Ecosystem Flow Recommendations for the Upper Ohio River Basin in Western Pennsylvania

Report to the Pennsylvania Department of Environmental Protection

French Creek
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March 2013

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We thank Cokie Lindsay and John Wenzel who hosted us at the Powdermill Nature Reserve.

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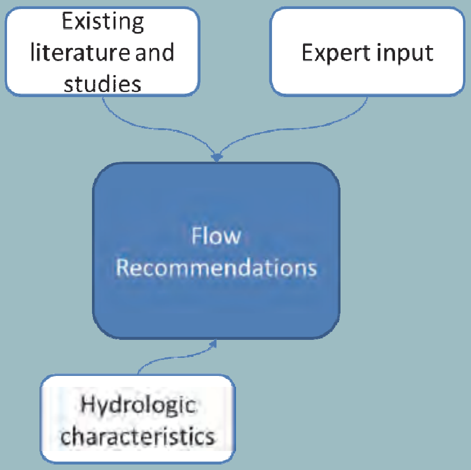
Ecosystem Flow Recommendations for the Upper Ohio Basin in Western Pennsylvania

Report by The Nature Conservancy to the Pennsylvania Department of Environmental Protection—March 2013

We customized **the Ecological Limits of Hydrological Alteration (ELOHA) framework to develop flow recommendations** for the Upper Ohio River in Western Pennsylvania. Our approach is cost-effective, relatively fast, and addresses multiple taxonomic groups over a large geographic area. We completed a similar project in the Susquehanna River basin and are currently managing one for the Delaware Basin. The ELOHA framework has been used to improve the ecological basis for water management throughout the U.S., including in Michigan, Rhode Island, Connecticut, the Colorado River basin.

The **project area was the Upper Ohio River basin in western Pennsylvania** and included the mainstem of the Three Rivers and all tributaries. We also discuss the transferability of the recommendations to the Great Lakes and Potomac River basins and incorporate results from concurrent studies in these watersheds.

Staff from **many agencies and research institutions contributed** by providing input throughout the process. In addition to Pennsylvania DEP, key agencies and organizations included Pennsylvania Fish & Boat Commission, U.S. Geological Survey, U.S. Fish & Wildlife Service, U.S. Environmental Protection Agency, U.S. Army Corps of Engineers, Ohio River Valley Water Sanitation Commission (ORSANCO) and Western Pennsylvania Conservancy.



Existing literature and studies

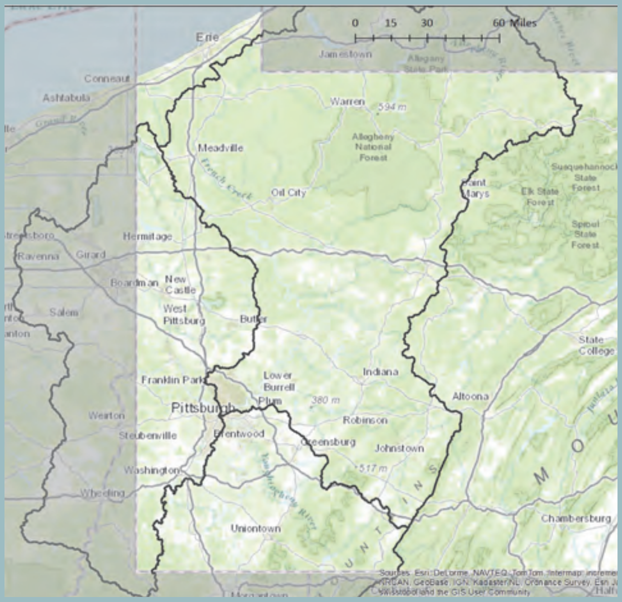
Expert input

Flow Recommendations

Hydrologic characteristics

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

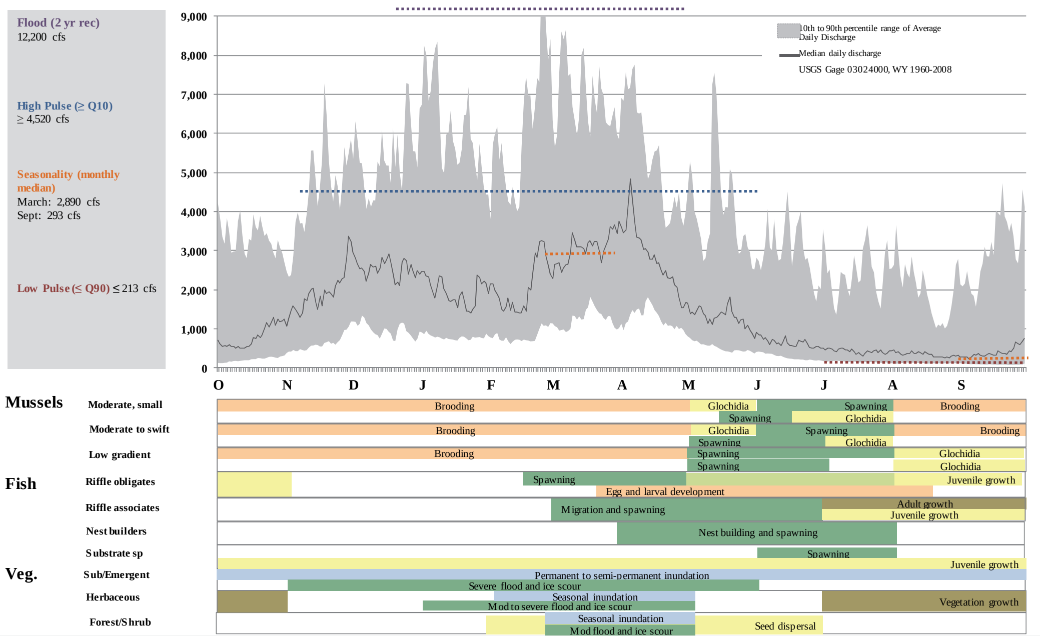
We also **synthesized over 150 publications and reports** on ecological responses to flow alteration and incorporated this information **into a weight-of-evidence based summary of the degree of support for each recommendation.**



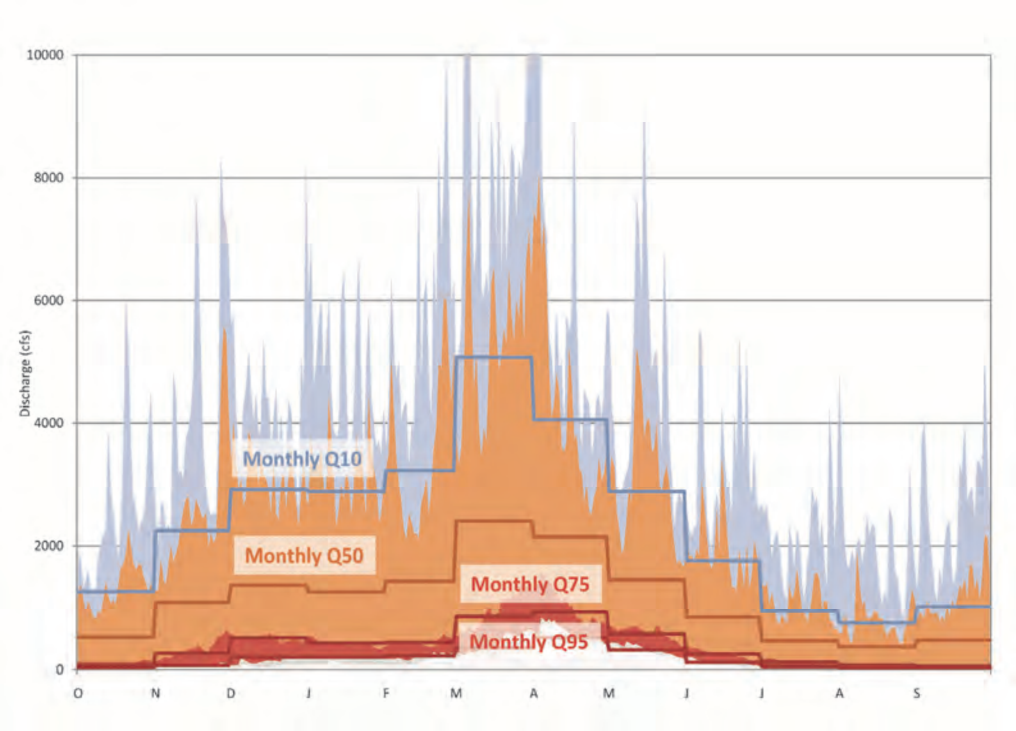
We identified 23 groups of species comprised of over 100 species – including **fish, mussels, aquatic insects, reptiles, amphibians, birds, mammals, and vegetation** – that are expected to be sensitive to changes in the flow regime. We also incorporated information on how streamflow affects **water quality and floodplain and channel maintenance.** These species groups are associated with one or more of **twelve habitat types** ranging from headwaters to large, navigational rivers.

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

Glaciated tributary: French Creek at Utica (1,028 sq mi)



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



Flow Recommendations are expressed as recommended limits to alteration a suite of flow statistics that are indicators of ecologically-important flows.

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

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

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

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

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Section 1: Introduction

1.1 Project Description and Goals

Providing basin-wide goals and standards for river flow management in Pennsylvania's major watersheds is a priority for the Pennsylvania Department of Environmental Protection (DEP), Pennsylvania Fish and Boat Commission (PFBC), The Nature Conservancy (Conservancy), and other partners. The project outcome is a set of ecologically-based flow recommendations that Pennsylvania DEP and other agencies can apply to instream flow protection within the Upper Ohio River basin in western Pennsylvania.

This project builds on a 2008 report that summarizes available data, tools and approaches that can be used to meet the overall goal of statewide instream flow protection criteria in Pennsylvania (Apse et al. 2008). This project also complements a recent project to identify ecosystem flow recommendations for the Susquehanna River basin and concurrent projects for the Delaware River, Great Lakes, and Potomac River basins.

This project was funded by Pennsylvania DEP who regulates the withdrawal of surface water by public water suppliers under the Water Rights Act and water sources (both surface and groundwater) used by the natural gas industry under the Oil and Gas Act (Chapter 78) and the Clean Streams Law. When issuing approvals for water withdrawals in the Ohio basin, DEP currently relies on the Pennsylvania Maryland Instream Flow study (for trout streams, where applicable) and the Susquehanna River Basin Commission's (SRBC) 2003 passby guidance[1,2] (Denslinger et al. 1998, SRBC 2003). Pennsylvania DEP seeks to improve upon this basis with a more in-depth study to define the ecological flow needs in the Upper Ohio River basin. They plan to use the resulting recommendations to inform the application of current regulations and to move toward the development of a statewide instream flow policy supportive of ecological integrity.

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.

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[1] SRBC defines a passby flow as a prescribed streamflow below which withdrawals must cease.

[2] In December 2012, SRBC adopted a new Low Flow Protection Policy and Technical Guidance that replaces the passby guidance in Commission Policy No. 2003-01. The new policy, technical guidance, and supporting materials are online http://www.srbc.net/policies/lowflowpolicy.htm. As of March 2013, Pennsylvania DEP is still using SRBC's 2003 passby guidance for water withdrawals in the Ohio basin.

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

- build on projects that produced flow recommendations for other river basins in the United States;
- provide information for all stream and river types in the basin;
- 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.

1.2 Project Approach

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

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

This project followed the general model of other projects that developed flow recommendations for large rivers, most specifically the Susquehanna River (DePhilip and Moberg 2010, USACE 2012). The *Ecosystem Flow Recommendations for the Susquehanna River Basin* were developed to support SRBC's water management programs and their collaborating agencies. The report was used to help develop the revised Low Flow Protection Policy (LFPP) adopted by SRBC in December 2012.

Our approach also applies principles that guided other projects that developed flow recommendations for large rivers, including the Savannah River, the Willamette River, the Rivanna River (Virginia), and the upper Colorado River (Bowler et al. 2006, Richter et al. 2006, Gregory et al. 2007, Wilding and Poff 2008). However, it differs from projects that focused on recommendations for specific reaches (e.g., Savannah River) and addressed operations of specific facilities (e.g., reservoir releases). Unlike reach-specific projects, our goal was to identify ecosystem flow needs that can be generally applied to the various stream and river types throughout the basin. 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 downstream impacts, especially during extreme low flow conditions.

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

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

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

Throughout the basin, there are many reaches that are affected by storage and releases made for navigation, water quality, recreation, hydropower and other purposes. This study gathers and summarizes available information about how flow affects suitability of habitat for species that use or migrate through these regulated reaches. However, defining reach-specific flow recommendations is beyond the scope of this project and will require more detailed hydrologic analyses at more locations to document current flow patterns, effects of current operations on streamflow, and potential ecological effects of existing management. To this end, the U.S. Army Corps of Engineers (USACE), Pittsburgh District and the Conservancy developed a Cooperative Agreement to examine reservoir operations at Stonewall Jackson Lake, Tygart Lake and Youghiogheny River Lake in the Monongahela River basin. This project will build on information contained in this report and the primary purpose will be to determine the impacts of reservoir operations on stream flows and to produce seasonal flow recommendations to maintain critical species, habitats, and ecological conditions that can be implemented through reservoir operations.

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

The majority of the work on this project was completed in approximately eighteen months between October 2011 and March 2013.

Oct 2011	Project orientation meeting
Jan 2012	Workshop I – Flow Hypotheses
May 2012	Workshop II – Flow Recommendations
Nov 2012	Circulate draft recommendations for comments and hold review meeting
Mar 2013	Final report complete

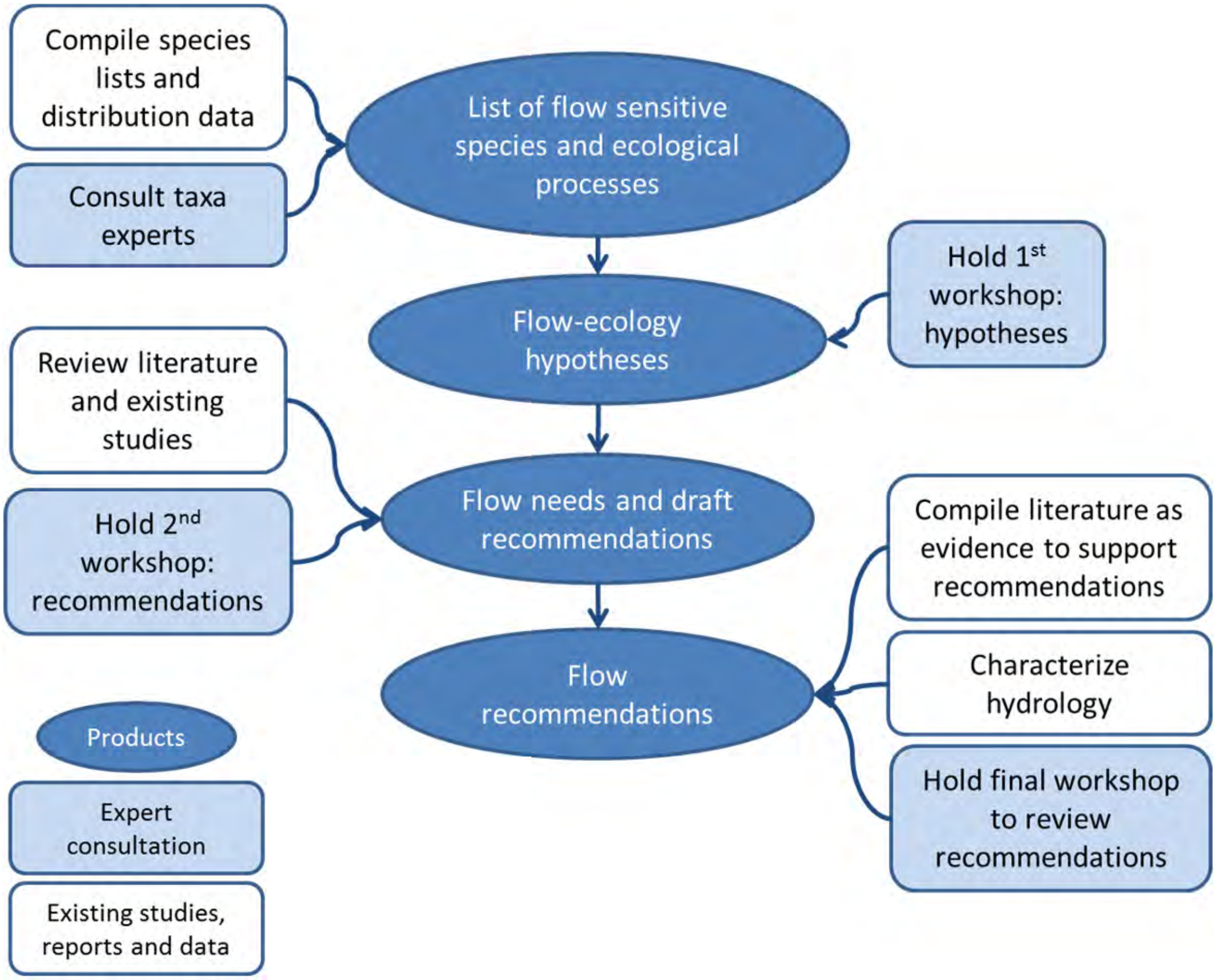


Figure 1.1 Process for developing flow recommendations. Multiple sources of information were integrated to support the recommendations. Interim and final products are within the ovals. Expert consultation occurred throughout and was organized around three workshops.

We 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. Workshops were held in October 2011, January 2012 and May 2012 at Powdermill Nature Reserve in Rector, PA, which is the environmental research center of Carnegie Museum of Natural History. In November 2012 we held a fourth workshop to present the flow recommendations and receive comments and suggestions for the written report.

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

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

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

Section 2: Basin Characteristics

The geographic scope of the study includes the Upper Ohio River watersheds in western Pennsylvania. This area is commonly referred to as the “Three Rivers” – the Allegheny River, the Monongahela River and the Ohio River – and drains an estimated 15,600 square miles over 23 counties in western Pennsylvania (Zimmerman and Podniesinski 2008, Ventorini 2011) (Figure 2.1). This area is referred to as the Ohio Region in the Pennsylvania State Water Plan (PADEP 2009). The headwaters originate in Potter County, Pennsylvania and eventually become the Allegheny River. The confluence of the Allegheny and the Monongahela Rivers occurs at Pittsburgh where the mainstem of the Ohio River begins. From the confluence, the Ohio River flows almost 1,000 miles, draining more than 200,000 square miles and including parts of 15 states before joining the Mississippi (Zimmerman and Podniesinski 2008, Ventorini 2011).

Several recent reports provide detailed information on hydrologic characteristics, water quality, water use and effects of dams and other infrastructure on physical habitat and biota of the Upper Ohio River basin.

- Three Rivers Management Plan (Ventorini 2011)
- Ohio River Basin Comprehensive Reconnaissance Report (USACE 2009)
- Biennial Assessment of Ohio River Water Quality Conditions (ORSANCO 2012)
- Monongahela River Watershed Initial Watershed Assessment (USACE 2012)
- Pennsylvania State Water Atlas – Ohio Watershed Region (Pennsylvania DEP 2009)

2.1 Physiography, Climate, and Vegetation

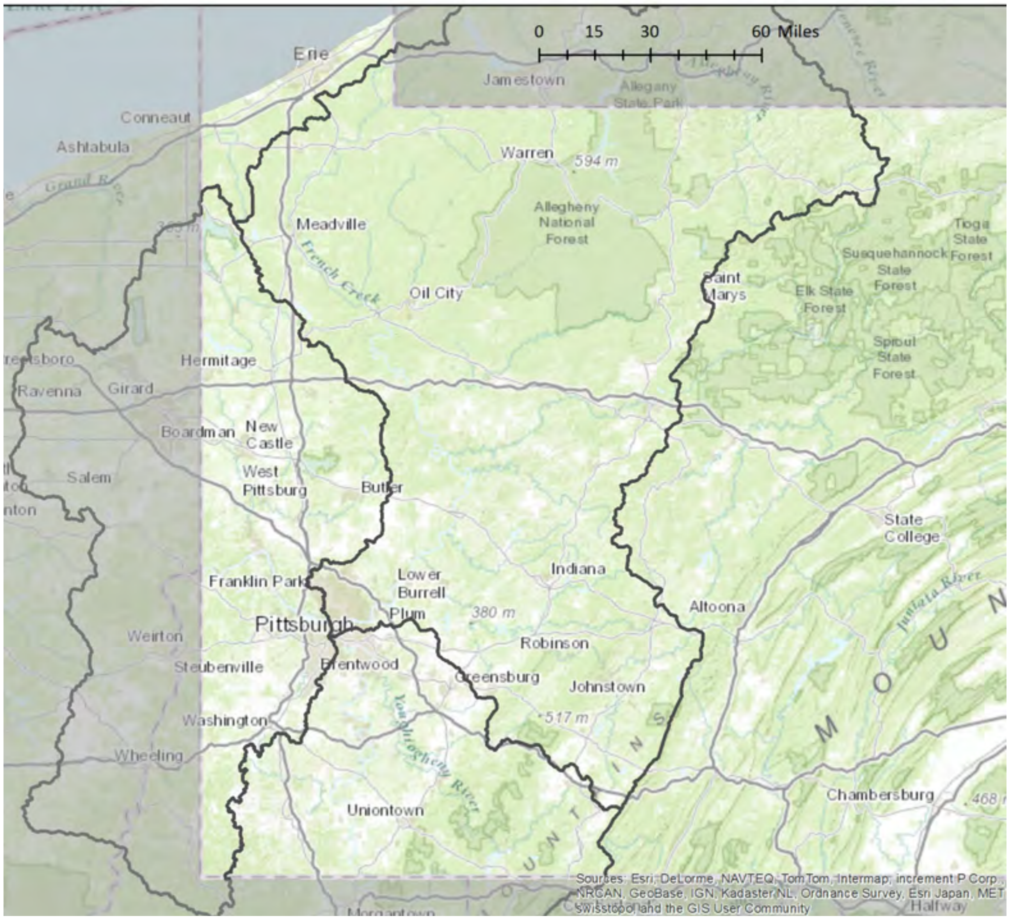
In the eastern United States, physiography, climate and vegetation are the primary variables influencing river processes, particularly hydrology (Cushing et al. 2006).

Hydrologic characteristics vary with basin physiography. Physiographic provinces and sections are areas 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).

The Upper Ohio basin in western Pennsylvania is within the Appalachian Plateau physiographic province, which is characterized by areas of high elevation, mostly unglaciated uplands. There are seven physiographic sections that underlie the project area: the High Plateau, the Deep Valleys, the Glaciated High Plateau, the Northwestern Glaciated Plateau, the Pittsburgh Low Plateau, the Allegheny Mountain and the Waynesburg Hills sections. Relief is highest in the Deep Valley, Allegheny Mountain, Waynesburg Hills and High Plateau sections. Streams and rivers originating in these sections tend to exhibit flashy hydrology due to high local relief and narrow and discontinuous valleys.

Relief is lowest in the Northwestern Glaciated Plateau section, an area modified by several glacial episodes, including the most recent Pleistocene glaciation. Characteristic features include broad valleys, rounded hilltops, moraines and glacial till (Fenneman 1938, Schultz 1999, Sevon 2000). Successive glacial episodes loaded the region with massive deposits of boulders, sand and gravel. Watersheds were transformed by glacial processes resulting in massive changes to drainage pattern and orientation (Harper 1997). French Creek, once part of the Lake Erie watershed, began flowing south to join the Allegheny River watershed. Due to ancestral connections to multiple basins, these glaciated regions support high biodiversity, containing over 80 species of fish and 29 native species of freshwater mussels (Ortmann 1919, Lachner 1956, Bier 1994). Many of the glacial deposits have high calcium content, which is important for buffering water quality and supporting freshwater mussels. Reaches of the Allegheny River flow over glacial outwash as thick as 80 feet; on the mainstem Ohio River, glacial deposits may be as thick as 100 feet (Ventorini 2011).

Underlying geology also influences the distribution and volume of groundwater. Within the Upper Ohio basin, groundwater discharge remains relatively constant throughout the year (Ventorini 2011). Two major aquifers supply groundwater to the Allegheny, Monongahela and Ohio Rivers. The most productive source stores an estimated 4.5 billion gallons of water and is recharged by a combination of precipitation, tributary inflow and high flow events (USACE 2006). This unconfined aquifer is relatively shallow, unconsolidated glaciofluvial sand and gravel and is contained in the three river valleys. The second major aquifer is confined and located beneath the glaciofluvial deposits in sandstone and shale formations (Fleeger 1999).



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, swisstopo, and the GIS User Community

Figure 2.1 Upper Ohio River Basin in Western Pennsylvania

The basin has a temperate climate. Temperatures are lowest in the High Plateau and Allegheny Mountain sections, where they range from an average annual minimum of 9°F to an average maximum of 75°F. These sections are dominated by cool-cold headwaters and creeks. The highest temperatures occur in the southwestern portion of the basin, in the Waynesburg Hills section, where temperatures range from an average annual minimum of 19°F to an average maximum of 84°F. Streams originating in this section are generally characterized as warm water. Across the basin, average annual precipitation ranges from 34 to 53 inches per year.

Changes in forest cover also influenced historic hydrology. In the early 1700s more than 80% of the basin was forested with a mix of deciduous and coniferous species. Today about 65% of the basin remains forested (dominated by deciduous forest) and about 15% is grassland or pasture (PADEP 2009). During periods of low forest cover, evapotranspiration was lower during the growing season, which generally resulted in higher baseflows. Periods of low forest cover are also associated with flashier hydrographs.

2.2 Seasonal Hydrologic Variability

From the headwaters to the mainstem, streamflow magnitude varies seasonally as illustrated in the hydrograph of the Ohio River at Sewickley (Figure 2.2). The lowest baseflows occur from late summer through early fall (July through October). Evapotranspiration rates are highest during these months and precipitation is relatively low compared to the winter and spring seasons. Baseflows are moderate in the winter months and highest during spring, particularly in March and April, when they are close to ten times the magnitude of flows during the late summer and fall. During winter and spring, soils are generally saturated or frozen, resulting in higher run-off ratios during precipitation events.

We reviewed the seasonal variability at 38 minimally-altered gages within the Upper Ohio River basin, and this seasonal pattern is consistent across watershed sizes (Figure 2.3). In all seasons, the magnitude of the monthly median is closely correlated to watershed size. In headwaters, the monthly median is often less than 1 cubic feet per second (cfs) during the summer and fall and 10 cfs during the spring. In watersheds ten times larger, monthly medians are around 100 cfs during the summer and fall and close to 1,000 cfs during spring.

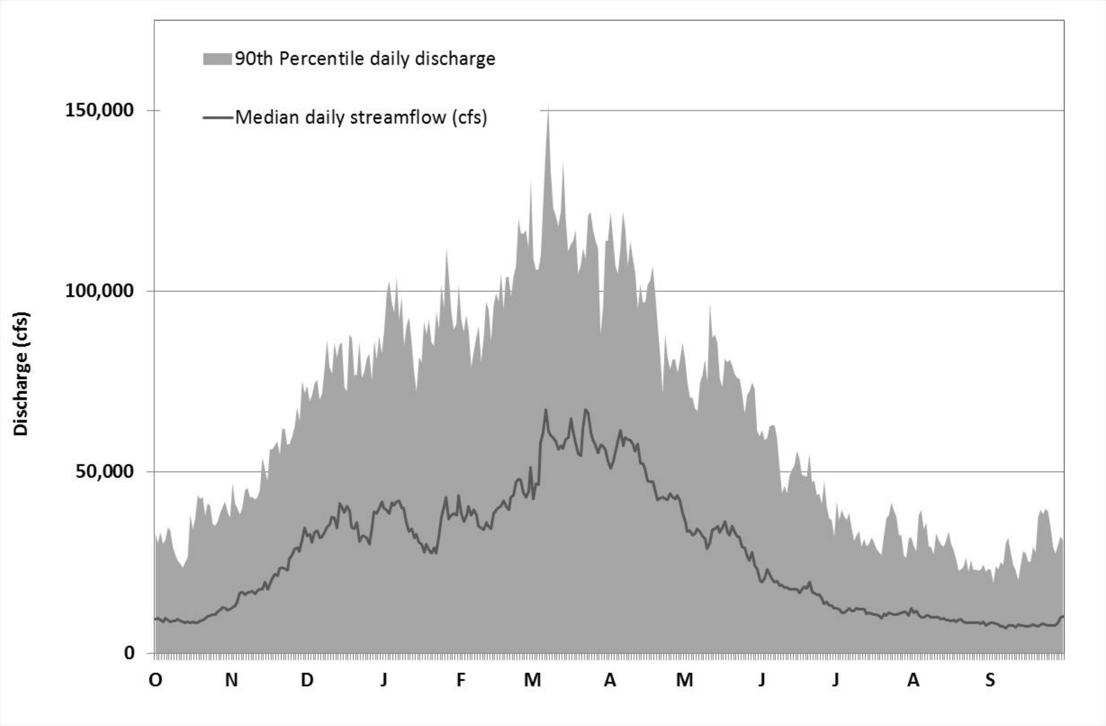


Figure 2.2 Hydrograph of the Ohio River downstream of Pittsburgh at Sewickley, PA (03086000)

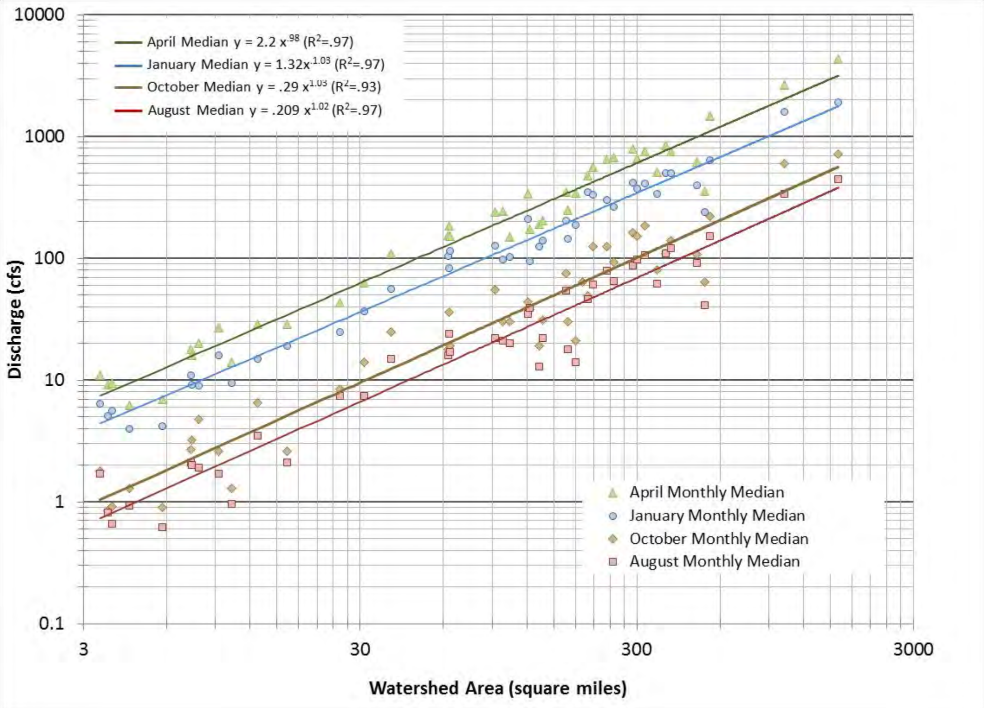


Figure 2.3 Relationship between median monthly (Q50) discharge and watershed area for 38 index gages within the Upper Ohio basin. Statistics were calculated from measured mean daily records for water years 1960-2008 and plotted for fall (October), winter (December), spring (April) and summer (August).

2.3 Flood and Drought History

Seasonal patterns of low summer and fall baseflows, relatively high winter baseflows and high spring baseflows are generally consistent from year to year, but extreme conditions can occur in any season. Hydrologic conditions can vary within years; floods and droughts can occur in the same year. Figure 2.4 illustrates the timing and magnitude of large floods on the Ohio River between 1934 and 2011. The flood of record, known as the Saint Patrick's Day flood of 1936, was estimated to be a 500-year event. The flood peaked at a discharge of 574,000 cfs and 21 feet above flood stage. It was considered the worst natural disaster in western Pennsylvania history and prompted the Flood Control Act of 1936 (Ventorini 2011). In response, over the following decades the USACE constructed 16 flood control projects on several major tributaries, tempering the magnitude of floods in the basin.

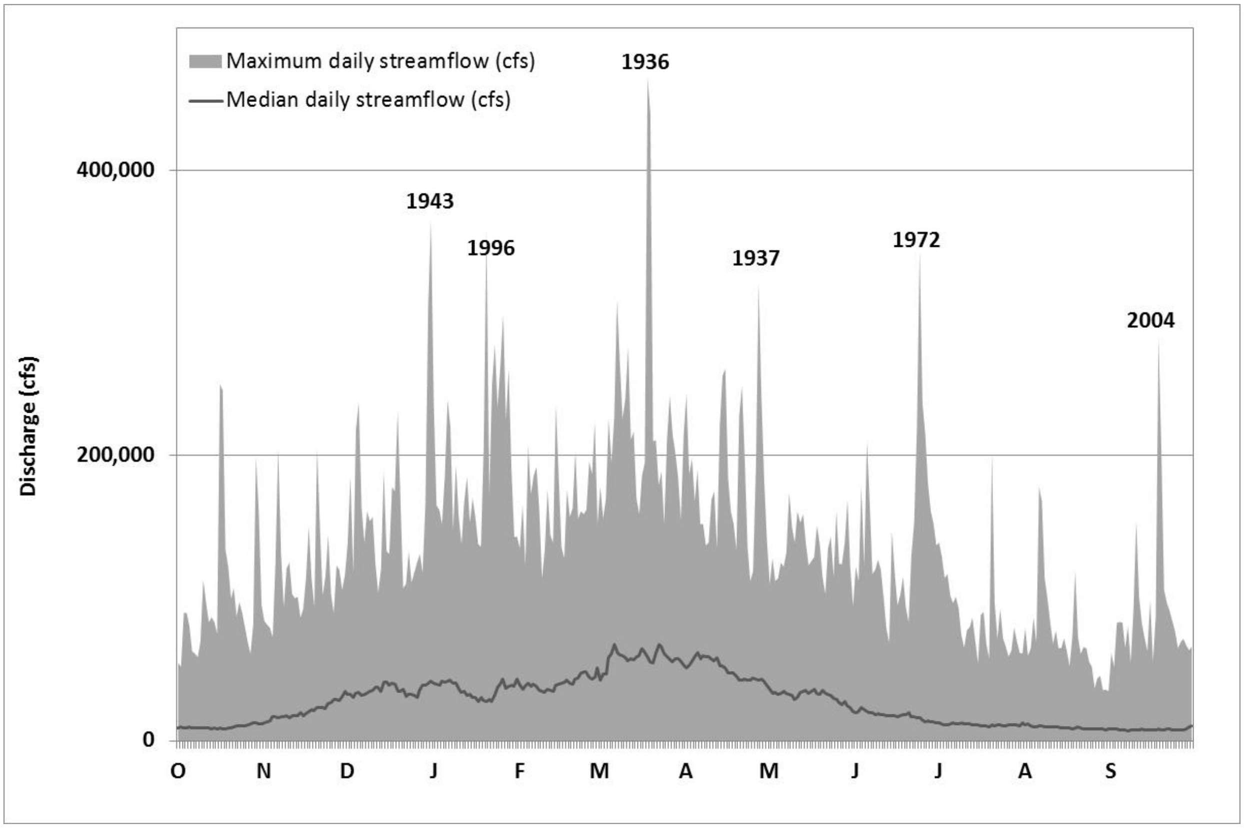


Figure 2.4 Flood events and maximum daily flow on the Ohio River at Sewickley, PA (03086000)

Droughts and subsequent low flow conditions occurred in 1934, 1939, 1957, 1958, 1964, 1988 and 1991 (USGS 2012, PFBC 1993). The lowest flow recorded on the Ohio River at Sewickley was 2,100 cfs on September 4, 1957. Since the mid-1900s, low flow conditions on major tributaries and the mainstem have been augmented by reservoir releases and the operation of navigational locks and dams.

2.4 Historical and Current Impacts to Water Quality

In response to resource extraction, industrial development, land use conversion and associated water quality impacts, many of the basin's flora and fauna have experienced drastic reductions in range and abundance, and in some cases, have been extirpated (Ortmann 1909, Lachner 1956, Yoder and Rankin

2005). In 1909, when Ortmann described biological conditions in the Upper Ohio basin, many tributaries were unfit to support native freshwater fauna (including the Clarion River, Tionesta Creek, Red Bank Creek, Mahoning Creek, Kiskiminetas River and tributaries, and the Monongahela River and most tributaries). In some cases, “life had entirely disappeared” (Ortmann 1909).

Through this period of intense development, some streams maintained adequate aquatic habitat, serving as refuges for the region’s biodiversity. Most notably, the tributaries and mainstem of French Creek harbored more than 80 species of fish, 26 species of freshwater mussels, and 10 species of salamanders in addition to many plants, birds and mammals (PADEP 2009). Tributaries in the Lower Allegheny and Monongahela basins – including Little Mahoning Creek, Ten Mile Creek, Dunkard Creek and Indian Creek – also served as biological refuges (Ortmann 1909). With improvements in water quality over the last few decades, these source populations have begun to recolonize formerly extirpated ranges (Koryak et al. 2011).

Land use conversion and several types of resource extraction – including logging, mining, oil and gas development – have influenced the hydrology and quality of habitat in the region. From the time of settlement, logging was a significant part of the region’s economy with demands driven by shipbuilding timbers, fuel, construction materials and eventually pulp production. America’s first paper mill was established in Pennsylvania in 1690. Timber was harvested and transported downstream by log drives. Conversion and deforestation peaked in the early 1900s; during that time, the region’s forest cover was reduced from an estimated 90 percent to less than 30 percent. Large clearcuts and land clearing resulted in erosion, decreases in bank stability, reduced shading and increases in stream temperatures.

The state’s most expansive and productive bituminous coal and oil and gas formations are located in western Pennsylvania (PADEP 2009). Development of these formations had a significant impact on water quality and ground and surface water hydrology in the basin. This development has also resulted in acid mine drainage (AMD), which is the most common water quality impairment in western Pennsylvania. As water travels through underground mine chambers and over open pit mines and large piles of coal refuse, it weathers pyrite and produces acid, sulfate and iron. The weathering process can increase the acidity of water to a point where it is unsuitable for aquatic life. Acidic water also increases the solubility of metals such as manganese, aluminum and zinc, which are toxic to freshwater fauna.

Coal development has also influenced regional hydrology. Common methods of coal extraction remove large panels of coal seams, often resulting in surface and subsurface subsidence. Surface subsidence can disconnect groundwater from surface water and disrupt groundwater recharge. Disconnection in ground and surface water hydrology has resulted in lower low flows and baseflows in affected watersheds (PADEP 2009).

Located at the confluence of the Allegheny, Monongahela and Ohio rivers, Pittsburgh’s access to markets and products in both the Great Lakes and the Gulf of Mexico was key to the region’s success during the industrial revolution. Iron, steel, and eventually aluminum mills flourished throughout the 19th and 20th centuries. At its peak, Pittsburgh produced more than one quarter of all steel made in the world (PADEP 2009). Significant volumes of untreated industrial waste were discharged to the mainstem for more than a hundred years. Pittsburgh’s industrial history also influenced population growth and land development throughout the region. Thousands of acres were developed along river banks and urban development sprawled from the city center. Sewage was also discharged directly to the three rivers. During the late 19th and early 20th centuries Pittsburgh had the highest rate of typhoid fever mortality of any U.S. city, largely due to contaminated drinking water (Tarr 2004).

In an effort to restore water quality in the Ohio River and its major tributaries, the Ohio River Valley Water Sanitation Commission (ORSANCO) was established in 1948 and ORSANCO began implementing water quality remediation and monitoring programs. In the early 1970s, state and federal water pollution control legislation and the federal Surface Mining Control and Reclamation Act (1977) were enacted, improving regulation of industrial waste discharge. ORSANCO began conducting extensive fish surveys to track changes in water quality and associated changes to aquatic life. In a recent summary of trends, ORSANCO reported that water quality and overall fish community health have improved over the last 40 years. The percent of pollution tolerant individuals has decreased, and native and intolerant species have increased (Thomas and Emery 2005, ORSANCO 2012).

Regional water quality monitoring is currently coordinated between state and federal agencies including Pennsylvania DEP, USACE Pittsburgh District, U.S. EPA Region 3, U.S. Geological Survey (USGS) and ORSANCO. Although water quality and aquatic habitat conditions have greatly improved, mining, shale gas drilling, industrial discharges, combined sewer overflows (CSOs) and emerging contaminants continue to threaten the condition, connectivity and recovery potential of the freshwater ecosystem.

Plans to restore AMD-impaired streams have been and are in the process of being developed as required by the Clean Water Act. These plans define pollution limits for a watershed (Total Maximum Daily Loads, or TMDLs) and identify ways to reduce pollutant discharges to meet those limits. Watersheds including the Clarion and Conemaugh have more AMD-impaired stream miles than any other watersheds in the Upper Ohio basin (PADEP 2009). Within the Conemaugh there are more than 300 surface mines, 170 coal refuse dumps and 200 miles of underground mines. In 2005 and 2006, TMDLs were established for the Conemaugh, Blacklick Creek, Stoney Creek and Little Conemaugh to address aquatic life impairments caused by aluminum, iron and manganese. The 2005 and 2006 TMDLs identified best management practices including treatment systems, plugging abandoned wells and creating wetlands that receive and buffer treated wastewaters before they enter surface waters (PADEP 2009).

The mainstem Ohio River from Pittsburgh to West Virginia line, lower portions of the Allegheny and lower portions of Monongahela are also impaired, not meeting the designated uses of fish consumption and recreation. Fish contain high concentrations of legacy pollutants including PCBs and chlordane. Even during modest high flow events, CSOs discharge untreated sewage to the river. Pennsylvania has the highest number of CSO outlets in the U.S.; half of these discharges are located in southwestern Pennsylvania (Regional Water Management Task Force 2010). Many streams in Allegheny County, including Chartiers Creek, Saw Mill Run and Turtle Creek, do not meet water quality standards because of this impairment.

Recent technology has led to significant expansion of unconventional gas development. The Pennsylvania portion of the Marcellus Shale formation has experienced more drilling than any other area within the gas play. The number of unconventional wells drilled in the state increased from 22 in 2004 to 6,247 in 2012 (PADEP 2013). Currently, there are more than 11,000 shale gas wells permitted in

Pennsylvania (PADEP 2009). Impacts to stream ecosystems can be described in terms of three pathways (1) changes in hydrology associated with water withdrawals; (2) elevated sediment inputs and loss of connectivity associated with pads, roads, pipelines and other infrastructure; and (3) water contamination from introduced chemicals or wastewater (Entrekin et al. 2011, Rahm and Riha 2012, Weltman-Fahs and Taylor 2013).

Two to seven million gallons of water are needed per hydraulic fracturing event. A single well can be fractured several times over its lifespan. In Pennsylvania, water is typically withdrawn directly from streams, although groundwater may also be used. The individual and cumulative effects of multiple surface and groundwater withdrawals have the potential to reduce stream habitat quality, change species composition and increase stream temperatures.

The design, construction and maintenance of infrastructure associated with unconventional gas development can increase sediment delivery to streams and create barriers within the channel. Construction of well pads, roads and pipelines can mobilize from tens to hundreds of metric tons of soil per hectare (Adams et al. 2011). Entrekin et al. (2011) found that the density of wells pads and roads was positively correlated with fine sediment accumulation in streams. In addition to increasing fine sediment, roads or pipelines that cross streams can create physical barriers, impacting species richness and potentially leading to local population extinction (Letcher et al. 2007, Nislow et al. 2011).

Leaching or overflow of wastewater from holding ponds and spills of hydraulic fracturing fluids can affect ground and surface water chemistry and habitat suitability (Rahm and Riha 2012). More than 300 constituents are used in the fracturing fluid, mobilized during fracturing and/or found in wastewater associated with hydraulic fracturing. Of those, only a couple of dozen have aquatic life and human health criteria defined based on known health and ecological risks; the remainder have unknown risks. Known ecological risks and health effects have been measured in fish, amphibians, birds and mammals and include genetic mutations, metabolic failure, reproductive failure, muscular paralysis and inhibited growth (EPA 2011).

2.5 Water Use and Water Resource Management

Stream and river flows within the Upper Ohio River basin are affected by dams operated for navigation, flood control, and hydropower. Water withdrawals and discharges also affect streamflow patterns, especially during low flow conditions. Multiple state, federal, and interstate agencies have jurisdictions related to the management of water resources, water quality protection and pollution reduction, and the species within the basin.

The lower 72 miles of the Allegheny River are impounded and regulated by eight fixed-crest, low-head, run-of-river navigation dams. The entire 128 miles of the Monongahela in Pennsylvania and West Virginia are impounded and regulated by nine run-of-river navigation dams. There are three navigation dams on the Ohio River in Pennsylvania – Emsworth, Dashields, and Montgomery. Emsworth Lock & Dam averages nearly 550 commercial lockages every month and an additional 350-400 recreational lockages during summer (PADEP 2009). The USACE Pittsburgh District is responsible for maintaining a minimum 9-foot deep navigation channel in the pools created by these 20 dams. Pools are periodically dredged to meet the minimum depth required for navigation.

Navigation dams reduce the natural velocity immediately upriver and trap sediments that would otherwise flow downstream. They also affect water quality in the pools – due to attachment of phosphorous to fine sediment, trapping of contaminants, and high biological oxygen demand, which decreases dissolved oxygen (Ventorini 2011, ORSANCO 2012). The river is more stream-like at the tailwaters of a dam, and these areas often provide suitable habitat for some species of fish and mussels (Ventorini 2011, Smith and Meyer 2010).

Navigation dams have altered hydrology in ways that have impacted ecological functions of riverine and riparian habitat. Effects include (a) loss of numerous islands, shallow sand and gravel bars, cobble riffles, channel wetlands; (b) elevated water tables; and (c) loss of contiguity with riparian habitat, including loss of floodplains and backchannels, and alteration of native floodplain plant communities. Navigation dams have little effect on high flow conditions (Ventorini 2011).

USACE also maintains 16 flood control projects within the upper Ohio River basin. These dams and impoundments were primarily constructed to retain runoff following precipitation events and to release water slowly to prevent or reduce downstream flooding. Other project purposes include water supply, recreation, water quality maintenance, hydropower generation. The drainage areas upstream of these 16 projects range from 46 to 2180 square miles. Approximately 80% of volume is released for water quality purposes.

