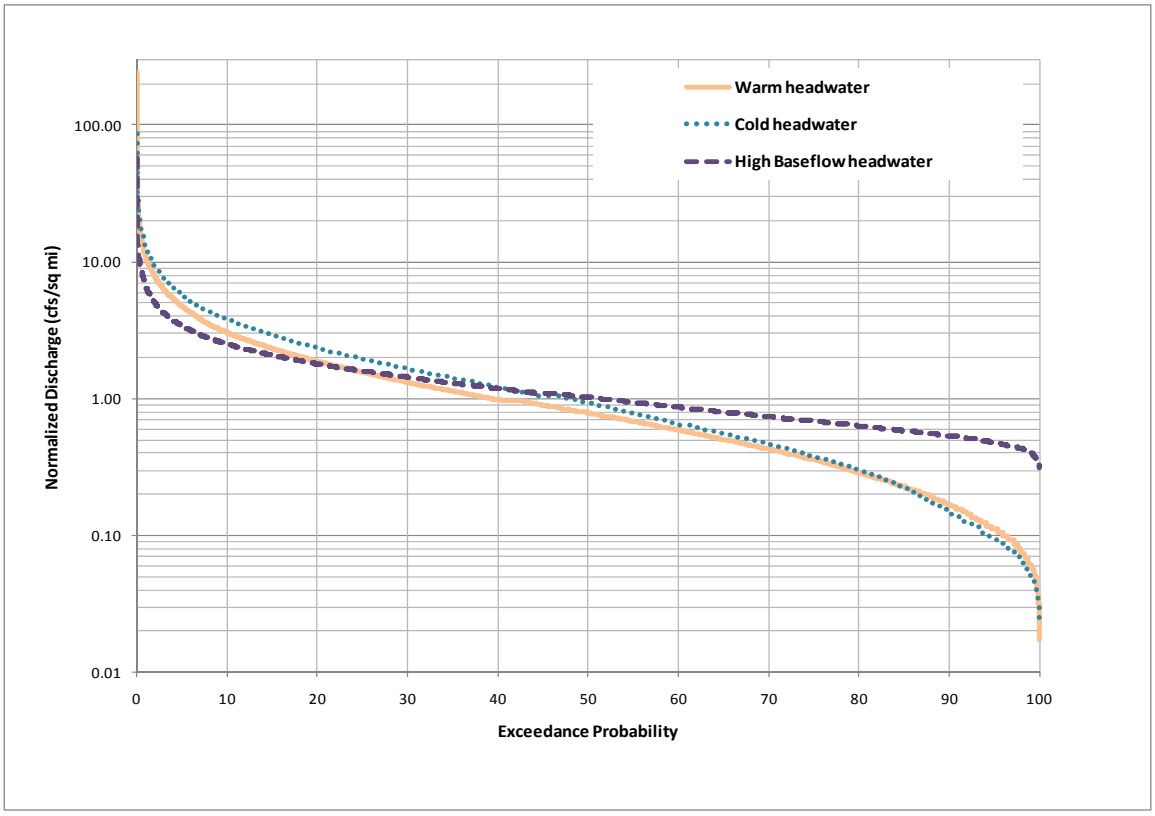


Figure 2.6 Normalized annual flow duration curves for cool and cold, warm and high baseflow headwaters and small streams (USGS Gages 01555500, 01550000, 01571500, respectively, 1960-2008).

We used this classification to organize information about species, communities, and physical processes associated with each type. We recognize that these types could be further subdivided using other variables and that there is considerable variability among streams and rivers assigned to a given type. Our goal was not to develop – or redevelop – a definitive classification, but rather to crosswalk existing classifications currently used in regulatory and management programs, illustrate the distribution of major habitat types, and use them to guide development and implementation of flow recommendations throughout the basin.

Section 3: Water Use and Water Resource Management

Key Elements

- Four hydroelectric dams on the Susquehanna River between Harrisburg, PA, and the Chesapeake Bay affect streamflow in the lower river and upper bay on a daily and subdaily basis.
- Thirteen Corps dams provide flood control for approximately 10% of the basin area.
- Public water supply and electricity generation comprise 75% of the basin's consumptive water use.
- Water demand for seasonal irrigation, including agriculture and golf courses, is highest during summer and early fall.
- Peak demand occurs from June through October.
- The basin states and federal government have nearly 40 years of joint water management experience through the Susquehanna River Basin Commission.

This section summarizes the operations and water uses that affect the flow regime. This includes the **lower mainstem hydroelectric dams**, **flood control dams and reservoirs, surface and groundwater withdrawals and consumptive use, and existing mitigation programs**.

3.1 Dams and Reservoirs

Four major **hydroelectric dams** were constructed on the lower mainstem of the Susquehanna River between 1904 and 1928: York Haven, Safe Harbor, Holtwood, and Conowingo Dams (Figure 3.1). Together with Muddy Run Pumped Storage Facility[3], these five dams provide the regional power grid with approximately 2134 megawatts (MW) of power. Because these dams create multiple physical barriers between the majority of the Susquehanna River basin and Chesapeake Bay, access to 98% of historic diadromous fish spawning habitat is severely restricted (Snyder 2005). Although fish ladders and lifts on each of the dams provide some upstream fish passage for American shad and other species, spawning runs are a small fraction of their historic size. Safe downstream passage, particularly crucial for juvenile alosid and adult eel out-migration, is limited or non-existent.

In addition to restricting access to upstream habitat, dams alter streamflow on a daily or subdaily basis, depending on the season, reservoir capacity, and operating schedule. Most of these dams have minimum release requirements included in their Federal Energy Regulatory Commission (FERC) licenses, and/or under other agreements and certifications (e.g., state 401 water quality certification). The FERC licenses for York Haven, Muddy Run and Conowingo Dams expire in 2014 and these projects are in the

[3] In coordination with Conowingo Hydroelectric Dam, Muddy Run Pumped Storage Facility began operation in 1966. It uses Conowingo Pond as an afterbay for producing power during peak demand. Both Conowingo and Muddy Run are currently operated by Exelon.

process of relicensing. Licenses for Holtwood and Safe Harbor expire in 2030. Holtwood Dam is currently undergoing structural and operational improvements to expand its generation capacity and improve instream flow and fish passage.

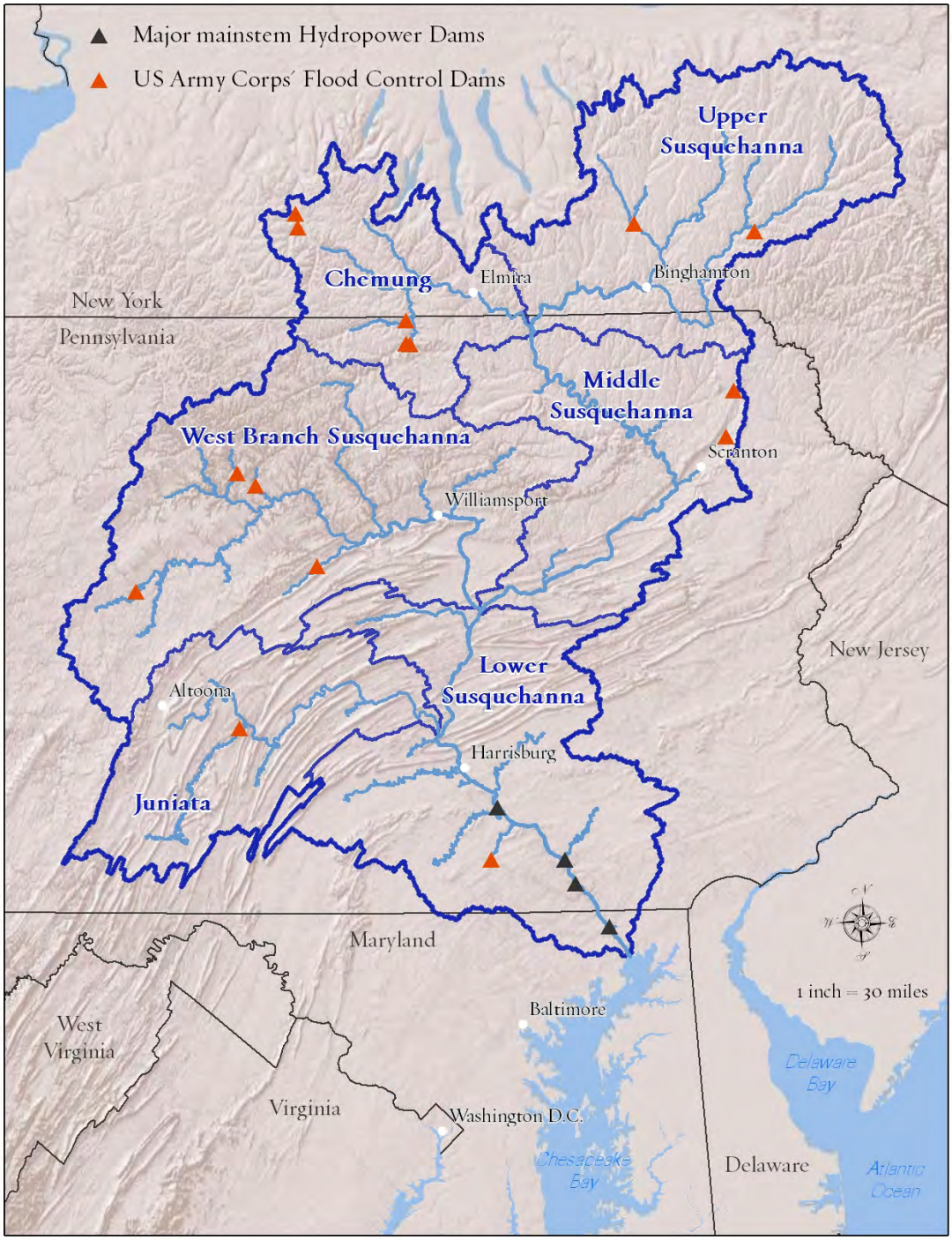


Figure 3.1 Map of major flood control reservoirs and lower Susquehanna hydroelectric dams.

In an effort to reduce the risk and damage associated with floods, the Corps constructed 13 **flood control reservoirs** throughout the subbasins between 1942 and 1980, selecting locations to minimize flood damage to population centers. The Corps also operates the George B. Stevenson reservoir, on behalf of the Commonwealth of Pennsylvania. These 14 flood control reservoirs have a total storage capacity of 1.5 million acre feet (AF), providing about 0.9 million AF of flood control storage and 0.6 million AF of conservation storage (Figure 3.1, Table 3.1). Total storage capacity is the storage volume (AF) between the lakebed and the spillway, partly occupied by water in conservation storage and partly vacant to accept excess flood runoff during high water events. Flood storage capacity is the normally vacant storage volume between the top of conservation pool and the spillway.

Table 3.1 Major Flood Control Reservoirs in the Susquehanna River basin

Subbasin	Reservoir Name	Year Built	Tributary	Upstream area (sq mi)	Project Purposes	Total Storage Capacity (AF)
Upper Susquehanna	Whitney Point Lake	1942	Otselic River	257	Flood risk management, low flow augmentation, recreation	84,233
	East Sidney Lake	1950	Ouleout Creek	102	Flood risk management, recreation	32,705
Chemung	Almond Lake	1949	Canacadea Creek	56	Flood risk management, recreation	13,397
	Arkport Dam	1940	Canisteo River	31	Flood risk management	7,000
	Cowanesque Lake	1980*	Cowanesque River	298	Flood risk management, water quality, recreation, water supply	84,747
	Tioga-Hammond Lakes	1980	Tioga River and	280	Flood risk management, recreation, water quality	125,818
			Crooked Creek	122		
Middle Susquehanna	Aylesworth Lake	1970	Aylesworth Creek	6	Flood risk management, recreation	1,842
	Stillwater Lake	1960	Lackawanna River	37	Flood risk management, recreation	11,558
West Branch	Alvin R. Bush Dam	1962	Kettle Creek	226	Flood risk management, recreation	74,941
	Curwensville Lake	1965	West Branch	365	Flood risk management, water supply, recreation	119,467
	Foster J. Sayers Dam	1969	Bald Eagle Creek	339	Flood risk management, recreation	100,505
	George B. Stevenson	1955	First Fork Sinnemahon ging	243	Flood risk management, recreation	75,800
Juniata	Raystown Lake	1973	Raystown Branch Juniata	960	Flood risk management, recreation, hydroelectric power	762,000
Lower Susquehanna	Indian Rock Dam	1942	Codorus Creek	94	Flood risk management	27,657

Although there are more than a dozen flood control reservoirs in the basin, the cumulative hydrologic impact of these structures on the magnitude of flood events is tempered by their location in the watershed. Half of the Corps' flood control reservoirs are on headwaters and small streams with upstream watersheds ranging from 6.5 to 122 square miles. The remaining structures occur on medium-sized tributaries such as Cowanesque River, Bald Eagle Creek, and the Raystown branch of the Juniata. There are no flood control reservoirs on the Upper Susquehanna, Chemung, Middle Susquehanna, West Branch, or Juniata mainstems. Collectively, the drainage area upstream of the 14 dams is about 3,416 square miles, which is about 12% of the total watershed area (Table 3.1).

In addition to flood risk management, most reservoirs are also operated and maintained for recreational purposes, and in some cases water supply, water quality, low flow augmentation and water releases for hydroelectric power. Typically, reservoirs are operated to maintain a specific recreation pool elevation during the recreation season (Memorial through Labor Day). This means that reservoir outflows are normally equal to reservoir inflows, except during high water events. At some reservoirs, however, there are established downstream minimum targets that are greater than summertime flows, resulting in net increases in streamflows below some projects. Only Cowanesque Lake (Chemung) and Curwensville (West Branch) reservoirs have a water supply component. SRBC maintains storage in each of these reservoirs to be released for mitigation of consumptive use during low flow periods. Releases from Whitney Point Lake provide low flow augmentation when specified low flow conditions are reached at key gages. Whitney Point Lake is operated for environmental restoration purposes, for in-lake resources, and to benefit the downstream aquatic ecosystem. Cowanesque and Tioga-Hammond Lakes (both in the Chemung basin) also have storage dedicated to water quality mitigation. Reservoir releases are made during low flow periods to dilute abandoned mine drainage, which lowers stream pH and is toxic to aquatic life. Raystown Lake is the only reservoir with a dedicated hydroelectric power facility. Releases that maintain hydropower production tend to augment streamflows on the Juniata River during the low flow season.

3.2 Withdrawals and Consumptive Uses

Currently, the basin's population exceeds 4.1 million people, with the majority of the population residing in the lower basin. The population of the lower basin is expected to increase by 30% over the next 20 years (SRBC 2010). Consumptive water use continues to increase throughout the basin, with power production, municipal supplies and agriculture sharing the highest demand. On average, more than 50 billion gallons of water per day falls as precipitation within the basin (SRBC 2010). Despite the overall abundance of water, peak demand typically occurs during late summer and fall and can exacerbate the effects of low flow and drought conditions.

When water is withdrawn from a river or groundwater, that portion which is not returned is referred to as **consumptive use.** The major sources of consumptive use in the basin are water supply and power generation, which make up 55% and 25% of total consumptive use respectively. Maximum daily consumptive use associated with water supply is 325 million gallons per day (mgd). **Public water systems** throughout the basin have more than 340 surface water intakes and 7,500 groundwater wells.

Additionally, more than 1.2 million residents depend on self-supplied sources (wells). Demand varies spatially with population density and peaks during June through August (SRBC 2010).

Twenty major **electric power generation** plants – including fossil-fueled, nuclear, and hydropower plants – rely on the basin for water. The eleven largest facilities withdraw over 4.2 billion gallons of water per day. Of that volume, an estimated 4% (168 million gallons) is consumed in the generation process, and 96% is returned to the stream (PADEP 2009). Similar to water supply, power generation demands peak in the summer months. Most demands occur on medium-sized tributaries and large rivers.

Although consumptive use from irrigation is relatively low compared to other sectors, the timing and magnitude of peak demands coincides with low flow conditions within the basin. Maximum daily consumptive use for **golf course irrigation** is an estimated 50 mgd. Golf courses occur throughout the basin, but the demand for irrigation is concentrated on headwaters and tributaries in the Ridge and Valley and Piedmont provinces. In a recent assessment of water use by the **agricultural sector**, SRBC found that 785 agricultural operations each use more than 20,000 gallons per day during peak demands of the growing season. As with the golf courses, the highest concentration of agricultural lands occurs in the Ridge and Valley and Piedmont provinces.

Industrial water use includes water for manufacturing and mining. In the last few years, water for hydrofracturing associated with natural gas drilling in the **Marcellus shale formation** has grown significantly. The Marcellus shale formation underlies more than 72% of the basin (predominantly the Appalachian Plateau and portions of the Ridge and Valley), and associated water use permits now comprise more than 5% of the basin's permitted consumptive use. It is estimated that each gas well requires between 4 and 7 million gallons of water. Marcellus gas drilling has increased demand in remote areas of the West Branch and Upper Susquehanna subbasins and from headwater and small streams near drilling sites.

3.3 Existing Water Management Programs

In the late 1960s, recognizing the value of the basin's cultural and natural resources, Maryland, New York, Pennsylvania and the Federal government developed and entered into the Susquehanna River Basin Compact (signed December 24, 1970) to jointly address concerns related to increasing water demands and water quality impairments. The Compact established the Susquehanna River Basin Commission, an agency that transcends political borders and provides the foundation for joint watershed management. The Compact is one of only a handful in the eastern U.S., and nationally, it was one of the first[4] to give multi-faceted authorities to the Compact's governing body, including resource conservation, planning, flood control, drought and water quality mitigation (Voigt 1972).

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[4] In 1961, President Kennedy and the governors of Delaware, New Jersey, Pennsylvania, and New York created the Delaware River Basin Commission, which was the first Commission to have the force of law to oversee a unified approach to managing a river system without regard to political boundaries. The Delaware River Basin Compact served as template for the Susquehanna River Basin Compact. These two Commissions are distinct among river

In accordance with the Compact, SRBC is currently managing resources in an effort to achieve sustainable water resource development. Current programs include the consumptive use regulation program and a water withdrawal review program, which includes pass-by guidance. SRBC coordinates closely with New York State Department of Environmental Conservation (NYSDEC), Pennsylvania Department of Environmental Protection (PADEP), Pennsylvania Fish and Boat Commission (PAFBC), Maryland Department of Environment (MDE), Maryland Department of Natural Resources (MDNR) and the Corps on implementation of these programs.

The **consumptive use regulation program** requires users to mitigate for that portion of their use that is consumptive, particularly during low flows. During defined low flow periods, the user is required to stop its consumptive use or replace its consumptive use by releasing stored water. An alternative mitigation measure involves paying a fee for all consumptively used water, which SRBC applies to aggregated mitigation. Existing mitigation under this program occurs through releases from consumptive use mitigation 'banks' stored in Cowanesque Lake and Curwensville reservoirs (owned and operated by the Corps), and is specific to major water users in the basin (mostly power plants). Water is released under a current operating agreement with the Corps, when flow at the Harrisburg or Wilkes-Barre stream gages falls below Q7-10. The reservoir releases provide a 1:1 compensation for consumptive use during the release; they do not maintain Q7-10 within the stream. Currently, SRBC and the Corps are conducting an assessment that may lead to changing the release trigger from Q7-10 to a more frequent flow. If changes to the release trigger are made, it is expected that they would be consistent with downstream ecosystems needs identified in this report. At this time, the consumptive use associated with the agricultural sector is not addressed in this program; however, SRBC is actively involved in the PADEP, Bureau of Abandoned Mine Reclamation's ongoing mine pools program and has identified and initiated several projects for the purposes of mitigating agricultural consumptive use.

Under their **water withdrawal review and pass-by guidance,** SRBC assesses the potential of a ground or surface water withdrawal to adversely affect associated systems (SRBC Policy 2003-01; SRBC 2009). The current threshold for requiring a user to provide pass-by flows is 10% of Q7-10. Pass-by requirements are currently determined using several methods depending on type of withdrawal and affected stream. For surface water withdrawals from cold headwater streams in unglaciated regions, the PA/MD instream flow model is used (Denslinger et al. 1998). The Tennant method is used for surface water withdrawals from other stream types, with 20% annual daily flow (ADF) being a common pass-by requirement. More protective standards (25% ADF) are in place for Exceptional Value/High Quality (EV/HQ) streams. For groundwater withdrawals, aquifer testing is required as part of the application process, and this testing can be used to assess the relationship between the well and the stream (or wetlands). In addition to assessing impacts of individual withdrawals, SRBC also conducts a cumulative impact assessment to determine the extent of impact in combination with other basin users and has used this analysis to identify water-stressed basins.

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basin commissions in that they have many authorities over water management, which elsewhere are handled almost exclusively by state governments.

Section 4: Defining Ecosystem Flow Needs

To articulate the ecological flows needed to support this complex ecosystem, we organized and synthesized information using major habitat types that describe the basin's tributaries and mainstem in terms of watershed size, temperature, and flow stability (See Section 2.2). We also identified **groups of fishes, mussels, macroinvertebrates, reptiles, amphibians, birds and mammals** that are representative of the flow needs for other species; **vegetation community types** that represent major successional states; and major **physical processes and conditions** within the basin.

We used expert consultation and species distribution data to define species groups and associate each group with one or more major habitat types (Cooper 1983, Merit 1984, Brauning 1992, Hulse 2000, Podniesinksi et al. 2002, Walsh et al. 2007, PNHP 2009). Species within a group share a sensitivity or response to one or more aspects of the flow regime due to a common aspect of their life history. In this section, we describe common traits and habitat preferences for each species group. Flow-ecology diagrams and life history tables used to define species groups are included in Appendix 4.

Ecosystem flow needs were developed using existing literature, relevant studies, expert workshops, and small group meetings held between March 2009 and April 2010. Workshop participants used life history information and hydrologic characteristics for each major habitat type to identify the most sensitive periods and life stages for each habitat type. Ecosystem flow needs were stated in relation to three flow components: high, seasonal, and low flows.

In this section, we summarize literature and studies relevant to how flow affects biological conditions and physical and chemical processes in the basin. We conclude with a summary of ecosystem flow needs for each season.

4.1 Biological and Ecological Conditions

4.1.1 Fish

Key Elements

- Extreme low flows reduce availability of high velocity habitats and may decrease abundance of riffle-dwelling fishes and species with small home ranges.
- Seasonal flows maintain connectivity among stream habitats, especially during spring and fall spawning periods, and provide access to thermal refugia during summer.
- A decrease in summer and early fall flows may reduce access to shallow, slow velocity nursery habitats in margins and backwaters.
- High seasonal flows are needed to maintain habitat, and keep redds sediment-free, but flows cannot be so high that they scour and flush eggs from redds.
- Winter baseflows are needed to provide thermal refuge.

- Fall high flow pulses cue adult eel out-migration and summer baseflows provide lower velocities conducive to elver upstream migration.
- High seasonal flows are needed to provide velocities sufficient for shad migration and spawning in the spring and to facilitate juvenile out-migration in the fall; flows that are too high can inhibit migration.

The basin has a rich history of icthyofaunal surveys and collection records dating to the 1800s, which estimates that there are 117 fish species in 26 families within the mainstem and tributaries. Of those, three families, Cyprinindae (carps and minnows, 32 species), Centrarchidae (sunfishes, 14 species) and Percidae (darters and perches, 9 species) represent almost half of the species diversity (Snyder 2005). Sixty species are mostly insectivores, many of which are considered intolerant or sensitive. Conversely, the majority of introduced species (33) are piscivores and few are sensitive or intolerant. More than one quarter of all species have been introduced through a combination of human dispersal (stocking and bait bucket), natural dispersal (hurricanes), and vicariant events (stream capture). Two fishes, the northern redbelly dace (*Phoxinus eos*) and the Maryland darter (*Etheostoma sellare*) are thought to be extirpated from the basin (Snyder 2005). Reductions in population size and distribution within several families, including Petromyzontidae (lamprey), Cyprinidae (carps and minnows), Catostomidae (suckers), Ictaluridae (catfishes), Centrarchidae (sunfishes) and Percidae (darters and perches) have also been documented (Argent 1998).

We used fish traits to group species that share similar life history strategies, habitat niches, or other characteristics that make them sensitive to hydrologic alteration. These traits include body size, fecundity, home range, habitat associations, feeding habits, and flow-velocity tolerances (Cooper 1983, Winemiller and Rose 1992, Jenkins and Burkhead 1993, Vadas and Orth 2000, Hitt and Angermeier 2008). Species within groups often share multiple traits. For example, body size is generally associated with size of home range, increasing flow-velocity tolerance and habitat preference (Winemiller and Rose 1992, T. Hitt, personal communication 2009). Building on these associations, we aggregated species into five groups based on similar life history traits and the timing and location of flow-sensitive life history stages (Table 4.1).

Each species group is linked to one or more habitat types; however, every species within each group may not be present in a particular habitat type. For example, the group 'nest-building fishes' occurs in all habitat types. This group includes redbreast sunfish, smallmouth bass, fallfish, river chub, and creek chub. Along the mainstem, the redbreast sunfish and smallmouth bass may be most common representatives of this group; in the warm headwater streams in the Upper Susquehanna basin, fallfish and creek chubs may be the most common representatives. While the particular species may differ among habitat types, the flow needs within each group are generally similar. In this case, although their habitat and egg laying strategies differ, all nest-building fishes are sensitive to spring high flows that may scour nests in channel margins.

Table 4.1 Key traits and representative species within each group of fishes.

Group	Key Traits	Species
Cold Headwater	Similar needs defined by temperature thresholds	Brook trout, brown trout, *Cottus* spp.
Riffle Obligates	Small bodied, flow-velocity specialists who spend most of their life in riffle/run habitat	Margined madtom, longnose dace, central stoneroller, fantail darter
Riffle Associates	Resident species with moderate-sized home range that migrate to spawn and need access to, and connectivity between, riffle habitats	White sucker, shorthead redhorse, northern hog sucker, walleye
Nest Builders	Similar timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy (includes true nests, mound construction and ledge spawners)	Fallfish, creek chub, river chub, redbreast sunfish, smallmouth bass
Diadromous	Large-bodied, large home range species need connectivity during in- and out-migration, and during spawning (alosids)	American shad, alewife, American eel

Cool-cold headwater species. **Brook trout** (*Salvelinus fontinalis*) is the basin's only native salmonid species. While temperature is the most limiting factor for suitable habitat, hydraulic conditions and turbidity during low flow periods (August through December) also affect adult growth (Raleigh 1982, Denslinger et al. 1998). Reductions of flows during this period have had measurable impacts on size of adults (Hakala and Hartman 2004, Walters and Post 2008). Brook trout spawn in the fall, between October and November, depositing eggs in redds constructed in gravel or, occasionally, sandy substrates (Jenkins and Burkhead 1993). High seasonal flows maintain suitable substrate for redd construction and maintenance. Eggs and larvae develop through the late fall and early winter and are sensitive to decreased flows that could increase sedimentation, thermal stress or exposure, as well as to increased flows that may cause scour (Raleigh 1982, Denslinger et al. 1998, Hudy et al. 2005, Kocovsky and Carline 2006). After emerging, fry depend on low velocity shallow habitats with interstitial spaces for cover. **Brown trout** (*Salmo trutta*) also spawn during fall and require similar habitats. Brown trout were introduced to Pennsylvania in the late 1800s and now persist throughout the basin. At times, they displace brook trout, although brown trout tolerate warmer water temperatures.

Sculpins (family Cottidae) are commonly associated with brook and brown trout communities, but may occasionally be found in waters too warm for salmonids. In the Susquehanna basin, they seem to prefer very shallow riffles with fast velocities, characteristic of high elevation headwater streams (Gray and Stauffer 1999). Winter is a particularly sensitive season for sculpins, as Rashleigh and Grossman (2005) found that population sizes were regulated by overwinter population density due to intraspecific habitat competition between juveniles and adults. Density is directly related to habitat availability; therefore,

decreases in streamflow during winter could limit population size. Spawning occurs in riffles during spring, with males selecting a cavity beneath a rock and guarding development (Cooper 1983). Compared to other species, sculpins have a relatively small home range (less than 15 m) making them vulnerable to localized disturbance (Hill and Grossman 1987). Decreased flows could lead to local extirpation.

Riffle obligate species. Riffle obligates may occur in a wide range of stream types, from cold headwater streams to mainstem habitats, but all share common hydraulic and substrate preferences, spending most life stages in riffles with moderate to fast currents over sand and gravel substrates. Shallow, swift-moving habitats are among the first to change velocity and depth in response to changing stream stage. The species that depend on this habitat type rely not only on its presence, but also on its persistence, and are among the most sensitive of our fish groups (Persinger et al. 2002). Within this group, the **longnose dace** (*Rhinichthys cataractae*) is most adapted to high velocity habitats. During the larval stage (summer months), fry develop in quiet shallow margins, moving into fast water within six weeks (Edwards et al. 1983). They are one of the longest lived minnow species in the Pennsylvania with a relatively small home range (Hill and Grossman 1987). The **margined madtom** (*Notorus insignis*), is a warmer water species that prefers moderate-current riffle habitats underlain with gravel. It nests during late spring and early summer (May and June) under rock slabs (Jenkins and Burkhead 1993). Summer is a critical time for juvenile growth, with most growth occurring from July through September (Gutowski and Stauffer 1993). The **central stoneroller** (*Campostoma anomalum*) is ubiquitous in riffle and run habitats throughout many of the basin's stream types, also spawning in the spring months. The **fantail darter** (*Etheostoma flabellare*) has a less extensive distribution, and is generally found in warmer streams of the Piedmont region. For all members of this group, published observations of habitat and hydraulic needs during the overwinter period are limited; however, it is hypothesized that winter baseflows are critical for providing thermal refuge (D. Fischer, personal communication, 2009).

Riffle associate species. Riffle associates, including **white sucker** (*Catostomus commersoni*), **shorthead redhorse**, (*Moxostoma macrolepidotum*), **northern hogsucker** (*Hypentelium nigricans*), and **walleye** (*Sander vitreus*) are resident migratory species that rely on access to or connectivity between riffle habitats for one or more life stages. From spring to early summer, suckers migrate from medium-large streams to spawn over gravel and cobble in the riffles of small streams and headwaters. Site selection factors include velocity and depth (30 to 60 cm/s and 15 to 27 cm respectively) (Twomey et al. 1984). Eggs and larvae need similar velocities during development (Twomey et al. 1984). Introduced to the Atlantic slope, walleye are one of the first spring spawners to begin their migration (PFBC 2005). Each year, they migrate long distances to spawning grounds which include a range of habitats from flooded marshes to rocky, gravelly shoals (Cooper 1983).

Nest builders. Nest builders, including **fallfish** (*Semotilus corporalis*), **creek chub** (*Semotilus atromaculatus*), **river chub** (*Nocomis micropogon*), **redbreast sunfish** (*Lepomis auritus*), and **smallmouth bass** (*Micropterus dolomieu*) begin constructing nests on sand, gravel, or rocky ledges, for spawning during spring. Whether they use pools or riffle habitats, the nesting period is hydraulically sensitive for several reasons. If discharge is too high, guarding parents may abandon the nest, or the nest may be scoured (Aho et al. 1986). Smith (2005) found that smallmouth bass recruitment was most successful

when flows during the nesting season (June) remained within 40% of the median. Several of the nest builders construct nests in channel margins of large streams under shade and debris. At the edge of the wetted perimeter, these habitats are also sensitive to reductions in discharge. If discharge is too low, siltation may occur or nests may be dewatered, desiccating eggs and stranding larvae. Some species, such as smallmouth bass, have the ability to nest more than once in a season, increasing resilience to high flow events that may limit success of spring nests. Further, the nests constructed by members of this group are typically used by other species. For example, 27 minnow species use nests constructed by the genus *Nocomis*, either simultaneously or once abandoned (Sabaj et al. 2000). As with most spring spawning fishes, juvenile growth occurs during the warm summer months.

Diadromous species. Hydroelectric dams built on the lower Susquehanna restrict access to 98% of former diadromous fish habitat (Snyder 2005). Historically, herring stocks were reported migrating to the Upper Susquehanna headwaters near Cooperstown, NY, making it the longest migration on the Atlantic Coast (PFBC 2005). The Susquehanna River Anadromous Fish Restoration Cooperative (SRAFRC) was established to restore migratory fish populations by supporting improvements including fishways and lifts on the mainstem dams, and rearing and stocking programs. While shad runs have increased from less than 100 individuals in the early 1980s to a peak of more than 200,000 in the early 2000s, stocks are still far from the historic runs of the 1800s when they were considered the region's most valuable 'crop' (PBFC 2005). We selected three species to represent the needs of diadromous fishes upstream of the major hydroelectric dams: American shad (*Alosa sapidissima*), Alewife (*Alosa pseudoharengus*), and American eel (*Anguilla rostrata*).

In the lower mainstem, river herrings have several flow-sensitive life stages. With the exception of gizzard shad (*Dorosoma cepedianum*), the basin's river herrings (American shad, hickory shad, blueback herring and alewife) are anadromous, spending most of their adult life stage in the open ocean. Once mature, they begin migrating to natal rivers during the late winter and early spring, spawning in the Susquehanna in April and May (Myers and Hendricks 2006, Greene et al. 2009). For **American shad,** velocity is a critical factor during migration and spawning (Steir and Crance 1985, Bilkovic et al. 2002). Preferred spawning habitats include broad flats and shallow runs with moderate current (Zimmerman 2006). Research has demonstrated that the larval stage may be one of the most critical to establishing year class strength. While moderate velocities are needed to prevent suffocation and infection, spring high flow events after spawning and hatching have been shown to decrease survival rates (Marcy 1976, Crecco et al. 1983, Myers and Hendricks 2006, Greene et al. 2009). Juveniles emigrate during fall in response to temperature changes and the lunar cycle. Moderate velocities, adequate depths and access to vegetated habitats are needed during out-migration (Steir and Crance 1985, Greene et al. 2009). Like shad, **alewives** migrate to freshwater spawning habitats in early spring. Alewives spawn two to three weeks earlier than shad. They spawn in relatively shallow, slow velocity habitats including river margins, floodplain backwaters, and headwater ponds. Egg and larval survival is closely associated with stream velocity during spring and summer. Decreased survival and recruitment have been documented when velocity is too low or too high (Greene et al. 2009).

While **American eel** is known for its historic regional abundance and distribution, long-term data sets (including data from stations at Conowingo Dam on the lower mainstem) indicate that the eel

population has decreased across its range since the 1980s (ASMFC 2000, Haro 2000). Within the Susquehanna basin, historic habitat has been reduced from an estimated 52,331 km to 251 km due to many factors, including construction of major dams on the lower mainstem (ASMFC 2000). American eel is the basin's only catadromous species, ascending freshwater environments as juveniles (elvers) and spending its sub-adult (yellow eel) life stage (10 to 30 years) in freshwater habitats. Recent surveys have documented that elvers reach Conowingo Dam starting in the late spring (May) and peak in June and July (SRAFRC 2009). Velocity is the primary driver for the rate of upstream migration of elvers and they may stop or delay upstream migration due to high flows (Jessop 2000, Jessop 2003, Greene et al. 2009). Yellow eels can make extensive upstream migrations, and they typically do so in spring in response to higher flows and changes in water temperature (Hammond and Welsh 2009). When mature, adult (silver) eels begin to out-migrate from inland rivers and estuaries to the Sargasso Sea. Out-migration occurs from early fall to early winter and is typically cued by temperature, streamflow and moon phase (Hildebrand and Welsh 2005). Specific depths and velocities have not been documented as significant habitat characteristics for adult eels prior to out-migration; rather, it is thought that out-migration begins in response to a high flow pulse (Hildebrand and Welsh 2005, Greene et al. 2009, Eyler et al. 2010).

4.1.2 Aquatic Insects

Key Elements

- Groundwater flow through hyporheic zones provides refugia for aquatic insects.
- Winter baseflows need to be maintained for winter emerging species.
- Flow depletion can reduce macroinvertebrate density and richness, abundance of sessile, rheophilic, large-bodied, filter feeding and grazing taxa, and shift communities to tolerant taxa.
- Rapid wetting and drying leads to loss of benthic biomass.
- Summer baseflows provide thermal refuge for cold-water dependent taxa (stenothermal).

Studies have used experimental withdrawals and diversions, experimental reservoir releases, and monitoring during extreme hydrologic conditions to describe how aquatic insects respond to changing flow conditions (Feminella 1996, Boulton et al. 1992, Boulton 2003). Although some studies are taxa specific (e.g., Franken et al. 2008), responses of aquatic insects are often described for taxa that share functional traits or by using assemblage metrics (e.g., species richness). Quantitative and qualitative responses of species that share functional traits and/or assemblage metrics in other river systems can help set expectations about the mechanisms and potential severity of taxa response in the Susquehanna River basin. Poff et al. (2006) published a synthesis of 20 **functional traits** for 70 North American lotic insect families. Biological and ecological traits are 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 environmental conditions (Vieira et al. 2006). Using published responses, we identified a subset of traits that have been or are expected to be most sensitive to changes in hydrology within the Susquehanna River basin (Table 4.2).

Table 4.2 Publications documenting responses of macroinvertebrates to low flow conditions.

Responsive Traits and Metrics		Response to Withdrawal or Low Flow	Publications
Functional Traits (from Poff et al. 2006)			
Life History	Voltinism	Increase in taxa that are multivoltine	Richards et al. 1997
	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 et al. 2010
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 et al. 2010
	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
	Trophic Habit	Decrease diversity in grazers and shredders Decrease in abundance of scrapers and shredders Decrease in density and size of collector-filterer taxa Decrease densities of filter feeding and grazing insect taxa Increased predator densities	McKay and King 2006 Richards et al. 1997 Walters et al. 2010 Wills et al. 2006 Miller et al. 2007 Walters et al. 2010
	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	Rader and Belish 1999 McKay and King 2006
		Decrease in biomass	Walters et al. 2010 Blinn et al. 1995 Dewson et al. 2007b
	Species Richness	Decrease to taxonomic richness	Boulton and Suter 1986 Englund and Malmqvist 1996 Rader and Belish 1999 Wood and Armitage 1999 Wood and Armitage 2004
		No change to taxonomic richness	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	Decrease in density of EPT taxa	Wills et al. 2006 Dewson et al. 2007b

In addition to functional traits, macroinvertebrate 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 has varied among publications, the magnitude of flow alteration has been positively correlated with ecological change (Poff and Zimmerman 2010).

Lotic insect functional traits. Voltinism and desiccation tolerance are two life history traits that have been shown to respond to decreases in streamflow. Voltinism describes the number of generations a species can produce per year. Those species capable of one or fewer generations per year (univoltine and semivoltine, respectively) are sensitive to extreme disturbances, due to both increased frequency and magnitude of floods or droughts that encourage larvae to drift downstream, or result in stranding (Richards et al. 1997). Apse et al. (2008) found an increase in the proportion of bi- and multi-voltine species along a withdrawal index gradient in the Susquehanna Basin. Several adaptations are embedded in the ability to survive desiccation (dessication tolerance) such as the ability to diapause. Research has demonstrated that the relative abundance of species with low desiccation tolerance decreases in response to decreased flow magnitude (Delucchi and Peckarsky 1989, Williams 1996, Resh et al. 1998, and Lytle and Poff 2004). Also, taxa with limited desiccation tolerance were last and fewest to recolonize dewatered reaches once rewetted (Boulton 2003).

Insects with low mobility (limited ability to drift, fly or swim) are also vulnerable to increased frequency or severity of disturbances caused by extreme high or extreme low flow conditions. Taxa that have high mobility have been shown to maintain their abundance and distribution post-disturbance (Boulton 2003, Walters et al. 2010). The ability to recolonize (through drift, adult flying or generations), rather than desiccation tolerance, may explain presence after a disturbance event (Rader and Belish 1999).

Size at maturity is another morphological trait related to changes in streamflow. Taxa with a larger size at maturity, such as the Perlodids (Stoneflies), have been shown to decrease in response to decreasing flows, while those with small body size persist (Hinton 1960, Richards et al. 1997, Rader and Belish 1999, Apse et al. 2008, Walters et al. 2010). Additionally, extreme low flow events disproportionately affect genera with a sessile attachment state, such as case-building caddisflies, and promote free-living taxa (Richards et al. 1997).

Other traits responsive to hydrologic alteration include rheophily, trophic habit, thermal preference, and movement habit. Rheophily refers to the genera's habitat association and includes three trait states: obligate depositional (pools), depositional and erosional (pools and riffles), and erosional (riffles) (Vieira et al. 2006). Lake (2003) and Wills et al. (2006) found that decreased flow magnitudes led to decreased velocity and available riffle habitat and resulted in a decrease in the number and abundance of erosional taxa and an increase in the abundance of obligate depositional taxa. Trophic habit refers to the dominant feeding habit and includes five trait states: collector-gatherer, collector-filterer, herbivore, predator, and shredder (Cummins 1973). Aquatic insect samples from the Susquehanna basin were assigned to rheophilic and trophic trait states to illustrate how the relative abundance of taxa with different trophic habits differs by habitat association (Figure 4.1).

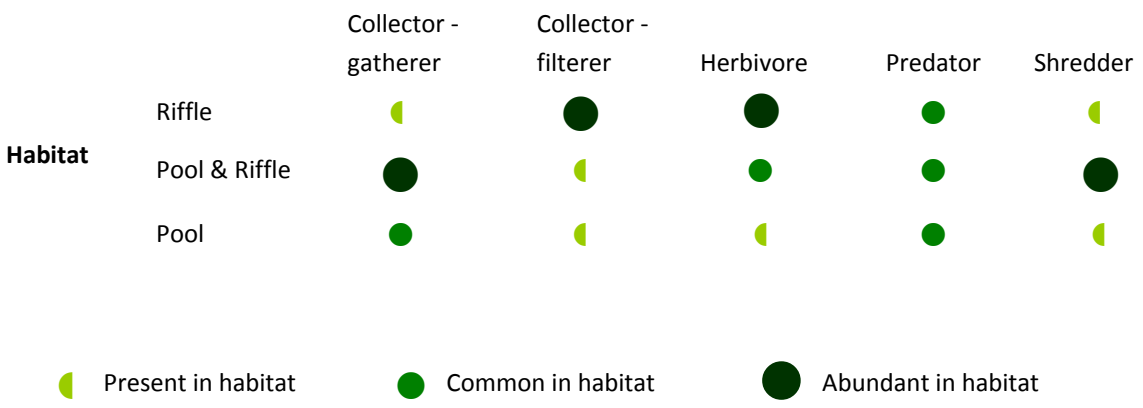


Figure 4.1 Relationship between trophic habit and habitat association for aquatic insect samples from the Susquehanna River basin (Data from SRBC).

Aquatic insect communities respond to shifts in habitat availability (velocity, depth, and wetted width) caused by hydrologic alteration. Decreases to seasonal flows that maintain persistent riffle and pool habitats have been found to alter trophic composition and abundance including decreases in densities of filter-feeding and grazing insect taxa (Richards et al. 1997, Wills et al. 2006, McKay and King 2006, Apse et al. 2008, Walters et al. 2010). With the decrease in feeding specialists, a commensurate increase in predator species' abundance and size has been documented (Miller et al. 2007).

Species, genera and assemblage metrics. Macroinvertebrate responses to hydrologic alteration have also been measured using assemblage metrics such as Hilsenhoff Biotic Index (HBI), species richness, EPT richness, and species abundance. In response to decreasing flow magnitudes, habitat persistence and species richness decreased (Boulton and Suter 1986). Documented responses to drought include elimination of taxa groups including free-living caddisflies and stoneflies, and an increase in Tipulidae and Chironomidae, two families associated with temporary lotic habitats (Williams and Feltmate 1992, Williams 1996). In response to increasing low flow magnitudes, specifically reservoir releases made to mitigate impacts of extreme low flow conditions, Bednarek and Hart (2005) measured an increase in family and EPT richness. Using more than 600 macroinvertebrate samples in the Susquehanna River basin, Apse et al. (2008) found a relationship between increasing withdrawal index and increasing tolerant taxa as measured by HBI. Several studies have also shown no response or an increase in diversity in response to flow alteration. While the direction of response has varied among publications, the magnitude of flow alteration has been positively correlated with ecological change (Poff and Zimmerman 2010).

Decreasing low flow magnitudes have also been associated with changes to abundance metrics, including density, biomass and total count (Rader and Belish 1999, McKay and King 2006). In studies using experimental withdrawals, responses included decreases in overall macroinvertebrate density, number of EPT taxa, number of filter-feeding and grazing insects, and available habitat (Wills et al. 2006, Dewson et al. 2007, Walters et al. 2010). Although many studies focus on flow conditions and macroinvertebrate assemblages in summer months, other studies underscore the importance of

maintaining suitable flow conditions during fall and winter months. In one study on a small stream, constant withdrawals through fall and winter reduced streamflow by approximately 90%; invertebrate density and richness were both reduced and the altered community was comprised of 80% 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 (Flannigan 1991, Clifford 1969). While the timing of flow needs for aquatic insects often parallels flow needs for fish, the sensitivity and potential severity of response may differ. For example, in small streams, instream flow recommendations developed using IFIM for target benthic fish (sculpin) underestimated habitat loss for aquatic insects by up to 25% (Gore et al. 2001).

Many studies have also documented the impacts of increased flow variability or rate of change on macroinvertebrate assemblage metrics. Blinn et al. (1995) found that rapid wetting and drying of stream margins led to a decrease of total available energy, biomass, and community shifts, with varial zone biomass totaling only 33% of persistent habitat biomass.

4.1.3 Mussels

Key Elements

- Extreme low flows increase risk of exposure and predation of mussel beds.
- Significantly reduced flow magnitudes may cause local extirpation or reduced growth.
- Drought can reduce individual fitness of mussels, even though some mussel species may be drought tolerant.
- Increased magnitude and frequency of high flow events can lead to habitat instability, reduced recruitment, and reduced carrying capacity of mussel habitat.
- Decreased magnitude or frequency of high flows can lead to habitat degradation, including embeddedness, lack of appropriate substrate size, and aggrading channel morphology
- During spawning season and glochidia release, flows are needed to facilitate host fish interaction and glochidia distribution.
- Increased high flows in spring or decreased low flows in summer may reduce host fish availability.
- Natural flow regimes can reduce risk of establishment of non-native mussel species.

At least a dozen species of native mussels are known to occur within the Susquehanna River basin. These species have a variety of traits related to habitat and velocity preference, body size, longevity, length of brooding, timing of spawning and glochidia release, and use of host fish (Strayer and Jirka 1997, Nedeau 2000, Bogan and Proch 1992, Grabarkiewicz and Davis 2008). In general, mussel species in the Susquehanna basin have been undersampled compared to other basins, and there is relatively little known about the mussel fauna and species populations throughout many of the basin's tributaries. There are a few exceptions, including surveys of the Upper Susquehanna in New York, monitoring associated with lower basin hydropower reservoirs and a recent aggregation of occurrence data into the

Pennsylvania Aquatic Community Classification database (Strayer and Fetterman 1999, Normandeau 2006, Walsh et al. 2007).

In consultation with regional malacologists, we selected eleven species known to currently occur in the basin and reviewed literature and studies that describe relationships between flow conditions and growth, fitness, and distribution of these species (Anderson and Bier 2007; D. Crabtree, personal communication, 2009; R. Villella, personal communication, 2009; Smith and Meyer in review). We aggregated these species into three groups defined by a combination of hydraulic habitat associations (velocity, depth, substrate and impoundments) and tolerance to changes in streamflow.

Primarily riverine species. These species are most associated with riverine habitats and include **green floater** (*Lasmigona subviridis*), **elktoe** (*Alasmidonta marginata susquehannae*), **brook floater** (*Alasmidonta varicosa*), and **creeper** (*Strophitus undulatus*). All four are long-term brooders that spawn between June and September, depending on the species. Females are gravid through the fall and winter and release glochidia during the following spring and early summer (CTDEP 2003, Mulcrone 2005, Zimmerman 2006). As opposed to short-term brooders, which complete the reproductive cycle within one season, long-term brooders are in a different reproductive stage during each season, and therefore thought to have a year-round sensitivity to changes in streamflow (R. Villella, personal communication, 2009). These species use a variety of fish hosts, including several small-bodied and localized riffle fishes. As discussed previously, riffle obligate fishes are particularly sensitive to changes in hydraulic habitat associated with reductions in streamflow magnitude. Reductions or localized extirpation of host-fish populations would impact recruitment. Conversely, increases in streamflow magnitude during low flow seasons can reduce the concentration of host fish and likelihood for glochidia infestation and deter display of intricate lures, also resulting in reduced recruitment efficiency (Layzer 2009, D. Crabtree, personal communication, 2009). Green floater and elktoe require good water quality (Grabarkiewicz and Davis 2008, North Carolina Resources Commission 2010). Green floater is not drought tolerant and is more commonly found in streams with stable streamflow than in streams with frequent droughts or spates (R. Villella, personal communication, 2009). Elktoe is intolerant of impoundments (Grabarkiewicz and Davis 2008).

