Ecosystem Flow Recommendations for the Susquehanna River Basin

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

Submitted by The Nature Conservancy

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Table of Contents

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.

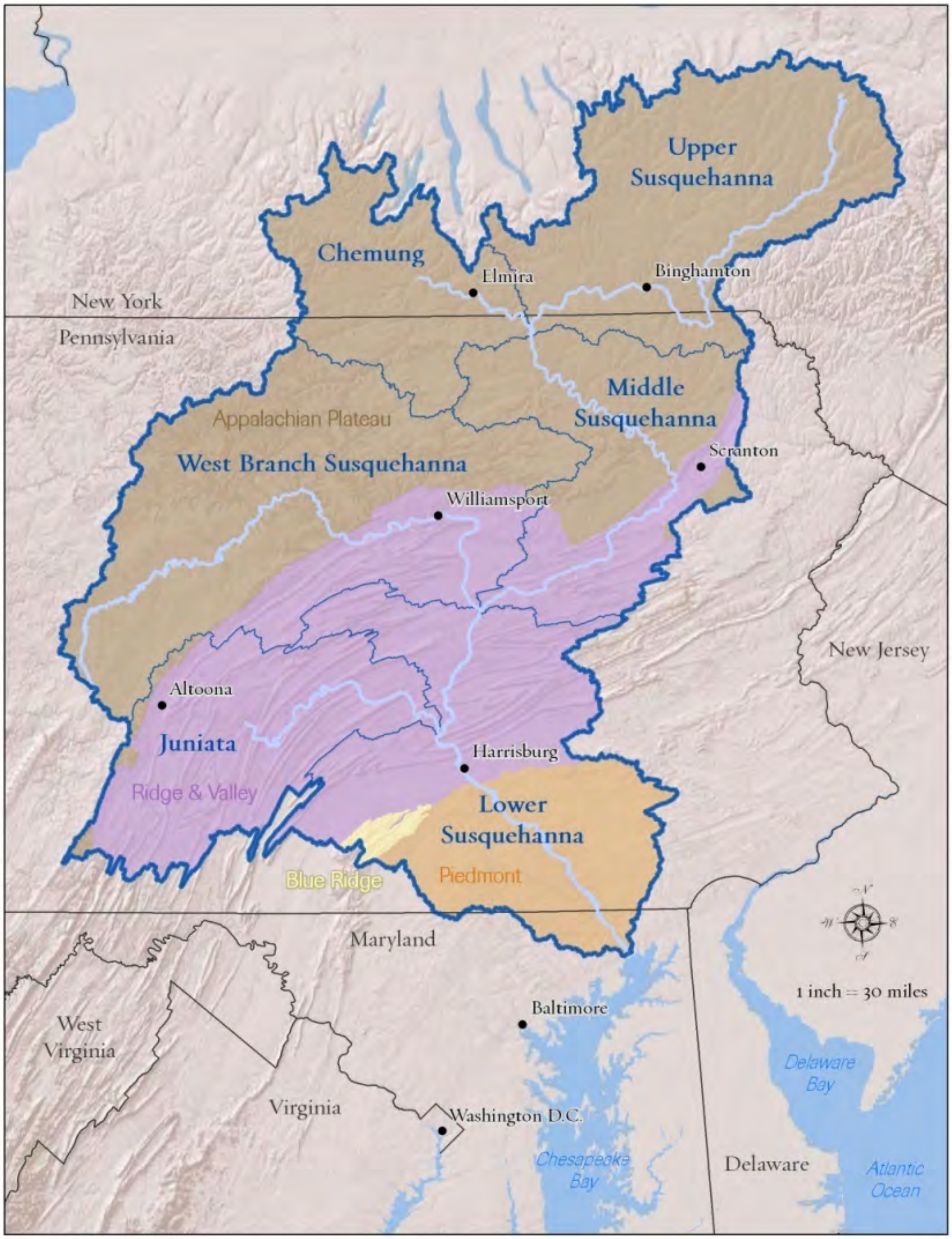

Figure 2.1 The Susquehanna River has six major subbasins and spans three major physiographic provinces.

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.