Multiple hydroelectric dams are located the Allegheny River, Beaver River, Conemaugh River and Youghiogheny River. Kinzua Dam and Youghigheny River Lakes are two of the larger facilities. Several USACE dams and impoundments provide hydropower, including Conemaugh Lake, Kinzua Dam, Youghiogheny River Lake, and Allegheny River Locks & Dams 5, 6, 8, and 9.

According to recent estimates, the Upper Ohio basin in western Pennsylvania supplies more than three million people with water for drinking and for industrial and commercial uses (PADEP 2009). An estimated 2.4 billion gallons of water is withdrawn each day in the basin (Table 2.1).

Table 2.1 Estimated water withdrawals and uses in the Upper Ohio basin (PADEP 2009)

Subbasin	Total gallons withdrawn per day (in million gallons)	Public water supply	Thermoelectric	Industry	Agriculture	Mining and commercial
Upper Allegheny	67	46%	2%	20%	25%	7%
Central Allegheny	213	8%	83%	8%	-	1%
Lower Allegheny	575	18%	79%	1%	-	2%
Monongahela	942	11%	61%	28%	-	-
Ohio	623	16%	45%	38%	-	1%

The most densely populated regions of the basin are served by public water suppliers; these include Pittsburgh and surrounding communities, New Castle, Washington, Butler, Johnstown, Meadville and other municipal water systems with centralized distribution. Sparsely populated areas are not included in the public supply service areas. Groundwater is largely used in rural areas, especially in the Allegheny and Ohio River valleys, which contain large sand and gravel aquifers (PADEP 2009).

The USACE, US Fish & Wildlife Service (USFWS), USGS, ORSANCO, Pennsylvania DEP, and PFBC are the agencies that are primarily responsible for the research, monitoring, and management of water quantity and quality in the basin. These agencies also have the most interest in instream flow management and ecologically-based standard setting.

ORSANCO is an interstate commission representing eight states (Illinois, Indiana, Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia) and the federal government. ORSANCO operates programs to improve water quality in the Ohio River and its tributaries, including setting discharge standards; developing water quality criteria to protect desired uses; performing biological assessments; monitoring for chemical and physical properties of waterways; and conducting special surveys and studies. Although ORSANCO has played a very limited role in management of water quantity, they are currently exploring whether they have a role to play in water quantity management, including but not limited to hydrologic modeling, basin-scale planning, and coordination among states (S. Dinkins, personal communication, 2012).

Pennsylvania DEP is responsible for protecting and preserving land, air, water, and energy resources through enforcement of Pennsylvania's environmental laws. DEP administers environmental permitting and enforcement programs, monitors surface and ground water quality and conducts biological assessment. Pennsylvania DEP administers the program to designate special protection waters according to guidelines listed in Pennsylvania Code Title 25, Chapter 93 Water Quality Standards: High Quality (HQ) and Exceptional Value (EV). HQ waters are designated based on the water chemistry and the presence of a high quality aquatic community. Approximately 323 streams or stream sections are designated as HQ throughout this region. EV waters are designated based on water quality and are waters of substantial recreational or ecological significance. There are approximately 55 streams or stream sections designated as EV in the region (PADEP 2009).

Pennsylvania DEP regulates the withdrawal of surface water by Public Water Suppliers under the Water Rights Act and water sources (both surface and groundwater) used by the natural gas industry under the Oil and Gas Act (Chapter 78) and the Clean Streams Law. When issuing approval for water withdrawals in the Ohio basin, DEP currently relies on the Pennsylvania Maryland Instream Flow Study (for trout streams, where applicable), and SRBC's 2003 passby guidance. DEP's primary interest in this current study is to improve upon this basis with a study to define the ecological flow needs of the Ohio River basin. DEP's intent is to use the recommendations developed through this process to inform the application of current regulations and to move toward the development of a statewide instream flow policy supportive of ecological integrity.

Unlike the Delaware and Susquehanna River basins, the Ohio River basin does not have an interstate compact agency that regulates water withdrawals.

PFBC is an independent state agency supported, in part, by fishing license and boating registration fees, federal grants, and royalties collected from commercial sand and gravel dredging operations. It does not receive tax revenues or funding from the Pennsylvania General Fund. PFBC has the jurisdictional authority to ensure the protection, propagation, and distribution of species classified as game fish, nongame fish, bait fish, fish bait, reptiles, amphibians, mussels, other aquatic invertebrates, and all aquatic organisms including plants. PFBC is responsible for water quality protection, habitat enhancement, management to protect naturally reproducing stocks, providing cultured fish for recreational angling, and angling regulations and law enforcement (Ventorini 2011). Approximately 62 waters in the Ohio Region are designated by the Pennsylvania Fish and Boat Commission as Class A Wild Trout Waters. These waters support a population of naturally-produced trout; these streams are not stocked. Class A Wild Trout Waters include wild brook trout, wild brown trout, mixed wild brook/brown and wild rainbow trout. The majority of the wild trout waters are brook trout fisheries; brown trout waters are second largest (PADEP 2009).

Additional Federal Land and Water Designations within the Upper Ohio River Basin

- The only national forest in Pennsylvania – **the Allegheny National Forest** – is within the Upper Ohio basin in Warren, McKean, Forest and Elk counties.
- Three reaches totaling 86.6 miles of the **Upper Allegheny River is designated as a Recreational River** under the National Wild and Scenic Rivers Act.
- The **Allegheny Islands Wilderness** is the smallest unit in the entire federal Wilderness System.
- Of the 22 islands that are partly or wholly within the **Ohio River Islands National Wildlife Refuge**, two are in Pennsylvania. USFWS also protects and restores floodplain habitat within the refuge.
- USFWS also has jurisdictional authority over **federally listed mussel species** in the Allegheny River.

2.6 Major Habitat Types

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

We used the following questions to frame the definition of major habitat types:

> *What hydroecological settings exist within the project area and what are the hydrological and biological characteristics of each setting (type)?*
>
> *Which existing sources of spatial data can be used to represent these types?*

We defined major habitat types based primarily on drainage area, temperature, glacial influence and influences of management, specifically navigation. These variables are known to influence both hydrological and biological characteristics (Figure 2.5). White boxes include the variables used to define each type; types are contained within each blue box.

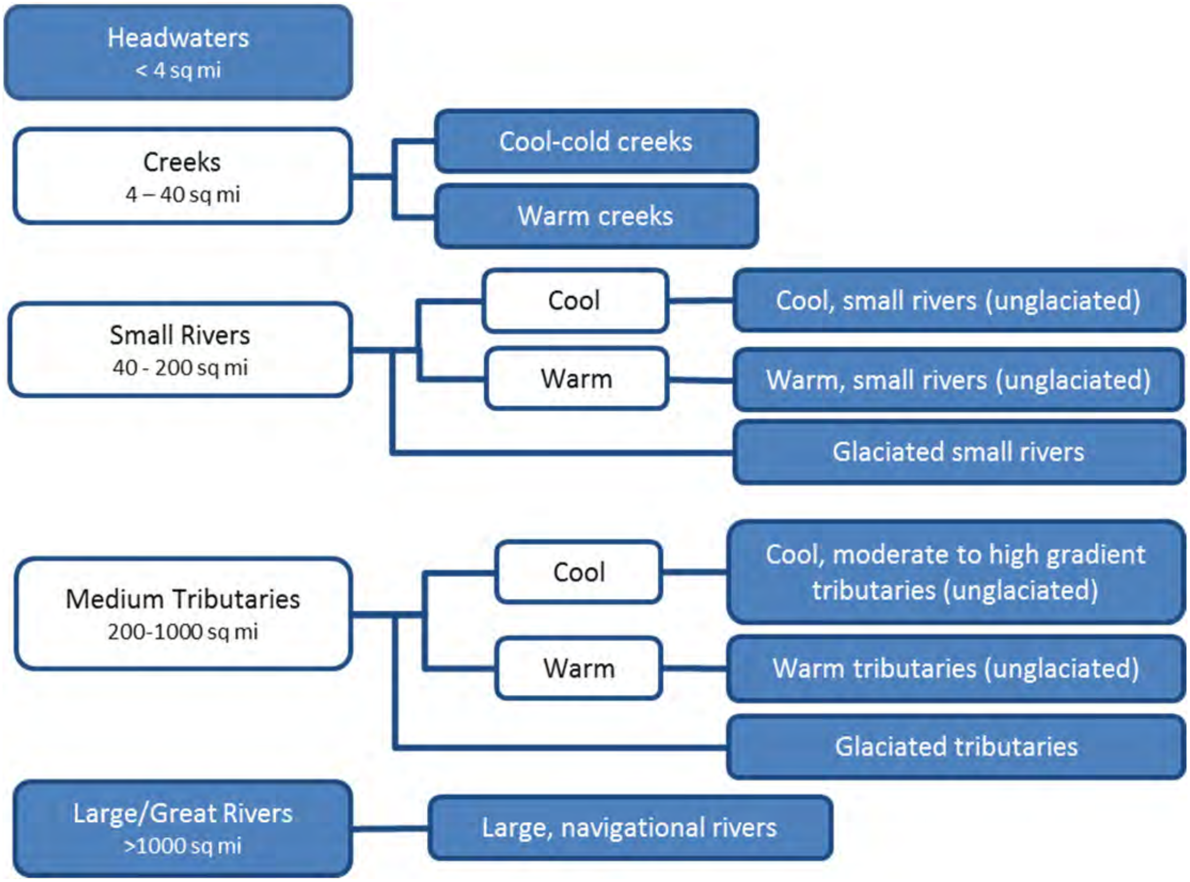


Figure 2.5 Eleven major habitat types for the Upper Ohio River in western Pennsylvania

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

In the Northeast Aquatic Habitat Classification System (NAHCS), thresholds for size classes were evaluated by analyzing distributions of freshwater species across size classes. Various size class breaks were tested using cluster analysis on a regional database of fish, mussels, snails, amphibians, and aquatic insect species. The results highlight large differences between rivers with drainage areas less than 200 square miles (mi^2) and those greater than 200 mi^2 (Olivero and Anderson 2008). Also as part of the development of the NAHCS, a separate analysis used fish data and measures of classification strength to test potential size breaks in the Atlantic and Ohio basins in Pennsylvania. The following size classes had relatively high classification strength for fish communities in both the Ohio-Great Lakes and the Atlantic basins: 0-29 mi^2, 30-199 mi^2, 200-999 mi^2, 1000-6999 mi^2, 7000+ mi^2 (Walsh et al. 2007). Based on these two results, we incorporated size breaks at 200 and 1000 mi^2into the classification. We also used a break at 40 sq mi to represent a creek setting (rounded up from 38 mi^2used in the NACHS and slightly larger than the 30 mi^2 drainage area break in the Pennsylvania analysis). We combined all rivers greater than 1000 mi^2 into one class.

Streams at the small end of the range of the smallest size class (0-40 mi^2 in the NAHCS classification) differ both hydrologically and biologically from larger streams within the same class. Based on workshop input, literature on characteristics and function of headwater streams and concern that flow recommendations that may be sufficient for larger streams may fail to protect hydrological conditions, biota and ecological processes associated with very headwater streams, we defined a headwaters class for drainage areas < 4 mi^2. These streams are likely to be more sensitive to hydrologic changes than larger streams.

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

Headwaters (< 4 mi^2)

- May be ephemeral or intermittent ("zero" flow days may occur in dry seasons and years)
- Stream channels are often poorly defined
- Stream network is highly dynamic and expands and contracts with precipitation
- Include macroinvertebrate species that are characteristic of headwater streams and seldom found in larger streams
- Amphibians may be top predator. If fish are present, the species and life stages are likely to feed on insects and alga, rather than being piscivorous
- Withdrawals may impact all parts of the flow regime and could increase intermittent conditions
- Increased intermittent conditions may affect processing of organic material and delivery to downstream network
- Streamflow estimates have high uncertainty
- Headwaters are not further subdivided by temperature or other characteristics

Creeks (4-40 mi^2)

- Typically perennial conditions
- Stream channels are usually well defined
- Fish are typically top predator
- Few mussels
- Species in bedrock reaches may be sensitive to drought conditions and flow depletion due to lack of hyporheic zones
- Withdrawals could lead to flow depletion in dry seasons/years

- Streamflow estimates may have high uncertainty during low flow conditions

Small Rivers (40-200 mi²)

- Perennial conditions
- Stream channels are well defined and have higher morphological complexity than smaller streams
- Higher fish and mussel diversity
- Some floodplain development
- Flow likely to be sufficient to support water withdrawal proportional to streamflow

Medium Tributaries (200-1000 mi²)

- Perennial conditions
- High fish and mussel diversity
- Stream channels are complex and may include complex margins, islands and backwater habitats
- Floodplains are more expansive than on smaller-sized rivers
- Some influence by flood control and hydropower operations
- Flow likely to be sufficient to support water withdrawal proportional to streamflow

Large/Great Rivers (> 1000 mi²)

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

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

Glaciation. Glacial history influences groundwater contributions, and therefore temperature and flow stability, channel hydraulics, and valley form. In the Upper Ohio basin, it is also one of the primary drivers of species distribution (Hocutt et al. 1986, Ventorini 2011). Within the project area, the extent of glaciation also coincides with the distribution of some of the species considered in this study.

Navigation. In general, we did not classify streams and rivers using variables that reflect condition or anthropogenic influences (e.g., impaired, effluent dominated, tailwaters) because (a) we prefer to consider these as modified examples of one of the other habitat types because it enables us to incorporate some baseline expectation of biological conditions; (b) there is insufficient information within the basin to support separate flow recommendations for these systems as a class; and (c) in general, these reaches would require more site-specific considerations and are not well addressed by general recommendations. However, we made an exception for navigation. These reaches are consistently modified in several ways: presence of lentic fish species that would not otherwise be present; maintenance of a standing pool level, which alters the low flow range; and changes to distribution of mussels and other aquatic organisms (e.g. mussels that would otherwise be present throughout the reach are only present near the lock) (Smith and Meyer 2010). Within the Upper Ohio basin, the following rivers were considered large navigational rivers: entire Ohio River (from the West Virginia border to the confluence of the Allegheny and Monongahela Rivers); the Allegheny River from the confluence with the Monongahela upstream to river mile 72; and the Monongahela from the confluence with the Allegheny River upstream to the West Virginia border (and continuing to Opekiska Lock and Dam at river mile 115.4).

To assign habitat types to stream reaches, we combined information from several existing classifications, including a regional aquatic biophysical classification (NAHCS) (Olivero and Anderson 2008); state water quality classification and designated uses; and the Pennsylvania Aquatic Community Classification (Walsh et al. 2007).

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

3.1 Flow Components

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

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

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

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

Seasonal flows. Seasonal flows provide habitat for spring, summer, and fall spawning fishes; ensure that eggs in nests, redds, and various substrates are wetted; provide overwinter habitat and prevent formation of anchor ice; maintain bank habitat for nesting mammals; and maintain a range of persistent habitat types. Naturally-occurring variability within seasons helps maintain a variety of habitats and provides conditions suitable for multiple species and life stages.

Seasonal flows – often represented by median daily and monthly flows – are correlated with area and persistence of critical fish habitat, juvenile abundance and year-class strength, juvenile and adult

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

growth, and overwinter survival. In summer, fall, and winter, studies in other rivers have shown that decreases in median monthly flow correspond to reduced macroinvertebrate density and richness, reduction of sensitive taxa, increase in tolerant taxa, and decrease in mussel density. Many studies cited tie ecological response to change in median monthly flows in a specific month or throughout a season.

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

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

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

3.2 Flow Statistics

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

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

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

Defining Flow Components

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

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

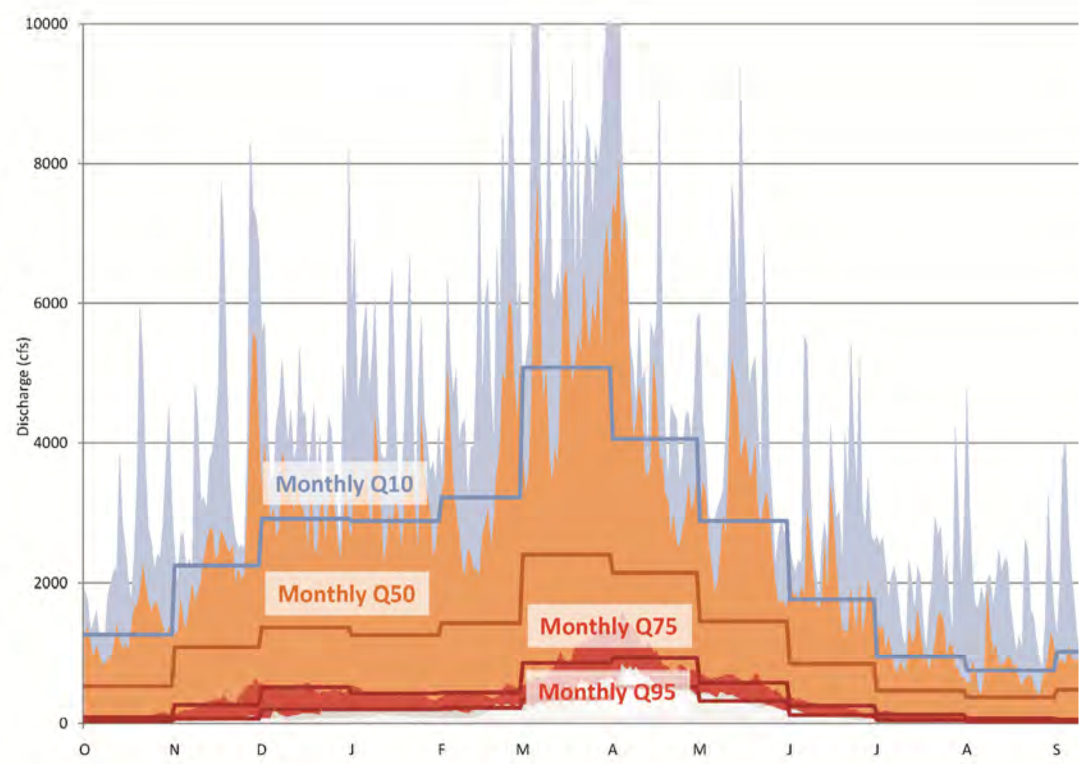

Table 3.2 Flow statistics used to track changes to high, seasonal, and low flow components

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

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

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

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

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

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

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

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

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

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

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

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

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

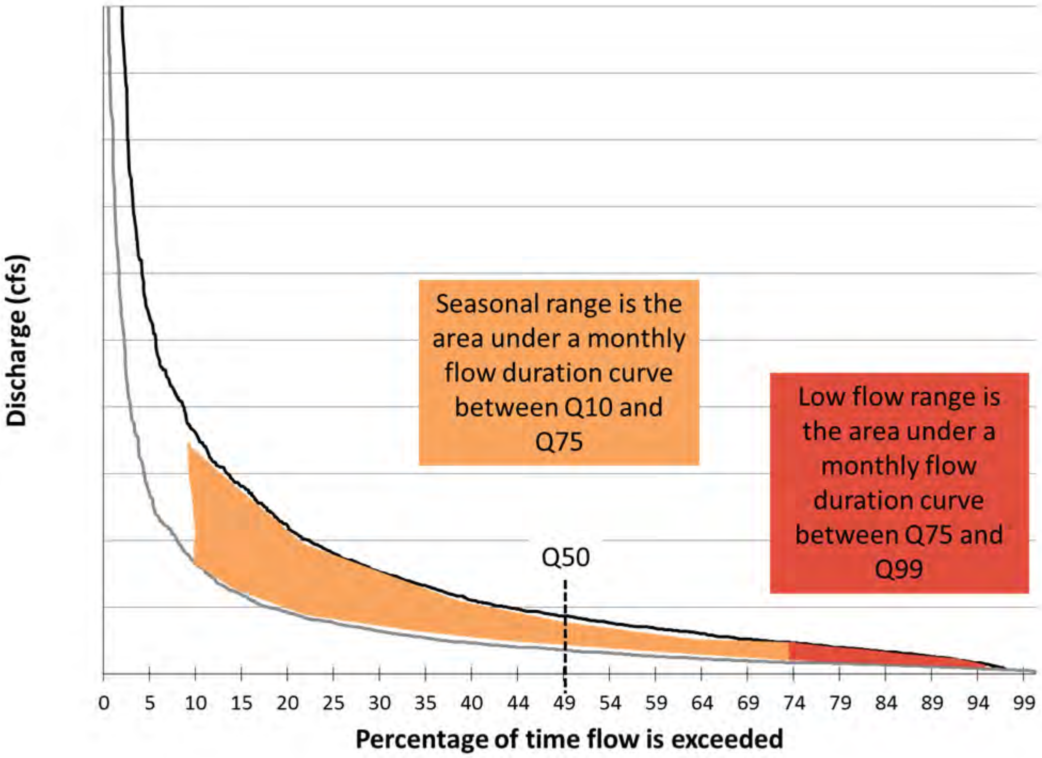


Figure 3.1 Seasonal range and monthly low flow range statistics. The black line represents unregulated conditions and the gray line represents regulated conditions. The colored area represents the difference in area between portions of the two curves.

Calculating Flow Statistics

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

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

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

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

3.3 Hydrologic Characteristics of Major Habitat Types

We used flow data from 38 index gages within the Upper Ohio basin to characterize the range of long-term monthly exceedence values within major habitat types. An index gage is a USGS stream gage where flows are not significantly affected by upstream regulation, diversions, mining, or development and therefore reflects minimally-altered hydrologic conditions. The 38 index gages encompass all stream and river types. For this analysis, we combined all types within each size class in order to increase the number of gages used to characterize each stream class.

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

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

Headwaters (< 4 mi^2) and creeks (< 40 mi^2)

- Compared to larger streams, magnitude of flows in headwaters and creeks is relatively low throughout the year.
- In summer and fall, 89% of median monthly flows are less than 10 cfs; 100% are less than 50 cfs.
- In winter and spring, 39% of median monthly flows are less than 10 cfs; 96% are less than 50 cfs.
- In headwaters, all monthly medians in the summer and fall are less than 5 cfs and often less than 1 cfs between July and October. This is within the range of gage measurement error.
- In summer and fall, 98% of monthly Q75 values are less than 10 cfs; 100% are less than 50 cfs.
- In winter and spring, 70% of monthly Q75 values are less than 10 cfs; 100% are less than 50 cfs.

Small rivers (40-200 mi^2)

- Monthly median flows range from a low of 11 cfs in fall to almost 500 cfs in spring.
- In summer and fall, 71% of median monthly flows are less than 50 cfs.
- In winter and spring, 100% of median monthly flows are greater than 50 cfs
- In summer and fall 54% of monthly Q90 values are less than 10 cfs; 99% are less than 50 cfs.
- In winter and spring, 45% of monthly Q90 values are less than 50 cfs.

Medium tributaries (> 200 mi^2) and large rivers (>1000 mi^2)

- Monthly Q50 ranges widely from 57 cfs in the fall to more than 4300 cfs in the spring.
- Monthly median flows are greater than 50 cfs in all seasons.

- In summer and fall, 38% of monthly Q90 values are less than 50 cfs.
- Low flows in the winter and spring are 5 to 10 times greater than the summer and fall. In winter and spring, 100% of monthly Q90 values are greater than 50 cfs.

Baseline Streamflow Estimator (BaSE)

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

The BaSE tool and accompanying report documenting the methods is available online http://pubs.usgs.gov/sir/2012/5142/.

BaSE was funded by Pennsylvania DEP and USGS provided cost-share as match. It was modeled after the Sustainable Yield Estimator developed for Massachusetts (Archfield et al. 2010). A similar tool is also being developed for New York.

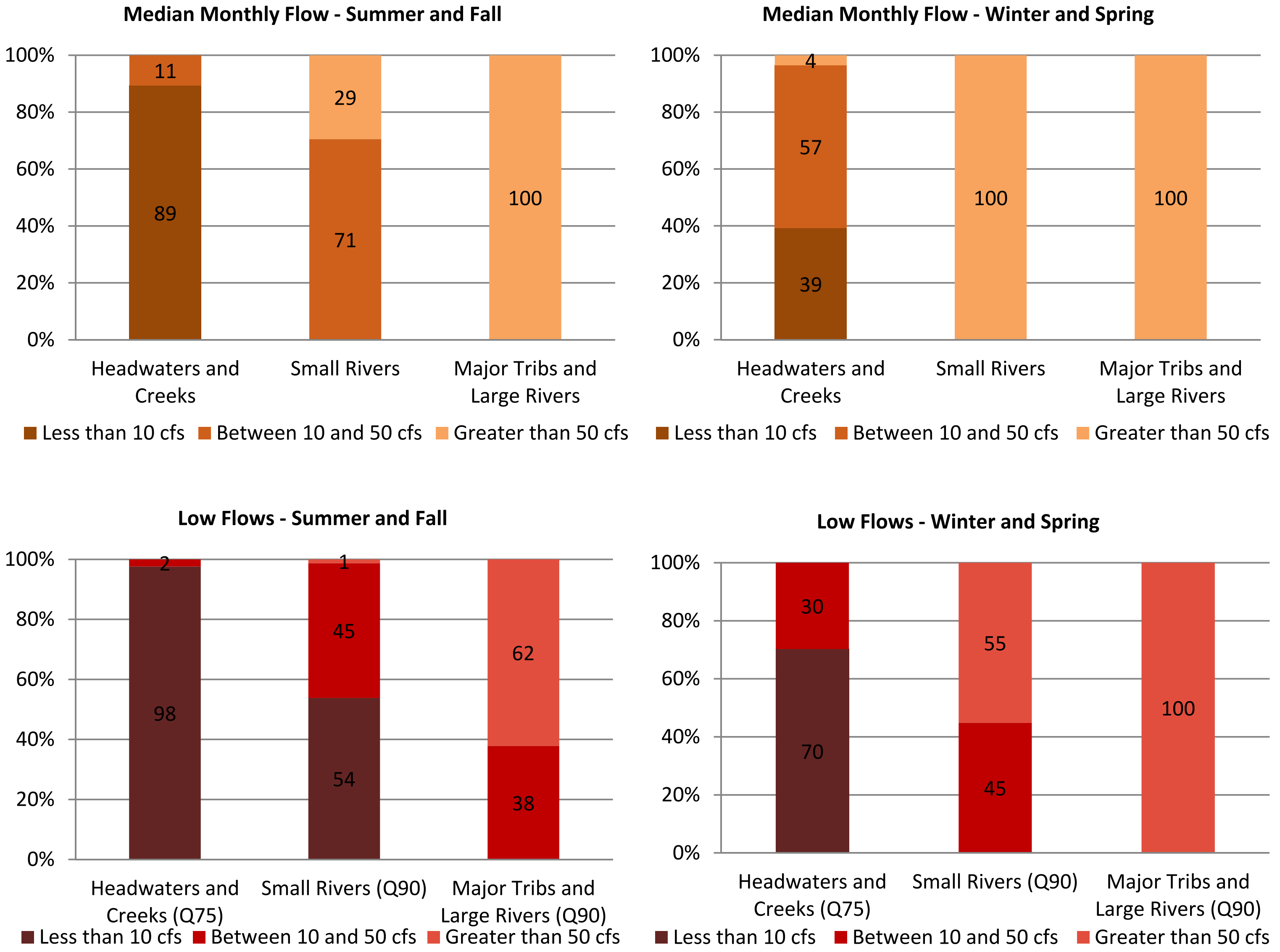


Figure 3.2 Distribution of monthly median and low flow statistics in each season based on index gages in the Upper Ohio River basin

Section 4: Defining Ecosystem Flow Needs

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

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

We identified 23 groups of species – including fish, mussels, aquatic insects, reptiles, amphibians, birds, mammals, and vegetation – that are expected to be sensitive to changes in the flow regime.

We identified 23 groups comprised of over 100 species to represent the characteristic biological communities of the Upper Ohio River basin. We summarized critical life history stages and timing for species within each group and used species distribution data to associate groups with habitat types (Cooper 1983, Merit 1987, Brauning 1992, Hulse 2000, Walsh et al. 2007, Zimmerman and Podniesinski 2008).

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

Expert input helped us state approximately 80 flow-ecology hypotheses that describe how specific taxa and ecological processes are expected to respond to changes to the flow regime. We aggregated related hypotheses by timing, flow-sensitive life stages and ecosystem function into a set of 20 flow needs that combine one or more responses of a group of taxa to a change in flow conditions.

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

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

- **Appendix 5. Flow needs figures** summarize the flow needs in each season and indicate whether these needs are related to high, seasonal, or low flow components.

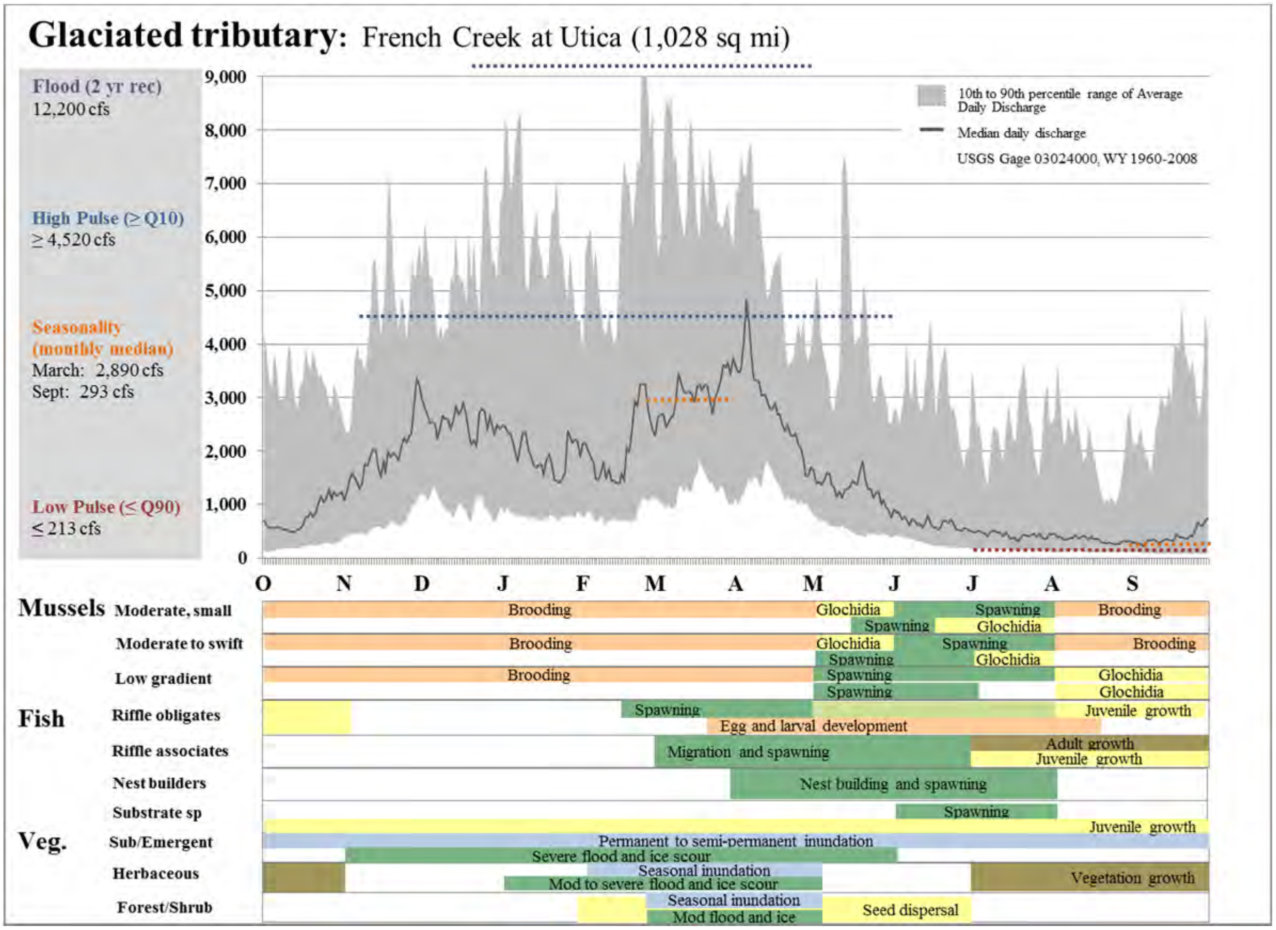


Figure 4.1 Example flow-ecology diagram for a warm glaciated tributary

4.1 Fish

In the early 1800s more than 100 fish species were documented from collections in the Ohio River basin (Rafinesque 1820). Industrial development and land conversion degraded aquatic habitats and resulted in extirpation of more than a dozen native species (Cooper 1983). In recent decades, water quality and habitat improvements made possible reintroduction programs for paddlefish (*Polyodon spathula*) and other species. Some species thought to be extirpated from portions of the basin – such as river darter (*Percina shumardi*), gilt darter (*Percina evides*) silver redhorse (*Moxostoma anisurum*) and smallmouth buffalo (*Ictiobus bubalus*) – have returned to formerly-occupied habitats (Freedman et al. 2009, Koryak et al. 2009).

Despite past impacts to fish assemblages, the Upper Ohio River basin sustains the highest fish diversity of any basin in Pennsylvania, represented by 22 families and more than 120 species (native and introduced) (Cooper 1983, Hendricks et al. 1983, Carlson and Eaton 1999, Argent et al. 2000). These species represent diverse life strategies and range in body size from two inches to four feet. We use regional data, reports and expert input to organize fish into eight groups representing 39 species (Cooper 1983, Argent 2000). Traits include body size, fecundity, home range, habitat associations, feeding habits and flow-velocity tolerances (Table 4. 1) (Cooper 1983, Winemiller and Rose 1992, Jenkins and Burkhead 1993, Vadas and Orth 2000, Frimpong and Angermeier 2009, Mims and Olden 2012).

Table 4.1 Fish groups in the Upper Ohio basin and shared life history traits

Group *example species*	**Life history traits**
Cold/cool fishes *mottled sculpin, brook and brown trout, burbot*	• thermal tolerance limits distribution to cool and cold habitats • sensitive to decreases in dissolved oxygen or increases in turbidity • across group, spawning occurs in all seasons
Slow moving, spring fed fishes *northern redbelly dace, pearl dace, johnny darter*	• occur in small systems (headwater seeps to small rivers) • rely on groundwater contribution to maintain flowing surface waters • small home-range makes them sensitive to localized extreme conditions
Riffle obligates *longnose dace, madtoms, darters*	• occur in all river types • require moderate to fast velocity habitats with coarse substrates • small home-range makes them sensitive to localized extreme conditions
Substrate specialists *eastern sand darter, juvenile lamprey*	• specific substrate required for successful reproduction and adult growth • locally abundant where habitat conditions persist, but regionally rare
Riffle associates *white sucker, northern hogsucker, smallmouth buffalo, redhorses*	• occur in all river types • require connectivity during spring to between overwinter habitats and upstream spawning riffles • upstream migration cued by temperature and rising water levels • most prefer clear water streams
Nest builders *river chub, spotted bass*	• sensitive to flow conditions during spring and summer nest building • most require maintenance coarse substrate for nest building
Migratory residents *lamprey, sauger, walleye*	• spring spawners requiring connectivity between tributary and small river habitats during upstream spawning migrations • medium body size requiring moderately deep habitats, particularly during overwinter period
Great river fishes *paddlefish, longnose gar, skipjack herring*	• occur in tributaries and large rivers • spring spawners with migration typically cued by temperature and rising water levels • require connectivity to floodplain and backwater habitats as well as to upstream tributaries • long-lived, large-bodied, pelagic feeders requiring maintenance of deep, open waters

Key flow-related needs for Upper Ohio basin fish

Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes

- During low flow seasons, a decrease in magnitude may result in downstream migration of headwater fishes, compressing species and thermal gradients
- Groundwater contributions support thermal buffers and provide refugia during summer and winter months
- Extreme low flows reduce availability of persistent, high velocity habitats and may decrease access to and abundance of food; species with small home ranges would be particularly sensitive

Maintain fall salmonid spawning habitat and promote egg, larval and juvenile development (brook and brown trout)

- Seasonal flows maintain sediment distribution for redd construction and maintenance
- Groundwater contributions and hyporheic zones support temperature and water quality requirements for developing salmonid eggs and larvae

Maintain overwinter habitats for resident fish

- Winter baseflows are needed to provide persistent habitats and thermal refuges

Support resident fish spawning; Cue spawning migration and maintain access to upstream spawning habitat

- High flows in spring cue spawning migration and maintain connectivity to upstream and floodplain spawning habitats
- High seasonal flows are needed to maintain spawning habitat and keep nests sediment-free, but flows cannot be so high that they scour and flush eggs

Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats

- A decrease in summer and early fall flows may reduce access to shallow, slow velocity nursery habitats in margins and backwaters

4.2 Mussels

More than 40 freshwater mussel species occur in the Upper Ohio basin. This is the most diverse mussel assemblage of any basin in Pennsylvania, with the majority of those species occurring in the Allegheny and Ohio mainstem (Ortmann 1909, Bogan and Proch 1992, Watters 1995, Smith and Crabtree 2010, Smith and Meyer 2012). Although many species have been extirpated, recent improvements in water quality and physical habitat provide the opportunity to reintroduce several species including fanshell (*Cyprogenia stegaria*), Ohio pigtoe (*Pleurobema cordatum*), purple wartyback (*Cyclonaias tuberculata*), butterfly mussel (*Ellipsaria lineolata*), pink mucket (*Lampsilis abrupta*) and monkeyface (*Quadrula* *metanevra*) (Chapman and Smith 2008, WPC 2009; B. Meyer, personal communication, 2011; C. Bier, personal communication, 2011). Four federally endangered mussel species, clubshell (*Pleurobema clava*), northern riffleshell (*Epioblasma torulosa rangiana*), rayed bean (*Villosa fabalis*) and snuffbox (*Epioblasma triquetra*) occur within the basin. Recent surveys found the largest reproducing populations of clubshell and northern riffleshell in the world on the Allegheny mainstem (Crabtree and Smith 2009, Smith and Meyer 2012). Two candidate species, rabbitsfoot (*Quadrula cylindrical cylindrica*) and sheepnose (*Plethobasus cyphyus*) also occur in the basin.

Mussels were organized into four groups based on traits including velocity preferences, body size, longevity, length of brooding, timing of spawning and glochidia release and use of host fish (Table 4.2) (Bogan and Proch 1992, Anderson and Bier 1997, Strayer and Jirka 1997, Nedeau 2000, Bogan 2008, Grabarkiewicz and Davis 2008). In consultation with regional malacologists, we selected 18 species to represent the flow-related needs of each group and associated species and groups with representative habitat types.

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

Group	Life history traits
Moderate gradient species *elktoe, snuffbox, rabbitsfoot, rainbow mussel*	• occur in dynamic habitats easily scoured or dewatered by extreme events • riverine species requiring swift to moderate velocities • sensitive to changes in water quality, • small-bodied host fish with small home range
Moderate to swift velocity species *mucket, northern riffleshell, clubshell, round pigtoe, rayed bean*	• riverine species occurring in small to large rivers • require swift to moderate velocities • most sensitive to changes in dissolved oxygen and temperature
Slow to moderate velocity, low gradient species *three-ridge, Wabash pigtoe, fatmucket, white heelsplitter, giant floater*	• facultative riverine species, tolerant of deeper habitats and a range of velocities • range of host fish • somewhat tolerant of higher temperatures
Great river, Ohio mainstem species *threehorn wartyback, pink heelsplitter, pink papershell, fawnsfoot*	• facultative riverine species in moderate to slackwater velocities • generally tolerant of siltation and impoundment

Key flow-related needs for Upper Ohio basin mussels

Support mussel spawning, glochidia transfer and juvenile growth

- Because of their limited mobility, some mussel species are sensitive to extreme high and low flow events and rapid changes in river stage
- High or low flow events may inhibit transfer of glochidia to host fish, reducing recruitment
- Extreme low flows may expose mussels in margin habitats and increase predation or desiccation
- Extreme low flows may increase temperature, reduce dissolved oxygen and increase ammonia toxicity
- During glochidia release and excystment, high flows and associated shear forces are primary factors in determining habitat suitability for juveniles
- Growth and fitness are influenced by high and low flow conditions
- Decreased magnitude or frequency of high flows can lead to habitat degradation including embeddedness, siltation and aggrading channel morphology
- Natural flow regimes can reduce risk of establishment of non-native mussels

Maintain overwinter thermal regimes for mussels

- Seasonal flows support thermal regimes critical in cueing gamete development and release
- Seasonal and low flows maintain surface and hyporheic temperatures and DO conditions

4.3 Aquatic Insects and Crayfish

Macroinvertebrates are a critical component of all river types, especially headwaters, creeks, small rivers and medium tributaries. They are consumers at intermediate trophic levels – grazers, predators, shredders – that serve as transmitters within the food chain. They influence nutrient cycles, primary productivity, decomposition and material transport and are an important source of food for fish, amphibians, reptiles, birds and mammals (Wallace et al. 1996).

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

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

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

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

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

Key flow-related needs for Upper Ohio basin aquatic insects and crayfish

Promote macroinvertebrate growth and insect emergence

- Decreased flow magnitudes can limit habitat availability causing community shifts (reducing sensitive groups, e.g., stenothermal, rheophilic, erosional taxa) or affect abundance
- In headwaters and creeks, a reduction of flows could cue exit of aquatic insects, particularly shredders, reducing energy transformation and export
- Hyporheic connectivity provides refuge for early instars and invertebrates during extreme conditions

Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates

- Altered seasonal flows may limit cues and available habitats for winter emerging insects (e.g., winter stoneflies)

4.4 Reptiles and Amphibians

Twelve families and 35 species of reptiles and amphibians use the basin's riverine and riverine-dependent habitats during some or all of their life cycle. We organized reptiles and amphibians into three groups based on habitat association and timing of life stages including breeding, juvenile development, adult growth and hibernation (Table 4.4). At least one species from each group occurs in each habitat type.

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

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

Key flow-related needs for Ohio basin reptiles and amphibians

Promote/support the development and growth of reptiles and amphibians

- A decrease in seasonal flows may reduce availability of stable, cool, highly oxygenated habitats for lungless salamanders and eastern hellbender
- Low flows facilitate access to benthic invertebrates, especially crayfish, which are eaten by specialist feeders, including the eastern hellbender and queen snake

Maintain stable hibernation habitat for reptiles and amphibians

- A decrease in flows may decrease water temperatures or dewater hibernation habitats resulting in stress or mortality during hibernation

Maintain streamside and vernal egg-laying and larval development habitat for reptiles and amphibians

- High flows of sufficient magnitude and duration are needed to inundate vernal pools in the floodplain that support amphibian egg-laying and larval development
- An increase in high flows may scour larvae that develop in stream margins
- Seasonal flows keep eggs and larvae of streamside salamanders wetted during the incubation period

4.5 Floodplain, Riparian and Aquatic Vegetation

Recent extensive floristic survey of riparian and floodplain communities of Upper Ohio basin headwater, tributary and large river settings identified 642 species of vascular plants representing 106 families (Kalisz and Dunn 2002, Kalisz and Dunn 2003, Zimmerman and Podneisinski 2008). These communities are distributed based on several interrelating factors including the frequency and duration of flooding, the amount of energy received as flood or ice flows, the position of the site within the watershed network, physiography, substrate stability and available propogules (Oliver and Larson 1996, Toner and Keddy 1997, Perles et al. 2004, Zimmerman and Podneisinksi 2008). They were summarized into twenty major community types that can be organized into four major successional states: submerged and emergent bed, herbaceous, scrub-shrub and floodplain forest (Figure 4.2, Appendix 2) (Zimmerman and Podneisinski 2008).

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.

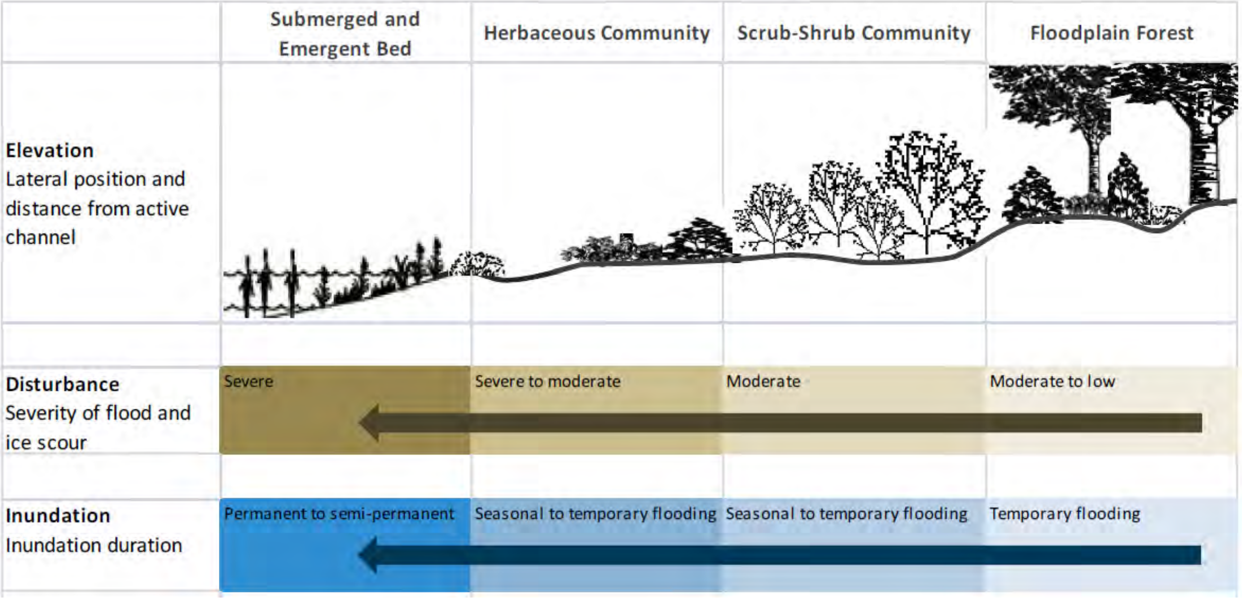


Figure 4.2 Floodplain, riparian and aquatic vegetation of the Ohio basin and shared life history requirements

Key flow-related needs for Ohio basin floodplain, riparian and aquatic vegetation

Maintain ice scour events and floodplain connectivity

- During winter, seasonal and high flow events maintain ice scour disturbance necessary for preparing riparian, island and floodplain seed beds and sustaining the riverine scour community
- High flows provide lateral connectivity to backwaters, providing inundation and soil moisture conditions that support seed dispersal and recruitment

Support establishment and growth of floodplain, riparian and aquatic vegetation

- During winter and spring, seasonal and high flow events provide disturbance to sustain communities with a high scour disturbance fidelity such as sycamore and silver maple floodplain forests
- High flows transport water-dispersed seeds and prepare seedbeds for propagules
- In headwater settings, groundwater elevation and overbank inundation events are critical to maintaining hydric soils and moisture regimes for mesic plants
- During the low flow season, flows must be adequate to support growth and maintain the extent of submerged aquatic vegetation

4.6 Birds and Mammals

Hundreds of species of birds and mammals use the basin's streams, riparian areas and floodplain forests as forage and nesting habitats (Merritt 1987, PGC and PFBC 2005, USFWS 2011). In the following discussion, we highlight major groups of birds and mammals with close associations to stream and river habitats. These species rely upon (rather than merely use) access to stream-derived food resources and habitats.