Facultative riverine species. These species include **yellow lampmussel** (*Lampsilis cariosa*), **triangle floater** *(Alasmidonta undulata*), **eastern lampmussel** (*Lampsilis radiata*), and **eastern elliptio** (*Elliptio complanata*). They are found in a wide range of habitats from small streams to large rivers and lakes. These species generally use slow to moderate current, including backwaters and standing water. Host fish include both lotic and lentic species. Yellow lampmussel is declining throughout its range; however, it remains relatively abundant in the Susquehanna mainstem, and has expanded its distribution in the Chemung and Upper Susquehanna basins (Strayer and Fetterman 1999, NatureServe 2005). Triangle floater is considered rare in the Susquehanna; it is generally an indicator of stable substrates and is widely distributed but rarely abundant (Watters 1995, Normandeau Associates 2006).

Yellow lampmussel, triangle floater, and eastern lampmussel are long-term brooders that spawn in late summer / early fall and release glochidia in spring / early summer. Eastern elliptio is a short-term brooder that spawns in spring / early summer and releases glochidia later in the summer. In the basin,

research has shown that American eel are likely to be a preferred host for eastern elliptio (R. Villela, personal communication, 2009). The decline of this species in the Susquehanna is thought to be tied to declining eel populations. In the southeastern U.S., eastern elliptio was found to be tolerant of emersion during drought conditions (Johnson 2001). While many mussel species are adapted to survive low flow conditions, reductions in individual fitness, specifically decreased glycogen content, have been documented during dry periods (J. Layzer, personal communication, 2010).

Primarily lentic species. These species include **white heelsplitter** (*Lasmigona complinata*), **eastern floater** (*Pyganodon cataracta*), and **cylindrical papershell** (*Anodontoides ferussacianaus*). These species primarily use slow-moving river habitats, including channel margins. They use a range of host fishes, including mobile, large-bodied species and small-bodied localized species. Of the three groups, these are generally the most tolerant of silt, mud, and nutrient-rich water. All three species are long-term brooders that spawn in summer / early fall and release glochidia the following spring. These species could respond locally to loss of backwater and slow-moving habitats along large rivers, but generally, of the three groups, these species are the most tolerant of disturbed conditions and can tolerate impoundments (Strayer and Jirka 1997, Nedeau 2000).

Most research documenting flow-ecology relationships for mussel species has been associated with community response to episodic drought events. Mussels have limited mobility during juvenile and adult stages and are therefore highly sensitive to localized physical and chemical changes in habitat conditions, specifically dissolved oxygen (DO), temperature, depth, and velocity (Sparks and Strayer 1998, Johnson et al. 2001, Golladay et al. 2004, Haag and Warren 2008). Johnson et al. (2001) found that during severe drought conditions in the southeastern U.S., individual mussel mortality was associated with two thresholds: a reduction in velocity to less than 0.01 m/s, and a reduction in DO to less than 5 mg/L. Layzer and Madison (1993) noted absence of mussel assemblages associated with low velocity and shallow stream depths (less than 6 cm). Haag and Warren (2008) also documented a 65-85% decrease in mussel density in small stream habitats when median summer flows were reduced approximately 50%. In small streams and tributaries that were completely dewatered, no live mussels were found. Mussels had a higher survival rate in large river habitats due to maintenance of surface flows and longitudinal connectivity during the drought event. Golladay et al. (2004) corroborated this result and emphasized the importance of longitudinal connectivity and refuges that maintain suitable DO and temperature during drought events.

4.1.4 Crayfish

Crayfish are a keystone species within the Susquehanna basin. They have a significant influence on periphyton and macrophyte composition and can regulate fine particulate organic matter (Hart 1992, Kulmann and Hazelton 2007). They are also an important, and at times exclusive, food source for basin fish, reptiles, amphibians, birds, and mammals, including the queen snake, hellbender, and to some extent, northern river otter (Hulse et al. 2000, P. Petokas, personal communication, 2009).

Crayfish species recently documented in the basin include the Allegheny crayfish (*Orconectes obscurus*) and northern clearwater crayfish (*Orconectes propinquus*), which are found in the upper reaches of mainstem tributaries; the Appalachian brook crayfish (*Cambarus bartonii*), which is found primarily in

the upper reaches of small headwater streams; and the invasive rusty crayfish (*Orconectes rusticus*), which is now the most abundant and widely distributed crayfish in the basin (Kuhlmann and Hazelton 2007). A recent survey in the Upper Susquehanna basin documented change to historic populations and found all species with the exception of the spiny-cheek crayfish (*Orconectes limosus*), which is thought to be extirpated. Crayfish are generally reproductively active in the fall, with females in berry (carrying eggs) through the spring. Young of year usually emerge during the summer (Jones and Bergy 2007).

During drought periods and on intermittent streams, crayfish have been found in burrows or in wetted habitat under cobbles and boulders (Jones and Bergy 2007). Unlike aquatic insects, they do not typically drift downstream. During drought conditions, reduced carapace growth and increased susceptibility to predation have been documented (Taylor 1982, Acosta and Perry 2001, Flinders 2003, Flinders and Magoulick 2007). Jones and Bergy (2007) found that riffle-dependent crayfish were especially sensitive under these conditions because they require maintenance of flow refuges under cobbles and boulders and in the hyporheic zone for aestivation[5].

4.1.5 Reptiles and Amphibians

Key Elements

- Winter and spring high flows fill vernal pools and intermittent streambeds used for amphibian breeding and egg and larval development.
- Several species are particularly sensitive to increased frequency and duration of low flow events, which can increase temperature and sediment concentrations, and decrease dissolved oxygen.
- Decreases in winter flows and/or increased flashiness could expose or destabilize stream beds, banks, and channel margins that several turtles and amphibians use for overwinter habitat.
- Small and large flood events are required to maintain floodplain habitats (sediment texture and vegetation) for turtle nesting and amphibian and reptile burrowing sites.

At least 35 species of reptiles and amphibians, including salamanders (12 species), toads (2), frogs (9), turtles (8) and snakes (4), use riverine and riparian habitats in the Susquehanna River during various life stages. Based on literature review and consultation, we selected fourteen species to represent the major life history traits of reptiles and amphibians and organized them into three major groups: aquatic-lotic species, semi-aquatic lotic species, and riparian and floodplain-terrestrial and vernal habitat species. Appendix 4 summarizes life history information for these species, including timing and habitats used during hibernation, breeding, juvenile development and adult growth.

Aquatic-lotic species. These species depend on flowing waters. Within this group, some species spend most life stages in flowing waters; others have specialized stream-dependent feeding habits; and others have phenotypic traits (e.g., lungless) adapted to flowing environments. Of all reptiles and amphibians,

[5] Similar to hibernation, aestivation is a state of reduced metabolism, but is used to persist through dry or warm conditions.

this group of species is expected to be most sensitive to changes in instream conditions, including water quality, flow velocity and depth, instream habitat availability, and abundance of specific food items.

Adult **northern map turtles** (*Graptemys geographica*) depend on large river habitat (generally more than 50 m wide) and prefer slow-flowing and deep water (more than 1 m) for hibernation, mating, and adult growth (Hulse 2000). They spend a significant amount of time basking on large woody debris and exposed rocky outcrops within the channel. Communal basking congregations form in the late spring and early fall (Hulse et al. 2000, Richards and Seigel 2009). Pluto and Bellis (1986) summarized 924 observations of habitat use on the Raystown Branch of the Juniata River, finding juveniles dominated shallow, near-shore habitats and adults dominated open-water habitats. Connectivity between habitats is important, as map turtles move to nest. On the lower Susquehanna River, Richards and Seigel (2009) documented map turtles making relatively long distance movements to nest. They primarily feed in the water on mollusks, aquatic insects, and fish; hibernate in river bottoms and under submerged logs; and require high overwinter dissolved oxygen levels (Crocker et al. 2000).

Like northern map turtles, **common musk turtles** (*Sternotherus odoratus*) use aquatic habitats for hibernation, mating, and adult growth. Regionally, hibernation occurs between October and mid-April in soft mud (Ernst 1986). Most mating takes place during spring and fall before and after hibernation. Musk turtles use a variety of habitats, including small shallow streams and backwaters of large rivers, primarily in the Ridge and Valley and Piedmont provinces. They are opportunistic carnivores that feed by walking along the river bottom (Stabler 2000, Hulse et al. 2000). The musk turtle basks in aquatic habitats and is seldom found out of water. It is typically found with the algae *Basicladia* covering its shell. *Basicladia* only grows on turtle shells (Stabler 2000).

Northern water snakes (*Nerodia sipedon*) and **queen snakes** (*Regina septemvittata*) are both specialist feeders that depend on aquatic food sources. The northern water snake feeds on fish and amphibians and is known to herd schools of fish and tadpoles to the water's edge. This snake is ubiquitous throughout the basin, using both fast- and slow-moving streams as well as lakes, marshes, and ponds (Gillilland 2000, Hulse et al. 2000). Queen snakes feed almost exclusively on crayfish, specifically newly molted crayfish. They require crayfish to be abundant, not just present. They are found primarily in moderate- to fast-flowing streams and small rivers throughout the Piedmont and are seldom found more than 2 m from the stream margin as their skin is permeable and prone to desiccation (Smith 1999). Hibernation occurs from mid-October to late April in crevices, including muskrat and crayfish burrows (Hulse et al. 2000).

Some salamanders also depend on aquatic habitats for all four of their major life stages: breeding and egg laying, egg and larval development, metamorphosis/transformation, and adult growth. The **eastern hellbender** (*Cryptobranchus alleganiensis*) inhabits medium-sized streams and large rivers (3rd and 4th order) (P. Petokas, personal communication, 2009). They prefer fast-moving cool- and coldwater streams and are sensitive to changes in dissolved oxygen, sediment, and temperature (Hulse et al. 2000, Humphries and Pauley 2005). They are the only salamanders to have lungs but do not use them to breathe; instead, they rely on the high surface area of their wrinkled skin for gas exchange (Petokas, personal communication, 2009). Adults can be found under large rock slabs, while juveniles find refuge

in the interstices of gravel beds and under smaller rocks. They have been surveyed at various depths ranging from 16 to 56 cm on a tributary to the New River, WV, to 8 to 20 inches in the French Creek drainage (Hulse et al. 2000, Humphries and Pauley 2005). Like the queen snake, they feed almost entirely on crayfish and are not found in streams that do not have substantial crayfish populations. Despite its size, the hellbender has a small home range, which makes the species particularly susceptible to localized alterations in water quality or streamflow (Hills and Bellis 1971).

Species of salamanders within the family Plethodontidae, or **lungless salamanders**, live within stream banks and riparian areas. These include dusky salamanders, brook salamanders, spring salamanders and red and mud salamanders. Because they require gas exchange through their skin, plethodontids are particularly sensitive to changes in surface hydrology, groundwater levels, and water and air temperatures (Moore and Sievert 2001). One of the most sensitive of the stream-dwelling plethodontids is the **northern dusky salamander** (*Desmognathus fuscus fuscus*). They tend to be common throughout headwater and small woodland streams. They are most common where predatory fish are absent and they can be the top predator. They require flowing water year-round, including during winter. They nest in stream banks and are highly dependent on streamside vegetation and bank stability (Orser and Shure 1975). Mating occurs in the spring and fall, with egg-laying in late summer. Egg and larvae develop instream through the early fall, and transformation occurs the following summer.

Semi-aquatic lotic species. These species rely on flowing waters or habitats within the active channel for one or more life stages, but spend part of their life cycle in floodplain or upland environments. These species may only be sensitive to instream conditions during particular life stages (for example, overwintering), but may require access to stream margins for specialized feeding or mating habitat during the rest of the year.

Wood turtles (*Glyptemys insculpta*) are most common in headwater streams and small and medium-sized rivers within mountainous areas of the Ridge and Valley province. They are associated with brook trout streams and are intolerant of pollution. They overwinter in banks and stream bottoms. Like the map and common musk turtles, wood turtles require flowing waters and high dissolved oxygen conditions during winter (Graham and Forseberg 1991, Crocker 2000, Greaves 2007). They are only capable of small and slow movements to avoid freezing or poor water quality conditions during the overwinter period (Graham and Foreseberg 1991). Mating occurs aquatically, primarily in the early fall. Nesting occurs the following spring in sandy, well-drained deposits in the riparian corridor. While the wood turtle is primarily found in riparian corridors, they have been documented using the stream channel for refuge during extremely cold periods or during droughts (Hulse 2000).

Bog turtles (*Glyptemys muhlenbergii*) are found in the lower Susquehanna basin tributaries in spring-fed wetlands, small, open streams, and seepages. They are extreme habitat specialists and require hydrophytic vegetation, including sedge tussocks, bulrush and smooth alder (Hulse et al. 2000). They also require interspersion of shallow wet and dry patches. These habitats are sensitive to changes in ground and surface water hydrology (T. Coleman and G. Gress, personal communication, 2010). Bog turtles have a relatively small home range. One Virginia study found that 75% of all net movements

were less than 20 m, and less than 2% more than 100 m (Carter et al. 2000). This implies that habitat degradation or loss could have severe implications for individual and genetic survival.

Eastern ribbon snakes (*Thamnophis sauritus*) are found in a variety of habitats within the Ridge and Valley and Piedmont provinces. Although it is a partially arboreal species, it is a specialized feeder (on amphibians and small fish) and requires proximity to permanent standing or flowing water. They may use a variety of habitats for hibernation, ranging from underwater to high ground.

Northern leopard frogs (*Rana pipiens*) are found along vegetated margins of slow-flowing rivers and streams and in marshes and swamps throughout the Appalachian Plateau and Ridge and Valley provinces. They overwinter at the bottom of streams and rivers, remaining in a quiescent state. They typically use vernal habitats for breeding and egg-laying.

Riparian and floodplain-terrestrial and vernal habitat species. These species do not use the stream channel for any life stage, but they do rely on overbank hydrologic processes to maintain floodplain habitats (T. Merit, personal communication, 2009). These species include **eastern hognose snake** (*Heterodon platirhinos*), **eastern gray treefrog** (*Hyla versicolor*), **fowler's toad** (*Bufo fowleri*), **eastern spadefoot** (*Scaphiopus holbrookii*), and **mole salamanders** (Jefferson salamander, [*Ambystoma jeffersonianum*], spotted salamander [*Ambystoma maculatum*] and marbled salamander [*Ambystoma opacum*]). These species benefit from seasonal and interannual high flow events that maintain vernal and intermittent habitats within the floodplain, maintain vegetation succession, and maintain channel processes. The eastern hognose snake typically uses sandy rivers and floodplains throughout the Ridge and Valley province. There is a discrete population along the Allegheny Front. The fowler's toad and eastern spadefoot are also commonly found in open, low-lying areas with sandy and gravelly well-drained soils, including within floodplains. Fowler's toads, eastern gray treefrogs and the mole salamanders use vernal habitats for mating and/or egg and larval development. Mole salamanders often use upland forests with vernal pools, but may also breed in intermittent streambeds that fill with water during winter and spring.

4.1.6 Floodplain, Riparian and Aquatic Vegetation

Key Elements

- Increases or decreased in duration of inundation may encourage community transition along the inundation gradient.
- Juvenile fish and many macroinvertebrate species depend on submerged and emergent aquatic vegetation.
- High flow pulses maintain wetland vegetation in headwaters and small streams.
- Decreased flow magnitude can lead to desiccation of submerged, emergent, and riparian vegetation.
- During winter, high flow events and associated ice scour promote early successional vegetation.
- Small and large floods maintain habitat structure and diversity.
- Spring high flows reduce encroachment of woody vegetation.

In addition to regional climate and underlying geology, the distribution and structure of aquatic, riparian and floodplain vegetation communities are driven by the river's flow regime and associated geomorphic and chemical processes (Naiman et al. 2005, Merritt et al. 2010). Vegetation community composition and structure are largely governed by several related factors, including disturbance frequency and severity, inundation frequency and duration, landscape position, substrate stability, and the available propagules or seed bank (Oliver and Larson 1996, Perles et al. 2004). Related species traits include seed dispersal mechanisms and timing, soil moisture requirements, and preferred substrate and light conditions (Burns and Honkala 1990, Zimmerman 2006, Merritt et al. 2010).

Several major field assessments have been completed for riparian and floodplain communities within the Susquehanna River basin and for similar communities in the adjacent Delaware River basin and other nearby basins (Fike 1999, Podniesinski et al. 2002, Perles et al. 2004, Eichelberger et al. 2009). These reports provide considerable information about the regionally dominant fluvial-related disturbance regimes (ice scour, flood, and drought) and successional relationships that sustain the complex and diverse structure and associated niche habitats critical to many insects, reptiles, amphibians, migratory and breeding birds and mammals (Perles et al. 2004).

Eleven vegetation community types can be organized into four major successional states: submerged and emergent bed, herbaceous, scrub-shrub, and floodplain forest (Podneisinski et al. 2002, E. Zimmerman, personal communication, 2010) (Figure 4.2). Within the community types, we focused on the life history strategies of canopy dominants, recognizing that their establishment, presence and abundance is both indicative of soil moisture and substrate composition and also determines light availability for subcanopy and understory vegetation. Detailed community descriptions are included in Appendix 5.

Islands are common in the Susquehanna mainstem and within major tributaries. Island shorelines are generally less modified than streambanks and often provide good illustrations of the community types and successional states with minimal physical modifications (Photo © T. Moberg / TNC).

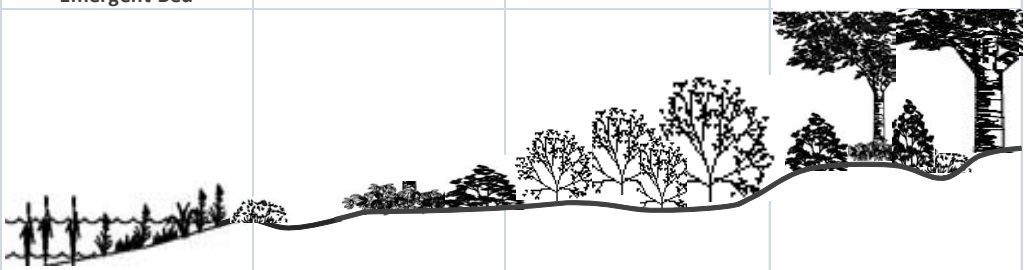
	Submerged and Emergent Bed	Herbaceous Community	Scrub-Shrub Community	Floodplain Forest
Elevation Lateral position and distance from active channel				
Disturbance Severity of flood and ice scour	Severe	Severe to moderate	Moderate	Moderate to low
Inundation Inundation duration	Permanent to semi-permanent	Seasonal to temporary flooding	Seasonal to temporary flooding	Temporary flooding
Example communities	Riverweed (*Podostemum ceratophyllum*)	Indian grass (willow) riverine shrubland (*Sorghastrum nutans*)	Speckled alder - dogwood riverine shrubland (*Alnus rugosa, Cornus florida*)	Sycamore floodplain forest (*Plantanus occidentalis)*
	Water willow emergent bed *(Justicia americana)*	Sedge-spotted joe-pye weed riverine herbaceous vegetation (*Eupatoriadelphus maculatus*)	Mixed hardwood riverine shrubland (*Plantanus, Acer, Betula*)	Sycamore mixed hardwood floodplain forest (*Betula nigra*)
	Lizard's tail emergent bed (*Saururus cernuus*)	Riverside scour vegetation	Black willow slackwater shrubland (*Salix nigra*)	Silver maple floodplain forest (*Acer saccharinum*)

Figure 4.2 Examples of aquatic, riparian, and floodplain communities of the Susquehanna basin along elevation, disturbance, and inundation gradients.

Submerged aquatic vegetation and emergent bed. **Submerged aquatic vegetation** (SAV) occurs within portions of the active channel that are permanently inundated during the growing season. It is present in both pools and riffles. SAV provides a substrate for epiphytic algae, increases habitat surface area, creates physical structure, and provides cover and low-velocity refuges. Presence of SAV is linked to increased macroinvertebrate abundance and is important for juvenile and adult fish, including juvenile alosids and adult silver eels preparing for out-migration (Hutchens and Wallace 2004). SAV requires flows that maintain inundation during the growing season, as growth rates are particularly sensitive to decreases in river stage that expose leaves and stems (Munch 1993).

One of the basin's most sensitive SAV species is *Podostemum ceratophyllum* (riverweed). *Podostemum* is a perennial macrophyte found in moderate to high velocity riffles. Extensive populations have been documented in many tributaries and mainstem reaches within the Susquehanna (Munch 1993). Summer observations during drought periods (1989-1992) documented stream flows low enough to expose plant leaves, branches, and bases. On Aughwick Creek, the loss of upright branches and leaves was associated with a five-day duration of 15 cfs (July Q80 or Aug Q60). Plant bases began to be exposed at streamflows of 10 cfs or less (July Q90 or Aug Q77). Although this disturbance stunted total seasonal growth, it was

followed by a second period of growth occurring from September to October when average hydrologic conditions resumed (Munch 1993).

Emergent bed communities occur within portions of the active river channel with a semi-permanent inundation frequency including island heads, edges of bars, channels and terraces. Communities within the basin include water willow (*Justicia americana*) and lizard's tail (*Sarurus cernuus*) emergent beds. These communities are subject to and rely upon severe ice and flood scour to promote regeneration (Perles et al. 2004). During the growing season, emergent beds can tolerate inundation under high flow conditions and exposure under low flow conditions, but the frequency and duration of inundation and exposure can impact the condition of emergent vegetation, specifically for water willow. Water willow has been shown to decline after just four weeks of complete inundation, and after eight weeks of desiccation, or exposure of the plant base. Experimentally extending desiccation led to a cumulative response during subsequent events in the same growing season (Strakosh et al. 2005).

Herbaceous communities. Herbaceous communities occur within portions of the channel that have undeveloped soils and are subject to seasonal temporary flooding. Community types include Indian grass (willow) riverine shrubland, the riverside scour community (including bedrock outcrops, shorelines and flats), and the sedge-spotted joe-pye weed community. These communities are maintained by moderate to severe ice scour associated with high flow events during the winter months and by inundation from seasonal and high flows in the spring and summer. Johnson (1994) found that decreases in magnitude and frequency of high flow pulses can lead to riparian encroachment and establishment of woody vegetation. Additionally, most of these communities persist on rapidly draining to well-drained substrates (cobble, gravel and sand) and have adapted to survive droughty conditions during the majority of the growing season. Low flow conditions also discourage woody recruitment.

Scrub/shrub. Considered the transition community between herbaceous and forested communities, the scrub/shrub community is maintained by a balance of inundation frequency and duration and moderate to severe flood and ice scour. Sites are dry enough for woody establishment but the scrub/shrub structure is maintained by structural damage from ice scour and floods, limited growth during periods of inundation, and poorly developed soils. Scrub/shrub communities are typically found on flats, bars and low terraces of islands and banks. During spring, floods and high flows scour stream margins, inundate and saturate floodplains, and facilitate seed dispersal. For some species, including black willow (*Salix nigra*), seed viability is greatly reduced after only a few days of dry conditions (Burns and Honkala 1990).

Floodplain forests. Sycamore, sycamore-mixed hardwood (river birch and green ash) and silver maple are the dominant floodplain forest communities (Podneisinski et al. 2002, E. Zimmerman, personal communication, 2010). These community types differ in lateral position on the river: sycamores compete best on well-drained coarse gravel and cobble substrate (higher energy environments) and silver maple dominates in slower, backwater habitats characterized by fine sands and silts and abundant organic matter. Both communities rely on high flow pulses and overbank processes to maintain suitable substrate size and moisture conditions for seedling establishment and dispersal and to reduce competition with upland woody species (Burns and Honkala 1990, Zimmerman 2006). These events

typically occur during winter and spring, although they may occur at any time of year. While species are dependent on temporary flooding during the growing season, semi-permanent inundation may cause mortality. Sycamore seedling mortality has been documented when inundation exceeds two weeks; silver maple may tolerate saturated and inundated conditions for at least a few days and up to three months.

4.1.7 Birds and Mammals

Key Elements

- Many bird and mammal species rely on riparian and floodplain habitats maintained by seasonal flooding.
- During winter and early spring, seasonal high flows are needed to reduce exposure of mammal dens (e.g., muskrat).
- Seasonal high flows are needed to limit connectivity or land bridges between mainland and island habitats to avoid predatory introduction to bird rookeries.
- Birds and mammals need access to aquatic food resources, including macroinvertebrates, small fishes, and vegetation.

Many bird and mammal species are frequently associated with riparian habitats and floodplain forests. Those with the closest associations rely upon (rather than merely use) access to stream-derived food resources and availability of bank, floodplain and island habitats. In addition to the species that are directly affected by streamflow, many other birds and mammals benefit from food and habitat available in riparian and floodplain habitats. These species may respond indirectly to shifts in food availability or vegetation composition and structure caused by streamflow alteration.

Birds. Dozens of bird species use riparian and floodplain habitats for nesting and breeding. In general, birds are sensitive to streamflow alterations that lead to a reduction of available food resources and/or reduction in quality of foraging or breeding habitats. A few species particularly sensitive to these changes include the Great Egret (*Casmerodius albus*), Great Blue Heron (*Ardea herodias*), Black-crowned Night Heron (*Nycticorax nycticorax*), Bald Eagle (*Haliaeetus leucocephalus*), Osprey (*Pandion haliaetus*), Belted kingfisher (*Megaceryle alcyon*), Bank Swallow (*Riparia riparia*), and Acadian Flycatcher (*Empidonax virescens*).

Colonial birds. Great Blue Heron, Great Egret and Black-crowned Night Heron are especially sensitive to prey availability and maintenance of rookeries. The **Great Blue Heron** is the largest native breeding bird in Pennsylvania and forages in aquatic habitats, including streams and rivers. It prefers fish, and it generally hunts opportunistically in shallow areas less than 50 cm in depth (Short and Cooper 1985). Forage habitats can be several miles (up to 50) from rookeries, which are typically located at higher elevations in tall trees isolated from disturbance (Brauning 1992, PGC and PFBC 2005). This species is particularly sensitive to changes in water quality and food availability in forage areas, and forest disturbance near colonial rookeries (PGC and PFBC 2005).

Wade Island, on the Susquehanna mainstem near Harrisburg, supports Pennsylvania's largest **Great Egret** colony with more than 140 nests. Nests are built 20 to 40 feet above the ground in mature riparian deciduous trees including river birch, silver maple and sycamore. **Black-crowned Night Herons** migrate to the basin between late March and early April to construct nests in riparian areas on islands in the lower Susquehanna River. While most regions have noted declines in nest abundance, the mainstem and tributaries in the Lower Susquehanna remain viable rookeries (Brauning 1992).

Fish-eating birds. The **Bald Eagle** and **Osprey** are both predominantly fish-eating birds that require access to and abundance of fish during nesting and rearing. The Bald Eagle has been documented nesting in medium-sized and large tributaries, and along the Susquehanna mainstem. During the nesting season, they are found close to aquatic habitats and abundant food resources (fish and small waterfowl). They typically nest in large, old trees including white pine, sycamore, red oak and red maple, between 40 and 100 feet from the ground. Osprey have returned to the lower Susquehanna basin in recent years and typically nest in large trees or on man-made platforms.

Bank and riparian-nesting birds. The **Belted Kingfisher** and **Bank Swallow** nest in streambanks. They prefer steep vertical banks, where they burrow laterally to build nests (Brauning 1992). The belted kingfisher primarily feeds on fish, although its diet also includes amphibians and aquatic insects. Bank swallows feed aerially on flying insects, occasionally capturing prey from the water's surface. The **Acadian flycatcher** is a habitat specialist, requiring both mature, closed canopy, deciduous forest and streamside habitat. They are generally insectivores and nest near open water (PGC and PFBC 2005).

Mammals. Mammal species include northern water shrew (*Sorex palustris*), muskrat (*Ondatra zibethicus*), northern river otter (*Lutra canadensis*), and several species of bats. The **northern water shrew** is semi-aquatic and can be found in high quality cold headwater streams and bogs of the Appalachian Plateau and small portions of the Ridge and Valley. They are adept swimmers with partially-webbed and bristled hind feet, and dense, water-repellent fur. They are very sensitive to food availability, as they feed every three hours (PNHP 2009). Food sources include caddisfly, stonefly and mayfly larvae, small fish and fish eggs, and aquatic snails (Merritt 1987, PGC and PFBC 2005).

Although less specialized in habitat and dietary needs than the northern water shrew, the **muskrat** has many similar adaptations to aquatic life. An opportunistic feeder, the muskrat primarily feeds on roots, shoots, stems, and leaves, but also consumes crayfish, frogs, fish, and snails. Muskrats construct dens within stream banks. The den entrance is typically underwater with the nest chamber located above. Muskrats are susceptible to increased predation if flows decrease and den entrances are exposed, particularly during the less active winter season. Increased flow variability can also lead to bank instability, erosion, and loss of habitat.

A ban on trapping, in combination with reintroduction programs, in New York, Pennsylvania and Maryland have resulted in the reestablishment of **northern river otter** within the basin. River otters feed primarily on nongame fish (minnows, carp and suckers) and crayfish. They are active year-round and live in family groups in dens built in stream banks, similar to the muskrat.

During the spring and summer seasons, several species of **bats,** including the little brown myotis (*Myotis lucifugus*), Indiana myotis (*Myotis sodalis*), small-footed myotis (*Myotis leibii*), silver haired bat (*Lasionycteris noctivagans*), big brown bat (*Eptesicus fuscus*) and the hoary bat (*Lasiurus cinereus*), typically roost and establish nursery colonies in close proximity to the river. With a high metabolic rate, and a need to store energy reserves before fall hibernation, bats consume significant quantities of insects each day during spring and summer; big brown bats can consume up to one-third of their weight in a given feeding. These bat species feed on moths and beetles in addition to aquatic insects such as caddisflies, stoneflies, and dragonflies.

4.2 Physical Processes and Conditions

4.2.1 Floodplain and Channel Maintenance

Key Elements

- High flow events during winter months catalyze ice scour processes, which maintain sites for early successional vegetation.
- Spring high flow pulses are needed to transport bedload material.
- Bankfull flows maintain active channel shape, form, and carrying capacity.
- Small floods, defined with a 5-year recurrence interval, provide connectivity between the active channel and low terrace riparian areas, and maintain island geomorphology and riparian habitat structure and diversity.
- Large floods, defined with a 20- to 25-year recurrence interval, provide connectivity between the channel and floodplain, and drive disturbance-dependent processes.
- High flow pulses during summer flush fine sediments, and transport and break down coarse particulate organic matter.

In previous sections, we described many of the relationships between high flow events and the maintenance of channel and floodplain habitats for reptiles, amphibians, birds, mammals, and vegetation communities in the Susquehanna basin. Here, we specifically discuss the relationship between the frequency and magnitude of high flow events and geomorphic processes for channel and floodplain maintenance. Most channel and floodplain maintenance is associated with four types of high flow events: **seasonal high flow pulses, bankfull flows, small floods, and large floods**. These events maintain geomorphic disturbance patterns by transporting large woody debris, mobilizing bedload, forming islands, ice scouring, inundating floodplains, and maintaining in-channel and floodplain habitat structure and diversity.

High flow pulses. Although the magnitude and frequency differ by season, high flow pulses support different physical processes throughout the year. During the winter months, pulses promote ice scour along shorelines and rocky outcrops, which is important for maintaining suitable habitat for pioneer species of vegetation (Podniesinski et al. 2002, Perles et al. 2004). High flow pulses during spring generally have the greatest magnitude relative to other seasons and are capable of transporting bedload material and large woody debris (B. Hayes, personal communication, 2009). In the summer and fall

months, these events are relatively low in magnitude but are responsible for mobilizing fine sediment, reopening interstices in substrates, and transporting and breaking down coarse particulate organic matter (CPOM) (Dewson et al. 2007).

Bankfull flows. Bankfull events are commonly referred to as the channel forming discharge and largely maintain channel geometry and sediment and fluvial transport capacity (Knighton 1998). The combination of frequency and magnitude make these events responsible for moving the most sediment over time and defining channel morphology, including macrohabitat geometry and substrate, and bank and margin morphology (Wolman and Miller 1960, Dunne and Leopold 1978, Leopold 1994).

In order to estimate bankfull discharge at ungaged sites, several regional curves have been developed for states within the basin (Chaplin 2005, Mulvihill et al. 2005, Westergard et al. 2005) (Table 4.3). All regional curves and associated regression equations use drainage area to predict bankfull discharge, cross-sectional area, width, and mean depth. In addition to drainage area, Chaplin (2005) tested the influence of physiographic province and underlying geology (specifically, carbonate bedrock) on curves and found that while physiographic province did not significantly influence the slope or intercept of regional curves, watersheds underlain by carbonate bedrock had significantly lower peak flows than those without carbonate bedrock (Stuckey and Reed 2000, Chaplin 2005). This difference warranted the development of two sets of curves and associated regression equations. Carbonate streams were defined as having more than 30% carbonate bedrock within their contributing catchments. Although bankfull recurrence intervals for all gages used in these three studies ranged from 1.0 to 3.4 years, the recurrence intervals for gages within the basin range **from 1.1 to 2.1, or every 1 to 2 years**. Regional regression equations can be used to estimate the recurrence interval at a specific site by calculating the discharge (cfs), and associating that discharge with its corresponding recurrence interval on a flow exceedance curve.

Table 4.3 Summary of regional studies to predict bankfull discharge.

Reference	Scope and Extent	Regression Equation	Correlation Coefficient (R^2)	Recurrence Interval (years) Min, Max
Chaplin 2005	Pennsylvania Region n = 66 gages watershed size = 1 - 226 sq mi	Noncarbonate: $y = 43.21x^{(.867)}$	0.92	1.4, 1.7
		Carbonate: $y = 44.29x^{(.634)}$	0.73	1.2, 1.8
Mulvihill et al. 2005	Chemung Subbasin n = 14 gages watershed size = 1 - 96.4 sq mi	$y = 48.0x^{(.842)}$	0.90	1.0, 2.4
Westergard et al. 2005	Upper Susquehanna Basin n = 16 gages watershed size = 0.7 - 332 sq mi	$y = 45.3x^{(.856)}$	0.96	1.1, 3.4

Small and large floods. Both small and large flood events are most common during the spring, although they can occur in any season. The magnitude of flood differentially influences sediment deposition, channel morphology and macrohabitat (McKenny 2001).

Small flood events (5-year recurrence interval) provide connectivity between active channel and low terrace riparian areas and maintain island shore and riparian habitat structure and diversity. These events deposit sediment and leaf litter on the floodplain, incorporating organic matter between layers of silt, sand, and fine gravel. The extent of overbank erosion or vertical accretion is influenced by the event's duration, magnitude, frequency, and sediment load (MacBroom 2008). In describing flood events and associated floodplain processes as a function of energy, Nanson and Croke (1992) found that floods with a 1- to 5-year return interval had low to moderate streampower, resulting in accretion of vertical fine strata (cohesive clay to sand), or lateral point bar development (sand and gravel).

Large floods occur at an estimated recurrence interval of 18 to 20 years and are associated with floodplain maintenance and valley formation (Shultz 1999, B. Hayes, personal communication, 2009). Floodplain and valley formation associated with large flood events can include significant morphological changes to both the profile and planform through lateral channel migration, abandoned channel accretion, overbank vertical accretion and channel avulsion processes (Nanson and Croke1992). These rare, high-energy floods are also capable of mobilizing coarse sands, cobbles, and boulders into the floodplain. Large floods maintain vegetative structure on islands and floodplains and transport large woody debris. When redeposited, large woody debris provides cover, promotes scour, and helps form plunge pools (Naiman et al. 2000).

4.2.2 Water Quality

Key Elements

- Decreased flow magnitudes can increase stream temperature and decrease dissolved oxygen, particularly in shallow margins and backwater habitats important for juvenile fish development.
- High flow pulses during summer flush fine sediments, decrease stream temperature, increase dissolved oxygen and transport and break down coarse particulate organic matter.
- Decreased flow magnitude could reduce assimilative capacity and decrease effectiveness of wastewater treatment and abandoned mine drainage remediation.

Within the basin, localized water quality impairments are mostly attributable to industrial, agricultural and urban development. The most recent 305(b) report indicates that 81% of the assessed waters met water quality standards and associated designated uses. For non-attaining streams, the leading cause of impairments was abandoned mine drainage (elevated metals and sulfate concentrations and low pH) (SRBC 2008). Abandoned mine drainage continues to be one of the basin's most prevalent water quality issues, with the majority of impairments occurring in the West Branch subbasin on the Appalachian Plateau. In the Ridge and Valley and Piedmont provinces, water quality impairments are associated with elevated sediment and nutrient concentrations caused by agricultural and urban development.

Historically, much of the emphasis on protecting instream flows has focused on maintaining the assimilative capacity of rivers downstream of wastewater treatment plants and other permitted discharges during extreme low flow conditions (Tennant 1976). In addition to extreme low flow conditions, water quality (specifically dissolved oxygen, temperature, and turbidity) is also correlated with high flow events and seasonal flow conditions.

Freshets and flushing flows following precipitation events have been shown to affect water quality. These high flow pulses (less than bankfull flows) can flush sediment, decrease temperature, and increase dissolved oxygen (DO). During summer, high flow events in the Susquehanna and major tributaries decrease temperatures and increase DO (Chaplin et al. 2009, USGS Unpublished data). While general correlations between streamflow, DO, and temperature are understood, research to quantify basin-specific relationships between the parameters is ongoing (M. McTammany, personal communication 2009, J. Chaplin, personal communication, 2010). Summer precipitation and associated high flow events are also needed to flush interstitial fine sediments (sands and silt) from the stream bed and to transport and break down coarse particulate organic matter (Dewson et al. 2007b, B. Hayes, personal communication, 2009).

Maintenance of seasonal flows provides suitable water quality, including temperature and dissolved oxygen, within mainstem and backwater habitats. Seasonal and low flows also maintain the stream's assimilative capacity below wastewater treatment plant discharges and can minimize local and downstream impacts of abandoned mine discharges. Assimilative capacity is calculated using the 7-day, 1 in 10 year, low flow event. On the Lower Susquehanna this translates to the monthly Q99 for July and August and the monthly Q96 for September and October (USGS Unpublished data).

In late summer/early fall of 2008, through the Large River Assessment Project, SRBC sampled 16 points along the Susquehanna mainstem and found only one sample did not meet temperature standards. All samples met the DO standard for adult fishes (> 4.0 mg/L)[6]. Streamflow during those months was close to median conditions, ranging from the monthly Q50 to Q70 (SRBC 2009 and USGS unpublished data).

Also during summer and fall of 2008, Chaplin et al. (2009) monitored several locations on major tributaries and the mainstem to compare water quality conditions between different habitat types, specifically the main channel (used by adult smallmouth bass) and shallow margins and backwater habitats (used by juveniles). They report results in reference to more stringent, national DO criteria for protection of early life stages for fish (instantaneous minimum of 5.0 mg/L and a 7-day average minimum of 6.0 mg/L) (U.S. EPA 1986, Chaplin et al. 2009). Comparing water quality conditions between habitats, they found that during the period critical for juvenile growth (May - July), daily minimum DO concentrations were 0.3 to 1.1 mg/L lower in shallow margins and backwater habitats than in the mainstem. In these habitats, they also found that daily minimum DO was frequently lower than the national criterion of 5 mg/L. These events generally occurred during the night time and early

[6] The DO standard of 4 mg/L is appropriate for adult fishes, but a higher standard of 5 mg/L is more suitable for egg and larval development (Chaplin 2009). This higher threshold was not included in the 2009 Large River Assessment Project report. All samples were collected during daylight hours, when DO concentrations are typically highest.

daylight hours (between midnight and 8:00 a.m.) when photosynthesis is minimized and respiration is maximized.

Studies have also found that in addition to the magnitude of alteration, the source of the withdrawal can have a significant impact on temperature. Surface water withdrawals can actually decrease stream temperatures during summer and increase temperature during winter because they increase the ratio of ground to surface water in the stream (Dewson et al. 2007b, Walters et al. 2010). Conversely, groundwater withdrawals tend to decrease the ratio of ground to surface water and can cause stream temperatures to increase during summer and decrease during winter.

4.3 Summary of Ecosystem Flow Needs by Season

In this section, we summarize the priority ecological flow needs for each season. Based on flow needs identified at the October 2009 workshop and additional literature review and consultation we conducted on reptiles and amphibians, birds and mammals, geomorphology and water quality, we formulated approximately 70 flow hypotheses (Appendix 1B, Attachment B). Each hypothesis states an anticipated response of a species, group of species, or habitat to a change in flow during a particular season. We consolidated these flow hypotheses into approximately 20 flow needs statements by grouping those with similar timing, taxa and/or function in similar habitats.

Figure 4.3 illustrates the flow needs by season and flow component for the major tributaries habitat type. Appendix 6 includes similar graphs for the other four habitat types. Flow needs often span multiple seasons; each need is listed with the season in which it begins (for example, the need for flows to maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development begins in fall but continues through winter and spring).

Tables 4.4 through 4.7 list the flow needs for fall, winter, spring, and summer, respectively. We also indicate the related flow component(s) and the applicable major habitat type for each need. The primary needs for each season are listed in bold; needs that continue from previous seasons are in gray text. Following each table, we briefly summarize and list references related to each primary (bold) need. Appendix 7 describes each need in more detail, lists the relevant months, and summarizes literature, studies, and other supporting information.

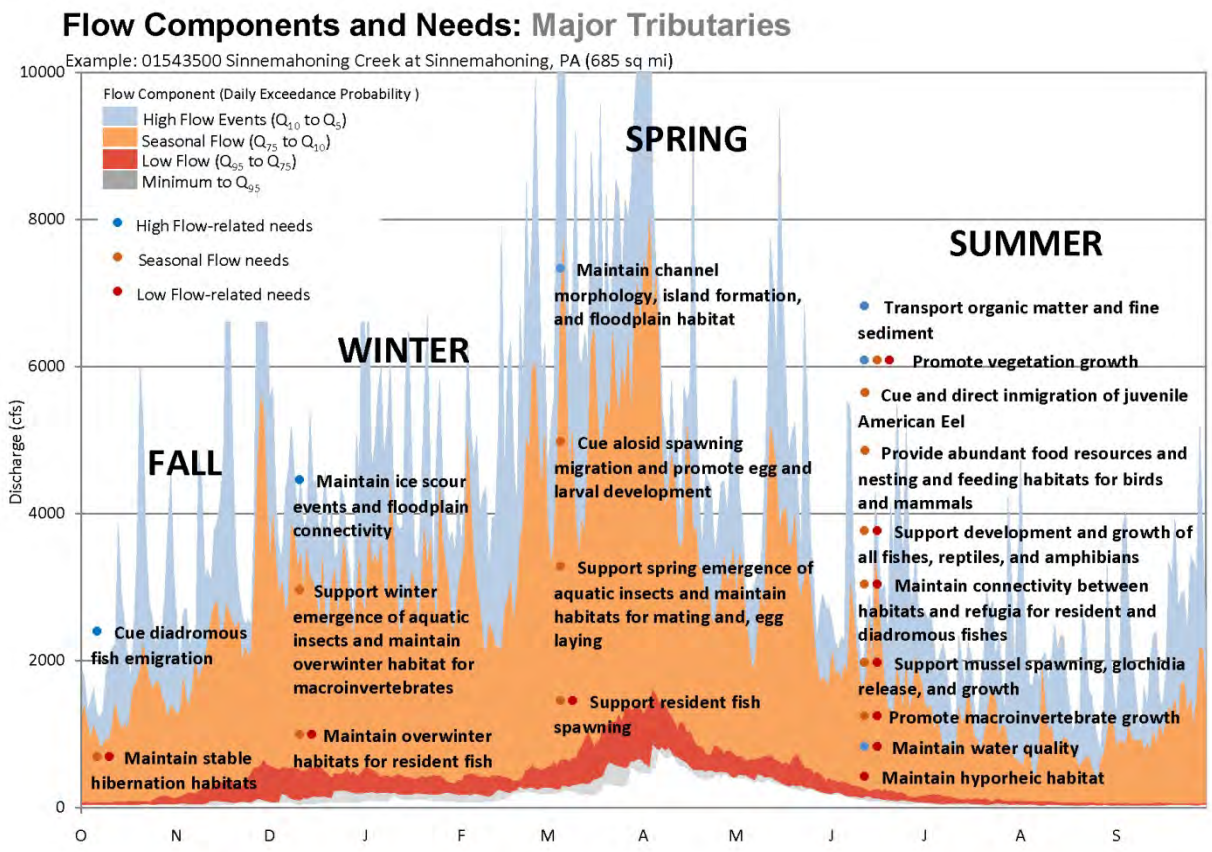


Figure 4.3 Example of flow needs associated with high, seasonal and low flows in major tributaries.

4.3.1 Fall

Key Elements

- High flow pulses, temperature decreases, and precipitation cue alosid juvenile and adult eel out-migration.
- Salmonids need flows within seasonal range to maintain suitable spawning conditions, to maintain connectivity between summer habitat and fall spawning areas, and to provide access to thermal refugia.
- Reptiles, amphibians and mammals begin hibernating and nesting during fall. Decreases in streamflow after hibernation and nesting begins can lead to habitat loss and stranding in streambeds and banks.
- Flows needed to maintain habitat availability, connectivity, temperature and water quality during summer continue through fall months.

Table 4.4 Fall (September to November) ecosystem flow needs. The primary needs for each season are listed in bold; needs that continue from previous seasons are in gray.

Flow Need	Flow Component			Habitat Type
	High Flows	Seasonal Flows	Low Flows	
Maintain channel morphology, island formation, and floodplain habitat	●			All habitat types
Transport organic matter and fine sediment	●			All habitat types
Promote vegetation growth	●	●	●	All habitat types
Cue diadromous fish out-migration	●	●		**Mainstem and major tributaries**
Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates		●		All habitat types
Maintain connectivity between habitats and refugia for resident and diadromous fishes		●		All habitat types
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals		●		All habitat types
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	**Cool and coldwater streams; high baseflow streams**
Maintain stable hibernation habitat for reptiles, amphibians, and nesting habitat for small mammals		●	●	**All habitat types**
Promote/support development and growth of all fishes, reptiles, and amphibians		●	●	All habitat types
Support mussel spawning, glochidia release, and growth		●	●	All habitat types
Promote macroinvertebrate growth and insect emergence		●	●	All habitat types
Maintain water quality	●		●	All habitat types
Maintain hyporheic habitat			●	All habitat types

High flow pulses and high seasonal flows are one of several cues for fall out-migration of juvenile shad and adult eels. Freshets (high pulses and flows above mean or median) coupled with lower temperatures initiate juvenile shad out-migration; out-migration may be inhibited by low flows. Out-migration occurs as early as October and as late as December. Once juvenile shad are cued and begin out-migrating, they will continue to move even if flow conditions change. High flows or pulses will speed out-migration (M. Hendricks and M. Hartle, personal communication, 2010). Without fall high pulses, eels may delay out-migration until as late as February (Eyler et al. 2010).

In addition to cuing out-migration, high flows during fall facilitate downstream passage through the hydroelectric dams on the lower Susquehanna. During extended high pulses, the lower Susquehanna dams spill. For juvenile shad, spilling over the dam is a safer route than through the turbines (M. Hendricks and M. Hartle, personal communication, 2010).

During fall and through winter and spring, salmonids need stable and sufficiently high flows to maintain connectivity to spawning habitats, suitable temperatures, and wetted, aerated, and silt-free redds (Raleigh 1982, Denslinger et al. 1998, Hudy et al. 2005, Kocovsky and Carline 2006). While temperature is the most limiting factor for suitable habitat, hydraulic conditions and turbidity during low flow months (August through December) also affect adult growth (Raleigh 1982, Denslinger et al. 1998).

During fall months, reptiles and amphibians, including the wood turtle, begin hibernation in stream banks and streambeds. Map, musk and wood turtles require continuously flowing water with high dissolved oxygen; extreme low flow conditions can reduce suitability of overwintering habitat (Graham and Forseberg 1991, Crocker 2000, and Greaves 2007). Rapid flow fluctuations during fall and winter can lead to bank instability and stranding.

4.3.2 Winter

Key Elements

- In general, very few studies address species' needs during winter.
- High flows during winter are important for ice scour to maintain channel and floodplain habitat structure and diversity.
- Population size for several species of fish is affected by overwinter habitat availability.
- Low winter flows have been correlated with anchor ice formation, which affects fish and macroinvertebrate abundance.
- Many species have limited mobility during winter, making local habitat conditions especially important.
- Increased flow variability during winter can lead to bank instability, erosion, and loss of overwinter habitat.

Table 4.5 Winter (December to February) ecosystem flow needs.

Flow Need	Flow Component			Habitat Type
	High Flows	Seasonal Flows	Low Flows	
Maintain ice scour events and floodplain connectivity	●			**Mainstem and major tributaries**
Cue diadromous fish out-migration	●	●		Mainstem and Major Tributaries
Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates		●		**All habitat types**
Maintain overwinter habitats for resident fish		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Maintain stable hibernation habitat for reptiles, amphibians, and nesting habitat for small mammals		●	●	All habitat types

Winter is recognized as a critical time for many species of fishes and aquatic insects, although relatively little is known about the species-specific overwinter habitat requirement.