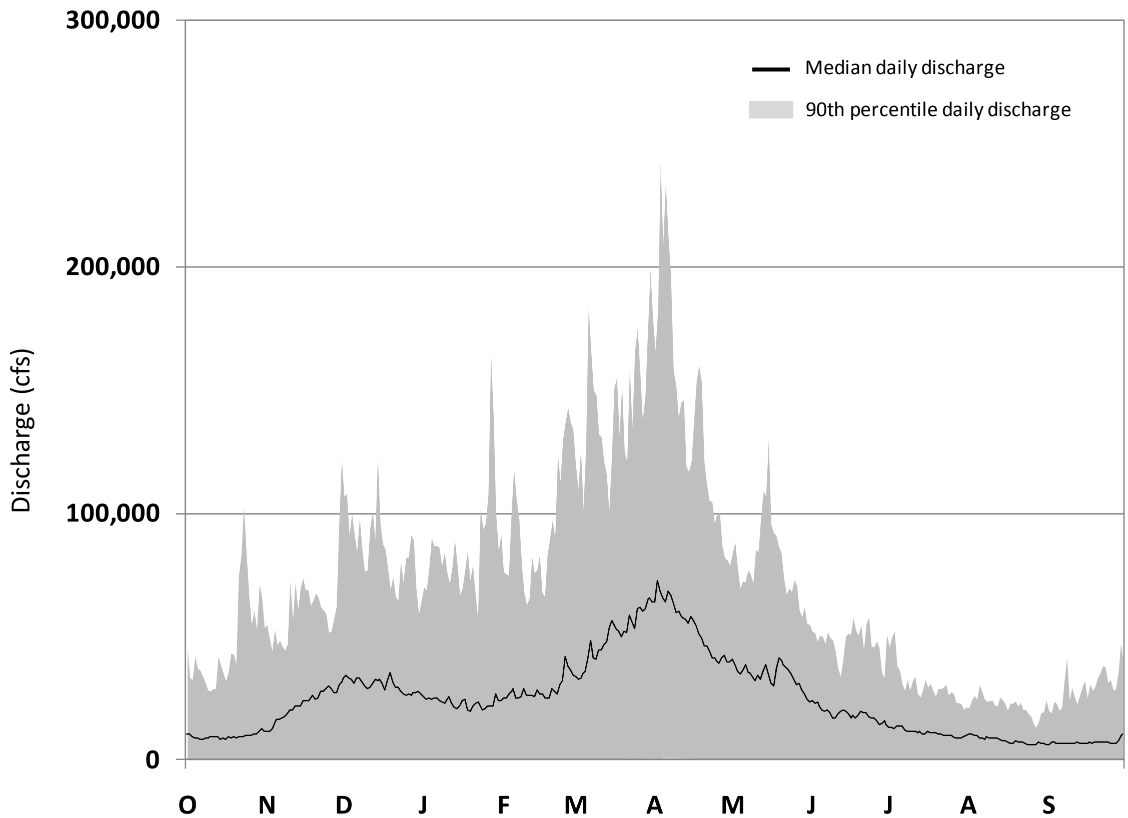

Figure 2.2 Hydrograph of the Susquehanna River at Harrisburg, PA (USGS gage 01570500).

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.

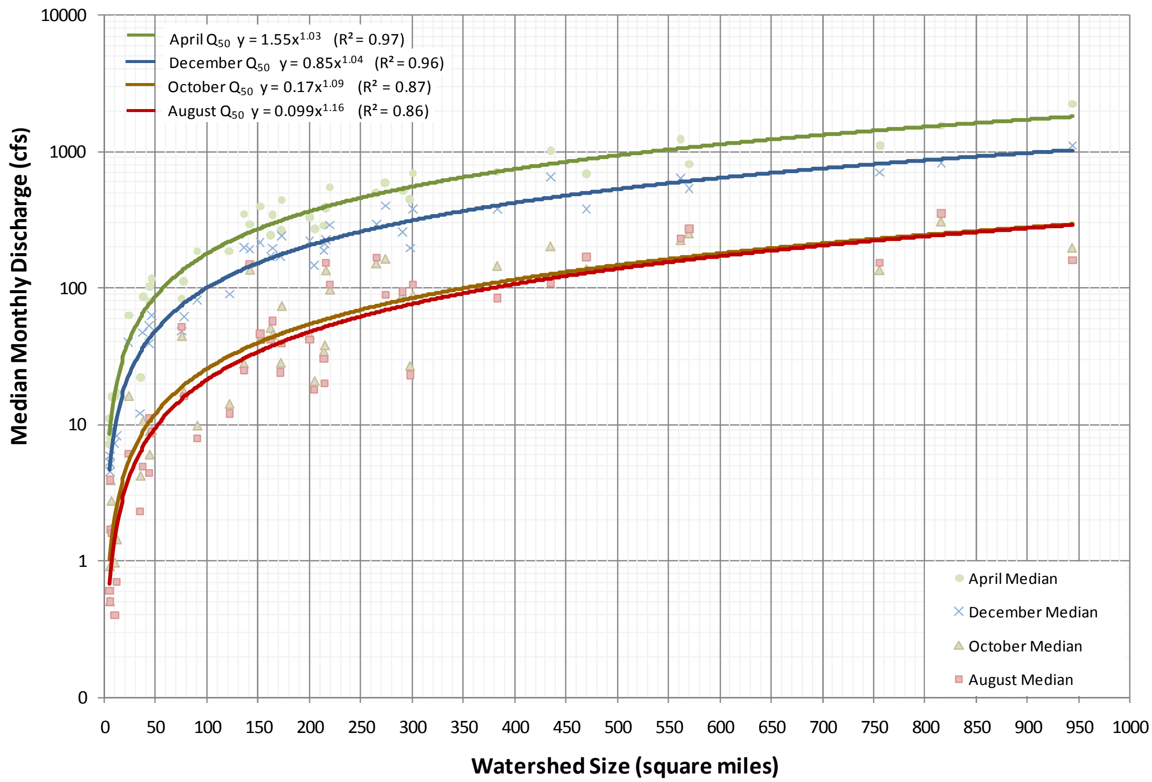

Figure 2.3 Relationship between median monthly (Q50) discharge and watershed size for gages (n=45) within the Susquehanna basin using a fall (Oct), winter (Dec), spring (Apr), and summer (Aug) month. Statistics were calculated using measured mean daily records for Water Years (WY) 1960-2008.

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.