Birds. Colonial birds, bank and riparian nesting birds, and fish-eating birds are sensitive to a reduction of stream-derived food resources and/or a reduction in the availability of foraging and breeding habitats in riverine, riparian and floodplain areas.

Colonial birds include Great Blue Heron (*Ardea herodias*), Great Egret (*Ardea alba*) and Black-crowned Night Heron (*Nycticorax nycticorax*). The Great Blue Heron is the largest breeding bird in Pennsylvania. It hunts for fish in shallow river habitats (< 50 cm). The Great Blue Heron, Great Egret and Black-crowned Night Heron migrate to the basin in the early spring and nest in floodplains and islands, showing preference for sycamore, silver maple and river birch. Large rookeries occur on Twelve Mile Island and Deer Creek. They are sensitive to changes in water quality, food availability in forage areas and forest disturbance near colonial rookeries (PGC and PFBC 2005). Fish-eating raptors include the Bald Eagle (*Haliaeetus leucocephalus*) and Osprey (*Pandion haliaetus*). They require access to and abundance of fish during nesting and rearing from spring through fall. Bank and riparian nesting birds include species like the Belted Kingfisher (*Megaceryle alcyon*), Bank Swallow (*Riparia riparia*), Spotted Sandpiper (*Actitis macularius*) and Acadian flycatcher (*Empidonax virescens*). This also includes some songbirds such as the warbling vireo, yellow-billed cuckoo, and over 25 species of warblers (USFWS 2011).

Mammals. Mammal species include southern water shrew (*Sorex palustris punctulatus*), mink (*Mustela vison*), muskrat (*Ondatra zibethicus*), northern river otter (*Lutra Canadensis*) and several species of bats. The southern water shrew is semi-aquatic and can be found in high quality cold headwater streams and bogs of the Appalachian Plateau. They feed about every three hours which makes them very sensitive to food availability. Prey include caddisfly, stonefly and mayfly larvae, small fish and fish eggs and aquatic snails (Felbaum et al. 1995). Mink den in ground cavities (beneath tree roots, in abandoned beaver lodges) along streambanks. They are carnivorous feeders and active year round subsisting on fish, frogs, crayfish, snakes and turtles and small mammals in the winter. They do best where water is unpolluted and prey is abundant (Fergus 2000). Similar to mink, muskrat and river otter construct dens within the streambanks. Muskrats are susceptible to increased predation if flows decrease and den entrances are exposed, particularly during winter when they are less active. River otters feed primarily on nongame fish (minnows, suckers and carp) and crayfish. They are active year-round and live in family groups in dens built in stream banks.

During spring and summer, several species of bats – including the little brown myotis (*Myotis lucifufus*), Indiana myotis (*Myotis sodalist*), small-footed myotis (*Myotis leibii*), silver haired bat (*Lasionycteris noctivagans*), big brown bat (*Eptesicus fuscus*) and the hoary bat (*Lasiurus cinereus*) – roost and establish nursery colonies in close proximity to streams and rivers. With a high metabolic rate and a need to store energy reserves during breeding, rearing and before 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. Many of these bat species prefer insects with an aquatic life stage, feeding on midges, mayflies, caddisflies, stoneflies and dragonflies.

Key flow-related needs for Ohio basin birds and mammals

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

- A decrease in low flows can reduce availability of aquatic prey for birds of prey and wading birds
- On medium tributaries and large rivers, low flow conditions can create land bridges, introducing predators and reducing breeding success
- Seasonal and low flows support small mammals that require continuous localized access to an abundance of aquatic insects
- A decrease in high flow events may reduce recruitment of riparian and floodplain trees for nesting

4.7 Floodplain, Island and Channel Maintenance

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

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

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

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

As mentioned in Section 2, the USACE operates and maintains 16 flood control projects within the upper Ohio River basin. The majority of the dams occur on small rivers and medium tributaries. They have reduced the magnitude and increased the duration of flood events on the small river, tributaries and on the large river habitats of the Allegheny, Monongahela and Ohio. This has contributed to a reduction in floodplain extent and condition and a loss of islands (Fortney et al. 2001). In addition to influences of flood control, mainstem large river habitat has been changed by routine dredging which has deepened and narrowed channels for navigation.

4.8 Temperature and Water Quality

This study focused on flow-mediated water quality interactions including temperature, DO and specific conductance (dissolved solids). Lotic species are generally adapted to thermal regimes that define the limits of their distribution. The effect of temperature on biota may be indirect, through its influence on metabolic rates and oxygen concentration. Most life stages of fish, insects, mussels and reptiles and amphibians are affected by temperature. This includes egg and larval development, growth rates, adult size and fecundity (Giller and Malmqvist 1998). Biological cues are often linked, not to instantaneous temperature, but to cumulative degree days (the number of days with temperatures above 0°F). Suitable flow conditions need to coincide with the timing of cumulative degree days in order for growth, emergence, migration, and other biological events to occur.

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

In addition to the magnitude of hydrologic alteration, changes that affect the ratio of groundwater to surface water can have a significant impact on stream temperatures. Groundwater withdrawals have been shown to decrease the ratio of ground to surface water and cause stream temperatures to increase during summer and decrease during winter. Similarly, surface water withdrawals have been shown to decrease temperatures in the summer and increase temperatures in the winter because they increase the ratio of ground to surface water in the stream (Dewson et al. 2007a, Walters and Post 2011a).

Key flow-related needs for Ohio basin physical and chemical processes

Maintain valley and island formation, channel morphology and sediment distribution

- During winter, seasonal and high flow events maintain ice scour disturbance necessary for preparing riparian, island and floodplain seed beds and sustaining the riverine scour community
- High flow events transport large woody debris
- 1- to 5-year events are associated with overbank inundation and channel maintenance

Transport organic matter and fine sediment

- High flow pulses transport fine and coarse particulate organic matter
- Seasonal and high flows transport fines and maintain interstitial habitats

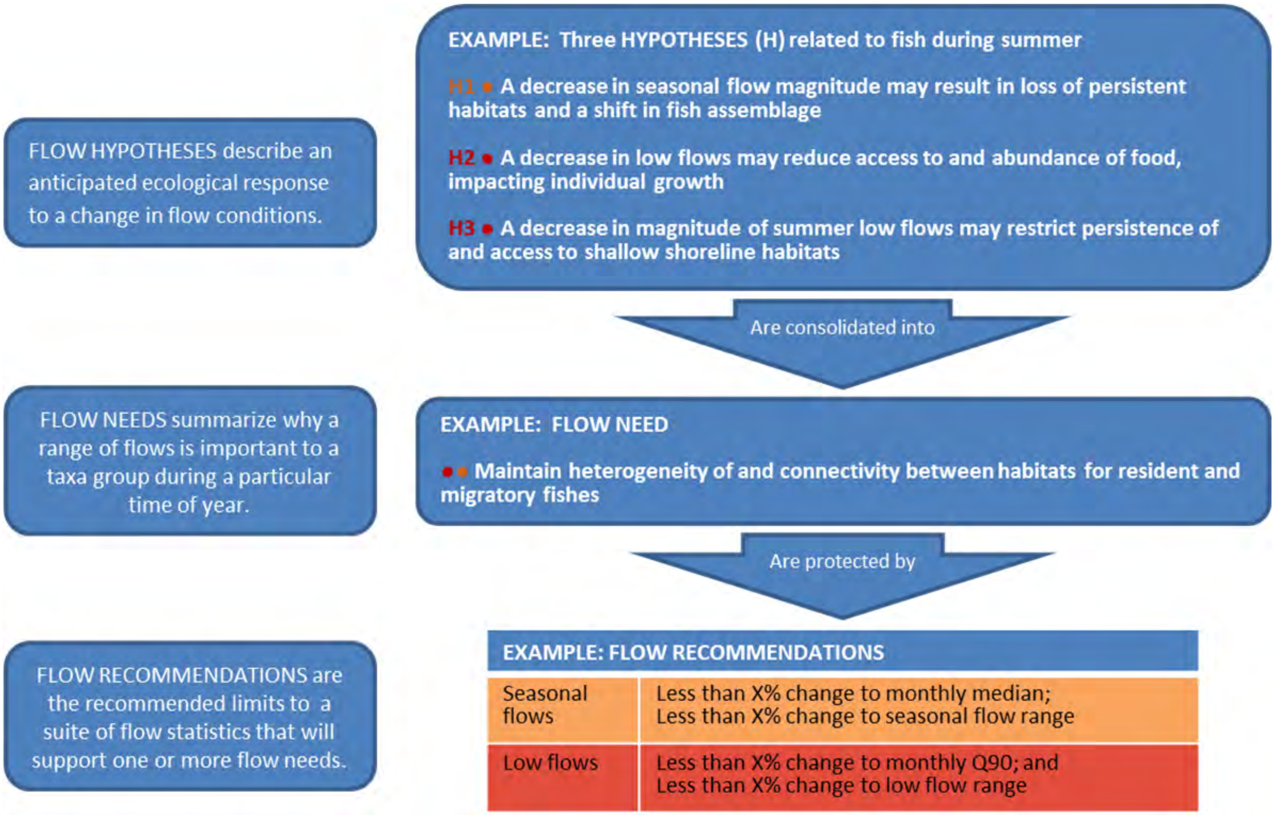
Maintain temperature and water quality

- During warm months, a decrease in high flow freshets may result in cumulative thermal and water quality stress
- During low flow months, a decrease in seasonal or low flows may reduce assimilative capacity; increased concentrations of total dissolved solids would alter osmotic potential

Section 5: Flow Recommendations

In this section, we present recommendations for limiting alteration to the flow statistics (described in Section 3.1) in order to meet the ecosystem flow needs of the species and natural communities (described in Section 4). The recommended limits to flow alteration are based on (a) literature that describes and/or quantifies relationships between flow alteration and ecological response; (b) an analysis of long-term flow variability at index gages; and (c) feedback on draft flow recommendations from expert workshops and consultation. We begin by describing how we synthesized literature, hydrologic analysis, and expert input to support the recommendations. Then we present the recommendations by habitat type. The last two pages of the section are a summary table that lists recommendations for all types and summarizes the ecological needs that these recommendations are intended to protect in each season.

To frame the flow recommendations, we consulted experts to define approximately 80 working hypotheses that describe anticipated ecological responses to changes to the flow regime. Then, we aggregated related hypotheses into a set of 20 flow needs that combine one or more responses of a taxa group to a change in flow conditions. This provided the structure for using a weight-of-evidence approach to document the degree to which literature supports the flow hypothesis, flow needs and ultimately the recommendations (Figure 5.1). Appendix 6 is an annotated bibliography that summarizes the key findings from literature used to support the recommendations.



FLOW HYPOTHESES describe an anticipated ecological response to a change in flow conditions.

EXAMPLE: Three HYPOTHESES (H) related to fish during summer

H1 ● A decrease in seasonal flow magnitude may result in loss of persistent habitats and a shift in fish assemblage

H2 ● A decrease in low flows may reduce access to and abundance of food, impacting individual growth

H3 ● A decrease in magnitude of summer low flows may restrict persistence of and access to shallow shoreline habitats

FLOW NEEDS summarize why a range of flows is important to a taxa group during a particular time of year.

EXAMPLE: FLOW NEED

● ● Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes

FLOW RECOMMENDATIONS are the recommended limits to a suite of flow statistics that will support one or more flow needs.

EXAMPLE: FLOW RECOMMENDATIONS	
Seasonal flows	Less than X% change to monthly median; Less than X% change to seasonal flow range
Low flows	Less than X% change to monthly Q90; and Less than X% change to low flow range

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

5.1 Using Literature to Support Recommendations

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

1. Evidence that supports the need to protect a given flow component for a particular taxa (qualitative evidence). A paper was determined to support the *need to protect a flow component* if it described the relationship or response of Ohio River basin species or processes to a seasonal or inter-annual flow condition (e.g., a paper indicating that winter flows are important for salmonid egg and larval development). In order to be relevant, the research had to be conducted in a temperate region ***or*** include an ecological response that is expected to occur independent of climatic region (e.g., reduction of EPT taxa to decreased velocities). Figure 5.2(a) provides examples of some of the ecological responses to changes in high, seasonal, or low flow components.

2. Evidence that supports the recommended range of values for a particular flow statistic (quantitative evidence). A paper was considered to support the *recommended range of values for a flow statistic* if it (a) addressed taxa or processes specific to the Ohio River basin; (b) was conducted either in the Ohio River basin or a similar temperate region; and (c) provided some quantitative flow-ecology relationship that supported our recommendations (e.g., a study that shows changes in species composition when summer flows are reduced below the Q90). These criteria helped us make sure that we did not apply papers outside of their hydrogeographic context. Figure 5.2(b) illustrates several ecological responses associated with changes to monthly exceedence values during summer.

Quantitative evidence came from papers in several categories:

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

Each relevant paper provides evidence to support a hypothesis. In general, each paper is considered one piece of evidence. However, some papers document more than one flow-ecology relationship. For example, a paper may document responses of multiple taxa to hydrologic alteration or the response of a species in more than one season. In these cases, a paper may provide evidence for more than one cause-effect hypotheses. We summarized findings of more than 150 flow-ecology publications relevant to Ohio basin species groups and habitats. Figure 5.3 illustrates the distribution of relevant sources that support the needs and recommendations throughout the year.

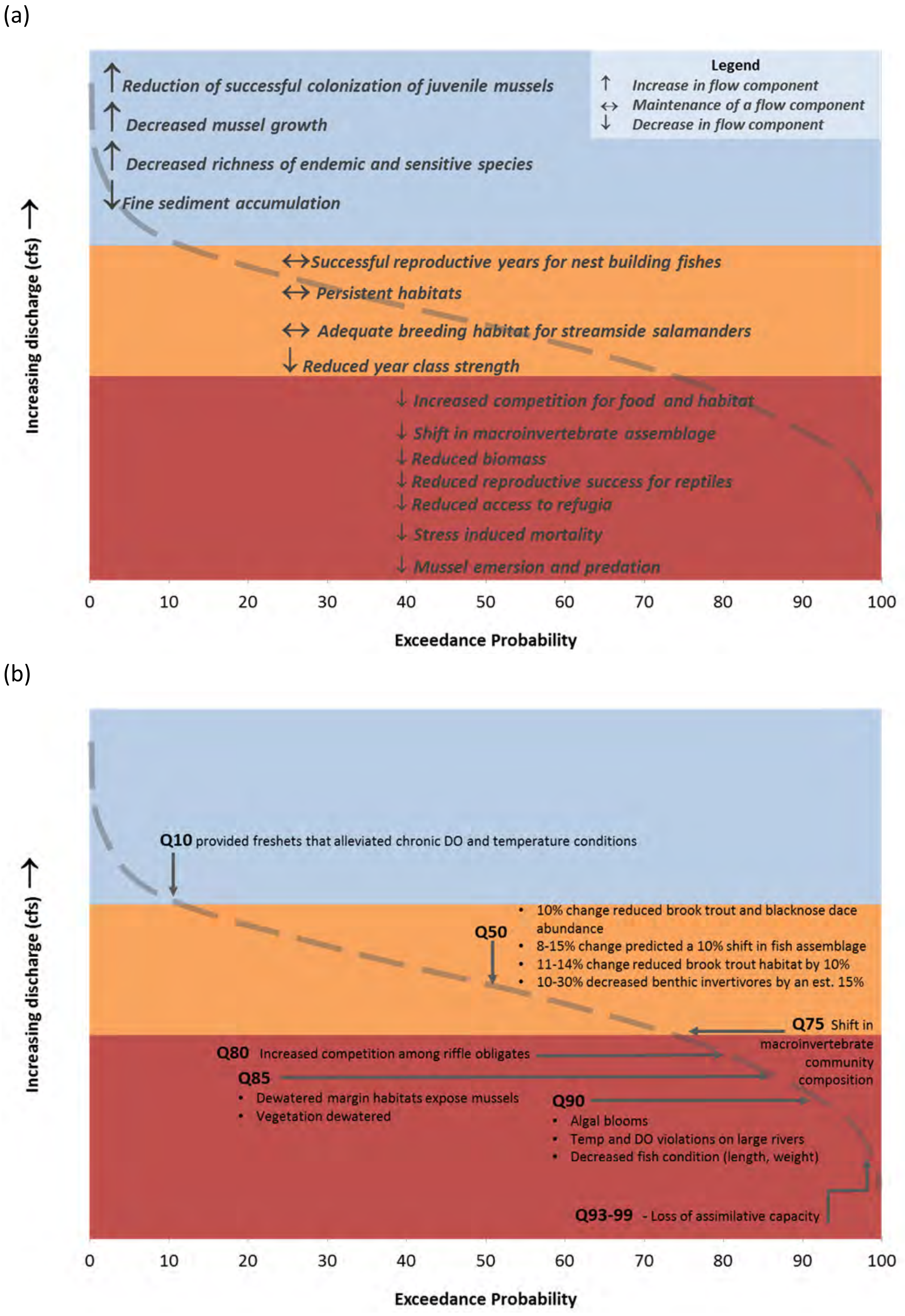


Figure 5.2 Examples of (a) qualitative ecological responses to changes in high, seasonal, and low flows and (b) quantitative published responses to changes in monthly exceedence values during summer

There was the most evidence (i.e., supporting sources) in summer, followed by fall and spring. There was least evidence in winter (31 references). When evidence in all seasons was combined, there were over twice as many sources of qualitative evidence (N=178) than quantitative evidence (N=67).

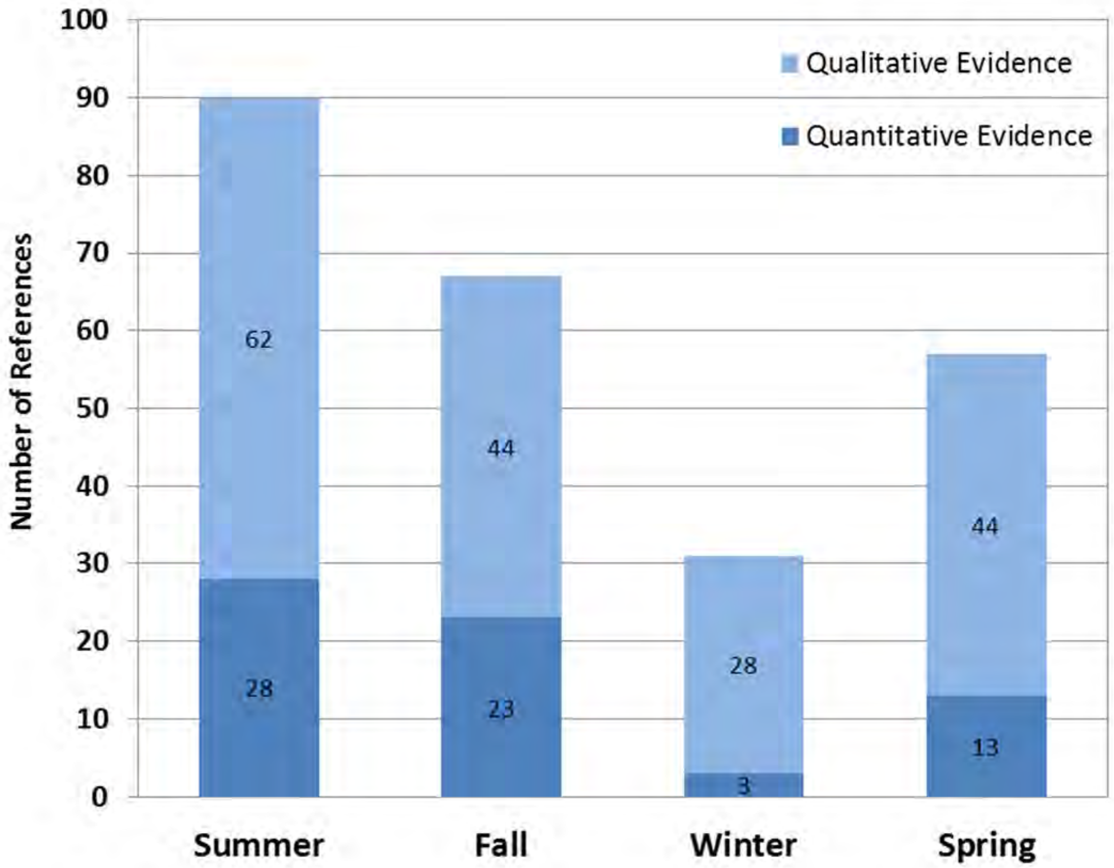


Figure 5.3 Distribution of evidence in literature that supports recommendations in each season

In addition to the number of references supporting each hypothesis, need and recommendation, we also evaluated the strength of support for each. The weight-of-evidence for each source is calculated based on the rigor of study design including controls and replication. The strength of support for each recommendation is the cumulative weight of evidence of relevant sources. Support strength is categorized as **supported**, **moderate support** or **some support** (Table 5.1).

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

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

Strength is summarized cumulatively to determine the support for each recommendation based on both qualitative and quantitative evidence. Table 5.2 summarizes the flow needs, months within which they apply, the associated flow component, the applicable habitat type(s), and whether the need is categorized as **supported**, **moderate support** or **some support.** Appendix 7 provides more detail on our methods for summarizing weight-of-evidence.

In the following four subsections, we summarize the primary flow needs in each season and discuss the corresponding level of support in the literature, highlighting specific studies. We precede each table with a summary of key elements describing how flow affects species and habitats in each season.

Table 5.2 Summary of flow needs, relevant habitat types, associated flow components, season, and level of support for each need in literature

Flow Need - *and applicable habitat type(s)*	**Flow Component and Season (Month)**												**Level of Support for Need**
	Summer			**Fall**			**Winter**			**Spring**			
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	
Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes – *All types*	🟧	🟧	🟧	🟧									*Supported*
	🟥	🟥	🟥	🟥									*Supported*
Support mussel spawning, glochidia transfer, juvenile colonization and growth – *All types except headwaters*	🟦	🟦	🟦	🟦								🟦	*Supported*
	🟧	🟧	🟧	🟧								🟧	*Moderate*
	🟥	🟥	🟥	🟥								🟥	*Supported*
Promote/support development and growth of reptiles and amphibians – *All habitat types*		🟧	🟧	🟧									*Some*
	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	*Moderate*
Promote macroinvertebrate growth and insect emergence – *All types except large rivers*	🟥	🟥	🟥	🟥	🟥	🟥						🟥	*Supported*
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout) – *All cool-coldwater types*					🟧	🟧	🟧	🟧	🟧	🟧			*Supported*
					🟥	🟥	🟥	🟥	🟥	🟥			*Some*
Maintain temperature and water quality – *All types*			🟦	🟦	🟦								*Some*
		🟧	🟧	🟧	🟧								*Some*
		🟥	🟥	🟥	🟥								*Moderate*
Transport organic matter and fine sediment – *All types*		🟦	🟦	🟦	🟦								*Moderate*
Maintain stable hibernation habitat for reptiles and amphibians – *All types*		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			*Some*
		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			*Moderate*
Maintain overwinter habitats for resident fish – *All types* (salmonids in *cool-coldwater types* only)							🟧	🟧	🟧				*Moderate*
							🟥	🟥	🟥	🟥			*Some*
Maintain overwinter thermal regimes for mussels – *All types except headwaters*							🟧	🟧	🟧	🟧	🟧		*Some*
							🟥	🟥					*Some*
Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates – *All types except large rivers*							🟧	🟧	🟧	🟧			*Some*
							🟥	🟥	🟥	🟥			*Some*
Maintain ice scour events and floodplain connectivity – *All types except headwaters and creeks*							🟦	🟦	🟦	🟦			*Moderate*
							🟧	🟧	🟧	🟧			*Moderate*
Support resident fish spawning – *All types*	🟦									🟦	🟦	🟦	*Supported*
	🟧	🟧	🟧							🟧	🟧	🟧	*Supported*
	🟥	🟥								🟥	🟥	🟥	*Moderate*
Cue spawning migration and maintain access to spawning habitat – *All types except headwaters*										🟦	🟦	🟦	*Moderate*
	🟧									🟧	🟧	🟧	*Some*

Flow Need - *and applicable habitat type(s)*	**Flow Component and Season (Month)**												**Level of Support for Need**
	Summer			**Fall**			**Winter**			**Spring**			
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	
Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats – *All types except headwaters and creeks*	🟦										🟦	🟦	*Moderate*
	🟧	🟧									🟧	🟧	*Moderate*
Support spring emergence of aquatic insects and maintain habitats for mating and egg laying – *All types except large rivers*	🟧	🟧	🟧							🟧	🟧	🟧	*Some*
	🟥										🟥	🟥	*Moderate*
Maintain habitats for streamside and vernal amphibian egg-laying and larval development – *All types*									🟦	🟦	🟦	🟦	*Some*
	🟥									🟥	🟥	🟥	*Moderate*
Support establishment and growth of floodplain, riparian and aquatic vegetation – *All types*										🟦	🟦	🟦	*Supported*
	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥	*Supported*
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals – *All types*	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥	*Some*
Maintain valley and island formation, channel morphology and sediment distribution – *All types except headwaters*	🟦	🟦	🟦	🟦	🟦					🟦	🟦	🟦	*Supported*

5.1.1 Summer

Key Elements

- The combination of baseflow and temperature during summer influence community composition and species abundance.
- Diversity of hydraulic habitats including riffles, runs, plunge pools, pools, and channel margins are maintained by seasonal flows.
- Low flows can limit connectivity between critical habitats and limit access to stream margins and thermal refugia.
- Mussels rely on relatively stable flows for successful transfer of glochidia (larvae) to host-fish and for juvenile establishment.
- For most species, stable flows and warmer temperatures make summer the peak season for growth.
- Typical seasonal flows support stream-derived food resources for birds and mammals.
- High flow pulses maintain soil moisture and prevent desiccation of streamside vegetation.

Summer is defined as the months of June, July and August. Many biological events that begin in spring – including fish spawning, insect emergence and vegetation establishment – continue during summer. Warm temperatures and high food availability make this the main season for growth for many species. Flows tend to decrease over summer, which can increase water temperature and decrease DO, creating stressful conditions. Low flows can also limit availability of and access to habitats, including thermal refugia.

There is more literature that documents or describes flow-ecology relationships in summer than in any other season. Overall, more publications focus on fish than on aquatic insects, mussels, or vegetation (Figure 5.4). For all four taxa groups, most papers document changes in growth, reproduction, and individual fitness or survival, but other papers describe or quantify changes to species composition and abundance or habitat availability. Within the fish literature, there are studies that address high flows, seasonal flows and low flows. Literature on aquatic insects and mussels most commonly document the effects of low flow or drought conditions. Both mussels and aquatic insect larvae have limited mobility and may have difficulty moving to avoid extreme conditions that cause stress.

In summer, low base flows in combination with high seasonal temperatures influence community assemblages, particularly for fish (Zorn et al. 2008). Freeman and Marcinek (2006) found that altered flow regimes increased the odds that a site's Index of Biological Integrity (IBI) score fell below a regulatory threshold. Their comparison of large warmwater streams along a withdrawal index gradient showed a shift in fish assemblages from fluvial specialists to habitat generalists as withdrawals increased from 50 to 100% of 7Q10 (the 7-day low flow event that occurs one in ten years). In the Upper Ohio basin, the 7Q10 translates to approximately 10 to 30% of the August median, depending on the site. Fluvial specialists included species in the cyprinid, catostomid, percid, ictalurid and stream-dwelling centrarchid families. On small streams in the northeast, Kanno and Vokoun (2010) found a similar response: benthic invertivores (riffle obligates) decreased by an estimated 10% when withdrawal rates were 50% of 7Q10.

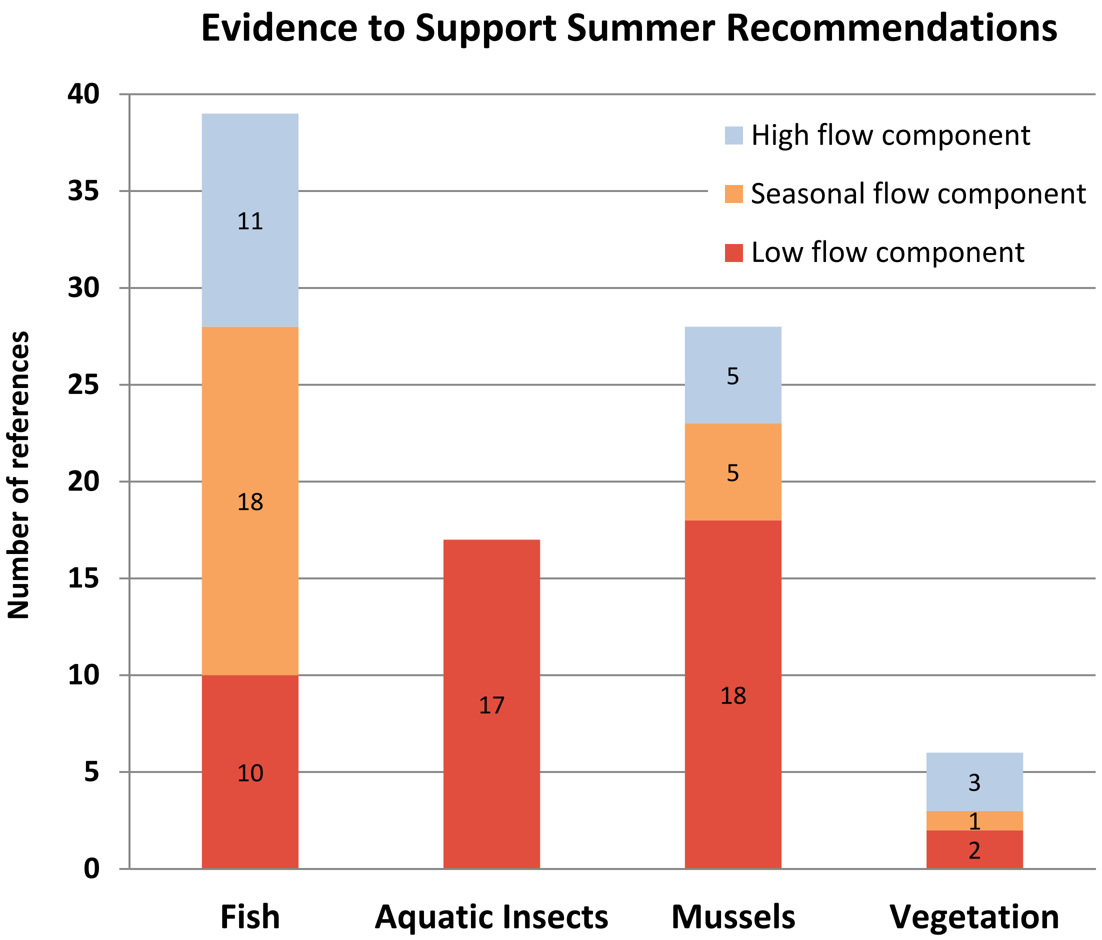


Figure 5.4 Evidence that supports summer flow recommendations from literature on fish, aquatic insects, mussels, and vegetation

In the northeast U.S., Armstrong et al. (2011) studied small to medium-sized streams and related fish assemblage characteristics to anthropogenic factors including estimated flow alteration (percent alteration of August median flow). A 10% reduction to the August median reduced brook trout abundance by an estimated 33%, blacknose dace abundance by 17%, fluvial-fish abundance by 8% and fluvial-fish species richness by 14%. A national study of flow alteration and biological response found that diminished flow magnitudes (proportion of summer low flow lost) were the primary predictors of biological integrity for fish and macroinvertebrate communities. The likelihood of biological impairment doubled with increasing severity of diminished streamflows. Fish assemblages transitioned to lotic species that preferred slow-moving currents and find-grained substrates (Carlisle et al. 2010).

Assemblages have been shown to respond differently according to habitat type. Zorn et al. (2008) simulated the influence of withdrawals on fish assemblages during the summer months and found that assemblages in headwater and small streams were more sensitive to withdrawals than large rivers. For headwater and small streams, a simulated removal of 8% to 15% of the August median predicted a 10% shift in fish assemblage; for large rivers, removal of 10 to 25 % of the August median predicted a 10% shift in fish assemblage.

A decrease in median summer flows has also been correlated with shifts in habitat persistence and young-of-year abundance. Seasonal flows provide persistent and connected habitats for resident and migratory fish. Freeman et al. (2001) found that a decrease in the magnitude of median daily flows resulted in a reduction in available shallow-slow habitat in summer. Young-of-year abundance was most correlated with shallow-slow habitat size and persistence. Suitable conditions were predicted by conditions including the seasonal median daily flow. Similarly, implementation of a minimum release program increased flows during the summer from extreme low flow conditions to low flows and increase diversity of the shallow shoreline fish assemblage to more closely resemble unaltered reaches. Several fluvial-specialist species in the genera *Cottus, Percina, Etheostoma, Lepomis, Hypentelium,* and *Notropis* returned (Travnicek et al. 1995).

Riffle habitats and riffle obligate fishes are very sensitive to changes in flow during the summer months. Low flows have been shown to limited habitat heterogeneity. During summer, a decrease in flows exacerbates already depressed resources (e.g., low prey densities and high metabolic demands) and increases inter- and intraspecific competition. Schlosser and Toth (1984) found rainbow and fantail darters reduced consumption as opposed to partitioning food resources by selecting different prey taxa or prey sizes and that the increased potential for competition for food was greatest during summer low flow conditions. In the Allegheny River, habitat partitioning among eleven species of darters occurred along gradients of depth, velocity and substrate during base flow conditions. Habitat heterogeneity increased as did partitioning among species, reducing competition above the July Q80 flows (Stauffer et al. 1996, USGS 2012). In a tributary to the Upper Ohio (Elk River), ten darters were observed during the summer and patterns of partitioning were significant between genera. *Etheostoma* occurred in riffles and were associated with benthic habitats (under, between and on top of rocks) whereas *Percina* were more common in riffle/run habitat within the water column. Eastern sand darters were only observed in shallow pool habitats in sandy substrates with low velocities (Welsh and Perry 1998).

In addition to reducing the heterogeneity and persistence of habitats, decreased flows may also limit the extent of the network by compressing the headwater-to-small-stream gradient or reducing connectivity between headwater and tributary streams. This is particularly critical for cold water fishes like brook and brown trout. In a study monitoring brook trout body temperatures during summer and fall, Baird and Krueger (2003) found that access to and use of areas of groundwater discharge and tributary confluences were critical for thermoregulation. A reduction in longitudinal connectivity was simulated by a brook trout population model. Barriers that eliminated longitudinal connectivity prevented upstream migration of brook trout and led to extinction of local brook trout populations within two to six generations. Extinction of source populations increased the probability of metapopulation extinction (Letcher et al. 2007).

Reductions in stream flow during the summer low flow period have been correlated to reductions in condition of individual fish. In brook trout, reduced summer flows resulted in reduced body length and weight (Hakala and Hartman 2004). In an experimental diversion that reduced flows to an estimated summer Q90 and Q95, fish body length was 30 to 40% smaller for larger bodied fishes and 10% smaller for small-bodied fishes (Walters and Post 2008). In Pennsylvania, in response to a low flow summer, brook trout biomass increased and brown trout decreased, which may be attributable to a competitive advantage (Greene and Weber 1993).

The stability of summer flows provides suitable habitat for fish-mussel interaction and successful colonization of juvenile mussels, as well as conditions for juvenile and adult growth. Most of the basin's mussels require a host fish for larval development. Hydrology during the period of transfer of larvae from mussel to host has been shown to influence reproductive success. Gravidity, fecundity and fertilization success of *Actinonaias ligamentina* were examined at four sites below the Green River dam (KY). Researchers found that females are not necessarily dependent on nearby males for fertilization and factors necessary for species recovery include presence of host fish and suitable conditions for juvenile survival and growth (Moles and Layzer 2008). Schwalb et al. (2011) found that rare mussels relied on host fish with small home ranges; mussels with a more secure conservation status had host fish with large movement distances. This suggests limited dispersal by host-fish affects the abundance and distribution of unionid mussels, and supports the need to consider host-fish mobility to ensure connectivity between and maintenance of metapopulations.

Once bound to the host fish, larvae develop over a three to four week period before dropping from the fish gills and establishing in substrate. During this period, called excystment, high flows and associated shear forces may be the primary factors in determining suitability of juvenile settlement locations (Hardison and Layzer 2001). Using a particle distribution model, Morales et al. (2006) found that suitable habitats for juvenile colonization occurred where shear stress ratio < 1 and hypothesized that annual peak flows limit the availability of colonization habitats. Similarly, a reverse-time, tag-recapture model was developed to estimate survival, recruitment and population growth rates for three endangered mussels in the Alabama, Coosa, and Tallapoosa River basin in Georgia. Model estimates indicate that mussel survival has a strong negative relationship to high flows during the summer (Peterson et al. 2011, Vaughn and Taylor 1999).

In addition to influencing the success of flow-sensitive life stages, flows have also been shown to structure mussel assemblages and abundance. While many species have adapted to survive episodic low flow events, stream reaches where surface and ground water became disconnected under drought conditions (exacerbated by groundwater withdrawals) had significant declines in taxa richness and abundance (Golladay et al. 2004). A greater than 50% reduction of median monthly flows in summer months resulted in a 60-85% decrease in mussel abundance (Haag and Warren 2008).

As has been documented in fish communities, mussel communities responded differently to low flow conditions in different habitat types. A record drought disconnected pools resulting in a loss of species in small stream habitats (watersheds with drainage areas of 4 to 105 mi^2). Mussels survived in tributary and large river habitats where connectivity among pools was maintained and where flow refuges persisted (Haag and Warren 2008). Below the Green River dam in Kentucky, Layzer (2009) found a relationship between reservoir conservation flow releases and increased mussel recruitment. Before low flow releases began, only 4% of the mucket population was < 100 mm long. After the releases, 28% of the muckets were < 100 mm long. They also found that *Lampsilinae* recruitment was related to releases made in the late spring and early summer; *Ambleminae* recruitment was also related to releases made during summer (Layzer 2009).

Several studies have also documented that individual mussels respond to flow reductions during summer, either directly or indirectly due to associated increases in water temperature or changes in water quality. Galbraith et al. (2010) found that thermal stress associated with low water levels was one of the proximate causes of reduction in species density, abundance and richness. Once the mussels began dying, tissue decay led to nutrient pulses and algal blooms which lowered DO, resulting in further mortality. For a study in the southeast U.S., thermally sensitive species, such as mucket *(Actinonaias ligamentina)* experienced sublethal stress in respiration patterns, the catabolization of glycogen stores, and reduced nutrient processing when water temperature exceeded 30 °C (Spooner et al. 2005, Spooner and Vaughn 2008). Researchers found that glycogen stores increased from summer to winter and decreased in the spring, likely due to seasonal energetic investment in reproduction. Therefore stressful conditions that cause mussels to catabolyze glycogen will be magnified during the reproduction period (Spooner et al. 2005, Spooner and Vaughn 2008). Thermal tolerances for glochidia and juvenile life stages for eight species of mussels ranged from 21.4 °C to 42.7 °C (Pandolfo et al. 2010). Pandolfo et al. (2012) found that freshwater mussels generally have a slightly greater thermal tolerance than their host fish, therefore the effective thermal tolerance is reduced by the obligate relationship with the host fish.

During a drought, mussel mortality increased when DO fell below 5 mg/L and water velocity below 0.01 m/s. Additionally, reduced flows resulted in mussel emersion and increased predation. Emersion did not result in mortality in all mussels. Small-bodied mussels incurred higher mortality than large-bodied mussels (Johnson et al. 2001). Similarly, during the late summer of 1988, low flows on French Creek dewatered margin habitats, exposing mussels and resulting in desiccation and increased predation. During this period, the minimum flow was the August Q90, and the median flow was the August Q85 (C. Bier, personal communication, 2012; USGS 2012). High flow events have also been related to reduced growth in individual mussels. In an analysis correlating unionid growth rings with long-term hydrology, Rypel et al. (2009) negatively correlated growth of some species with higher May and June median flows and with frequency of high pulses (events > 75th percentile).

5.1.2 Fall

Key Elements

- Some of the lowest flows occur in September; the period of extended low flows typically associated with late summer continues into fall and often contributes to warm temperatures and low DO.
- Flows tend to increase during fall months as vegetation growth ends and evapotranspiration decreases.
- Mid-fall, salmonids (brook and brown trout) need flows within the seasonal range to maintain suitable spawning conditions and to maintain connectivity between summer habitat and fall spawning areas.
- Fall is an energetically-demanding time for long-term brooding mussel species, which typically spawn during fall.
- High flow events during fall transport fine sediment, detritus and organic matter.
- During fall, most aquatic insects are present in their larval (aquatic) state.

- Connectivity between surface, groundwater and hyporheic zones needs to be maintained to buffer increasing water temperatures and provide access to subsurface refugia.
- Reptiles, amphibians and mammals begin hibernating and nesting during fall. Decreases in streamflow can lead to habitat loss and stranding in streambeds and banks.

Fall is defined as September, October and November. Compared to summer, there are fewer published studies on ecological responses to streamflow changes in fall, but because fall is an extension of the summer low flow season, many of the publications that support the flow needs during summer are also applicable during fall (Figure 5.5). In addition, fall marks the beginning of the spawning period for brook and brown trout and several studies describe the interrelationship of low and seasonal flows to spawning success and egg and larval development.

In the fall, brook and brown trout begin constructing redds and spawning in cold and cool-water habitats. A decrease in groundwater or surface flows may reduce access to and quality of redds during salmonid spawning. A recent study on a small tributary to the Monongahela found 60 distinct brook trout spawning redds. Redds were most frequently located in the tail sections of pools or the heads of low-gradient riffles; both locations often represent transitions in bed slope that may increase groundwater circulation and upwelling. Redds occurred at an average depth of 41 cm over gravel substrate and 80% occurred in segments with an upstream basin of 3.0 km or less. Spawning site selection may relate partially to the proportion of groundwater available in these settings (Petty et al. 2005). Other studies have found that localized groundwater contributions attract salmonids to habitats capable of supporting egg and larval development over winter and through the spring (Hazzard 1932, Raleigh 1982, Curry et al. 1995, Curry et al. 1994). Similarly, over a three year study on small streams in New York, all observed brook trout redds were constructed either immediately below springs or in places where seepage entered the redd through gravel (Hazzard 1932). In addition to groundwater contribution, depth and velocity are also critical to suitable spawning areas. A regional IFIM study predicted a loss of 10% of habitat loss for withdrawals of 11 to 14% of the November median (Denslinger et al. 1998).

In fall (and spring), hydrologic conditions and associated available habitat are critical for macroinvertebrate growth and productivity. Several studies have documented community shifts in response to decreased magnitude of low flows. A comparison of streams along a withdrawal gradient showed that assemblage change was proportional to the amount of water withdrawn. Changes included decreased relative abundance and shifts from collector-gatherer and filterer to predatory insects, non-insect taxa and scraping beetles (Miller et al. 2007). In headwater streams, Walters and Post (2011a) used an experimental withdrawal to quantify changes in macroinvertebrate density, community composition and available habitat. A threshold seems to occur when withdrawals were reduced to between the summer Q75 and Q85 (Walters and Post 2011). Decreases in low flow magnitude have resulted in many other documented community shifts including a transition from stenothermyl taxa (cold-water specialist) to eurythermal (generalist), a reduction in taxa intolerant of desiccation, an increase in species with small body size at maturity and an increase in predator densities (Richards et al. 1997, Lake 2003, Boulton 2003, Miller et al. 2007, Apse et al. 2008, Walters and Post 2011a, Walters and Post 2011b). In addition to shifting community composition, reductions in low flow magnitude have also resulted in a decrease in overall taxonomic richness (Boulton and Suter 1986, Englund and Malmqvist 1996, Wood and Armitage 1999 and Wood and Armitage 2004). In a national study (~250 sites) relating flow alteration to biological response, Carlisle et al. (2010) found that the likelihood of biological impairment doubled with increasing severity of diminished stream flows. Other studies documented responses to extreme experimental reductions (up to 90% of baseflow), including a decrease in overall density, EPT taxa, filter feeding insects and grazing insects (Wills et al. 2006, Dewson et al. 2007a).

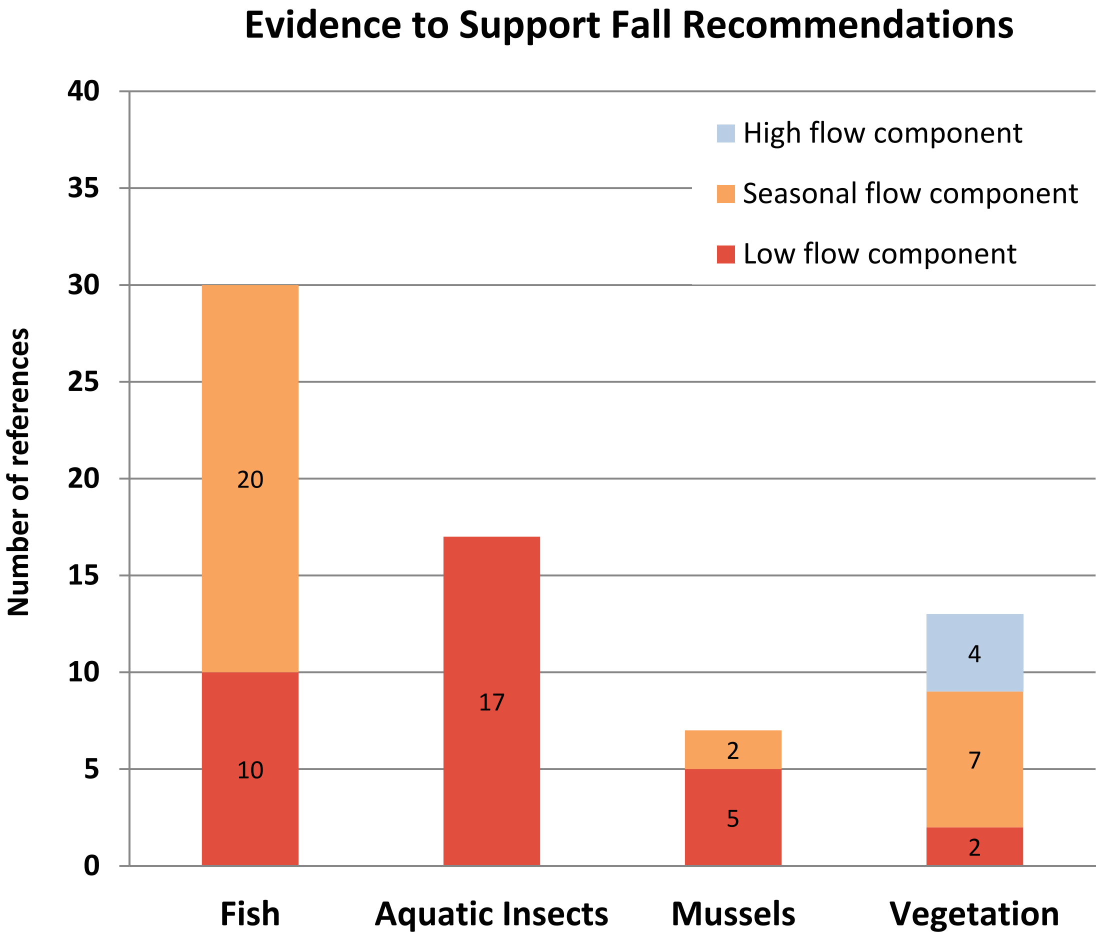


Figure 5.5 Evidence that supports fall flow recommendations from literature on fish, aquatic insects, mussels, and vegetation

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

Studies have also documented the effects of low flow conditions on crayfish. Flinders and Magoulick (2003) found that stream permanence had a significant effect on crayfish community density and composition. Small crayfish also grew faster in shallow habitats where they may have benefited from high prey availability and reduced predation risk (Flinders and Magoulick 2007).