Winter can be a particularly sensitive season for coldwater fishes. Sculpin population sizes were regulated by overwinter population density due to intraspecific habitat competition between juveniles and adults (Rashleigh and Grossman 2005). Brook trout spawn in the fall; eggs and larvae develop through the late fall and early winter, and are sensitive to decreased flows that could increase sedimentation, thermal stress or exposure, and to increased flows that may cause scour (Jenkins and Burkhead 1993, Raleigh 1982, Denslinger et al. 1998, Hudy et al. 2005, Kocovsky and Carline 2006).

Fishes, reptiles, and amphibians have limited mobility during winter due to high bioenergetic costs. Many species are only capable of small, slow movements to avoid freezing or poor water quality conditions during overwinter periods.

Streamflow reductions during fall and winter can reduce invertebrate density, richness, and community composition (Rader and Belish 1999). Low winter flows have been correlated with anchor ice formation and reduction or elimination of (winter emerging) stonefly taxa (Flannigan 1991, Clifford 1969).

During winter, high flow events and associated ice scour maintain conditions for early successional vegetation (Nilsson 1989, Fike 1999, Podniesinski et al. 2002).

4.3.3 Spring

Key Elements

- Spring is a critical period for maintenance of channel and floodplain habitats and for maintaining connections between the channel and floodplain.
- Bankfull and overbank events occur more often in spring than in any other season.
- High spring flows play a role in seed dispersal and seasonal inundation is a critical factor in seed establishment.
- Spring spawning fishes are affected by both extreme high and extreme low flows; flows that are too high or too low can affect spawning success.

Table 4.6 Spring (March to May) ecosystem flow needs.

Flow Need	Flow Component			Habitat Type
	High Flows	Seasonal Flows	Low Flows	
Maintain channel morphology, island formation, and floodplain habitat	●			**All habitat types**
Promote vegetation growth	●	●	●	All habitat types
Cue alosid spawning migration and promote egg and larval development		●		**Mainstem and major tributaries**
Support spring emergence of aquatic insects and maintain habitats for mating and, egg laying		●		**All habitat types**
Support resident fish spawning		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Maintain stable hibernation habitat for reptiles, amphibians, and small mammals		●	●	All habitat types
Cue and direct upstream migration of juvenile American eel		●		Mainstem and major tributaries
Promote/support development and growth of all fishes, reptiles, and amphibians		●	●	All habitat types

Spring floods and associated high flow pulses transport bedload material in large river habitats (B. Hayes, personal communication, 2009). Although bankfull events and small and large floods may occur throughout the year, they most often to occur in response to spring snowmelt and precipitation.

High spring flows play a role in seed dispersal and seasonal inundation is a critical factor in seed establishment. Floodplain forests of the Susquehanna were found in locations inundated by an estimated range of flows from the Annual Q45 to the Annual Q0.5 (Podniesinski et al. 2002).

Adult migrating shad prefer moderate flows (around median or mean) and avoid moving in high flows. Increased magnitude or frequency of high flow events could inhibit migration (M. Hendricks, personal communication, 2010). In June 2006, extremely high flows likely negatively impacted juvenile American shad survival (both wild and hatchery) (SRARFC 2008). In addition to inhibiting migration in free-flowing reaches, extremely high spring flows can reduce the effectiveness of fish passage structures on the Lower Susquehanna hydroelectric facilities by making it more difficult for fish to locate attraction flows at the entrances of fishways and fish lifts.

Nest-building fishes are also affected by high flows and low flows. If discharge is too high, guarding parents may abandon the nest, or the nest may be scoured (Aho et al. 1986). Several of the nest builders construct nests in river margins of large streams under shade and debris at or near the edge of the wetted perimeter. These habitats are sensitive to reductions in discharge. If discharge is too low, siltation may occur or nests may be dewatered, desiccating eggs and stranding larvae.

4.3.4 Summer

Key Elements

- Late summer and early fall are often the driest months of the year.
- Summer low flows strongly affect habitat availability and connectivity among habitats.
- Extreme low flows, especially when combined with high temperatures, affect water temperature and dissolved oxygen.
- Typical seasonal flows support stream-derived food resources for birds and mammals.
- Channel margins provide habitat for larval and juvenile fishes; habitat quality and availability may be decreased during low flow conditions.
- Submerged and emergent vegetation provides refugia for juvenile fishes, including diadromous species.
- Groundwater connectivity and hyporheic habitats regulate stream temperature and provide refugia for aquatic invertebrates during drought conditions.
- High flow pulses during summer flush fine sediments, decrease stream temperature, increase dissolved oxygen, and transport and break down coarse particulate organic matter.
- High flow pulses also maintain soil moisture and prevent desiccation of streamside vegetation.

Table 4.7 Summer (June to August) ecosystem flow needs.

Flow Need	Flow Component			Habitat Type
	High Flows	Seasonal Flows	Low Flows	
Transport organic matter and fine sediment	●			All habitat types
Maintain channel morphology, island formation, and floodplain habitat	●			All habitat types
Promote vegetation growth	●	●	●	**All habitat types**
Cue and direct upstream migration of juvenile American eel		●		**Mainstem and major tributaries**
Maintain connectivity between habitats and refugia for resident and diadromous fishes		●		**All habitat types**
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals		●		**All habitat types**
Cue alosid spawning migration and promote egg and larval development		●		Mainstem and major tributaries
Support spring emergence of aquatic insects and maintain habitats for mating, and egg laying		●		All habitat types
Promote/support development and growth of all fishes, reptiles, and amphibians		●	●	**All habitat types**
Support mussel spawning, glochidia release, and growth		●	●	**All habitat types**
Promote macroinvertebrate growth and insect emergence		●	●	**All habitat types**
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)		●	●	Cool and coldwater streams; high baseflow streams
Support resident fish spawning		●	●	All habitat types
Maintain water quality	●		●	**All habitat types**
Maintain hyporheic habitat			●	**All habitat types**

High flow pulses are important for maintaining water quality and sediment transport during summer. Summer precipitation and associated high flow events flush interstitial fine sediments from stream beds (B. Hayes, personal communication, 2009). High flow events along the mainstem and in major tributaries decrease temperatures and increase dissolved oxygen during summer months (Chaplin et al. 2009). In other rivers, decreased summer flows have been shown to reduce transport and breakdown of coarse particulate organic matter (Dewson et al. 2007b).

Seasonal flows are needed to maintain a range of persistent habitat types, including high velocity riffles, low velocity pools, backwaters, and stream margins. Decreased streamflow can reduce the availability of riffle habitats in headwaters and small streams. It may also limit the availability, persistence, and quality of shallow water habitats near channel margins. Persistence and availability of these habitats are correlated with fish abundance (Bowen et al. 1998, Freeman et al. 2001).

Many studies document macroinvertebrate responses to summer streamflow reductions (e.g., Walters et al. 2010, Boulton 2003, Wills et al. 2006, Dewson et al. 2007), including loss of free-living taxa, reduction of sensitive taxa, reduction of filter feeders and grazers, and reduction of overall density.

In small stream habitats, an estimated 50% reduction of median monthly flows was correlated with a 65-85% decrease in mussel density. In large river habitats, unionid assemblages have survived exceptional drought where longitudinal connectivity was maintained in the channel (Haag and Warren 2008). Although some mussel species are adapted to low flow conditions, decreases in individual fitness have been documented during dry periods (J. Layzer, personal communication, 2010).

Streamflow reductions can reduce exchange between surface water and hyporheic zone. Upwelling provides stream with nutrients and downwelling provides DO and organic matter to hyporheos. This zone is also refuge to early instars and stream invertebrates during extreme conditions including drought (Boulton et al. 1998).

Section 5: Flow Statistics and Flow Recommendations

5.1 Flow Statistics

Once we defined flow components (see Section 2.1.4 and Box 1) and associated ecosystem flow needs with these 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.

Table 5.1 lists our ten recommended flow statistics and relates each statistic to the high, seasonal, or low flow component. 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.

Table 5.1 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 summer 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
Low flows	
Monthly low flow range	Area under monthly flow duration curve between Q75 and Q99
Monthly low flow magnitude	Monthly Q75 Monthly Q95

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. Figure 5.1 illustrates four long-term monthly flow exceedance frequencies in relation to the long-term distribution of daily flows sorted into high, seasonal, and low flow components.

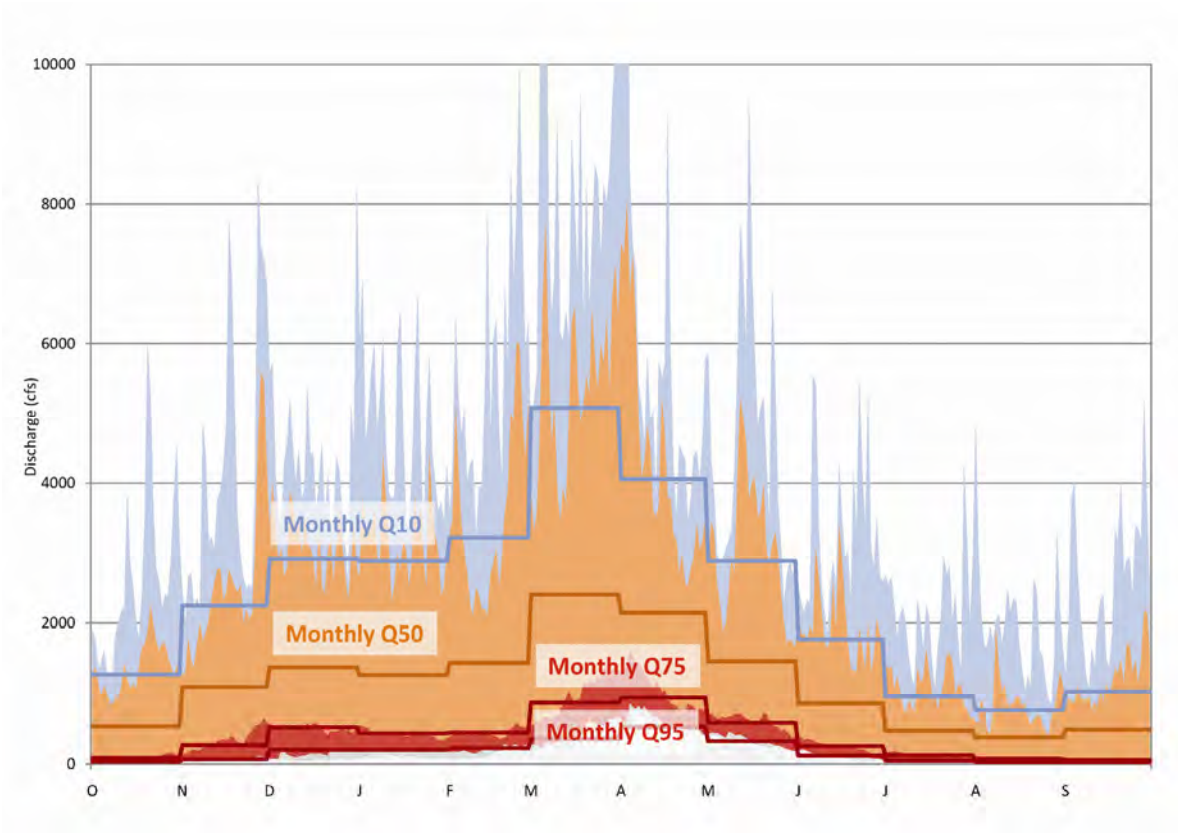


Figure 5.1 Four monthly flow exceedance frequencies selected as indicators of high, seasonal and low flow components. Solid hydrograph indicates the long-term distribution of daily flows sorted into high, seasonal, and low flow components.

The magnitude and frequency of bankfull events and small and large floods are critical for floodplain and channel maintenance, floodplain connectivity, island formation, and maintenance of floodplain vegetation. Chaplin (2005), Mulvihill et al. (2005) and Westergard et al. (2005) published recurrence intervals and regression equations for bankfull events within the basin (See Section 4.2.1, Table 4.3). Based on these studies, we selected the **1 to 2-year event** to represent the bankfull flow. We define

small and large floods as the **5-year and 20-year floods**, respectively, based on studies within the basin and in similar systems that indicate these events are commonly associated with maintaining floodplain, bank and island morphology, and floodplain vegetation (Nanson and Crook 1992, Shultz 1999, Podniesinksi et al. 2002, Perles et al. 2004, and B. Hayes, personal communication, 2009).

High flow pulses that are less than bankfull flows also promote ice scour during winter, maintain riparian and floodplain vegetation, maintain water quality, transport organic matter and fine sediment, and cue diadromous fish out-migration (Nilsson 1989, Burns and Honkala 1990, Fike 1999, Podniesinski et al. 2002, Bowen et al. 2003, Hildebrand and Welsh 2005, Zimmerman 2006, Dewson et al. 2007b, Chaplin 2009, Greene et al. 2009, Eyler et al. 2010). These pulses have different magnitudes – and different ecological functions – in different seasons. They usually occur in response to precipitation events or snowmelt. To capture the importance of these flows, we selected the **monthly Q10** to represent high flow pulses. Most of the high flow pulses occur as peaks above the monthly Q10. Figure 5.1 illustrates that the monthly Q10 (solid blue line) generally tracks the solid blue portion of the hydrograph (high flow component). The frequency of these events (that is, the number of pulses above the monthly Q10) is particularly important in summer and fall when these flows maintain water quality, transport organic matter and fine sediment, and cue diadromous fish out-migration.

Median monthly flow (Q50) is frequently used to represent typical monthly flow conditions. Months with similar flow conditions may also be grouped into seasons or one month may be used to represent an entire season. Many studies cited in Section 4 of this report describe ecological responses to changes in median monthly flow.

Monthly low flow magnitude can be represented using either the **monthly Q95 or monthly Q75**, depending on drainage area. We recommend using the Q75 in headwater streams with drainage areas less than 50 square miles and Q95 for larger streams and rivers. For headwater streams, we propose the Q75 instead of the Q95 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 et al. 2010). Also, our analysis of streamflow at index (minimally-altered) gages in the basin showed that monthly Q95 values in headwater streams were often less than 0.1 cfs, especially in summer and fall months. Therefore, we concluded that a higher flow exceedance value (Q75) is needed to ensure that these flow values are outside of the measurement error of the streamflow gage. At our April 2010 workshop and subsequent consultation, project advisors supported this conclusion.

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). Characterizing a change to the shape of all of, or a portion of, a flow duration curve provides additional information about the changes to the distribution of flows beyond what is provided by looking at changes to the median (Q50) or other flow exceedance values.

We chose two statistics that quantify changes to specific portions of a long-term monthly flow duration curve: the **typical monthly range** and the **monthly low flow range**. Both statistics allow comparison of two flow duration curves; for example, curves before and after a water withdrawal or change to a reservoir release. These statistics build on the nondimensional metrics of ecodeficit and ecosurplus, which are flow duration curve-based indices used to evaluate overall impact of streamflow regulation on flow regimes (Vogel et al. 2007, Gao et al. 2009). 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). 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.

Building on the ecodeficit approach, we define the **typical monthly range** statistic as the area under the middle of a monthly flow duration curve, specifically between the Q10 and Q75. This statistic allows comparison of two monthly flow duration curves (e.g. under regulated and unregulated conditions) by calculating the ratio of the area between the two curves to the total area under the unregulated flow duration curve. Figure 5.2 illustrates the typical monthly range statistic and an analogous monthly low flow range statistic used to measure changes to the low flow tail of the curve. **Monthly low flow range** 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. **Box 2, Calculating Flow Alteration,** describes two useful tools that we applied in this study.

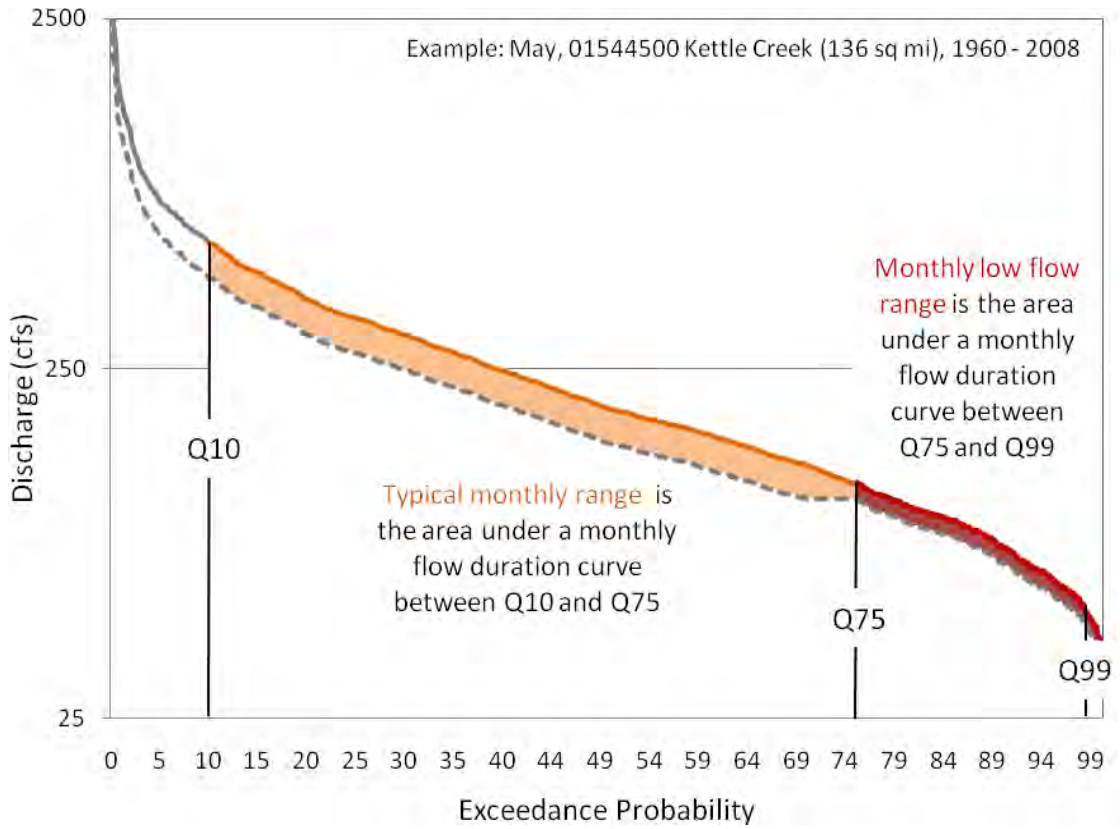


Figure 5.2 The typical monthly range and monthly low flow range statistics. The solid line represents unregulated conditions and the dashed line represents regulated conditions. The colored area represents the difference in area between portions of the two curves.

Box 2. Calculating Flow Alteration

Indicators of Hydrologic Alteration (IHA), version 7.1 calculates the median monthly flow (**Q50**) and monthly **Q10, Q75,** and **Q95** 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. We also ran two-period analyses to analyze the effects of water withdrawal scenarios on selected flow statistics. The IHA software can be downloaded (free) at http://www.nature.org/initiatives/freshwater/conservationtools/.

Calculating change to flow duration curves. Although the IHA 7.1 generates flow duration curves, calculating the **typical monthly range** and **monthly 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.

In the current study, we calculated monthly exceedance values, magnitude and frequency of bankfull events and small and large floods, and frequency of high flow pulses (by season) using a daily flow time series between water years 1960-2008. Monthly flow duration curves were also generated for this period. To test the effects of water withdrawal scenarios on these streamflow statistics, we generated a post-withdrawal time series by simply subtracting flows from a baseline time series, recalculated post-withdrawal values, and compared the two using the IHA and flow duration curve calculator. Results of these water withdrawal scenarios are included in Appendix 9.

5.2 Flow Recommendations

In this section, we present flow recommendations that build on ecosystem flow needs described in Section 4 and flow statistics presented in Section 5.1 (Table 5.1). These recommendations are based on (a) literature that describes and/or quantifies relationships between flow alteration and ecological response; (b) feedback on draft flow recommendations presented at the April 2010 workshop; (c) an analysis of long-term flow variability at index gages; and (d) results of water withdrawal scenarios that showed how each flow statistic responded to hypothetical withdrawals. The resulting recommendations seek to maintain the range of variability that supports the variety of taxonomic groups and ecological processes in the basin.

In Appendix 7, we summarize the main sources of literature that supports each flow need and corresponding flow recommendation. In general, literature we reviewed fell into one of several categories:

- studies on extreme low flow conditions, either observed (e.g. extreme droughts) or simulated (using experimental diversions) (e.g., Haag and Warren 2008, Wills et al. 2006);
- studies that use a model to predict how species or communities respond to simulated withdrawals (e.g., Zorn et. al 2008);
- studies that document the effects of loss of high flow events (e.g., Johnson et al. 1994, Bowen et al. 2003); and
- studies that describe (but may not quantify) an ecological response to hydrologic conditions (e.g., Crecco and Savoy (1984) observed that high June mean flow is negatively correlated with shad year-class strength).

To complement the literature review, we also analyzed long-term variability of the selected streamflow statistics using flow data from index gages. 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 is also being used for a concurrent project to simulate baseline (minimally-altered) flows for ungaged streams in Pennsylvania based on the Massachusetts Sustainable Yield Estimator (SYE) approach (Archfield et al. 2010). This concurrent project used the following criteria to select index gages: (1) streamflow at gage not significantly affected by upstream regulation, diversions, or mining; (2) less than 15% urban area in watershed; and (3) minimum 15 years of record, except where shorter periods of record improved spatial coverage and included major drought. Appendix 8 lists the 45 index gages that meet these criteria within the Susquehanna basin.

Prior to making these recommendations, we also used hypothetical water withdrawal scenarios to explore the sensitivity of each flow statistic. At our April 2010 workshop, participants suggested this analysis to better understand what a 5%, 10%, or 20% change to various flow statistics translated to in terms of water volume for different sizes of streams and how much a typical water withdrawal would affect each statistic. We ran scenarios for headwater, small streams, major tributaries, and the mainstem river. The eight scenarios represented water withdrawals from various sectors, including shale

gas development, golf course irrigation, public water supply, and nuclear power generation. For each scenario, we used the IHA and a flow duration curve calculator (See Box 2) to calculate values for each flow statistic before and after a simulated water withdrawal then calculated the change to each statistic. Our goal with this analysis was to ensure that our recommendations were not constrained by the limitations of the statistic to detect change (or conversely, by extreme sensitivity). Results from all water withdrawal scenarios are included in Appendix 9.

Our flow recommendations for high, seasonal, and low flows are presented in Table 5.2. Each recommendation is expressed in terms of recommended values for one of the flow statistics described in Section 5.1. 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 proscribing a specific cubic feet per second or cfs/square mile. Flow recommendations may be season-specific, may apply to all seasons, or may address more extreme annual or interannual events.

In Section 2.2, we described three major habitat types for headwaters and small streams: cool and cold headwater streams, warmwater streams, and high baseflow streams. These habitat types were useful for organizing information about flow-sensitive species and physical processes associated with each type. However, because our flow recommendations incorporate naturally-occurring variability and are expressed in terms of acceptable variation from baseline values for a particular stream, we are able to apply the same recommendations to multiple 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 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.

Although we did not make different recommendations for cool and coldwater, warmwater, and high baseflow streams, we did make specific recommendations for all headwater streams less than 50 square miles. At the April 2010 workshop, participants suggested explicit consideration for headwater streams because these streams are characterized by (a) low median monthly flow, especially in summer and fall months and (b) high flow variability relative to larger streams. Approximately one-third of our index gages have drainage areas less than 50 sq mi. When we calculated monthly exceedance values for these gages, we noted that for all streams, monthly Q50 was less than 10 cfs in October and August (See Figure 2.3) and monthly Q95 was often less than 0.1 cfs. Because streamflows can be so low in these streams, even small changes could result in zero streamflow. Also, the results of the water withdrawal scenarios showed that high flows – represented by monthly Q10 – often decreased by 10 to 50 % in response to water withdrawals (especially during summer and fall). Because the hydrologic characteristics – and their sensitivity to withdrawals – differ from other streams and small rivers with drainage areas less than 200 square miles, we believe they warrant specific recommendations. We propose using different statistics (i.e., Q75 instead of Q95) and recommend more protection for low flows in headwater streams.

Table 5.2 Flow recommendations for the Susquehanna River ecosystem.

Season	Flow Component	Flow Statistic	Flow Recommendations		
			Headwater streams < 50 sq mi	**Streams and small rivers (50 – 200 sq mi)**	**Major tributaries and mainstream (>200 sq mi)**
Annual and Interannual Events	High Flows	Large flood	Maintain magnitude and frequency of 20-yr flood	Same for all streams	Same for all streams
		Small flood	Maintain magnitude and frequency of 5-yr flood	Same for all streams	Same for all streams
		Bankfull	Maintain magnitude and frequency of 1 to 2-yr high flow event	Same for all streams	Same for all streams
All Months	High flows	Monthly Q10	< 10% change to magnitude of monthly Q10	Same for all streams	Same for all streams
	Seasonal flows	Monthly Median	Between 45th and 55th percentiles	Same for all streams	Same for all streams
		Monthly Range	≤ 20% change to area under curve between Q10 and Q75	Same for all streams	Same for all streams
	Low flows	Monthly Low Flow Range	No change to area under curve between Q75 and Q99	≤ 10% change to area under curve between Q75 and Q99	≤ 10% change to area under curve between Q75 and Q99
		Monthly Q75 Monthly Q95	No change	No change	No change
Fall	High flows	Frequency of events > Monthly Q10	NA	NA	Maintain 1-5 events
Summer		Frequency of events > Monthly Q10	Maintain 2-8 events	Maintain 2-8 events	Maintain 2-8 events

High flows

Annual and interannual events. 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 landcover change, 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 expert input, regional studies of bankfull flows, and analysis of streamflow at index gages between WY 1960 and 2008.

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.

High flow pulses. Nilsson (1989), Burns and Honkala (1990), Fike (1999), Podniesinski et al. (2002), Bowen et al. (2003), Hildebrand and Welsh (2005), Zimmerman (2006), Dewson et al. (2007b), Chaplin (2009), Greene et al. (2009), and Eyler et al. (2010) cite the importance of high flow pulses for promoting ice scour during winter, maintaining riparian and floodplain vegetation, maintaining water quality, transporting organic matter and fine sediment, and cueing diadromous fish out-migration. Podniesinski et al. (2002) showed that floodplain forests in the Susquehanna basin were found in locations inundated by an estimated range of flows between the annual Q45 and the magnitude of the 1 to 2-year high flow event. In a large floodplain river, Johnson (1994) demonstrated that a 25-50% reduction in spring high flows and mean annual flows resulted in encroachment of riparian vegetation into the stream channel. Bowen et al. (2003) showed that a 70% reduction in high flow pulses resulted in a 300-350% decrease in area of inundated woody vegetation.

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 on 49 years of values at index gages. To characterize long-term variation, we calculated the monthly Q10 for every month in every year between WY 1960-2008 for all index gages. We then divided the distribution into quartiles and expressed the middle two quartiles – 25th to 75th percentiles of the distribution – as percentages of the median value. Across all index gages and all months, the 25th to 75th percentiles were generally within 10% of median monthly Q10. Thus, limiting change to the long-term monthly Q10 to less than 10% should maintain high flow pulses within their naturally-occurring distribution.

In headwater streams, our water withdrawal scenario analyses demonstrated that withdrawals have potential to reduce or eliminate frequency of high flow pulses (Appendix 9). The loss of high flow pulses, especially in summer and fall, has consequences for water quality, temperature, and transport of

sediment and organic matter. 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 headwaters, the magnitude or frequency of high flow events is unlikely to be affected by water withdrawals.

We also analyzed data from index gages to estimate the frequency of high flow pulses in each season. For each index gage, we used the IHA to calculate the number of high flow pulses in summer and fall for every water year between 1960 and 2008. Our recommendation reflects the range of variability of high flow pulses from year to year and across many streams. During summer, in three out of four years, there are at least two high pulse events. In one out of four years, there are as many as eight events. During fall, in three out of four years, there is at least one high pulse event in nearly every stream. In one out of four years, there are as many as five events. We recommend maintaining the frequency of high flow pulses in these two seasons. Maintaining 2 to 8 events in summer and 1 to 5 events in fall is a general recommendation based on high pulse frequencies at multiple streams. The frequency for a specific stream could be calculated using a baseline flow time series for that stream.

Fall high flow pulses cue diadromous fish out-migration. The recommendation to maintain 1 to 5 high pulse events in fall only applies to the mainstem and major tributaries because, in the Susquehanna basin, diadromous fish are most commonly associated with streams more than 200 square miles. Summer high flow pulses maintain water quality, moderate temperature, support growth of vegetation, and transport sediment and organic matter. The recommendation to maintain 2 to 8 high flow events in summer applies to all habitat types.

Seasonal flows. Seasonal flow variation – typical monthly flows – support nearly all fish, macroinvertebrates, reptiles and amphibians, birds, mammals, and floodplain, riparian, and aquatic vegetation. Many studies tie ecological responses to changes to median monthly flows or to flows around the central tendency. Our recommendation for seasonal flows is based on results from studies that quantify ecological responses to changes in median monthly flows and maintaining the long-term variation in the distribution of flows around the median.

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 (Freeman et al. 2001, Raleigh 1982, Hudy et al. 2005, Kockovsky and Carline 2006, Denslinger et al. 1998, Smith et al. 2005, Zorn et al. 2008). For example, in Michigan, Zorn et al. (2008) used an empirical model to predict that an 8% decrease in August Q50 led to a 10% change in fish assemblage in headwater streams. Reducing the August median by 10% in large rivers predicted a 10% change in fish assemblages. In Virginia, Smith et al. (2005) showed that when June flows were within 40% of the long term mean, smallmouth bass year classes were strongest. Flows that are too high in spring negatively affect shad year class strength and juvenile survival (Crecco and Savoy 1984 and SRAFRC 2008); flows that are too low in summer and fall may fail to trigger out-migration of shad and eels (Greene et al. 2009).

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. Rader and Belish (1999) demonstrated that constant withdrawals of up to 90% during fall and winter reduced invertebrate density by 51% and richness by 16%. A 73% decrease in median summer flow resulted in statistically significant decrease in number of taxa, number of sensitive taxa, and an increase in tolerant taxa (Nichols et al. 2006). Summer drought (flows 50% or more below median monthly flows) resulted in a 65-85% decrease in mussel density (Haag and Warren 2008). Based on these studies and assuming a similar magnitude of response in the Susquehanna, we would expect that a 50-90% reduction in median summer, fall, and winter flow would have dramatic effects on macroinvertebrates.

These and other studies cited in Appendix 7 tie ecological response to change in median monthly flows in a specific month or throughout a season. Often, these studies document ecological impacts when median monthly flows change in excess of 30, 40, or 50 %, depending on the month and the taxonomic group responding. Our flow recommendations for typical seasonal flows incorporate published responses for several taxonomic groups and limit alteration to less than threshold levels published in other studies.

Other studies cited in Appendix 7 document ecological responses to changes to median flows, but do not quantify the degree of response. These studies can still be used to support protection of naturally-occurring monthly (and therefore seasonal) flow variability.

We recommend that the long-term median monthly flow be maintained within the long term 45th and 55th percentiles of all monthly values. To assess interannual variability, we calculated median monthly flow for all months of all years between WY 1960-2008. The 45th and 55th percentiles create a bracket around the 50th percentile. The width of this bracket varies depending on the distribution of annual monthly values. For example, this bracket is wider in April and May (when flows are higher and more variable) than in August and September (when flows are lower and less variable). By maintaining the long-term distribution of median flows in each month, we account for seasonal differences in water availability.

Figure 5.3 uses one index gage to illustrate the distribution of median monthly flows for WY 1960-2008, the long-term 50th percentile of all years, and the bracket created by the 45th and 55th percentile. Each triangular point represents the median of daily flows for one month of one year. The points show the distribution of median monthly flow for each month during the period WY 1960-2008.

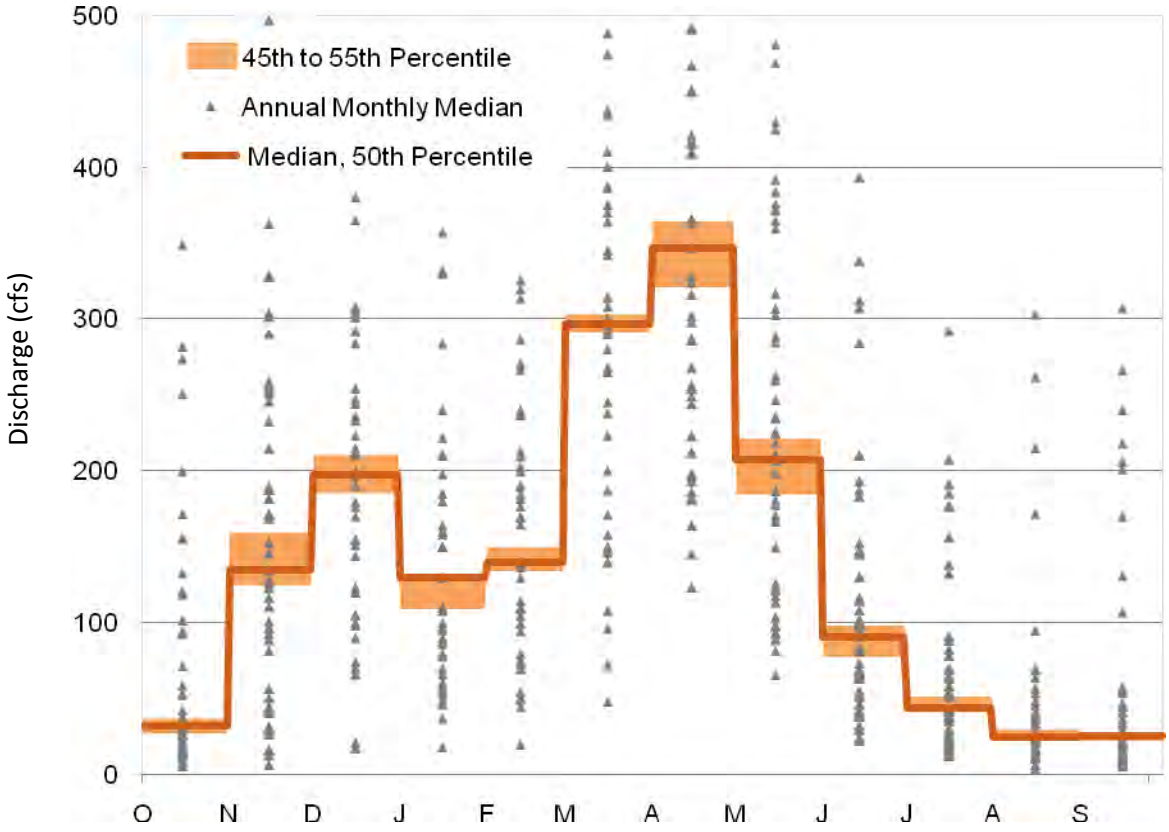


Figure 5.3. Illustration of flow recommendation for monthly median flow.

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 recommend limiting the amount of change to the middle portion of each monthly flow duration curve. Specifically, we recommend limiting the change to the area under the flow duration curve between the Q75 and Q10 to less than 20% (See Figure 5.2 for the illustration of the typical monthly range statistic). This statistic is based on flow duration curve approaches described by Vogel et al. (2007) and Gao et al. (2009), but because we proposed the typical monthly range statistic specifically for this study, our flow recommendation is based on the sensitivity analyses of this statistic in water withdrawal scenarios and best professional judgment, rather than on quantitative relationships in published literature. We believe this has potential to be a very useful statistic to help quantify changes to the shape of a flow duration curve, but we recognize that more research and analyses are needed to further support the recommendation to limit change to less than 20%.

Low flows. 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. Our recommendation for low flows is based on (a) combining results from studies and consultation that quantify or describe ecological responses to changes in low flow

magnitude, frequency or duration; and (b) maintaining the naturally occurring variation in the distribution of flows in the low flow tail of a flow duration curve.

Decreases in low flow magnitude, frequency and duration have been correlated with changes to abundance and diversity of aquatic insects, mussels, and fish. In Connecticut, Walters et al. (2010) conducted experimental withdrawals in headwater streams and quantified relationships between summer flow and aquatic insect density, species composition, and available habitat. A threshold response seems to occur when flows are reduced between summer Q75 and Q85. In Michigan, an experimental flow reduction of 90% resulted in a 41% decrease in macroinvertebrate taxa, a 50% decrease in EPT taxa, a 90% decrease in filter feeding insects, and a 48% decrease in grazing insects (Wills et al. 2006). A decrease in magnitude of low flow conditions has also been correlated with an increase in tolerant taxa as measured by the Hilsenhoff Biotic Index (Rader and Belish 1999, Apse et al. 2008 and Wills et al. 2006).

Boulton (2003) documented elimination of free-living caddisflies and stoneflies in response to extreme low flow (drought) conditions. Several other publications also document decreases in aquatic insect biomass and taxonomic richness in response to both experimental flow reductions and drought conditions (Boulton and Suter 1986, Englund and Malmqvist 1996, Rader and Belish 1999, Wood and Armitage 2004, Blinn et al. 1995, McKay and King 2006). Johnson et al. (2001) documented that mussel assemblages can also shift in response to extreme low flow conditions. Specifically, the abundance and distribution of rare mussel species decreased in response to a summer drought event. Similarly, studies have documented shifts in fish assemblage from fluvial specialists to habitat generalists in response to decreased flow magnitudes (Armstrong et al. 2001, Freeman and Marcinek 2006).

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. For fish, several studies emphasize the importance of maintaining low flow conditions throughout the year: during spring to support spring spawning fishes (Freeman et al. 2001); during fall and winter to maintain overwinter habitat for cool and coldwater fishes (Hakala and Hartman 2004, Letcher et al. 2007); and during fall to support out-migration of shad and eel (Greene et al. 2009, Eyler et al. 2010). Boulton et al. (1998) and DiStefano (2009) documented the importance of low flows in maintaining hyporheic habitats as refuge for aquatic insects (particularly early instars) and crayfish.

Because of mussel species' low mobility, habitat persistence and connectivity are particularly important. All mussel species within the basin either spawn or release glochidia between June and November. Spawning requires sufficient depths and velocities to transport gametes between mussels. Successful release of glochidia requires habitat conditions favorable to attract host fish to mussel beds. Although there is a lack of documentation on the effect of low flow conditions on these interactions, it is reasonable to expect that reducing low flows to a degree that depth and velocities are unsuitable for host fish would decrease mussel reproductive success (Johnson 2001, Golladay 2004).

Water quality, specifically DO concentrations, is directly correlated to low flow magnitudes. Allowable point source discharges are calculated using the assimilative capacity of the 7-day, 1 in 10 year, low flow

event (Q7-10). Under the Q7-10 condition, effluent discharge must not cause DO concentrations to fall below the standard of 4 mg/L. On the lower Susquehanna the Q7-10 flow translates to the monthly Q99 for July and August and the monthly Q96 for September and October (USGS unpublished data). During summer and fall, flows less than the monthly Q96 could result in DO concentrations less than 4 mg/L. Further, egg, larval and juvenile fishes, and species such as the eastern hellbender and wood turtle, require higher concentrations (5 mg/L), and most likely, higher flows. Chaplin et al. (2009) also demonstrated that DO concentrations in shallow margin and backwater are frequently lower than in main channel habitats. In other words, even if DO concentrations exceed 4 mg/L in the main channel, they may likely be lower in shallow margin and backwater habitats that are critical for egg, larval, and juvenile life stages (EPA 1986, Greene 2009). Therefore, water withdrawals should not cause streamflows to fall below the monthly Q96 more often than they would under unregulated conditions, and flows greater than the monthly Q96 may be necessary to maintain water quality conditions that support sensitive species, life stages and habitats.

As low flow magnitudes decrease, competition for refugia and food resources increase. Small-bodied fishes with small home ranges, such as the mottled sculpin, are particularly sensitive to decreases in low flow magnitude. Population size for mottled sculpin is regulated by overwinter habitat availability. Juveniles and adults directly compete for refuge (Rashleigh and Grossman 2005). Several studies have documented increased predation under low flow conditions and decreased access to and increased competition for refuges. This is true for both aquatic species such as mussels and crayfish (Johnson 2001, Flinders 2003, Flinders and Magoulick 2007) and terrestrial species, specifically birds. Extreme low flow conditions can create land bridges between the mainland and island rookery habitats, introducing predators which may threaten breeding success (Brauning 1992, PGC and PFBC 2005).

Impacts of low flow conditions on the individual fitness, including length, weight and condition of fish, aquatic insects, mussels, and submerged aquatic vegetation has also been documented. In summer and early fall, reductions in streamflows have had measurable impacts on size of adult brook trout (Hakala and Hartman 2004, Walters and Post 2008). For mussels, decreases in low flow magnitude have been associated with a decrease in individual fitness and, under extreme conditions, 76% mortality has been documented (Johnson et al. 2001). In response to low flow conditions in the summer and fall, studies have documented reduced carapace length for crayfish (Taylor 1982, Acosta and Perry 2001). During summer and fall, Munch (2003) documented the response of one species of submerged aquatic vegetation (*Podostemum ceratophyllum*) to streamflows of 10 cfs or less (July Q90 or August Q77). Loss of upright branches and leaves, and exposure of the plant base occurred under these conditions. Although this disturbance stunted total seasonal growth, it was followed by a second period during September and October when average hydrologic conditions resumed.

The relevant studies that provide quantitative relationships between flow alteration and ecological response often document responses when flows are reduced to levels between the monthly Q75 and Q99, especially during summer and fall months. Other studies cited above and listed in Appendix 7 highlight the importance of adequate low flows in all seasons, but do not provide quantitative relationships. These studies can still be used to support protection of low flows in all seasons. Below, we present flow recommendations for maintaining the monthly low flow range and low flow magnitude for

headwater streams and all streams with drainage areas greater than 50 square miles. Using monthly flow statistics, rather than a constant value (e.g., Q7-10), accounts for seasonal variability in low flow conditions.

For **headwater streams with drainage areas less than 50 square miles**, we recommend no change to the long-term monthly Q75 based on the monthly flow exceedance curves. As discussed in Section 5.1, we recommend using Q75 (rather than Q95) as the low flow magnitude statistic for headwater streams because the absolute values of Q95 are so low (often less than 1 cfs). This recommendation is based on quantitative responses of mussels and macroinvertebrates to streamflow reduction in headwater streams (see Rader and Belish 1999, Haag and Warren 2008, Walters et al. 2010) and other studies that document loss of habitat and decreased individual fitness of cold and coolwater species as a result of streamflow reductions during summer, fall and winter (Hakala and Hartman 2004, Rashleigh and Grossman 2005, Letcher 2007, Walters and Post 2008).

Consistent with this recommendation, we also recommend no change to the monthly low flow range, which is the area under the flow duration curve between the Q75 and Q99. Since we recommend no change to the monthly Q75, it follows that the shape of the low flow tail (which begins at the Q75) also should not change. In these small streams, the area under the low flow tail between of the monthly flow duration curve is so small – and the absolute magnitude of flows are so low – that even small changes risk creating zero-streamflow conditions.

For **streams and rivers with drainage areas greater than 50 square miles**, we recommend less than 10% change to the monthly low flow range. This recommendation is intended to protect against increases in the frequency and duration of extreme low flow events, while still allowing some flexibility for water use and management within this range.

This less than 10% change to monthly low flow range is a parallel to the recommendation for less than 20% change to the typical monthly range, which protects seasonal flows. We recommend more protection (i.e., less change) for the low flow end of the flow duration curve than for the middle of the curve because (1) there are more documented impacts associated with increased frequency and duration of extreme low flow conditions than with changes to median monthly streamflow; (2) the magnitude of low flows is relatively small therefore even small changes could change hydraulic characteristics (e.g. width, depth, velocity) and therefore, there is less of a margin of safety.

Finally, we recommend no change to the long-term monthly Q95 based on the monthly flow exceedance curves. To clarify, this does not mean that we are recommending *maintaining* minimum flows at this level. Using these flow exceedance values recognizes 5% of the streamflow observations for all dates in a given month during the period of record will be less than the Q95. If these values are calculated using a minimally-altered time series, flows below these levels are assumed to be naturally-occurring. Decreases to these flow statistics would indicate an increased magnitude or frequency of extreme low flow conditions; increases may reflect low flow augmentation.

Section 6: Conclusion

Maintaining flow regimes has been widely 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). In this study, we began by identifying the species, natural communities, and physical processes within the Susquehanna River basin that are sensitive to flow alteration. Through literature review and expert consultation, we identified the most critical periods and flow conditions for each taxa group. Using this information, we summarized key 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 between years. What emerged was a set of recommendations that focuses on limiting alteration of a key set of flow statistics representing high, typical seasonal, and low flows.

We structured these flow recommendations to accommodate additional information. At our April 2010 workshop, we provided a table that contained ecological flow needs, indicated whether the need related to high, seasonal, or low flows, listed a recommended range of values for a relevant flow statistic, and noted literature and studies used to support the recommendation. We revised this table extensively based on input at and after the workshop. The revised version is included as Appendix 7. This structure was extremely useful during the process, and provides a framework for (a) adding or refining flow needs; (b) substituting flow statistics; (c) revising flow recommendations; and (d) documenting additional supporting information. This structure also sets up hypotheses that can guide additional studies to quantify relationships between specific types of flow alteration and specific ecological responses.

Our project goal was to develop a set of flow recommendations that generally apply to all streams and tributaries within the Susquehanna River basin. It is important to recognize that some streams may need more site-specific considerations due to ecological needs (e.g., presence of a rare species with very specific flow requirements) or to constraints due to existing water demands (e.g., operation of flood control reservoirs). Understanding the naturally-occurring variability of high, seasonal, and low flow can provide a starting point for developing site-specific flow recommendations. Instream flow policy based on these recommendations could possibly also incorporate greater protection for high quality waters and habitats, waters containing rare aquatic species, and/or stream classes and designated uses that warrant even greater protections.

Through this study, we developed methods to (a) characterize hydrologic variability; (b) calculate alteration to selected hydrologic statistics; and (c) present flow alteration in the context of flow recommendations. These methods can be used to screen potential withdrawals and other changes to water management based on available hydrologic data, models and tools, including the IHA and flow duration calculators. We look forward to working with SRBC and the commission members to refine these tools and methods to create a decision-support tool for water management and planning.

Implementation of these flow recommendations will be facilitated by a concurrent project to simulate baseline (minimally-altered) flows for ungaged streams. This collaboration between USGS, PADEP, SRBC and the Conservancy builds on methods developed by the USGS Massachusetts-Rhode Island Water Science Center and applied to develop a Sustainable Yield Estimator (SYE) for Massachusetts (Archfield et al. 2010). By spring 2011, collaborators will have developed a tool to simulate a baseline daily flow time series for any point on any stream in Pennsylvania. This tool is a key step in creating a hydrologic foundation that represents both baseline and current (developed) conditions, and that can be used to make water allocation or other water management decisions.

The number of studies that have used various methods to quantify ecological relationships to flow alteration has increased dramatically over the last five years, and this recent body of literature provided much of the information incorporated into this report. We anticipate that the number of studies will continue to grow as more basins, states, and countries implement the Ecological Limits of Hydrological Alteration framework (Poff et al. 2010), with its emphasis on using quantitative relationships between flow alteration and ecological response. We anticipate that these forthcoming examples will provide additional information to further refine or confirm these flow recommendations.

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Appendices

Appendix 1. Meeting Summaries

A. March 2009 Orientation Meeting

B. October 2009 Flow Needs Workshop

C. April 2010 Flow Recommendations Workshop

Appendix 2. Description of Streams within each Physiographic Province

Appendix 3. Maps of All Major Habitat Types

Appendix 4. Life History Diagrams and Tables

Appendix 5. Description of Floodplain, Riparian and Aquatic Vegetation Communities

Appendix 6. Graphs of Flow Needs for Each Major Habitat Type

Appendix 7. Seasonal Flow Needs, Recommendations, and Supporting Literature and Studies

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Appendices

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Susquehanna River Ecosystem Flows Study
Orientation Meeting Summary

Monday, March 9, 2009
10 a.m. – 4 p.m.
Fort Hunter Centennial Barn, Harrisburg PA

Meeting Objectives

The goal of the meeting was to (a) introduce the Susquehanna River Basin Ecosystem Flows Study process, describe intended outcomes and receive feedback from project advisors, (b) identify resources – both expert knowledge and existing data – that support the study, and (c) gather follow-up items / leads for staff to pursue in developing literature and model review.

Presentation Summary

The meeting began with presentations from the three main project partners: the U.S. Army Corps of Engineers, the Susquehanna River Basin Commission, and The Nature Conservancy.

Review of Susquehanna River Basin Low Flow Management Study

Dan Bierly, U.S. Army Corps of Engineers (for Steve Garbarino)

The USACE and the Susquehanna River Basin Commission (SRBC) entered into a cost-share agreement in December of 2008 to conduct a study of the Susquehanna River Basin under the Section 729 authority of the Water Resource Development Act. This authority authorizes an assessment of water resource needs of river basins and is unique to the Corps in that it does not involve construction of new infrastructure. The approach of this particular 729 study is to assess the Basin and develop recommendations to allow water managers to establish environmental flow release schemes that meet both human and ecosystem needs. This phase of the study emphasizes ecological impacts of changes to low flow conditions. The SRBC is interested in pursuing a second phase, which would focus on implementation of these recommendations using consumptive use mitigation and consideration of ecosystem needs. The estimated study cost is $380,000, with a 75:25 Federal- Non-Federal cost-share. The Nature Conservancy is not a signatory to the agreement but is a member of the Study Team and a contractor to the SRBC.