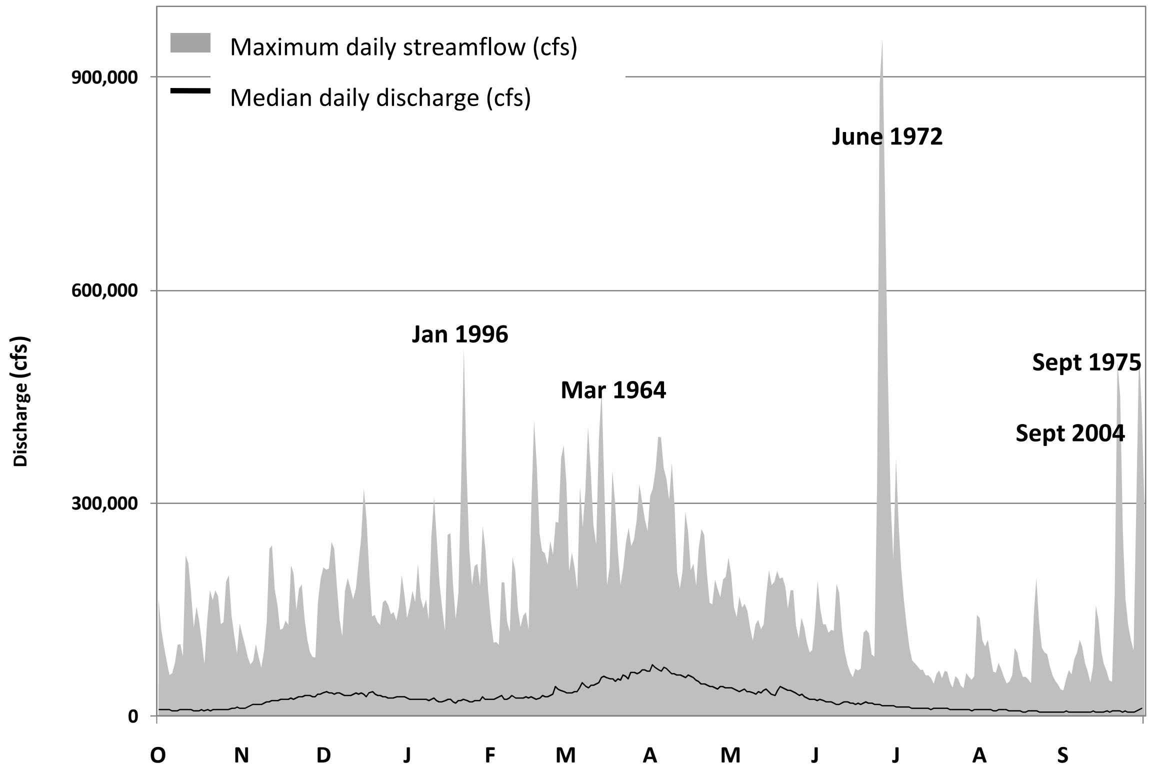

Figure 2.4 Flood events and maximum daily flow on the Susquehanna River at Harrisburg (1960-2008)

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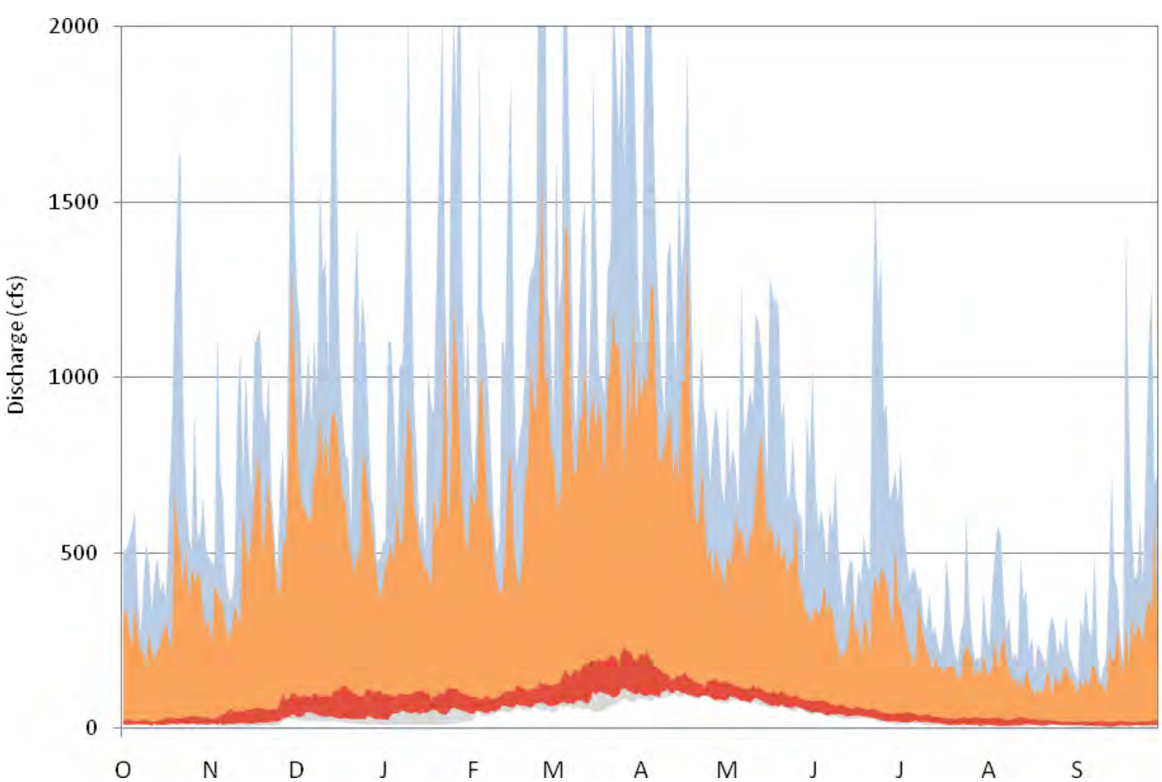
[2] For the Susquehanna, high flows include high flow pulses, bankfull flows and small floods, so we are effectively representing all of the components defined by Mathews and Richter (2007).