For both aquatic insects and crayfish, maintenance of connectivity between the hyporheic zone and surface waters is critical. The hyporheic zone acts as refuge for early instars and stream invertebrates during extreme conditions and drought. Exchange between surface water and the hyporheic zone occurs in response to variations in discharge and bed topography (Boulton et al. 1998). In an Appalachian headwater stream, abundance and taxa richness were positively correlated with interstitial flow, especially during the late summer/fall when stream flow was lowest (Angradi et al. 2001). Crayfish were found in the hyporheic zone during seasonal summer drying; they did not migrate downstream to avoid desiccation. Hyporheic crayfish burrows served as refuge for other invertebrates during extreme low flow conditions (DiStefano et al. 2009). Surface waters may become disconnected under extreme low flow conditions and in a setting of over allocation (Armstrong et al. 2001).

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

Extended low flows during late summer and fall facilitate warm stream temperatures, sags in DO and low pH. Under these conditions, headwater reservoirs within the Allegheny and Monongahela are operated to mitigate poor water quality (low DO, high temperature and increasing total dissolved solids) on the mainstem rivers (USACE 2011). In the Upper Ohio River, recent hot, dry conditions caused algal blooms and violations of DO and temperature standards (ORSANCO 2010). Water quality conditions exceeded standards during August and September of 2010. During August 2010, the daily discharges were typically between the long term August Q60 and Q90; the minimum daily flow during this period was equal to the August Q90. During September 2010, the daily discharges were typically between the long term September Q70 and Q95; the minimum daily flow was equal to the September Q95 (ORSANCO 2010, USGS 2012).

Assimilative capacity for streams is calculated using the 7Q10 flow. We used data from index gages within the basin to calculate 7Q10 and compare it with monthly exceedence values in summer and early fall (July thru September). In general, the 7Q10 flow corresponds to the July, August, or September monthly Q99 to Q93; for most sites, 7Q10 falls between the Q96 and Q98 in these months (USGS 2012).

5.1.3 Winter

Key Elements

- Low winter flows have been correlated with anchor ice formation, which affects fish and macroinvertebrate abundance, especially in headwaters and creeks.
- Fall spawning salmonids require winter flows to be maintained at or near fall spawning levels to ensure egg and larval development.
- Fewer species use shallow, channel margin habitats in winter than in other seasons. Many fishes move to deeper refugia to lower bioengergetic costs.
- Mussels may bury themselves within the stream channel to avoid freezing and desiccation.
- Many species have limited mobility during winter, making local habitat conditions especially important.
- Relative to other seasons, there are few studies that address species' needs during winter, but year class strength of several fish species has been linked to overwinter habitat availability.

Winter is recognized as a critical time for many species of fishes, mussels, and aquatic insects; although relatively little is known about species-specific overwinter habitat requirements. Shoreline ice scour along channel margins provides a disturbance necessary to support early successional riparian vegetation communities.

Relatively few publications document flow-ecology relationships during winter and, of these, only a couple of studies relate an ecological change to a flow statistic or range around a statistic (Figure 5.6). Of the studies that do exist, the majority describes or provide evidence for winter as a resource-limited period when streamflow changes can increase stress due to increased bioenergetic demands. Most papers address the importance of seasonal conditions (as opposed to extreme high or low flow conditions) for maintaining physical habitat and thermal regimes. Compared to other taxa, there are more papers focused on vegetation, specifically how physical processes (ice scour, overbank events, seed and sediment transport, energy export) sustain spring vegetation recruitment and establishment.

Winter can be a particularly sensitive season for coldwater fishes. During winter, a decrease in flow magnitude may also decrease availability and access to riffle habitats needed by cold water and riffle obligate fishes. Mottled sculpin population size has been shown to be regulated by overwinter population density due to intraspecific habitat competition between juveniles and adults (Rashleigh and Grossman 2005).

Brook trout spawn in the fall; eggs and larvae develop through the late fall and early winter, and fish are sensitive to decreased flows that could increase thermal stress or exposure (Raleigh 1982, Jenkins and Burkhead 1993, Denslinger et al. 1998, Kocovsky and Carline 2006, Hudy et al. 2008). Groundwater upwellings that buffer stream temperatures (from fall spawning through incubation) have been shown to be critical for maintaining DO levels and for protecting redds from cold surface water and ice formation. Curry et al. (1995) documented the lowest egg survival (6%) in the redd with the lowest proportion of groundwater contribution and lowest temperatures. Brown et al. (1993) also observed trout aggregations in areas where groundwater buffered temperatures by 2 to 6 °C. Formation of frazil and/or anchor ice may occur during low flow conditions and has potential to pose direct physiological effects (e.g., attaching to fish gills) and/or restrict availability of suitable habitat.

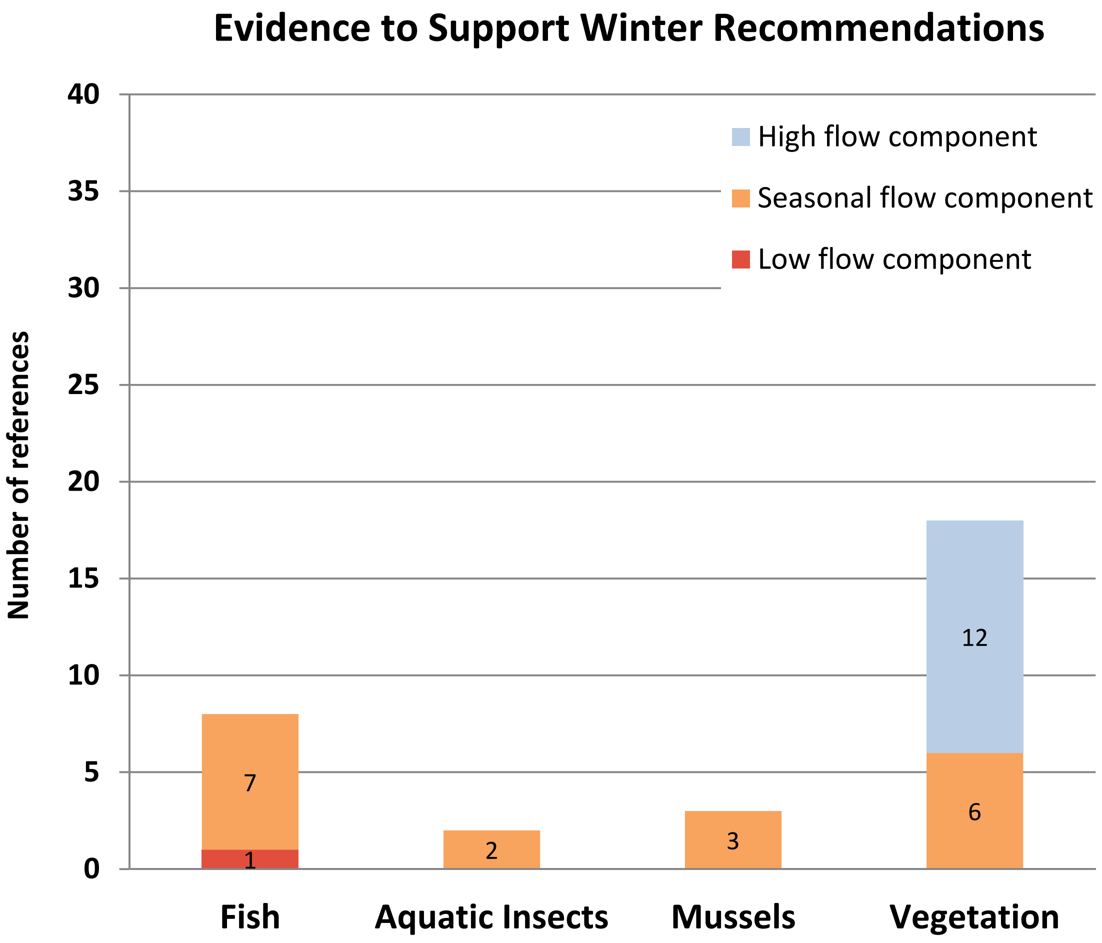


Figure 5.6 Evidence that supports winter flow recommendations from literature on fish, aquatic insects, mussels, and vegetation

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. For migratory resident fishes that use deep pools as refugia, low flows may reduce availability of suitable pools in some stream types and result in increased bioenergetic costs in order to seek suitable habitat (R. Ventorini, personal communication, 2012). During winter spawning, burbot need connectivity to upstream spawning habitats and maintenance of pools and runs for overwintering (D. Fischer, personal communication, 2012).

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

From winter through summer, decreased flow magnitude may reduce temperatures and shift thermal regimes that are critical during mussel gametogenesis. Temperatures less than 10°C have been shown to limit individual growth (Spooner and Vaughn 2008). Reproductive success of long-term brooders may be influenced by overwinter flow magnitude (R. Villella, personal communication, 2010). Both field and lab studies suggest that thermal regimes are important cues for the timing of gamete development and potentially for gamete release. For all species in the study, the timing of reproduction was correlated with the number of accumulated degree days (Galbraith and Vaughn 2009).

During winter, high flow events and associated ice scour maintain conditions for early successional vegetation (Nilsson et al.1989, Fike 1999, Podniesinski et al. 2002). A decrease in flows may reduce shoreline ice scour, a disturbance necessary for the propagation of species in the riverine scour community that occurs throughout the Ohio watershed on streams of all sizes. This community is dependent on ice scour, floods and high water velocities. Five high quality examples of the riverine scour community occur at the elevation that would be scoured around and above the February median flow (February Q48 to Q66). These examples occur on French Creek, the Allegheny, Beaver, and Monongahela Rivers (Zimmerman and Podniesinski 2008, USGS 2012). Flows below this range may reduce the distribution and/or quality of these communities.

5.1.4 Spring

Key Elements

- Spring is a season when flows are highly variable, both within and among years. Year-to-year variability affects year class strength and strongly influences population structure, vegetation recruitment and geomorphic conditions.
- Migration and movement of spring-spawning fishes frequently coincides with high flow events that are synchronized with temperature and other cues. Maintaining frequent high flow events is essential to provide opportunities for migration when other conditions are right.
- High flow pulses followed by stable, high flows are key to spawning success for many fish species. For example, nest building fishes may spawn more than once in a season. The length of time between high flow pulses increases the chances of nest success.
- For many fish species, year class strength often correlated with wet spring seasons.
- Larval transport to slow-moving habitats is essential for spring-spawning fishes, including walleye and northern pike.
- Spring spawning fishes can be affected by both extreme high and extreme low flow events; flows that are too high or too low can affect spawning success.
- Amphibians, especially stream salamanders, are highly sensitive to increased frequency of low flow conditions.
- 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.

Spring is defined as the months of March, April and May, although fish spawning, insect emergence, vegetation establishment and other biological events that are characteristic of the spring season frequently extend into June.

Spring is a critical time for migratory and resident fish spawning, emergence of aquatic insects, and establishment and growth of floodplain, riparian, and aquatic vegetation. Flows are needed to maintain longitudinal and lateral access among riverine and floodplain habitats, including shallow-slow channel margin and backwater areas that are important for fish productivity and species diversity. It is also a critical period for streamside amphibians, many of which use vernal pools and intermittent stream beds that are wet during spring. High flows during spring also maintain channel morphology, island habitats, and redistribute habitat-forming sediments. Although bankfull events and small and large floods may occur in any season, they most frequently occur during spring.

Literature supports several spring ecosystem needs, including vegetation establishment, fish spawning and egg and larval development, and mussel spawning and glochidia release (Figure 5.7). Because flows in this season are relatively high, few publications document flow-ecology relationships associated with low flow conditions. More commonly, spring flow needs are related to “typical” flows during this season or to the frequency, magnitude and duration of high flow events (including bankfull and flood events).

Spring is typically a high-flow season and elevated monthly flows and high flow events help maintain connectivity between large river and tributary habitats and between river and side- or back-channel habitats. During spring and early summer, a decrease in median flows may reduce access to and availability of preferred fish spawning habitats. These decreases may affect riffle-spawning fishes that occur across a variety of stream and river sizes (e.g. darters, redhorses, paddlefish). For example, white sucker, creek chub, northern hogsucker, and black redhorse are typically partitioned by timing and location of spawning. However, Curry and Spacie (1984) found that stream alterations that affect temperature, flow regimes, substrate or connectivity may reduce niche diversity and increase potential for competition among catostomid species. Decreases in seasonal flows may also shift species assemblages. Freeman et al. (2001) documented more spring spawners and fewer summer spawners in response to a decrease in the magnitude of median daily flows in spring.

During spring and summer, a reduction in high flow events may limit connectivity to and quality of oxbow and backwater habitats potentially reducing fish production and species diversity. Zeug et al. (2005) found that within oxbow habitats, fish assemblage structure was associated with both macrohabitat features (depth, temperature, conductivity) and the frequency of floods that connected backwater habitats to the channel. Six species that were collected in oxbow lakes were never collected in river channel surveys and several species that were rare in river channels were abundant in oxbows.

Great river fish species, such as longnose gar, paddlefish, and bigmouth buffalo, may be particularly sensitive to flow changes that affect availability and quality of shallow-slow habitats. Bowen et al. (2003) demonstrated that the distribution, location, and extent of shallow-slow habitat in an unregulated river was tied to the spring and summer hydrograph. The side channels and tributary backwaters that were available during spring benefitted larval stages, which typically have poor swimming ability and rely on zooplankton and detritus as food sources. By the time spring flows recede to the main channel, these larvae have developed to juvenile stages that have better swimming and foraging ability. For several populations of paddlefish, spawning success and year-class strength have been associated with years of high sustained spring discharge. Paddlefish did not migrate upstream during an extreme low flow spring (Paukert and Fisher 2001). Firehammer and Scarnecchia (2007) found that in years of moderate or low discharge, site-fidelity may be as influential as the spring flow regime in determining duration of river residency and ascent distance for paddlefish. In high flow years, however, discharge may override site fidelity in dictating locations of spawning fish.

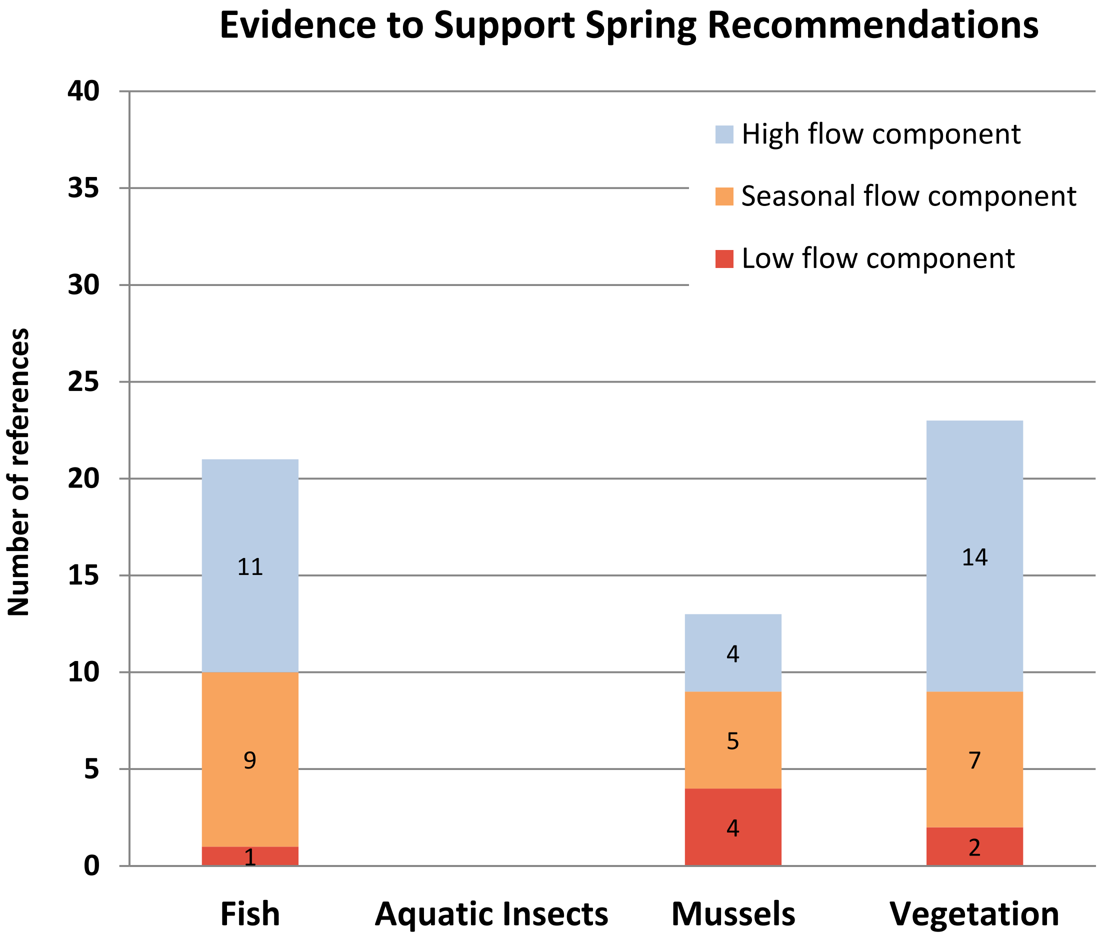


Figure 5.7 Evidence that supports spring flow recommendations from literature on fish, aquatic insects, mussels, and vegetation

Resident and nest-building fish may also be affected by increases in frequency and magnitude of high flow events; several studies document the importance of maintaining magnitude and frequency of high seasonal flow events less than bankfull. Increases in high flow magnitude may reduce availability of suitable spawning riffles or impair egg and larval development for riffle obligate fishes. This may result in a habitat limitation for successful reproduction of percids (*Etheostoma* and *Percina spp*.) and increase relative abundance of species preferring deep fast habitat (Bowen et al. 1998). Increases in magnitude or frequency of high flow events can also scour nests or damage eggs of nest-building fishes. Smith et al. (2005) also showed strongest smallmouth bass year class survival when June flows were within 40% of the long-term mean. Years when June flow was more than 40% above the mean resulted in near year class failures. Peak recruitment was observed when June flows were within 4% of the long-term mean. Survival of walleye larvae were directly related to the frequency of high flow events with low survival during years with multiple events during the spring (Mion et al. 1998). Freeman et al. (2001) also showed suitable habitat for young-of-year fishes was predicted by conditions including high pulse magnitude, duration and rate of change.

In addition to creating suitable spawning habitat for spring-spawning fishes, high spring flows are important for maintaining clean gravel for salmonid eggs and larval fish. Decreases in spring flows may result in deposition of fine sediment and suffocation of salmonid eggs. Increases in fine sediment and sand reduce intragravel permeability, DO, and survival of eggs, larvae, and juveniles (Alexander and Hansen 1986, Argent and Flebbe 1999, Louhi et al. 2011).

In headwaters, small streams and in riparian areas of larger streams and rivers, streamside salamanders depend on sufficient streamflow and inundation to provide habitat and cue breeding. If the frequency, duration or magnitude of high flow events decreases during spring, inundation of vernal pools and intermittent stream beds will decrease, reducing the hydroperiod and success of egg and larval development for streamside and mole salamanders. Under dry conditions, it is estimated that 90% of mole salamanders may skip a breeding year (Kinkead 2007). Streamside salamander eggs may also be desiccated. Nesting sites of lungless salamanders (Genus *Desmognathus*) are generally found in aquatic habitats including cascading waterfalls, streambeds, stream banks and seepage areas. Trauth (1998) documented that the breadth of viable nesting habitat is greatly increased in years with normal precipitation and hydrology.

Spring is also a critical period for establishment and growth of floodplain, riparian and aquatic vegetation. Riparian assemblages in large rivers are particularly sensitive to changes to the minimum flow and high flow events (Auble et al. 1994). Loss of bankfull and overbank events can limit dispersal of riparian tree seeds, reduce scour for scour-dependent species and communities and lead to encroachment of woody species. Seeds of riparian trees including American sycamore, river birch and silver maple depend on high flows for dispersal (Burns and Honkala 1990). Johnson (1994) showed that a 25 to 50% reduction in spring high flows and mean annual flow resulted in riparian encroachment into former channels.

High flow events prior to leaf out support the distribution and composition of disturbance-driven vegetation communities. Loss of magnitude and frequency of flood events has shifted plant communities, including loss of moist-soil species, increase in woody species, increased late-successional woodland and grassland species, loss of pioneer species, and homogenization of plant communities in temperate rivers (Johnson et al. 1998, Townsend et al. 2001, Elderd et al. 2003, Ahn et al. 2004).

Many floodplain and riparian vegetation species rely on high flows for seed dispersal and to prepare the seedbed for propagules. Changes to the timing or magnitude of high flows may reduce seed dispersal and recruitment. Comparisons of regulated reaches and free-flowing reaches have shown that regulated reaches have a higher proportion of wind-dispersed species and species with general dispersal mechanisms (Jansson et al. 2000). The width of the area of seedling establishment may be wider along an unregulated river reach as compared to a regulated reach (Shafroth et al. 2002).

Along streams within the Upper Ohio basin, high quality examples of silver maple and sycamore floodplain forest communities, which are disturbance-driven, occur at elevations close to the 1 to 2-year flood (Zimmerman and Podniesinski 2008, USGS 2012). Regulated high flows on the Allegheny River have altered the flow regime and led to failure in recruitment of silver maple and American sycamore along portions of the river (Walters et al. 1999). Spring scour is insufficient to open sites for colonization. The absence of flood disturbance favors later successional stages and a closed canopy that creates light conditions that were atypical of the pre-dam environment (Cowell and Dyer 2002).

Beginning in spring and throughout the growing season, a decrease in groundwater elevation or overbank inundation may encourage a transition from mesic (moist) to xeric (dry) communities. Williams et al. (1999) examined the influence of inundation potential (high, moderate or low probability of seasonal inundation) and forest overstory on species richness, biomass and cover of the summer ground-layer (vascular plants) at six riparian sites in the Allegheny National Forest. Richness and biomass were significantly greater for high inundation sites. Obligate and facultative wetland species occurred most often at high inundation sites. Facultative upland and upland species occurred most often in moderate to low inundation sites. Sites with high inundation potential (seasonal inundation during spring median flows) support great ground-layer species richness, biomass and cover and a relatively distinct wetland flora compared to mesic floodplains.

In a headwater setting in the Allegheny National Forest, Hanlon et al. (1998) evaluated the influence of flood frequency on seedbank composition and extant vegetation at sites with different geomorphic settings and cover types. Species composition varied across inundation classes. Forbs dominated seed bank composition for frequently inundated sites. Graminoids and forbs (grasses and other herbaceous plants) were codominant in the seed banks of moderately inundated sites. Low inundation sites were similar to moderate inundation sites and included woody species.

Small and large floods and bankfull events that typically occur during spring maintain valley and island formation, channel morphology, island formation, channel structure and sediment distribution. One-in-five year high flow events are associated with channel maintenance and overbank events (Nanson and Croke 1992). These regularly-occurring flood events transport large woody debris, specifically “key member” logs which initiate formation of stable bar apex and meander jams that alter the local flow hydraulics leading to pool and bar formation. Individual jams provide interim stability, bank protection and refugia for local forest patches and influence pool intervals and depth (Abbe 1996). Regression equations to estimate bankfull discharge for streams in Pennsylvania fall within the one-in- two year recurrence interval (Chaplin et al. 2005).

5.2 Using Hydrologic Analysis to Support Recommendations

As discussed in the previous section, we identified dozens of hypotheses that relate biological, physical habitat and water quality needs to the hydrologic regime of each stream or river type in the Upper Ohio basin. Based on literature and expert consultation, we drafted recommended limits of alteration of seasonal and low flows.

We then completed a simple hydrologic analysis that included calculating all median monthly stream flow and monthly low flow statistics for the major habitat types using 38 index gages[5]. We reviewed the draft recommendations for each habitat to determine whether they would protect the hydrologic regime of each habitat type, including the seasonal and interannual variability.

Our goal was to make sure the following three conditions were met:

1. **Recommended limits to alteration should protect hydrologic regimes characteristic of each stream or river type.** The recommendations should prevent alterations that would cause a stream to have hydrologic characteristics of a smaller stream. In other words, alteration should not cause a medium tributary to have the hydrologic characteristics of a small stream; a small stream to have hydrologic characteristics of a creek; a creek to have characteristics of a perennial headwater; or a perennial headwater to have characteristics of an intermittent stream.

   For each stream type, we reviewed the draft recommended limits of alteration around the monthly median to identify the level of alteration (expressed as % change) where that risk was reduced. Draft recommendations were: no change to the median in headwater and creek settings; < 10% change in small river settings; and < 15% for medium tributaries and large rivers. For example, we reviewed the monthly medians at medium tributary index gages (n=10) and whether those values, when altered by 15%, would shift the monthly median of a medium tributary to one that is more characteristics of a small river. Figure 5.8 illustrates that this overlap begins to occur at around 15% alteration. At 20% alteration, several medium tributaries would have a median monthly discharge within the range of small rivers. Further, several medium tributaries would have a median monthly discharge < 50 cfs, which is more characteristic of small rivers. This comparison confirmed that limiting alteration to the monthly median to less than 15% should protect the magnitude and variability of seasonal flows (represented by the monthly median) on medium tributaries. We did this comparison for each stream type by incrementally increasing and decreasing percent change to confirm that our draft recommendations should protect hydrologic regimes characteristic of each stream or river type.

   We did similar comparisons using low flow statistics for each habitat type. For headwaters and creeks, the draft low flow recommendation was no change to the monthly Q75. For all other stream types, recommendations were: no change to the monthly Q90 during summer and fall, and < 10% change during winter and spring. We confirmed that for small rivers, medium tributaries and large rivers, reducing the Q90 by these amounts would not move them to within the range of the Q75 values for headwaters and creeks.

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[5] These values were summarized in Section 3.3 and presented in Appendix 1.

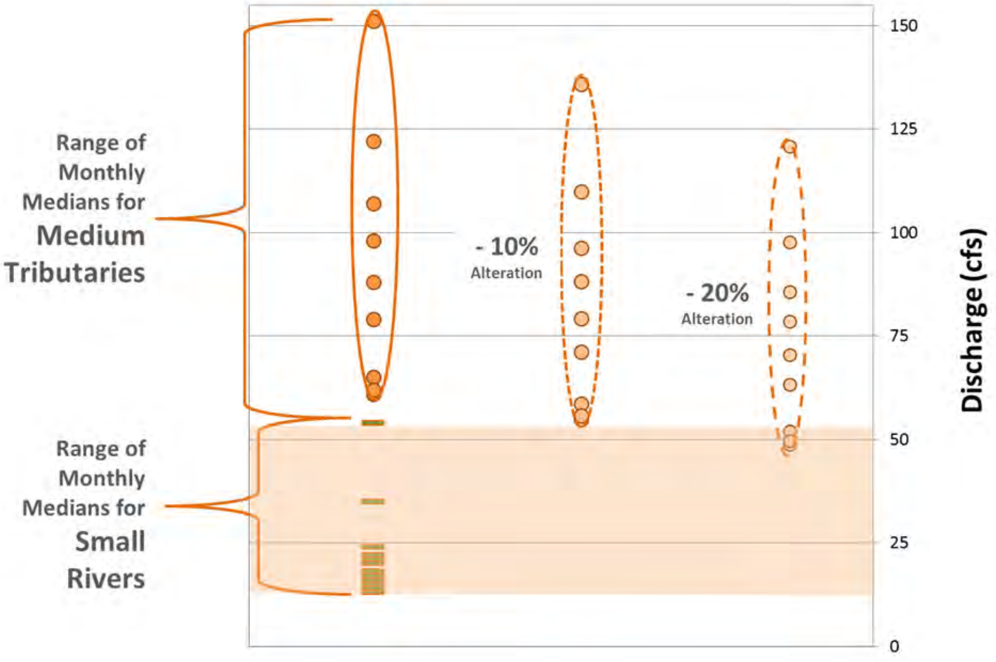


Figure 5.8 Illustration of how incrementally decreasing monthly medians for medium tributaries shifts these values into the range that is characteristic of small rivers

2. **Recommended limits to alteration should protect variability associated with months and seasons.** For example, alteration to a statistic should not decrease winter magnitudes to the extent they are similar to typical summer or fall magnitudes. They should not decrease spring magnitudes to the extent that they are similar to typical winter magnitudes.

   For each type, we reviewed the draft recommendations for limiting alteration to the monthly median to identify the degree of alteration at which these risks increase. As stated above, draft recommendations were: no change to the median in headwaters and creeks; < 10% change in small rivers; and < 15% for medium tributaries and large rivers. In headwaters and creeks, median monthly flows are often less than 5 cfs in summer and fall. A decrease in median flows could increase the frequency and duration of extreme low flow conditions and extend the dry season. In small rivers, a 10% alteration to the monthly median maintained seasonal characteristics, but when monthly median flows were decreased by 15%, the median flow in winter months shifts into the range of fall months and late fall months shift into the range of summer months. In medium tributaries and large rivers, the draft recommended change to the monthly median maintained seasonal characteristics. We also reviewed the draft recommended change of 10% to the monthly Q90 in winter and spring. We focused on the most hydrologically similar seasons, winter and fall. A 10% alteration to the winter Q90 would not shift into the range of fall low flow conditions.

3. **Recommended limits to alteration should prevent major changes in the distribution of high, seasonal or low flows.** For example, for a given stream, recommended limits should prevent monthly Q50 from decreasing to within the range of monthly Q75.

In headwaters and creeks, the magnitude of the monthly Q50 and monthly Q75 are typically within 2 cfs of one another. The magnitude of Q50 and Q75, and the difference between them is so small that their estimation is potentially affected by gage measurement error and by the error of estimating flows for ungaged stream sites (M. Stuckey, personal communication, 2012). The draft recommendation for small rivers was no change to the Q90 in summer and fall. During these months, decreases to the monthly Q90, even by 10%, could shift the flow regime for small streams, increasing the duration and frequency of interannual low flow events (transitioning the Q90 to the Q95). The magnitudes in winter and spring are higher and can support 10% alteration without increasing the risk of more frequent interannual low flow events.

5.3 Structure and Principles for Flow Recommendations

We used several principles to help structure the flow recommendations and the limits to alteration that would reduce risk of ecological changes. The first three principles are derived from the ELOHA framework. The second three emerged through workshops and consultation with technical advisors who helped by providing input on the most sensitive habitat types and periods and by putting the risk of hydrologic alteration in the context of other water quality and habitat impacts within the basin.

1. **Flow recommendations address high, seasonal, and low flows for each season**. The flow needs summarized above highlight the importance and functions of all flow components in each season. For example, even though summer is typically considered a dry season and low flow conditions during summer may be limiting for many species, high flows are important for maintaining temperature and water quality and transporting fine sediment. Conversely, spring is a wet season, but low flow conditions during spring can limit access to habitats during spawning migration.
2. **Flow recommendations for all the statistics, taken together, are intended to protect the entire flow regime.** We provide recommendations that limit alteration to the entire flow regime by using a suite of high flow, median, and low flow-related statistics. Individual recommendations will likely be applicable to variety of water uses and water management and regulatory programs that affect different aspects of the flow regime. For example, water withdrawal permit programs may incorporate low flow recommendations since water withdrawals can lead to flow depletion. High flow recommendations may be incorporated into reservoir releases on regulated rivers or through stormwater management in watersheds where increased frequency and magnitude of high flow events could negatively affect instream habitat.
3. **Flow recommendations are expressed in terms of acceptable limits (amount of change) from baseline values to capture naturally-occurring variability.** We recommend values for one of the flow statistics described in Section 3.2. Recommendations related to flow magnitude are expressed in terms of acceptable deviation (i.e., percent or absolute change to distribution) from reference conditions for a particular site rather than prescribing a specific cfs or cfs/square mile. Because our flow recommendations are expressed in terms of acceptable variation from baseline values for a particular stream, we are able to apply the same recommendations to multiple habitat types. In other words, although the *relative* (percent) change to a particular statistic may be similar between two stream types, the absolute change may be different. For example, because groundwater-fed,

high baseflow streams are generally less variable than cool-coldwater and warmwater streams, a 10% change to the typical monthly range will likely mean less *absolute* change in the high baseflow stream.

4. **Flow recommendations are more conservative (protective) for stream types, seasons, and flow components that are more likely to be sensitive to water withdrawals.** To reflect these differences in sensitivity, we apply higher levels of protection (i.e., more conservative limits to hydrologic alteration):
    - To small streams as compared to large rivers (e.g., no change to monthly median in headwaters, < 10% change in small rivers, and < 15% change in medium tributaries and large rivers).
    - In dry seasons compared to wet seasons (e.g., for medium tributaries and large rivers: no change to monthly Q90 in summer and fall and < 10% change to monthly Q90 in winter and spring).
    - For low flow conditions than median or high flow conditions. (e.g., for medium tributaries and large rivers: <15% change to monthly median and < 10% change to monthly Q90)
5. **Flow recommendations protect the most sensitive taxa in a season.** In most cases, there are many species and natural communities that benefit from a particular flow condition. In developing these recommendations, we considered the most sensitive taxa and used information on those taxa to establish the recommendation. For example, spring is an important season for emergence of aquatic insects. Spring is also a critical period for fish spawning and because of the importance of seasonal flows in maintaining access to and connectivity among spawning habitats, experts indicated that fish will be more likely than insects to be sensitive to changes in streamflow.
6. **Flow recommendations are intended to protect water quality.** Our goal is to recommend limits to hydrologic alteration that will protect existing water quality, including current assimilation capacity, which is typically calculated using the 7Q10 as the design flow condition. If these flow recommendations conflict with or are insufficient to protect water quality, then they should be modified and more protective limits to alteration should be set.

5.4 Flow Recommendations by Habitat Type

In this section, we present flow recommendations by habitat type, discussing differences among habitat types and how they influence the recommendations. These recommendations were reviewed by regional experts at a workshop in November 2012. For each habitat type, we highlight studies and hydrologic characteristics that provide particularly useful support for recommending limits to alteration of selected flow statistics.

5.4.1 Headwaters (< 4 mi^2) and Creeks (< 40 mi^2)

Recommendations for headwaters and creeks are based primarily on analysis of hydrology, expert input, literature that emphasizes the importance of ecological functions and potential sensitivity to flow alteration, and some studies that quantify responses to flow manipulation (Table 5.3).

Headwaters and creeks may be ephemeral or seasonally intermittent, may have poorly defined stream channels and the stream network may be highly dynamic and expand and contract depending on season and precipitation (Gomi et al. 2002, Williams 2006, Fritz et al. 2008). The importance of headwaters and creeks in supporting unique habitats and species and providing a significant contribution to downstream hydrologic and biogeochemical processes is documented extensively in literature and was confirmed by regional experts (Meyer et al. 2002, Lowe and Likens 2005, Morley et al. 2011, Keller et al. 2011). Although there is a significant amount of literature documenting these processes, there are few studies that quantify the flows at which these processes are disrupted.

Because of their relatively narrow channels and high canopy cover, headwaters and creeks support vegetation, particularly bryophytes, that are seldom found in larger systems (Williams et al. 1999, Fritz et al. 2009). Allochthonous inputs from riparian vegetation support a macroinvertebrate assemblage dominated by shredders and grazers. These functional feeding groups play a critical role in energy conversion and export (Wallace et al. 1996). The relatively shallow depths and coarse substrate in these settings provide distinct habitat for streamside salamanders, fish spawning and nurseries for juvenile fish development (Trauth 1988, Fritz et al. 2009a, and Hartman and Logan 2010).

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

Experimental manipulation studies are more common in headwaters and creeks than in other stream types because it is often possible to divert or otherwise manipulate large proportions of the flow volume and measure a biological response. These studies have typically measured the response of macroinvertebrate and fish communities to hydrologic alteration in the summer season.

In headwaters and creeks, the high flow recommendations are intended to maintain flows that recruit and transport coarse and fine particulate organic matter and large woody debris; in larger streams and rivers the high flow recommendations are intended to maintain channels and floodplains. The importance of this function in headwater streams is well supported in the literature (e.g., Wallace et al. 1991, Gomi et al. 2002, Neatrour et al. 2004) but there are few studies that document the threshold of flow alteration that would impair or eliminate this function. Therefore, for these streams we recommend maintaining the magnitude and frequency of high flow events based on their expected naturally-occurring range. In headwaters and creeks, typical withdrawals may remove enough flow volume to reduce the magnitude of high flows (i.e., monthly Q10) during some seasons. ***Importance of High Flow Recommendations for All Types*** provides additional explanation of high flow recommendations for all seasons.

Williams et al. (1999), Freeman and Marcinek (2006), and Kanno and Vakoun (2010) published studies that quantify responses of fish and riparian and wetland vegetation to changes to median flow conditions in headwaters and creeks. These studies are used to support the recommendation to maintain the long-term monthly median. Additionally, few studies quantify the flows at which the functions and processes of headwaters and creeks are disrupted, regional experts agreed that maintenance of the long-term monthly median should support these functions.

Table 5.3 Flow recommendations for headwaters and creeks

<table>
<tr><th></th><th>Summer</th><th>Fall</th><th>Winter</th><th>Spring</th></tr>
<tr><td>**High flows**
Annual / Interannual (>= bankfull)</td><td colspan="4">**All seasons**
• Maintain magnitude and frequency of 20-year (large) flood
• Maintain magnitude and frequency of 5-year (small) flood
• Maintain magnitude and frequency of bankfull (1 to 2-year) high flow event</td></tr>
<tr><td rowspan="2">*High flow pulses (< bankfull)*</td><td colspan="4">**All seasons**
• < 10% change to magnitude of monthly Q10</td></tr>
<tr><td></td><td>**Fall**
Maintain **frequency of high flow pulses > Q10** between Sept and Nov</td><td></td><td>**Spring**
Maintain **frequency of high flow pulses** > Q10 between Mar and May</td></tr>
<tr><td>**Seasonal flows**</td><td colspan="4">**All seasons**
• Less than 20% change to seasonal flow range (monthly Q10 to Q50);
• No change to monthly median; and
• No change to seasonal flow range (monthly Q50-Q75)</td></tr>
<tr><td>**Low flows**</td><td colspan="4">**All seasons**
• No change to **monthly Q75;** and
• No change to **low flow range (monthly Q75 to Q99)**</td></tr>
</table>

Because we recommend no change to the monthly median in these smallest streams, we also recommend no change to the seasonal flow range (monthly Q50 to Q75). The recommendation to maintain the seasonal flow range is supported by other studies that document change in fish year class strength and/or species composition when flows either (a) increase too much above the median or (b) decrease much below the median, resulting in loss of spawning habitats (Stauffer et al. 1996, Bowen et al. 1998).

Low flow recommendations in headwaters are supported by a stream manipulation study on aquatic insects in headwater streams that showed a reduction in aquatic insect density, species composition, and available habitat when flows were reduced to a level that is between summer Q75 and Q85 (Walters and Post 2011a).

We believe that the studies in small rivers (drainage areas between 40-200 mi^2) that quantify responses to reduction in streamflow can also apply to headwater streams and creeks with drainage areas less than 40 mi^2. Here, we are making the assumption that if such responses can be documented in larger streams, similar responses would likely occur in smaller streams. Those studies are discussed below under small rivers.

Recommendations to maintain seasonal and low flow statistics are further supported by the hydrologic characteristics of headwaters and creeks. For headwaters and creeks, we recommend no change to the long-term monthly Q50 and Q75 based on the monthly flow exceedance curves. As discussed in Section

3.2, we recommend using Q75 (rather than Q90) as the low flow magnitude statistic for these types because the absolute values of Q90 are so low (76% are below 5 cfs).

To be 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 of the monthly flow duration curves is so small – and the absolute magnitude of flows are so low – that even small changes risk creating zero-streamflow conditions.

5.4.2 Small Rivers (40-200 mi^2)

Compared to headwaters and creeks, there are more studies on small rivers that quantify some type of biological response to change in streamflow. This is likely because most stream sampling occurs in small (wadeable) streams and these data are typically used in such assessments. These studies address multiple taxa groups and a variety of biological and habitat responses, including assemblage shifts, habitat loss, loss of assimilative capacity, and desiccation. Table 5.4 contains the flow recommendations for small rivers.

Table 5.4 Flow recommendations for small rivers

	Summer	**Fall**	**Winter**	**Spring**
High flows ***Annual / Interannual* (*>= bankfull*)**	**All seasons** • Maintain magnitude and frequency of 20-year (large) flood • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude and frequency of bankfull (1 to 2-year) high flow event			
***High flow pulses* (*< bankfull*)**	**All seasons** • <10% change to magnitude of monthly Q10			
		Fall Maintain **frequency of high flow pulses > Q10** between Sept and Nov		**Spring** Maintain **frequency of high flow pulses** > Q10 between March and May
Seasonal flows	**All seasons** • Less than 20% change to seasonal flow range (monthly Q10 to Q50); • Less than 10% change to monthly median; and • Less than 10% change to seasonal flow range (monthly Q50-Q75)			
Low flows	**Summer and Fall** • No change to **monthly Q90;** and • Less than 10% change to **low flow range (monthly Q75 to Q99)**		**Winter and Spring** • Less than 10% change to **monthly Q90;** and • Less than 10% change to **low flow range (monthly Q75 to Q99)**	

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

For small rivers, we recommend limiting the change to monthly median to less than ten percent. This differs from the recommendation for headwaters and creeks (no change to monthly median) because the monthly medians in small rivers are higher than in streams with drainage areas less than 40 mi^2. This recommendation is also supported by studies showing that fish and mussels respond to change in the monthly median or changes to flows within the seasonal flow range (Denslinger et al. 1998, Armstrong et al. 2001, Freeman et al. 2001, Freeman and Marcinek 2006, Haag and Warren 2008, Rypel et al. 2009).

As with the headwater and creek types, there are few studies that *quantify* ecological responses to changes in median flows during winter, yet there are over 30 relevant studies that document the importance of maintaining sufficient flows during winter for flow-sensitive taxa. Zimmerman and Podniesinski (2008) is one of the few studies to quantify a relationship; they documented high quality examples of the river scour community at elevations that would be scoured between the February Q48 and Q66.

Low flow recommendations during summer and fall are supported by studies on multiple taxa groups that document fish and macroinvertebrate community shifts, dewatering of mussel habitat, loss of assimilative capacity, and desiccation of aquatic vegetation when flows are within the low flow range (Walters and Post 2011a, Walters and Post 2011b, C. Bier, personal communication, 2012; USGS 2012; Munch 1993).

Because the values of the monthly Q90 in small rivers are so low in summer and fall (49% of are below 10 cfs), we recommend no change to the long term monthly Q90 during these seasons. The monthly Q90 values are higher in winter and spring, and therefore we recommend limiting the change to these statistics to less than 10%. The differences in these recommendations are based on (a) the hydrologic characteristics and (b) the fact that most studies that exist are during dry seasons. In all seasons, we recommend less than 10% change to the low flow range between the Q75 and Q99.

5.4.3 Medium Tributaries (200-1000 mi^2) and Large Rivers (> 1000 mi^2)

In medium tributaries and large rivers, flows are influenced primarily by precipitation, large infrastructure, cumulative impacts of water use and discharges and by land cover changes that affect water budgets on a basinwide scale. Large reservoirs have potential to affect the magnitude and frequency of high flow events and may either augment or reduce flows during dry seasons. Table 5.5 contains the flow recommendations for medium tributaries and large rivers.

We recommend limiting change to the monthly median and seasonal flow range to less than 15%. Compared to all other habitat types with drainage areas < 200 mi^2, the recommendations for medium tributary and large rivers allow more change. 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.

Providing it does not conflict with other goals, including designated uses, water quality and temperature, some water can be used on medium tributaries and large rivers with minimal effects on naturally-occurring hydrologic variation and we expect the biota to be able to tolerate small changes. However, there are multiple factors affecting flows in medium tributaries and large rivers – probably more than in smaller streams. Therefore, it is probably necessary to make specific flow recommendations for reaches along large rivers to account for existing impairments, other objectives, other water quality and habitat impacts, and interactions among these factors. The recommendations presented here can be a starting point for developing more reach-specific recommendations.

Table 5.5 Flow recommendations for medium tributaries and large rivers

	Summer	**Fall**	**Winter**	**Spring**
High flows ***Annual / Interannual (>= bankfull***)	**All seasons** • Maintain magnitude and frequency of 20-year (large) flood • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude and frequency of bankfull (1 to 2-year) high flow event			
High flow pulses (< bankfull)	**All seasons** • <10% change to magnitude of monthly Q10			
		Fall Maintain **frequency of high flow pulses > Q10** between Sept and Nov		**Spring** Maintain **frequency of high flow pulses** > Q10 between March and May
Seasonal flows	**All seasons** • Less than 20% change to seasonal flow range (monthly Q10 to Q50) • Less than 15% change to monthly median; • Less than 15% change to seasonal flow range (monthly Q50-Q75)			
Low flows	**Summer and Fall** • **No change to monthly Q90;** and • Less than 10% change to **low flow range (monthly Q75 to Q99)**		**Winter and Spring** • Less than 10% change to **monthly Q90;** and • Less than 10% change to **low flow range (monthly Q75 to Q99)**	

Compared to other habitat types, there are relatively few minimally-altered gages on medium tributaries and large rivers. These low flow recommendations are based on hydrologic characteristics from a few gages on medium tributaries. Despite the large watershed area upstream, these gages have monthly Q90 that are very low in summer – especially in August and September – and 10% reduction in monthly Q90 could approach the monthly Q95 and the Q710. For these reasons, we recommend no change to the monthly Q90 during summer and fall months.