Overview of Existing Water Management Programs in the Susquehanna River

Drew Dehoff, Susquehanna River Basin Commission

In response to surface and groundwater withdrawals, consumptive use, reservoir operations, land use and potentially climate change, we're noticing ecological impacts including: depletion of flow and aquatic habitat, alteration of the natural flow regime, temperature modifications, loss of dilution flows and concentration of pollutants.

The SRBC is currently managing resources in an effort to achieve sustainable water resource development. Current programs include their consumptive use mitigation program and a water withdrawal review program which includes pass-by guidance. The **Consumptive Use Regulation Program requires** the user to mitigate for that portion of their use that is consumptive, particularly during low flows. During defined low flow periods, the user is required to replace their consumptive use, either by stopping their use, releasing stored water, or paying a consumptive use fee which SRBC applies to aggregated mitigation (usually a reservoir release). Existing mitigation under this program occurs

through releases from SRBC water stored in Cowanesque Lake and Curwensville reservoirs (owned and operated by USACE), and is specific to major water users in the basin (power plants). This water is released under a current operating agreement with USACE, when flows at the Harrisburg or Wilkes-Barre stream gages falls below Q7-10. The releases provide a 1-for-1 compensation for consumptive use at that time, they do not maintain Q7-10. It is important to note that at this time, the consumptive use associated with agricultural uses are not addressed in this program, however SRBC is starting to develop agreements to do so through treated releases from the Barnes and Tucker mine. Further, a new consumptive user, Marcellus shale extraction, is emerging in the Basin.

Under the water withdrawal review and pass-by guidance, SRBC assesses the potential of the withdrawal, whether ground or surface water, to adversely affect associated systems. Their current threshold for requiring a user to provide pass-by flows is 10% of Q7-10. For groundwater withdrawals pump tests are conducted, and for surface water withdrawals, the PA/MD instream flow model is used for small coldwater streams. The Tennant method is used for other systems, and 20% ADF (average daily flow) is a common pass-by requirement.

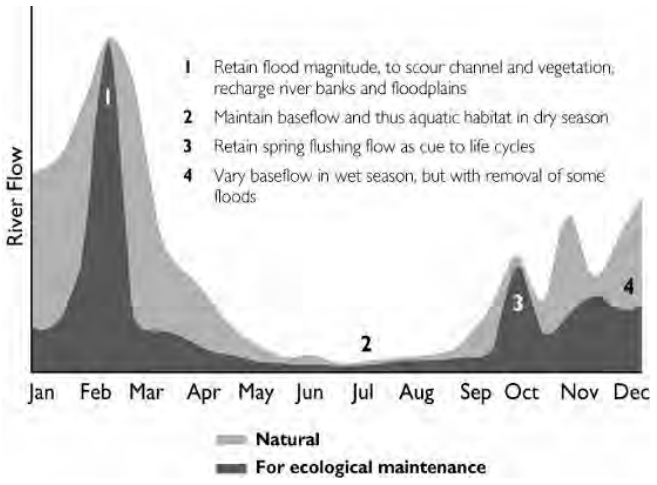
In addition to assessing impacts at the withdrawal point, SRBC also conducts a cumulative impact assessment to determine the extent of impact in combination with other basin users. This process is evolving. The Commission has identified water stressed basins (at the HUC8 scale). There are several **current challenges** to sustainably managing water in the Basin. Within the Basin there are dual (Q-FERC vs. Q7-10) and conflicting instream flow requirements, the latter of which is based on statistics and not ecosystem needs. Site-specific understanding of ecosystem needs is limited to cold-headwater streams (PA and MD instream flow model), specifically fish habitat. The statistical triggers for determining drought status are incompatible with the low-flow release trigger.

The **goal of the Low Flow Management Study** will be to better characterize flow alteration in the Basin, identify ecologically-based indicators and objectives, and attempt to meet localized and specific needs and will help SRBC to answer management questions such as: Is it appropriate to put caps or other limits on consumptive use? The influence of this study on flow requirements for the upper Chesapeake Bay is limited by the operation of Conowingo Dam. However, as Conowingo will undergo FERC relicensing in the near future, this study is seen as an opportunity to inform future operations. Additionally, SRBC is working with TNC staff to define flow needs for the Upper Chesapeake Bay.

Ecologically Sustainable Water Management-Proposed Process for Assessing Environmental Flow Needs

Michele DePhilip, The Nature Conservancy (TNC)

The SRBC has contracted TNC in an effort to meet the goals of the Low Flow Management Study. With a mission to preserve biodiversity, TNC has identified a major gap in the protection of water quantity in relation to biological integrity. In an effort to fill that gap, TNC has developed the Ecologically Sustainable Water Management approach to meet both human and ecological needs by protecting



environmental flows. Environmental flows are defined as the flow of water in a natural river or lake that sustains healthy ecosystems and the goods and services that humans derive from them. Recognizing that we need to continue to use water, **the goal in restoring the natural variation in the hydrograph is not to restore natural, or pre-disturbance, flows all of the time, but rather create adequate conditions of all species enough of the time.**

TNC has implemented these concepts in several projects throughout the country under the Sustainable Rivers Project. The **Sustainable Rivers Project** is a partnership between TNC and the USACE to develop environmental flow recommendations and manage reservoirs in a way that meets both human and ecological needs[1]. The SRP uses the general approach of identifying ecosystem flow requirements, determining the influence of human activities, and identifying gaps or potential areas of incompatibility.

The SRP projects are all at different stages with respect to developing and implementing environmental flow recommendations and monitoring management changes. Case studies from the Savannah River (Georgia and South Carolina), the Green River (Kentucky) and the Willamette River (Oregon) were used to illustrate various steps for developing environmental flow recommendations.

These and other case studies share a common analytical framework, with each taking an individual approach to implementation. It's important to note that environmental flow recommendations are developed using existing information. The approach is to make recommendations in a way that documents the varying degrees of confidence around the recommendations. This allows an opportunity to implement those recommendations with greater confidence first, and time to gather additional information or conduct research on those with less confidence.

One key difference between this project in the Susquehanna River basin and the other case studies is that this project was not driven by a need for reoperations of a specific dam, but to provide an ecological foundation for basin-wide resource management. There is an emphasis on low flow conditions to meet the needs of SRBC, however the scope is not limited to assessing low flow conditions. We recognize that we will have information gaps, but this project benefits from the wealth of experience of the project partners and advisors.

In the first six months, the proposed process includes a hydrologic characterization and literature and model review. The goal of the **hydrologic characterization** is to summarize the range of baseline and current flow variability in the subwatersheds and along selected points on the mainstem. This will provide information on low, average, high and flood conditions, in addition to an understanding of magnitude, timing, frequency, duration and rate of change between flow conditions using gage and model data. The **literature and model review** will synthesize existing data literature and knowledge of flow-dependent species and relationships to support the development of basin-wide ecosystem flow recommendations. Both the hydrologic characterization and the literature and model review will result in summary reports to support flow recommendations for target species, habitats and river processes. Draft reports will be completed by August 2009. TNC has several good examples of summary reports developed for other rivers, including the Connecticut River, Savannah River, Willamette River, and Rivanna River (Virginia).

In August / September 2009, we plan to host a 1.5 day workshop to develop a set of hypotheses about potential responses to flow alteration that will help focus the remainder of the study. Hypotheses will be

[1] More information about the Sustainable Rivers Project is available at http://www.nature.org/success/dams.html

based on information in the literature and model review, results of the hydrologic characterization, and input from the project advisors. At this workshop, we will also identify potential analyses that can be done using existing data to test these hypotheses.

In March 2010, we will host a second workshop to develop draft flow recommendations and assess the level of confidence in these recommendations. Recommendations will be included in the final report to SRBC and USACE.

Project Timeline

March 2009: form project team and hold orientation meeting, begin literature and model review and assessment of flow alteration
Aug / Sept 2009: Complete draft summary report to support flow recommendations, hold first workshop to develop flow hypotheses
March 2010: Conduct analyses to test hypotheses, complete lit/model review and assessment of flow alteration, hold second workshop to develop flow recommendations
April 2010: TNC submits summary report and flow recommendations to SRBC and USACE

Project Partners and Roles

USACE: Overall project coordination, Translate technical findings to scope for Phase 2
SRBC: Participate in assessment of hydrologic characterization, Provide direction to ensure development of useful flow recommendations
TNC: Lead technical portion of study. Summarize information on ecological flow needs, lead assessment of hydrologic characterization, host workshops, compile summary report and flow recommendations
Project advisors: This group is informal and includes those parties with information or expertise related to flow dependent species and processes in the Basin – including meeting participants and others unable to attend. Provide feedback for improving process, contribute information on ecosystem flow needs, provide input on flow hypotheses and flow recommendations through workshops and review

Break-Out Group Summary

In the afternoon, participants divided into three breakout groups to:

- Identify flow-dependent species and communities that should be considered in this process
- Share existing sources of information to support the development of draft flow recommendations
- Identify potential data gaps

Each group had a facilitator and notetaker and was charged with the same task. **Below, we have combined and summarized highlights from the three group discussions.** This list includes potentially flow-sensitive taxa and conditions. For example, some invasive species may be flow-sensitive; particular flow conditions may facilitate their establishment or and other flows could help minimize their ecological impacts.

I. Biological/Ecological Conditions

Aquatic Invertebrates:
- Mussels
- Macroinvertebrates
- Dragonflies (as a backwater indicator species)

Aquatic Vertebrates:

Resident Fish- brown, brook and rainbow trout, quillback sucker
Recreational Fish- walleye, smallmouth bass
Migratory Fish- American eel, shad, herring
Reptiles and amphibians (hellbenders)

Aquatic Vegetation:
Algae, Eel grass, invasive species

Terrestrial Vegetation
Invasive species (purple loosestrife)
Floodplain forests

Terrestrial Vertebrates
Waterfowl

II. Physical Processes and Conditions

Habitat Forming Flows
Water Quality
Suspended Sediment and Nutrients (algal blooms)
Assimilative Capacity, CSO's
Acid Mine Drainage
Temperature

III. Reaches of Interest

Susquehanna flats (Upper Chesapeake Bay), Middle Susquehanna,
Streams in NY that might be intermittent or glacial in nature

List of Suggested Data & Literature and Academic & Professional Contacts

Participants provided the following names, contact information, and reports / studies related to each of these resources and topics

BIOLOGICAL CONDITION AND PROCESSES

Macroinvertebrates

Academics/Professional Contacts	Mike Bilger, Aquatic Biologist, Manager EcoAnalysts' Northeast Office
	DEP: Dan Bogar, Aquatic Biologist, Clark Schiffer- DEP retired, dragonfly communities
Data and Literature	DEP Macroinvertebrate Samples- mostly on tributaries, georeferenced
	SRBC Basin-wide macroinvertebrate data
	Poff, N.L., J.D. Olden, N.K.M. Vierra, D.S. Finn, M.P.Simmons, and C.C. Kindratieff. 2006. Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. Journal of the North American Benthological Society 25: 730-755.

Mussels

Data and Literature	Cole, J.C., P.A. Townsend, K.N Eshleman, 2008. Predicting Flow and Temperature Regimes at Three Alasmidonata heterodon Locations in the Delaware River. Technical Report NPS/NEP/NRTR--2008/109. National Park Service. Philadelphia, PA.

Fish

Academics/Professional Contacts	WPC/PNHP: Mary Walsh, Community Classification and Element Occurrences
	DEP Water Management Program, William Botts, Water Pollution biologist; Joe Hepp and Bob Schott Regional Biologists
	PAFBC: Doug Fischer, Biologist; Michael Hendricks, Biologist; Kris Kuhn-Lower Susquehanna; Jason Detar-West Branch; Rob Wnuk-North Branch, Geoff Smith-Susquehanna River Biologist Susquehanna River Institute: Dr. Brian Mangan, Director SRI, King´s College Wilkes-Barre Penn State: Jay Stauffer, Professor of Ichthyology; Tim Stecko, Instructor and Researcher
	PA Amer. Fisheries Soc and PAFBC: Geoff Smith, Aquatic Ecologist
	York College: Dannacourt, (retired)- focused studies of fish of Susquehanna
	Ted Jacobsen- Consultant for Berwick power station 316b Entrainment Studies
Data and Literature	PAFBC: Index sites for smallmouth catch per unit effort in relation to flows-multi year study (Mark Hartle)
	DEP fish survey reports and data
	Cooper, Edwin 1983. Fishes of Pennsylvania and the Northeastern US. Penn State University Press
	Zorn, T.G., P.W. Seelbach, E.S. Rutherford, T.C. Wills, S.T. Cheng, and M.J. Wiley. In preparation. A regional scale habitat suitability model to assess the effects of flow reduction on fish assemblages in Michigan streams.

Amphibians and Reptiles

Academics/Professional Contacts	Dr. Peter Petokas, Department of Biology, Lycoming College
	Chris Urban, PA FBC and PA Natural Heritage, Chief, Natural Diversity Section

Algae

Academics/Professional Contacts	Dr. Jack Holt, Susquehanna University
	Dr. Hunter Carrick, Penn State

Birds

Academics/Professional Contacts	Audubon Society
	DCNR

Riparian and Floodplain

Academics/Professional Contacts	Chris Firestone, Botanist, DCNR, Bureau of Forestry
	Susquehanna Water Trails (canoe group) installing plots to track purple loosestrife
Data and Literature	DEP Dams and Waterways may have some floodplain mapping- also have a specific layer of the 1000´s of lowhead dams in the state

PHYSICAL CONDITION AND PROCESSES

Fluvial Geomorphology

Academics/Professional Contacts	Craig Kochel, Bucknell University

Data and Literature Recent Publication regarding the movement of legacy sediments through the Susquehanna River (Ben Hayes)

Suspended Sediment, Nutrients, Temp

Academics/Professional Contacts USGS: Contact for Backwater DO Studies and Floodplain Connectedness

Elizabeth Boyer, Penn State

Acid Mine Drainage

Academics/Professional Contacts Scott Roberts, DEP Deputy Secretary for Mineral Resources Management

Thomas Clark, SRBC

WATER USE AND HYDROLOGY

Academics/Professional Contacts PA Instream Flows Technical Committee

USGS: Marla Stuckey, Hydrologist and Stream Stats lead

Susquehanna River Heartland Coalition for Environmental Studies-Consortium

Susan Veleski: Copies of environmental studies for power plant construction

Dr. Thorsten Wagner, Penn State (climate change)

NRCS- Land use

Data and Literature HSPF- Chesapeake Bay Program

OASIS- SRBC

Susquehanna Literature Review- Access Database (Ben Hayes, Bucknell University)

USGS Stream gage data, USACE Reservoir Daily State levels and inflow data

USGS Study- Influence of Juniata inflows to the mainstem

Whitney Point Low Flow Release Study (Drew Dehoff, SRBC)

Denslinger, T.L., W.A. Gast, J.J. Hauenstein, D.W. Heicher, J. Henriksen, D.R. Jackson, G.J. Lazorchick, J.E. McSparran, T.W. Stoe, and L.M. Young. 1998. Instream flow studies: Pennsylvania and Maryland. Susquehanna River Basin Commission, Harrisburg, PA.

Lake, P.S. 2003. Ecological effects of perturbation by drought in flowing waters. Freshwater Biology 48: 1161-1172.

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

Roland, M.R. and Stuckey, M.H. 2008. Regression Equations for Estimating Flood Flows at Selected Recurrence Intervals for Ungaged Streams in Pennsylvania. Scientific Investigations Report 2008-5102. U.S. Geological Survey, Washington, D.C.

Sloto, R.A. 2004. Geohydrology of the French Creek Basin and simulated effects of drought and ground-water withdrawals, Chester Country, Pennsylvania. Water Resources Investigations Report 03-4263. U.S. Geological Survey, Washington, D.C.

Sloto, R.A. and D.E. Buxton. 2005. Water budgets for selected watersheds in the Delaware River Basin, Eastern Pennsylvania and Western New Jersey. Scientific Investigations Report 2005-5113. U.S. Geological Survey, Washington, D.C.

Stuckey, M.H. 2006. Low-flow, base-flow, and mean-flow regression equations for Pennsylvania Streams. Scientific Investigations Report 2006-5130. U.S. Geological Survey, Washington, D.C.

Weiskel, P.K., R.M. Vogel, P.A. Steeves, P.J. Zarriello, L.A. DeSimone, and K.G. Reis, III. 2007. Water use regimes: characterizing direct human interaction with hydrologic systems. Water Resources Research 43: 1-11.

Young, L. 2006. Pennsylvania Statewide Instream Flow Studies Issues Paper. Division of Fisheries Management, Pennsylvania Fish and Boat Commission, Harrisburg, PA.

STREAM CLASSIFICATION

Data and Literature

Walsh, M.C., J. Deeds, and B. Nightingale. 2007a. Classifying Lotic Systems for Conservation: Methods and Results of the Pennsylvania Aquatic Community Classification. Pennsylvania Natural Heritage Program, Western Pennsylvania Conservancy, Middletown, PA and Pittsburgh PA.

Walsh, M.C., J.Deeds, and B. Nightengale. 2007b. User's Manual and Data Guide to the Pennsylvania Aquatic Community Classification. Pennsylvania Natural Heritage Program, Western Pennsylvania Conservancy, Middletown, PA and Pittsburgh, PA.

Wolock, D.M. 2003. Hydrologic landscape regions of the United States. Open-File Report 03-145. U.S. Geological Survey, Washington D.C.

Other Follow-up Items and Summary Points

- TNC will follow up with staff from the Sustainable Rivers Project (TNC-USACE) to determine if there is an opportunity to become an SRP site, the criteria for being included, the advantages of doing so, and the process / timing. TNC will share this information with SRBC, USACE and project advisors.
- For those parties unable to make it to the orientation meeting, TNC will visit and speak with them directly regarding information and knowledge available to support the project. We anticipate meeting with staff from NYSDEC, faculty from Penn State University, members of the Heartland Coalition and representatives from the natural resource agencies in Maryland.
- A similar flow study is beginning for the Potomac River basin. Some staff from TNC and USACE will be involved in both studies, and there is potential for a lot of efficiencies and shared information between the two studies. TNC, USACE, SRBC and ICPRB will work together to figure out common tasks and share the labor.
- The study will first focus on the scientific basis to support ecological flow needs .TNC will consult with SRBC and PA DEP to identify any active watershed groups and other non-government organizations that may have data or technical expertise to this phase of the project. Project partners anticipate that more stakeholder engagement will follow in the second phase of this study when potential management changes / reoperation alternatives are considered.
- TNC will assess hydrological alterations in general; this includes alterations coming from multiple sources such as reservoir operation and consumptive use (which are part of SRBC's water management programs), as well as land use and development. While the focus will on the consumptive use impact, the analysis might help to understand the relative contribution of land use and development
- Climate change is seen as a future change in baseline conditions. This project will assess the issue by documenting current ecological needs/demands. If a model becomes available to project future hydrology under a climate change scenario, we could compare the need deficit today to that of the future.

Meeting Attendees

	Name	Agency / Organization / Affiliation	Email
1	Ben Hayes	Bucknell	brh010@bucknell.edu
2	Curtis Schreffler	USGS-PA Water Science Ctr	clschref@usgs.gov
3	Dan Bierly	USACE - Baltimore District	Daniel.M.Bierly@usace.army.mil
4	Dave Ladd	SRBC	dladd@srbc.net
5	Drew Dehoff	SRBC	adehoff@srbc.net
6	Herb Sachs	Maryland Department of Environment	hsachs@mde.state.md.us
7	Hoss Lighat	PA Dept of Environmental Protection	aliaghat@state.pa.us
8	Jason Zhang	SRBC	jzhang@srbc.net
9	Jim Cummins	Interstate Commission on the Potomac River Basin	Jcummins@ICPRB.org
10	Julie Zimmerman	TNC, Maryland	Jzimmerman@tnc.org
11	Larry Miller	USFWS	Larry_M_Miller@fws.gov
12	Mark Bryer	TNC, Chesapeake Bay Program	mbryer@tnc.org
13	Mark Hartle	PA Fish & Boat Commission	mhartle@state.pa.us
14	Michele DePhilip	TNC, Pennsylvania	mdephilip@tnc.org
15	Rick Shertzer	PA Dept of Environmental Protection	rshertzer@state.pa.us
16	Rod Kime	PA Dept of Environmental Protection	rkime@state.pa.us
17	Stephanie Flack	TNC, Maryland	sflack@tnc.org
18	Tara Moberg	TNC, Pennsylvania	tmoberg@tnc.org
19	Yvonne Grant	USACE - Baltimore District	Yvonne.Y.Grant@usace.army.mil
20	Dave Heicher	SRBC	DHeicher@srbc.net
21	Matt McTammany	Bucknell	mmctamma@bucknell.edu
22	Matt Shank	SRBC	mshank@srbc.net
23	Andrew Roach	USACE - Baltimore District	Andrew.A.Roach@usace.army.mil
24	Jennifer Hoffman	SRBC	jhoffman@srbc.net

Susquehanna River Ecosystem Flows Study
Flow Hypotheses Workshop–Meeting Summary

Wednesday and Thursday, October 14-15, 2009
Kings Gap Environmental Education Center, Carlisle, Pennsylvania

Workshop Objectives

The goals of the workshop were to (a) draft hypotheses about the relationships between flow and the species, ecosystems, and physical processes in the Susquehanna River watershed using professional experience and workshop materials; (b) prioritize additional information to include in draft summary report; and (c) identify analyses that would support development of flow recommendations.

Attachment A includes a list of workshop participants.

Presentation Summary

Application of the Ecosystem Flow Study to Water Management Programs in the Susquehanna River Basin *Mike Brownell, Susquehanna River Basin Commission (SRBC)*

SRBC began the workshop by reiterating the importance and application of the Susquehanna River Basin Ecosystem Flow Study to their current and future water management programs in the Basin, specifically the Consumptive Use Regulation Program and their Passby Guidance for water withdrawal permits. Currently, the basis for these programs range from species specific-habitat models (for cold headwater streams) to general rules based on streamflow statistics (i.e. passby of 20% average daily flow). SRBC is looking for a more consistent and ecologically-based approach to apply to all habitat types within the Basin. Further, demand for withdrawal permits from SRBC is increasing, especially for withdrawals associated with gas well development in the Marcellus Shale formation and power generation.

Review of Project Goals, Schedule and Progress since March 2009 Orientation meeting
Michele DePhilip and Tara Moberg, The Nature Conservancy

Project Scope and Schedule

The overarching goal of the Susquehanna River Ecosystem Flow Study is to develop flow recommendations for major habitat types within the Basin based on the needs of aquatic ecosystems. The process of developing flow recommendations includes a literature and model review to identify the flow needs of aquatic ecosystems within the Basin and a hydrologic assessment of how flow conditions have or are likely to change. Generally, flow needs are defined as the timing, magnitude, frequency, duration and rate of change of streamflow events that sustain healthy ecosystems. While there is an emphasis on low flow conditions as described in the needs of the Susquehanna River Basin Low Flow Management and Environmental Restoration Study[1], the scope is of this Project is not limited to assessing low flow conditions. A brief outline of the project schedule from start to finish is outlined in Table 1.

[1] The USACE and the Susquehanna River Basin Commission (SRBC) entered into a cost-share agreement in December 2008 to conduct a study of the Susquehanna River Basin under the Section 729 authority of the Water Resource Development Act. This approach of this particular 729 study emphasizes ecological impacts of changes to low flow conditions. SRBC has contracted with TNC to contribute to the technical portion of this study.

Table 1. Susquehanna River Ecosystem Flow Study Project Schedule

Oct., 2008	Study agreement signed between SRBC and The Nature Conservancy
Mar., 2009	Project Orientation Meeting- The goal of the meeting was to (a) introduce the Susquehanna River Basin Ecosystem Flows Study process, describe intended outcomes and receive feedback from project advisors, (b) identify resources – both expert knowledge and existing data – that support the study, and (c) gather follow-up items / leads for staff to pursue in developing literature and model review
Mar.-Sept., 2009	Conduct literature review, consult with academic and professional experts and summarize flow-sensitive biological and physical processes in the Basin
Oct., 2009	**Flow-Hypotheses Workshop with Project Advisors**
Oct.-Feb., 2010	Continue literature review and academic and professional expert consultation, verify hypotheses, complete hydrologic characterization and draft summary report.
Mar., 2010	Flow -Recommendations Workshop with Project Advisors
Apr., 2010	Final Report to SRBC and USACE

Progress since March 2009 Orientation Meeting

The Orientation Meeting provided an excellent launching point for the literature review by identifying flow-sensitive resources within the Basin including biological resources (migratory and recreational fishes, mussels, reptiles and amphibians, floodplain forests) and physical and chemical processes (stream temperature, channel-forming flows, and acid mine drainage). Of those resources identified, the majority of literature review and summary to date has focused on fishes (migratory and resident, including recreational), aquatic insects, mussels, and vegetation (aquatic, riparian and floodplain vegetation). The intent is to continue literature review and consultation on all flow-sensitive resources after this workshop.

This workshop provides the opportunity to receive feedback on the information synthesized to date and the process used to aggregate that information. We followed a similar literature review process for each taxonomic group, starting with a follow up on the literature and contacts recommended at the Orientation Meeting. With relevant literature and academic and professional expert advice, we developed draft species lists with the goal of selecting species representative of the range of characteristic traits in the Basin (Table 2, *first column*). We then conducted a targeted literature review focusing on life histories of selected species, using published papers, in- and out-of-basin studies and reports, and gray literature. We used that information to aggregate species into groups based on similar life history traits, flow sensitivities and needs (Table 2, *second column*) and to develop the life history tables found in the materials distributed prior to the workshop. Major sources used to define species traits are outlined in Table 2, third column. A complete list of references to date and their full citations can be found in the Workshop Materials.

Table 2: Summary of flow-sensitive taxa groups, relevant traits, and major information sources. A complete list of species associated with each group, as well as full citations can be found in the Workshop Materials.

	Traits	Flow-sensitive Groups	Major Sources
Fishes	body size, fecundity, home range, habitat associations, feeding habit, flow-velocity tolerance	*Cold headwater*- similar needs defined by temperature thresholds *Riffle Obligates*- small bodied, flow-velocity specialists who spend most of their life in riffle/run habitat *Riffle Associates*- moderate-sized home range, species that migrate from large to small tributaries/headwaters to spawn in riffle habitats, share sensitivity in these habitats during spawning periods *Nest Builders*- similar sensitivity in timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy *Migratory (Diadromous)*- large-bodied, large home range species with sensitivity to connectivity during in- and out-migration, and during spawning (alosids)	Vadas and Orth 2000, Frimpong and Angermeier in review, Walsh et al 2007, Hitt and Angermeier 2008, PA and MD ISF Study 1998, Hudy et al 2005, ASFMC 2009, Cooper 1983, Jenkins and Burkhead 1993
Mussels	host-specificity, longevity, habitat association, velocity association, brooding length, spawning and glochidia release	*Primarily riverine*- predominantly occur in moderate to swift velocity riverine habitats *Facultative riverine*- occur in slow to moderate, and sometimes swift, riverine and lake habitats *Primarily lentic*- predominantly occur in slow backwater habitats on rivers and commonly found in lakes and reservoirs	Bogan and Proch 2004, Pers Com Villella 2009, Pers Com Crabtree 2009, Strayer and Jirka 1997, Fetterman and Strayer 1999, Meyer et al in review, CTDEP 2003, Grabarkiewicz 2008, Nedeau 2000, Normandeau Associates 2006, Johnson 2001
Aquatic Insects	habitat association, trophic habit	*Riffle Communities (erosional habitats)*- dominated by collector-filterers and herbivores; commonly occur in headwater streams *Pool and Riffle Communities*- dominated by collector-gatherers and shredders, habitat type likely to occur on tributaries that have a variety of habitats, including pools, riffles, and runs *Pool Communities (depositional habitat)*- dominated by collector-gatherers and predators, commonly found in backwaters of large tributaries and mainstem habitats	Poff et al 2006, Vieira et al 2006, Cummins 1973, Richards et al 1997, Lake 2003, McKay and King 2006
Aquatic, Riparian and Floodplain Vegetation	inundation tolerance, frequency and severity of flood and ice scour, seed dispersal mechanism, seed dispersal timing, hydrophytic designation, dominant disturbance regime	*Emergent bed*- characterized by semi-permanent inundation and severe flood and ice scour *Herbaceous Community*- occurs in rapidly draining soils and is characterized by seasonal to temporary flooding, and severe flood and ice scour *Scrub/Shrub Community*- characterized by seasonal to temporary flooding and moderate to severe flood and ice scour *Floodplain Forest*- temporary flooding, low to moderate flood and ice scour, range of inundation lengths due to differences in soil texture, not flood duration	Fike 1999, Podniesinski et al 2002, Perles et al 2004, Eichelberger et al 200X, Bowler 2006, Zimmerman 2006, USFWS 1999, Burns and Honkala 1990

Flow-Ecology Diagrams

To illustrate the relationships between species life stages and seasonal hydrologic conditions, we developed flow-ecology diagrams that overlay life history information for various species with a representative hydrograph within the Basin (Figure 1). Daily hydrologic data was retrieved from USGS index gages, for the period of 1960 to 2008 (water years). This forty-nine year period was identified as representative of a range of hydrologic conditions from extreme droughts to major flood events. Each group of species was paired with a USGS index gages near where those particular species have been collected. Please note that the hydrograph is not intended to illustrate ideal or reference conditions for the group of species, but rather to illustrate the annual and interannual flow conditions that occur at a site where these particular species are known to be present and to facilitate conversation about how various flow components affect life stages of selected species. All flow-ecology diagrams are included in the Workshop Materials.

To illustrate both seasonal and interannual variability, the 10th to 90th percentile range of average daily discharge, as well as the median daily discharge were calculated and are included in the gray shaded hydrograph in Figure 1. The frequency, duration and magnitude of low (red line) and high flow pulses (blue line) were calculated as the Q90 and Q10 statistics, respectively, over the period of record. The frequency, magnitude and duration of the > 2 year recurrence flood event were also calculated and are represented by the purple line.

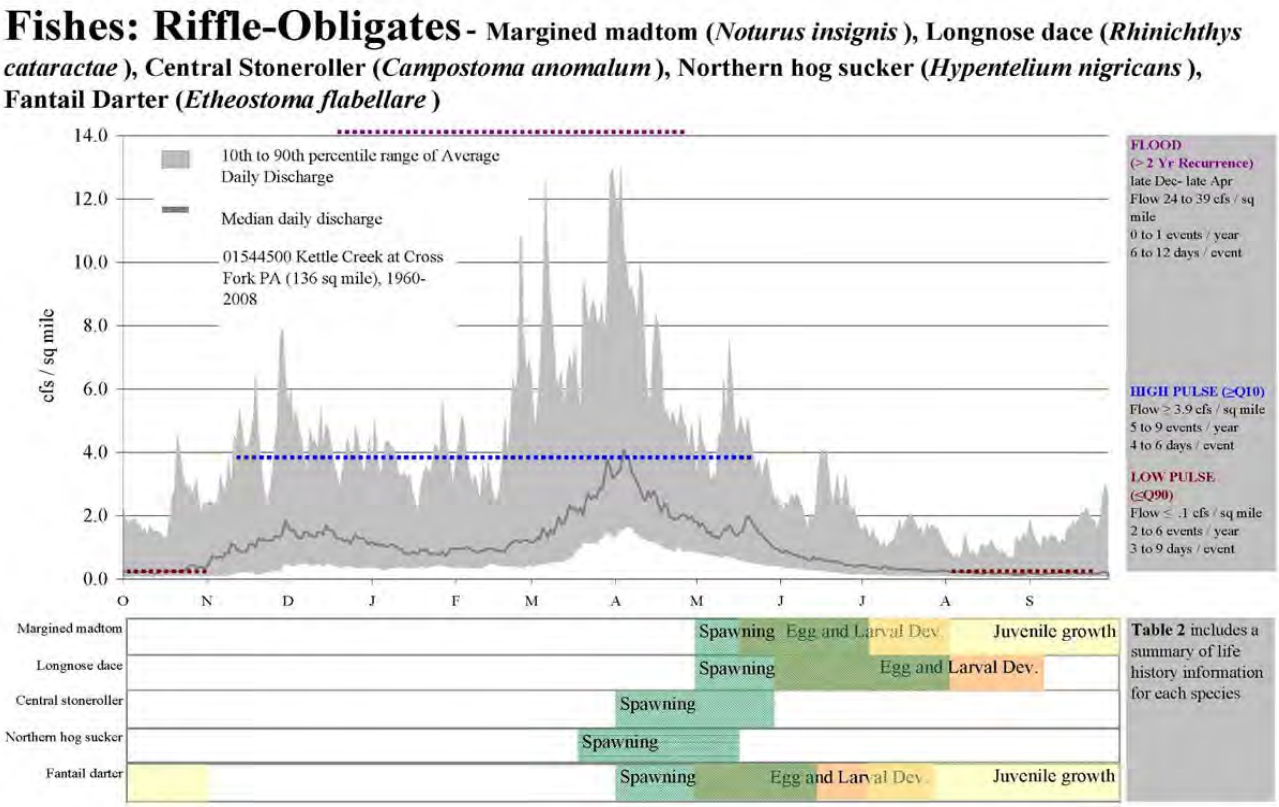


Figure 1: Flow-ecology diagram relating life history information to a representative hydrograph

Linking Flow-sensitive Taxa Groups to River Types and Reaches

Lastly, we used existing species and community distribution information to associate each group of flow-sensitive taxa with general river types or mainstem reaches within the basin. Much of the distribution

information was taken from Walsh et al (2007). We created draft maps using the cold and warmwater stream designations for Pennsylvania and the Northeast Aquatic Habitat Classification (Anderson et al 2007) (Figure 2, for example). We identified **seven general river types or reaches** within the basin:

1. Cold headwater and small streams- cold/cool water streams within watersheds < 200 sq mi primarily found within the Appalachian Plateau and Ridge and Valley province. The type currently includes glaciated and unglaciated streams. We may consider further dividing this classification to reflect differences in glaciated versus unglaciated and/or Appalachian versus Ridge and Valley streams.
2. Calcareous headwaters and small streams- includes all streams < 200 sq mi classified as calcareous, or highly buffered systems, by Anderson et al (2007). These streams typically flow through limestone and have higher baseflow than other streams.
3. Warm headwater and small streams- warmwater streams within watersheds < 200 sq mi primarily found within the Ridge and Valley and Piedmont provinces, although they are present in other provinces.
4. Upper Susquehanna and Chemung- mainstem Chemung and Upper Susquehanna rivers as well as contributing tributaries >200 sq mi.
5. West Branch and Juniata- mainstem West Branch and Juniata rivers and contributing tributaries > 200 sq mi.
6. Middle Susquehanna- mainstem from the confluence of the Chemung to the confluence of the West Branch.
7. Lower Susquehanna- mainstem from confluence with West Branch to York Haven reservoir.

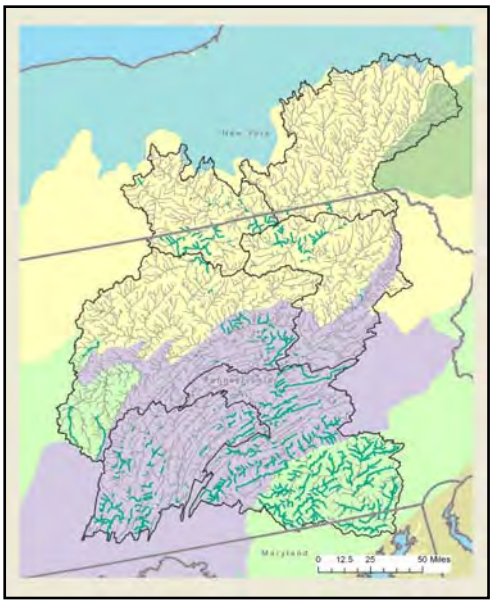


Figure 2: Example Map Illustrating the Distribution of Warm Headwater and Small Streams

Constructing Hypotheses about Flow Needs

The elements of a flow recommendation include an ecosystem function, specific location, time period, flow magnitude, frequency and duration of event, and rate of change. In drafting our hypotheses about the flow needs, we can target the elements by addressing who (species or group), what (flow component), when (month or season), where (habitat type or unit), why/how (ecological response). Figure 3 includes an example hypothesis outlining these components. The hypothesis can both be written as a positive (needs based) and negative (threshold based) statement.

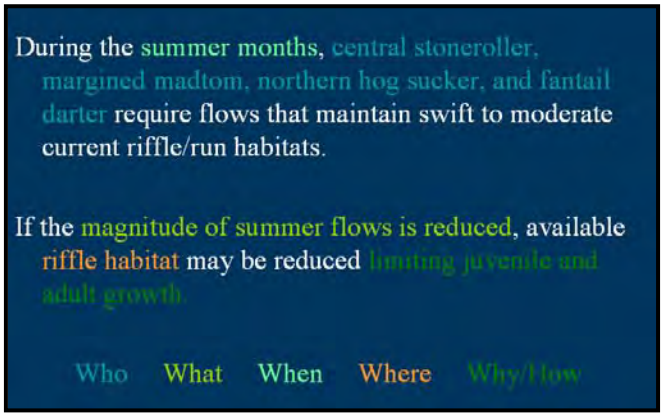


Figure 3: Example hypothesis highlighting key elements

Break Out Groups - By River Type or Reach

TNC staff facilitated groups of 10 to 12 people in breakout groups by river type or reach to accomplish the following tasks: (1) develop a prioritized list of species, groups of species, or physical process for their river type or reach and identifying any missing species or groups, (2) construct hypotheses that include the components outlined above to describe responses to flow conditions based on life history information, and (3) document gaps, technical questions and uncertainties.

Day 1 (3 groups): Warm Headwater and Small Streams; West Branch of the Susquehanna; Lower Mainstem of the Susquehanna

Day 2 (2 groups): Upper Susquehanna River and Chemung; Cold/Cool Headwater and Small Streams and Calcareous Streams

On the morning of Day 2, we presented all hypotheses from the three groups that met on Day 1. As a large group, we filled gaps related to season, flow condition, or taxa, and this list was used as a starting point for Day 2 breakout groups. Attachment B includes all hypotheses associated with each river type.

Summary and steps between now and project completion

Follow up items:

- Review hypotheses – clarify and revise as necessary, consolidate as appropriate
- Beginning with this list, develop hypotheses about flow needs for Middle Mainstem and Juniata
- Revise maps of major habitat types – the types were generally confirmed at the workshop, but we recognize we can improve our maps showing their distribution using additional data sources.
- Summarize information on other flow-sensitive resources, including reptiles and amphibians, water quality, and geomorphology
- Continue consultation with taxa experts to review and supplement life history information and information on flow needs

We will host a second workshop focused on flow recommendations in Spring 2010. Between now and then, we will focus on:

Confirming hypotheses – Although data does not exist to "test" all these hypotheses, there are several types of information sources that we can use to confirm that these hypotheses reflect the needs of aquatic species in the Basin. Major sources include: professional judgment, studies from other basins, existing studies within the Susquehanna, and new analyses of existing data. This project can also identify future studies that could help confirm or reject hypotheses about responses to flow changes. We will provide as much basis as possible to support each hypothesis, indicate gaps, and present this at the spring workshop.

Draft flow recommendations – We will use the qualitative flow hypotheses to develop draft flow recommendations that include the range of flows needed to sustain species and communities within the basin. We will draft recommendations that include acceptable ranges of values of a series of flow statistics representing flow magnitude and the frequency, duration, and rate of change of flow conditions. This will be a primary focus of the spring workshop.

Draft summary report – We will present all information compiled to date, including the outcomes of this workshop, in draft summary report that we will distribute for comment before the spring workshop.

ATTACHMENT A
WORKSHOP PARTICIPANTS

Participant	Organizational Affiliation
Andrew Dehoff	Susquehanna River Basin Commission
Andrew Roach	USACE, Baltimore District
Andrew Warner	The Nature Conservancy
Chad Pindar	Delaware River Basin Commission
Claire O'Neill	USACE, Baltimore District
Colin Apse	The Nature Conservancy
Curtis Schreffler	US Geological Survey
Dan Bierly	USACE, Baltimore District
Dave Heicher	Susquehanna River Basin Commission
Dave Kovach	Delaware River Basin Commission
Dave Ladd	Susquehanna River Basin Commission
Doug Fischer	Pennsylvania Fish and Boat Commission
Erik Silldorff	Delaware River Basin Commission
Hoss Liaghat	Pennsylvania Department of Environmental Protection
Jen Hoffman	Susquehanna River Basin Commission
Jim Cummins	Potomac River Basin Commission
John Balay	Susquehanna River Basin Commission
Julie Zimmerman	The Nature Conservancy
Larry Miller	US Fish and Wildlife Service
Mark Hartle	Pennsylvania Fish and Boat Commission
Mark Smith	The Nature Conservancy
Mark Woythal	New York State Department of Environmental Conservation
Mary Walsh	Pennsylvania Natural Heritage Program
Matt Shank	Susquehanna River Basin Commission
Michele DePhilip	The Nature Conservancy
Mike Brownell	Susquehanna River Basin Commission
Pam Bishop	Pennsylvania Department of Environmental Protection
Randy Bennett	US Geological Survey
Rick Shertzer	Pennsylvania Department of Environmental Protection
Scott Stranko	Maryland Department of Natural Resources
Stephanie Flack	The Nature Conservancy
Steve Garbarino	USACE, Baltimore District
Sue Weaver	Pennsylvania Department of Environmental Protection
Tara Moberg	The Nature Conservancy
Tom Denslinger	Pennsylvania Department of Environmental Protection

ATTACHMENT B
WORKING FLOW-HYPOTHESES FOR RIVER TYPES WITHIN THE SUSQUEHANNA RIVER BASIN

Warmwater Headwater and Small streams, < 200 sq mi

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
	Fish												
1	**Riffle obligate (longnose dace**) Decrease in seasonal flows below normal lows will negatively affect species abundance through loss of high velocity habitat availability.								Decreased low flows will reduce high velocity habitat				
2	**White sucker, N. hogsucker, shorthead redhorse (riffle associates):** Increase of extreme high flow events (frequency and magnitude) during spawning can negatively effect development of larvae through flushing of larvae downstream						Increase in high flow events flushes larvae downstream						
3	**White sucker, N. hogsucker, shorthead redhorse (riffle associates):** Increase of extreme low flow events (decreased magnitude, increased duration) pre-spawning and spawning will restrict adult movement into spawning habitats through riffles.						Increase extreme low flow events restricts movement b/t habitats						
4	**Walleye:** Decrease in spring or summer flows and/or increased duration of low flows leads to increased temperatures, so in summer movements, need increased connectivity and adequate flows to move between pools and over riffles.								Decreased flow magnitude reduces connectivity between pools over riffles				
5	**All Nestbuilders:** Lack of spring flushing flows may result in accumulation of fines, reducing spawning success due to a lack of suitable substrate for nest building					Loss of flushing flows reduces spawning success							
6	**Small mouth bass, redbreast sunfish** (and inverts, same issue, any time of year when there are scouring floods)								Increased high flows reduces spawning success				
7	**Smallmouth bass**								Stable flows are needed to keep males on nest				
8	**Central stoneroller (riffle obligate):** reduced low flows, less preferred habitat (depth, velocity), increased frequency and duration of low flows, reduced area for their preferred food (algae) to live.									Decrease flow magnitude leads to decreased habitat and food availability			
9	**All headwater fishes (shorthead redhorse, northern hogsucker and smallmouth mentioned),** decrease in magnitude of low flows caused by groundwater withdrawals will result in loss of small-stream habitats and lead to faunal shift of small-stream species to larger streams		Decreased flow magnitude leads to loss of small-stream habitats										
	Mussels												
10	**Riverine mussels, and host fish (all three mussel groups):** Decreased magnitude or frequency of winter or spring scouring flows can lead to embeddedness, lack of appropriate substrate size, aggrading channel morphology, reduced carrying capacity.				Decreased mag or frequency of scouring flows leads to embeddedness (all year, esp winter & spring)								
11	**Mussels, and inverts**, if stream is flashier (rate of change outside of natural variation), will see reduced habitat stability, reduced recruitment, and reduced carrying capacity of mussel habitat.		Increased flashiness reduces suitable habitat										
12	**Mussels, all groups,** an increase in the magnitude and variation of high flows in the Spring may decrease host fish availability, likewise a decrease in low flow magnitudes in the Summer may decrease host fish availability						Flows too high decreases host fish availability				Flows too low decreases host fish availability		

Warmwater Headwater and Small streams, < 200 sq mi

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
13	**Mussels, other invertebrates, YOY fish, herps,** reduced low flow magnitudes may reduce both access and quality (temperature and DO) of slow-moving backwater refugia											Decreased quality and quantity of available habitats (temp and water quality) with decreased magnitude of low flow	
14	**Mussels, all groups,** extreme lows increase risk of exposure and predation of mussel beds											Extreme lows increses risk of exposure and predation of mussel beds	
	Additions												
15	**Herps** (turtles frogs overwinter in banks)	Flows maintain wetted margins for hibernating herps											
16	**For herps**, maintain range of variability of highs and lows												
17	**For all taxa,** support of baseflow within normal range to support aquatic habitat	Baseflows required to maintain habitat for all taxa											
18	**For bank-nesting mammals**, specifically muskrats, dens may be exposed under extreme low flow conditions			Extreme low flows expose muskrat dens									

Cold/Cool Headwaters and Small streams < 200 sq mi

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
COLDEST STREAMS													
	Fish												
1	**Brook trout (Cold headwater)-** maintaining the natural variation of flushing flows, or high flow pulses, necessary to clear gravel and maintain riffle habitat before Fall spawning			High flows for habitat maintenance									
2	**Brook trout (Cold headwater)- during overwinter egg incubation period,** redds and riffle habitats must be kept sediment free with high flows, but not so high that redds are scoured and eggs are flushed from the redds		Avoid high flow events outside of range that may scour redds or flush eggs										
3	**See above**		Maintain flows over redds and riffles, keeping them wetted and silt-free										
4	**Brook trout (Cold headwater)-** During the spawning period, flows must be high enough to maintain connectivity, allowing migration to spawning areas	Maintain longitudnal connectivity during spawning											
5	**Brook trout (Cold headwater)-** extreme summer low flow magnitudes can negatively affect juvenile and adult growth and survival by reducing habitat availability and temperatures, as well as reducing connectivity between source populations										Maintain summer flows for habitat, temperature, and source population connectivity		
6	**Sculpin-** covered by previous day's recommendations for riffle obligates- See below												
7	**Riffle Obligates, all,** In all seasons, significantly reduced flow magnitudes will cause local extirpation or reduced growth	Decreased flows lead to loss of riffle habitat											
8	**Riffle Obligates, all,** During the spawning season (March-July), decreased low flows during spawning would reduce recruitment					Decreased flows during spawning limits recruitment							
9	**Riffle Obligates, all**, A decrease in low flow magnitudes during the juvenile growth (July-Sept) and development period could reduce population size										Decreased flows during spawning limits juvenile growth		
	Macroinvertebrates												
10	**Stenothermal invertebrates-** avoid extreme low flows in the summer to maintain temperature regime, increased low flows may lead to a shift from univoltine to multivoltine inverts										Maintain summer flows for habitat and temperature		
	Herps, Vegetation, and Geomorph												
11	**Salamanders-** sensitive to extreme high flows, and increased flashiness (rate of change) within the system as they reduce quality and quanity of available margin habitats	Increases to rate of change alter quality and availability of stream margin habitats											
12	**Salamanders-** sensitive to flow changes that would influence temperatures, particularly increases												
13	**Glaciated cold headwaters-** these systems are particularly susceptible to changes in habitat availability (wetted perimeter, depth, velocity) and increased temperatures during the summer										Maintain summer flows for habitat and temperature		

Cold/Cool Headwaters and Small streams < 200 sq mi

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
14	**Downstream impacts** can lead to loss of coldest headwater streams – extreme low flows downstream of small hw/seeps can result in disappearance of these u/s habitats (tie to gw withdrawals)												
15	**Wetlands and Vegetation**- in these small systems, riparian wetlands/plant communities are dependent on high flow pulses				High Flow Pulses necessary to maintain wetland and riparian communties								
TRANSITIONAL STREAMS													
16	**Similar flow needs to coldest streams,** but less sensitive to flow changes. Incorporate flow needs of rock bass, spottail shiner, and megaloptera												
CALCAREOUS HEADWATER STREAMS													
	Fish												
	Add Brook trout and sculpin needs from Coldwater												
17	**Brook trout (Cold headwater)-** maintaining the natural variation of flushing flows, or high flow pulses, necessary to clear gravel and maintain riffle habitat before Fall spawning					High flows for habitat maintenance							
18	**Brook trout (Cold headwater)- during overwinter egg incubation period,** redds and riffle habitats must be kept sediment free with high flows, but not so high that redds are scoured and eggs are flushed from the redds			Avoid high flow events outside of range that may scour redds or flush eggs									
	See above			Maintain flows over redds and riffles, keeping them wetted and silt-free									
19	**Brook trout (Cold headwater)-** During the spawning period, flows must be high enough to maintain connectivity, allowing migration to spawning areas	Maintain longitudnal connectivity during spawning											
20	**Brook trout (Cold headwater)-** extreme summer low flow magnitudes can negatively affect juvenile and adult growth and survival by reducing habitat availability and temperatures, as well as reducing connectivity between source populations									Maintain summer flows for habitat, temperature, and source population connectivity			
21	**Sculpin-** covered by previous day's recommendations for riffle obligates- See below												
22	**Riffle Obligates, all,** In all seasons, significantly reduced flow magnitudes will cause local extirpation or reduced growth	Decreased flows lead to loss of riffle habitat											
23	**Riffle Obligates, all,** During the spawning season (March-July), decreased low flows during spawning would reduce recruitment					Decreased flows during spawning limits recruitment							
24	**Riffle Obligates, all**, A decrease in low flow magnitudes during the juvenile growth (July-Sept) and development period could reduce population size									Decreased flows during spawning limits juvenile growth			
	Additional Needs in this System Type												
25	**All species** (see notes for team-derived taxa priorities), sensitive to reduced base flows	Baseflows required to maintain habitat for all taxa											
26	**Cave-dwelling species**- particularly T&E cave shrimp and amphipods occupy very specific niche- needs should be researched/considered												