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.

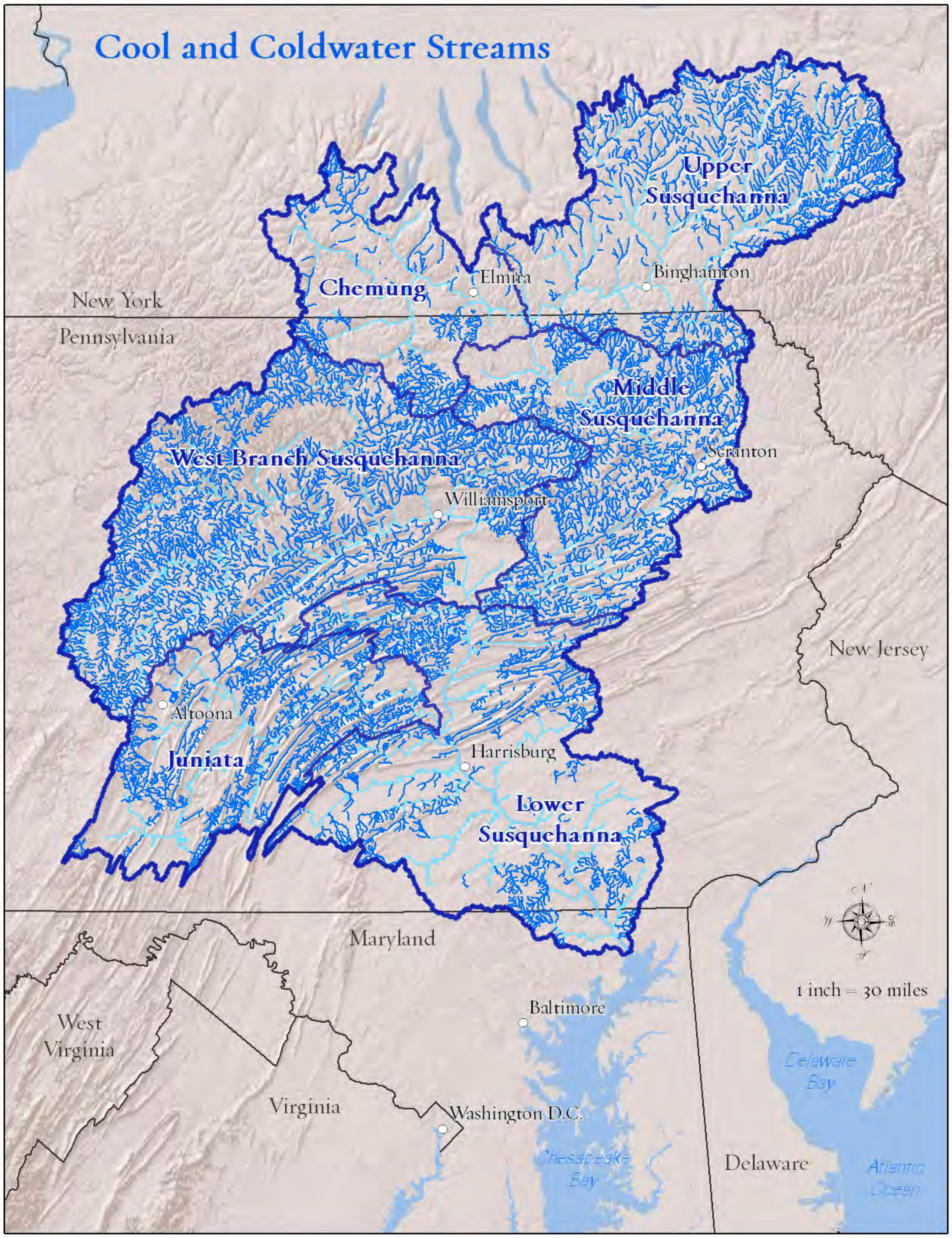


Figure 2.5 Cool and coldwater streams in the Susquehanna basin based on New York, Pennsylvania, and Maryland state water quality classifications.

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.