Importance of High Flow Recommendations for All Types

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

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

Many studies document the importance of high flow pulses (below bankfull) for promoting ice scour during winter, maintaining riparian and floodplain vegetation, maintaining water quality, transporting organic matter and fine sediment, and cueing fish migration. However, because of the limited amount of information to quantify the degree to which high flow pulses can decrease without ecological impacts, our recommendation of less than 10% change to the monthly Q10 is based on maintaining the long-term distribution of monthly Q10 based on 49 years of values at index gages.

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

There are at least two exceptions where alterations to high flow pulses in the Upper Ohio River basin may occur and may have ecological effects:

Reduced flow magnitude during spring – Although reservoirs typically spill at flows above bankfull, reservoirs are filling during spring to store water for releases later in the year. During filling, the high flow events below bankfull may be captured, creating low flow conditions downstream of the reservoir. This can reduce high flows that are typical of the spring season and may affect availability of and quality of downstream habitat.

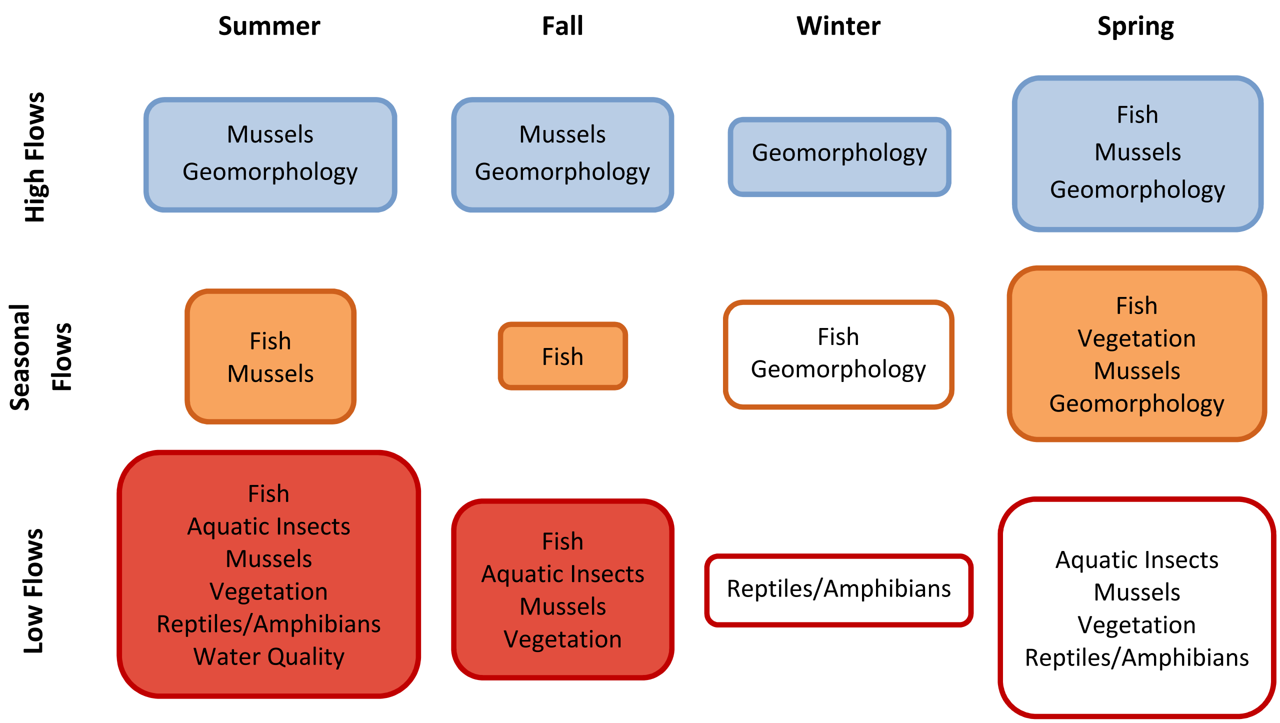
Increased magnitude and frequency of high flow events during summer – In headwaters and small streams with extensive impervious surface and stormwater runoff, the magnitude and frequency of high flow events often increases and can cause channel and bank instability, increased sediment load, and poor habitat. Studies document increased frequency of summer storm flows were related to decreased richness of endemic, sensitive, and cosmopolitan (i.e., native to multiple watersheds) fish species (e.g., Roy et al. 2005).

5.5 Summary of Supporting Information

In this brief section we summarize (a) which taxa groups provide most support for the recommendations and (b) how the hydrologic characteristics support the recommendations.

5.5.1 Literature

Figure 5.9 illustrates which taxa and/or processes provide the most evidence to support each flow recommendation. At the intersection of each season (columns) and flow component (rows), we list the taxa groups or ecological processes that support or provide moderate support for the corresponding flow recommendation based on the weight-of-evidence scoring method. The size of the box gives some indication of the degree to which each recommendation is supported in the literature. Colored boxes indicate that there is also some *quantitative* evidence in the literature for at least one taxa or process (i.e., at least three sources specifically support the recommended range of values for a particular flow statistic). If the box is not shaded, there is only qualitative evidence for the taxa listed. This only occurs for the winter seasonal and low flow recommendation and the spring low flow recommendations.



	Summer	**Fall**	**Winter**	**Spring**
High Flows	Mussels Geomorphology	Mussels Geomorphology	Geomorphology	Fish Mussels Geomorphology
Seasonal Flows	Fish Mussels	Fish	Fish Geomorphology	Fish Vegetation Mussels Geomorphology
Low Flows	Fish Aquatic Insects Mussels Vegetation Reptiles/Amphibians Water Quality	Fish Aquatic Insects Mussels Vegetation	Reptiles/Amphibians	Aquatic Insects Mussels Vegetation Reptiles/Amphibians

Figure 5.9 Synthesis of qualitative and quantitative support for high, seasonal, and low flow recommendations in each season

To summarize:

- The summer and fall low flow recommendations are supported by the most evidence. There are more flow needs addressed by these recommendations and studies during these seasons provide more quantitative evidence than during other seasons.

- There is only qualitative evidence to support the low flow recommendations in winter and spring. This is not surprising because there are relatively few studies that focus on low flow conditions during the wetter seasons and there are fewer studies done in winter and spring compared to summer and fall.
- There are fish studies that provide evidence to support seasonal flow recommendations in every season; there is quantitative evidence in every season except winter. Again this is not surprising because there are relatively few studies focused on winter flows.
- There is quantitative evidence to support high flow recommendations in all seasons. Geomorphology is the most common ecological process. Studies on the impacts of high flows on mussels typically relate to shear stress and conditions during spawning and glochidia release.

5.5.2 Hydrologic characteristics

In Section 5.2, we explained how the hydrologic analysis was used to complement the synthesis of supporting information from the literature and included a list of points summarizing the distribution of values for monthly Q50, Q75 and Q90 for each of the habitat types. Calculating those values was the first step to addressing the following question:

> *If monthly exceedence values were altered to various degrees (e.g., 10%, 15% or 20%), would they still be within the range of values for a given type and season?*

Below we summarize applicable conclusions from the hydrologic analysis in the context of the risk of altering the hydrologic regime of each stream or river type, including seasonal and interannual variability.

Headwaters (< 4 mi^2) and creeks (< 40 mi^2)

Seasonal flows	**All seasons** • No change to monthly median
Low flows	**All seasons** • No change to monthly Q75

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

- **Limit risk of increased intermittency.** Because low flows are so low during summer, change to the monthly median or to the low flow range could increase the frequency and duration of extreme low flows and potentially increase intermittency.
- **Limit risk of alteration to seasonal variability.** With relatively low flows throughout the year, change to the monthly median statistic in most months, even by as little as 10%, could increase the duration of the dry season.
- **Limit risk where there is high uncertainty with measurement or estimation.** Monthly Q50 and Q75 values are so low that (a) they are potentially affected by gage measurement error and/or error associated with estimating streamflow for small, ungaged sites.

Small Rivers (40-200 mi^2)

Seasonal flows	**All seasons** • Less than 10% change to monthly median	
Low flows	**Summer and Fall** • No change to monthly Q90	**Winter and Spring** • Less than 10% change to monthly Q90

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

- **Limit risk of alteration to seasonal variability.** Less than 10% change to the monthly median in any month would preserve seasonal variability (i.e., not change the long-term monthly median to the extent that it would be characteristic of a different season). However, monthly median values are typically within 15% of each other; therefore if the monthly median were altered by 15%, it is possible the resulting monthly value could be characteristic of a different season.

- **Limit risk of alteration to hydrologic regime characteristic of the type.** Less than 10% change to the monthly median in any month would reduce the risk that the flow regime of a small river would transition to one that is more characteristic of a headwater or creek. In summer and fall, decreases to the monthly Q90 could change the flow regime to one that is more characteristic of a creek or headwater. In winter and spring, these values are higher and there is less risk.

Medium tributaries (> 200 mi^2) and large rivers (> 1000 mi^2)

Seasonal flows	**All seasons** • Less than 15% change to monthly median	
Low flows	**Summer and Fall** • No change to monthly Q90	**Winter and Spring** • Less than 10% change to monthly Q90

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

- **Limit risk of alteration to hydrologic regime characteristic of the type.** Higher magnitudes throughout the year means that there could be up to 15% change to monthly Q50 without shifting the seasonality of the stream or changing the flow regime to one that is more characteristic of a small river. Compared to headwaters, creeks, and small rivers, there is less risk of small changes having negative ecological impacts.

- **Limit risk of alteration to seasonal variability.** During winter and spring, a 10% change to the monthly Q90 would maintain seasonal and interannual variability and prevent medium tributaries and large rivers from transitioning to flow regimes that are more characteristic of small rivers.

- **Limit risk of alteration to interannual variability.** During summer and fall, changes to the Q90 statistic would alter the distribution of low flows, specifically increasing the frequency and duration of extreme low flow events (summer and fall Q95)

Summary of Flow Recommendations for all Habitat Types – Upper Ohio River Basin

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

Summary of Flow Needs in Each Season – Upper Ohio River Basin

Flow Need - *and applicable habitat type(s)*	**Flow Component and Season (Month)**											
	Summer			**Fall**			**Winter**			**Spring**		
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**
Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes – *All types*	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥								
Support mussel spawning, glochidia transfer, juvenile colonization and growth – *All types except headwaters*	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥								🟦 🟧 🟥
Promote/support development and growth of reptiles and amphibians – *All habitat types*	🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥
Promote macroinvertebrate growth and insect emergence – *All types except large rivers*	🟥	🟥	🟥	🟥	🟥	🟥						🟥
Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout) – *All cool-coldwater types*					🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥		
Maintain temperature and water quality – *All types*		🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥							
Transport organic matter and fine sediment - *All types*		🟦	🟦	🟦	🟦							
Maintain stable hibernation habitat for reptiles and amphibians – *All types*		🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥		
Maintain overwinter habitats for resident fish – *All types* (salmonids in *cool-coldwater types* only)							🟧 🟥	🟧 🟥	🟧 🟥	🟥		
Maintain overwinter thermal regimes for mussels – *All types except headwaters*							🟧 🟥	🟧 🟥	🟧	🟧	🟧	
Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates – *All types except large rivers*							🟧 🟥	🟧 🟥	🟧 🟥	🟧 🟥		
Maintain ice scour events and floodplain connectivity – *All types except headwaters and creeks*							🟦 🟧	🟦 🟧	🟦 🟧	🟦 🟧		
Support resident fish spawning – *All types*	🟦 🟧 🟥	🟧 🟥	🟧							🟦 🟧 🟥	🟦 🟧 🟥	🟦 🟧 🟥
Cue spawning migration and maintain access to spawning habitat – *All types except headwaters*	🟧									🟦 🟧	🟦 🟧	🟦 🟧
Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats – *All types except headwaters and creeks*	🟦 🟧	🟧									🟦 🟧	🟦 🟧
Support spring emergence of aquatic insects and maintain habitats for mating and egg laying – *All types except large rivers*	🟧 🟥	🟧	🟧							🟧	🟧 🟥	🟧 🟥
Maintain habitats for streamside and vernal amphibian egg-laying and larval development – *All types*	🟥								🟦	🟦 🟥	🟦 🟥	🟦 🟥
Support establishment and growth of floodplain, riparian and aquatic vegetation – *All types*	🟥	🟥	🟥	🟥	🟥					🟦 🟥	🟦 🟥	🟦 🟥
Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals – *All types*	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥
Maintain valley and island formation, channel morphology and sediment distribution – *All types except headwaters*	🟦	🟦	🟦	🟦	🟦					🟦	🟦	🟦

Section 6: Conclusion

Maintaining flow regimes has been emphasized as a holistic approach to conserving the various ecological processes necessary to support freshwater ecosystems (Richter et al. 1997, Poff et al. 1997, Bunn and Arthington 2002, Richter et al. 2011). In this study, we began by identifying the species, natural communities, and physical processes within the Upper Ohio 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 and 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 among years. The emerging set of recommendations focuses on limiting alteration to a key set of flow statistics that represent high, typical seasonal, and low flows.

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

6.1 Conclusions from Other Ecological Flow Studies in Pennsylvania's Rivers

6.1.1 Susquehanna River Basin

The study follows the approach used previously to develop the *Ecosystem Flow Recommendations for the Susquehanna River Basin* (DePhilip and Moberg 2010). There are many similarities between the two processes and the recommendations that resulted from each, specifically:

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

There are also several notable differences due to innovations in our process and differences between the two basins:

- The Eco Evidence framework described by Norris et al. (2012) helped us **systematically assess the strength of support for the flow recommendations**. In the Susquehanna, we summarized major findings from all relevant studies as support for each recommendation, but we did not use the weight-of-evidence structure to evaluate and compare the level of support for each recommendation.

- **The number of published studies that describe or quantify biological responses to flow alteration has increased** since the Susquehanna recommendations were completed. We incorporated as much of this new information as possible into this report. We expect the number of studies will continue to grow as more basins, states, and countries evaluate ecological impacts of flow alteration.
- We **defined a headwaters class** of < 4 mi^2 drainage area based on concern that flow recommendations that may be sufficient for larger streams may fail to protect hydrologic conditions, biota and ecological processes associated with very small headwater streams. In the Susquehanna report, all streams < 50 mi^2 were included in the same class. However, in SRBC's Low Flow Protection Policy, they defined a headwater class < 10 mi^2 to protect small streams that may be especially sensitive to withdrawals.
- We completed a **hydrological characterization** that included calculating all monthly median and low flow statistics for all index gages within the project area. We used these values to evaluate the increment of change (e.g., 10%, 15%, or 20%) where change to the hydrologic regime of each stream or river type was detectable.
- We recommended **different limits to alteration of low flows during winter and spring than during summer and fall** to account for the fact that flows tend to be higher in winter and spring compared to summer and fall and that many species are likely to be more sensitive to flow depletion during dry seasons than during wet seasons.
- The Upper Ohio River basin has **higher fish and mussel diversity** than the Susquehanna River basin, and we were able to incorporate more species distribution data into the study. Many of these species are found in headwaters and creeks. Information on species diversity, sensitivity of these species and expert input on draft recommendations also influenced more protective recommendations for headwaters and creeks in the Upper Ohio basin compared with the Susquehanna basin.
- The **history of pollution in the Upper Ohio River** basin means that flow alteration can compound potential ecological impacts where water quality and habitat have already been degraded. This is also an issue in portions of the Susquehanna basin, but water quality impacts in the Upper Ohio River basin are more widespread, well documented, and were frequently discussed by experts as a factor that should influence recommendations during the Upper Ohio study.

6.1.2 Great Lakes and Potomac River Basins

The Nature Conservancy has also been a partner on flow studies for the Great Lakes and Potomac River basins, through our New York and Maryland chapters. In our scope of work for the Upper Ohio study, Pennsylvania DEP also asked us to address the Great Lakes and Potomac River basins within Pennsylvania. We focus specifically on (1) applicable conclusions from the Great Lakes and Potomac studies; and (2) potential transferability of recommendations for the Upper Ohio basin.

In Appendix 8, we summarize the approach, methods and conclusions for these two projects. Both projects are expected to be completed in spring 2013, shortly after this report is complete. We also discuss potential transferability of Upper Ohio recommendations to Great Lakes and Potomac basin streams and rivers based on similarities and differences in the habitat types and biological characteristics in each basin. Finally, we present a list of next steps to be completed before these recommendations could be applied outside the Upper Ohio River basin.

6.1.3 Delaware River Basin

We are currently collaborating with the Delaware River Basin Commission (DRBC) on an ecosystem flow study for the Delaware River basin. Understanding the instream flow needs necessary to protect ecological communities for the range of habitats in the Delaware River basin is vital for the DRBC to effectively manage and plan to meet future water needs. The resulting recommendations will be a key component in a subsequent policy development process. Such a policy will likely address passby requirements for water withdrawals, conservation release requirements for reservoirs, consumptive use mitigation triggers and flow targets. The recommendations will also help DRBC and other basin partners in the planning, design, location, and operation of future water supply storage facilities.

The project area includes all tributary rivers and streams in the Appalachian Plateau, Ridge and Valley, New England, and Piedmont Physiographic Provinces. The study will not address streams in the Coastal Plain Physiographic Province. The Delaware flow study will be complete in December 2013.

6.2 Potential Applications

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

Water withdrawal policy. In December 2012, SRBC adopted a new Low Flow Protection Policy (LFPP) and accompanying technical guidance to replace their previous technical guidance for establishing conditions on water withdrawal permits. With this policy and guidance, SRBC (1) changed the method for determining passby flows from one based on an annual value to one based on monthly exceedence values; (2) established the use of a percent-of-flow-based withdrawal limit to preserve natural flow variability and meet seasonal flow protection; and (3) revised the aquatic resources classes used to determine the applicable passby. The LFPP was accompanied by a proposed regulation change that would limit surface and groundwater withdrawals in headwater areas to prevent significant adverse impacts to the areas that are most sensitive to water withdrawals.

Under this policy, SRBC simulates the potential individual and cumulative impacts of proposed water withdrawals. A comparison of pre- and post-withdrawal streamflow conditions is used to determine the degree to which withdrawals affect monthly flow statistics used as indicators of flow alteration. BaSE is one tool that facilitates this type of pre-and post-withdrawal scenario analysis (Stuckey et al. 2012).

Reservoir operations. Our project goal was to develop a set of flow recommendations that generally apply to all streams and rivers within the project area. It is important to recognize that some streams may need more site-specific considerations due to ecological needs (e.g., presence of rare species with very specific flow requirements) or to constraints due to existing water demands (e.g., influence of reservoirs operated for flood control and other purposes). Understanding the naturally-occurring variability of high, seasonal, and low flows 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.

In 2012, the Conservancy and the USACE, Pittsburgh District developed a Cooperative Agreement to examine reservoir operations at Stonewall Jackson Lake, Tygart Lake and Youghiogheny River Lake (all within the Monongahela River basin) to assess the impacts of reservoir operations on natural hydrographs and stream flows and to provide optimum seasonal flow prescriptions needed to maintain critical species, habitats, and ecological conditions. This study builds on the general flow recommendations for large rivers presented in this report, refines them with reach-specific hydrologic and biological data, and considers them in the context of other management objectives and operating constraints. If this pilot study is successful, it could provide a model for how these flow recommendations could inform reservoir operations throughout the Upper Ohio River basin.

Application in context of landscape alteration and changing climate. We recommended limits to flow alteration using 1960-2008 as the baseline period because this period included both the flood and drought of record for most of the study area. We recognize that (a) significant hydrologic changes occurred in the watershed prior to this period, perhaps most notably the extensive deforestation and the subsequent forest regeneration; (b) development occurred between 1960-2008 that influenced hydrological and ecological conditions; and (c) future changes to temperature and precipitation are expected.

Since 1970, the average annual temperature in the northeast U.S. has increased, resulting in increased heavy precipitation, less winter precipitation falling as snow and more as rain, earlier breakup of winter ice and earlier spring snowmelt (Karl et al. 2009). Projections for much of the northeast U.S. – including the Upper Ohio River basin – are for increases in both temperature and precipitation and for more precipitation to be delivered in extreme events. Increased magnitude and severity of precipitation will likely increase magnitude and frequency of high flow events and could change timing of events. These changes will have implications for the species and natural communities discussed in this report.

And although changes to precipitation patterns will likely manifest altered streamflow regimes, riverine and riparian species will also respond directly to climate change, not just indirectly through flow-mediated changes. Even if flow regimes are maintained, species distributions will change as thermal tolerances are exceeded, both locally and regionally. Temperature cues may occur at different times. The duration of the growing season will change.

Palmer et al. (2009) provides an excellent summary of species-level impacts and anticipated impacts to water quality and ecological processes associated with climate change. Our recommendations can be used to help draw more basin-specific expectations for ecological changes that could accompany increases in frequency or duration of high flow events, changes in timing of these events or overall increases in flow magnitude that change the long-term distribution of monthly streamflow statistics.

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

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List of Appendices

Appendix 1. Seasonal and low flow statistics from index gages

Table 1. Long-term median monthly streamflows (1960-2008) at index gages across stream types

Type		Stream name	Drainage area	Median Monthly Streamflow (cfs)											
			sq mi	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Headwaters		North Fork Bens Creek at North Fork	3.5	7.3	6.4	7.5	13	11	7	3.6	2.2	1.7	1.4	1.8	4.9
		Clear Run near Buckstown, Pa.	3.7	5.4	5.1	6	12	9.2	5.5	2.7	1.3	0.8	0.6	0.9	3.6
		Lick Run at Hopwood, Pa.	3.8	6.4	5.6	7.2	11	9.4	5.4	2.2	1.0	0.7	0.5	0.9	3.7
		Abers Creek near Murrysville, Pa.	4.4	4.1	4	5.3	8.3	6.2	3.9	2.1	1.3	0.9	0.9	1.3	2.6
Creeks		Little Pine Creek near Etna, Pa.	5.8	4.2	4.2	6	9.1	7	4.1	1.8	1.0	0.6	0.6	0.9	2.2
	Cool-cold	Little Yellow Creek near Strongstown	7.4	12	11	13	23	18	10	5.4	3.0	2.1	2.0	2.7	8.4
		Big Run nr Sprankle Mills, Pa.	7.4	13	9.2	10	20	16	9.4	4.8	2.7	2.0	2.0	3.2	8.5
		Sevenmile Run near Rasselas, Pa.	7.8	13	9	9	18	20	12	5.3	2.4	1.9	1.6	4.8	12.0
		Poplar Run near Normalville, Pa.	9.3	18	16	19	33	27	15	5.7	2.7	1.7	1.8	2.6	13.0
		Brush Run near Buffalo, PA	10	8	9.4	13	19	14	8.7	3.8	2.0	1.0	0.8	1.3	3.8
		Jackson Run near North Warren, Pa.	13	23	15	15	32	29	15	6.6	4.1	3.5	3.5	6.5	19
		Georges Creek at Smithfield, Pa.	16	19	19	25	35	29	16	6.4	3.4	2.1	1.7	2.6	9.6
		Montour Run at Scott Station	25	24	25	34	50	43	29	16	11	7.4	6.5	8.5	15
		Woodcock Creek at Blooming Valley, Pa.	31	51	37	40	72	63	35	17	9.5	7.4	7	14	37
Small Rivers		French Creek near Wattsburg, Pa.	92	190	127	139	296	240	106	46	26	22	25	55	169
	Glaciated	Oswayo Creek at Shinglehouse, Pa.	99	147	98	97	218	243	125	60	33	21	18	30	109
		Little Shenango River at Greenville, Pa.	104	130	103	110	195	150	92	45	27	20	20	30	79
		Sugar Creek at Sugarcreek, Pa.	166	280	203	219	399	350	210	110	66	54	48	76	202
		Pymatuning Creek near Orangeville, Pa.	169	203	144	163	353	247	128	49	25	18	18	30	108
	Cool	Kinzua Creek near Guffey, Pa.	39	76	56	52	104	109	64	33	20	15	15	25	61
		Casselman River at Grantsville	63	105	105	118	198	155	95	45	23	16	12	18	65
		West Branch Clarion River at Wilcox, Pa.	63	121	83	76	174	185	106	52	31	24	21	36	100
		Laurel Hill Creek at Ursina, Pa.	121	235	210	233	418	341	199	89	49	35	30	44	176
	Warm	Deckers Creek at Morgantown	63	115	115	130	186	152	96	45	23	17	11	19	65
		Tenmile Creek near Clarksville, Pa	133	106	125	170	238	191	111	47	24	13	12	19	50
		Buffalo Creek near Freeport, Pa.	137	170	140	170	280	204	128	63	33	22	19	31	84
		South Fork Tenmile Creek at Jefferson, Pa	180	219	189	229	476	344	163	55	23	14	11	21	134
Medium Tributaries		Tionesta Creek at Lynch, Pa.	233	440	300	265	620	648	370	174	100	79	68	125	341
	Cool	Allegheny River at Port Allegany, Pa.	248	399	265	253	588	677	342	177	98	65	57	93	312
		Allegheny River at Eldred, Pa.	550	945	640	600	1320	1480	788	396	223	151	136	220	705
	Glaciated	French Creek at Carters Corners, Pa.	208	499	336	350	715	561	262	120	71	61	58	125	401
		Conewango Creek at Waterboro NY	290	623	422	389	882	795	354	169	106	88	87	163	500
		French Creek at Utica, Pa.	1008	2292	1601	1733	3172	2652	1305	618	379	340	322	598	1873
	Warm	Oil Creek at Rouseville, Pa.	300	524	375	390	725	658	397	196	120	98	85	153	388
		Brokenstraw Creek at Youngsville, Pa.	321	605	410	400	842	755	394	192	121	107	104	186	506
		Connoquenessing Creek near Zelienople, Pa.	356	379	340	431	667	506	297	152	90	62	59	80	181
		Slippery Rock Creek at Wurtemburg, Pa.	398	496	504	627	934	757	496	302	203	122	109	141	288
Large River		Allegheny River at Salamanca, NY	1608	2820	1900	1800	3940	4300	2390	1175	651	448	400	722	2200

Table 2. Long-term Q75 and Q90 monthly streamflows (1960-2008) for summer and fall months at index gages across stream types

Type		Stream name	Drainage area	Dec		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sept		Oct		Nov	
			sq mi	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90	Q75	Q90
Headwaters		North Fork Bens Creek at North Fork	3.5	3.9	2.5	3.8	2.6	4.4	3	8.2	5.1	7.1	4.9	4.2	3	2.1	1.5	1.3	0.9	1.0	0.6	0.8	0.5	1.0	0.6	2.2	1.0
		Clear Run near Buckstown, Pa.	3.7	2.9	1.7	2.9	1.8	3.1	2.2	6.6	4.1	5.6	3.8	3.3	2.2	1.4	0.9	0.7	0.4	0.4	0.2	0.3	0.2	0.5	0.3	1.3	0.5
		Lick Run at Hopwood, Pa.	3.8	3.1	1.7	2.9	1.6	3.7	2.2	6.5	3.9	5.4	3.5	2.8	1.6	1.0	0.6	0.5	0.2	0.3	0.2	0.2	0.1	0.4	0.2	1.6	0.7
		Abers Creek near Murrysville, Pa.	4.4	2.1	1.1	2.1	1.1	3	1.7	4.6	2.9	3.8	2.5	2.2	1.4	1.1	0.6	0.7	0.4	0.5	0.3	0.4	0.2	0.7	0.3	1.3	0.8
Creeks		Little Pine Creek near Etna, Pa.	5.8	1.6	0.71	2	1	3	1.6	5	2.9	4.1	2.7	2.2	1.4	0.9	0.5	0.4	0.2	0.3	0.1	0.3	0.1	0.4	0.2	1.0	0.5
	Cool-cold	Little Yellow Creek near Strongstown	7.4	6.6	4.5	6	4	7	4.5	13	8.7	11	7.5	6.1	3.9	2.8	1.5	1.5	0.9	1.1	0.8	1.0	0.6	1.4	0.8	3.9	1.5
		Big Run nr Sprankle Mills, Pa.	7.4	6.8	3.5	5.2	3.5	5.2	3.4	12	7.5	10	7.2	5.5	3.7	2.5	1.5	1.5	0.9	1.1	0.7	1.1	0.7	1.4	0.9	4.2	1.7
		Sevenmile Run near Rasselas, Pa.	7.8	8.2	4.8	5.1	3.4	4.9	3.1	10	6.1	13	9	7.4	4.6	2.9	1.7	1.3	0.8	0.8	0.5	0.8	0.4	1.3	0.7	5.9	2.1
		Poplar Run near Normalville, Pa.	9.3	9.2	5.5	8	4.8	9.6	6	19	12	15	9.8	7.8	4.3	2.7	1.4	1.1	0.4	0.8	0.3	0.6		1.1	0.6	4.9	2.0
		Brush Run near Buffalo, PA	10	3.2	1.3	4.3	2.3	7	4.3	12	7.1	9	6.1	4.5	2.6	1.7	0.9	0.8	0.3	0.4	0.1	0.3	0.0	0.5	0.2	1.6	0.6
		Jackson Run near North Warren, Pa.	13	13	7.8	8.6	5.9	8.6	5.5	18	11	18	13	8.8	6.3	4.3	3.2	2.6	2.0	2.1	1.6	1.9	1.3	3.1	2.1	9.6	3.4
		Georges Creek at Smithfield, Pa.	16	8.8	4.3	9.7	5.4	14	8.6	21	13	16	11	8.5	5.2	3.2	1.7	1.5	0.7	0.9	0.5	0.6	0.4	1.0	0.5	4.4	1.4
		Montour Run at Scott Station	25	12	6.8	13	8.4	20.5	12	33	22	29	22	19	13	9.8	6.5	6.2	4.3	4.5	3.1	4.0	2.7	5.0	3.5	8.7	5.3
		Woodcock Creek at Blooming Valley, Pa.	31	31	18	23	18	27	18	44	29	40	29	22	15	11.0	7.7	6.1	4.2	4.5	3.3	4.0	3.0	6.6	3.9	19.0	8.8
Small Rivers		French Creek near Wattsburg, Pa.	92	120	72	84	66	89	66	156	93	139	90	56	38	28	18	16	10	12	8.4	13	8.1	25	14	85	33
	Glaciated	Oswayo Creek at Shinglehouse, Pa.	99	85	50	56	36	60	42	119	68	158	111	77	50	35	21	18	11	12	7.7	10	7	13	8	43	15
		Little Shenango River at Greenville, Pa.	104	72	35	62	40	70	40	118	76	99	72	56	40	30	21	17	12	13	8.9	11	7.6	16	9.7	37	21
		Sugar Creek at Sugarcreek, Pa.	166	163	90	125	89	144	102	249	161	240	181	139	108	73	55	45	33	34	25	29	22	38	26	99	42
		Pymatuning Creek near Orangeville, Pa.	169	94	40	74	42	90	42	181	101	142	94	66	42	29	19	14	9	10	5.5	8	3.9	13	6.2	41	21
	Cool	Kinzua Creek near Guffey, Pa.	39	51	30	34	23	34	25	61	38	73	54	40	28	21	14	12	8.8	9.3	6.3	9.1	6	12	7.6	33	16
		Casselman River at grantsville	63	61	36	61	39	71	47	120	76	97	67	57	38	25	14	12	6.5	7.5	4	5.7	3.1	8.6	4.9	27	11
		West Branch Clarion River at Wilcox, Pa.	63	72	43	47	31	47	35	98	60	120	85	69	45	31	22	18	13	13	9	12	8.4	15	10	49	22
		Laurel Hill Creek at Ursina, Pa.	121	130	82	115	78	134	88	251	159	215	145	115	70	48	29	25	14	17	10	13	8.2	20	12	80	35
	Warm	Deckers Creek at Morgantown	63	65	35	65	41	77	51	117	65	91	64	57	35	23	12	11	5.2	7.9	3.8	5.2	2.6	8.8	4.8	29	10
		Tenmile Creek near Clarksville, PA	133	51	23	62	37	93	58	148	91	117	81	61	39	24	13	11	6	6.4	3.6	4.9	2.7	8.3	4.2	24	12
		Buffalo Creek near Freeport, Pa.	137	80	30	76	47	100	60	166	105	133	93	77	54	36	22	17	12	12	7.9	10	7.3	14	9	31	14
		South Fork Tenmile Creek at Jefferson, PA	180	95	47	85	43	106	56	235	118	180	106	74	37	22	11	9.1	4.2	5	2.6	3.7	1.8	6.7	3.8	44	14
Medium Tributaries		Tionesta Creek at Lynch, Pa.	233	270	150	161	110	170	120	360	212	435	304	243	161	107	75	61	44	43	28	41	25	54	36	170	77
	Cool	Allegheny River at Port Allegany, Pa.	248	225	142	144	96	140	98	319	179	426	301	221	149	101	67	55	32	34	22	28	19	40	23	133	46
		Allegheny River at Eldred, Pa.	550	552	340	350	230	360	240	751	441	958	669	513	334	233	152	127	79	86	53	69	43	98	58	337	124
	Glaciated	French Creek at Carters Corners, Pa.	208	290	175	205	154	200	150	381	233	340	240	154	111	74	52	41	28	35	22	31	19	61	36	201	87
		Conewango Creek at Waterboro NY	290	390	260	266	195	260	170	486	294	498	348	220	151	108	80	68	53	56	43	51	39	79	48	254	100
		French Creek at Utica, Pa.	1008	1404	840	1029	780	1022	758	1900	1174	1647	1180	791	594	410	307	237	177	205	136	175	110	307	178	986	378
	Warm	Oil Creek at Rouseville, Pa.	300	320	181	230	172	260	185	450	292	446	335	260	200	130	98	77	57	62	45	54	39	77	50	204	92
		Brokenstraw Creek at Youngsville, Pa.	321	380	220	260	190	250	180	480	309	480	353	248	184	135	104	83	66	69	52	62	45	94	64	271	116
		Connoquenessing Creek near Zelienople, Pa.	356	169	73	179	110	240	150	388	254	317	221	184	126	89	58	53	37	37	26	34	22	42	25	81	44
		Slippery Rock Creek at Wurtemburg, Pa.	398	271	134	267	160	388	220	606	382	514	380	318	231	175	117	112	72	78	56	69	50	89	56	152	91
Large River		Allegheny River at Salamanca, NY	1608	1690	1000	1100	780	1100	700	2220	1300	2880	2020	1520	997	732	470	379	273	278	190	248	184	333	218	1110	471

Appendix 2. Life history diagrams and tables

Life history diagrams for representative stream types:

Life history tables for flow-sensitive species groups:

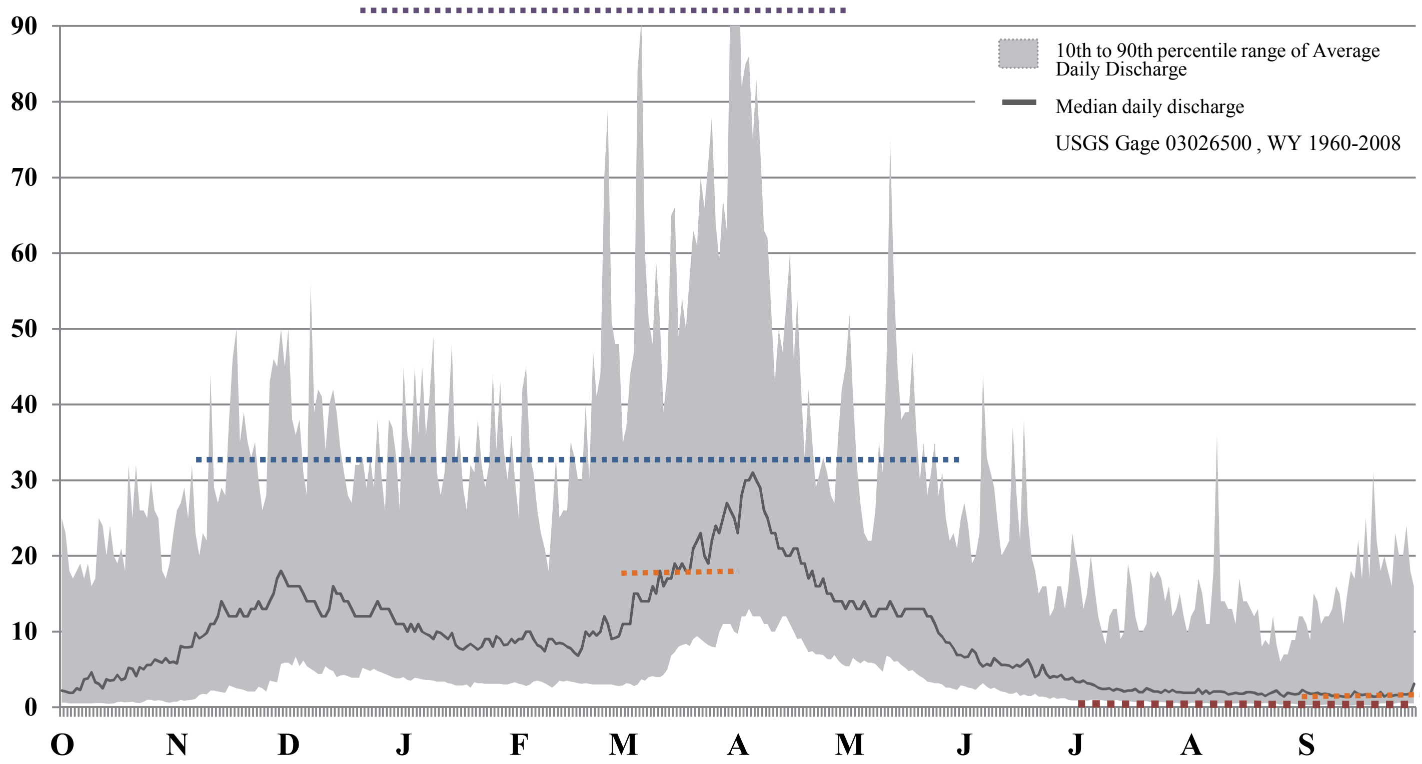
Cool-cold creek: Sevenmile Run near Rasselas (7.8 sq mi)

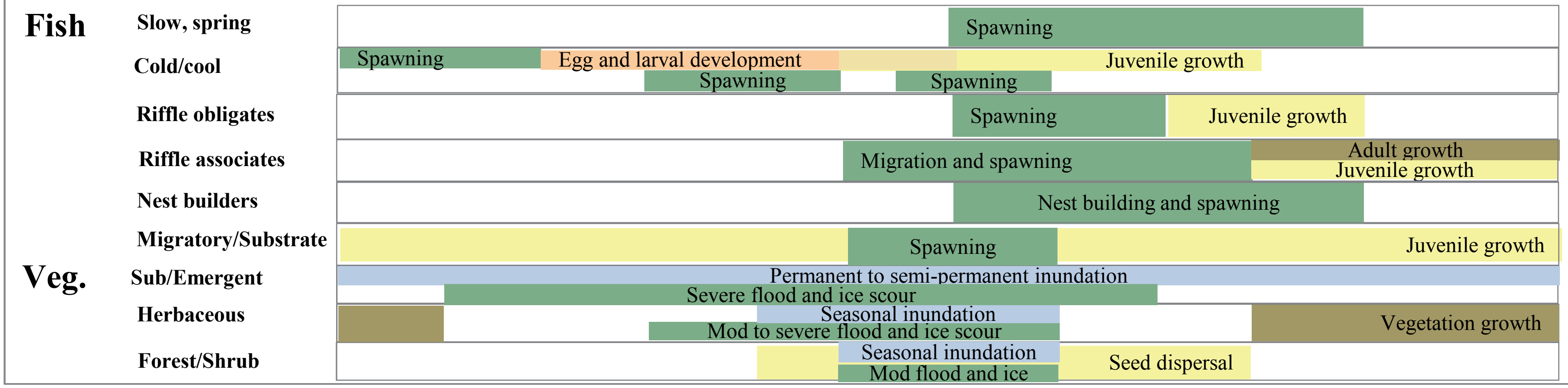
Flood (2 yr rec)
181 cfs

High Pulse (≥ Q10)
32 cfs

Seasonality (monthly median)
March: 18 cfs
Sept: 1.9 cfs

Low Pulse (≤ Q90)
1.1 cfs





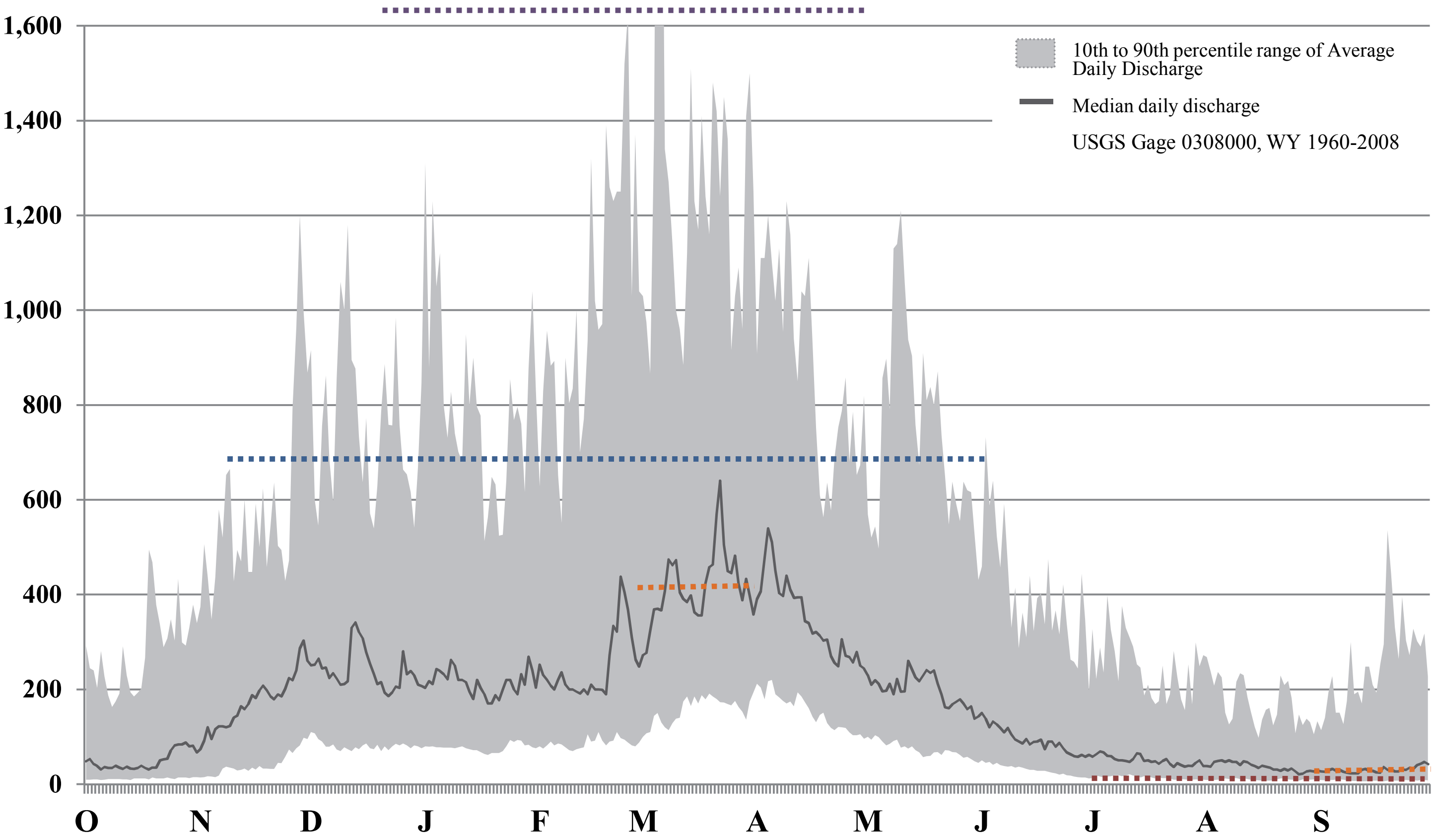
Cool, small river: Laurel Hill Creek near Ursina (121 sq mi)

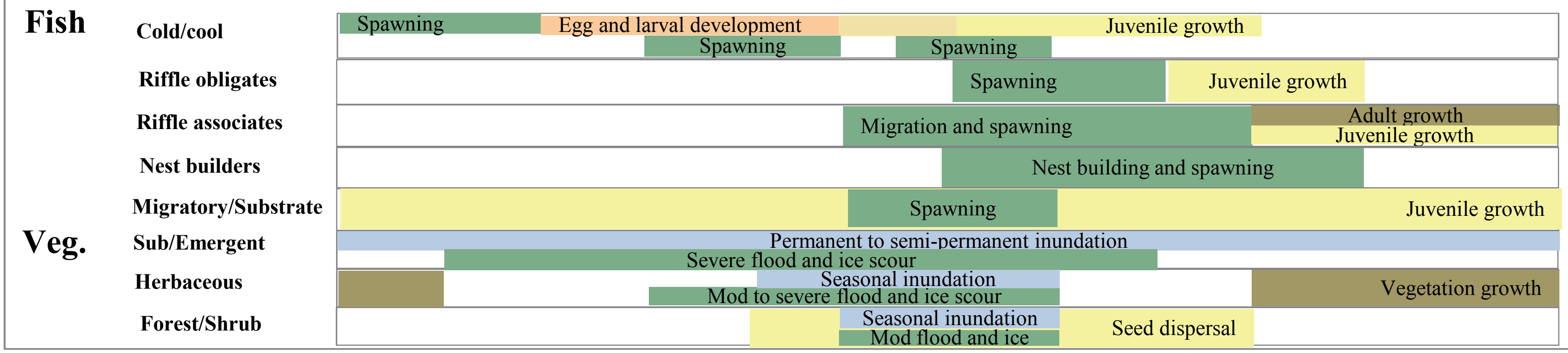
Flood (2 yr rec)
2,980 cfs

High Pulse (≥ Q10)
648 cfs

Seasonality (monthly median)
March: 419 cfs
Sept: 25.5 cfs

Low Pulse (≤ Q90)
19 cfs





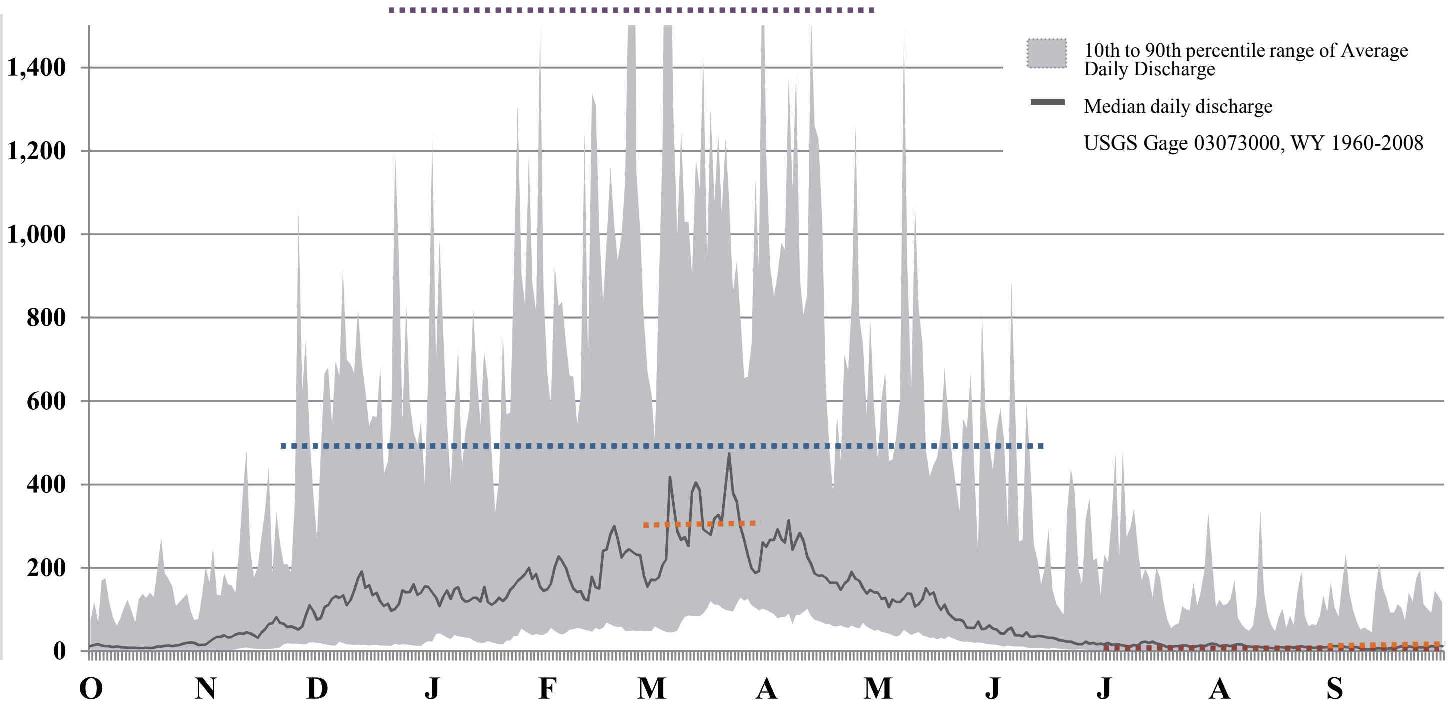
Warm, small river: South Fork Tenmile Creek at Jefferson, PA (180 sq mi)