Cold/Cool Headwaters and Small streams < 200 sq mi

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
27	Increased frequency and magnitude of high flow events will destabilize the stream **banks and beds** of these systems				Increased frequency and magnitude o fHigh Flow pulses will destabilize streambanks and beds								
28	**Aquatic Invertebrates**- maintenance of baseflows for winter emerging species		Maintain baseflows for winter emergence										
29	An increase in the magnitude and frequency of High flow pulses during the summer could increase **temperatures** and alter community composition										High flow events dilute groundwater inputs/ temperature influences and potentially increase temperatures		

Large Rivers: West Branch and Lower Mainstem Susquehanna (including tributaries > 200 sq mi)

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
1	**Riffle Obligates, all,** In all seasons, significantly reduced flow magnitudes will cause local extirpation or reduced growth	Decreased flows lead to loss of riffle habitat											
2	**Riffle Obligates, all,** During the spawning season (March-July), decreased low flows during spawning would reduce recruitment					Decreased flows during spawning limits recruitment							
3	**Riffle Obligates, all**, A decrease in low flow magnitudes during the juvenile growth (July-Sept) and development period could reduce population size										Decreased flows during spawning limits juvenile growth		
4	**White sucker and shorthead redhorse (riffle associates)** need riffles for spawning (depth should be covered by riffle obligate needs) during the spawning season (March-June),					Decreased flows during spawning limits recruitment							
5	**For smallmouth bass (nest builder)**, flood flows during Apr-May could delay spawning, reducing recruitment						High flows could delay spawning						
6	**For smallmouth bass (nest builder)**, high base flows, steady flows from April through May are necessary to maintain spawning habitat in stream margins						Stable flows needed to maintain stream margin habitat						
7	**For smallmouth bass (nest builder)** June flows outside of the mean (specify) reduces juvenile recruitment and growth (cite study)							Flows outside mean reduce recruitment					
8	**For smallmouth bass (nest builder)** adults, pools must be maintained for successful adult growth										Pools maintained for adult growth		
9	**All nestbuilders**, need stable flows for nest success; extreme low flows can expose nests							Extreme low flows expose nests					
10	**MIgratory Fish-** maintenance of large open water habitats as well as SAV cover							Juvenile habitat maintenance before outmigration					
11	**MIgratory Fish-** Cue outmigration of juvenile alosids and Adult american eel, need estimated velocities of .3 ft/s	Cue outmigration of juvenile alosids and Adult american eel											
12	**Migratory (Diadromous) Fish**						Adult upstream migration						
13	**Migratory (Diadromous) Fish-** draft guideline for sufficient migration flows include a cross-sectional area 12' wide, 3'deep with velocities of 1 to 3 ft/s [Larry Miller FWS]						Adult upstream migration						
14	**For all fishes,** increase in the freq. of winter high flow pulses could negatively impact overwinter survival			Increased high pulses could affect overwinter survival									

Large Rivers: West Branch and Lower Mainstem Susquehanna (including tributaries > 200 sq mi)

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
15	**Walleye:** Decrease in spring or summer flows and/or increased duration of low flows leads to increased temperatures, so in summer movements, need increased connectivity and adequate flows to move between pools and over riffles.								Decreased flow magnitude reduces connectivity between pools over riffles				
16	**Riverine Mussels**, During the spawning season and glochidia release, need flows that support riffle habitat adequate for host fishes (should be covered by Riffle Ob and Riffle Assoc)						Flows to maintain riffle habitat during spawning and glochidia release						
17	**Submerged / emergent aquatic vegetation-** needs unknown at this time, but instream species dependent on SAV for habitat									flows to maintain SAV			
18	**For herps,** increase in the freq. of winter high flow pulses could negatively impact overwinter survival (wood turtle)			Increased high pulses could affect overwinter survival									
19	**For bank-nesting mammals**, specifically muskrats, dens may be exposed under extreme low flow conditions			Extreme low flows expose muskrat dens									
20	**Water Quality-** Extended periods below 7Q10 (natural or due to withdrawal) may not provide assimilative capacity for WWTP discharges												
21	**Water Quality** For some rivers(dependent on mine type), increased freq. of low fow events could increase AMD concentrations									Increased frequency of low flow events could increase AMD concentration			
22	**Water Quality-** Increased freq. of low flow events decreases DO, increases temps (research on correlations) in mainstem and backwater habitats									Flows to maintain oxygenated conditions			
23	**Backwater habitat - connectivity-** reduced low flow magnitudes may reduce both access and quality (temperature and DO) of slow-moving backwater refugia									Flows to maintain connections between channel and backwater			

Large Rivers: Upper Susquehanna and Chemung (including tributaries > 200 sq mi)

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
	Fishes												
1	**Riffle Obligates, all,** In all seasons, significantly reduced flow magnitudes will cause local extirpation or reduced growth	Decreased flows lead to loss of riffle habitat											
2	**Riffle Obligates, all,** During the spawning season (March-July), decreased low flows during spawning would reduce recruitment					Decreased flows during spawning limits recruitment							
3	**Riffle Obligates, all**, A decrease in low flow magnitudes during the juvenile growth (July-Sept) and development period could reduce population size										Decreased flows during spawning limits juvenile growth		
4	**White sucker and shorthead redhorse (riffle associates)** need riffles for spawning (depth should be covered by riffle obligate needs) during the spawning season (March-June),					Decreased flows during spawning limits recruitment							
5	**For smallmouth bass (nest builder)**, flood flows during Apr-May could delay spawning, reducing recruitment						High flows could delay spawning						
6	**For smallmouth bass (nest builder)**, high base flows, steady flows from April through May are necessary to maintain spawning habitat in stream margins						Stable flows needed to maintain stream margin habitat						
7	**For smallmouth bass (nest builder)** June flows outside of the mean (specify) reduces juvenile recruitment and growth (cite study)							Flows outside	mean reduce	recruitment			
8	**For smallmouth bass (nest builder)** adults, pools must be maintained for successful adult growth										Pools maintained for adult growth		
9	During the spawning season and glochidia release, **riverine mussels** need flows that support riffle habitat adequate for host fishes (should be covered by Riffle Ob and Riffle Assoc)								Extreme low flows expose nests				
10	**MIgratory Fish-** maintenance of large open water habitats as well as SAV cover								Juvenile habitat maintenance before outmigration				
11	**MIgratory Fish** (note: for juvenile alosids in Chemung/Upper Susq, can go from Sept-Oct., based on high flow pulses -- as early as Aug. or as late as Nov.)	Cue outmigration of juvenile alosids and adult american eel											
12	**Migratory (Diadromous) Fish**						Adult upstream migration						
13	**Migratory (Diadromous) Fish-** draft guideline for sufficient migration flows include a cross-sectional area 12' wide, 3'deep with velocities of 1 to 3 ft/s [Larry Miller FWS]						Adult upstream migration						
14	**For all fishes, increase in the freq. of winter high flow pulses could negatively impact overwinter survival**			Increased high pulses could affect overwinter survival									
15	**Submerged / emergent aquatic vegetation**									flows to maintain SAV			
16	**Backwater habitat - DO**									flows to maintain oxygenated conditions			
17	**Backwater habitat - connectivity**									flows to maintain connections between channel and backwater			
18	**Increased freq. of low flow events decreases DO, increases temps (research on correlations)**												
19	**For some rivers(dependent on mine type), increased freq. of low fow events could increase AMD concentrations**									Increased frequency of low flow events could increase AMD concentration			
	Additions												
20	**For herps,** increase in the freq. of winter high flow pulses could negatively impact overwinter survival (wood turtle)			Increased high pulses could affect overwinter survival									
21	**For bank-nesting mammals**, specifically muskrats, dens may be exposed under extreme low flow conditions			Extreme low flows expose muskrat dens									
22	**Water Quality-** Extended periods below 7Q10 (natural or due to withdrawal) may not provide assimilative capacity for WWTP discharges												

Large Rivers: Upper Susquehanna and Chemung (including tributaries > 200 sq mi)

	Working Hypotheses	October	November	December	January	February	March	April	May	June	July	August	September
23	**Riffle obligates -- habitat maintenance**, high channel forming flows that redistribute substrate. These may not be impacted by hydro alteration		Channel-forming flows for habitat maintenance										
24	**Riffle obligates -- pool connectivity**, making sure SAV standing water is not becoming stagnant in low flow periods. In glaciated landscapes with fines, this is a particular issue.										low flows effects on pools		
25	**Stream margins and juvenile fish, mussels, SAV, inverts** -- Increase in rate of change and frequency of flow fluctuations, rapid wetting and drying an issue throughout the year but particularly during low flow seasons								juvenile fish subject to increased predation, loss of habitat, stranding				
26	**Stream margins** continued								SAV subject to dessication, thermal stress				
27	**Stream margins** continued								Mussels and other inverts subject to increased predation, stranding, dessication				
repeat	**Migratory (Diadromous) fish** (ie, for shad restoration in this area) -- want to have connected zone of passage, 12 ft. wide by 3 ft. deep channel with flow velocities between 1 and 3 ft./sec.						Upstream migration, spawning time						
28	**Riparian and aquatic veg** -- not much in these systems, b/c of nature of substrates and groundwater flow. High flows take out large willows.												
29	Maintain flow through **hyporheic zone** for **groundwater invertebrates** along stream margins --								Groundwater and hyporheic flow important important for invertebrates				
30	Flow as strategy to deal with **non-native invertebrates (mussels) or vegetation?** Maintaining natural and moderate to high baseflows would be decent first iteration control strategy for zebra mussels. Currently found in pools below hydropower reservoirs i												
	Mussels												
31	**Riverine mussels, and host fish (all three mussel groups):** Decreased magnitude or frequency of winter or spring scouring flows can lead to embeddedness, lack of appropriate substrate size, aggrading channel morphology, reduced carrying capacity.			Decreased mag or frequency of scouring flows leads to embeddedness (all year, esp winter & spring)									
32	**Mussels, and inverts**, if stream is flashier (rate of change outside of natural variation), will see reduced habitat stability, reduced recruitment, and reduced carrying capacity of mussel habitat.								increased flashiness reduces suitable habitat				
33	**Mussels, all groups,** an increase in the magnitude and variation of high flows in the Spring may decrease host fish availability, likewise a decrease in low flow magnitudes in the Summer may decrease host fish availability						flows too high decreases host fish availability				flows too low decreases host fish availability		
34	**Mussels, other invertebrates, YOY fish, herps,** reduced low flow magnitudes may reduce both access and quality (temperature and DO) of slow-moving backwater refugia										decreased quality and quantity of available habitats (temp and water quality) with decreased magnitude of low flow		
35	**Mussels, all groups,** extreme lows increase risk of exposure and predation of mussel beds										extreme lows increases risk of exposure and predation of mussel beds		

Susquehanna River Ecosystem Flows Study
Flow Recommendation Workshop–Meeting Summary

Wednesday and Thursday, April 7-8, 2010
Kings Gap Environmental Education Center, Pennsylvania

Workshop objectives

The goals of the workshop were to

- review updated flow needs revised through literature review and consultation
- discuss proposed flow statistics to track flow needs and assess alteration
- review and receive comments on draft flow recommendations for headwaters and small streams, major tributaries and the mainstem Susquehanna River.

Presentation summary

Project Scope and Schedule – Michele DePhilip, The Nature Conservancy (TNC)

The overarching goal of the Susquehanna River Ecosystem Flow Study is to describe the flow needs and develop flow recommendations for major habitat types within the Basin. The project began in October 2008 under US Army Corps of Engineers' (USACE) WRDA 729 study authority with the specific goal of informing water management programs implemented by the Susquehanna River Basin Commission (SRBC) and USACE, including consumptive use mitigation and water withdrawal permitting.

Since March 2008, we have completed several major project elements:
(1) identification of flow-sensitive species, communities and habitats,
(2) a targeted literature review on flow-sensitive biological and physical processes,
(3) definition and basin-wide mapping of major habitat types, and
(4) two advisory group workshops – Orientation and Scoping (March 2009) and Flow Hypotheses/Needs (October 2009)

The goal of this third and final workshop was to review and discuss draft recommendations. We will incorporate input on these draft recommendations into a final report that we will submit to SRBC and USACE this summer.

Workshop presentations and discussion were structured to follow the organization of the Draft Flow Recommendations table that we included in the workshop materials. This table includes Flow Needs (Column 1), Flow Components and Statistics (Column 2), draft Recommended Ranges (Column 3) and Supporting Literature and Studies (Column 4).

Literature Review and Revisions to Flow Needs – Tara Moberg, TNC

As of the October 2009 workshop, the majority of literature review and flow hypotheses focused on life history stages and needs of fishes (diadromous and resident), aquatic insects, mussels, and vegetation (aquatic, riparian and floodplain vegetation). Since then, we added information on reptiles and amphibians, water quality, geomorphology and birds and mammals. This review followed a similar process, including the development of a list of flow-sensitive species and physical processes in consultation with regional experts within the respective disciplines.

At the October workshop, the group developed over 60 flow hypotheses that described the anticipated changes to biological and physical processes in response to changing hydrologic conditions in the basin. After adding reptiles and amphibians, water quality, geomorphology and birds and mammals, this list included over 70 flow needs statements.

Between workshops, we consolidated the hypotheses by grouping those with similar timing, taxa and/or function in similar habitats. This consolidation resulted in 19 flow needs statements. Each statement was then associated with its characteristic season, either fall, winter, spring or summer. Some needs span multiple seasons – in these cases, we listed them in the season when they begin but indicate the months when this need is relevant.

The workshop materials contain one diagram illustrating the needs associated with each of the five major habitat types: Cold/Cool headwater and small streams, High baseflow headwater and small streams, Warm headwater and small Streams, Major Tributaries, and Mainstem. The diagrams include needs related to low flows, seasonal flows and high flows. These components are described in the workshop materials and below.

Proposed Flow Statistics – Michele DePhilip

In the workshop materials, we proposed a series of flow statistics for defining flow components and tracking changes to the hydrologic regime. Our goal was to select hydrologic statistics that

- represent the natural variability in the flow regime,
- are sensitive to change and have explainable behavior,
- are easy to calculate, repeatable and have limited redundancy,
- are/can be correlated to ecological response, and
- facilitate communication/are understood by scientists, water managers and water users.

We used flow exceedance values (Q_{ex}) to divide flows into low flow, seasonal and high flow components. For example, a 5-percent exceedance probability (Q_5) represents a high flow that has been exceeded only 5-percent of all days of the flow period. Conversely, a 95-percent exceedance probability (Q_{95}) represents a low flow, because 95 percent of daily mean flows in the period are greater than that amount. The statistics associated with each of those components are outlined in Table 1.

Table 1. Summary of draft flow statistics related to each flow component

Low Flows (Monthly Q95-Q75)	Monthly Q95, and % of long term daily flows between monthly Q95 and Q75
Seasonal Flows (Monthly Q75-Q10) High Flows (> Monthly Q10)	Monthly mean, and % of long term daily flows between monthly Q75 and Q10 Seasonal Frequency of events > monthly Q10 in fall, spring, and summer Annual/Internannual Magnitude and frequency of bankfull event Magnitude and frequency of small flood (1 in 5 year event) Magnitude and frequency of large flood (1 in 20 year event)

Draft Flow Recommendations – Tara Moberg and Michele DePhilip

We used a combination of peer reviewed literature, research reports, unpublished studies and professional input to support these flow recommendations. Our sources included data, literature, and expertise specific to the Susquehanna Basin; studies with the same or similar species or processes in the mid-Atlantic region; and studies on other temperate rivers with similar taxa. These sources either provided *qualitative* information that confirms the flow need or *quantification* of an ecological response to flow alteration. In general, studies included (1) measured responses to a quantified hydrologic alteration; (2) modeled responses to simulated hydrologic alterations; (3) species-specific habitat models; or (4) observations related to extreme conditions (droughts, summer low flows, floods). We gave an example of each type of study, explained how we applied it to the draft recommendations, and discussed some of the strengths and weaknesses of each type of study (specifically for identifying thresholds at a regional scale). A list of works cited is included in the workshop materials.

Breakout groups and comments on flow recommendations

A significant portion of the workshop was dedicated to breakout sessions to discuss the needs, flow statistics, draft recommended ranges, and additional information that may be available to support each recommendation.

Breakout groups were organized by season. Each participant had an opportunity to comment on three seasons. All participants commented on Summer and Fall. Half of the participants commented on Winter and the other half on Spring.

In general, the group agreed that the framework for and the structure of the recommendations was useful. Specifically, they agreed it was useful to divide the flow regime into components and identify statistics related to magnitude and distribution of flows – this structure emphasizes the importance of limiting alteration to the entire flow regime.

We received very specific input on several of the flow needs – specifically related to timing of events and additional references that could be used to refine these recommendations. In addition, we received several more general suggestions for changes to the statistics and recommended ranges, including:

- Consider using monthly median instead of monthly mean as the central tendency statistic associated with seasonal flows.

- When defining recommendations for seasonal and low flow ranges, use percentile values instead of a percent change. For example, rather than stating that we recommend <20% change to monthly median, state that the monthly median should be within the reference Q65 and Q35.

- Incorporate some flexibility into the seasonal and low flow ranges. For example, consider replacing ">65% of daily flows within seasonal range (between the monthly Q75 and Q10)" with "58-72% of daily flows within seasonal range" (this example was based on a rule of thumb suggestion that no statistic should change more than 10%).

- Consider tighter ranges for low flow statistics than for seasonal statistics. For example, perhaps low flow-related statistics should only change 5% but seasonal statistics (e.g., median) could change 10%.

- Consider defining a category of headwater streams (e.g, <38 sq mi) because these streams are likely to be especially sensitive. Then:

- For minimum flow, consider replacing Q95 with Q75 based on responses in literature and expert opinion.
- Consider tighter ranges around statistics to protect seasonal and low flow related needs (in other words, accept less alteration to headwater streams than to other small streams and major tributaries).

- Define rate of change statistic and acceptable alteration – especially for rate of change during bankfull conditions when rapid recession could lead to stranding and/or bank instability.

- Eliminate defining acceptable change in magnitude of high flow/ flood events.

- Use USGS publications (Chaplin 2005) and associated empirical equations to estimate magnitude and recurrence statistic for bankfull events.

- Consider adding a duration statistic to fall pulse events.

Summary of steps between now and project completion

We will either incorporate these general suggestions or explore how we could incorporate them after additional analyses. Specifically, we will:

(1) Update flow needs based on specific comments from workshop participants. This includes specific follow up with experts (e.g., on flows related to shad migration) and incorporating information from recommended studies (e.g., USGS publication on estimating bankfull discharge). These revisions will be incorporated into the revised flow recommendations table and included in the draft report.

(2) Conduct pilot hydrologic analyses to refine flow statistics and recommended ranges. Specifically, we will:
   a. Compare the variation in flow statistics for index and non-index (altered) gages. We will use this understanding of variability during the last 40+ years of record to help define an acceptable range for selected statistics.
   b. Test sensitivity of draft flow statistics by developing reasonable water withdrawal scenarios and determining how these withdrawals affect draft flow statistics. Determine whether different stream types are more or less sensitive (e.g. do headwater streams <38 sq mi respond differently than larger streams; do high baseflow streams warrant specific recommendations)
   c. Correlate changes in these flow statistics with changes in habitat based on the PA-MD IFIM.

   TNC and SRBC will define a scope of work for these analyses. We'll review the results with SRBC staff and others and determine together how to incorporate them into the flow recommendations.

(3) Draft report. We will incorporate the results of the pilot analyses into draft our final report. We will circulate the final report for comments in July. TNC will submit our final report to SRBC and USACE by July 2010.

Thanks again for your participation!

WORKSHOP PARTICIPANTS

Participant	Organizational Affiliation
Andrew Dehoff	Susquehanna River Basin Commission
Andrew Roach	USACE, Baltimore District
Claire Buchanan	Potomac River Basin Commission
Claire O'Neill	USACE, Baltimore District
Colin Apse	The Nature Conservancy
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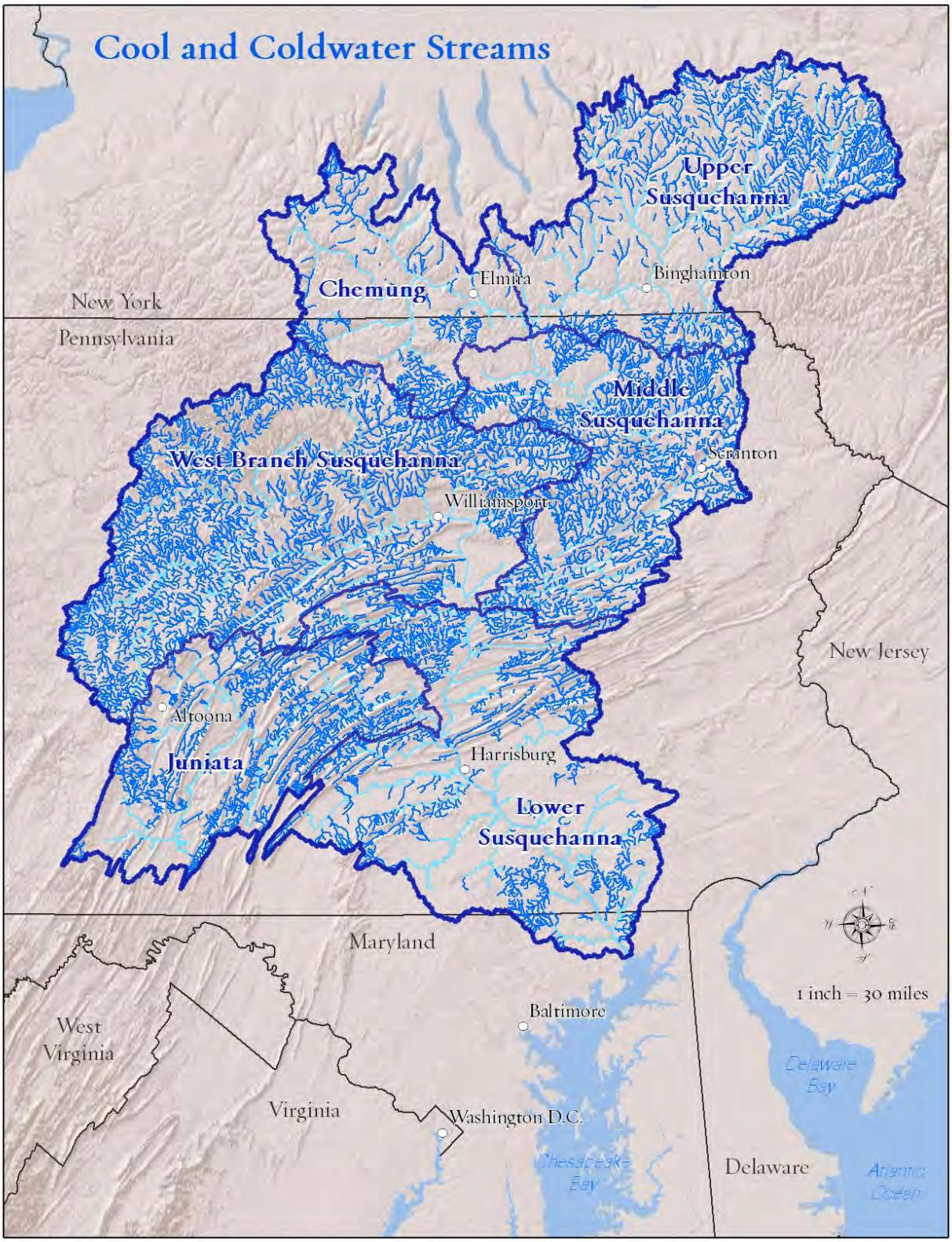
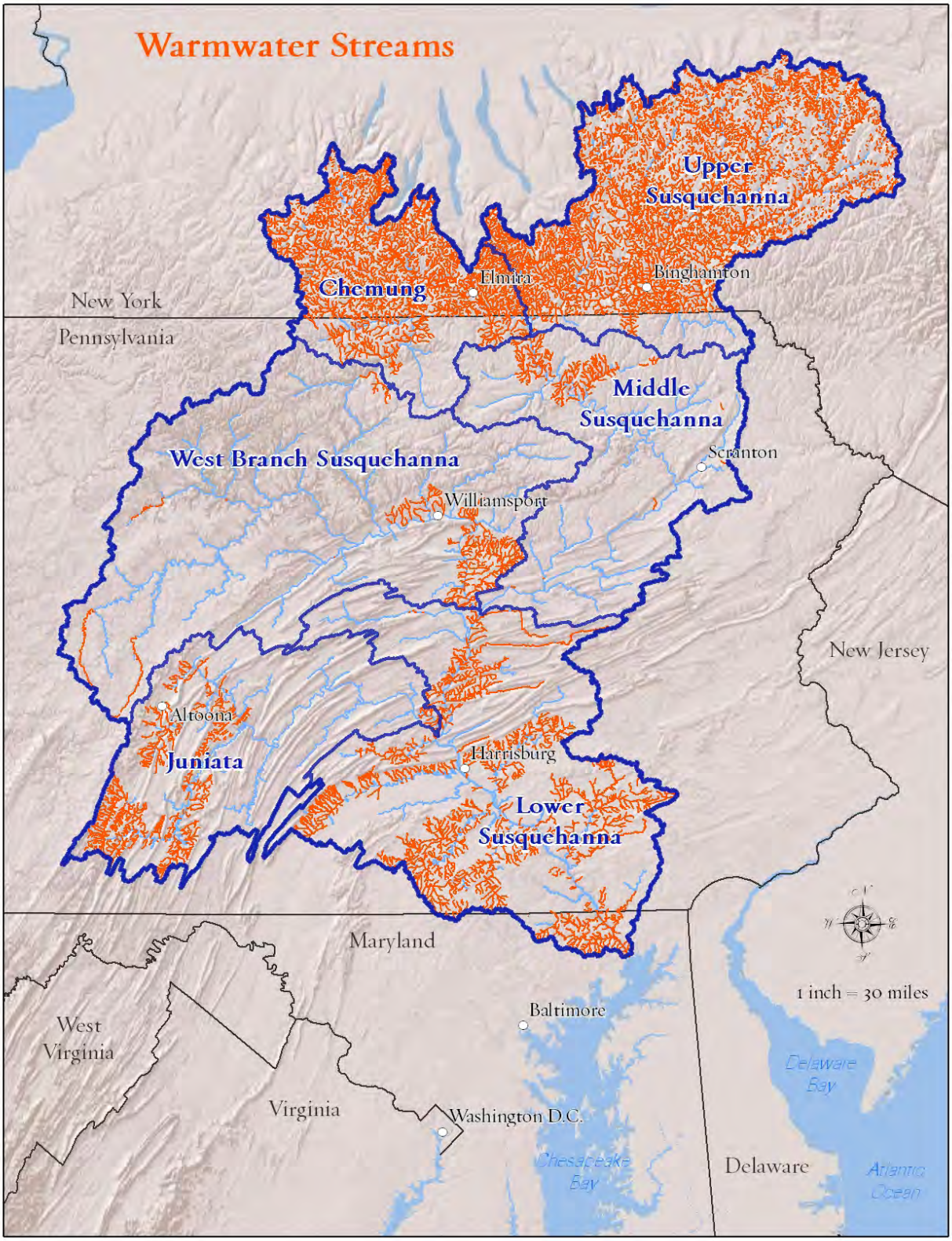
Tom Denslinger	Pennsylvania Department of Environmental Protection

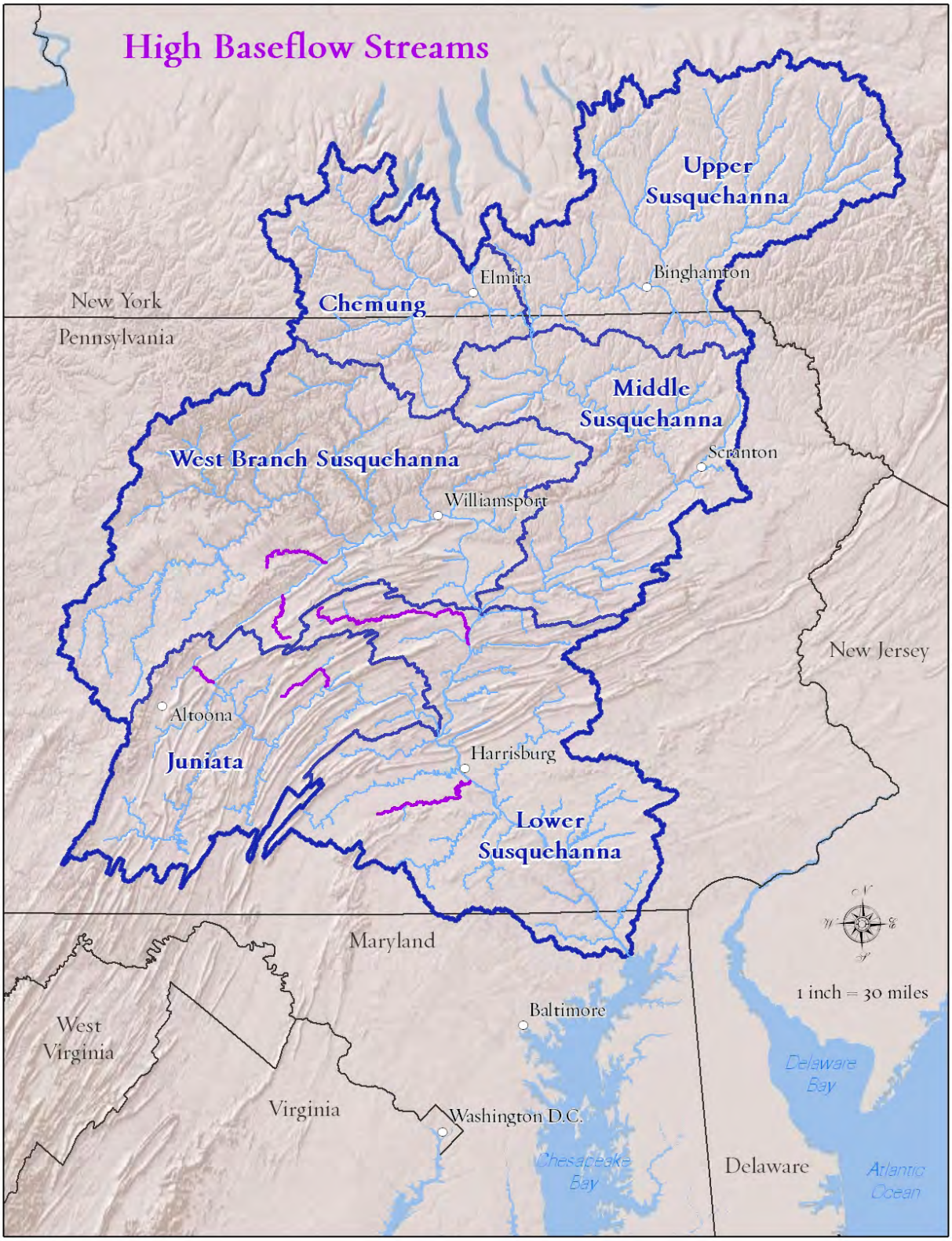
Appendix 2. Description of Streams within each Physiographic Province.

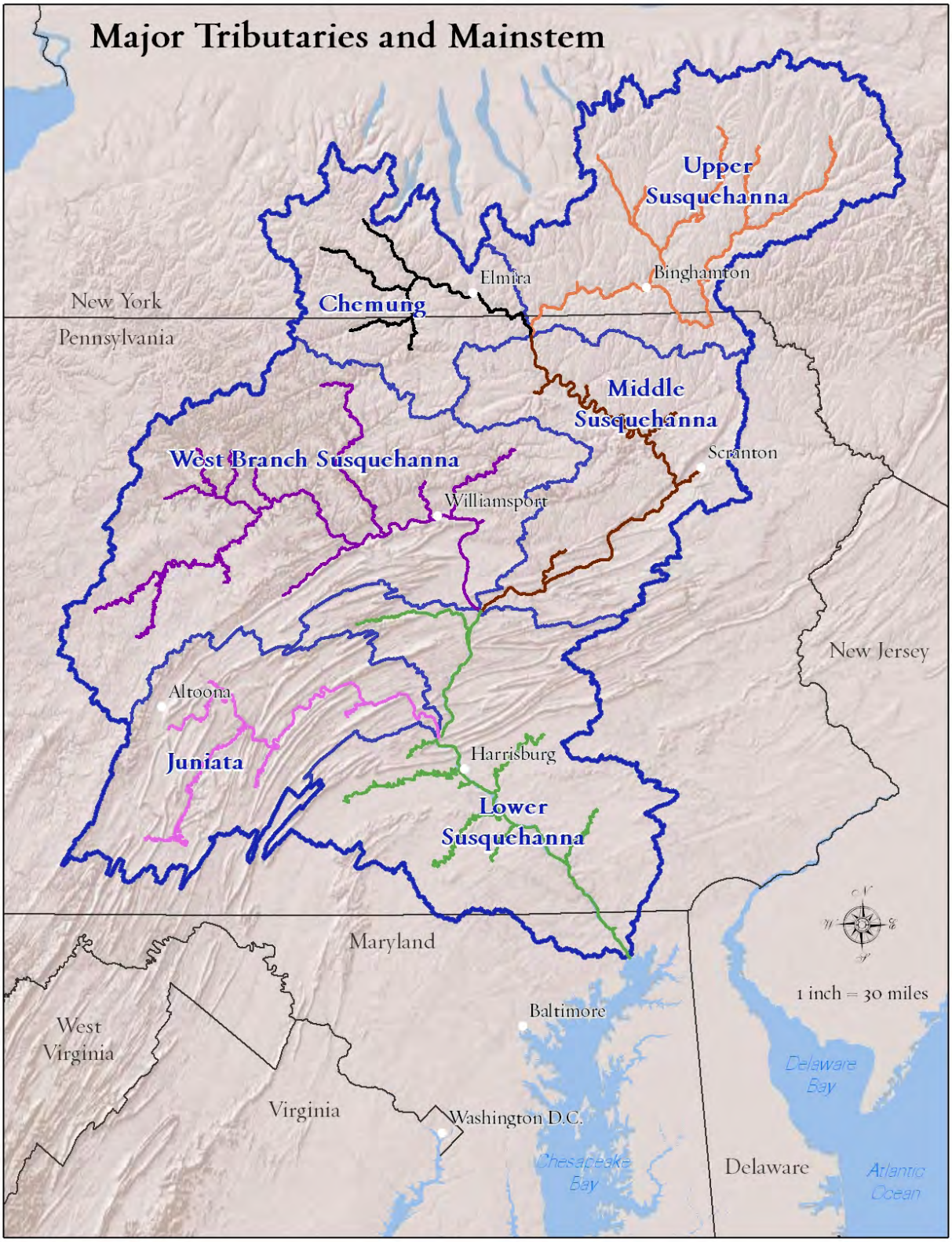
Physio graphic Province	Subbasins	Section	Dominant Form	Underlying Rock	Local Relief	Min	Max	Drainage Pattern	Dominant Channel Forming Processes
Appalachian Plateau	West Branch, Juniata	Allegheny Mountain	Wide ridges separated by broad valleys, ridge elevations decrease in north	Sandstone, siltstone, shale and conglomerate, some limestone and coal	Mod to High	775	3210	Dendritic	Fluvial erosion, some peri-glacial mass wasting
	West Branch, Juniata	Allegheny Front	East: rounded to linear hills rising by steps to an escarpment, hills cut by narrow valleys, west, undulating hills sloping away from escarpment	Shale, siltstone and sandstone	Mod to High	540	2980	Parallel and trellis	Fluvial, peri-glacial mass wasting
	Upper Susquehanna, West Branch	Deep Valleys	Very deep, angular valleys and some broad to narrow uplands	Sandstone, siltstone, shale and conglomerate	Mod to Very High	560	2560	Angulate and rectangular	Fluvial erosion, some peri-glacial mass wasting
	Upper Susquehanna, Chemung	Glaciated High Plateau	Broad to narrow, rounded to flat, elongate uplands and shallow valleys	Sandstone, siltstone, shale and conglomerate some coal	Low to High	620	2560	Angulate and dendritic	Fluvial and glacial erosion, glacial deposition
	Upper Susquehanna, Middle Susquehanna, Chemung	Glaciated Low Plateau	Rounded hills and valleys	Sandstone, siltstone and shale	Low to Moderate	440	2690	Dendritic	Fluvial and glacial erosion, glacial deposition
Ridge and Valley	West Branch, Juniata	Appalachian Mountain	Long narrow ridges and broad to narrow valleys, some karst	Sandstone, siltstone, shale, conglomerate, limestone and dolomite	Moderate to Very High	440	2775	Trellis, angulate and some karst	Fluvial erosion, solution of carbonate rocks, peri-glacial mass wasting
	Middle Susquehanna, West Branch, Juniata	Susquehanna Lowland	Low to moderately high linear ridges, linear valleys, Susquehanna River Valley	Same	Low to Moderate	260	1715	Trellis and angulate	Fluvial erosion, some glacial erosion and deposition in northeast
	Middle Susquehanna	Anthracite Valley	Narrow to wide canoe shaped valley having irregular to linear hills, valley enclosed by steep sloped mountain rim	Sandstone, siltstone, conglomerate and anthracite	Low to moderate	500	2368	Trellis and parallel	Fluvial and glacial erosion, some glacial deposition
	Mainstem Tributaries, Lower Susquehanna	Great Valley	Very broad valley, northwest half, dissected upland, southeast half, low karst terrain	northwest Shale and sandstone, slate, southeast, limestone and dolomite	Low to Moderate	140	1100	Dendritic and Karst	Fluvial erosion, solution of carbonate rocks, some peri-glacial mass wasting
	Mainstem Tributaries, Lower Susquehanna	South Mountain	Linear ridges, deep valleys and flat uplands	Metavolcanic rocks, quartzite, and some dolomite	Moderate to High	450	2080	Dendritic	Fluvial erosion of highly variable rocks, some peri-glacial mass wasting
Piedmont	Mainstem Tributaries, Lower Susquehanna	Gettysburg-Newark Lowland	Rolling lowlands, shallow valleys and isolated hills	Mainly red shale, siltstone and sandstone, some conglomerate and diabase	Low to Moderate	20	1355	Dendritic and trellis	Fluvial erosion of rocks with variable resistance
	Mainstem Tributaries, Lower Susquehanna	Piedmont lowland	Broad, moderately dissected karst valleys separated by broad low hills	Dominantly limestone and dolomite, some phylitic shale and sandstone	Low	60	700	Dendritic and Karst	Fluvial erosion, some peri-glacial mass wasting
	Mainstem Tributaries, Lower Susquehanna	Piedmont upland	Broad, rounded to flat-topped hills and shallow valleys	Mainly schist, gneiss, and quartzite, some saprolite	Low to Moderate	100	1220	Dendritic	Fluvial erosion, peri-glacial mass wasting

Appendix 3. Maps of All Major Habitat Types




Warmwater Streams
Upper Susquehanna
Chemung
Elmira
Binghamton
New York
Pennsylvania
Middle Susquehanna
West Branch Susquehanna
Scranton
Williamsport
New Jersey
Altoona
Juniata
Harrisburg
Lower Susquehanna
Maryland
1 inch = 30 miles
Baltimore
West Virginia
Delaware Bay
Virginia
Washington D.C.
Chesapeake Bay
Delaware
Atlantic Ocean


High Baseflow Streams
Upper Susquehanna
Chemung
Middle Susquehanna
West Branch Susquehanna
Juniata
Lower Susquehanna
Elmira
Binghamton
Scranton
Williamsport
Altoona
Harrisburg
Baltimore
Washington D.C.
New York
Pennsylvania
New Jersey
Maryland
West Virginia
Virginia
Delaware
Delaware Bay
Chesapeake Bay
Atlantic Ocean
1 inch = 30 miles


Major Tributaries and Mainstem
Upper Susquehanna
Binghamton
Elmira
Chemung
New York
Pennsylvania
Middle Susquehanna
Scranton
West Branch Susquehanna
Williamsport
New Jersey
Altoona
Juniata
Harrisburg
Lower Susquehanna
Maryland
1 inch = 30 miles
Baltimore
West Virginia
Delaware Bay
Virginia
Washington D.C.
Chesapeake Bay
Delaware
Atlantic Ocean

Appendix 4. Life History Diagrams and Tables

Fish

Cold headwater

Riffle obligates

Riffle associates

Nest builders

Diadromous (migratory)

Mussels

Primarily riverine

Facultative riverine

Primarily lentic

Reptiles and Amphibians

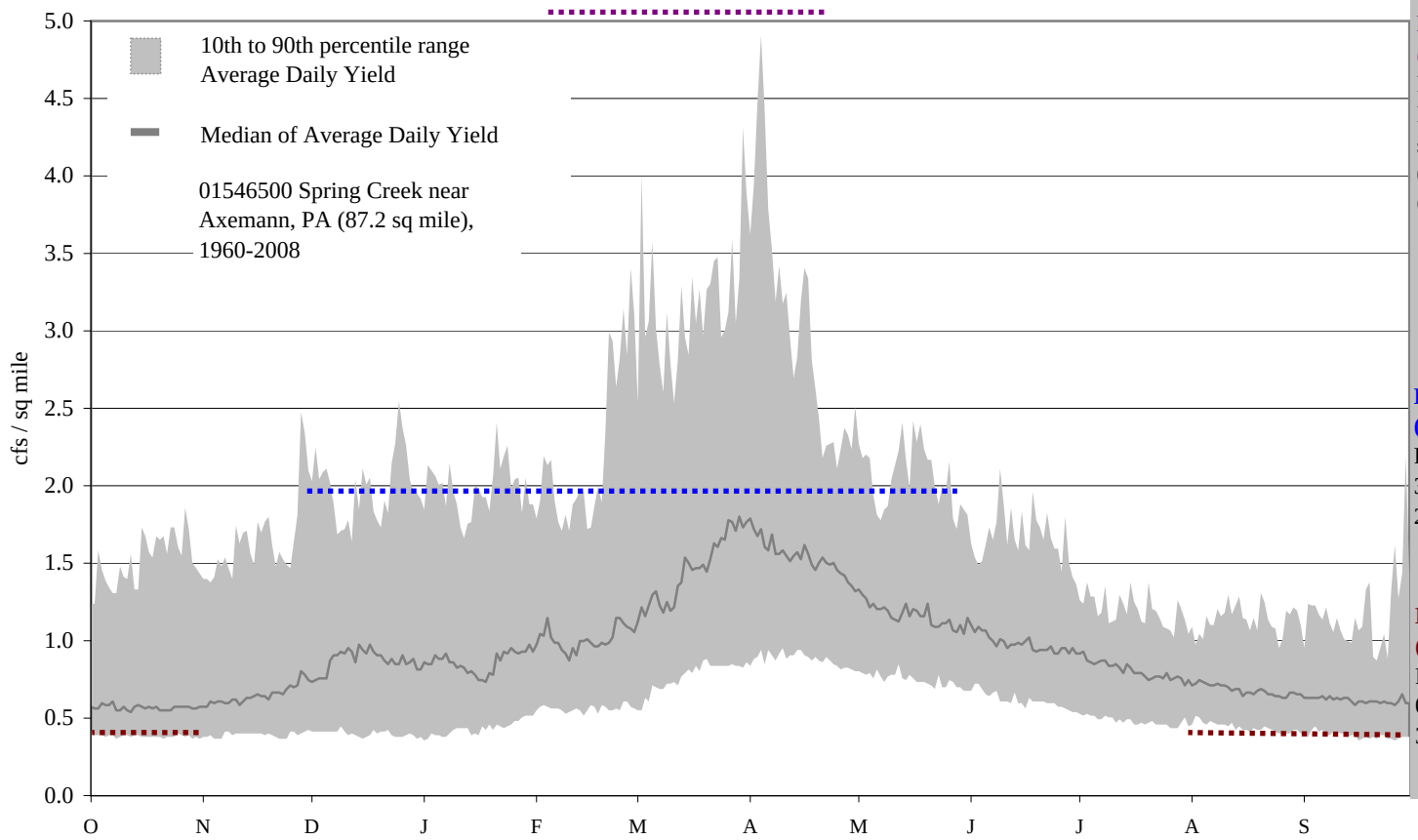
Aquatic –lotic

Semi-aquatic lotic

Riparian and floodplain-terrestrial and vernal

Aquatic and Riparian Vegetation

Fishes: Cold Headwater - Brook trout (*Salvelinus fontinalis*) and *Cottus spp*.