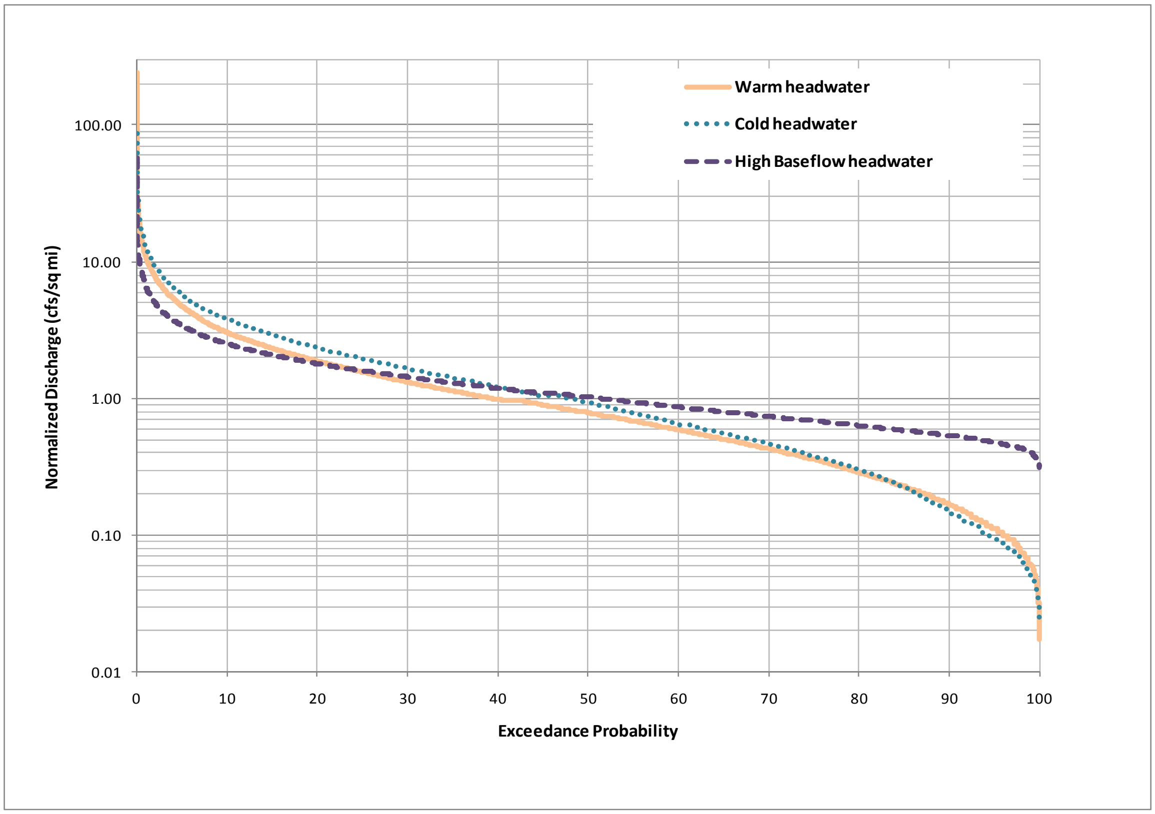


Figure 2.6 Normalized annual flow duration curves for cool and cold, warm and high baseflow headwaters and small streams (USGS Gages 01555500, 01550000, 01571500, respectively, 1960-2008).

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.