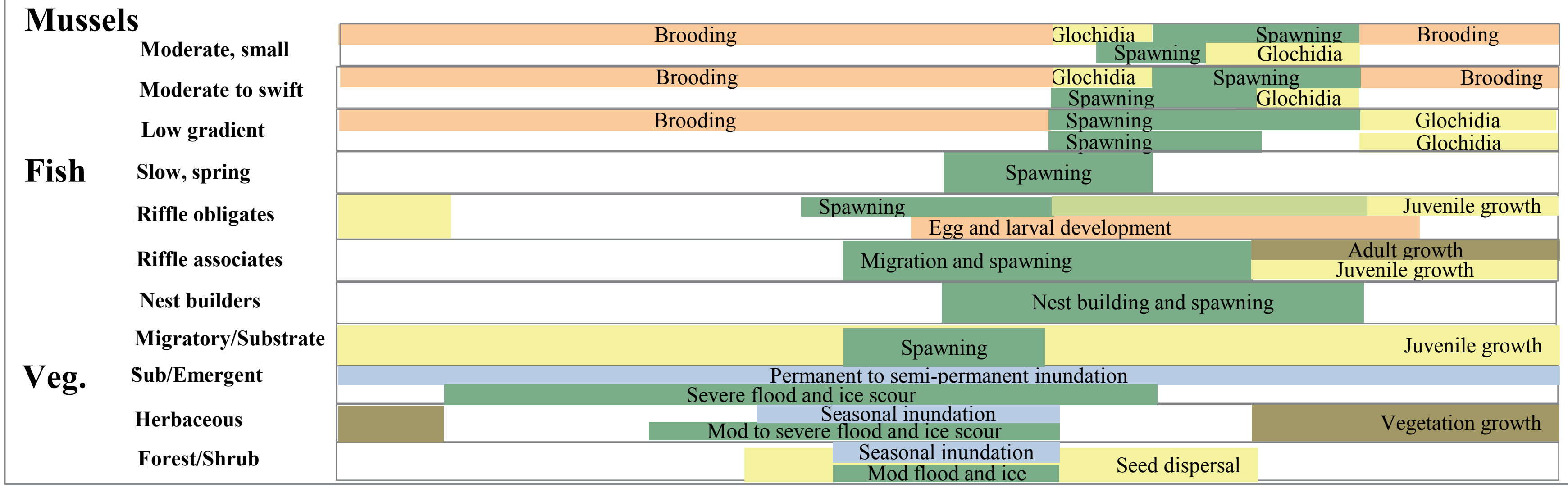
Flood (2 yr rec)
3,510 cfs

High Pulse (≥ Q10)
491 cfs

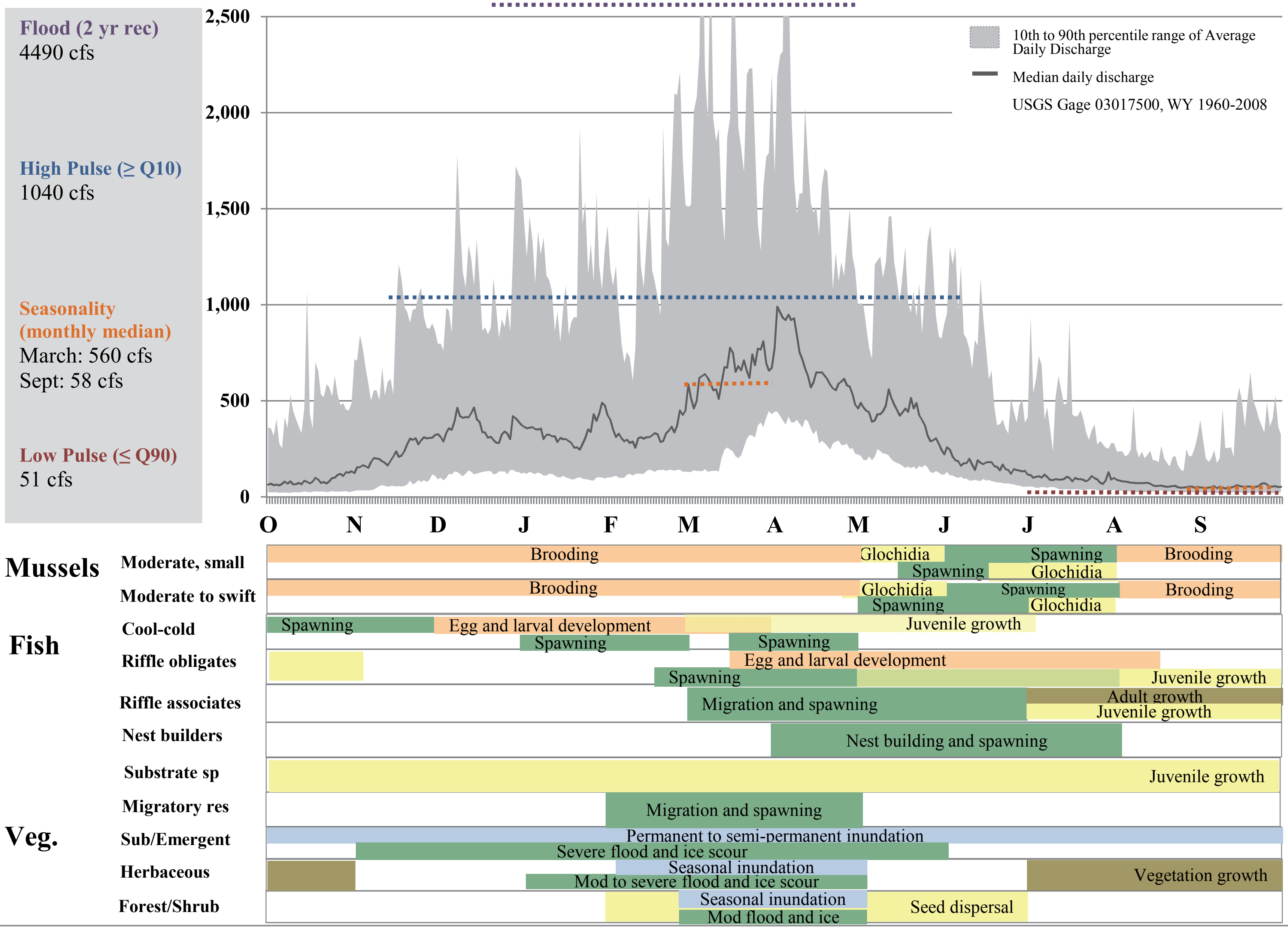
Seasonality (monthly median)
March: 294 cfs
Sept: 9 cfs

Low Pulse (≤ Q90)
4.1 cfs

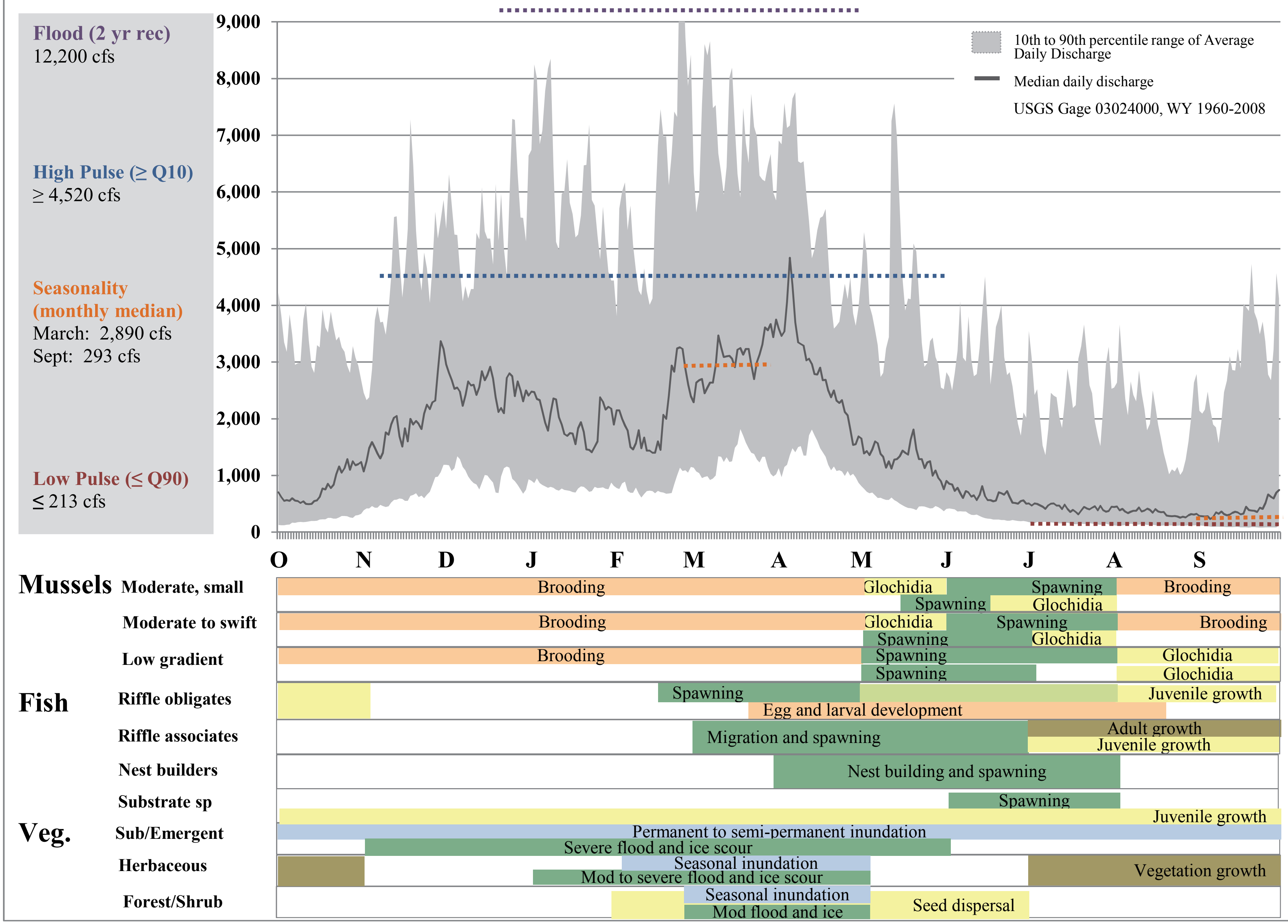




Cool, moderate to high gradient tributary: Tionesta Creek at Lynch (233 sq mi)



Glaciated tributary: French Creek at Utica (1,028 sq mi)



Flood (2 yr rec)
12,200 cfs

High Pulse (≥ Q10)
≥ 4,520 cfs

Seasonality (monthly median)
March: 2,890 cfs
Sept: 293 cfs

Low Pulse (≤ Q90)
≤ 213 cfs

Large river: Allegheny River at Franklin (5,982 sq mi)

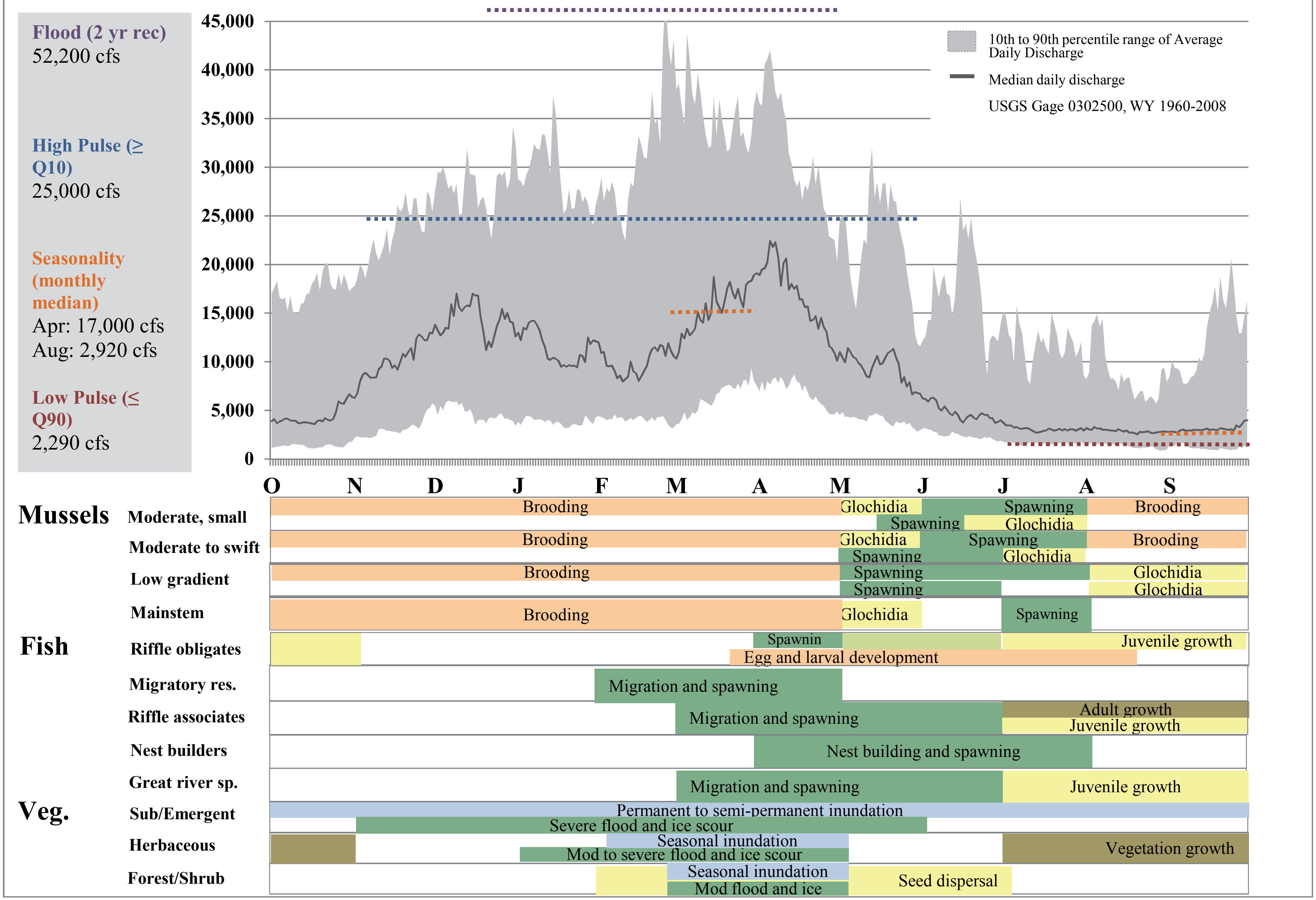


Table 1. Cold -cool fishes life history summary

	Life Stage	**Timing**	**Habitat**			**Feeding**	**Other**
		Months	River Type	Hydraulic Habitat	Physical		
Brook Trout, *Salvelinus fontinalis*	**Egg and Larval development**	Nov. -Apr.	cold and cool headwaters and creeks of moderate to high gradient	riffles	fines limit development	feeding habits greatly influenced by turbidity	• intersitial oxygen during fall and winter crucial for egg and larval development; • spawning preference in areas of groundwater upwelling; • most critical period of adult and juvenile growth during baseflow (late summer to winter); • very sensitive to temperature increases
	Juvenile Growth	Mar.-Jun.		margins and shallows	gravel and cobble provide winter cover		
	Adult Growth	Aug.-Dec.		connected riffle-run, deep pools	gravel and cobble		
Raleigh 1982, Denslinger 1999, Hudy 2005, Hunt 1969	**Spawning**	Oct.-Nov.		riffles	redds built in gravel, sometimes sand		
Brown Trout, *Salmo trutta*	**Egg and Larval development**	Nov. -Apr.	cool creeks to small rivers of moderate to high gradient	riffle-run areas with access to slow deep pools		adult diet includes fish, crayfish; juveniles primarility feed on aquatic insects	• more tolerant of siltation and higher water temperatures than brook trout (up to low 70's); • spawning may be cued by increased late fall flows, decreases in temperature and decreased daylength; • overwinter flow conditions critical for egg development, low flows caused redds to freeze and high flows can displace eggs;
	Juvenile Growth						
	Adult Growth	Aug.-Dec.					
Raleigh 1986, Denslinger 1999	**Spawning**	Oct.-Nov.			gravel depression		
Southern redbelly dace, *Phoxinus erythrogaster*	**Egg and Larval development**		cool creeks to small rivers	slow runs and quiet pools		diet dominated by algae and detritius with some aquatic insect larvae	• undercut banks with overhanging vegetation provide important places for refuge; • groundwater pumping, stream diversion, and water development have been found to negatively affect this species
	Juvenile Growth						
	Adult Growth						
Trautman 1981, Stasiak 2007	**Spawning**	May - Jul.		riffles and runs	sand and gravel		
Burbot, *Lota lota*	**Egg and Larval development**	Early Spring	cold and cool creeks to small rivers	pools	cobble and gravel	diet of fish and aquatic invertebrates	• only winter spawning fish in basin; • occurs in upper Allegheny river drainage; • environmental conditions may affect year class with only 1 YOY collected in 2002 and 56 collected in 2003 from the same stream in the upper Allegheny; • adults consume primarily fishes and crayfishes while juvenile diets were dominated by *Ephemeroptera*
	Juvenile Growth			deep pools with sluggish flows			
	Adult Growth				boulders, undercut banks		
Tzilkowski et al 2004	**Spawning**	Jan.-Mar.		pools	cobble and gravel		
Mottled Sculpin, *Cottus bairdi*	**Egg and Larval development**						
	Juvenile Growth	Dec.-Feb.	cold, cool, and cool-transitional headwaters to medium rivers	shallow riffles and margins	use interstitial spaces in substrate for cover		• habitat specialist requiring fast velocity riffles; • juvenile survival regulated by overwinter density; • small home range, typically within a reach
Hill and Grossman 1987, Freeman and Stouder 1989, Rashleigh and Grossman 2006, Grossman et al 2006	**Adult Growth**			shallow fast riffles			
	Spawning	Mid Mar.-Apr.		riffles	cavity beneath substrate		

Table 2. Riffle-obligate fishes of the Ohio river basin life history summary

	Life Stage	Timing	Habitat Use			Feeding	Other
		Months	River Type	Hydraulic Habitat	Substrate		
Longnose dace, *Rhinichthys cataractae* Edwards 1983, Hill and Grossman 1987, Mullen and Burton 1998, Gibbons and Gee 1972, Thompson et al. 2001	**Egg and Larval development**	Jun.-Jul.	cold or cool headwaters to small rivers	fry abundant in slow, shallow margins	gravel and sand	insectivore preferring mayflies, blackflies and midge larvae	• juveniles and adults are adapted to high velocity areas; • small home range, typically at reach scale; • habitat suitability index availabe; • after spawning, males defend spawning site
	Juvenile Growth			within 6 wks move to fast riffles			
	Adult Growth	age 2		fast to very fast riffles	gravel		
	Spawning	Apr. - Jun.		fast riffles	gravel and sand		
Central stoneroller, *Campostoma anomalum* Jenkins and Burkhead 1993; Gagnon 2011, Mundahl and Ingersoll 1989	**Egg and Larval development**		moderate to high gradient streams			filamentous algae, diatoms, detritus	• prefer cool, clear water moderate to fast currents; relatively intolerant of siltation which affects algal growth; male excavates nest by moving gravel; • small home range (reach length); • spawning depth documented between 8" and 24"
	Juvenile Growth						
	Adult Growth	1 to 5 years		runs and riffles			
	Spawning	Apr.- May		heads of riffles	gravel		
Stonecat Madtom, *Noturus flavus* Simon and Burr 2004, Brewer and Rabeni 2008, Gutowski and Reasley 1993	**Egg and Larval development**	Mid Jun. - Mid Sep.	warm creeks to large rivers	shallow, moderate to fast velocity riffles	gravel, cobble	insectivore preferring midges, caddis, stoneflies and mayflies	• most common of the basin's madtoms; • latest maturing, longest lived and largest basin madtom; • deposits eggs on firm substrate, often beneath rock slabs in flowing water
	Juvenile Growth						
	Adult Growth						
	Spawning	Jun.-Aug.		deeper riffles	beneath rock slabs		
Greenside darter, *Etheostoma blennioides* Greenberg 1991, Stauffer 1996, Walsh and Perry 1998	**Egg and Larval development**		warm creeks to small rivers	found in swift riffles on top of rocks	gravel, sand, SAV	insectivore preferring mayfly and midge larvae	• associated with SAV (*Podostemum*); • intolerant of siltation; • make small upstream movements to spawn; • narrow velocity niche, during low flow period shifted to smoother substrates (lower roughness, higher velocity); • largest species in Etheostoma
	Juvenile Growth						
	Adult Growth			swift riffles and runs			
	Spawning	Apr. - Jun.		riffles	attach eggs to SAV and rocks		
Bluebreast darter, *Etheostoma camurum* Schwartz 1965, Freedman et al 2009, Chipps et al. 1994, Howell 2007	**Egg and Larval development**	7 to 10 days	warm medium to large rivers	clean riffles and runs	large gravel, boulders	juveniles fed on predominantly chironomids while adults preference diptera and stoneflies while	• associated with spotted and Tippecanoe darters in dam tailwaters on mainstem • recent range extension associated with improved water quality conditions; • small migrations during low flows to persistent habitats • needs high quality water • Allegheny river the most northwestern range extent
	Juvenile Growth						
	Adult Growth			high velocity riffles	under boulders, gravel		
	Spawning	Mid. May - Jun.		riffles	bury eggs in gravel		

Table 2. continued

	Life Stage	**Timing**	**Habitat Use**			**Feeding**	**Other**
		Months	River Type	Hydraulic Habitat	Substrate		
Rainbow darter, *Etheostoma caeruleum*	**Egg and Larval development**	10 to 12 days		riffles	gravel	insectivore, forages over the tops of substrates	• earliest Etheostoma to spawn, migrates to breeding riffles • during a late summer low flow period, emigrated to deeper water, and/or mortality; • almost completely absent from standing water habitats; • males territorial in riffles
	Juvenile Growth		warm small to medium rivers	shallow riffles and small pools			
	Adult Growth			riffles and runs	between and under gravel and small cobble		
Schlosser and Toth 1984, Welsh and Perry 1998, Natureserve 2011	**Spawning**	Early June		riffles			
Fantail darter, *Etheostoma flabellare*	**Egg and Larval development**			slackwater areas and slower currents		insectivore, forages between rocks for mayfly, caddisfly and midge	• ubiquitous in the basin; • when spawning males establish territories beneath substrate where eggs are attached; • tolerant of siltation compared with other darters
	Juvenile Growth	Jun.-Nov.		dominates shallow riffle habitats			
	Adult Growth		cool to warm small to medium rivers		gravel, cobble		
Hlohowskyj et al 1986, Roberts and Angemeier 2007, Jenkins and Burkhead 1993	**Spawning**	Apr.- May.		moderate current above riffles	gravel, cobble		
Banded darter, *Etheostoma zonale*	**Egg and Larval development**						• sensitive to siltation and pollution; • most growth occurs in first year and matures at age 2; • eggs deposited on periphyton and macrophytes • moves to smaller streams to spawn • associated with SAV Podostemum
	Juvenile Growth		warm creeks to small rivers				
	Adult Growth			shallow riffles	gravel, cobble, periphyton	insectivore - midges and mayfly larvae	
Page and Burr 1981, Troutman 1981	**Spawning**	May - Jun.		riffles	fine gravel		
Gilt darter, *Percina evides*	**Egg and Larval development**						• require high water quality free of silt; • found in high abundance in riffle habitats below dams on mainstem; • intolerant of slow currents
	Juvenile Growth		warm medium to large rivers	moderate to swift riffles and runs; spend most time above bottom compared to	gravel and cobble and	insectivore feeding on dipteran, caddis, and mayfly larvae and fish ova	
	Adult Growth						
Greenberg 1991, Stauffer 1996, Welsh and Perry 1998, EPA 2008	**Spawning**	May - Mid. June					
Rosyface shiner, *Notropis rubellus*	**Egg and Larval development**						• intolerant of siltation and pollution; • typically use chub associate's nest for spawning; • schooling fish which spawns in large groups
	Juvenile Growth		warm small to medium rivers with moderate			insectivore feeds on benthic insects and those drifting in the water column	
	Adult Growth			swift riffles and runs	sand, gravel and cobble		
Cooper 1983, Pfeiffer 1955, Reed 1957	**Spawning**	May - Jun.		riffles	gravel		
Silver shiner, *Notropis photogenis*	**Egg and Larval development**						• relatively intolerant of siltation and associated with clear

Troutman 1981, Natureserve 2011	**Juvenile Growth**		warm medium to large rivers with	downstream end of swift riffles in eddys	uses a range of substrates	insectivore primarily feeds at the surface, but may feed within the water column as well	streams; • avoids dense vegetation; • can jump out of stream to take advantage of hatches; • schooling fish
	Adult Growth						
	Spawning	Apr. - May		slow to moderate riffles			

Table 3. Riffle-associate fishes life history summary

	Life Stage	Timing	Habitat			Feeding	Other
		Event	River Type	Hydraulic Habitat	Substrate		
White sucker, *Catostomus commersoni***	**Egg and Larval development**	3 wks after spawning		riffles	stay in gravel	zooplankton, aquatic insects, mollusks and crustaceans	• longlived (10 years common and up to 17 years); • spawning migration up to 6.4 km and found in headwaters; • spawning site selection influenced primarily by water velocity and depth of gravel; • max growth of juveniles and adults occurs Jul. -Aug.; • migration triggered by temperature and streamflow but can be impeded by swift currents;
	Juvenile Growth	Jul.-Aug.	warm small streams to large rivers	deep connected pools and slow runs			
	Adult Growth	Jul.-Aug.					
Twomey 1984, Cooke et al 2005	**Migration and Spawning**	Apr.-Jun.	warm creeks and small streams	riffles	gravel		
River redhorse, *Moxostoma carinatum*	**Egg and Larval development**	3 days to hatch		pools		site feeders; mollusks (freshwater clams), and aquatic insect larvae	• intolerant of turbidity and silation; • latest to spawn of the redhorses, migrates from pools and runs to rocky riffles to spawn; male creates a redd for spawning; • during early 1900's may have been confined to Allegheny but has since recolinized the Monogahela; Ohio and Shenango
	Juvenile Growth		warm medium to large rivers				
	Adult Growth			long, deep runs and pools	gravel and rocky substrates		
Curry and Spacie 1984, Mosley and Jennings 2007, Reighard 1920, Reid 2006	**Migration and Spawning**	May - Jun.		riffles	gravel shoals		
Shorthead redhorse, *Moxostoma macrolepidotum*	**Egg and Larval development**			pools		mollusks (freshwater clams), and aquatic insect larvae	• several studies document retracted ranges due to pollution barriers; • during summer and fall, deep, inundated riffle habitats where water willow was present; • spawning migrations more than 16 km documented; • most ubiquitous of the redhorse species
	Juvenile Growth		warm large rivers				
	Adult Growth			deep pools and runs			
Cooper 1983, Sule and Skelly 1985, Bunt and Cooke 2001, Cooke et al 2005	**Migration and Spawning**	Apr.-Jun.		slow moderate runs	gravel		
Golden redhorse, *Moxostoma erythrurum*	**Egg and Larval development**			pools		mollusks (freshwater clams), and aquatic insect larvae	• tend to spawn in slower, shallower riffles compared to other redhorses; • in a controlled experiement, subdaily high flow pulses stunted egg and larval development and reduced survival
	Juvenile Growth		warm medium to large rivers				
	Adult Growth						
Kwak and Skelly 1992, Weyers et al 2003, Pritchett et al 2011	**Migration and Spawning**	Apr.-Jun.		shallow riffles	gravel shoals		
Smallmouth Buffalo, *Ictiobus bubalus*	**Egg and Larval development**			shallow pools and backwaters		zooplankton, algae and aquatic insect larvae	• prefer deep, clear waters, growth can be inhibited in turbid waters; • spawning is most successful in years when spring water levels flood and provide access to terrestrial vegetation; • spawning is cued by rising water levels and increasing temperatures;
	Juvenile Growth		warm large river habitats				
	Adult Growth			moderate current deep runs and pools			
Gasaway 1970, Kallemeyn and Novotny 1977, Edwards and Twomey 1982	**Migration and Spawning**	Apr.-early Jun.		slow current backwaters and pools	generalist		
Northern Hogsucker, *Hypentelium nigricans*	**Egg and Larval development**	Apr.- late May				insect larvae, crustaceans, mollusks, diatoms	• requires clear water streams; • feeds and rests on bottom of stream in shallow riffles; • move from larger streams to smaller headwaters to spawn, over riffles, like other suckers;
	Juvenile Growth		cool to warm				
	Adult Growth			shallow riffles	cobble and gravel		
Curry and Spacie 1984, Reighard 1920, Buyak and Mohr 1978	**Spawning**	late Mar. - early May		shallow fast riffles	gravel; gravel and sand		

Table 4. Nest-builder fishes life history summary

	Life Stage	Timing	Habitat			Feeding	Other
		Months	River Type	Hydraulic Habitat	Substrate		
Spotted bass, *Micropterus punctulatus*	**Egg and Larval development**	5 days				life stage dependent; zooplankton, insects, as mature crayfish and fish	• rocky substrate and large deep pools and well defined riffles major factors in habitat suitability; • less tolerant of impounded conditions than some other Centrarchids;
	Juvenile Growth		warm medium to large rivers				
	Adult Growth			slow to moderate long, deep pools			
Vogele 1975, McMahon et al 1984	**Nest building and spawning**	Early summer		edges of pools	gravel or sand		
Creek Chub, *Semotilus atromaculatus*	**Egg and Larval development**	1 to 2 weeks		fry use margins			• stream margins important habitat for developing fry; • well defined pools, riffles and cover are important components to habitat quality ; • spawn immediately up or downstream of riffles in shallow water;
	Juvenile Growth	Jun.-Sept.	cool small to medium rivers	stream edges and margins		terrestrial and aquatic insects, molluscs and fish	
	Adult Growth	Mature 2 to 5		pools and riffles	gravel		
McMahon et al 1982, Schlosser 1989	**Nest building and spawning**	Apr- July		riffles			
River Chub *Nocomis micropogon*	**Egg and Larval development**	Late May - Jun.		slow to moderate current	gravel	Aquatic insect larvae, worms, crustaceans, mollusks, fish, plants	• 27 minnow species recorded to be nest associates of Nocomis; • nest can be 2 to 3' across and 8 -12"high
	Juvenile Growth		warm medium to large rivers				
	Adult Growth	Mar.-Apr.: gonadal		tolerant to high flows in early			
Jenkins and Burkhead 1993	**Nest building and spawning**	Apr-May		slow to moderate	gravel		
Hornyhead Chub, Nocomis biguttatus	**Egg and Larval development**						• shown to be sensitive to hydrologic alteration from groundwater diversions and reservoir operation; • constructs nest 1 to 2 feet in diameter and 6" high at center;
	Juvenile Growth		cool to warm small to medium sized streams		gravel or sand	primarily insect larvae,	
	Adult Growth			low to moderate gradient			
Miller et al 2005	**Nest building and spawning**	May-June					
Smallmouth Bass *Micropterus dolomieui*	**Egg and Larval development**	up to 1 month past spawn		pools and margins		larvae and juveniles eat zooplankton and insects; adults crayfish and fish	• mean June flows have significant influence on survival, tend to spawn during the receding limb of a high flow event • flood after spawning reduces survival if scouring occurs and an event can split the spawning season in two; • prefer areas of abundant shade and cover; • mean daily water temperature most important variable (as it interacts with discharge),
	Juvenile Growth	June			no clear preference		
	Adult Growth			pools with slow current	no clear preference		
1995, Smith 2005, Dauwalter and Fisher 2007	**Nest building and spawning**	Mid Apr.-Jul.		slow current	nests built on sand, gravel, or rock		

Table 5. Slow, spring-fed headwater fishes life history table

	Life Stage	Timing	Habitat			Feeding	Other
		Event	River Type	Hydraulic Habitat	Substrate		
Pearl Dace, *Margariscus margarita*	**Egg and Larval development**		cool spring-fed streams and creeks; boggy	high in water column		algae, plant debris, zooplankton, microcrustaceans, insects, clams	• prefers cooler temperatures and may emmigrate in response to inscreases in temperature; • reservoir construction, groundwater pumping and stream diversions have been shown to impact local populations; • actively feeds all year -overwintering in pools
	Juvenile Growth and emigration			pools	sand, gravel, aquatic		
Cooper 1983, Jenkins and Burkhead 1993, Cunningham 2006	**Adult Growth**						
	Spawning	Mid-Apr-early May		weak to moderate current	sand and gravel		
Northern redbelly dace, *Chrosomus eos*	**Egg and Larval development**	8 to 10 days	pools of headwaters and creeks, low gradient, beaver ponds		fine detritus or silt;	diatoms, filamenous algae, some aquatic insects	• usually occuring in wetlands and seeps at the beginning of surface headwaters and creeks; • activities that compromise the hydrology of these areas have been shown to impact populations; • site-feeders relying on relatively low turbidity
	Juvenile Growth and emigration			pools			
	Adult Growth	Mature at 1 or 2					
Smith 1985, Stasiak 2006	**Spawning**	May to early Aug.			mats of filamentous		
Johnny darter, *Etheostoma nigrum*	**Egg and Larval development**	up to 2 wks	headwaters, creeks and small rivers			invertivore, midge larvae and microcrustaceans	• generally small home range with minor migrations preceding spawning; • site-feeders
	Juvenile Growth and emigration				sand or silt		
	Adult Growth			quiet, slow velocity areas			
Page and Burr 1991	**Spawning**	Apr.-Jun.					

Table 6. Substrate specialist fishes life history table

	Life Stage	Timing	Habitat			Feeding	Other
		Event	River Type	Hydraulic Habitat	Substrate		
Eastern sand darter, *Ammocrypta pellucida*	**Egg and Larval development**				eggs individually buried in sand		
	Juvenile Growth and emigration		medium to large rivers, also lakes	slower waters, downstream of meander		favors chironomids, also diptera	• burrows into sand for extended periods of time which may be to avoid predators, conserve energy, and/or capture prey; • the spawning season must be synchronized with low silt levels; • egg development most successful in characteristic habitat
Cooper 1983, Grandmaison et al 2004, Criswell and Stauffer 2005	**Adult Growth**	Mature at age 1			requires clean sand and fine gravel		
	Spawning	Jun. - Jul.					
Juvenile lamprey, *Ichthyomyzon*	**Egg and Larval development**		tributaries	slow velocity stream margins	sand, organic matter and clay	suspension feeders: detritus, bacteria and algae	• juveniles develop burrow and can easily be suffocated by accumulations of silt; • depend on unidirectional flow of water through burrow to received food and uptake dissolved oxygen
Page and Burr 1991, Smith 2009	**Juvenile Growth and emigration**	3 to 7 years					

Table 7. Resident migratory fishes life history summary

	Life Stage	Timing	Habitat			Feeding	Other
		Event	River Type	Hydraulic Habitat	Substrate		
Walleye, *Sander vitreus*	**Egg and Larval development**	2 to 3 weeks					• flow during drift period is critical: too fast can impose physical damage/ too slow can result in starvation; • high flows can cause egg dislodgement decreasing recruitment; • spawning runs returning to spawning sites between 2 and 4 ft depth;
	Juvenile Growth and emigration		large rivers and lakes, need relatively cool water			top predators eating fish, crayfish and amphibians	
	Adult Growth				cobble and gravel		
	Migration and Spawning	Early spring, after ice melt		moderate to fast-flowing water	gravel shoals		
Sauger, *Sander canadensis*	**Egg and Larval development**	2 weeks					
	Juvenile Growth and emigration		large, muddy rivers			fish, crayfish and insect larvae	• runs upstream to shallow waters to spawn; • silt tolerant;
	Adult Growth			deeper pools			
	Migration and Spawning	Early spring		shallow runs	gravel		
Ohio lamprey, *Ichthyomyzon bdellium*	**Egg and Larval development**	up to 4 years	tributaries		burrow		
	Juvenile Growth and emigration					larvae eat microscopic organisms; adults parasitic and feed on other fish	• juveniles develop burrowed in fine silt, sand and organic matter and can easily be suffocated by accumulations of silt; • require connectivity between large rivers and spawning habitats
	Adult Growth		medium to large rivers				
Page and Burr 1991, PA Heritage 2007	**Migration and Spawning**	March and April	creeks and small rivers	riffles	gravel		

Table 8. Great River fishes life history summary

	Life Stage	Timing	Habitat			Feeding	Other
		Event	River Type	Hydraulic Habitat	Substrate		
Paddlefish, *Polyodon spathula*	**Egg and Larval development**	1 week		larvae typically drift into slower waters			• larvae subject to stranding if streamflows decrease; • habitats selected by juveniles were in tailwaters, typically deep (~5 m) with slow surface velocity (~1.5 m/s); • adults prefer depths greater than 1.5 m; • have been documented migrating up to 418 km to spawning grounds; • spawning cued by rising temperatures and water levels
	Juvenile Growth and emigration	Spring		sluggish pools, backwaters, and oxbows		feeds by swimming continuously, using gill rakers to strain zooplankton and algae	
	Adult Growth	Males mature at age 7 and females between 9 and 10	warm large rivers	sluggish pools, backwaters, and oxbows			
Sources: Barry et al 2007, Argent et al 2007, Argent et al 2005, Robinson 1966	**Migration and Spawning**	Spring		shoals	clean gravel bars		
Longnose gar, *Lepisosteus osseus*	**Egg and Larval development**	1 week			young attached to SAV and gravel during yolk sac absorption		• during high flow years, longnose gar will use oxbow and backwater habitats for feeding and growth; • long-lived (20 years); • spawning migrations up to 74 km have been documented (cued by temperature)
	Juvenile Growth and emigration	up to 2 feet in first year	medium streams to large rivers			juveniles feed on copepods and cladocerans while adults are piscivorous	
	Adult Growth	Matures in 3 to 4 years		sluggish pools, backwaters			
Sources: Criswell and Stauffer 2005, Robertson et al 2008, McGrath 2010	**Migration and Spawning**	May to June		shallow weed beds or gravelly riffles	gravel bars		
Skipjack herring, *Alosa chrysochloris*	**Egg and Larval development**						• avoid turbid areas by congregating in creek mouths during high water; • populations in upper Ohio are likely resident; • in the Ohio found on the lower sections of the Allegheny, Monongahela and Ohio mainstem
	Juvenile Growth and emigration	Summer and Fall				juveniles feed on plankton and insect larvae, the proportion of fish in the diet increases with size	
	Adult Growth	Matures in 2 to 3 year	large rivers	open, swift waters	sand and gravel		
Sources: Criswell and Stauffer 2005b	**Migration and Spawning**	Spring					

Table 9. Moderate gradient, small to medium creeks and streams mussel species' life history table

		Timing		**Habitat Use**			**Reproduction**		**Comments**
	Life Stage	Months	River Type	Hydraulic Habitat	Bier and Anderson 2007	Substrate	Host Fish Species	Host fish traits	
Elktoe, *Alasmidonta marginata*	Spawning	June-July	small to medium streams and rivers, but can be found in medium to large	moderate to swift current	riverine (lotic)	sand and gravel	not known	not known	• not drought tolerant, • found to be at sites with stable hydrograph as opposed to ones with droughts or spates, • associated with good to excellent water quality conditions
	Brooding	overwinter							
Watters 1995, Grabarkiewicz et al 2008	Glochidia Release	May							
Snuffbox, *Epioblasma triquetra*	Spawning	August	small to medium sized streams	moderate to swift currents	riverine (lotic)	sand and gravel	banded sculpin, logperch, mottled sculpin, blackside darter	small bodied, small home range, moderate to fast velocity	• needs clear, high quality streams; • low persistence in impounded habitats or downstream of cold hypolimnetic tailwater releases; • usually deeply buried unless spawning or during glochidia release
	Brooding	overwinter							
Carman et al 2000, Watters 2005, Schwalb et al 2010	Glochidia Release	May to mid-July							
Rabbitsfoot, *Quadrula cylindrica cylindrica*	Spawning	Spring	moderate sized streams	moderate currents	riverine (lotic)	fine and coarse substrates, gravel and cobble	blacktail shiner, spotfin shiner, rosyface shiner, rainbow darter, striped shiner	small bodied, small home range, moderate to fast velocity	• typically found on top of substrate (not burrowers) • tolerant of silt and disturbance; • known to prematurely abort conglutinates when disturbed; • found in flow refuges including water willow beds and woody debris
	Brooding								
Yeager and Neves 1986, Grabarkiewicz et al 2008, Fobian 2007	Glochidia Release	Summer							
Rainbow Mussel, *Villosa iris*	Spawning	July - May	creeks to small rivers	moderate to swift current	riverine (lotic)	clean sand, coarse gravel and cobble	mottled sculpin, rainbow, greenside and bluebreast darter, green sunfish, striped shiner, small- and largemouth bass	range of traits	• clean, well oxygenated stream reaches; • sensitive to pollution and used as indicator; • clean, well oxygenated stream reaches; • sensitive to pollution; • in riffles/runs along edges of emergent vegetation • depths no greater than 3 feet
	Brooding	overwinter							
USFWS 1994, Bogan 2002	Glochidia Release								

Table 10. Moderate to swift, medium to large river mussel species' life history table

		Timing	**Habitat Use**				**Reproduction**		**Comments**
	Life Stage	Months	River Type	Hydraulic Habitat	Bier and Anderson 2007	Substrate	Host Fish Species	Host fish traits	
Mucket, *Actinonaias ligamentina*	Spawning	May	medium creeks to large rivers	riffle, strong current	riverine (lotic)	stable sand, gravel and cobble	central stoneroller, silverjaw minnow, centrarchids, tippecanoe darter and yellow perch	small to medium bodied, small to moderate home range	• very sensitive to high water temperatures
	Brooding	overwinter							
Spooner 2005, Grabarkiewicz et al 2008	Glochidia Release	August							
Northern Riffleshell, *Epioblasma torulosa rangiana*	Spawning	August	medium creeks to large rivers	swift moving riffle and runs	riverine (lotic)	stable sand, gravel and cobble	bluebreast darter, banded darter, banded sculpin and brown trout	small to medium bodied, small to moderate home range	• occupies less than 5% of its former range; • largest remaining populations occur in the Allegheny River and French Creek; some present in navigational pools that haven't been dredged; • partially buried except for breeding season • requires well oxygenated water and sensitive to siltation
	Brooding	overwinter							
Watters 1996, Carmen and Goforth 2000,USFWS 2007	Glochidia Release	Spring							
Rayed Bean Mussel, *Villosa fabalis*	Spawning	August-July	creeks to medium rivers	riffles and shoals	riverine (lotic)	fine and coarse substrates	darter species (Tippecanoe darter)	small bodied, small home range	• can tolerate silt and disturbance; • often associated with water willow and can be found buried in roots of emergent vegetation
	Brooding	overwinter							
Ortmann 1909, Parmalee and Bogan 1998, Grabarkiewicz et al 2008	Glochidia Release	Spring							
Clubshell, *Pleurobema clava*	Spawning	May to mid-June	creeks to large rivers	shallow, runs, often downstream of riffles	riverine (lotic)	clean sand, coarse gravel and cobble	central stoneroller, striped siner, blackside darter and logperch	small bodied, small home range, moderate to fast velocity	• occupies less than 5% of its former range; • intolerant to slackwater conditions or fine sediment (mud), impoundment, siltation; • typically found in less at a water depth of 2 feet or less;
	Brooding	overwinter							
Watters 1990, USFWS 1994	Glochidia Release	late summer							
Round Pigtoe, *Pleurobema sintoxia*	Spawning	May	medium creeks to large rivers	moderate current	riverine (lotic)	sand and gravel	central stoneroller, spotfin shiner, northern red belly dace, bluntnose minnow and bluegill sunfish	small to medium bodied, small to moderate home range	• indicator of good water quality; • little evidence of recruitment in the Upper Ohio; • has also been found to occur in packed mud, sand and gravel substrates
	Brooding	summer							
Taylor 1989, Parmalee and Bogan 1998, ESI 2000	Glochidia Release	July							

Table 11. Moderate to slow current, low gradient mussel species' life history table