FLOOD
(> 2 yr Recurrence)
February- mid April
Flow 7.3 to 10.9 cfs/ sq mi
0 to 1 events / year
6 to 21 days / event

HIGH PULSE
(≥Q10)
Flow >1.95 cfs/sq mi
3 to 8 events / year
2 to 5 days / event

LOW PULSE
(≤Q90)
Flow < . 46 cfs/sq mi
0 to 4 events / year
3 to 11 days / event

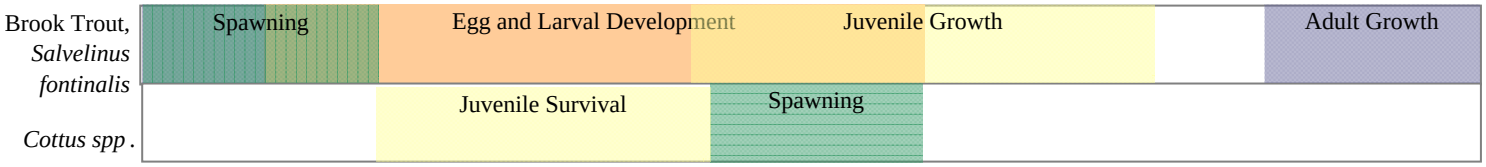


Table 1 includes a summary of life history information for these species

Table 1 Cold headwater fishes life history summary

	Life Stage	Timing		Habitat				Hydro- Ecology Relationships			
		Event	Cue	Substrate	Temp	DO +	pH	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
Brook Trout, *Salvelinus fontinalis*	**Egg and Larval development**	November through April: Fry emergence- 28 to 165 days depending on temperature		10-40 cm; eggs buried in gravel, presence of fines limits development	range 14.8 to 2.8 C, warmer temperatures decrease development time			Range: 0 - .88 ft/s, Opt. 0-.38 ft/s,	Range: .38-2.88 ft, Opt: 1.13- 1.88 ft		embryo development maximized at v 30 to 60 cm/s, fry overwinter in shallow areas with low velocity (.984 to 1.96 ft/s)
	Juvenile Growth	Cool months (March-June): Juvenile Growth		use substrate (10 to 40 cm) as winter cover				Range: 0 to 1.63 ft/s, Opt: 0 to .88 ft/s; 8-9 cm/s, max 24 cm/s (.26-.78 ft/s)	Range: .63-2.88, Opt: 1.13-1.88 ft	margins, shallows	
	Adult Growth	Aug-Dec: most critical period during baseflow (lowest flows of late summer to winter)	sexual maturity varies, as early as age '0', Usually age 1 or 2	rocky	cold, range: 0 to 24 C, with optimal range 11-16 C, the most limiting factor in suitable habitat	feeding habits greatly influenced by turbidity	tolerance 4-9.5, optimal 6.5-8	Range: 0 to .25 ft/s, Opt 0 to .38 ft/sBFI > 50% excellent, <25% poor	Range .63-5 ft, Opt 1.13 to 2.63 ft	riffle-run areas with 1:1 pool-riffle ratio including areas of slow, deep water	
	Spawning	October and November	temperature 3 to 10 C,	redds built in gravel, sometimes sand		intergravel O_2 concentration important for spawning success		Opt. 0-.38 ft/s, Range: 0 - .88 ft/s,	Range: .38-2.88 ft, Opt: 1.13- 1.88 ft	strong preference for areas of groundwater upwelling; found in all habitat types, higher tendency in downstream end of pools	
Mottled Sculpin, *Cottus bairdi*	**Egg and Larval development**										
	Juvenile Survival	Dec-February: population size regulated by overwinter density-dependence among juveniles and adults							shallowest habitats throughout life cycle	margins and shallow riffles, specific habitat is dependent on adult sculpin density	
	Adult Growth		Mature by age 2	use interstitial spaces in substrate for cover, generalistic patterns in preference	tolerant of warm water			habitat specialist with regard to velocity (fast)* site specific values in Gray and Stauffer 1999 25 cm/s	shallow habitats throughout life cycle	riffles	
	Spawning	Mid March and April (Early spring)	small home range, same reach recapture, average 12.9 m							males select cavity beneath a rock in a stream riffle, eggs laid on underside of stones	

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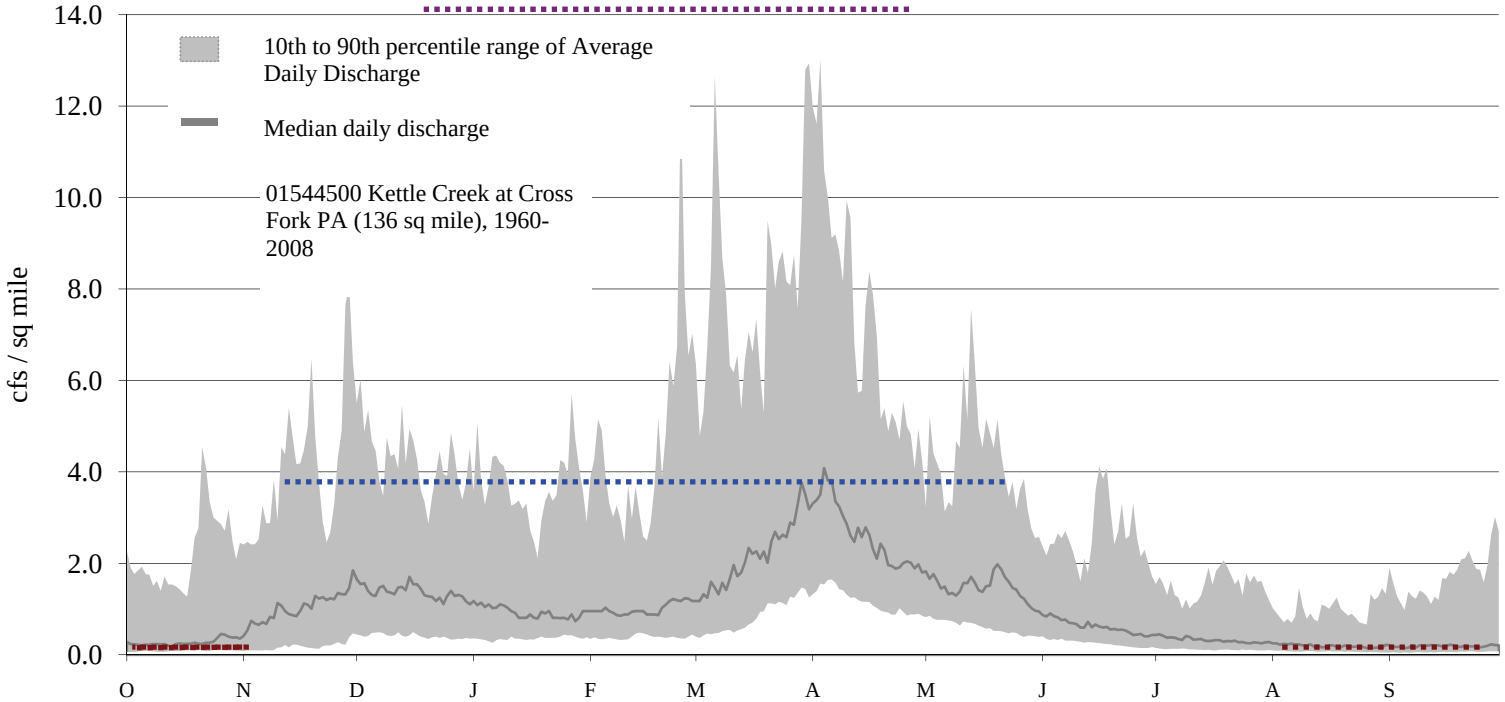
Fishes: Riffle-Obligates - Margined madtom (*Noturus insignis*), Longnose dace (*Rhinichthys cataractae*), Central Stoneroller (*Campostoma anomalum*), Fantail Darter (*Etheostoma flabellare*)



FLOOD
(> 2 Yr Recurrence)
late Dec- late Apr
Flow 24 to 39 cfs / sq mile
0 to 1 events / year
6 to 12 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.9 cfs / sq mile
5 to 9 events / year
4 to 6 days / event

LOW PULSE (≤Q90)
Flow ≤ .1 cfs / sq mile
2 to 6 events / year
3 to 9 days / event

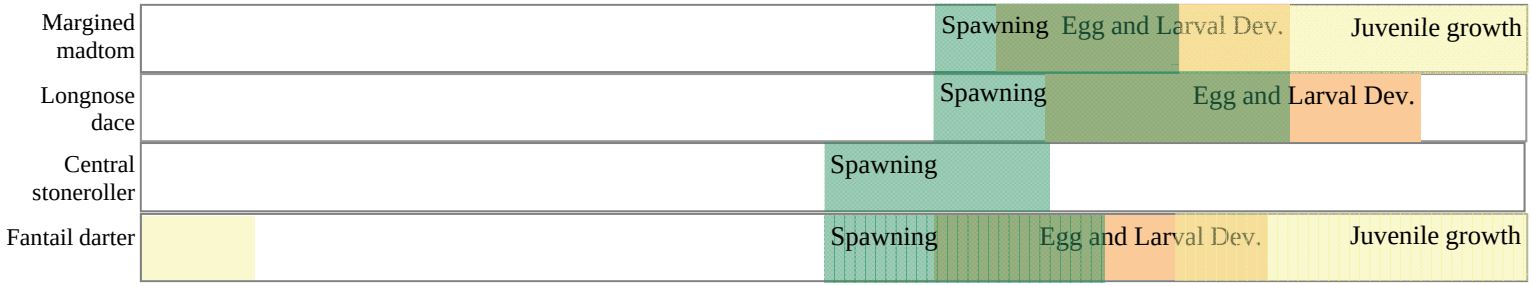


Table 2 includes a summary of life history information for each species

Table 2 Riffle-obligate fishes life history summary

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
Margined Madtom, *Noturus insignis*	**Egg and Larval development**	Late May to August, 1 to 3 weeks from spawning	Incubation 7-10 days at 15.6 C yolk sac absorbed 7 days after hatch						riffles	
	Juvenile Growth	Most growth occurs in July, August and Sepember after Spawning has occured								
	Adult Growth		Mature by age 2, live up to 4 years	sand or gravel bottom	warm water		moderate current		riffles	
	Spawning	May to June		nests beneath flat rocks			moderate current			
Longnose dace, *Rhinichthys cataractae*	**Egg and Larval development**	June-end Aug. (three weeks after fertilization)					within 6 weeks of age, move to swift water areas (> 45 cm/s)		fry abundant in protected margins of quiet shallow water,	
	Juvenile Growth						v > 45 cm/s	< .3 m rarely > 1m	riffles	juveniles and adults are adapted to high velocity areas
	Adult Growth		mature at age 2, live up to 5 years				v = 45 to 60 cm/s, observed living as high as 182 cm/s	< .3 m rarely > 1m	swift flowing, steep gradient headwater streams of larger river systems, shelter from current must be present	small home range, most recaptures in same reach, average distance 13.4 m
	Spawning	As early as May, Late as August, peak from June to early July	when daily maximum temp exceeds 15 C (Bartnik 1970)	gravel and rock smaller than 20 cm diameter	Optimum 14-19 C			< .3 m rarely > 1m		
Central Stoneroller, *Campostoma anomalum*	**Egg and Larval development**			in a depression of gravel or gravel and sand mix						
	Juvenile Growth									
	Adult Growth		Mature in 1 to 5 years	hard bottomed streams					runs and riffles, males commonly school over Nocomis nests	
	Spawning	April to May		males dig pits in shallow-gravel bottomed areas, may maintain spawning pits in close proximity			slow to moderate			
Fantail darter, *Etheostoma flabellare*	**Egg and Larval development**	May-July: Hatch one month behind spawning (30 to 35 days at 17-20 C)	14-16 days at 23 C							
	Juvenile Growth	Mid July-November- Juvenile development							pools and slackwater areas downstream of riffles	
	Adult Growth		Mature at age 1 or 2	particularly abundant in streams with slabs of limestone or shale; many stones and rocks for cover	cool and warm streams			shallow to very shallow	riffles or along the shallow banks	
	Spawning	April to Mid June	correlated with temperature		temps 15 to 24 C				runs and slow riffles including shallows	

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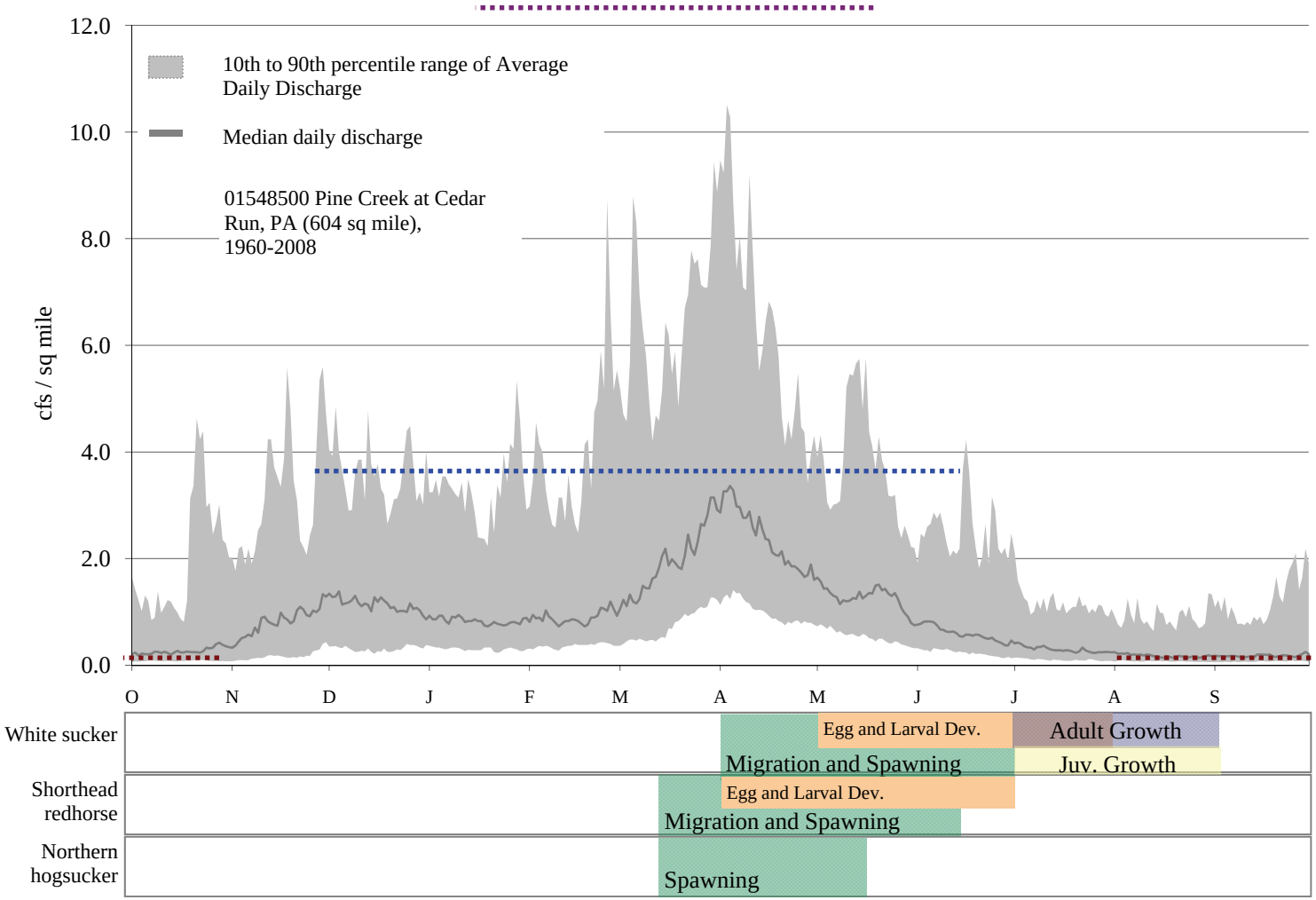
Fishes: Riffle-Associates - White Sucker (*Catostomus commersoni*), Shorthead redhorse (*Moxostoma macrolepidotum*), Northern hogsucker (*Hypentelium nigricans)*



FLOOD
(> 2 Yr Recurrence)
Late Jan-Mid May
Flow 19 to 28 cfs / sq mile
0 to 1 events/ year
7 to 12 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.4 cfs / sq mile
5 to 10 events / year
3 to 5 days / event

LOW PULSE
(≤Q90)
Flow ≤ .12 cfs / sq mile
2 to 6 events / year
4 to 8 days / event

Table 3 includes a summary of life history information for each species

Table 3 Riffle-associate fishes life history summary

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Event	Cue	Substrate	Temp	DO +	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
White sucker, *Catostomus commersoni*	**Egg and Larval development**	May-July (three weeks to one month after spawning)	embryo development temperature dependent		max hatching success 15 C		riffle velocity Opt: 30 to 60 cm/s			longlived (common 10, max found up to 17 years)
	Juvenile Growth	July-August: Max growth occurs July through August							pools: HSI Optimal 30 to 60 % pools	
	Adult Growth	July-August: Max growth occurs July through August			geographically dependent, but wide range	optimal 6 to 10, Range 1.2 to 10	moderate current, migration can be impeded by swift currents		deep connected pools and slow runs (10-19 cm/s), Max abundance in low to moderate gradient streams (2.8 to 7.8 km/m, few inhabit > 28.4 m/km), Pools: 30 to 60 % (HSI)	growth inhibited during gonadal development and spawning
	Migration and Spawning	April through June	upstream migration triggered temperature (50 deg F) or streamflow	gravel (2 to 16 mm), can have clean sand, but gravel necessary	range 6 to 24 C, Opt 12 to 16 C, migration ceases > 18 C		spawning site selection influenced primarily by water velocity and depth of substrate type, HSI riffle velocity Opt: 30 to 60 cm/s	shallow waters (HSI Range: about 4 to 45 cm, Optimal 15 to 27 cm)	migrate from stream pools to riffles of small creeks and rivers,	migration distance ranging from a few hundred meters to 6.4 km,
Shorthead Redhorse, *Moxostoma macrolepidotum*	**Egg and Larval development**	April through late June: 1 to 2 weeks after fertilization			hatched at mean temperature of 15.6 C					
	Juvenile Growth	Oct-February					.75-3.4 ft/s optimal	1.5-3.0 ft		
	Adult Growth						1.5-4.3 ft/s optimal, 23-63 cm/s, 0-1 ft/s	2.0-12 ft, 1-6 ft, 1-2 m		
	Migration and Spawning	Mid March-Early June		course mixed substrate, gravel and cobble			0-.5 ft/s, .6-.9 m/s	30-60 cm, 1-2 ft		
Northern Hogsucker, *Hypentelium nigricans*	**Egg and Larval development**	April through late May	estimated 2 weeks to hatch another 1 to 2 for yolk sac absorbtion	hatch in 10 days at mean temp 17.4 C;						eggs and small young predated by other fish
	Juvenile Growth									disturb bottom sediment, sympatric relationship with fish following to take advantage of drift
	Adult Growth			mature at age 2-4	gravelly/ stony streams				feeds and rests in very shallow riffles	rests on bottom of stream in shallow riffles
	Spawning	late March through early May			gravel; gravel and sand	60 F		fast-flowing	shallow	move from larger streams to smaller headwaters to spawn, over riffles, like other suckers

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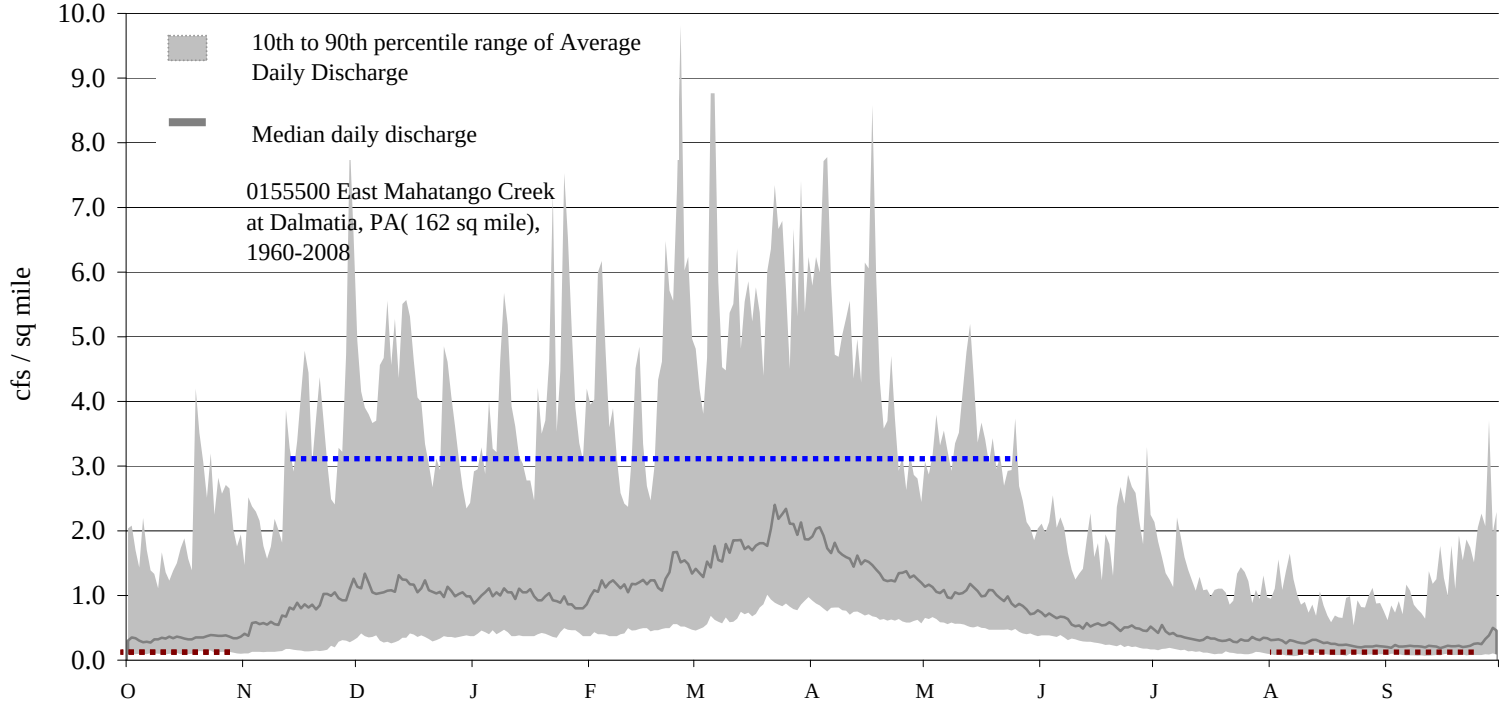
Fishes: Nest-builders - Fallfish (*Semotilus corporalis*), Creek chub (*Semotilus atromaculatus*), River chub (*Nocomis micropogon*), Redbreast sunfish (*Lepomis auritus*), Smallmouth bass (*Micropterus dolomieui*)



FLOOD
(> 2 Yr Recurrence)
End Dec- Early Apr
Flow 21 to 39 cfs / sq mile
0 to 1 events/ year
6 to 12 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.1 cfs / sq mile
7 to 12 events / year
3 to 4 days / event

LOW PULSE (≤Q90)
Flow ≤ .1 6 cfs / sq mile
1to 6 events / year
3 to 10 days / event

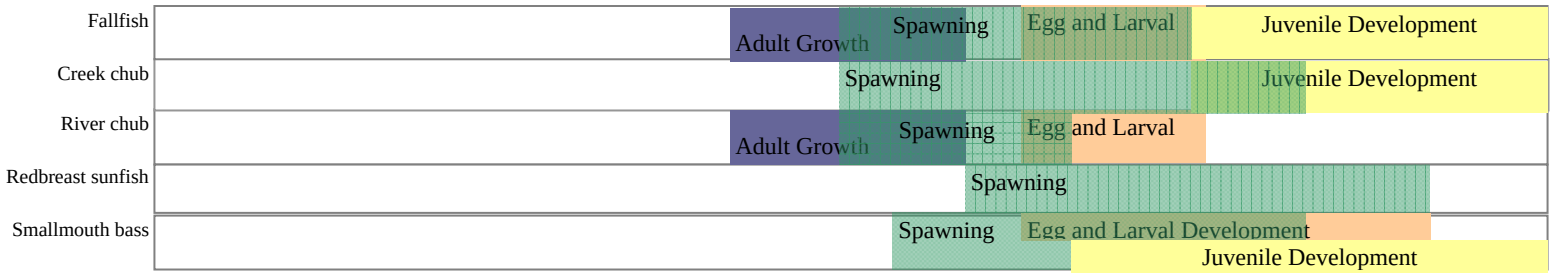


Table 4 includes a summary of life history information for each species

Table 4 Nest-builder fishes life history summary

	Life Stage	Timing			Habitat		Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO +	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
Fallfish, *Semotilus corporalis*	**Egg and Larval development**	Late May-June	eggs hatch in 5 to 6 days, fry emerge 9 to 11 days after hatching and drift downstream at night		incubation occurs between 16 and 18 C,					Longlived (up to 11 years), similar to creek chub
	Juvenile Growth	Warm months							juveniles occur in smaller streams than adults	largest minnow east of the rockies, constructs the largest stone mound nest known
	Adult Growth		Reach maturity at age 4 (as early as 2)	Sand and gravel	warmest water temperatures, Range 5-27 C, Opt- 10-20 C; seldom occur > 28 C		tolerant to high flows in early spring		clear gravel bottomed streams, commonly found near base of cascades and falls	Turbidity < 30 JTU's * assumption that this equates to clear water
	Nest building and spawning	April - June	temperature		Throughout spawning season Range: 15-18, Opt: 16.5-17.5, spawning may cease if temps drop below 15 C		5-69 cm/s	Avg depth across stream Opt: ≤.5 m	move from larger waters into smaller streams to spawn, prefer habitats with overhead cover,	Select spawning grounds based on abundance of instream cover over preferred substrate type
Creek Chub, *Semotilus atromaculatus*	**Egg and Larval development**				15 -20 C	5 mg/L; some studies have shown tolerance to low DO concentrations (last to die at AMD sites)	Opt < 10 cms	between 30 and 100 cm	fry- edges of stream edges and margins	Cover is also an important compentent to habitat quality (an HSI var)
	Juvenile Growth	Warm months					10 cm/s	< 1m depth	juveniles prefer stream edges and margins	
	Adult Growth		Mature between ages 2 and 5	gravel	average temperature 18-22 C; always < 32 C			< 1 m average depth and .5 to 7 m in width	small, clear, cool stream with moderate to high gradient, well defined riffles and pools (greatest abundance in gradients 7 to 13.4 m/km), 45-60% pools	
	Nest building and spawning	Apr- July	temperature		temp 14 C		< 1.25 cfs (xxx), 20-60 cms in riffle areas from April to June (HSI)	depth > 100 cm, width .15-7 m	immediately up or downstream of riffles in shallow water	
River Chub *Nocomis micropogon*	**Egg and Larval development**	Late May - June		gravel			slow to moderate current			Bigmouth chub a similar species, bigmouth chub closely related relative to cladistic analysis,
	Juvenile Growth		mature at age 2 or 3							
	Adult Growth	March-April: gonadal development			temp 13 C (during gonadal development)		tolerant to high flows in early spring (during gonadal development)		riffles in high gradient streams of moderate size; medium to large tributaries, pools runs and riffles	
	Nest building and spawning	Apr-May	temp > 20 C, 17-26.7 C	gravel	Range: 17-26.7 C			slow to moderate current, 5 - 69 cm/s or .16- 2.2 ft/s (bigmouth chub)	> 15 cm, a nest height at center recorded as 10 cm	3 to 8 m in width; 27 minnow species recorded to be nest associates of Nocomis

Table 4 Nest-builder fishes life history summary

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO +	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
Redbreast Sunfish *Lepomis auritus*	**Egg and Larval development**			redds preferrably located in sand or gravel			very succeptible to high flows (male guarders desert nests), 0-.25 ft/s optimal	stable water levels are critical for egg adhesion, nests in shallow water <1 m optimal	physical obstructions in lotic systems (logs, stumps, etc.)	
	Juvenile Growth						.4-.6 ft/s optimal	.5-5.2 ft optimal		
	Adult Growth			gravel and cobble optimal			.5-.8 ft/s optimal	2-6.1 ft optimal		
	Nest building and spawning	May- August		coarse sand, gravel no silt	temperature 20 to 28 C	optimal - seldom below 5 mg/L	varies by study, < 20 cm/s, .59 ft/s and 0 to .5 ft/s	.2 to 1.5 meters	calm pools, protected areas such as near logs, fallen trees, or stumps	suceptible to high flow after nest building, adults desert nest and/or nests destroyed in high flow events
Smallmouth Bass *Micropterus dolomieui*	**Egg and Larval development**	up to 1 month past spawn		nests built on sand, gravel, or rock	15-25 C		< .2 m/s, flood after spawning reduces survival if scouring occurs	.3-.9 m deep	pools, successful nests closer to the stream bank	
	Juvenile Growth	June flows have significant influence on survival, growth during warm months		no clear preference			strongest year classes when June flows within 40% of the longterm mean			
	Adult Growth			no clear preference	21-27 C in summer		10 cm/s or less		pools	
	Nest building and spawning	Mid April-July	mean daily water temperature most important variable (as it interacts with discharge), tend to spawn during the receding limb of a high flow event	nests built on sand, gravel, or rock with almost always under protection of cover	> 15 C and < 25 C		slow current, a flood event can split the spawning season in two	.3-.9 m deep	pools, protected areas, very strongly prefer areas of abundant shade and cover	

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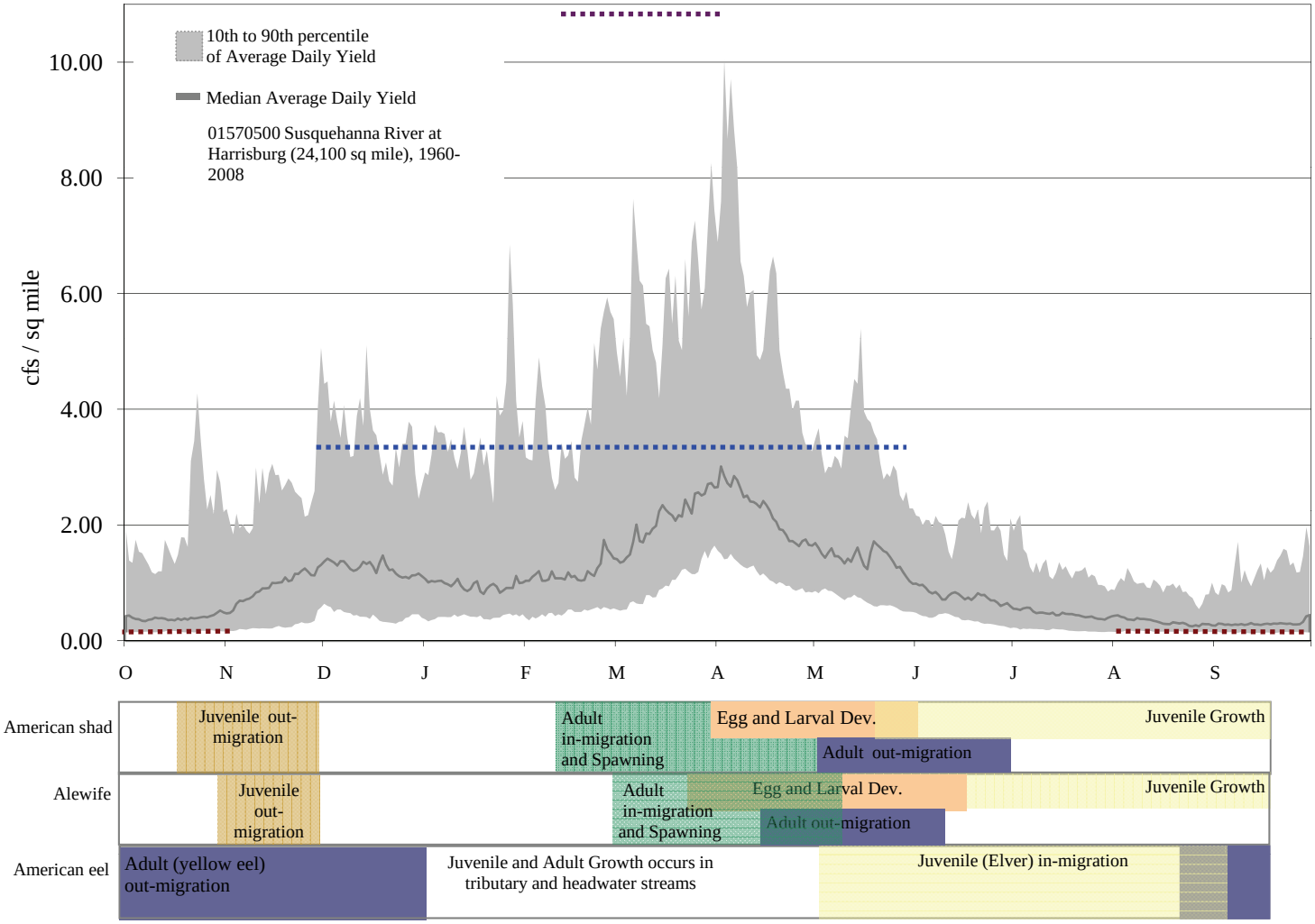
Fishes: Migratory - American shad (*Alosa sapidissima*), Alewife (*Alosa pseudoharengus*), and American eel (*Anguilla rostrata*)



FLOOD
(> 2 yr Recurrence)
Late Feb. to Early April
Flow 10.8 to 16.6 cfs / sq mile
0 to 1 events / year
0 to 27 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.2 cfs / sq mile
4 to 8 events / year
4 to 6 days / event

LOW PULSE
(≤Q90)
Flow ≤ .2 cfs / sq mile
1 to 4 events /year
4 to 17 days / event

Table 5 includes a summary of life history information for each species

Table 5. Migratory Fishes life history summary

	Life Stage	Timing		Habitat				Hydro- Ecology Relationships			
		Event	Cue	Substrate	Temp	DO +	pH	Q or Velocity	Depth	Hydraulic Habitat Unit	Comments
American Shad *Alosa Sapidissima*	**Egg and Larval development**	Early April to Late May	development time correlated inversely to temperature	eggs drift 5- 25 m downstream of spawning area; higher survival in gravel, rubble and sand	range 10 to 30 C, Optimal 15-25 C	DO ≥ 5 mg/L		optimal .3 to .9 m/s (.98 to 2.95 ft/s), minimum flow beneficial to prevent suffocation and infection	tolerable .46-15.4 m, Optimal: 1.5 to 6.1 m	yolk sac larvae found deeper in the water column, offshore-near bottom	year class strength is negatively correlated to river flow (Marcy 1976), survival rates greater when spring high flows preceed hatch, decrease when June pulse occurs
	Juvenile Growth and emigration	Emigration late Oct to Late Nov	cue likely a combination of temperature and lunar cycle; juveniles can't tolerate a change +/- 1 to 4 C from ambient	boulder cobble gravel sand, where SAV exists, there is a correlation between SAV habitat (>50% cover) and juvenile abundance,	8 to 19 C	DO ≥ 5 mg/L		optimal: .1 - .8 m/s (.33 to 2.62 ft/s), moderate velocity needed for migration, also thought to orient juveniles downstream	range: .46-15.4 m, Optimal: 1.5 to 6.1 m		
	Adult Growth	Adults return to sea and migrate to summer feeding grounds after spawning	remain in ocean 2 to 6 years before sexual maturity (male avg. 4.3, and female 4.6 yrs), return to spawn in natal river				Anadromous- In marine environment for this life stage				
	Migration and Spawning	Begin to enter freshwater in winter, gonadal development early March-Apr, spawning peak in early May (on Delaware)	temperature 13-20 C* in CT River, temp at peak spawning found to vary from year to year	substrate not constraining to site selection	Range: 8-26 C, Optimal: 14-24.5 C	DO ≥ 4 mg/L		velocity an important factor, Optimal .3 to .9 m/s (.98 to 2.95 ft/s)	< 300 cm, tolerable .46-15.4 m (1.5-50'), Optimal: 1.5 to 6.1 m (4.92-20'),	broad flats, runs, shallow water with moderate current, avoid pools but prefer slow flow	
Alewife *Alosa pseudoharengus*	**Egg and Larval development**	Range 2 to 15 days after spawning, most often 3 to 5 days after spawning	development time after fertilization, correlated inversely to temperature	75% silt or substrate containing detritus and vegetation	Optimal: 14-21 C Range 10-27 , cease hatching >29.7 C,	≥5.0 mg/L	5 to 8.5	velocity one of strongest predictors of egg presence (O'Connell 1997), rapid decline when flows too high (Pamunkey 1989), or too low (Rhode Island 1981)			
	Juvenile Growth and emigration	Growth March-Oct, Emigration November	changes in water flow, stage, precipitation, light intensity or temperature and moon phases	75% silt or substrate containing detritus and vegetation, HSI available (1) ≥ 75% mud or silt or other soft material containing detritis and vegetation, (2) ≥ 50% mud or silt, some sand and vegetation, (3)≥ 75% sand or other	Range: 5 to 27 C, Optimal: 15 -20 C,	min 3.6 mg/L	8.2	avoid high flows, avoid narrow channels where v > 10 cm/s			net gain in biomass highest at 26.4 C in Kellogg 1982 study
	Adult Growth	After spawning, adults return to estuary and feed until migrating to wintering grounds	sexual maturity occurs at a minimum age of 2, spawning populations 3 to 8 in the Ches. Bay				Anadromous- In marine environment for this life stage				
	Migration and Spawning	Enter freshwater in March and April, spawning begins 2 to 3 wks earlier than shad (late April)	most predictably temperature, may also be triggered by high flow periods		10.5 C-21.6, Cease spawning when > 27 C	≥5 mg/L	found spawning in streams from 5.0 to 7.3	sluggish water flows	15 cm to 3 m, typically less than 1 m	floodplains, river margins, ponds, backwaters of lower CT River, slow moving sections of rivers, in rivers with headwater ponds; shore-bank eddies or deep pools below dam	
American Eel Anquilla rostrata	**Egg and Larval development**						Catadromous- In marine environment for this life stage				
	Juvenile Growth and immigration	Juveniles (elvers) enter Susquehanna from May - September, peaking in June and July	bottom habitat with coarse substate preferred	burrow in sand, mud, tubes, snags, plant masses, etc. during the day and in between movements	wide range			tolerant of 25 cm/s			no feeding during migration
	Adult Growth-Yellow Eel	May-Oct	migration continues					most in areas with wide variety of velocities	most in areas with wide variety of depths		
	Emigration of Silver Eel	Mid-Sept to Dec: emigrate to Sargasso Sea to spawn mostly during the fall			reported at 18-19 C						

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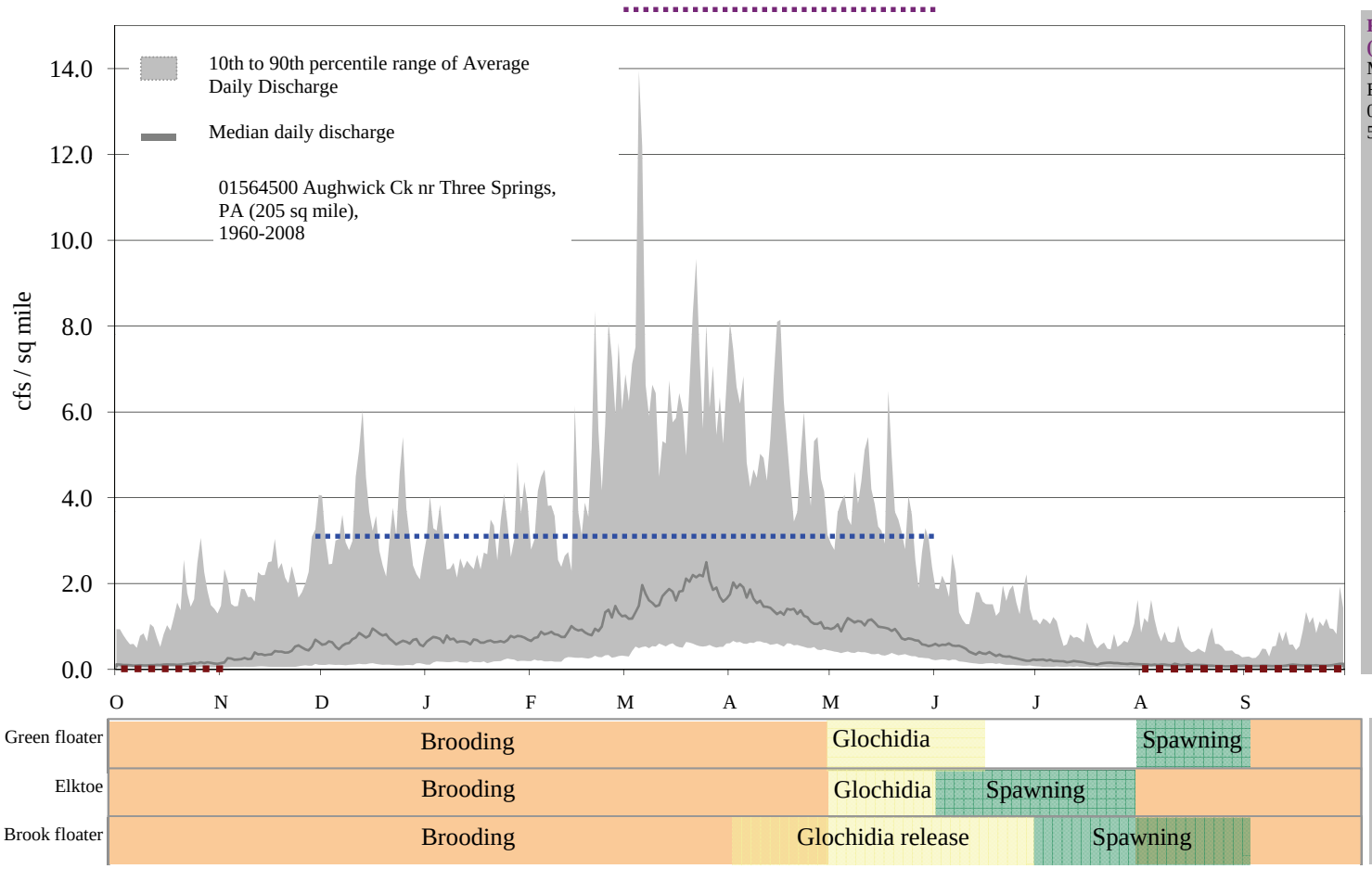
Mussels: Primarily Riverine - Green floater (*Lasmigona subviridis*), Elktoe (*Alasmidonta marginata susquehannae*), Brook floater (*Alasmidonta varicosa*) and Creeper (*Strophitus undulatus*)



FLOOD
(> 2 Yr Recurrence)
March - June
Flow 22- 32 cfs
0 to 1 events/ year
5 to 12 days / event

HIGH PULSE (≥Q10)
Flow ≥ 2.92 cfs / sq mile
7 to 12 events / year
3 to 4 days / event

LOW PULSE
(≤Q90)
Flow ≤ .06 cfs / sq mile
1 to 6 events / year
4 to 10 days / event

Table 6 includes a summary of life history information for these species

Table 6. Primarily riverine mussels life history summary

	Life Stage	Timing		Habitat			Hydro-Ecology				Reproduction		Comments
		Months	Cue	Substrate	Temp	DO	Stream type	Hydraulic Habitat Unit	Q or Velocity	Depth	Host Traits	Host Fish	
Green floater, *Lasmigona subviridis*	Spawning	August	most Unionids cue on temp	sand and gravel			more abundant in small streams, also found in medium streams and rivers	areas protected from scour including backwaters and sidechannels near islands, quiet but not stagnant water, active inflow required	moderate, intolerant of strong currents	shallow, 1-4 ft	not known	not known	not drought tolerant, found to be at sites with stable hydrograph as opposed to ones with droughts or spates, associated with good to excellent water quality conditions
	Brooding	August-May											
	Glochidia Release	May-Early June											
Elktoe, *Alasmidonta marginata susquehannae*	Spawning	June-July	most Unionids cue on temp	sand, gravel and small cobble substrate			small to medium streams and rivers, but can be found in medium to large streams	fast currents and riffles	moderate to swift		range of mobile, larger bodied and smaller localized species	identified host species of white sucker, northern hog sucker, shorthead redhorse, rock bass and warmouth sunfish	indicative of rivers with high water quality, does not tolerate impoundment
	Brooding	August-May											
	Glochidia Release	May											
Brook floater, *Alasmidonta varicosa*	Spawning	in the summer	most Unionids cue on temp	relatively stable, course sands gravel and cobble			small to large streams and rivers	riffles	moderate to swift		small bodied, localized species	longnose dace, golden shiner, pumpkinseed, slimy sculpin	frequently found in streams with low calcium levels/ oligotrophic or nutrient-poor, trait in common with many other Alasmidonta
	Brooding	August-May											
	Glochidia Release	April-June											
Creeper, *Strophitus undulatus*	Spawning	July-August	most Unionids cue on temp	coarse and fine substrates, gravel, fine gravel and sand			small to medium streams and rivers		slow to moderate	shallow, < 3- 4 ft deep	range of mobile, larger bodied and smaller localized species	largemouth bass, creek chub, fallfish, fathead minnow, golden shiner, common shiner, slimy sculpin, bluegill, long-nose dace, yellow perch,	relatively tolerant species, widely distributed, rarely abundant
	Brooding	August-May											
	Glochidia Release	Late April-Early June											

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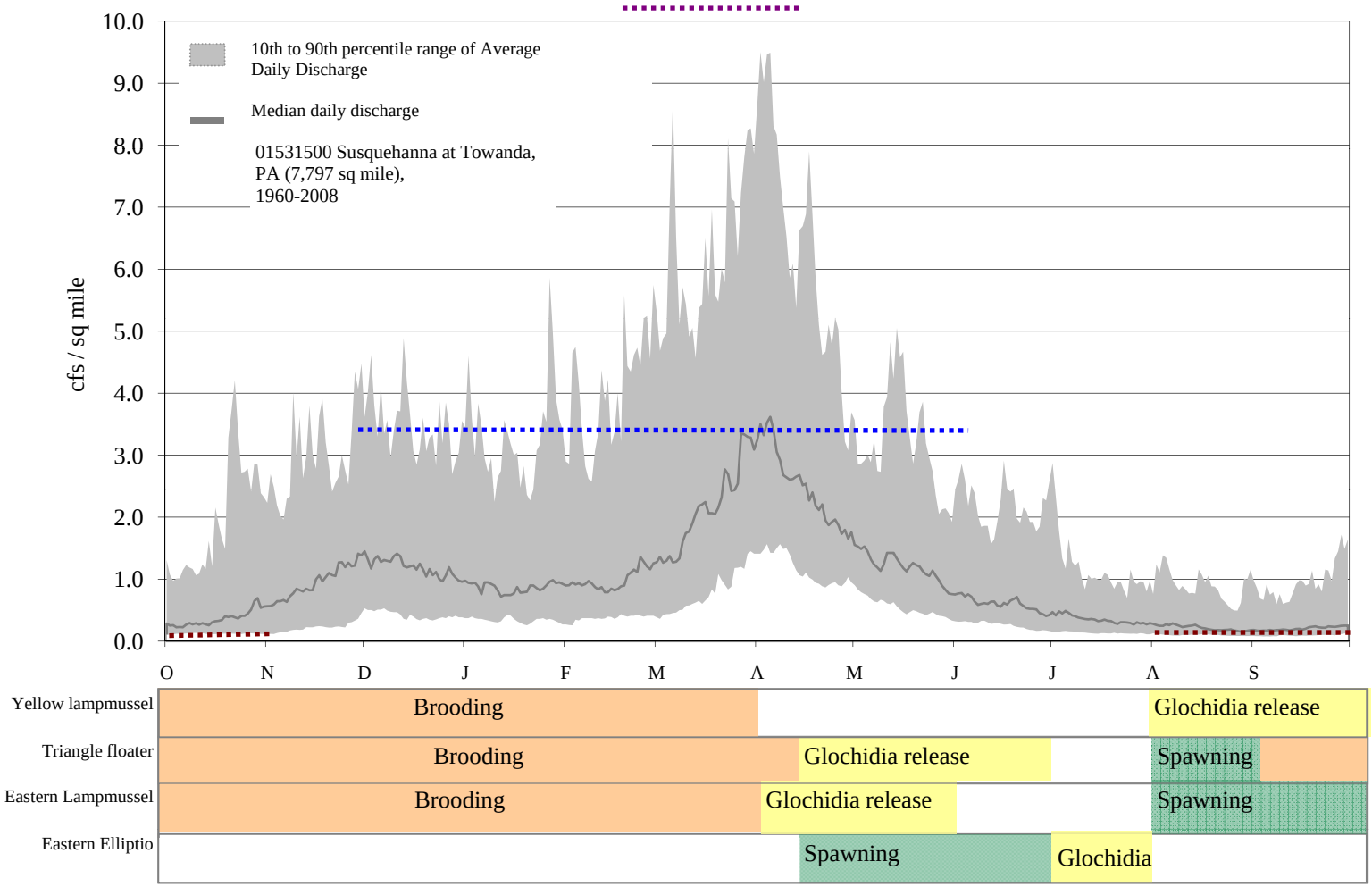
Villella R. F. Villella, D. R. Smith, D. P. Lemarié, D. R. Smith, D. P. Lemarié Estimating Survival and Recruitment in a Freshwater Mussel Population Using Mark-Recapture Techniques Author(s):

Mussels: Facultative Riverine - Yellow lampmussel (*Lampsilis cariosa*), Triangle floater (*Alasimidonta undulata*), Eastern lampmussel (*Lampsilis radiata*) and Eastern Elliptio (*Elliptio complanata*)



FLOOD
(> 2 Yr Recurrence)
Late Feb-Early Apr
Flow 12 to 19 cfs / sq mile
0 to 1 events / year
7 to 17 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.4 cfs / sq mile
5 to 10 events / year
3 to 4 days / event

LOW PULSE (≤Q90)
Flow ≤ .16 cfs / sq mile
1 to 4 events / year
6 to 17 days / event

Table 7 includes a summary of life history information for each species

Table 7 Facultative riverine mussel species life history table

		Timing		Habitat			Hydro-Ecology				Reproduction		
	Life Stage	Months	Cue	Substrate	Temp	DO	Stream type	Hydraulic Habitat Unit	Q or Velocity	Depth	Host Traits	Host Fish Species	**Comments**
Yellow lampmussel, *Lampsilis cariosa*	Spawning	Early Summer	most Unionids cue on temp	Various (sand, silt and gravel)			Medium to Large Rivers and Lakes	gravel bars, and river margins	Slow to moderate		larger-bodied, mobile species	Yellow perch, white perch, small mouth bass, large mouth bass	declining through its range, with the exception of the Chemung and Upper Susquehanna
	Brooding												
	Glochidia Release	Late summer (August - September)											
Triangle floater, *Alasmidonta undulata*	Spawning	August	most Unionids cue on temp	Sand and gravel			Small to medium-sized rivers and lakes	can tolerate standing water	Slow to moderate		small bodied, localized species	Broad range of host fish, primarily blacknose dace, commmon shiner, blacknose dace, longnose dace, shite sucker, pumpkinseed sunfish, fallfish, large-mouth bass, slimy sculpin	considered rare in the Susquehanna, generally valuable indicator of flowing habitat and stable substrates, widely distributed-rarely abundant
	Brooding	August-April											
	Glochidia Release	Late April-June											
Eastern lampmussel, *Lampsilis radiata*	Spawning	Late Summer spawning	most Unionids cue on temp	Sand and gravel			Small to medium-sized rivers and lakes		Slow to moderate		larger-bodied, mobile species	Broad range of host fish, warm water species including yellow perch, largemouth bass, smallmouth bass, black crappie, and pumpkinseed fish	tolerant of a range of environmental conditions, stable or increasing through its range
	Brooding	Late summer-spring											
	Glochidia Release	Spring											
Eastern elliptio, *Elliptio complanata*	Spawning	Late April-June	temperature	All types	temp rise to 20 C	when exposed to low O2, increased stress and mortality	Small to large streams and rivers and lakes	Generalist: riffles, runs, pools, near banks and in channels	Slow to swift current	most common from 1-1.6 m	larger-bodied, mobile species	Broad range of host fish, banded killifish, green sunfish, pumpkinseed , bluegill, orange-spotted sunfish, largemouth bass , yellow perch, and white crappie, potentially American eel	tolerant of emersion (drought) ability to withstand many forms of habitat disturbance,
	Brooding	May-July											
	Glochidia Release	July-August											