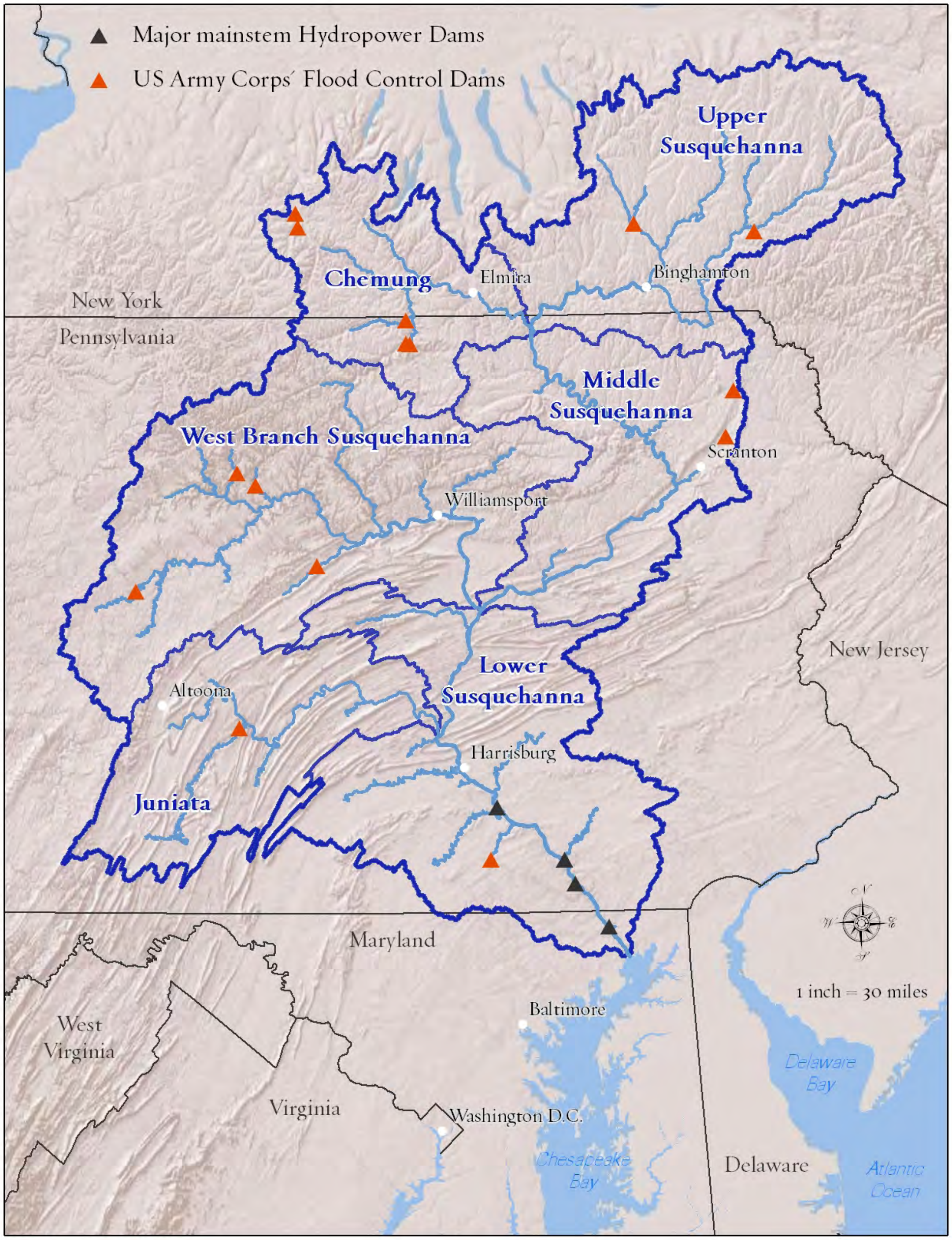


Figure 3.1 Map of major flood control reservoirs and lower Susquehanna hydroelectric dams.

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).

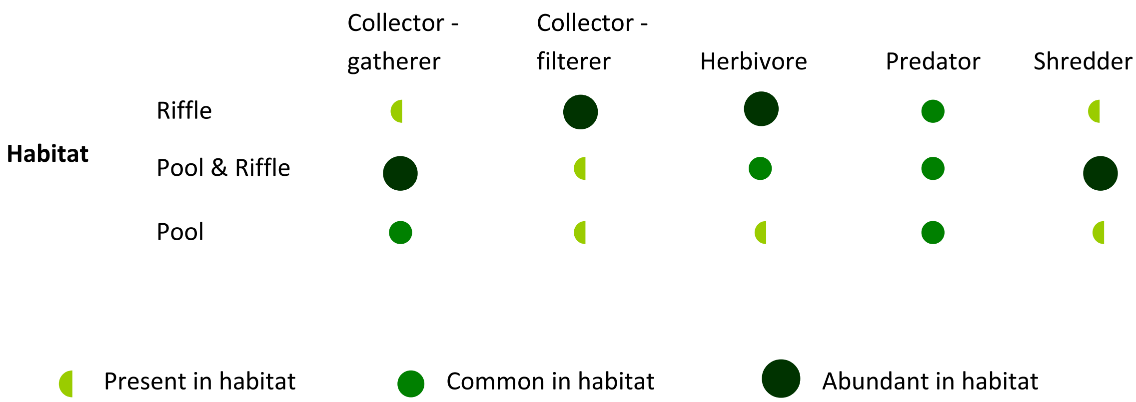

Figure 4.1 Relationship between trophic habit and habitat association for aquatic insect samples from the Susquehanna River basin (Data from SRBC).

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: $y = 43.21x^{(.867)}$ Carbonate: $y = 44.29x^{(.634)}$	0.92 0.73	1.4, 1.7 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

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[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.