		Timing	Habitat Use				Reproduction		Comments
	Life Stage	Months	River Type	Hydraulic Habitat	Bier and Anderson 2007	Substrate	Host Fish Species	Host fish traits	
Three-ridge, *Amblema plicata* Weiss and Layzer 1995, Spooner et al 2005, Walsh et al 2007	Spawning	May to Aug	small to medium rivers	variety of habitats, typically low gradient	facultative riverine	variety- clay, mud, sand, gravel	bluegill, channel catfish, logperch, freshwater drum	small to large-bodied, small to large home range	• common in shallow habitats, but has been found in up to 30' of water; • also found in a range of velocities from swift current to backwater areas
	Brooding	overwinter							
	Glochidia Release								
Wabash Pigtoe, *Fusconaia flava* Watters 1996, USFWS 1994 and 2007, Walsh et al 2007	Spawning	May to August	small to large rivers	reaches greatest abundance in slow stable habitats	facultative riverine	stable coarse sand and gravel but tolerant of fines	silver shiner and creek chub	small-bodied, moderate home range	• in the Ohio, typically occurs in 4th order streams and higher; • have been found in habitats up to 15 ft in depth
	Brooding								
	Glochidia Release								
Fatmucket, *Lampsilis siliquoidea* USFWS 2003, Walsh et al 2007 ,Grabarkiewicz et al 2008	Spawning	July-August	creek to medium river	sluggish to moderate currents, typically avoids riffles	facultative riverine	fine and coarse substrates	sunfish and perch species	moderate home range, moderate to slow velocity	• in the Ohio, typically occurs in 4th order streams and higher; • tolerant of silt and disturbance
	Brooding	overwinter							
	Glochidia Release								
White Heelsplitter, *Lasmigona complanata* Taylor 1989, USFWS 1994, ESI 2000	Spawning	May to late July	medium creeks to large rivers	low gradient, runs, often downstream of riffles	facultative riverine	variety of substrates	green sunfish, white crappie, largemouth bass	moderate home range, moderate to slow velocity	• may be pollution tolerant • commonly found in sloughs, backwaters, lakes and reservoirs
	Brooding	overwinter							
	Glochidia Release	late summer							
Giant floater, *Pyganodon grandis* Bogan 2002, Grabarkiewicz et al 2008	Spawning	August	medium creeks to large rivers	low gradient stream reaches and backwater areas	primarily lentic	can persist in softer substrates	many species including skipjack herring, gar, sunfish, freshwater drum;	large-bodied, large home range species	• found to colonize newly impounded streams; • more tolerant of low oxygen conditions than most Unionids
	Brooding	overwinter							
	Glochidia Release	Early spring (April)							

Table 12: Ohio River mainstem mussel species' life history table

		Timing	Habitat Use						Hydro-Ecology
	Life Stage	Months	River Type	Hydraulic Habitat	Bier and Anderson 2007	Substrate	Host Fish Species	Host fish traits	Comments
Threehorn Wartyback, *Obliquaria reflexa*	Spawning	June to August	medium to large rivers	slow to moderate currents	facultative riverine	mud, sand, gravel	goldeye, common shiner and longnose dace	range of traits	• tolerant of impounded conditions; • found at depths up to 20' does best in depths around 6'
	Brooding								
Watters 1998, Barnart and Baird 2000	Glochidia Release								
Pink Heelsplitter, *Potamilus alatus*	Spawning	Summer	medium to large rivers	slow to swiftly flowing currents	facultative riverine	generalist	freshwater drum	large bodied, large home range	• typically bury themselves completely in substrate
	Brooding	overwinter							
Sietman 2009	Glochidia Release	Spring							
Pink Papershell, *Potamilus ohiensis*	Spawning		medium to large rivers	slow currents	facultative riverine	sand, gravel or mud	freshwater drum and white crappie	moderate to large bodied, moderate to large home range	• may establish in slackwater habitats where it may become abundant; • varying depths, typically 3'or less
	Brooding								
Parmalee and Bogan 1998, Sietman 2009, NatureServe 2011	Glochidia Release								
Fawnsfoot, *Truncilla donaciformis*	Spawning	Spring	medium to large rivers	moderate gradient, pools and riffles	facultative riverine	prefer coarser sands	freshwater drum and sauger	large bodied, large home range	• found in shallow and deep habitats; • tolerant of embayments and impoundments
	Brooding								
Parmalee and Bogan 1998, Holland-Bartels 1990, Sietman 2009	Glochidia Release								

Table 13. **Aquatic-lotic-** Species that spend most life stages in flowing waters, have specialized stream-dependent feeding habits, and/or other traits (e.g., lungless) that are characteristic of an evolutionary history of instream habitat use

				Month													Habitat preference		Traits	Comments
Common Name, *Scientific name*	**Life History Stage**	**Location during Life Stage A(quatic) or T(errestrial)**	**Timing**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**River Type or Location**	**Vegetation and or Substrate**	**Hydraulic Habitat Unit**	**Size, Diet, Home Range, Clutch size**	
Eastern Hellbender, *Cryptobranchus alleganiensis*	Breeding and Egg Laying	A	Late August - Early Sept (mating)	🟩										🟩	🟩		Create shallow nest depressions under large slabs	Nest on river bottom		Not found in streams that lack substantial crayfish populations
	Egg and Larval Development	A	60 to 87 days to hatch,	🟧	🟧	🟧										Medium sized streams to large rivers, cool-cold waters, 3rd and 4th order streams			Very large (giant salamander) with a small home range (3200 ft); Feed almost entirely on crayfish, infrequently fishes (minnows and suckers), hellgrammites, northern water snakes	
	Metamorphisis/ Transformation	A	Spend 2 years in larval stage	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		Gravel or sandy bottom, under large slabs of rock (22 to 40" in diameter)	Prefer fast- flowing waters (likely linked to gas exchange), need high DO		
	Adult	A	mature at estimated 5 to 6 years	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					Found 8 to 20" deep in French Ck
(Lungless Salamanders) **Northern Dusky Salamander**, *Desmognthus fuscus fuscus*	Breeding and Egg Laying	A	Mating in Spring and Fall, Egg Laying in July	🟩	🟩					🟩	🟩							Nest in stream banks, require flowing water particulary during hibernation		Require flowing water year round (particularly winter), dessication has been documented at a temperature of 26 C
	Egg and Larval Development	A	Late Aug - early Oct, temp dependent, 40 to 60 days to larval emergence	🟧										🟧	🟧	Ubiquitous throughout headwater and small woodland streams with abundant cover. Tend to be absent from streams where predatory fish are present. Found to dominate intermittent streams in a NC study		Larvae develop in stream	Small size; feeding opportunistic- flies, mayflies, beetles, amphipods and snails; one PA study documents an average of 28 eggs clutch size; home ranges vary by source population from 1.5 to 50 sqm	Will move to subterranean retreats during cold periods
	Metamorphisis/ Transformation	A	End of May to early July of following summer								🟨	🟨	🟨				Streamside cover of vegetation and or medium to large rocks	Generally stay within 2 meters of stream bed		High dependence on stream side vegetation and bank stability
	Adult	A/T		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					

Table 13. Continued

Common Name, *Scientific name*	Life History Stage	Location during Life Stage A(quatic) or T(errestrial)	Timing	O	N	D	J	F	M	A	M	J	J	A	S	River Type or Location	Vegetation and or Substrate	Hydraulic Habitat Unit	Size, Diet, Home Range, Clutch size	Comments
Common map turtle, *Graptemys geographica*	Hibernation	A	Early Winter (late as 1st week Dec)- Early Apr.		🟦	🟦	🟦	🟦	🟦	🟦						Prefer tributaries and large river habitats (> 50 m wide). Migrate long distances, typically upstream, to nest.		river bottoms, wedged under submerged logs		Require high DO levels during hibernation. In the spring and autum, spends a significant portion of its time basking. During basking, they require relatively stable flows that are high enough to provide a buffer between the basking structure and the shoreline.
	Mating	A	Spring and Fall	🟩	🟩				🟩	🟩								Deep Waters		
	Nesting, Egg Laying and Incubation	T	most nesting in June, can occur May - July; for most, incubation through Fall and Winter	🟧	🟧	🟧	🟧	🟧	🟧		🟧	🟧	🟧	🟧	🟧		prefer open canopy sites with well drained sandy soils near water; a range of soil types from sandy to coal, to hard-packed clay and gravel mix		Medium-sized; always feed in water- molluscs, aquatic insects and fish (mostly carrion); clutch of 6 to 20	
	Hatchling Emergence	T	April-May, most found morning following rain (another paper stated Aug-Sept)							🟨	🟨							Prefer slow-flowing sections, generally in water or basking, when found on land they are not far from shore, males move from deep water in spring to shallow water in summer		
	Adult Growth	A	Peak basking from Apr June; Oct-Nov, less basking July-Sept	🟪	🟪					🟪	🟪	🟪					locations with suitable basking sites (snags or rocks), bask communally 20 m from shore			
Spiny softshell, *Apalone mutica mutica*	Hibernation	A	Oct - mid April	🟦	🟦	🟦	🟦	🟦	🟦	🟦							river bottoms in sand and silt, avoid course substrate			
	Mating	A	April-June							🟩	🟩	🟩						relatively deep water	Large bodied; moderate clutch size with 75% survival (1 to 25 eggs); carnivorous (fish, amphibians and aquatic insects)	
	Nesting, Egg Laying and Incubation	T	Late May to Early July, Early July-Aug (8 to 12 weeks)								🟧	🟧	🟧	🟧		Prefer tributaries and large river habitats such as the Ohio, Missouri and Mississippi		hatchlings prefer shallow habitats in the river margins		nests are typically located within 18 m of the waters edge
	Hatchling Emergence	T	Aug-Sept											🟨	🟨					
	Adult Growth	A	Males mature at age 4, females at age 9														prefer areas with sandy or silty bottoms	open water, medium to fast currents		
Northern water snake, *Nerodia sipedon*	Hibernation		October - early to mid April	🟦	🟦	🟦	🟦	🟦	🟦	🟦								Use crayfish tunnels, ant mounds and meadow vole tunnels		emerge earlier if temperatures warmer
	Mating	T	Early June									🟩				Ubiquitous throughout basin, use lakes, marshes, ponds, slow- and fast moving streams and rivers			Known to heard schools of fish and tadpoles to waters edge, primarily fish, also amphibians (frogs), viviparous with a litter of 11 to 36	
	Justation and Parturition	T	Justation 3 to 5 months, Parturition late August to mid Sept									🟧	🟧	🟧	🟧					
	Adult Growth	T/A																Capable of submergence for 1.5 hours, adults use water as retreat/refuge and feeding		

Table 14. Semi-aquatic-lotic- Species that rely on flowing waters or habitats within the active channel for a one or more life stages, but may spend part of their life cycle in floodplain or upland environments

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

Table 15. Riparian and Floodplain-terrestrial and vernal habitats- Species that rely on overbank hydrologic processes to influence floodplain habitats, including wetting or refreshing vernal pools, driving vegetative composition, maintaining sediment composition, and substrate

																Habitat preference			Comments
Common Name, ***Scientific name***	**Life History Stage**	**Location during Life Stage A(quatic) or T(errestrial)**	**Timing**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**River Type or Location**	**Vegetation and or Substrate**	**Hydraulic Habitat Unit**	**Size, Diet, Home Range, Clutch size**	
Bog Turtle, *Clemmys muhlenbergii*	Hibernation	A	Begins in late Sept.- mid to late March	🟦	🟦	🟦	🟦	🟦	🟦						🟦			Stream bottom or may use muskrat dens, in streams they have been found under 8 to 10 inches of water and 1 to 3 inches under the stream	Very small body size; feeds on primarily insects (catepillars, beetles, caddisfly larvae, earthworms, crayfish) but also carrion and vegetation; Home range includes staying in or close to water, estimated 3 acre range; lay 1 clutch per year of 1 to 5 eggs	extreme habitat specialist
	Mating	A/T	Late Apr.- early June							🟩	🟩	🟩								
	Nesting, Egg Laying and Incubation	T	Nesting mid May - July, most eggs laid in June, Incubation 45 to 55 days								🟧	🟧	🟧	🟧	🟧	Found within spring-fed wetlands, open and slow, small streams or surface seepages	nests constructed in moss or sedge tussocks			
	Hatchling Emergence	T	Late August to early Oct	🟨										🟨	🟨					
	Adult Growth	A/T	Mature between ages 4 and 10, can live more than 40 years	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪		both soft mud and rocks and abundant low grasses and sedges, relatively open, smooth alder and bullrush	requires spring-fed habitats, with wet and dry pockets, shallow and slow waters		
Eastern Gray treefrog, *hyla versicolor*	Hibernation	T	Oct- early to mid April	🟦	🟦	🟦	🟦	🟦	🟦	🟦							little known, but likely that they hibernate on land because they are freeze tolerant		moderate-sized frog; insectivores: terrestrial and aerial, but not much information available	cued by temperature and moisture levels
	Breeding and Egg Laying	A	Breeding- Mid May- mid Aug						🟩	🟩	🟩	🟩	🟩	🟩		Wide but spotty distribution, most common in Southeast and Southwest PA , an arboreal species of deciduous forest types				
	Egg and Larval Development, Metamorphisis	A																use temporary and permanant bodies of water, woodland pools, ditches, cattle tanks and margins of small ponds and lakes		arboreal species, generally found in deciduous overstory, in the vicinity of ponds, temporary pools, or roadside ditches
	Adult	T																		
(Mole salamanders) **Marbled Salamander**, *Ambystoma opacum*	Breeding and Egg Laying	T	Sept.-Nov.	🟩	🟩										🟩		Upland forests, in vernal depressions, or occasionally in intermittent or ephemeral stream beds	NA	Small body-size; Diet of spiders, earthworms, grasshoppers, beetles- **Larvae diet includes microcrustacean zooplankton and aquatic beetles; clutch size ranges from 41 to 200 eggs	
	Egg and Larval Development	A	Winter and Spring, when vernal pools fill, or during intermittent stream flow						🟧	🟧						Upland forests that support vernal ponds, and intermittent stream beds, filling with water during the winter and spring		NA		
	Metamorphisis/ Transformation	A	June-July; about 135 days from									🟨	🟨				Spend most of their time, outside of the reproductive, season in subterranean retreats	NA		
	Adult	T	Spring, Summer and Winter			🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪					

Table 16. Aquatic, riparian and floodplain communities, life history summaries

Groups	**Community Types**	**Landscape Position**		**Canopy Dominants**	**Seed Dispersal/ Establishment**		**High Flows (Flood and Ice Scour, and Inundation events)**		
	Zimmerman and Podniesinski 2008	Lateral Position	Stream Size (longitudnal)		Timing and Dispersal	Substrate	magnitude	frequency	duration
Emergent Bed	Water Willow Emergent Bed	island heads, edges of bars, terraces and spits	all order streams	water-willow, Justicia americana	new shoots along rhizomes, fragmentation and seed; rhizomes are dormant in winter	variable	subject to severe ice and flood scour	SEMI-PERMANENT (flooded most of the year, may become exposed during dry periods)	
	Lizard's Tail Emergent Bed	island heads, edges of bars, terraces or channels	all order streams; abandoned oxbows and wet depressions	lizard's tail, *Saururus cernuus*		sand, silt or with cobbles	subject to severe ice and flood scour	SEMI-PERMANENT (lower portions flooded most of the year, entirely submerged by high flow events)	
Herbaceous Community	Big Bluestem - Indian-grass Floodplain Grassland	sand/gravel deposits and broad cobble/boulder shores	large rivers; Middle Allegheny (Emlenton)	big bluestem (Andropogon gerardii), switchgrass (Panicum virgatum), and Indian-grass (Sorghastrum nutans)	July-August-September; perennial warm-season grass	Sand and gravel or cobbles	subject to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	
	Hairy-fruited Sedge (Carex trichocarpa) Floodplain Wetland	floodplain edges, deposition bars, and islands where tree canopy is lacking,	intermediate to large-sized rivers	Hairy-fruited sedge, Carex trichocarpa	July-September most apparent at low flows	cobbles mixed with silt, sand and overlain by muck	subject to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	
	Japanese Knotweed Floodplain Thicket	floodplain edges, deposition bars, levees, and floodplain terraces	all rivers	Dominated by Invasive Species: Japanese Knotweed, Fallopia japonica		establishment: fine sand and silt, soils with organic matter, moderatley well-drained (scour zones) to poorly drained			
	Reed Canary-grass Floodplain Grassland	low floodplain terracees	intermediate to large-sized rivers	Dominated by Invasive Species: Reed Canary-grass , Phalaris arundinacea		gravel or cobbles overlain by silt			
	Twisted Sedge Floodplain Margin	floodplain margin	smaller to intermediate tributaries	Twisted sedge, Carex torta	July-September	establish in wet alluvium, very well-drained course sand, gravel and cobbles	subject to severe ice and flood scour		
	Floodplain Meadow	Island heads, edges of bars, terraces or channels	smaller to intermediate tributaries	Joe pye weed (Eutrochium fistulosum)	July-September	cobbles mixed with silt, sand and overlain by muck	subject to moderate flood scour	SEASONAL TO TEMPORARY FLOODING	
	Floodplain Scour Community	island heads, edges of bars, terraces and spits; outcrop community specifically on large river banks	all order streams, with outcrop community on large rivers; Clarion, Youghiogheny Rivers	sparsely vegetated; Hypericum spp., Osmunda regalis, many rare plant species such as Marshalia grandiflora	July-September	cobble and bedrock	severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	
	Periodically Exposed Shoreline Community	a wide variety of riverine settings including island heads, bars, spits, low terraces, and river banks.	all orders of streams,	sparsely vegetated; smart weed (Persicaria spp) and other annuals	July-September	sand, gravel, cobble, bedrock	severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	

Groups	Community Types *Zimmerman and Podniesinski 2008*	Landscape Position		Canopy Dominants	Seed Dispersal/ Establishment		High Flows (Flood and Ice Scour, and Inundation events)		
		Lateral Position	Stream Size (longitudnal)		Timing and Dispersal	Substrate	magnitude	frequency	duration
Scrub/Shrub Community	Alder - Dogwood Floodplain Thicket	flats within active channels	smaller to intermediate tributaries	speckled alder, *Alnus incana ssp. rugosa*	September-April; wind dispersed	cobble substrate	moderate to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	
	Mixed Hardwood Floodplain Thicket	bars and low terraces, transition community between low floodplain herbaceous and upland floodplain forest,		See associated floodplain forest	See associated floodplain forest		moderate to severe ice and flood scour	SEASONAL TO TEMPORARY FLOODING	
	Buttonbush wetland	Flooded oxbows, wet floodplain swales or along floodplain margins	intermediate to large tributaries	Buttonbush, Cephalanthus occidentalis	April -August; water and wind dispersed	establish in very moist, almost flooded exposed soils, deeper soils of silt and loam,	low to moderate flood scour	PROLONGED TO PERMANENT FLOODING	
	Black Willow Floodplain Thicket	stream and riverbanks, downstream ends and heads of islands where stream velocity is reduced such as back channels and oxbows		black willow, *Salix nigra*	April -August; water and wind dispersed	establish in very moist, almost flooded exposed soils, deeper soils of silt and loam,	low to moderate to ice and flood scour	SEASONAL TO TEMPORARY FLOODING Inundation period may be longer due to macrotopography, high groundwater, and poor drainage	
Floodplain Forest	Sycamore floodplain forest	floodplains, small islands, low bars and lower terraces, oldest cohorts furthest from active stream channel	intermediate order tributaries	American syacamore, *Plantanus occidentalis*	February - May; water dispersed,establishment after flood event	establish in wet alluvium, very well-drained course sand, gravel and cobbles	moderate ice and flood scour	TEMPORARY FLOODING (saturated or inundated for > 2 wks and < growing season), *P. Occidentalis* seedlings will die if inundated > 2 wks	
	Silver maple floodplain forest	well-developed floodplains and islands, low and occasionally high terraces	major tributaries and the mainstem	silver maple, *Acer saccharinum*	April-June; Establishment: after flood event, high flow years	establishment: fine sand and silt, soils with organic matter, moderatley well-drained (scour zones) to poorly drained	low to moderate ice and flood scour	TEMPORARY FLOODING	
	Sugar Maple - Mixed Hardwood Floodplain Forest	high terraces	intermediate order tributaries	sugar maple, Acer saccharum; American basswood, Tilia americana	April-June; Establishment: after flood event, high flow years	establishment: fine sand and silt, soils with organic matter, moderatley well-drained	low flood scour	TEMPORARY FLOODING	
	Green Ash - Mixed Hardwood Floodplain Forest	behind levees and on low terraces which may frequently be temporarily flooded but with a shorter duration of flooding than the Silver Maple Floodplain Forest.	intermediate order tributaries	green ash, Fraxinus pennsylvanica	April-June; Establishment: after flood event, moderate to high flow years	establishment: fine sand and silt, soils with organic matter, moderatley well-drained (scour zones) to poorly drained	low to moderate ice and flood scour	TEMPORARY FLOODING	
	Bitternut Hickory Floodplain Forest	high terraces	intermediate order tributaries	bitternut hickory, Carya cordiformis	April-June; Establishment: after flood event, high flow years	establishment: fine sand and silt, soils with organic matter, moderatley well-drained	low flood scour	TEMPORARY FLOODING	
	Red Maple - Elm - Willow Floodplain Forest	old oxbows along the floodplain, or in depressions behind natural levees	major tributaries and the mainstem	red maple, Acer rubrum; American elm, Ulmus americana, black willow, Salix nigra		establishment: fine sand and silt, soils with organic matter, poorly drained	low flood scour	TEMPORARY TO SEMI-PERMANENT FLOODING	

Appendix 3. Distribution of species among habitat types

Table 1. Fish groups, focal species and associated habitats types for the Pennsylvania portion of the Ohio River Basin.

			Headwaters and Creeks (0 to 40 sq mi)		**Small Rivers (40 to 200 sq mi)**			**Medium Tributaries (200 to 1000 sq mi)**			**Large Rivers (> 1,000 sq mi)**	
Draft Species Groups	**Common name**	**Scientific name**	Cool-cold headwaters and creeks	Warm headwaters and creeks	Cool, small rivers, unglaciated	Warm, small rivers, unglaciated	Glaciated small rivers	Cool, moderate to high gradient tributaries, unglaciated	Warm, tributaries, unglaciated	Glaciated tributaries	Large River	Large, navigational river
cold/cool	Mottled sculpin	*Cottus bairdii*	x		x		x					
	Brown trout	*Salmo trutta*	x		x		x					
	Brook trout	*Salvelinus fontinalis*	x		x		x					
	Southern red belly dace	*Phoxinus erythrogaster*	x		x							
	Burbot	*Lota lota*	x		x			x				
slow moving, spring fed	Pearl dace	*Margariscus margarita*	x	x								
	Northern red belly dace	*Chrosomus eos*	x									
	Johnny darter	*Etheostoma nigrum*	x	x	x	x	x	x	x	x	x	x
riffle obligates	Longnose dace	*Rhinichthys cataractae*	x		x			x				
	Central stoneroller	*Campostoma anomalum*	x	x	x	x	x	x	x	x		
	Noturus											
	Stonecat madtom	*Noturus flavus*		x		x			x	x		
	Etheostoma											
	Greenside darter	*Etheostoma blennioides*	x	x		x		x	x	x	x	x
	Rainbow darter	*Etheostoma caeruleum*	x		x	x	x		x	x	x	
	Bluebreast darter	*Etheostoma camurum*			x	x	x	x	x	x	x	x
	Fantail darter	*Etheostoma flabellare*		x	x	x	x	x	x	x	x	
	Banded darter	*Etheostoma zonale*	x	x	x	x	x	x	x	x		x
	Percina											
	Gilt darter	*Percina evides*				x	x		x	x	x	x
	Blackside darter	*Percina maculata*	x	x	x	x	x				x	x
	Notropis											
	Rosyface shiner	*Notropis rubellus*	x	x	x	x	x		x	x	x	
	Silver shiner	*Notropis photogenis*							x	x	x	x
substrate specialists	Ammocetes	*Petromyzontidae*	x	x	x	x	x	x	x	x	x	x
	Eastern sand darter	*Ammocrypta pellucida*					x			x	x	
riffle associates	White sucker	*Catosomus commersonii*		x		x			x	x		
	Northern hogsucker	*Hypentelium nigricans*	x	x	x		x					
	Smallmouth buffalo	*Ictiobus bubalus*						x			x	x
	Moxostoma											
	River redhorse	*Moxostoma carinatum*						x	x	x	x	x
	Shorthead redhorse	*Moxostoma macrolepidotum*				x			x	x	x	x
	Golden redhorse	*Moxostoma erythrurum*				x		x	x	x	x	x
nest builders	Spotted bass	*Micropterus punctulatus*									x	x
	Smallmouth bass	*Micropterus dolomieui*			x	x	x	x	x	x	x	x
	River chub	*Nocomis micropogon*							x	x	x	
	Hornyhead chub	*Nocomis biguttatus*	x		x		x					
	Creek chub	*Semotilus atromaculatus*			x		x	x				
potadromous	Walleye	*Sander vitreus*						x	x	x	x	x
	Sauger	*Sander canadensis*						x	x	x	x	x
	Ohio lamprey	*Ichthyomyzon bdellium*	x		x	x	x	x	x	x	x	x

great river fish	Paddlefish	*Polyodon spathula*							x		x	x
	Longnose gar	*Lepisosteus osseus*							x	x		x
	Skipjack herring	*Alosa chrysochloris*										x

Table 2. Mussel groups, focal species and associated habitats types for the Pennsylvania portion of the Ohio River Basin.

			Creeks (0 to 40 sq mi)		**Small Rivers (40 to 200 sq mi)**			**Medium Tributaries (200 to 1000 sq mi)**			**Large Rivers (> 1,000 sq mi)**	
Draft Species Groups	**Common Name**	**Scientific name**	Cool-cold creeks	Warm creeks	Cool, small rivers, unglaciated	Warm, small rivers, unglaciated	Glaciated small rivers	Cool, moderate to high gradient tributaries	Warm tributaries, unglaciated	Glaciated tributaries	Large River	Large, navigational river
Moderate gradient, small to medium creeks and streams	Elktoe	*Alasmidonta marginata*			x	x	x	x	x	x	x	x
	Snuffbox	*Epioblasma triquetra*	x		x	x	x		x	x		
	Rabbitsfoot	*Quadrula cylindrica cylindrica*				x	x		x	x	x	
	Rainbow Mussel	*Villosa iris*	x	x	x	x	x	x	x	x	x	
Mod to swift current, medium to large rivers	Mucket	*Actinonaias ligamentina*							x	x	x	x
	Northern Riffleshell	*Epioblasma torulosa rangiana*					x		x	x	x	x
	Clubshell	*Pleurobema clava*					x		x	x	x	x
	Round Pigtoe	*Pleurobema sintoxia*				x	x	x	x	x	x	x
	Rayed Bean Mussel	*Villosa fabalis*				x	x	x	x	x	x	x
Moderate to slow currents, low gradient	Three-ridge	*Amblema plicata*			x	x	x		x	x	x	x
	Wabash Pigtoe	*Fusconaia flava*				x			x			x
	Fatmucket	*Lampsilis siliquoidea*						x	x	x	x	x
	White Heelsplitter	*Lasmigona complanata*			x	x	x		x	x	x	x
	Giant floater	*Pyganodon grandis*							x	x	x	x
Great rivers and Ohio river mainstem	Threehorn Wartyback	*Obliquaria reflexa*										x
	Pink Heelsplitter	*Potamilus alatus*				x	x		x	x	x	x
	Pink Papershell	*Potamilus ohiensis*										x
	Fawnsfoot	*Truncilla donaciformis*										x

Table 3. Vegetation groups, communities and associated habitats types for the Pennsylvania portion of the Ohio River Basin.

Draft Species Groups	Community Types	Canopy dominants	Headwaters and Creeks (0 to 40 sq mi)		Small Rivers (40 to 200 sq mi)			Medium Tributaries (200 to 1000 sq mi)			Large Rivers (> 1,000 sq mi)	
			Cool-cold headwaters and creeks	Warm headwaters and creeks	Cool, small rivers, unglaciated	Warm, small rivers, unglaciated	Glaciated small rivers	Cool, moderate to high gradient	Warm tributaries, unglaciated	Glaciated tributaries	Large, Great River	Large, navigational river
Submerged and Emergent Bed	River weed	river weed, *Podostemum ceratophyllum*	x	x	x	x	x	x	x	x	x	
	Water Willow Emergent Bed	water-willow, *Justicia americana*	x	x	x	x	x	x	x	x	x	x
	Lizard's Tail Emergent Bed	lizard's tail, *Saururus cernuus*	x	x	x	x	x	x	x	x	x	x
Herbaceous Community	Big Bluestem - Indian-grass Floodplain Grassland	big bluestem, *Andropogon gerardii* ; switchgrass, *Panicum virgatum* ; and Indian-grass, *Sorghastrum nutans*									x	
	Hairy-fruited Sedge (Carex trichocarpa) Floodplain Wetland	Hairy-fruited sedge, *Carex trichocarpa*						x	x	x	x	x
	Japanese Knotweed Floodplain Thicket	Dominated by Invasive Species:Japanese Knotweed, *Fallopia japonica*			x	x	x	x	x	x	x	x
	Reed Canary-grass Floodplain Grassland	Dominated by Invasive Species: Reed Canary-grass *Phalaris arundinacea*						x	x	x	x	x
	Twisted Sedge Floodplain Margin	Twisted sedge, *Carex torta*			x	x	x	x	x	x		
	Floodplain Meadow	Joe pye weed, *Eutrochium fistulosum*			x	x	x	x	x	x		
	Floodplain Scour Community	sparsely vegetated; *Hypericum spp.* , *Osmunda regalis* , rare species such as *Marshalia grandiflora*	x	x	x	x	x	x	x	x	x	x
	Periodically Exposed Shoreline Community	sparsely vegetated; smart weed (*Persicaria spp*) and other annuals	x	x	x	x	x	x	x	x	x	x
Scrub/Shrub Community	Alder - Dogwood Floodplain Thicket	speckled alder, *Alnus incana ssp. rugosa*	x	x	x	x	x	x	x	x		
	Mixed Hardwood Floodplain Thicket	See associated floodplain forest			x	x	x	x	x	x	x	x
	Buttonbush wetland	Buttonbush, *Cephalanthus occidentalis*			x	x	x	x	x	x	x	x
	Black Willow Floodplain Thicket	black willow, *Salix nigra*						x	x	x	x	x
Floodplain Forest	Sycamore floodplain forest	American syacamore, *Plantanus occidentalis*			x	x	x	x	x	x		
	Silver maple floodplain forest	silver maple, *Acer saccharinum*						x	x	x	x	x
	Sugar Maple - Mixed Hardwood Floodplain Forest	sugar maple, *Acer saccharum* ; American basswood, *Tilia americana*	x	x	x	x	x	x	x	x		
	Green Ash - Mixed Hardwood Floodplain Forest	green ash, *Fraxinus pennsylvanica*			x	x	x	x	x	x		
	Bitternut Hickory Floodplain Forest	bitternut hickory, *Carya cordiformis*			x	x	x	x	x	x		
	Red Maple - Elm - Willow Floodplain Forest	red maple, *Acer rubrum* ; American elm, *Ulmus americana* , black willow, *Salix nigra*						x	x	x	x	x

Appendix 4. Flow-ecology hypotheses

Table 1. Working Hypotheses developed for mussels in Ohio River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	During winter months, in riffle and runs, a decrease in low flow magnitude could lead to anchor ice formation and scour of mussel habitat			🟥	🟥	🟥								All habitats where present
2	During glochidia release, if flow magnitudes decrease, water clarity and depth may decrease, reducing the potential for host-fish to reach mussels and for successful glochidia transfer								🟥	🟥	🟥	🟥	🟥	All habitats where present
3	During spawning and glochidia release, high flows may increase turbidity, limiting interaction between host-fish and mussels. Species with intricate lures and requiring direct contact for transfer of glochidia (such as Northern riffleshell and snuffbox), would be especially sensitive.								🟦	🟦	🟦	🟦	🟦	All habitats where present
4	Moderate to swift mussels (rabbitsfoot) rely on channel margins and are senstiive to increased temperatures and low flow events during the summer									🟧	🟧	🟧		All habitats where present
5	Several mussels depend on stream margin habitats (rabbitsfoot and slow, low gradient species). A decrease in low flow magnitude could dewater these habitats and lead to increased predation or dessication.									🟥	🟥	🟥	🟥	All habitats where present
6	During the low flow months, mussels are most sensitive to a decrease in low flow magnitude in small streams and are less sensitive as stream size increases.									🟥	🟥	🟥	🟥	Small cool glaciated, Small cool moderate gradient
7	Any time of year, especially summer and early fall, a decrease in low flow magnitude may increase temperature and algal production and decrease DO, leading to reduced growth or mortality (French Creek, 1988 and example of high mortality event)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	All habitats where present
8	Anytime of year, juvenile mussels need high flow pulses to maintain substrate size and distribution. A decrease in the frequency and magnitude of these events could lead to embeddedness.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All habitats where present
9	Anytime of year, a high rate of decrease to a low flow condition may strand mussels, particularly in margin and riffle habitats.	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	All habitats where present

Table 2. Working Hypotheses developed for fishes in Ohio River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	During winter months, in riffle and runs, a decrease in low flow magnitude could lead to anchor ice formation and scour of mussel habitat			🟥	🟥	🟥								All habitats where present
2	During glochidia release, if flow magnitudes decrease, water clarity and depth may decrease, reducing the potential for host-fish to reach mussels and for successful glochidia transfer								🟥	🟥	🟥	🟥	🟥	All habitats where present
3	During spawning and glochidia release, high flows may increase turbidity, limiting interaction between host-fish and mussels. Species with intricate lures and requiring direct contact for transfer of glochidia (such as Northern riffleshell and snuffbox), would be especially sensitive.								🟦	🟦	🟦	🟦	🟦	All habitats where present
4	Moderate to swift mussels (rabbitsfoot) rely on channel margins and are senstiive to increased temperatures and low flow events during the summer									🟧	🟧	🟧		All habitats where present
5	Several mussels depend on stream margin habitats (rabbitsfoot and slow, low gradient species). A decrease in low flow magnitude could dewater these habitats and lead to increased predation or dessication.									🟥	🟥	🟥	🟥	All habitats where present
6	During the low flow months, mussels are most sensitive to a decrease in low flow magnitude in small streams and are less sensitive as stream size increases.									🟥	🟥	🟥	🟥	Small cool glaciated, Small cool moderate gradient
7	Any time of year, especially summer and early fall, a decrease in low flow magnitude may increase temperature and algal production and decrease DO, leading to reduced growth or mortality (French Creek, 1988 and example of high mortality event)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	All habitats where present
8	Anytime of year, juvenile mussels need high flow pulses to maintain substrate size and distribution. A decrease in the frequency and magnitude of these events could lead to embeddedness.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All habitats where present
9	Anytime of year, a high rate of decrease to a low flow condition may strand mussels, particularly in margin and riffle habitats.	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	All habitats where present
10	During winter, migratory residents need seasonal flows that maintain deep pools and refugia from current. If seasonal flows are reduced, fish may expend too much energy seeking refuge.			🟧	🟧	🟧								All habitats where present
11	During winter, a decrease in streamflow and groundwater contributions may decrease depth and temperature. These conditions may encourage ice infiltration of salmonid eggs leading to reduced survival or impaired development.			🟥	🟥	🟥								Headwaters, cool-cold, Small rivers, cool-cold,
12	During winter, a decrease in streamflow may decrease availability and access to riffle habitats needed by riffle obligate fishes			🟥	🟥	🟥								All habitats where present
13	After spawning, during egg and larval development, a decrease in seasonal flows may dewater salmonid redds impairing development or reducing survival rates	🟧	🟧	🟧	🟧	🟧	🟧							Headwaters, cool-cold, Small rivers, cool-cold,

14	During spring, seasonal flows needed to maintain sediment free salmonid redds. A decrease in flow magnitude may lead to suffocation.						🟧	🟧						Headwaters, cool-cold, Small rivers, cool-cold,
15	During spawning and egg and larval development, riffle obligates need stable flows, if the magnitude of low flows decreases, fines may accumulate, suffocating eggs.						🟥	🟥	🟥	🟥	🟥			All river types
16	During March and April, riffle associates (redhorses) and potadromous fish (specifically walleye, sauger and Escocids), rely on temperature and increased streamflow to provide spawning cues. If low flow magnitude decreases, spawning cues and connectivity may be lost						🟥	🟥						All river types
17	During spawning and egg and larval development, riffle obligates need stable flows, if the magnitude of high flows increases, it may cause egg scour						🟦	🟦	🟦	🟦	🟦			All river types
18	During spawning and egg and larval development, riffle obligates need stable flows, increased flashiness may restrict access to gravel spawning habitats						🟪	🟪	🟪	🟪	🟪			All river types
19	Similarly, if high flow magnitude and duration increase, upstream spawning migration may be delayed (salmonids, burbot, migratory residents, riffle associates)	🟦	🟦	🟦			🟦	🟦						All river types
20	From March to June, a decrease in median flows may reduce fish movement to, and availability of, preferred spawning habitats. Fish spawning in riffles are especially sensitive and they vary in body-size and river types (eg darters, redhorses, paddlefish)						🟧	🟧	🟧	🟧				All river types
21	From March to June, great river fish and riffle associates in the navigation reaches need high flows to provide connectivity to upstream tributary habitats						🟦	🟦	🟦	🟦				Large navigational river
22	From April to July, the larvae larvae of migratory residents (walleye) and riffle associates (suckers) need slackwater habitats (often in stream margin), for development. An increase in the magnitude or frequency of high flow events would increase the velocity along stream margins reducing available slackwater habitat.							🟦	🟦	🟦	🟦			All Small, Tributary and Large river types
23	From April to July, larvae of migratory residents (walleye) and riffle associates (suckers) need slackwater habitats (often in stream margin), for development. A decrease in low flow magnitude may disconnect stream margin and backwater habitats from the main channel							🟥	🟥	🟥	🟥			All Small, Tributary and Large river types
24	From April to June, great river species including longnose gar and bigmouth buffalo need SAV or floodplain access for adhesive egg laying. Flooding duration must allow larvae to move back out into the channel							🟦	🟦	🟦				Large navigational river, Large river
25	During spring, an increase in the magnitude or frequency of high flows can scour nests. River chub may be particularly sensitive to this change in tributaries and large rivers and hornyhead chub in headwaters and small rivers.							🟦	🟦	🟦	🟦	🟦		All river types
26	During nest building and egg and larval development (spring) increased flashiness, may dewater nests and has been associated with decreased abundance of YOY.							🟪	🟪	🟪	🟪	🟪		All river types
27	During egg and larval development (spring), increased magnitude, frequency or duration of high flows may decrease egg and larval survival and associated year class strength.							🟦	🟦	🟦	🟦	🟦		All river types
28	From April through August, in riffles, if seasonal flows are too low then egg and larval development may be impaired by oxygen depletion, dessication or suffocation							🟧	🟧	🟧	🟧	🟧		All river types
29	From April through August, in riffles, if high flow magnitude or frequency increase, developing eggs and larvae may be scoured and/or physically damaged							🟦	🟦	🟦	🟦	🟦		All river types

30	During summer months, a decrease in median flow may limit the quality and availability of riffle habitats for riffle obligate fishes	🟧	All river types
31	During the summer low flow period, a decrease in low flow magnitude can result in downstream migration of headwater fishes, compressing the species and thermal gradient, and increasing predator-prey interactions (eg brook trout and brown trout)	🟥	All headwater types
32	During the summer low flow period, a decrease in low flow magnitude may result in loss of refugia and a shift toward a top-predator dominated system	🟥	All river types
33	During summer months, riffle obligates that specialize in highly oxygenated, lower riffle/plunge turbulent environments (redside dace in headwaters, rosyface shiner in small warm streams, silver shiner in small cool-cold streams) are sensitive to decreasing flow magnitude which would contract or eliminate this habitat niche.	🟥	All river types
34	A decrease in the magnitude of summer low flows may restrict access for centrarchids and escocids to SAV habitats	🟥	All small river, medium tributaries and large river types
35	For substrate specialists an increase in high flowfrequency, magnitude or duration may destabilize habitats and flush preferred substrates	🟦	All river types
36	For substrate specialists (specifically the eastern sand darter), high flow events maintain sandy substrates, a decrease in high flow magnitude, frequency or duration or may reduce habitat quality or abundance. Similarly, an increase in extreme high flow events may flush sands reducing abundance and quality of habitat	🟦	glaciated and Medium tributary, warm glaciated

Table 3. Working Hypotheses developed for aquatic, riparian and floodplain vegetation in Ohio River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	From January through March (prior to leaf out), flood flows and associated ice scour promote scrub shrub establishment and structure; a decrease in flood flow magnitude and frequency may result in transition from scrub shrub to forested habitats; an increase in flood flow magnitude, frequency and duration may result in transition of forested habitats to scrub shrub				🟦	🟦	🟦	🟦						All small river, medium tributaries and large river types
2	During winter and spring, if flood magnitude is too low, then scouring does not occur and seedbed will not be prepared for propagules			🟦	🟦	🟦	🟦	🟦	🟦					All small river, medium tributaries and large river types
3	During winter and spring, herbaceous species, such as buttonbush, need low intensity, moderate duration flood events to promote establishment			🟦	🟦	🟦	🟦	🟦	🟦					All small river, medium tributaries and large river types
4	During the spring months, if the rise and fall rates increase, total indundation days within backwater/paleochannel habitats will be reduced, reducing the establishment probability for shrub, emergent and aquatic vegetation						🟪	🟪	🟪					All small river, medium tributaries and large river types
5	From April to May, during SAV establishment, if high flows are too high, then suspended sediment may limit available sunlight reducing native submerged vegetation, consequently, because many native species need less light, it could increase the abundance of non-native species							🟦	🟦					All small river, medium tributaries and large river types
6	From June to October, if the magnitude, frequency or duration of high flow events decreases, indundation within oxbows will decrease and may result in a transition from emergent to flood tolerant vegetation	🟦								🟦	🟦	🟦	🟦	All small river, medium tributaries and large river types
7	During the growing season, increased flashiness may increase decomposition rates and associated nutrient availability and enhance establishment and persistence of non-native species	🟪								🟪	🟪	🟪	🟪	All small river, medium tributaries and large river types
8	During the growing season, a decrease in groundwater elevation may encourage a transition from mesic toward xeric communities, riparian and wetland species in headwater settings may be particularly senstive to this change	🟥								🟥	🟥	🟥	🟥	All river types
9	During the growing season, an increase in low flow duration may result in increased algal production, increasing photosythensis and pH and effectively increasing ammonia toxicity - mussels are most senstive to this change	🟥								🟥	🟥	🟥	🟥	All small river, medium tributaries and large river types
10	During summer, a decrease in low flow magnitude and increase in duration may encourages fine sediment capture and growth of emergent vegetation, eventually resulting in fill of backwater areas	🟥								🟥	🟥	🟥	🟥	All small river, medium tributaries and large river types
11	During summer, and increase in the magnitude and duration of high flows may decrease water clarity and the abundance of native submerged and emergent vegetation.									🟥	🟥	🟥		All small river, medium tributaries and large river types

Table 4. Working Hypotheses developed for aquatic insects and crayfish in Ohio River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	During spring, high flows are needed to maintain substrate for riffle/run invertebrates; if high flow magnitude, duration or frequency is reduced, gravel substrates may become armored with fines reducing benthic habitat and causing downstream drift						🟦	🟦	🟦					All river types
2	During spring and early summer, if high flow magnitude increases, then long-lived pupae (megaloptera) may be scoured from banks and floodplain						🟦	🟦	🟦	🟦				All river types
3	From May to June, low flows are needed to support large, long lived (2 year) aquatic insects in riffls and runs (eg Odonate family). If magnitude decreases, habitats for these species may be displaced.								🟥	🟥				All river types
4	During summer low flow period, decreased low flows can result in compression of species and thermal gradients									🟥	🟥	🟥	🟥	All headwater types
5	During summer, shredders need maintenance of low flows to persist. A decrease in flow magnitude could cue exit from headwater systems, resulting in a reduction of energy transformation and export (from CPOM to FPOM).										🟥	🟥	🟥	All headwater types
6	During the summer low flow period, a decrease in low flow magnitude may reduce available refugia resulting in a community transition toward one that is predator-dominated.									🟥	🟥	🟥	🟥	All headwater and small stream types
7	During summer, during mating and aquatic insect egg development, flows are needed to provide egg laying habitats and for incubation.									🟥	🟥	🟥		All river types
8	During fall, aquatic insects rely on flows to need flows to provide habitat and food availability. A decrease in flows may limit habitat niches and food availability									🟥	🟥	🟥		All river types
9	During the baseflow period, decreased magnitudes can cause community shifts for macroinvertebrates from stenothermal to warm, rheophilic and erosional to depositional	🟧									🟧	🟧	🟧	All river types
10	During summer and fall, insects in depositional habitats (eg family Gomphidae) need oxic, fine substrates. If low flow magnitude decreases, organic deposition may decrease available oxygen	🟥	🟥							🟥	🟥	🟥	🟥	All river types
11	Anytime of year, crayfish seek refuge in burrows which are sensitive to fines and armoring; a decrease in high flow magnitude, frequency or duration may result in armoring and a reduction of habitat	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types

12	Anytime of year, high flow pulses and flood events maintain a mosaic of habitat types as is explained by the intermediate disturbance hypotheses. Maintaining the magnitude, frequency and duration of these events within their natural range of variability supports regional diversity.	🟦	All river types
13	At all times, if groundwater table elevation decreases in zero order settings, may see a decline in leptophlebeid cepida (mayfly); and species who use intermittent streambeds and adjacent wetlands to complete their lifecycle	🟥	All headwater types
14	At all times, burrowing mayflies (long-lived) need connectivity between surface water and hyporheic zone. A reduction of low flow magnitude may decrease connectivity between habitat types		

Table 5. Working Hypotheses developed for reptiles and amphibians in Ohio River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	October through April, the wood turtle hibernates in stream beds and banks. A decrease in low flow magnitude may decrease water temperatures or dewater hibernacula increasing risk of mortality.	🟥	🟥	🟥	🟥	🟥	🟥	🟥						All habitats where present
2	October through April, the wood turtle hibernates in stream beds and banks. An high rate of decrease during this time may strand individual or communal hibernacula.	🟪	🟪	🟪	🟪	🟪	🟪	🟪						All habitats where present
3	October through April, eastern massasauga relies on groundwater to provide insulation during hibernation. If groundwater elevations decrease in hibernacula, there is an increased risk of freezing and mortality.	🟥	🟥	🟥	🟥	🟥	🟥	🟥						All habitats where present
4	During spring, if high flow magnitude or frequency increases, streamside salamander eggs may be scoured from the stream bed and margins.						🟦	🟦	🟦					All habitats where present
5	Eastern hellbender are specialized feeders relying on the presence and abundance of crayfish to support their diet. During the summer, a decrease in low flow magnitude may decrease crayfish abundance and food availability for the hellbender.									🟥	🟥	🟥		All habitats where present
6	During August and September, in shallow margins, eastern hellbender eggs, larvae and juveniles require stable, highly oxygenated streamflows for development. If seasonal flow magnitude decreases, eggs may be exposed, impairing development or survival.											🟧	🟧	All habitats where present
7	Mudpuppies act as a host for the glochidia of salamander mussels (present in the navigation channel). During spawning and glochidia release, a decrease in low flow magnitude may decouple this interaction.								🟥	🟥	🟥	🟥	🟥	Large navigational channel
8	Anytime of year, in the active channel of the uppermost reaches (1st and 2nd order), if flows are too high, streamside salamander larvae could be scoured. Species with a two-year larval development stage would be particularly sensitive.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All headwater habitat types
9	Anytime of year, if high flow magnitude, duration and frequency increases, then habitat and food availability for streamside salamanders would be reduced	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All habitats where present