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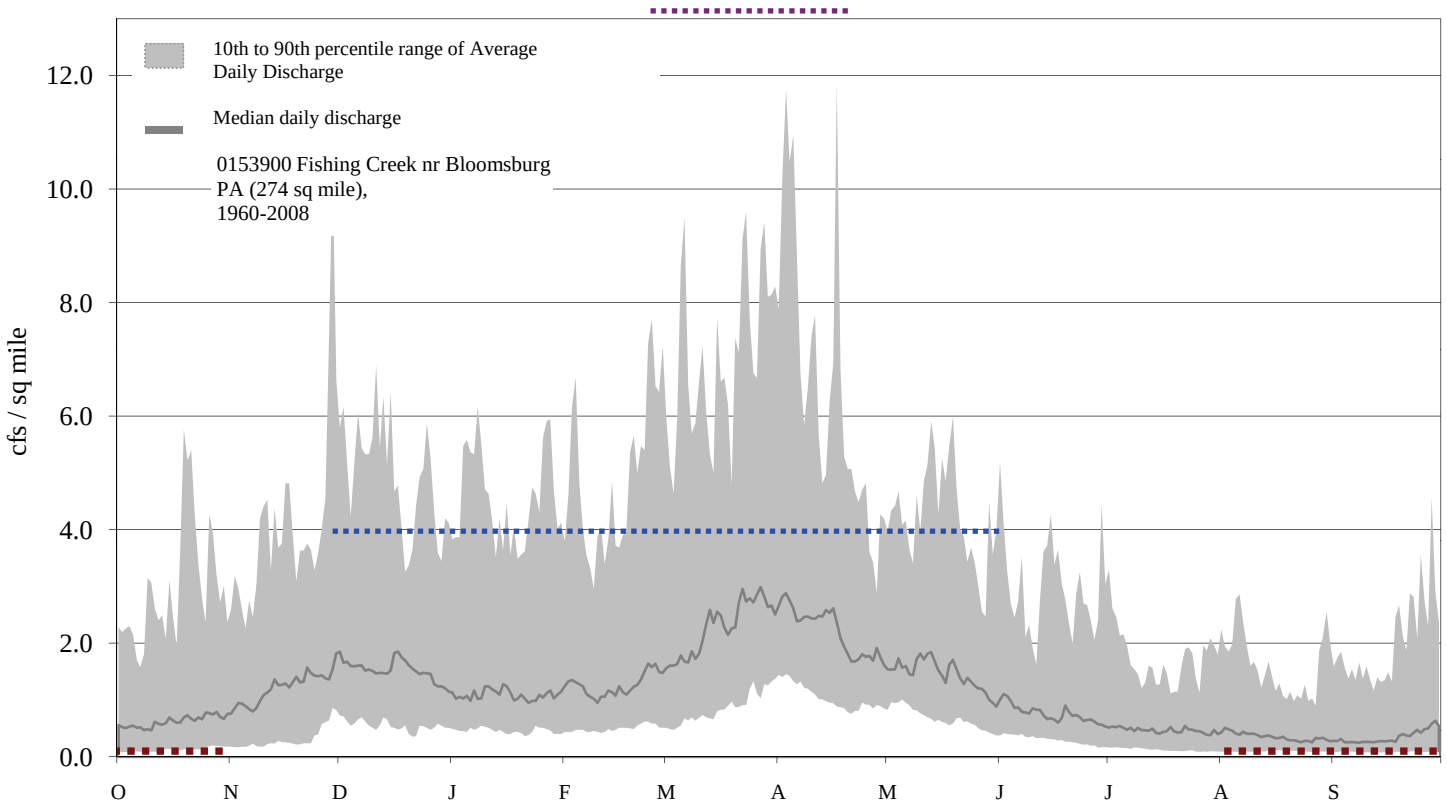
Villella R. F. Villella, D. R. Smith, D. P. Lemarié, D. R. Smith, D. P. Lemarié Estimating Survival and Recruitment in a Freshwater Mussel Population Using Mark-Recapture Techniques Author(s)

Mussels: Primarily Lentic - White heelsplitter (*Lasmigona complinata*), Eastern floater (Pyganodon cataracta) and Cylindrical papershell (*Anodontoides ferussacianus*)



FLOOD
(> 2 Yr Recurrence)
Early Feb-Early Apr
Flow 28-37 cfs / sq mile
0 to 1 events/ year
7 to 11 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.94 cfs / sq mile
7 to 12 events / year
2 to 3 days / event

LOW PULSE
(≤Q90)
Flow ≤ .21 cfs / sq mile
1 to 5 events / year
4 to 16 days / event

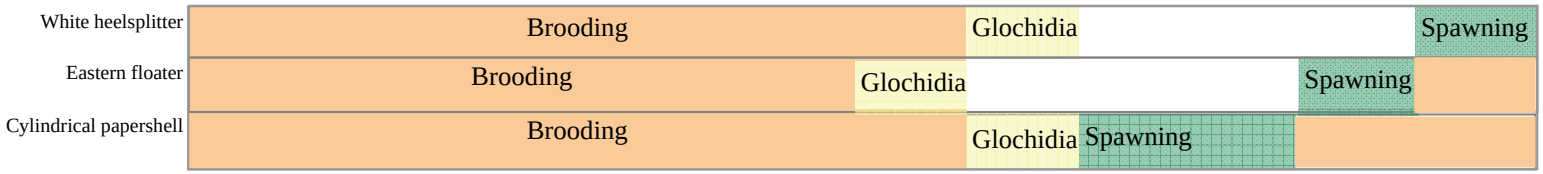


Table 8 includes a summary of life history information for these species

Table 8: Primarily lentic mussels life history summary

		Timing		Habitat			Hydro-Ecology				Reproduction		
	Life Stage	Months	Cue	Substrate	Temp	DO	Stream type	Hydraulic Habitat Unit	Q or Velocity	Depth	Host Traits	Host Fish Species	**Comments**
White heelsplitter, *Lasmigona complanata*	Spawning	September		one of the few unionoids that seems to do well in disturbed sediments (Strayer and Jirka 1997)			creeks, rivers, reservoirs, lakes and embayments	opportunistic: may exploit marginal areas	Slow		range of mobile, larger bodied and smaller localized species	common carp, banded killifish, green sunfish, orangespotted sunfish, largemouth bass, white crappie	tolerant of silt, habitat disturbance and impoundment,
	Brooding	October-May											
	Glochidia Release	May											
Eastern floater, *Pyganodon cataracta*	Spawning	August		Various substrate types, including deep silt and mud			Streams, rivers, ponds and lakes	slow moving reaches	Slow		range of mobile, larger bodied and smaller localized species	common carp, bluegill, pumpinseed sunfish, yellow perch, three-spined stickleback and white sucker are among suspected hosts	Widely distributed in the Susquehanna basin. Introduced to many man-made ponds, thrives in nutrient rich water, tolerant of deep silt and mud, tolerant of habitat modification and many forms of pollution
	Brooding	August-March											
	Glochidia Release	April											
Cylindrical papershell, *Anodontoides ferussacianus*	Spawning	June-July		Various, commonly sand or mud			Small streams, creeks and lakes, headwater species	near shore, margins	Slow	Shallow water	range of mobile, larger bodied and smaller localized species	bluegill, black crappie, spotfin shiner, largemouth bass, bluntnose minnow, common shiner, iowa darter, white sucker and the sea lamprey	
	Brooding	Early Apr-May											
	Glochidia Release	May											

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Table 9. Aquatic-lotic- Species that spend most life stages in flowing waters, have specialized stream-dependent feeding habits, and/or other traits (e.g., lungless) that are characteristic of an evolutionary history of instream habitat use

Common Name, *Scientific name*	Life History Stage	Location during Life Stage A(quatic) or T(errestrial)	Timing	Month (O N D J F M A M J J A S)	River Type or Location	Habitat preference: Vegetation and or Substrate	Habitat preference: Hydraulic Habitat Unit	Traits: Size, Diet, Home Range, Clutch size	Comments
Common map turtle, *Graptemys geographica*	Hibernation	A	Early Winter (late as 1st week Dec)- Early Apr.				river bottoms, wedged under submerged logs		Require high overwinter DO levels, Spends a significant portion of its time basking
	Mating	A	Spring and Fall				Deep Waters		
	Nesting, Egg Laying and Incubation	T	most nesting in June, can occur May - July; for most, incubation through Fall and Winter		Found on mainstem Susquehanna and Juniata tributary, likely in other large tributaries, Prefer large lakes and rivers (> 50 m wide)	prefer open canopy sites with well drained sandy soils near water; a range of soil types from sandy to coal, to hard-packed clay and gravel mix		Medium-sized; always feed in water- molluscs, aquatic insects and fish (mostly carrion); clutch of 6 to 20	
	Hatchling Emergence	T	April-May, most found morning following rain (another paper stated Aug-Sept)				Prefer slow-flowing sections, generally in water or basking, when found on land they are not far from shore, males move from deep water in spring to shallow water in summer		
	Adult Growth	A	Peak basking from Apr-June; Oct-Nov, less basking July-Sept			locations with suitable basking sites (snags or rocks), bask communally 20 m from shore			
Common musk turtle, *Sternotherus odoratus*	Hibernation	A	Oct - mid April			soft mud beneath cover, and near muskrat dens			In SC drought study, found to remain in water through drought (did not migrate), although reproduction was significantly impacted
	Mating	A	Mostly spring and fall		Most of the Valley and Ridge Province as well as the Piedmont in small streams to large rivers (in large rivers found in backwaters and embayments), rare to find out of water		River bottom	small bodied; opportunistic carnivore: and insectivore worms, snails, small clams, aquatic insects, crayfish; little known about home range; variable clutch size of 2 to 7 eggs	
	Nesting, Egg Laying and Incubation	T	Late May to Early July, Early July-Aug (75 to 82 days incubation)				Lay eggs under object or bury under surface debris at the waters edge; maximum distance of 36 ft from waters edge, avg distance of 23 ft (Cagle 1937)		Float at the surface of the water to absorp heat from the sun, not aerial baskers
	Hatchling Emergence	T	Aug-Sept						
	Adult Growth	A	Mature at age 4			Grow Basicladia on their shells during basking	Avoid fast currents, feed by walking on the bottom, not swimming, and bask just		
Northern water snake, *Nerodia sipedon*	Hibernation	?	October - early to mid April				Use crayfish tunnels, ant mounds and meadow vole tunnels		emerge earlier if temperatures warmer
	Mating	T	Early June		Ubiquitous throughout basin, use lakes, marshes, ponds, slow-and fast moving streams and rivers			Known to heard schools of fish and tadpoles to waters edge, primarily fish, also amphibians (frogs), viviparous with a litter of 11 to 36	
	Justation and Parturition	T	Justation 3 to 5 months, Parturition late August to mid Sept of following year?						
	Adult Growth	T/A					Capable of submergence for 1.5 hours, adults use water as retreat/refuge and feeding		

Table 9. Continued

Queen snake, *Regina septemvittata*	Hibernation	A or T	mid Oct-late April		Found in the Piedmont region in moderate to fast-flowing streams, creeks and small rivers, (occasionally slow moving streams)		Muskrat burrows, crayfish burrows and deep cracks in rocky sections of stream, hibernate in congregations	Specialist feeders- almost exclusively crayfish, must be present and abundant; seldom found > 2m from water, skin prone to dessication; bear 4 to 15 young	Dependence on dwindling crayfish may threaten population
	Mating		Likely Spring						
	Justation and Parturition	A/T	Gravid Spring Early to late August, Give birth late summer and early fall			rocky streams, bulrushes, goldenrods, willows			
	Adult Growth		max life span in wild 11 years			zone, but generally open canopy to allow sunlight on basking sites, must also have ample	moderate to swift current		
Eastern Hellbender, *Cryptobranchus alleganiensis*	Breeding and Egg Laying	A	Late August - Early Sept (mating)		Medium sized streams to large rivers, cool-cold waters, 3rd and 4th order streams	create shallow nest depressions under large slabs	nest on river bottom	Very large (giant salamander); Feed almost entirely on crayfish, infrequently	Not found in streams that lack substantial crayfish populations
	Egg and Larval Development	A	60 to 87 days to hatch,						
	Metamorphisis/ Transformation	A	Spend 2 years in larval stage			gravel or sandy bottom, under large slabs of rock (22 to 40" in diameter)	Prefer fast- flowing waters (likely linked to gas exchange), need high DO		
	Adult	A	mature at estimated 5 to 6 years						found 8 to 20" deep in French Ck
Northern Dusky Salamander, *Desmognthus fuscus fuscus*	Breeding and Egg Laying	A	Mating in Spring and Fall, Egg Laying in July		Ubiquitous throughout headwater and small woodland streams (tend to be absent from streams where predatory fish are present) with abundant cover, found to dominate intermittent streams in a NC study		nesting in stream banks, require flowing water particulary during hibernation	Small size; feeding opportunistic- flies, mayflies, beetles, amphipods and snails; one PA study documents an average of 28 eggs clutch size; home ranges vary by source population from 1.4 to 48.4 sqm	Require flowing water year round (particularly winter), dessication has been documented at a temperature of 26 C
	Egg and Larval Development	A	Late Aug - early Oct, temp dependent, 40 to 60 days to larval emergence				larvae develop in stream		Will move to subterranean retreats during cold periods
	Metamorphisis/ Transformation	A	End of May to early July of following summer			streamside cover of vegetation and or medium to large rocks	generally stay within 2 meters of stream bed		High dependence on stream side vegetation and bank stability (Orser and Shure 1975)
	Adult	A/T							
Bullfrog, Rana catesbeiana	Hibernation	A	mid Oct.- mid April (as early as Feb)		Variety of habitats from small ponds to small and Large Rivers, generally slow-moving creeks and streams, in swift streams use backwater habitats, close to shore, present in every county, but native distribution unknown due to State stocking programs	covered with mud and litter	stream or pool bottom	Large bodied; Most commonly, adults feed on crayfish and other amphibians, occasionally reptiles (box turtles, young water snakes) and mammals; clutch size-6,000-20,000 eggs	time to complete metamorphisis largely relies on food availability and length of growing season
	Breeding and Egg Laying	A	May-July			eggs laid in 'rafts' among low emergent vegetation	margins		
	Egg and Larval Development, Metamorphisis	A	Hatch within 3 days; Metamorphisis the summer after hatch						
	Adult	A							

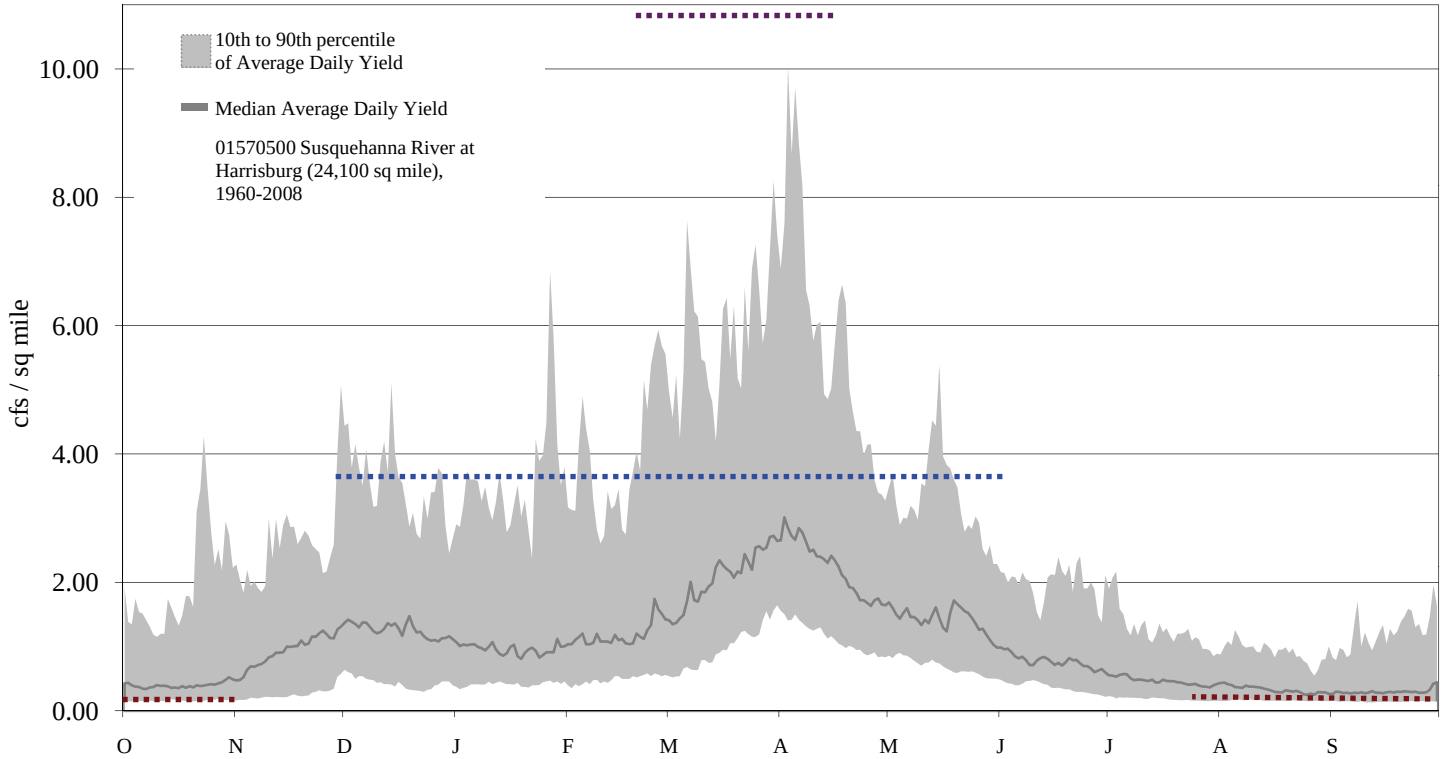
Table 10. Semi-aquatic-lotic- Species that rely on flowing waters or habitats within the active channel for a one or more life stages, but may spend part of their life cycle in floodplain or upland environments

				Month												Habitat preference			Traits	Comments
Common Name, *Scientific name*	**Life History Stage**	**Location during Life Stage A(quatic) or T(errestrial)**	**Timing**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**River Type or Location**	**Vegetation and or Substrate**	**Hydraulic Habitat Unit**	**Size, Diet, Home Range, Clutch size**	
Wood turtle, *Glyptemys insculpta*	Hibernation	A	Oct - Early April													Most commonly found in the mountainous areas of the Ridge and Valley, in headwaters (2nd order streams) to medium rivers, associated with streams hosting native brook trout populations		within cut banks (root wads) and buried in muddy bottoms of slow moving streams, banks and bottoms, root wads, can hibernate in large groups (up to 30 individuals documented in PA)	Small body size; opportunistic omnivores- herbaceous and woody plants, fruits, slugs, worms, incapable of capturing fish, molluscs, tadpoles, dead fish; homerange estimated to be 10.3 acres, noting that travel primarily occurs along river corridorsclutch size typically 5 to 13 eggs and are highly predated	More terrestrial in the summer months, but generally return to water at night, also enter during day during cold snaps and droughts for refuge
	Mating	A	Primarily Mid Sept-Oct., other reports have documented spring mating															mate in water, habitat unknown		Appropriate nesting habitat found to be limiting factor in population viability, late maturity, low fecundity, high adult survival rates, low egg and juvenile survival rates
	Nesting, Egg Laying and Incubation	T	Mid June, as early as May, as late as early July; 70 day incubation period														use sandy, well drained soils for nesting sites, near the river, usually 1 m above normal water level	eggs laid in depression over a short period in mid-June, females may migrate up to 1 km to find nest site		
	Hatchling Emergence	T	Late Aug -early Sept (early October)														hard-bottomed			
	Adult Growth	T/A	Aquatic in the Spring and Fall, Terrestrial in the Summer, mature between 9 and 20 years, max life span 46 in the wild								prenesting	nesting			prehibernation		open-canopy riparian thickets (alders), well drained soils, open, **edge species, shrublands**	Found in slow and fast-moving streams, but prefer slower-moving habitat; aquatic activity occurs almost exclusively in flowing water; this species is pollution intolerant		
Bog Turtle, *Clemmys muhlenbergii*	Hibernation	A	Begins in late Sept.- mid to late March													Found in Lower Susquehanna Basin tributaries in Franklin and Cumberland counties and east within spring-fed wetlands, open and slow, small streams or surface seepages		Stream bottom or may use muskrat dens, in streams they have been found under 8 to 10 inches of water and 1 to 3 inches under the stream bottom (mud)	feeds on primarily insects (catepillars, beetles, caddisfly larvae, earthworms,	extreme habitat specialist
	Mating	A/T	Late Apr.- early June																	habitat requirements from PA A and R < Chase et al 1999
	Nesting, Egg Laying and Incubation	T	Nesting mid May - July, most eggs laid in June, Incubation 45 to 55 days														nests constructed in moss or sedge tussocks			Talk with Tracy and George
	Hatchling Emergence	T	Late August to early Oct																	
	Adult Growth	A/T	and 10, can live more than 40 years														abundant low grasses and sedges, relatively open, smooth	requires spring-fed habitats, with wet and dry pockets, shallow and slow waters		
Eastern Ribbon Snake, *Thamnophis sauritus*	Hibernation	T/A	Sept-March													Found in the Piedmont and Ridge and Valley, within a variety of habitats, but must be in proximity to permanent water, either standing or flowing	underground or high ground, or underwater	may migrate to higher elevations for hibernation	Specialized Feeder- preying almost exclusively on amphibians, may also eat small fish; home range of .8 ha in Michigan study, and litter size of 3 to 27	a partially arboreal species
	Mating	T	April and May																	
	Parturition and juvenile growth	T	Partutition August;																	
	Adult Growth	T/A	Mature 2 to 3 years (Michigan)															most prey is captured in water or at waters edge		
Northern leopard frog, *Rana pipiens*	Hibernation	A	Oct. -March													Found in the Appalachian Plateau and Ridge and Valley Province within vegetated margins of ponds, lakes, and slow-flowing rivers and streams, as well as in marshes and swamps		overwinter at the bottom of streams and lakes		* not a true hibernation- quiescent state, temperature dependent, may be earlier or later
	Breeding and Egg Laying	A	April															typically vernal habitats, not the same habitats used for overwintering	Medium-sized, Terrestrial feeding (insectivore), clutch size 2,000 to 6,000 eggs	
	Egg and Larval Development	A	Hatch in 10 days																	
	Metamorphisis/ Transformation	A	Transform by Mid-July																	
	Adult	T																		movement precipitation dependent

Table 11. Riparian and Floodplain-terrestrial and vernal habitats- Species that rely on overbank hydrologic processes to influence floodplain habitats, including wetting or refreshing vernal pools, driving vegetative composition, maintaining sediment composition, and substrate

					Habitat preference				Comments
Common Name, *Scientific name*	**Life History Stage**	**Location during Life Stage A(quatic) or T(errestrial)**	**Timing**	**O N D J F M A M J J A S**	**River Type or Location**	**Vegetation and or Substrate**	**Hydraulic Habitat Unit**	**Size, Diet, Home Range, Clutch size**	
Eastern Hognose snake, *heterodon platirhinos*	Hibernation	T	Mid Oct- late April early May						seek refuge in burrows, either dug, or existing mammal burrows
	Mating	T	April or May						
	Nesting, Egg Laying and Incubation	T	Lay clutch early June-mid July, incubation 60 to 65 days		Discrete population of the Alleghany front- distributes through the rivers of the ridge and valley province, typically sandy rivers and floodplains			Feed on wide variety of animals: specialize for frogs and toads, also salamanders, hatchling turtles, insects; clutch size 4 to 61 eggs	
	Hatchling Emergence	T	Late Aug-Sept						
	Adult Growth	T	Mature at 2 to 3 years, lifespan unknown, up to 11 years in captivity			sandy soils for burrowing	grasslands and open forests near water, along sandy rivers and stream bottoms		
Eastern Gray treefrog, *hyla versicolor*	Hibernation	T	Oct- early to mid April			little known, but likely that they hibernate on land because they are freeze tolerant		moderate-sized frog; insectivores: terrestrial and aerial, but not much information available	cued by temperature and moisture levels
	Breeding and Egg Laying	A	Breeding- Mid May-mid Aug		Wide but spotty distribution, most common in Southeast and Soutwest PA , an arboreal species of deciduous forest types		use temporary and permanant bodies of water, woodland pools, ditches, cattle tanks and margins of small ponds and lakes		in the vicinity of ponds, temporary pools, or roadside ditches
	Egg and Larval Development, Metamorphisis	A							? Not sure which habitat types/elevation/basin
	Adult	T							
Fowler's toad, *Bufo fowleri*	Hibernation	T	October- end of April/beginning of May		Found in the lowlands of the Ridge and Valley province, primarily an inhabitant of low lying areas with, open, with sandy, gravelly well drained soils (floodplains near streams and rivers)	hibernation sites not found in PA, but likely sand and loose soils of the floodplain			Habitat specialist requiring sandy floodplains
	Breeding and Egg Laying	A	Mid May- late June, both breeding and laying				Ponds in the floodplain of streams and rivers	Insectivores, mostly ants and beetles; Clutch size estimated 8,000 eggs, home range relatively large between 51 and 2500 square meters	
	Egg and Larval Development, Transformation	A	eggs hatch 2 to 3 days after laying, transformation 40 to 55 days						
			mature by July or August the following year						
	Adult	T							
Marbled Salamander, *Ambystoma opacum*	Breeding and Egg Laying	T	Sept.-Nov.			Upland forests, in vernal depressions, or occasionally in intermittent or ephemeral stream beds	NA	Small body-size; Diet of spiders, earthworms, grasshoppers, beetles- **Larvae diet includes microcrustacean zooplankton and aquatic beetles; clutch size ranges from 41 to 200 eggs	
	Egg and Larval Development	A	Winter and Spring, when vernal pools fill, or during intermittent stream flow		Upland forests that support vernal ponds, and intermittent stream beds, filling with water during the winter and spring		NA		
	Metamorphisis/ Transformation	A	June-July; about 135 days from			Spend most of their time, outside of the reproductive, season in subterranean retreats	NA		
	Adult	T	Spring, Summer and Winter						

Aquatic and Riparian Communities- Disturbance regimes of Emergent Bed, Herbaceous, Shrub-Scrub, and Forested Communities



FLOOD
(> 2 yr Recurrence)
Late Feb. to Early April
Flow 10.8 to 16.6 cfs / sq mile
0 to 1 events/ year
0 to 27 days / event

HIGH PULSE (≥Q10)
Flow ≥ 3.2 cfs / sq mile
4 to 8 events / year
4 to 6 days / event

LOW PULSE (≤Q90)
Flow ≤ .2 cfs / sq mile
1 to 4 events /year
4 to 17 days / event

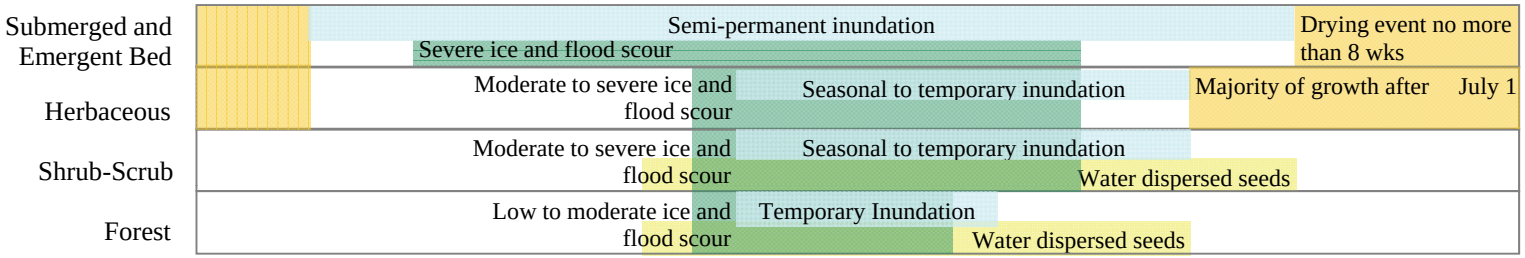


Table 12 includes a detailed community and life history descriptions

Table 12: Aquatic, riparian and floodplain communities, life history summaries

Successional State	Community Types (Perles, S. Podniesinski G., and J. Wagner 2002 and 2004, PNHP 2010)	Landscape Position		Canopy Dominants	Seed Dispersal/ Establishment		High Flow conditions (Flood and Ice Scour, and Inundation events)			Drought conditions		
		Lateral Position	Stream Size (longitudnal)		Timing and Dispersal	Substrate	magnitude	frequency	duration	magnitude	frequency	duration
Emergent Bed	Water Willow Emergent Bed	island heads, edges of bars, terraces and spits	all order streams	water-willow, Justicia americana	new shoots along rhizomes, fragmentation and seed; rhizomes are dormant in winter	variable	subject to severe ice and flood scour	SEMI-PERMANENT (flooded most of the year, may become exposed during dry periods)		in the summer months, condition rapidly declined after 8 weeks of dessication, and further with a second, subsequent dessication event		
	Lizard's Tail Emergent Bed	island heads, edges of bars, terraces or channels	Juniata drainage and smaller tributaries of the main stem in the Ridge and Valley province	lizard's tail, *Saururus cernuus*		sand, silt or with cobbles	subject to severe ice and flood scour	SEMI-PERMANENT (lower portions flooded most of the year, entirely submerged by high flow events)				
Herbaceous Community	Indian Grass (Willow) Riverine Shrubland	banks, sand and gravel deposits and river islands	North and West Branch and upper portions of the mainstem.	indian grass, *Sorghastrum nutans*	perennial warm-season grass	sand mixed with cobble, rapidly draining soils	moderate to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING		drier sites, rapidly draining soils, droughty conditions may prevent establishment of woody vegetation, 70% growth after July 1		
	Sedge-spotted joe pye weed riverine herbaceous vegetation	Island heads, edges of bars, terraces or channels	smaller tributaries	*Carex trichocarpa, Carex torat, Eupatorium mauclatum*		cobbles mixed with silt, sand and overlain by muck	subject to moderate flood scour	SEASONAL TO TEMPORARY FLOODING				
	Riverine scour community (includes bedrock outcrop community and shoreline and flats community)	island heads, edges of bars, terraces and spits; outcrop community specifically on large river banks	all order streams, with outcrop community on large rivers	sparsely vegetated; Hypericum spp., Osmunda regalis, smart weed (Persicaria spp) and other annuals		gravel and bedrock	severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING				
Scrub/Shrub Community	Speckled Alder - Dogwood Riverine Shrubland	flats within active channels	Upper portion of the West Branch on smaller order streams; Small to Moderate streams;	speckled alder, *Alnus incana ssp. rugosa*	September-April; wind dispersed	cobble substrate	moderate to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING				
	Mixed Hardwood Riverine Shrubland, Silver maple-river birch- Mixed Hardwood shrubland	bars and low terraces, transition community between low floodplain herbaceous and upland floodplain forest,	Sycamore-mixed community on small and intermediate tributaries of the upper mainstem; River birch community occurs on islands of the North and West Branch	See associated floodplain forest	See associated floodplain forest		moderate to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING				
	Black Willow Slackwater Shrubland	stream and riverbanks, downstream ends and heads of islands where stream velocity is reduced such as back channels and oxbows	Tributaries and Large Rivers	black willow, *Salix nigra*	April -August; water and wind dispersed	establish in very moist, almost flooded exposed soils, deeper soils of silt and loam,	low to moderate to ice and flood scour	SEASONAL TO TEMPORARY FLOODING Inundation period may be longer due to macrotopography, high groundwater, and poor drainage		seed viability greatly reduced by only a few days of dry conditions. Seedlings growth is dependant upon available moisture throughout the growing season		

Table 12: Continued

Successional State	Community Types (Perles, S. Podniesinski G., and J. Wagner 2002 and 2004, PNHP 2010)	Landscape Position		Canopy Dominants	Seed Dispersal/ Establishment		High Flow conditions (Flood and Ice Scour, and Inundation events)			Drought conditions		
		Lateral Position	Stream Size (longitudnal)		Timing and Dispersal	Substrate	magnitude	frequency	duration	magnitude	frequency	duration
Floodplain Forest	Sycamore floodplain forest	floodplains, small islands, low bars and lower terraces, oldest cohorts furthest from active stream channel	intermediate order tributaries to the Susquehanna	American syacamore, *Plantanus occidentalis*	February - May; water dispersed,establishment after flood event	establish in wet alluvium, very well-drained course sand, gravel and cobbles	moderate ice and flood scour	TEMPORARY FLOODING (saturated or inundated for > 2 wks and < growing season), *P. Occidentalis* seedlings will die if inundated > 2 wks				
	Sycamore mixed hardwood floodplain forest	low to intermediate elevation islands and terraces (higher terraces as compared to Sycamore Floodplain Forest)	smaller and Intermediate tributaries	river birch, *Betula nigra*	Late Spring to Early Summer, water and wind dispersed	as above- course substrates	low to moderate ice and flood scour	TEMPORARY FLOODING (saturated or inundated <1 wk to 3 mths, typically 7 wks)		seedlings growth is dependent upon available moisture throughout the growing season		
	Silver maple floodplain forest	well-developed floodplains and islands, low and occasionally high terraces	major tributaries and the mainstem Susq	silver maple, *Acer saccharinum*	April-June; Establishment: after flood event, high flow years	establishment: fine sand and silt, soils with organic matter, moderatley well-drained (scour zones) to poorly drained	low to moderate ice and flood scour	TEMPORARY FLOODING				

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Appendix 5. Description of Floodplain, Riparian and Aquatic Vegetation Communities

Community Types (Canopy Dominants)	Landscape Position	Seed Dispersal/Establishment	Flow Disturbance Frequency and Duration (Flood and ice scour, inundation and response to drought)
Submerged and Emergent Bed			
Riverweed (*Podostemum ceratophyllum*)	Stream bed	- Gravel or cobble substrate in moderate to high velocity riffles - Exposure of leaves and/or stem inhibits growth	- Subject to severe ice and flood scour - Permanent inundation (flooded most of the year, may become exposed during drought periods) - Intolerant of long periods of desiccation
Water Willow Emergent Bed (*Justicia Americana*)	Island heads, edges of bars, terraces and spits	- New shoots along rhizomes, fragmentation and seed; rhizomes are dormant in winter - Variable substrates	- Subject to severe ice and flood scour - Semi-permanent inundation (flooded most of the year, may become exposed during dry periods) - Intolerant of long periods of desiccation
Lizard's Tail Emergent Bed (*Saururus cernuus*)	Island heads, edges of bars, terraces or channels	- Sand, silt or with cobbles	- Subject to severe ice and flood scour - Semi-permanent inundation (lower portions flooded most of the year, entirely submerged by high flow events)
Herbaceous Community			
Willow-Indian Grass Riverine Shrubland (*Sorghastrum nutans*)	Banks, sand and gravel deposits and river islands	- Sand mixed with cobble, rapidly draining soils - Drought conditions may prevent establishment of woody vegetation	- Moderate to severe ice and flood scour - Seasonal to temporary flooding
Scrub/Shrub Community			
Speckled Alder Riverine Shrubland (*Alnus incana ssp. Rugosa*)	Flats within active channels	- Wind-dispersed during September-April - Cobble substrate	- Moderate to severe ice and flood scour - Seasonal to temporary flooding

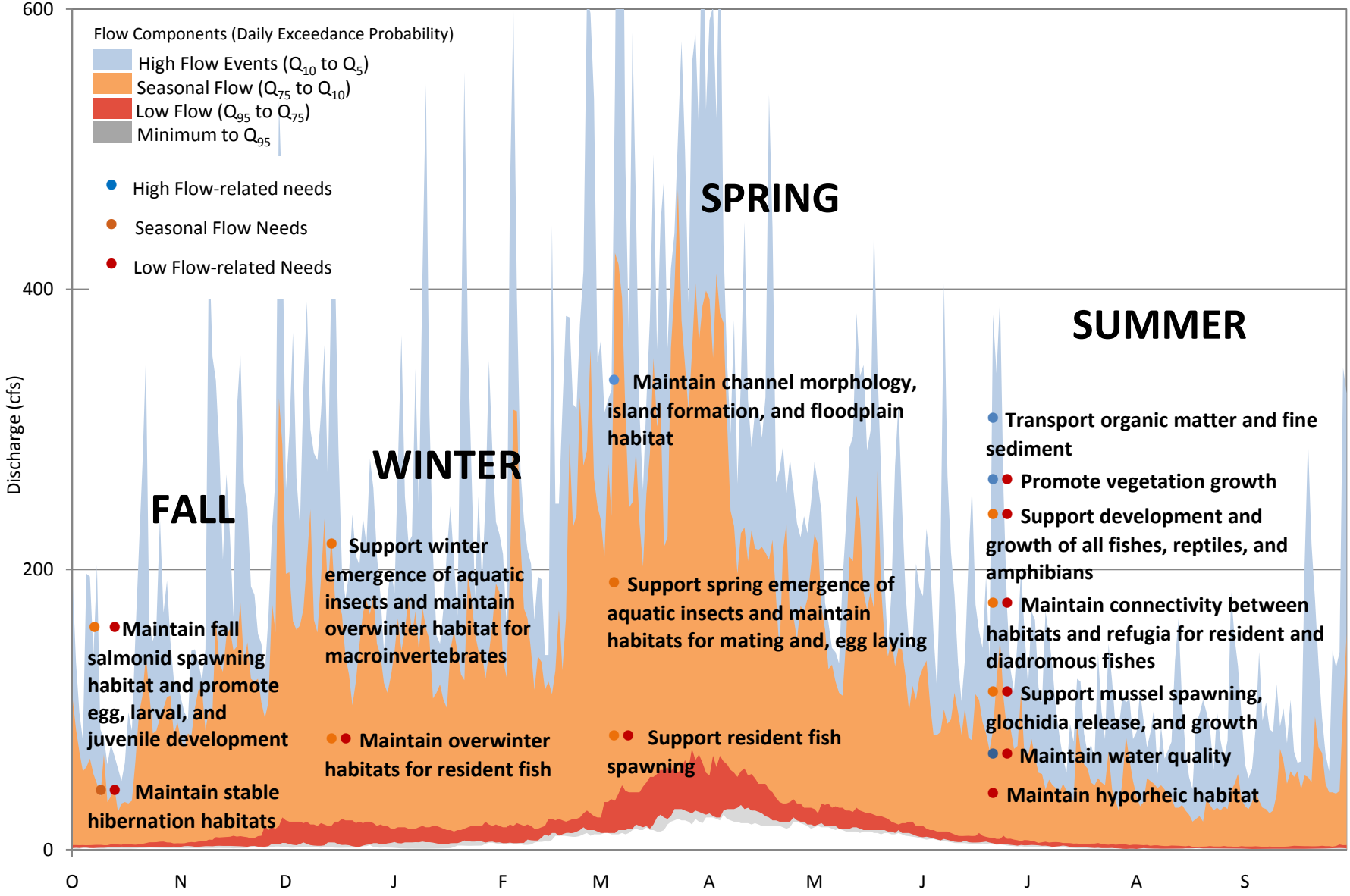
Community Types (Canopy Dominants)	Landscape Position	Seed Dispersal/Establishment	Flow Disturbance Frequency and Duration (Flood and ice scour, inundation and response to drought)
Sycamore-mixed hardwood, River birch-mixed hardwood, and Silver Maple-mixed hardwood riverine shrublands (See associated floodplain forest)	Bars and low terraces, transition between low floodplain herbaceous and upland floodplain forest	- See associated floodplain forest	- Moderate to severe ice and flood scour - Seasonal to temporary flooding
Black Willow - mixed hardwood riverine shrubland (*Salix nigra*)	Stream and riverbanks, downstream ends and heads of islands	- Water and wind dispersed during April -August - Establish in very moist, almost flooded exposed soils - Seedling growth depends upon available moisture throughout growing season	- Moderate to severe ice and flood scour - Seasonal to temporary flooding
Floodplain Forest			
Sycamore floodplain forest (*Plantanus occidentalis*)	Floodplains, small islands, low bars and lower terraces, oldest cohorts furthest from active stream channel	- Water-dispersed during February - May - Establish after flood in wet alluvium, very well-drained course sand, gravel and cobbles	- Moderate ice and flood scour - Temporary flooding (saturated or inundated for > 2 wks and < growing season), P. Occidentalis seedlings will die if inundated > 2 wks
Sycamore mixed hardwood floodplain forest (*Betula nigra*)	Low to intermediate elevation islands and terraces (higher terraces than Sycamore floodplain forest)	- Water and wind dispersed during late spring to early summer - Seedlings establish in coarse substrates; growth depends upon available moisture throughout the growing season	- Low to moderate ice and flood scour - Temporary flooding (saturated or inundated <1 wk to 3 months, typically 7 wks)
Silver maple floodplain forest (*Acer saccharinum*)	Well-developed floodplains and islands, low and occasionally high terraces	- April-June; Establishment: after flood event, high flow years - Establishment on fine sand and silt, soils with organic matter, moderately well-drained (scour zones) to poorly drained	- Low to moderate ice and flood scour - Temporary flooding

Community Types (Canopy Dominants)	Landscape Position	Seed Dispersal/Establishment	Flow Disturbance Frequency and Duration (Flood and ice scour, inundation and response to drought)
Silver maple mixed hardwood floodplain forest (*Acer negundo*)	Floodplain depressions, low and upper terraces of major tributaries of the mainstem; young stands on active scour channels	- Wind dispersed from October -Spring - Establishment on moist silt loam, clay loam,	- Low to moderate ice and flood scour - Temporary flooding, long inundation (actually flooded less than 1 wk per year, but may stay inundated for long periods due to high groundwater for much of the growing season)
Green Ash, mixed Hardwood Floodplain Forest (*Fraxinus pennsylvanica*)	Old oxbows along the floodplain or depressions behind levees on low terraces	- Wind dispersed, September-winter - Somewhat poorly drained-poorly drained	- Low to moderate flood and ice scour - Temporary flooding, long inundation (actually flooded less than 1 wk per year, but may stay inundated for long periods due to high groundwater for much of the growing season)

Appendix 6. Graphs of Flow Needs for Each Major Habitat Type

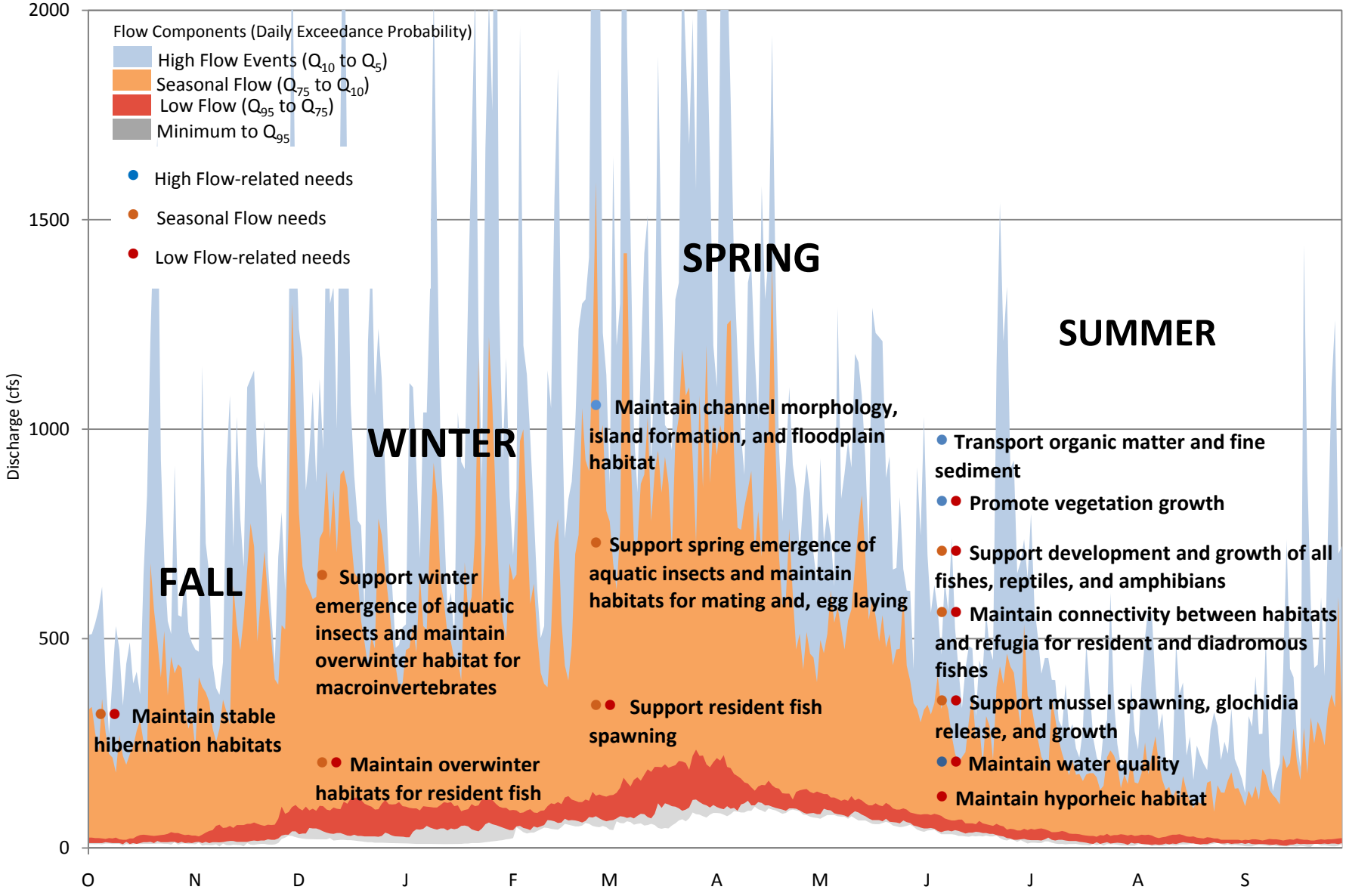
Flow Components and Needs: Cold and Cool Headwaters and Small Streams

Example: 01547700 Marsh Creek at Blanchard, PA (44.1 sq mi)



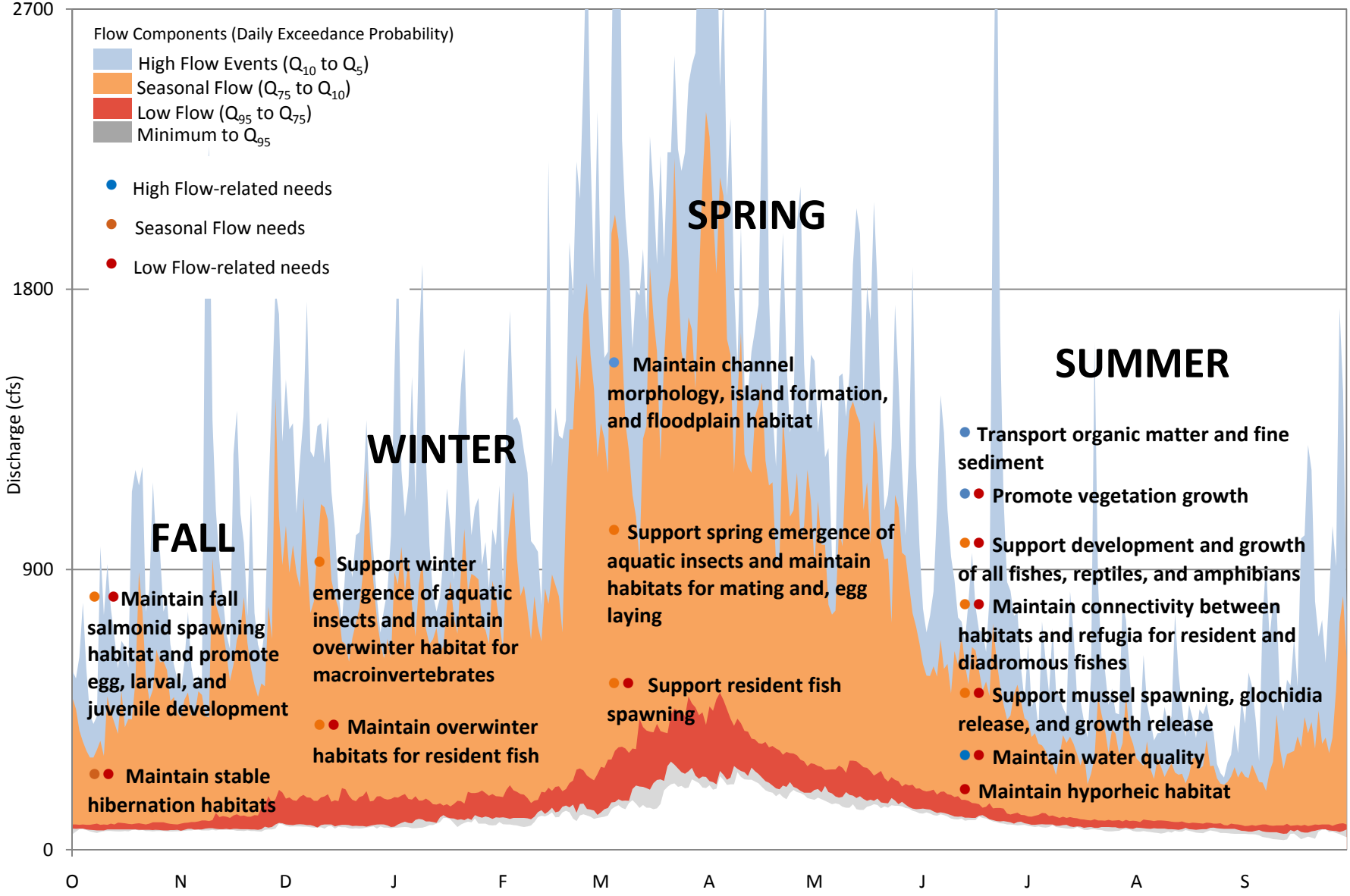
Flow Components and Needs: Warm Headwaters and Small Streams