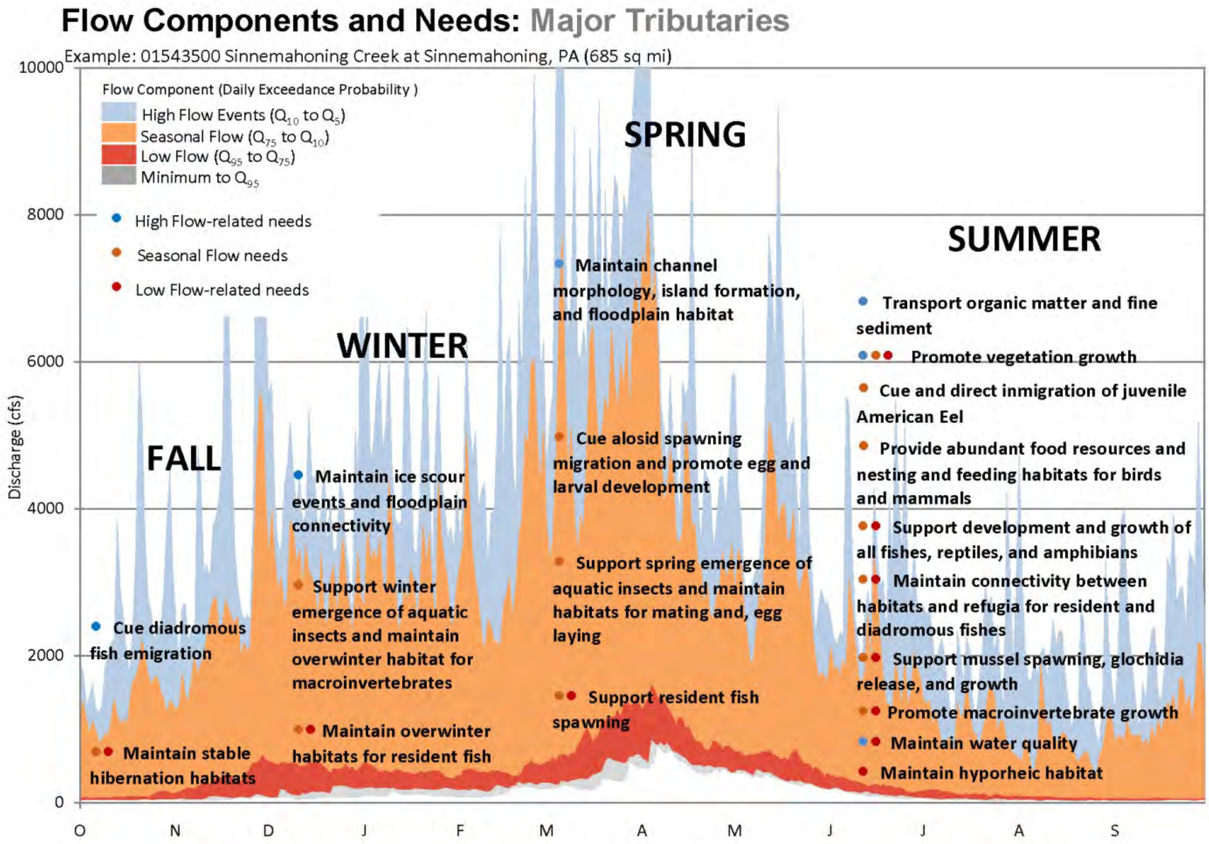

Figure 4.3 Example of flow needs associated with high, seasonal and low flows in major tributaries.

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: 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 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: 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 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.

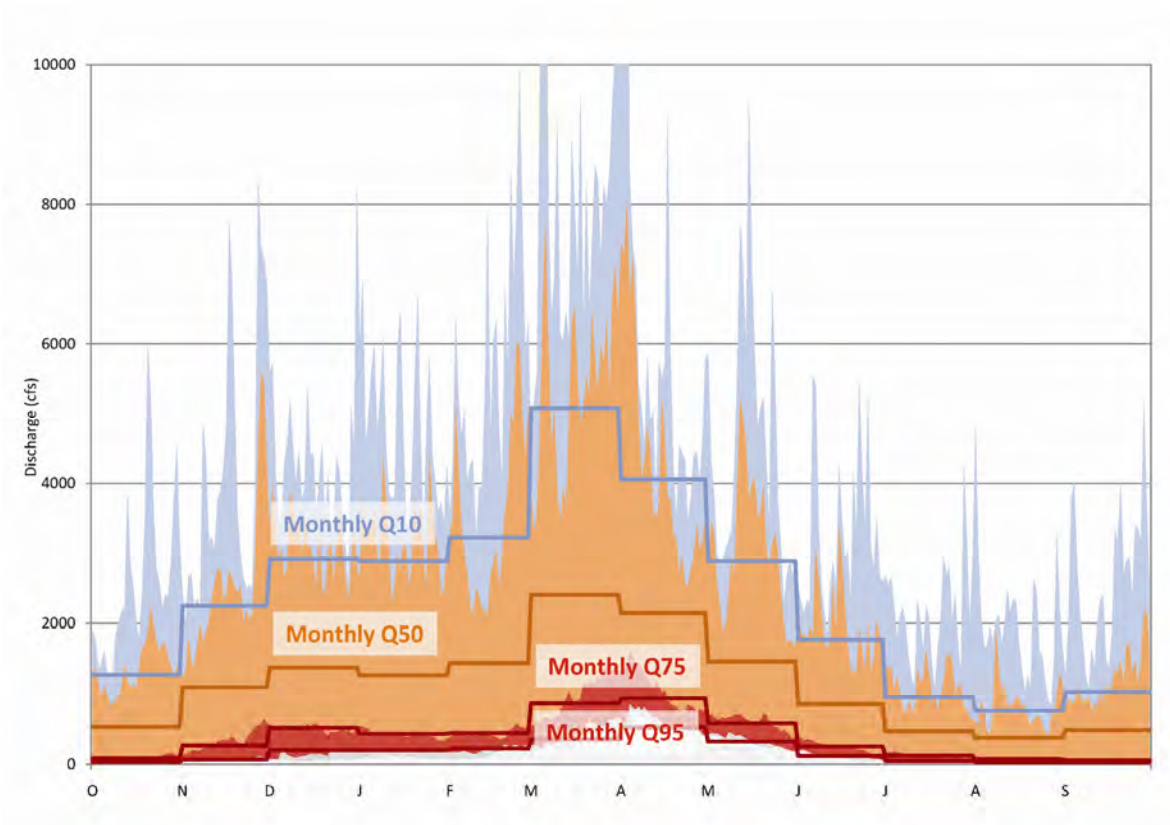

Figure 5.1 Four monthly flow exceedance frequencies selected as indicators of high, seasonal and low flow components. Solid hydrograph indicates the long-term distribution of daily flows sorted into high, seasonal, and low flow components.

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.

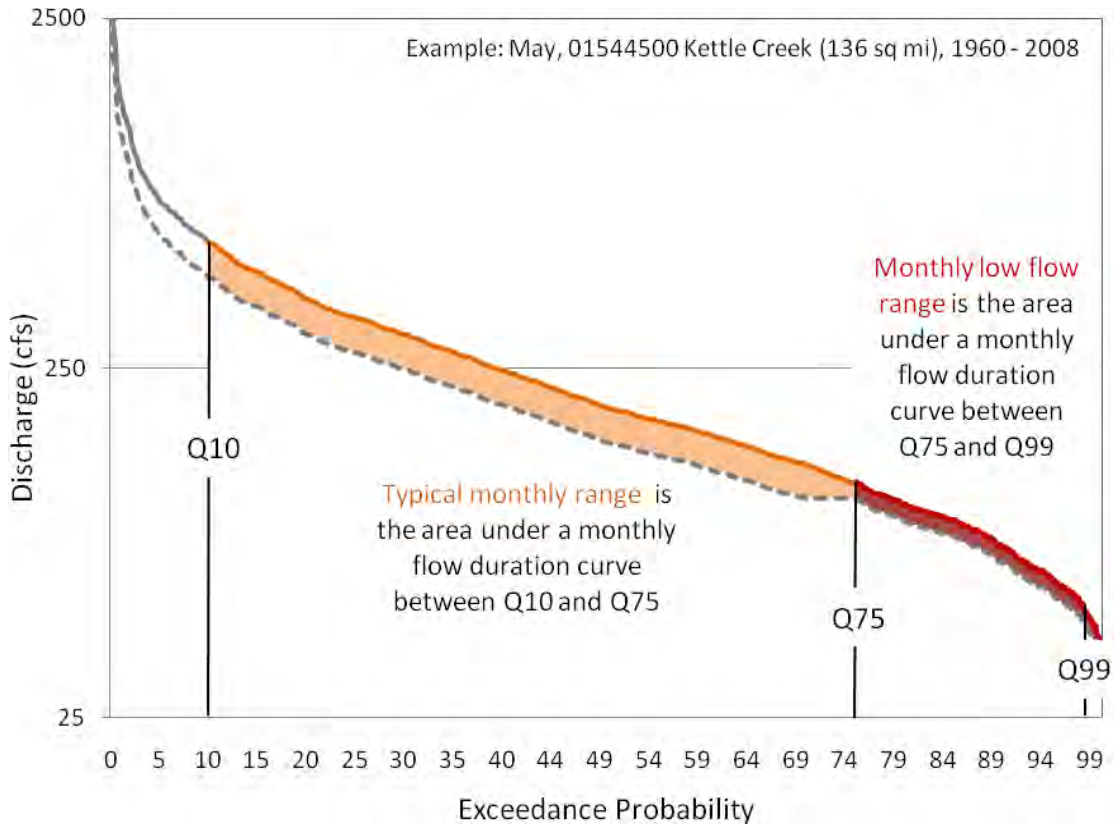

Figure 5.2 The typical monthly range and monthly low flow range statistics. The solid line represents unregulated conditions and the dashed line represents regulated conditions. The colored area represents the difference in area between portions of the two curves.

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 45^{th} and 55^{th} 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.

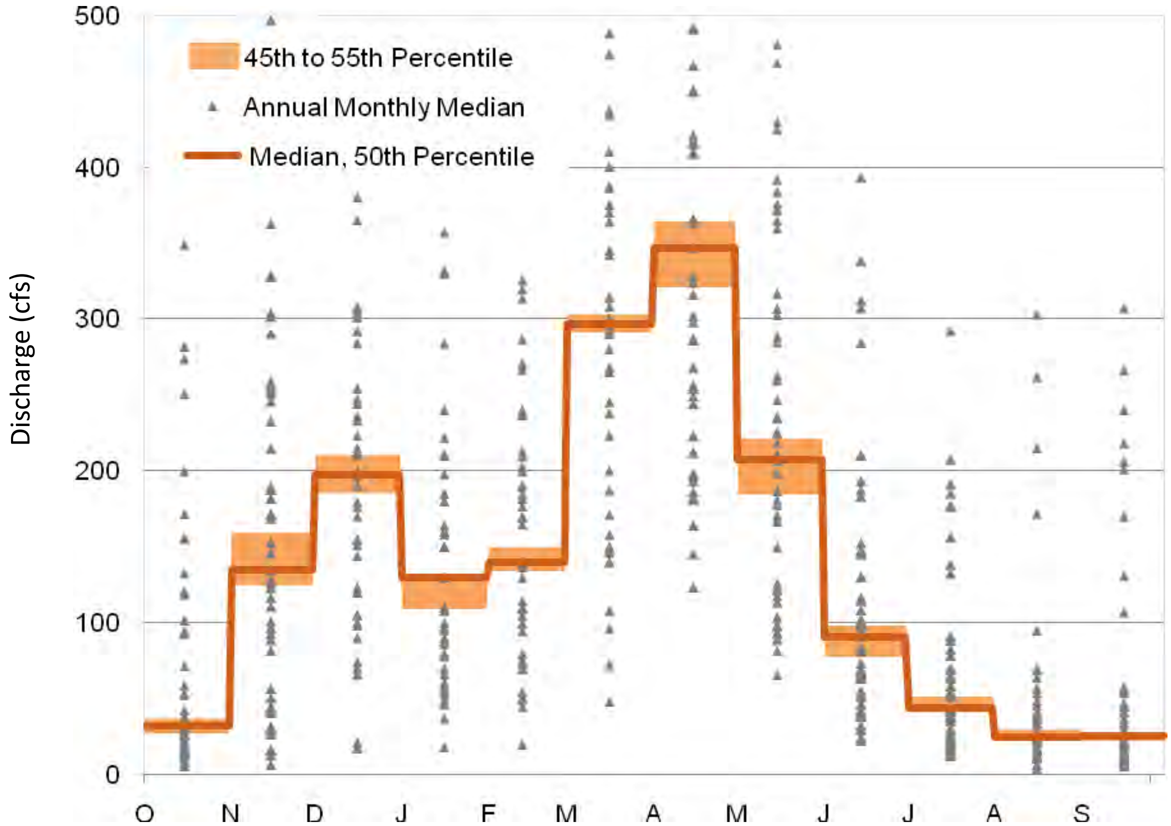

Figure 5.3. Illustration of flow recommendation for monthly median flow.

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