Example: 01555500 East Mahantango Creek near Dalmatia, PA (162 sq mi)



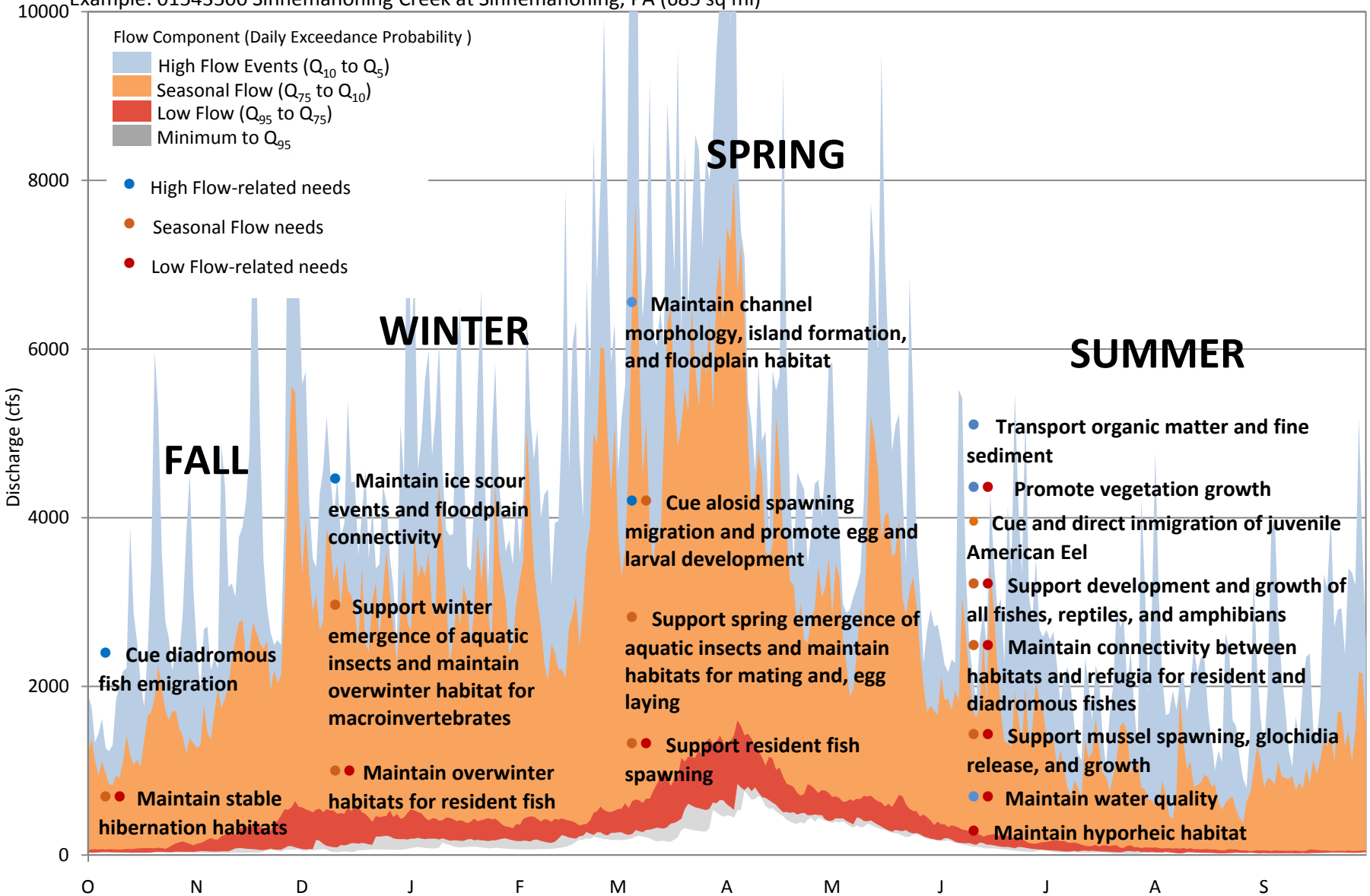
Flow Components and Needs: High Baseflow Headwaters and Small Streams

Example: 01558000 Little Juniata River at Spruce Creek, PA (220 sq mi)



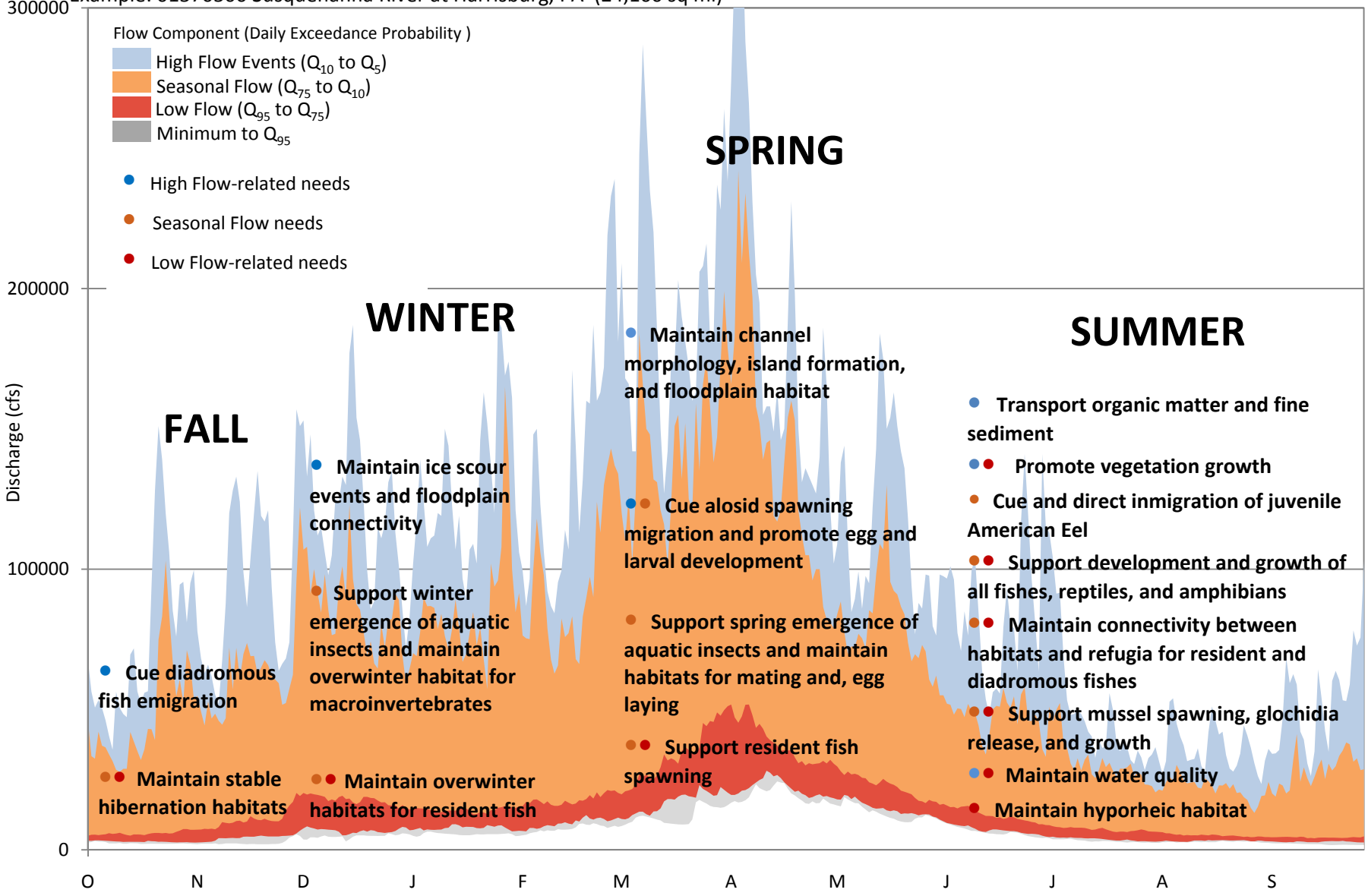
Flow Components and Needs: Major Tributaries

Example: 01543500 Sinnemahoning Creek at Sinnemahoning, PA (685 sq mi)



Flow Components and Needs: Mainstem

Example: 01570500 Susquehanna River at Harrisburg, PA (24,100 sq mi)



Appendix 7: Seasonal Flow Needs, Recommendations, and Supporting Literature and Studies

Flow statistics in this table are defined and described in Section 4 of the main report. Section 5 includes additional explanation of the flow recommendations. This table summarizes relevant literature and studies used to confirm flow need, support the selection of particular flow statistics and/or summarize studies that quantify ecological responses.

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
FALL		
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout) - fall flows are needed to maintain connectivity to spawning habitats, suitable temperatures and wetted, aerated, and silt-free redds. *Cool and coldwater and High baseflow headwaters and small streams*	**Seasonal Flow - Oct-Jun** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Oct- Jun** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Eggs and larvae develop through the late fall and early winter and are sensitive to decreased flows that could increase sedimentation, thermal stress or exposure, and increased flows that may cause scour. Juvenile development occurs from March to June, during which they need access to margins and shallows between 0.5-2ft in depth (Raleigh 1982, Denslinger et al. 1998, Hudy et al. 2005, Kocovsky and Carline 2006) While temperature is the most limiting factor for suitable habitat, hydraulic conditions and turbidity during baseflow periods (August through December) are also critical for adult growth of trout (Raleigh 1982, Denslinger et al. 1998) PA-MD Instream Flow Study predicted a 10% habitat loss for withdrawals of 7 to 8% Average Daily Flow (ADF) on freestone and unglaciated streams, and 10 to 23% ADF in limestone (high baseflow) streams (Denslinger et al. 1998).
Cue diadromous fish emigration - high flow pulses and seasonal flows needed to cue, direct, and provide access to submerged aquatic vegetation refuge during emigration of juvenile Alosids and adult silver eels. *Mainstem and major tributaries*	**High Flow - Sept-Dec** • 1 to 5 high flow events > monthly Q10 between Sept-Nov **Seasonal Flow – Sept-Dec** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Cues for juvenile Alosid and adult silver eel emigration include precipitation and high flow pulses, temperature decreases of > 1-4 C, and lunar cycle (Hildebrand and Welsh 2005, Greene et al. 2009). Freshets (high pulses and flows above mean or median) coupled with lower temperatures initiate juvenile shad outmigration. Outmigration occurs as early as October and as late as December. Once outmigration begins, juvenile shad will continue to move. Outmigration may be inhibited by low flows. High flows or pulses will speed outmigration (M. Hendricks and M. Hartle, personal communication, 2010). Lower Susquehanna dams spill during extended high pulses. For juvenile shad, spilling is a safer route than through the turbines (M. Hendricks and M. Hartle, personal communication, 2010). Without fall high flow cues, eels delayed outmigration from fall to winter on the Shenandoah River (Eyler et al. 2010).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
FALL		
Maintain stable hibernation habitat for reptiles, amphibians, and small mammals – seasonal flows needed during amphibian and reptile hibernation in stream banks and beds, and small mammals nesting in banks. *All habitat types: Cool and cold, High Baseflow, and Warm headwaters and small streams; Mainstem and major tributaries*	**Seasonal Flow - Sept-Apr** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Sept-Apr** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	During hibernation period, map, common musk, and wood turtles need flowing waters (that generally do not freeze) and high DO concentrations (Graham and Forseberg 1991, Crocker et al. 2000, and Greaves 2007). Wood turtles only capable of small and slow movements to avoid freezing or poor water quality conditions during overwinter period. (Graham and Forseberg 1991).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
WINTER		
Maintain overwinter habitats for resident fish – winter flows needed to a) maintain a range of habitat types including high velocity riffles to low velocity pools, backwaters and stream margins; and b) sustain depths and velocities to moderate freezing air temperatures and minimize formation of anchor ice. *All habitat types*	**Seasonal Flow - Dec-Feb** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Dec-Feb** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Brook trout migrated (mostly downstream) to winter habitats with low velocities and relatively deep water; surface and subsurface ice can exclude habitats that are available in other seasons. This condition needs to be considered in weighted usable area models (Chisholm 1987). Population size for mottled sculpin is regulated by overwinter habitat availability. Juveniles and adults directly compete for refuge (Rashleigh and Grossman 2005). Burbot require connectivity to and maintenance of winter spawning habitats in cool to cold headwaters of the Upper Susquehanna. They typically spawn under ice cover (D. Fischer, personal communication, 2009). For all riffle-obligate fishes, published observations of habitat and hydraulic needs during the overwinter period are limited, however it is hypothesized that winter baseflows are critical for providing thermal refuge (D. Fischer, personal communication, 2009).
Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates - seasonal flows maintain hydraulic habitat and buffer instream temperatures for mussels, crayfish, and aquatic insects *All habitat types*	**Seasonal Flow - Nov-Feb** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	On a small stream, constant withdrawals through the fall and winter (≥90%) reduced invertebrate density by 51% and richness by 16%. 80% of the altered community was comprised of 'tolerant' species (Rader and Belish 1999). Low winter flows have been correlated with anchor ice formation and reduction (Flannigan 1991) or elimination of stonefly taxa (Clifford 1969). Reproductive success of long-term brooders may be influenced by overwinter flow magnitude (R. Villella, personal communication, 2010).
Maintain ice scour events and floodplain connectivity - seasonal high flow pulses maintain geomorphic disturbance patterns, including ice scour and floodplain inundation, and maintain in-channel and floodplain habitat structure and diversity. *Mainstem and major tributaries*	**High Flow - Dec-Feb** • 1 to 2 **bankfull** events every 2 years	During the winter, high flow events and associated ice scour maintain sites for early successional vegetation (Nilsson 1989, Fike 1999, Podniesinsksi et al. 2002). USGS developed regional curves to predict bankfull discharge in NY, PA, and MD. For gages within the Susquehanna Basin, the recurrence interval ranges from 1.1 to 2.1 years (Chaplin 2005, Mulvihill et al. 2005, Westergard et al. 2005).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SPRING		
Support resident fish spawning - maintenance of seasonal flows to support nest construction (nest-building fishes) and rearing and growth of resident and migratory fish. *All habitat types*	**Seasonal Flow - Mar-July** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Mar-July** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Survival of walleye larvae directly related to discharge; low during years with multiple high flow events during the spring (Mion et al 1998). Strongest smallmouth bass year class observed when June flows within 40% of long-term mean (Smith et al. 2005). A decrease in the magnitude of median daily flows in spring results in a decrease in the abundance of spring spawners and an increase in summer spawners (Freeman et al. 2001).
Cue alosid spawning migration and promote egg and larval development - seasonal flows needed to cue spawning migration and provide access to natal spawning streams. *Mainstem and major tributaries*	**Seasonal Flow - Mar-June** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Greene et al. 2009, cited above Adult migrating shad have strong velocity preferences; they seek moderate flows (around median or mean) and avoid moving in high flows. Spawning migration is cued by seasonal flows in around median. Increased magnitude or frequency of high flow events could delay migration (Bilkovic 2002, M. Hendricks, personal communication, 2010). In June 2006, extremely high flows likely negatively impacted juvenile American shad survival (both wild and hatchery) (SRARFC 2008). High June mean flow is negatively correlated with shad year-class strength (in addition to temp and precip). High flow conditions reduce larval feeding success and survival (Crecco and Savoy 1984).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SPRING		
Support spring emergence of aquatic insects and maintain habitats for mating and, egg laying – seasonal flows neede to maintain riffle and pool habitats. *All habitat types*	**Seasonal Flow - May - June** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Reservoir mitigation releases increased discharge by 6 x (from .7 to 4.3 m3/s) resulting in 36% increase in family richness, up to 119% increase in EPT taxa family richness, and a 13% decrease in tolerant taxa [May to June surveys] (Bednarek and Hart 2005). In small streams, instream flows recommendations developed using IFIM for target benthic fish (sculpin) underestimated habitat loss for macroinvertebrates by up to 25% (Gore et al. 2001).
Maintain channel morphology, island formation, and floodplain habitat - floods and seasonal high flow pulses are needed to maintain geomorphic disturbance patterns, including bedload transport, island formation, ice scour, floodplain inundation, and maintenance of in-channel and floodplain habitat structure and diversity, and to redistribute alluvium and organic matter. *All habitat types*	**High Flow** - Mar - Nov Headwaters • 1 to 2 **bankfull** events every 2 years Streams > 50 square miles • 1 to 2 **bankfull** events every 3 years All habitat types • Maintain magnitude and frequency of **small (5-yr) flood** • Maintain magnitude and frequency of **large (20-year) flood**	Bankfull recurrence intervals from Chaplin 2005, Mulvihill et al. 2005, Westergard et al. 2005, cited above. 1 in 5 year high flow events are associated with channel maintenance and overbank events (Nanson and Crook 1992, B. Hayes, personal communication, 2009). Floods with a recurrence interval of 18 to 20 years are associated with floodplain maintenance and valley formation (Shultz 1999, B. Hayes, personal communication, 2009). Spring floods and associated high flow pulses transport bedload material in large river habitats (B. Hayes, personal communication, 2009). Floodplain forests of the Susquehanna were surveyed in areas inundated by an estimated range of flows from the Annual Q45 to the Annual Q0.5 (Podniesinski et al. 2002). Seeds of riparian trees including American sycamore, river birch and silver maple dependent on high flows for dispersal (Burns and Honkala 1990, Zimmerman 2006). An estimated 70% reduction in seasonal high flow pulses results in a -300 to 350% in area of inundated woody vegetation (Bowen et al. 2003). Spring high flows and mean annual flows reduced by 25-50% results in riparian encroachment into former channels (Johnson 1994). Riparian assemblages in large rivers are particularly sensitive to changes in minimum flow and high flow events (Auble et al. 1994).

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

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SUMMER		
Cue and direct inmigration of juvenile American Eel - seasonal flows are needed to direct upstream migration and provide connectivity between mainstem and tributary habitats *Mainstem and major tributaries*	**Seasonal Flow - May-July** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Discharge and velocity influence the rate of upstream migration. Migrating eels may delay migration when velocities are too low or too high (Greene et al. 2009). In recent surveys, elvers have been documented reaching the lower mainstem (Conowingo Dam) starting in the late spring (May) through the summer, peaking in June and July (SRAFRC 2009). Juveniles have limited swimming ability and difficulty moving long distances against high velocities (Greene et al. 2009).
Support mussel spawning, glochidia release, and growth - maintenance of seasonal flows and low flows to support spawning, glochidia release, and interaction between mussels and host fish. *All habitat types*	**Seasonal Flow - Jun-Sept** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Jun-Sept** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Research on the Green River (KY) confirmed that augmented flows during summer months can reduce mussel recruitment (Layzer 2009). Increased high flow pulses during low flow season may impact efficiency of spawning and glochidia release, particularly for species with intricate lures (D. Crabtree, personal communication, 2010). Individual mussel mortality during drought conditions was associated with two thresholds: velocity < .01 m/s and DO ≤5 mg/L (Johnson et al. 2001). In small stream habitat, >50% reduction of median monthly flows in summer months resulted in a 65-85% decrease in mussel density. No live mussels were found on streams that were completely dewatered. In large river habitat, unionid assemblages survive exceptional drought when surface flow connectivity was maintained (Haag and Warren 2008). Some mussel species are adapted to low flow conditions in headwater streams but decrease in individual fitness during dry periods has been documented (J. Layzer, personal communication, 2010).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SUMMER		
Promote macroinvertebrate growth and insect emergence - seasonal and low flows needed to maintain depth, velocity, and temperature in riffle and pool habitats. *All habitat types*	**Seasonal Flow - Jul-Oct** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - Jul-Oct** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	An experimental withdrawal in headwater streams quantifies response between summer flow and macroinvertebrate density, community composition and available habitat. A threshold seems to occur between summer Q75 and 85 (Walters et al. 2010). Macroinvertebrate responses to drought included elimination of taxa groups including free-living caddisflies and stoneflies. Taxa with limited desiccation tolerance were last and fewest to recolonize once rewetted (Boulton 2003). An experimental summer flow reduction of 90% resulted in a decrease in macroinvertebrate density including -41% of all macroinvertebrate taxa, -50% EPT taxa, -90% filter feeding insects, -48% grazing insects (Wills et al. 2006). An experimental summer flow reduction of 90% of summer discharge resulted in -31% wetted width, -57% invertebrate density, and -26% density of EPT taxa (Dewson et al. 2007b). Multiple alterations including 73% decrease in median summer flow resulted in statistically significant decreases in macroinvertebrate taxa, total number of sensitive taxa, and increases in tolerant taxa (Nichols et al. 2006). Rapid wetting and drying of stream margins led to a decrease of total available energy, biomass, and community shifts. Varial zone benthic biomass was 33% of persistent habitat biomass (Blinn et al. 1995). Studies have documented reduced carapace length for crayfish exposed to low flow conditions (Taylor 1982, Acosta and Perry 2001). Crayfish are susceptible to increased predation during low flow conditions (Flinders 2003, Flinders and Magoulick 2007).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SUMMER		
Promote vegetation growth – seasonal flows and high flow pulses needed to sustain inundation frequencies, maintain substrate size and soil moisture, and deter establishment of non-native vegetation. *All habitat types*	**High Flow - May-Sept** • 2 to 8 high flow events > Q10 **Seasonal Flow - May-Sept** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range** **Low Flow - May-Sept** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Podniesinksi et al. 2002, cited above. On a large river habitat, riparian assemblages are particularly sensitive to changes in minimum flow and high flow (magnitude, freq, duration) events (Auble et al. 1994). On Aughwick Creek, loss of upright branches and leaves was associated with a 5-day duration of 15 cfs (July Q80 or Aug Q60). Plant bases began to be exposed at streamflows of 10 cfs or less (July Q90 or Aug Q77). Although this disturbance stunted total seasonal growth, it was followed by a second period of growth occurring from September to October when average hydrologic conditions resumed (Munch 1993)
Maintain hyporheic habitat – connectivity between surface and groundwater maintains hyporheic habitat within the channels, which provides provide refugia for aquatic invertebrates during drought conditions and for seasonal temperature regulation. *All habitat types*	**Low Flow - Jun-Oct** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	Exchange between surface water and hyporheic zone occurs in response to variations in discharge, bed topography and transmissivity. Upwelling provides stream with nutrients and downwelling provides DO and organic matter to hyporheos. This zone is also refuge to early instars and stream invertebrates during extreme conditions including drought (Boulton et al. 1998). Crayfish were found in the hyporheic zone (within 30 cm below streambed) during seasonal summer drying; they did not migrate downstream to avoid desiccation. Hyporheic burrows served as refuge for other invertebrates (DiStefano 2009).
Transport organic matter and fine sediment - seasonal high flow pulses needed to flush fine sediment and to transport and breakdown leaf litter (CPOM). *All habitat types*	**High Flow - Jun-Nov** • 2 to 8 high flow events > Q10	Experimental diversion 80% of summer flows demonstrates need for high flow pulses during summer months to transport and breakdown coarse particulate organic matter (Dewson et al. 2007b). Summer precipitation and associated high flow events flush interstitial fine sediments (sands and silt) from stream bed (B. Hayes, personal communication, 2009).

Flow Need	Flow Statistic and Recommendation	Supporting Literature and Studies
SUMMER		
Maintain water quality - maintenance of seasonal low flows needed to provide habitable water quality including temperature and dissolved oxygen in mainstem and backwater habitats, maintenance of assimilative conditions below wastewater discharges and minimize local and downstream impacts of AMD discharges. *All habitat types*	**High Flow – July -Nov** • 2 to 8 high flow events > Q10 **Low Flow - July-Oct** Headwaters • No change to **monthly Q75; and** • No change to **monthly low flow range** Streams > 50 square miles • No change to **monthly Q95; and** • <10% change to **monthly low flow range**	High flow events in Susquehanna and major tributaries decrease temperatures and increase DO during summer months (Chaplin et al. 2009 and USGS unpublished data). In late summer/early fall of 2008, the Large River Assessment Project sampled 16 points along the Susquehanna mainstem and found that 93% of water quality parameters met standards. Only one sample did not meet temperature standards. All samples met state water quality standard for DO (> 4 mg/L). Streamflow during those months ranged from the monthly Q50 to Q70 (SRBC 2009 and USGS unpublished data). An instantaneous minimum DO of 5.0 mg/L and a 7-day average minimum of 6.0 mg/L are recommended to protect early life stages of fishes (US EPA 1986, Chaplin et al. 2009, Greene et al. 2009). Assimilative capacity is calculated using the 7-day, 1 in 10 year, low flow event. On the Lower Susquehanna this translates to the monthly Q99 for Jul and Aug and the monthly Q96 for Sept and Oct (USGS unpublished data).
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals *All habitat types*	**Seasonal Flow - Jun-Oct** • **Monthly median** between 45th and 55th percentile; **and** • Less than 20% change to **monthly range**	Low flows can reduce aquatic prey availability for birds and create land bridges between mainland and island habitats, introducing predators which may threaten rookeries and breeding success (Brauning 1992, PGC and PFBC 2005). Small mammals including the northern water shrew and many bat species require continuous localized access to an abundance of aquatic insects (Merritt 1987, PNHP 2009)

Appendix 8. List of Index Gages

Habitat Type	Gage #	Stream Name	Drainage Area
Cold Headwater and Small Stream	01542810	Waldy Run near Emporium, PA	5.2
	01549780	Larrys Creek at Cogan House, PA	6.8
	01517000	Elk Run near Mainesburg, PA	10.2
	01516500	Corey Creek near Mainesburg, PA	12.2
	01567500	Bixler Run near Loysville, PA	15.0
	01552500	Muncy Creek near Sonestown, PA	23.8
	01533500	North Branch Mehoopany Creek near Lovelton, PA	35.2
	01549500	Blockhouse Creek near English Center, PA	37.7
	01547700	Marsh Creek at Blanchard, PA	44.1
	01557500	Bald Eagle Creek at Tyrone, PA	44.1
	01545600	Young Womans Creek near Renovo, PA	46.2
	01518500	Crooked Creek at Tioga, PA	122.0
	01544500	Kettle Creek at Cross Fork, PA	136.0
	01550000	Lycoming Creek near Trout Run, PA	173.0
	01514000	Owego Creek Near Owego, NY	185.0
	01564500	Aughwick Creek near Three Springs, PA	205.0
High Baseflow Headwater and Small Streams	01578400	Bowery Run near Quarryville, PA	6.0
	01565700	Little Lost Creek at Oakland Mills, PA	6.5
	01547100	Spring Creek at Milesburg, PA	142.0
	01547950	Beech Creek at Monument, PA	152.0
	01565000	Kishacoquillas Creek at Reedsville, PA	164.0
	01571500	Yellow Breeches Creek near Camp Hill, PA	216.0
	01558000	Little Juniata River at Spruce Creek, PA	220.0
	01547200	Bald Eagle Creek bl Spring Creek at Milesburg, PA	265.0
	01555000	Penns Creek at Penns Creek, PA	301.0
Warm Headwater and Small Streams	01559700	Sulphur Springs Creek near Manns Choice, PA	5.3
	01574500	Codorus Creek at Spring Grove, PA	75.5
	01518862	Cowanesque River at Westfield, PA	90.6
	01555500	East Mahantango Creek near Dalmatia, PA	162.0
	01560000	Dunning Creek at Belden, PA	172.0
Mainstem Tributaries	01568000	Sherman Creek at Shermans Dale, PA	207.0
	01532000	Towanda Creek near Monroeton, PA	215.0
	01539000	Fishing Creek near Bloomsburg, PA	274.0
	01534000	Tunkhannock Creek near Tunkhannock, PA	383.0
	01570000	Conodoguinet Creek near Hogestown, PA	470.0
	01576754	Conestoga River at Conestoga, PA	470.0
Upper Susquehanna Major Tributaries	01525500	Canisteo River at West Cameron, NY	340.0
	01502500	Unadilla River at Rockdayle, NY	520.0
Chemung Major Tributaries	01520000	Cowanesque River near Lawrenceville, PA	298.0

Habitat Type	Gage #	Stream Name	Drainage Area
West Branch Major Tributaries	01543000	Driftwood Br Sinnemahoning Cr at Sterling Run, PA	272.0
	01541000	West Branch Susquehanna River at Bower, PA	315.0
	01552000	Loyalsock Creek at Loyalsockville, PA	435.0
	01548005	Bald Eagle Creek near Beech Creek Station, PA	562.0
	01548500	Pine Creek at Cedar Run, PA	604.0
	01543500	Sinnemahoning Creek at Sinnemahoning, PA	685.0
	01549700	Pine Creek bl L Pine Creek near Waterville, PA	944.0
	01542500	WB Susquehanna River at Karthaus, Pa.	1462.0
Juniata Major Tributaries	01566000	Tuscarora Creek near Port Royal, PA	214.0
	01556000	Frankstown Br Juniata River at Williamsburg, PA	291.0
	01562000	Raystown Branch Juniata River at Saxton, PA	756.0
	01559000	Juniata River at Huntingdon, PA	816.0

Appendix 9. Summary of Water Withdrawal Scenarios and Impacts on Flow Statistics

To better understand how existing or proposed withdrawals affect flow statistics, we worked with SRBC to develop hypothetical water withdrawal scenarios and analyze them in context of the draft flow recommendations. Eight scenarios represent water withdrawals from various sectors, including shale gas development, golf course irrigation, public water supply, and nuclear power generation. For each scenario, SRBC provided a pre-withdrawal daily time series for WY1960-2008, a post-withdrawal scenario (created by subtracting the quantity withdrawn over the same time period) and a post-withdrawal scenario with pass-by conditions imposed, if applicable.

Table A9.1 lists hypothetical water withdrawal scenarios. Each scenario includes five descriptors that help determine which flow recommendations are applicable and how pass-by flows would be determined under existing guidance. These elements include (a) major habitat type; (b) designated use; (c) drainage area; (d) volume withdrawn and schedule (if variable); and (e) other characteristics of the withdrawal, including options for preventing impacts to low flow conditions.

Table A9.1 Descriptions of hypothetical water withdrawal scenarios

Scenario	Description
Scenario 1	Marcellus shale gas industry variable surface water withdrawal from extreme headwater tributary to Sugar Creek a) Cold and Cool Headwaters and Small Streams b) Trout Stocked Fishery c) Drainage Area = 1.7 sq mi d) Withdrawal (variable) = 10% of daily flow, not to exceed 1.000 mgd e) Interruptible withdrawal = build storage
Scenario 2	Marcellus shale gas industry surface water withdrawal from upper South Branch Sugar Creek a) Cold and Cool Headwaters and Small Streams b) Trout Stocked Fishery c) Drainage Area = 3.5 sq mi d) Withdrawal = 0.9 mgd e) Interruptible withdrawal = build storage

Scenario	Description
Scenario 3	Golf course surface water withdrawal from Honey Run a) Cold and Cool Headwaters and Small Streams b) Trout Stocked Fishery c) Drainage Area = 3.6 sq mi d) Withdrawal = 0.382 mgd e) e. Interruptible withdrawal = secure conjunctive/alternative sources
Scenario 4	Marcellus shale gas industry surface water withdrawal from Young Womans Creek a) Cold and Cool Headwaters and Small Streams b) Exceptional Value c) Drainage Area = 49.9 sq mi d) Withdrawal = 1.6 mgd e) Interruptible withdrawal = build storage
Scenario 5	Public water supply surface water withdrawal/diversion from Octoraro Creek/Reservoir a) Major Tributaries b) Warmwater Fishery c) Drainage Area = 139 sq mi d) Withdrawal = 30.000 mgd e) Grandfathered source/diversion
Scenario 6	Marcellus shale gas industry cumulative surface water withdrawal from Sugar Creek watershed a) Cold and Cool Headwaters and Small Streams b) Trout Stocked Fishery c) Drainage Area = 188 sq mi d) Withdrawal (cumulative) = 5.350 mgd e) Interruptible withdrawals = build storage
Scenario 7	Public water supply surface water withdrawal from lower Conestoga River a) Major Tributaries b) Warmwater Fishery c) Drainage Area = 320 sq mi d) Withdrawal = 12 mgd e) Interruptible withdrawal = secure conjunctive/alternative sources

Scenario	Description
Scenario 8	Nuclear power facility cooling water surface water withdrawal from middle Susquehanna River a) Mainstem Rivers b) Warmwater Fishery c) Drainage Area = 10,253 sq mi d) Withdrawal = 44 mgd e) Uninterruptable withdrawal = provide mitigation

We used the IHA and a flow duration curve calculator to compare the pre- and post- withdrawal values of six flow statistics: monthly Q10, monthly median (Q50), monthly range (change in area under monthly flow duration curve between Q75 and Q10); low flow range (change in area under monthly flow duration curve between Q75 and Q99); monthly Q75 (streams <50 square miles) and monthly Q95 (streams and rivers > 50 square miles).

Table A9.2 shows the changes to each flow statistic. The flow recommendation for each statistic is listed in Table 5.1 of this report and also at the top of each column in Table A9.2. We color-coded the results to illustrate how various scenarios affect each flow statistic:

- For monthly Q10, monthly range, and monthly low flow range, changes are expressed as percent change to flow statistic: <10% (green); 10-20% (yellow); 20-50% (red); and >50% (black). For monthly range, the recommendation is <20% change to the area under this portion of the curve, so both green and yellow indicate that the recommendation was met. For monthly Q10 and monthly low flow range, the recommendation is <10% change, so only green indicates that the recommendation was met.
- For monthly median, change is expressed as within (green) or outside (black) the range between the pre-withdrawal 45th and 55th percentiles of the annual monthly medians during WY 1960-2008.
- For monthly Q75 and Q95, the flow recommendation is no change to the pre-withdrawal value. The table indicates if the withdrawal changed (black) or did not change (green) the value. Monthly Q75 is used for headwaters (<50 mi^2) and monthly Q95 for all other streams and rivers.

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- Less than 10% change OR Within if the alternative is Within/Outside of recommendation
- 10 to 20% change
- 20 to 50% change
- more than 50% change OR Outside if the alternative is Within/Outside of recommendation
- Passby Alternative
- Alternative results in Augmentation

			High Flows	Seasonal Median	Seasonal Range	Low Flow Range		Low Flow Magnitude	
		Statistic	**Monthly Q10**	**Monthly Median** Median of Monthly Medians	**Monthly Range (Q75 to Q10)**	**Monthly Q75 to Q99**: Headwaters < 50 sqmi	**Monthly Q75 to Q99:** Sheds > 50 sqmi	**Monthly Q75** Headwaters < 50 sqmi	**Monthly Q95** Sheds > 50 sq mi
		Flow Recommendation	≤ 10% change to Q10	Between the 45th and 55th Percentiles	≤ 20% change to area under curve between Q10 and Q75	No Change	≤ 10% change to area under curve between Q75 and Q99	No Change	No Change
	Scenarios	**Month**	% change to Q10	Within/Outside	% change to area	Within/Outside	% change to area	Within/Outside	Within/Outside
Scenario 1	Headwater 1.7 sqm 10% daily flows withdrawal - no min	**Oct**	🟡	🟢	🟡	⚫		🟢	
		Nov	🟢	⚫	🟡	⚫		⚫	
		Dec	🟢	🟢	🟡	⚫		🟢	
		Jan	🟡	🟢	🟢	⚫		⚫	
		Feb	🟢	🟢	🟢	⚫		🟢	
		Mar	🟡	⚫	🟡	⚫		⚫	
		Apr	🟡	⚫	🟢	⚫		⚫	
		May	🟡	🟢	🟢	⚫		🟢	
		Jun	🟡	⚫	🟢	⚫		🟢	
		Jul	🟢	⚫	🟡	⚫		🟢	
		Aug	🟢	🟢	🟡	🟢		🟢	
		Sep	🟡	🟢	🟡	⚫		⚫	
	Headwater 1.7 sqm 10% daily flows 20% ADF passby	**Oct**	🟡	🟢	🟢	🟢		🟢	
		Nov	🟢	⚫	🟢	🟢		🟢	
		Dec	🟢	🟢	🟡	⚫		🟢	
		Jan	🟡	🟢	🟢	⚫		⚫	
		Feb	🟢	🟢	🟢	⚫		🟢	
		Mar	🟡	⚫	🟡	⚫		⚫	
		Apr	🟡	⚫	🟢	⚫		⚫	
		May	🟡	🟢	🟢	⚫		🟢	
		Jun	🟡	⚫	🟢	🟢		🟢	
		Jul	🟢	🟢	🟢	🟢		🟢	
		Aug	🟢	🟢	🟢	🟢		🟢	
		Sep	🟡	🟢	🟢	🟢		🟢	
Scenario 2	Headwater 3.5 sqm .9mgd withdrawal - no min	**Oct**	🔴	⚫	⚫	⚫		⚫	
		Nov	🔴	⚫	⚫	⚫		⚫	
		Dec	🟡	⚫	🔴	⚫		⚫	
		Jan	🟡	⚫	⚫	⚫		⚫	
		Feb	🟡	⚫	🔴	⚫		⚫	
		Mar	🟢	⚫	🔴	⚫		⚫	
		Apr	🟢	⚫	🔴	⚫		⚫	
		May	🟡	⚫	🔴	⚫		⚫	
		Jun	🔴	⚫	⚫	⚫		⚫	
		Jul	⚫	⚫	⚫	⚫		⚫	
		Aug	⚫	⚫	⚫	⚫		⚫	
		Sep	⚫	⚫	⚫	⚫		⚫	
	Headwater 3.5 sqm .9mgd 20% ADF passby	**Oct**	🔴	🟢	🔴	🟢		🟢	
		Nov	🔴	⚫	🔴	🟢		🟢	
		Dec	🟡	⚫	🔴	⚫		⚫	
		Jan	🟡	⚫	🔴	🔴		⚫	
		Feb	🟡	⚫	🔴	⚫		⚫	
		Mar	🟢	⚫	🔴	⚫		⚫	
		Apr	🟢	⚫	🔴	⚫		⚫	
		May	🟡	⚫	🔴	⚫		⚫	
		Jun	🔴	🟢	🔴	🟢		🟢	
		Jul	⚫	🟢	🟡	🟢		🟢	
		Aug	🔴	🟢	🟢	🟢		🟢	
		Sep	⚫	🟢	🟡	🟢		🟢	
Scenario 3	Headwater 3.6 sqm .382 mgd withdrawal - no min	**Oct**	🟡	⚫	🔴	⚫		⚫	
		Nov	🟢	⚫	🔴	⚫		⚫	
		Dec	🟢	⚫	🟡	⚫		⚫	
		Jan	🟢	⚫	🟡	⚫		⚫	
		Feb	🟢	⚫	🟡	⚫		⚫	
		Mar	🟢	⚫	🟢	⚫		⚫	
		Apr	🟢	⚫	🟡	⚫		⚫	
		May	🟢	⚫	🟡	⚫		⚫	
		Jun	🟢	⚫	🔴	⚫		⚫	
		Jul	🟡	⚫	🔴	⚫		⚫	
		Aug	🔴	⚫	⚫	⚫		⚫	
		Sep	🟡	⚫	⚫	⚫		⚫	
	Headwater 3.6 sqm .382 mgd 20% ADF passby	**Oct**	🟡	🟢	🟡	🟢		🟢	
		Nov	🟢	⚫	🟡	🟢		🟢	
		Dec	🟢	⚫	🟡	⚫		⚫	
		Jan	🟢	⚫	🟡	⚫		⚫	
		Feb	🟢	⚫	🟡	⚫		⚫	
		Mar	🟢	⚫	🟢	⚫		⚫	
		Apr	🟢	⚫	🟡	⚫		⚫	
		May	🟢	⚫	🟡	⚫		⚫	
		Jun	🟢	⚫	🔴	🟢		🟢	
		Jul	🟡	🟢	🔴	🟢		🟢	
		Aug	🔴	🟢	🟡	🟢		🟢	
		Sep	🟡	🟢	🟡	🟢		🟢	

			High Flows	Seasonal Median	Seasonal Range	Low Flow Range		Low Flow Magnitude	
		Statistic	**Monthly Q10**	**Monthly Median** Median of Monthly Medians	**Monthly Range (Q75 to Q10)**	**Monthly Q75 to Q99**: Headwaters < 50 sqmi	**Monthly Q75 to Q99:** Sheds > 50 sqmi	**Monthly Q75** Headwaters < 50 sqmi	**Monthly Q95** Sheds > 50 sq mi
		Flow Recommendation	≤ 10% change to Q10	Between the 45th and 55th Percentiles	≤ 20% change to area under curve between Q10 and Q75	No Change	≤ 10% change to area under curve between Q75 and Q99	No Change	No Change
	Scenarios	**Month**	% change to Q10	Within/Outside	% change to area	Within/Outside	% change to area	Within/Outside	Within/Outside
Scenario 4	Headwater 49.9sqm 1.6 mgd withdrawal - no min	**Oct**	🟢	🟢	🟢	⚫		⚫	
		Nov	🟢	🟢	🟢	⚫		⚫	
		Dec	🟢	🟢	🟢	⚫		⚫	
		Jan	🟢	🟢	🟢	⚫		⚫	
		Feb	🟢	⚫	🟢	⚫		⚫	
		Mar	🟢	🟢	🟢	⚫		⚫	
		Apr	🟢	🟢	🟢	⚫		⚫	
		May	🟢	🟢	🟢	⚫		⚫	
		Jun	🟢	⚫	🟢	⚫		⚫	
		Jul	🟢	⚫	🟢	⚫		⚫	
		Aug	🟢	⚫	🟢	⚫		⚫	
		Sep	🟢	🟢	🟢	⚫		⚫	
	Headwater 49.9 sqm 1.6 mgd 4% ADF Passby (IFIM)	**Oct**	🟢	🟢	🟢	⚫		⚫	
		Nov	🟢	🟢	🟢	⚫		⚫	
		Dec	🟢	🟢	🟢	⚫		⚫	
		Jan	🟢	🟢	🟢	⚫		⚫	
		Feb	🟢	⚫	🟢	⚫		⚫	
		Mar	🟢	🟢	🟢	⚫		⚫	
		Apr	🟢	🟢	🟢	⚫		⚫	
		May	🟢	🟢	🟢	⚫		⚫	
		Jun	🟢	⚫	🟢	⚫		⚫	
		Jul	🟢	⚫	🟢	⚫		⚫	
		Aug	🟢	⚫	🟢	⚫		⚫	
		Sep	🟢	🟢	🟢	⚫		⚫	
Scenario 5	Headwater 139 sqm 30 mgd withdrawal - no min	**Oct**	🔴	⚫	⚫		⚫		⚫
		Nov	🟡	⚫	🔴		⚫		⚫
		Dec	🟡	⚫	🔴		⚫		⚫
		Jan	🟡	⚫	🔴		⚫		⚫
		Feb	🟡	⚫	🔴		⚫		⚫
		Mar	🟢	⚫	🟡		🔴		⚫
		Apr	🟢	⚫	🟡		🔴		⚫
		May	🟡	⚫	🔴		⚫		⚫
		Jun	🟡	⚫	🔴		⚫		⚫
		Jul	🟡	⚫	🔴		⚫		⚫
		Aug	🔴	⚫	⚫		⚫		⚫
		Sep	🔴	⚫	⚫		⚫		⚫
	Headwater 139 sqm 30mgd 27 cfs release	**Oct**	🟢	⚫	🔴		🟡		⚫
		Nov	🟢	⚫	🟡		🔴		⚫
		Dec	🟢	⚫	🟡		🔴		⚫
		Jan	🟢	⚫	🟢		🔴		⚫
		Feb	🟢	⚫	🟢		🔴		⚫
		Mar	🟢	⚫	🟢		🟡		⚫
		Apr	🟢	🟢	🟢		🟡		⚫
		May	🟢	⚫	🟡		🔴		⚫
		Jun	🟢	⚫	🟡		🔴		⚫
		Jul	🟢	⚫	🟡		🔴		⚫
		Aug	🟡	⚫	🔴		🟡		⚫
		Sep	🟡	⚫	🔴		🟢		⚫
Scenario 6	Headwater 188 sqm 5.35 mgd withdrawal - no min	**Oct**	🟢	🟢	🟢		⚫		⚫
		Nov	🟢	🟢	🟢		🔴		⚫
		Dec	🟢	🟢	🟢		🟡		⚫
		Jan	🟢	⚫	🟢		🟡		⚫
		Feb	🟢	🟢	🟢		🟡		⚫
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟡		⚫
		Jun	🟢	⚫	🟢		🔴		⚫
		Jul	🟢	⚫	🟡		⚫		⚫
		Aug	🟢	⚫	🔴		⚫		⚫
		Sep	🟢	⚫	🔴		⚫		⚫
	Headwater 188 sqm 5.35 mgd 20% ADF passby	**Oct**	🟢	🟢	🟢		🟢		🟢
		Nov	🟢	🟢	🟢		🟢		🟢
		Dec	🟢	🟢	🟢		🟢		🟢
		Jan	🟢	⚫	🟢		🟢		🟢
		Feb	🟢	🟢	🟢		🟢		🟢
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟡		⚫
		Jun	🟢	⚫	🟢		🟢		🟢
		Jul	🟢	🟢	🟢		🟢		🟢
		Aug	🟢	🟢	🟢		🟢		🟢
		Sep	🟢	🟢	🟢		🟢		🟢

			High Flows	Seasonal Median	Seasonal Range	Low Flow Range		Low Flow Magnitude	
		Statistic	**Monthly Q10**	**Monthly Median** Median of Monthly Medians	**Monthly Range (Q75 to Q10)**	**Monthly Q75 to Q99**: Headwaters < 50 sqmi	**Monthly Q75 to Q99:** Sheds > 50 sqmi	**Monthly Q75** Headwaters < 50 sqmi	**Monthly Q95** Sheds > 50 sq mi
		Flow Recommendation	≤ 10% change to Q10	Between the 45th and 55th Percentiles	≤ 20% change to area under curve between Q10 and Q75	No Change	≤ 10% change to area under curve between Q75 and Q99	No Change	No Change
	Scenarios	**Month**	% change to Q10	Within/Outside	% change to area	Within/Outside	% change to area	Within/Outside	Within/Outside
Scenario 7	Major Trib 320 sqm 12 mgd withdrawal - no min	**Oct**	🟢	⚫	🟢		🔴		⚫
		Nov	🟢	⚫	🟢		🔴		⚫
		Dec	🟢	🟢	🟢		🟡		⚫
		Jan	🟢	🟢	🟢		🟡		⚫
		Feb	🟢	🟢	🟢		🟢		⚫
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟢		⚫
		Jun	🟢	🟢	🟢		🟡		⚫
		Jul	🟢	⚫	🟢		🔴		⚫
		Aug	🟢	⚫	🟢		🔴		⚫
		Sep	🟢	⚫	🟡		🔴		⚫
	Major Trib 320 sqm 12 mgd 20% ADF passby	**Oct**	🟢	⚫	🟢		🟢		🟢
		Nov	🟢	⚫	🟢		🟡		🟢
		Dec	🟢	🟢	🟢		🟡		🟢
		Jan	🟢	🟢	🟢		🟡		⚫
		Feb	🟢	🟢	🟢		🟢		⚫
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟢		⚫
		Jun	🟢	🟢	🟢		🟡		⚫
		Jul	🟢	⚫	🟢		🟡		🟢
		Aug	🟢	⚫	🟢		🟢		🟢
		Sep	🟢	⚫	🟡		🟢		🟢
Scenario 8	Mainstem 10,253 sqm 44 mgd withdrawal - no min	**Oct**	🟢	⚫	🟢		🟢		⚫
		Nov	🟢	🟢	🟢		🟢		⚫
		Dec	🟢	🟢	🟢		🟢		⚫
		Jan	🟢	🟢	🟢		🟢		⚫
		Feb	🟢	🟢	🟢		🟢		⚫
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟢		⚫
		Jun	🟢	🟢	🟢		🟢		⚫
		Jul	🟢	🟢	🟢		🟢		⚫
		Aug	🟢	🟢	🟢		🟢		⚫
		Sep	🟢	🟢	🟢		🟢		⚫
	Mainstem 10,253 sqm 44 mgd 20% ADF passby	**Oct**	🟢	⚫	🟢		🟢		🟢
		Nov	🟢	🟢	🟢		🟢		🟢
		Dec	🟢	🟢	🟢		🟢		⚫
		Jan	🟢	🟢	🟢		🟢		⚫
		Feb	🟢	🟢	🟢		🟢		⚫
		Mar	🟢	🟢	🟢		🟢		⚫
		Apr	🟢	🟢	🟢		🟢		⚫
		May	🟢	🟢	🟢		🟢		⚫
		Jun	🟢	🟢	🟢		🟢		🟢
		Jul	🟢	🟢	🟢		🟢		🟢
		Aug	🟢	🟢	🟢		🟢		🟢
		Sep	🟢	🟢	🟢		🟢		🟢