Table 5. Working Hypotheses developed for water quality and geomorphology and unique habitats in Ohio River basin

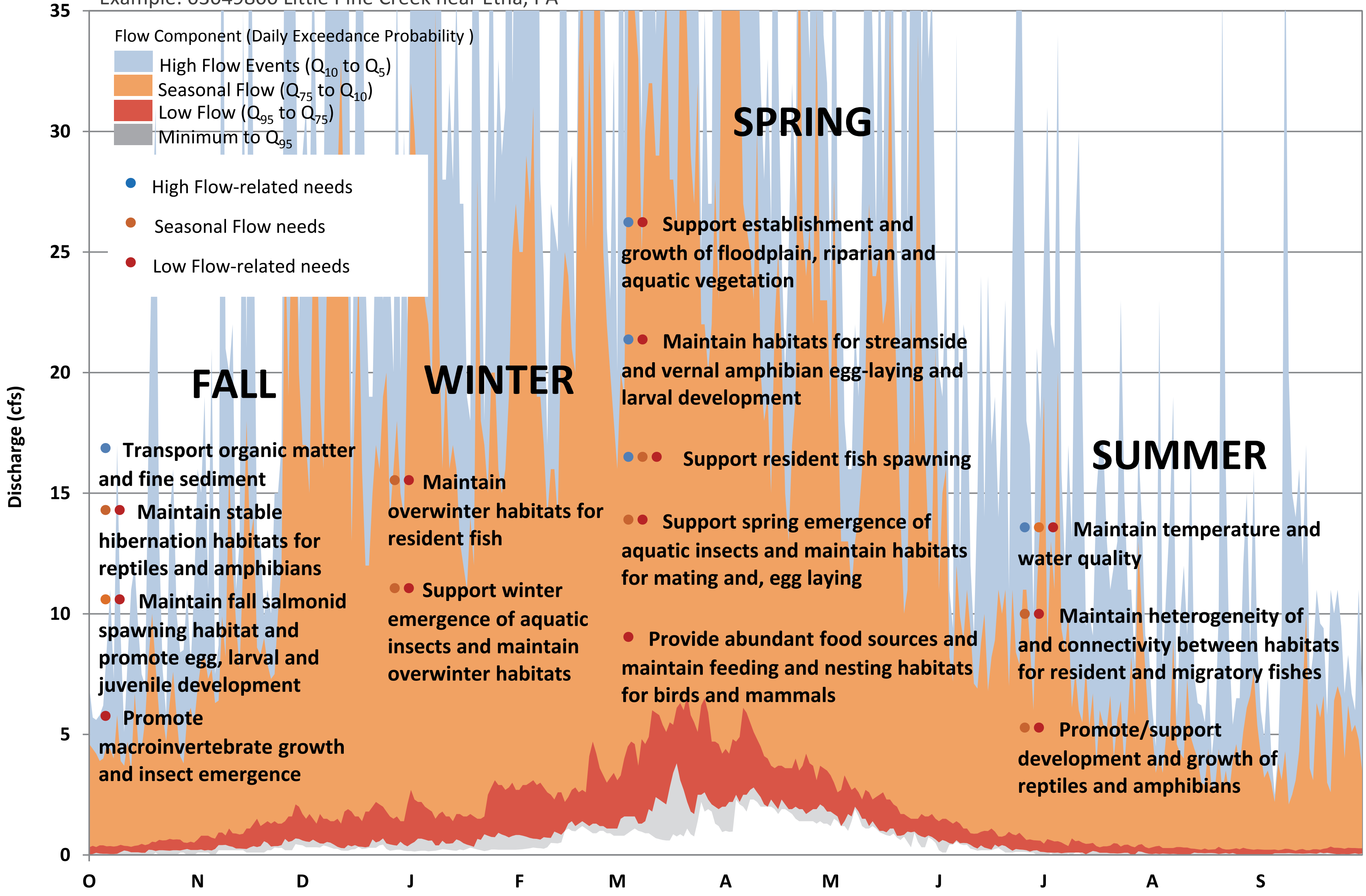
🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
1	During spring, high flows are needed to maintain substrate for riffle/run invertebrates; if high flow magnitude, duration or frequency is reduced, gravel substrates may become armored with fines reducing benthic habitat and causing downstream drift						🟦	🟦	🟦					All river types
2	During spring, high flows are needed to create and transport large woody debris. A decrease in high flow magnitude, frequency or duration would reduce transport. Similarly an increase in high flow magnitude and frequency may blow out existing debris jams and plunge pool habitats.						🟦	🟦	🟦					All river types
3	During spring and early summer, high flow events create connectivity between the mainstem and backwater habitats. A decrease in the magnitude, frequency or duration of theses events may disconnect these habitats.						🟦	🟦	🟦	🟦				All river types
4	On the navigational reach, floodplain connectivity and river island processes have been lost in response to the construction and operation of dozens of locks and dams. A reintroduction of high flow events may restore presence of floodplain forest and function.						🟦	🟦	🟦					Large navigational channel
5	During summer, a decrease in low flow magnitude in proximity to a point source discharge would reduce dilution capacity and may result in water quality impairments									🟥	🟥	🟥	🟥	All river types
6	During summer, a decrease in low flow magnitude and duration may increase water temperatures, cold-cool stream types would be particularly sensitive to these changes									🟥	🟥	🟥	🟥	Headwater, small rivers and medium tributaries, cool-cold
7	During low flow periods, with thelack of hyporheic refuge and subsurface flow, bedrock microhabitats would be very sensitive to a decrease in low flow magnitude	🟥								🟥	🟥	🟥	🟥	All habitats where present
8	During baseflow months, in warm water streams, a decrease in flow magnitude would ecrease capacity to assimilate TDS (salt) changing osmotic potential. Mussels are particularly sensitive as glochidia close at certain TDS levels.	🟥								🟥	🟥	🟥	🟥	Headwater and small warm water river types
9	During baseflow periods, the hyporheic zone provides refuge, a decrease in flow magnitude may contract the hyporheic zone or disconnect it from surface waters. Species adapted to the glaciated river types may be most senstive to this change.	🟥								🟥	🟥	🟥	🟥	All habitats where present, especially glacially influenced types
10	Anytime of year, on the Monogahela, power plants impose daily fluctuation. This may limit the influence of these operation	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	Large navigational river
11	Channel forming flows are needed to maintain channel morphology and substrate. If the magnitude, frequency or duration of these events decreases, available habitats for benthic organisms (riffle obligates, juvenile lamprey, mussels, aquatic invertebrates) will be reduced or eliminated	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All habitats where present

Appendix 5. Flow components and needs figures

Flow Components and Needs: Headwaters

Example: 03049800 Little Pine Creek near Etna, PA



FALL

● Transport organic matter and fine sediment

●● Maintain stable hibernation habitats for reptiles and amphibians

●● Maintain fall salmonid spawning habitat and promote egg, larval and juvenile development

● Promote macroinvertebrate growth and insect emergence

WINTER

●● Maintain overwinter habitats for resident fish

●● Support winter emergence of aquatic insects and maintain overwinter habitats

SPRING

●● Support establishment and growth of floodplain, riparian and aquatic vegetation

●● Maintain habitats for streamside and vernal amphibian egg-laying and larval development

●●● Support resident fish spawning

●● Support spring emergence of aquatic insects and maintain habitats for mating and, egg laying

● Provide abundant food sources and maintain feeding and nesting habitats for birds and mammals

SUMMER

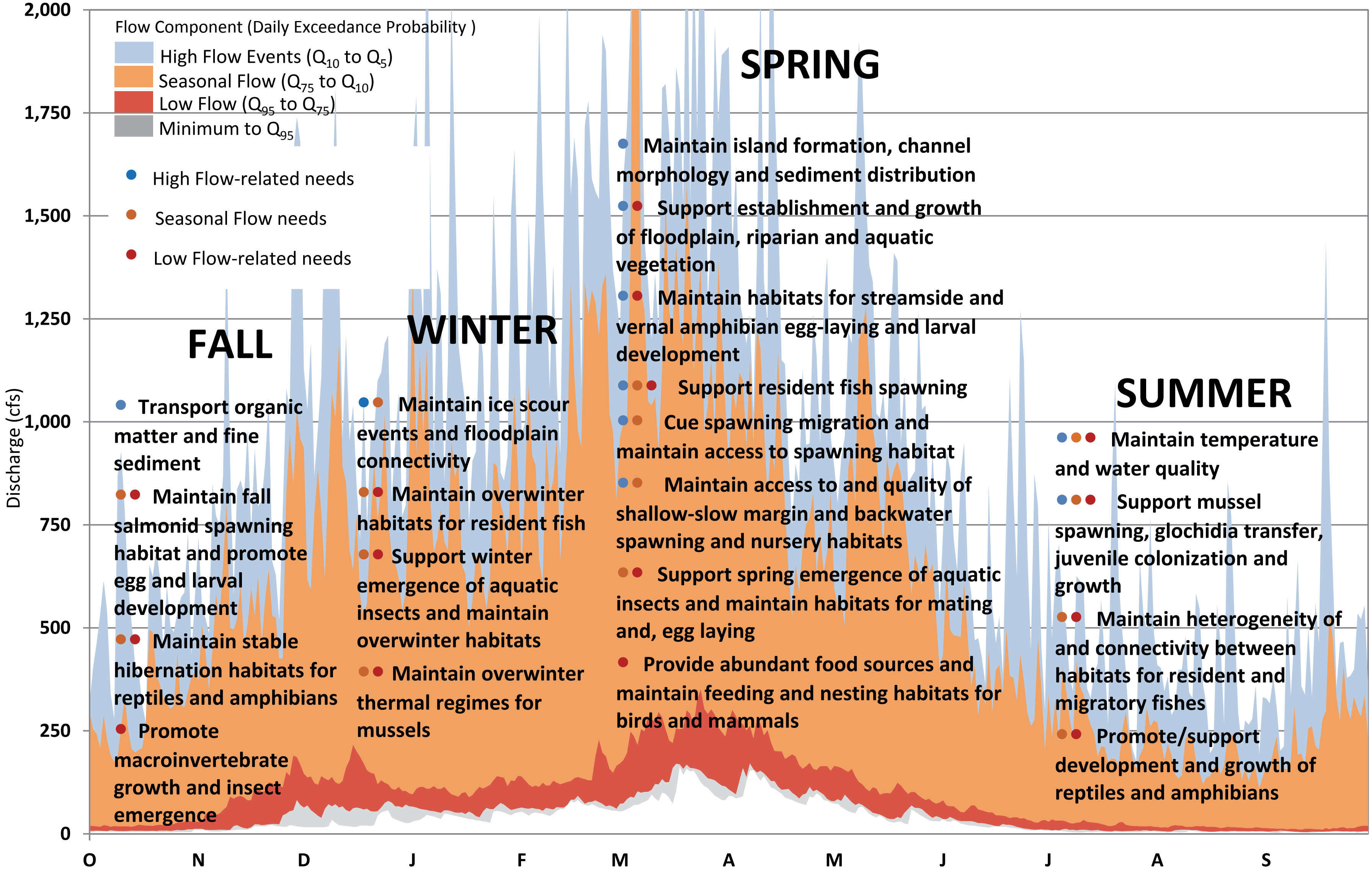
●●● Maintain temperature and water quality

●● Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes

●● Promote/support development and growth of reptiles and amphibians

Flow Components and Needs: Small Cool River

Example: 03080000 Laurel Hill Creek at Ursina, PA



FALL

- ● Transport organic matter and fine sediment
- ●● Maintain fall salmonid spawning habitat and promote egg and larval development
- ●● Maintain stable hibernation habitats for reptiles and amphibians
- ● Promote macroinvertebrate growth and insect emergence

WINTER

- ●● Maintain ice scour events and floodplain connectivity
- ●● Maintain overwinter habitats for resident fish
- ●● Support winter emergence of aquatic insects and maintain overwinter habitats
- ●● Maintain overwinter thermal regimes for mussels

SPRING

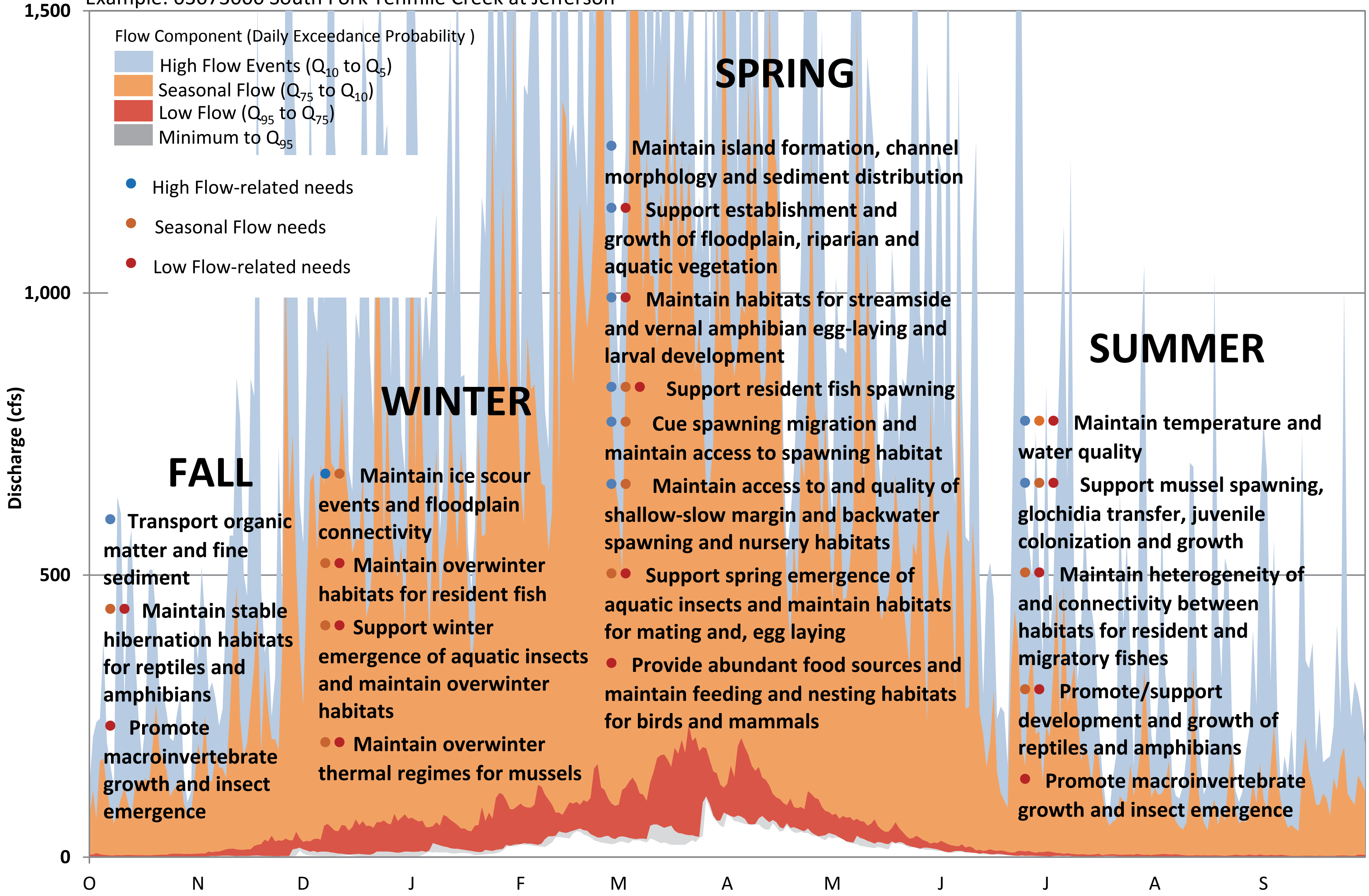
- ● Maintain island formation, channel morphology and sediment distribution
- ●● Support establishment and growth of floodplain, riparian and aquatic vegetation
- ●● Maintain habitats for streamside and vernal amphibian egg-laying and larval development
- ●●● Support resident fish spawning
- ●● Cue spawning migration and maintain access to spawning habitat
- ●● Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats
- ●● Support spring emergence of aquatic insects and maintain habitats for mating and, egg laying
- ● Provide abundant food sources and maintain feeding and nesting habitats for birds and mammals

SUMMER

- ●●● Maintain temperature and water quality
- ●●● Support mussel spawning, glochidia transfer, juvenile colonization and growth
- ●● Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes
- ●● Promote/support development and growth of reptiles and amphibians

Flow Components and Needs: Small warm river

Example: 03073000 South Fork Tenmile Creek at Jefferson



FALL

- 🔵 Transport organic matter and fine sediment
- 🟠🔴 Maintain stable hibernation habitats for reptiles and amphibians
- 🔴 Promote macroinvertebrate growth and insect emergence

WINTER

- 🔵🟠 Maintain ice scour events and floodplain connectivity
- 🟠🔴 Maintain overwinter habitats for resident fish
- 🟠🔴 Support winter emergence of aquatic insects and maintain overwinter habitats
- 🟠🔴 Maintain overwinter thermal regimes for mussels

SPRING

- 🔵 Maintain island formation, channel morphology and sediment distribution
- 🔵🔴 Support establishment and growth of floodplain, riparian and aquatic vegetation
- 🔵🔴 Maintain habitats for streamside and vernal amphibian egg-laying and larval development
- 🔵🟠🔴 Support resident fish spawning
- 🔵🟠 Cue spawning migration and maintain access to spawning habitat
- 🔵🟠 Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats
- 🟠🔴 Support spring emergence of aquatic insects and maintain habitats for mating and, egg laying
- 🔴 Provide abundant food sources and maintain feeding and nesting habitats for birds and mammals

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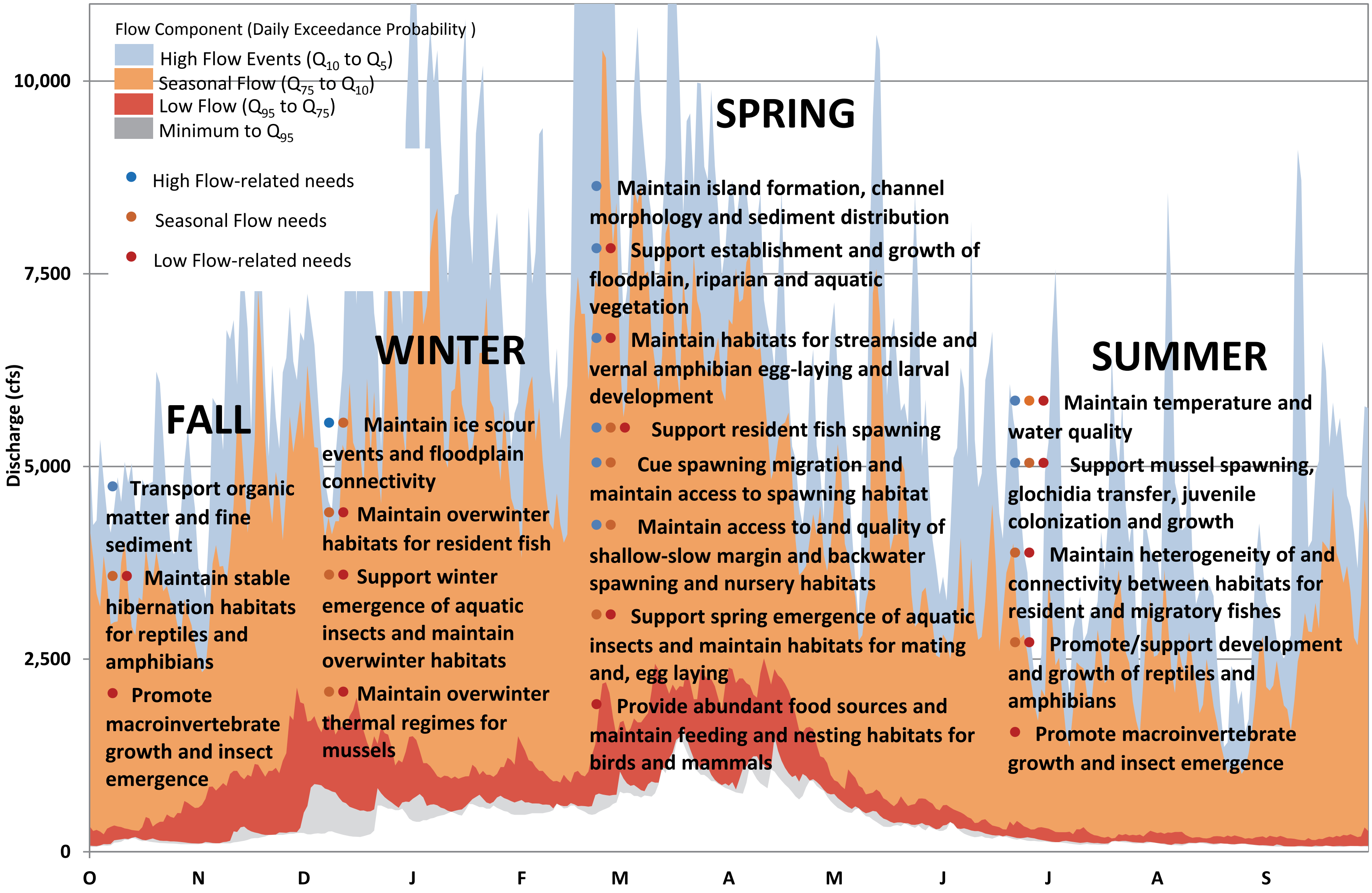
Flow Components and Needs: Glaciated Tributary

Example: 03024000 French Creek at Utica, PA



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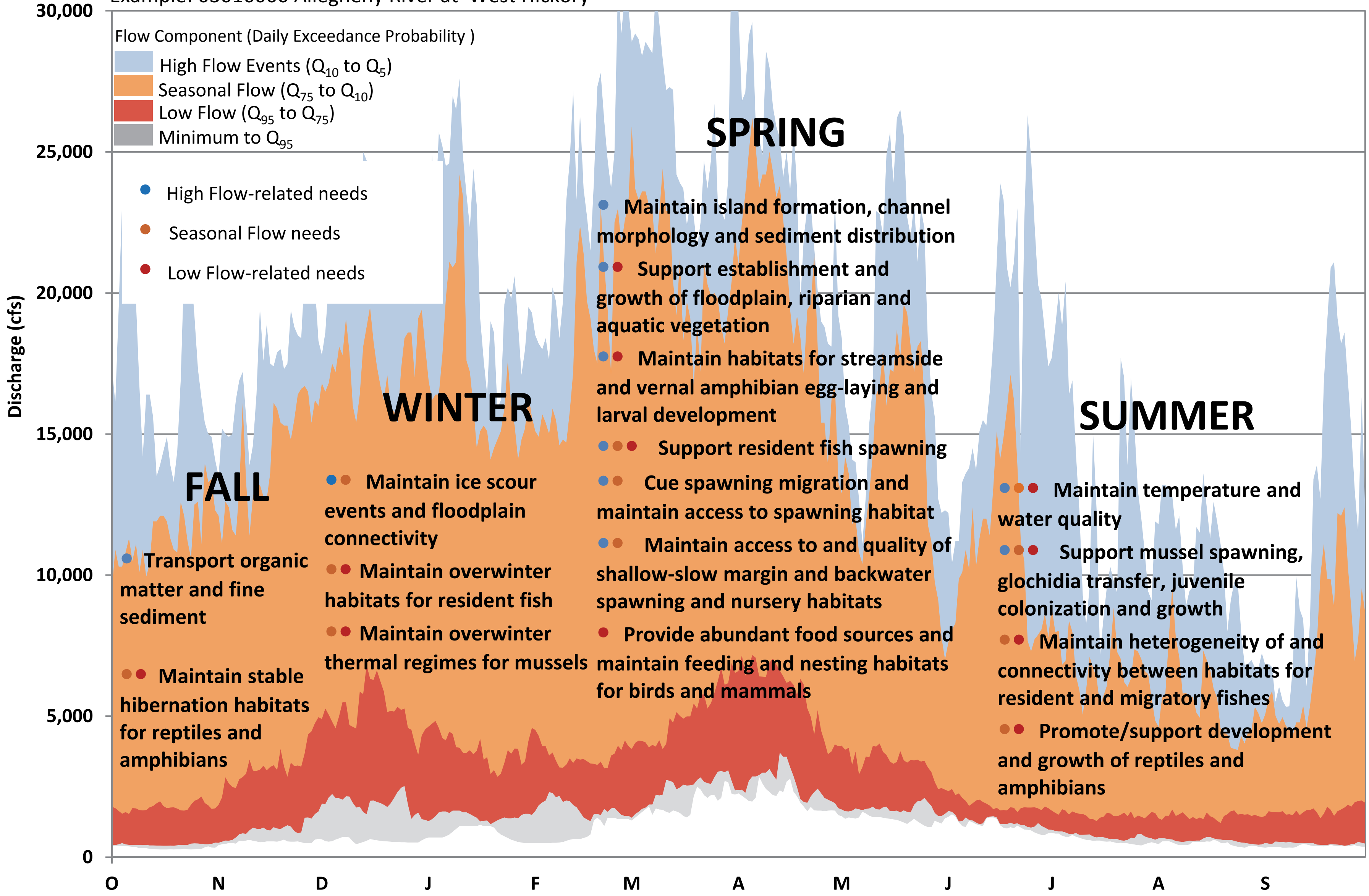
Flow Components and Needs: Large River

Example: 03016000 Allegheny River at West Hickory



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●● Support establishment and growth of floodplain, riparian and aquatic vegetation

●● Maintain habitats for streamside and vernal amphibian egg-laying and larval development

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●● Cue spawning migration and maintain access to spawning habitat

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Appendix 6. Summary of Literature Supporting Upper Ohio River Ecosystem Flow Needs

This document is organized by

SEASON

Flow Need – a statement summarizing why a range of flows is important to a taxa group

● **Hypothesis – states an anticipated ecological response to a change in high ●, seasonal ● or low ● flow conditions.** [Brackets include a **code for the hypothesis]**

- Summary of findings relevant to the hypothesis followed by the citation. Any quantitative thresholds in the paper are in **bold text.**

SUMMER

Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes

●During the summer and early fall, a decrease in seasonal flow magnitude may result in loss of persistent habitats and cause a shift in species abundance or assemblage [F24].

- A decrease in the **magnitude of median daily flows** resulted in an assemblage shift and a reduction in available shallow-slow habitat in summer. Young-of-year abundance was most correlated with shallow-slow habitat size and persistence. Suitable conditions were predicted by conditions including the seasonal median daily flow (Freeman et al. 2001).
- In a small Massachusetts river (Ipswich), overallocation of groundwater has led to a reduction in baseflow. In response, fish communities have shifted from fluvial dependent or fluvial-specialist species to macrohabitat generalists. A handful of riffle locations were the first to dry, reducing connectivity and inhibiting fish passage. (Armstrong et al 2001).
- A comparison of large warmwater streams along a withdrawal index gradient finds a shift in fish assemblages from fluvial specialists to habitat generalists as withdrawals increase from 50 to 100% of 7Q10 or **(>10% of August median**). Vulnerable species included Cyprinids, Catostomids and Percids, Ictalurids and stream-dwelling Centrarchids. Altered flow regimes affected biota in relation to the degree of alteration and increased the odds that a site's IBI score fell below the regulatory threshold (Freeman and Marcinek 2006).
- On headwater and small streams, a simulated removal of **8% to 15% of the August median** predicted a 10% shift in fish assemblage; on large rivers, removal of **10 to 25 % of the August median** predicted a 10% shift in fish assemblage (Zorn et al. 2008).
- On headwaters, creeks and small streams (1st to 4th order), a regional assessment of the influence of water withdrawal magnitude on fish assemblage found that streams with high withdrawal rates were generally characterized by lower proportions of fluvial dependent fishes and benthic invertevores (many riffle obligates). Benthic invertevores decreased by an estimated 10% when withdrawals were 50% of 7Q10 (> **5% of August median**) and by an estimated 15% when withdrawals were 100% of 7Q10 (>**10% of August median**) (Kanno and Vokoun 2010).

- On creeks and small streams, fish assemblage characteristics were related to percent alteration of August median flow. **A 10% reduction of the August median** reduced brook trout abundance by an estimated 33%, blacknose dace abundance by 17% and fluvial-fish species richness by 14% (Armstrong et al. 2011).
- A national study (coterminous US) of flow alteration and biological response found that diminished flow magnitudes were the primary predictors of biological integrity for fish and macroinvertebrate communities (~250 sites). The likelihood of biological impairment doubled with increasing severity of diminished streamflows. Fish assemblages transitioned to those with increasing lotic species, preferring slow-moving currents and fine-grained substrates as well as high mobility (some aquatic insects able to temporarily leave the aquatic environment) Carlisle et al 2010.

●**During summer months, a decrease in median flow may limit the quality and availability of riffle habitats for juvenile and adult growth [F22].**

- **Resource depression and the competition for food between darter species was highest during summer months** (low prey densities and high metabolic demands). Rainbow and fantail darter were found to reduce consumption as opposed to partitioning food resources (Schlosser and Toth 1984).
- In the Allegheny River, habitat partitioning among eleven species of darters occurred along depth, velocity and substrate during base flow conditions. Habitat heterogeneity increased as did partitioning among species, **reducing competition above the July Q80** flows (Stauffer et al. 1996, USGS 2012, IHA Analysis).
- In a tributary to the Upper Ohio (Elk River), ten darters were observed during the summer to find patterns of partitioning were significant between genera. **Etheostoma** occurred in riffles and were associated **with benthic habitats** (under, between and on top of rocks) whereas **Percina** were more common in riffle/run habitat **within the water column** (Welsh and Perry 1998).
- Low stream discharge tends to reduce riffle area habitats first and to a greater extent than pool area habitats (Hakala and Hartman 2004, Armstrong et al. 2001).
- Chipps et al. 1994; Freeman and Stouder 1989;

●**During the summer and early fall, a decrease in low flow magnitude can result in downstream migration of headwater fishes, compressing the species and thermal gradient, and increasing predator-prey interactions (eg brook trout and brown trout) [F23].**

- Body temperatures of brook and brown trout were monitored during the summer and early fall. Access to and use of areas of groundwater discharge and tributary confluences were critical for thermoregulation, particularly for brook trout (Baird and Krueger 2003).

●**During the summer and early fall, a decrease in low flow magnitude may result in loss of persistent habitats and cause a shift in species assemblage [F25].**

- Overallocation of water led to a reduction in baseflow. In response, fish communities shifted from fluvial dependent/specialist species to macrohabitat generalists (Armstrong et al. 2001).
- Increased duration of low flow during late summer and early autumn and was correlated to increased richness of lentic tolerant species (Roy et al. 2005).

●**During the summer and early fall, a decrease in low flows may reduce access to and abundance of food, including algae and benthic macroinvertebrates, for insectivores and omnivores impacting**

individual growth (species such as central stoneroller, hornyhead and river chub would be particularly sensitive[F26+F28]).

- Extreme low flow conditions resulted in individual fish (brook trout) having significant lower body condition during the drought relative to the post-drought period. Proportionally larger decreases in riffles and reduced flow velocity combined to limit food availability. Restricted habitat availability increased competition for limited food resources. (Hakala and Hartman 2004).
- In an experimental diversion (to an estimated **summer Q90 and 95), fish body length was 30 to 40% smaller for larger bodied fishes and 10% smaller for small bodied fishes** (Walters and Post 2008).
- Knight (2008);

●**During summer and early fall, a decrease in the magnitude of summer low flows may restrict persistence of and access to shallow shoreline habitats (centrarchids and escocids to SAV, juveniles and small-bodied fishes)[F29].**

- Implementation of **a minimum release program increased flows** during the summer from extreme low flow conditions to low flows and **increase diversity of the shallow shoreline fish assemblage** to more closely resemble unaltered reaches. Several fluvial-specialist species in the genera Cottus, Percina, Etheostoma, Lepomis, Hypentelium, Notropis returned (Travnichek et al. 1995).

Support mussel spawning, glochidia transfer, juvenile colonization and growth

●**In summer and fall, during juvenile deposition (between two weeks and a month after glochidia release), an increase in high flows may increase velocity and shear stress and inhibit successful colonization of juveniles [M6]**.

- During glochidia release and excystment, high flows and associated shear forces may be the primary factors in determining suitability of juvenile settlement locations. High flow releases from Green River dam (above median) in the spring and summer likely limit recruitment (Hardison and Layzer 2001).
- Using a particle distribution model, authors find that suitable habitats for juvenile colonization occur where shear stress ratio <1 and hypothesize that annual peak flows limit the availability of colonization habitats (Morales et al. 2006).
- High flows increase water column velocity inhibiting juvenile settlement after excystment from fish-host. Once reaching the substrate, velocity and shear forces can displace juveniles before they burrow or for some species, attach to substrate with their byssal thread (Holland-Bartels 1990; Layzer and Madison 1995).

●**Any time of year, an increase in the frequency or magnitude of small or large flood events may eliminate flow refuges and reduce recovery and recruitment time, resulting in reduced abundance and shifts in assemblage.[M13]**

- A small flood event (5 to 7 year return interval) redistributed bedload and unionids. Post-flood, individuals were 5 to 15 times more likely to occur within flow refuges than outside of them. Species were abundant in areas where shear stresses during the 3 to 30 year floods are too low to displace them (Strayer 1999).

- A large flood event (> 100 year return interval) resulted in loss of 4 to 8% of the regional mussel population (>50,000 individuals). Increased frequency of this magnitude of flood puts many mussel species at risk (Hastie et al. 2001).
- A large flood event (> 50 year return interval) resulted in significant decreases in the abundance and distribution of unionids, especially those in narrow, high gradient reaches lacking flow refuges (Fraley and Simmons 2006).
- DiMao and Corkum 1995

●**Any time of year, a rapid decrease in stream flow may decrease depth and result in mussel stranding, particularly in margin habitats [M14].**

- While mussels have been documented to move under extreme high and low flow conditions, movements are slow, limited by substrate, and do not occur over long distances. They are not adapted to follow receding water levels when low flows quickly change (Layzer and Madison 1995).
- Instream flow conditions supportive of mussel habitat need to consider persistent suitable habitat that combine the limiting factors of high flow (shear stress) and low flow (low velocity and restricted depth (Maloney et al. 2012).

●**From spring to fall, an increase in seasonal flow magnitude may increase velocity and associated shear stress, reducing abundance, richness, or individual growth [M4].**

- In an analysis correlating unionid growth rings with long-term hydrology, growth for some species was negatively correlated with increasing **May and June medians** and **high pulse count** (events > 75th percentile) (Rypel et al. 2009).
- A mussel extinction gradient was observed downstream from an impoundment. In increase in high flow frequency and magnitude and increased shear stress was considered one factor in the reduced diversity and abundance (Vaughn and Taylor 1999).

●**In summer and fall, during larval transfer, development and juvenile establishment (between two weeks and a month after glochidia release), a decrease in low flows may increase TDS concentrations, causing glochidia to close before attaching to host fish gills or may reduce suitable habitat for juvenile establishment [M7].**

●**From spring to fall, during reproduction (spawning and glochidia release) a decrease in extreme low flows may decrease depth, velocity and/or clarity, reducing the potential for host-fish to reach mussels and for successful glochidia transfer [M5].**

- Maintenance of host fish habitat is critical in streams where mussels use hosts that exhibit upstream spawning migrations. If migrations occur during glochidial release periods, the movements of infested host fish may be crucial for mussel dispersal and maintenance of upstream populations. Maintenance of hydrology for host-fish interaction may be most critical for highly mobile fish species (riffle associates and migratory fishes) that are not obligated to a specific hydraulic condition (Layzer and Madison 1995).
- On the Green River, below the Green River dam, researchers found relationship between reservoir conservation flow releases and mussel recruitment. Before low flow releases began, only 4% of the mucket population was <100 mm long. After the releases, 28% of the muckets were <100 mm long. **Find that *Lampsilinae* recruitment is related to low flow releases made in the late spring and early summer, and *Ambleminae* recruitment is related to low flow releases made during summer months**. Quantification:

Daily stream gage data is available below the dam. It may be possible to translate hydraulic conditions preceding successful recruitment years (Layzer 2009).

- Gravidity, fecundity and fertilization success of *Actinonaias ligamentina* were examined at 4 sites below the Green River dam, Kentucky. Find that females are not necessarily dependent on nearby males for fertilization and **factors necessary for species recovery include presence of host-fish and suitable conditions for juvenile survival and growth** (Moles and Layzer 2008).
- At the regional scale, authors found that rare mussels relied on host fish with short movement distances, where mussels with a more secure conservation status had host fish with 2 to 3 orders of magnitude movement distances. This suggests **limited dispersal by host-fish affects the abundance and distribution of unionid mussels**, and supports the need to consider host-fish mobility to ensure connectivity between and maintenance of metapopulations (Schwalb et al. 2011).

●In summer and fall, during the baseflow months, a decrease in low flow magnitude may increase temperatures in margin and backwater habitats, reducing fitness of thermally sensitive species that occur in these habitats [M8].

- For a study conducted in the southeast, above 30 C, thermally sensitive species, such as mucket *(Actinonaias ligamentina)* experience sublethal stress in respiration patterns, the catabolization of glycogen stores, and reduce nutrient processing. They find a seasonal pattern to glycogen stores increasing from summer to winter and declining in the spring, likely due to seasonal energetic investment in reproduction. Therefore stressful conditions that cause mussels to catabolyze glycogen, will be magnified during the reproduction period. (Spooner et al. 2005, Spooner and Vaughn 2008).
- Low flow events resulted in decreased velocity, disconnected habitats and increased water temperatures. Mortality rates of thermally sensitive species (including *Actinosis ligament* (mucket) and species in the *Truncilla, Quadrula* and *Lampsilis* genera). Authors believe that thermal stress associated with low water levels was one of the proximate causes of decline in species density, abundance and diversity (Galbraith et al. 2010).
- Pandolfo 2010, Pandolfo 2012

●In summer and fall, during the baseflow months, a decrease in low flow magnitude may reduce depth or dewater shallow riffle or margin habitats. Mussels associated with these habitats (rabbitsfoot and slow, low gradient species) may be subject to increased predation or desiccation [M9].

- During the late summer of 1988, low flows on French Creek **dewatered margin habitats exposing mussels**. During this period, the minimum flow was the **August Q90**, and the median flow was the **August Q85** (Pers Comm, Charles Bier 2012, USGS Unpublished data, IHA Analysis).
- During a record drought, reduced flows resulted in mussel emersion and increased predation. Emersion did not result in mortality in all mussels. Small-bodied mussels incurred higher mortality than large-bodied mussels (Johnson et al. 2001).
- During a summer low flow event, researchers found a significant negative relationship between water depth and mussel mortality (Galbraith et al. 2010).
- During a drought, discharge was 50% less than median conditions and, in small streams resulted in disconnected pools. On large river reaches, stream margins dried, but the stream remained hydrologically connected (Haag and Warren 2008).

●**In summer and fall, during the baseflow months, a decrease in low flow magnitude may have more significant impacts on mussel populations in creeks and small streams than on large rivers [M10].**

- A record drought resulted in disconnected pools resulting in a loss of species in small stream habitats (4 to 105 square miles). Tributary and large river habitats maintained connectivity and flow refuges and mussel assemblages survived the drought. A > 50% reduction of median monthly flows in summer months resulted in a 60-85% decrease in mussel abundance (number/m2)(Haag and Warren 2008).
- Under drought conditions, higher habitat impairments (hydrologic connectivity, temperature and DO stress) occurred in small streams than larger tributaries) (Johnson et al. 2001).

●**During the baseflow months, a decrease in low flow magnitude may significantly increase and algal production and decrease DO resulting in reduced growth or mortality for individuals, and reduced abundance and richness for populations [M11].**

- Thermal stress associated with low water levels was one of the proximate causes of reduction in species density, abundance and richness. Once the mussels began dying, tissue decay led to nutrient pulses and algal blooms which lowered DO, resulting in further mortality (Galbraith et al. 2010).
- During a drought, mortality increased when DO fell below 5 mg/L and velocity below .01 m/s (Johnson et al. 2001).
- Stream reaches that ceased surface and ground water connectivity under drought conditions (exacerbated by groundwater withdrawals) had significant declines in taxa richness and abundance (Golladay et al. 2004).

●**During the late summer, in the navigational pools of the large river, a decrease in low flow magnitude may increase sediment deposition and biological oxygen demand impacting mussel beds [M14]**

●**From summer through fall, a decrease in the frequency and duration of extreme low flow events may reduce the abundance of colonizer species [M15]**

Promote/support development and growth of reptiles and amphibians

●**During summer and early fall, a decrease in seasonal low flow magnitude may reduce the availability of stable, cool, highly oxygenated streamflows necessary for development of eastern hellbender eggs, larvae and juveniles [H10].**

- Foster et al. (2009) documents declines in Eastern Hellbender populations in the New York portion of the Allegheny river over the last 20 years with thoughts that declines could be driven by environmental factors including habitat degredation, chemical pollution and siltation.
- Chapman pers comm (2012) ; Netting 1929; Nickerson and Mays 1973
- External respiration for Cryptobranchus is predominantly cutaneous. This study measured the effects of progressive hypoxia in blood oxygen tension of Hellbenders. As the oxygen content of the water was lowered

from 75 to 25% saturation, there was a significant increase in rocking (a behavioral adaptation to increase oxygen flow over longitudinal folds). (Harlan and Wilkinson 1981).

- For a hellbender population in the West Virginia appalachians, home range estimates averaged 198 m2 and water depths ranged from 16 to 56 cm. Individuals were never captured in heavily silted areas (Humphries and Pauly 2005).

●**During the summer, a decrease in low flow magnitude may decrease benthic invertebrate presence and abundance, specifically crayfish, for specialist feeders like the eastern hellbender and queen snake [H9].**

- Humphries et al. (2002); Humphries and Pauly (2005)

●**Year round, a decrease in low flows may reduce available habitats, temperature and DO, critical for water quality sensitive aquatic and semi-aquatic species (e.g. eastern hellbender and wood turtle) [H12]**

A major drought in South Carolina provided opportunity to observe reproductive and emigration responses of freshwater turtle populations that had been studied for 15 years. Clutch numbers were significantly lower and emigrations were much higher than average in the years preceding the drought. *Sternotherus odoratus* and aquatic turtle, did not emigrate and ceased reproduction. (Gibbons et al. 1983).

- Guimond and Hutchinson (1973); Hutchinson et al. (1973; Hopkins et al. (2001); Humphries 2007

●**From late summer through early spring, a decrease in low flow magnitude may dewater eastern hellbender nests and eggs [H12]**

FALL

Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)

●**During fall, a decrease in seasonal groundwater or surface flows may reduce access to and quality (temperature and dissolved oxygen) of redds during salmonid spawning [F1].**

- On headwaters to small streams in the unglaciated plateau, a regional IFIM study predicted a 10% brook trout habitat loss for withdrawals of 11 to 14% of average daily flow (Figure 6.10) (roughly equivalent to the November Q50) (Denslinger et al. 1998).

- Kraft; Petty et al. 2005

Promote macroinvertebrate growth and insect emergence

●**During summer and fall, decreased magnitudes can cause community shifts for macroinvertebrates (e.g. stenothermal to warm, rheophilic and erosional to depositional, shifts in trophic dominance, dominant trophic habit) [A7,A10].**

- A comparison of streams along a withdrawal gradient, **finds direct effects were proportional to the amount of water withdrawn**. Indirect effects were more closely related to change in the macroinvertebrate community. Changes included decreased relative abundance and shifts from collector-gatherer and filterer to predatory insects, non-insect taxa and scraping beetles (Miller et al. 2007).
- An experimental withdrawal in headwater streams quantifies response between summer flow and macroinvertebrate density, community composition and available habitat. **A threshold seems to occur between summer Q75 and 85** (Walters and Post 2011).
- An experimental **summer flow reduction of 90% of baseflow** resulted in a decrease in EPT taxa (-50%), filter feeding insects (-90%), and grazing insects (-48%) (Wills et al. 2006).
- An experimental **summer flow reduction of 90%** resulted in a decrease in macroinvertebrate density (-57%) and density of EPT taxa (-26%) (Dewson et al. 2007b).
- **Following a drought event, taxa groups including free-living caddisflies and stoneflies were eliminated**. Once rewetted, taxa with limited desiccation tolerance were the last and fewest to recolonize (Boulton 2003)
- In response to decreased low flow magnitudes, there was an increase in the abundance of species with small-body size at maturity (Richards et al. 1997, Apse et al. 2008, Walters and Post 2011).
- A decrease in low flow magnitude resulted in an increase in eurythermal taxa and a decrease in stenothermal taxa (Lake 2003).
- A decrease in low flow magnitude resulted in a decrease in taxonomic richness (Boulton and Suter 1986, Englund and Malmqvist 1996, Wood and Armitage 1999, Wood and Armitage 2004).
- A decrease in low flow magnitude resulted in increased predator densities (Miller et al. 2007, Walters and Post 2011).
- After increasing low flow magnitude and structural improvements to increase DO through a Reservior Release Improvement Program, macroinvertebrate family richness increased and the percentage of pollution-tolerant macroinvertebrates decreased (Bednarek and Hart 2005).

●**During fall and summer, a decrease in flow magnitude could cue exit of shredders from headwater systems, resulting in a reduction of energy transformation and export (from CPOM to FPOM) [A9].**

- Export of fine particulate organic matter from headwater streams was measured during a 5 year period in three catchments. Annual export of FPOM was strongly related to annual discharge. Macroinvertebrate populations were experimentally eliminated in one catchment (insecticides). In this catchment, FPOM concentrations were reduced by an estimated 170 to 200 kg. **Macroinvertebrate reduction altered the magnitude of FPOM export during summer and fall storms, the seasonal pattern of export and the total annual export** (Wallace et al. 1991).

●**Anytime of year, if low flow magnitude decreases, habitats for large, long-lived (2 year) aquatic insects in riffles and runs (e.g. Odonate family) may decrease [A6].**

●**During summer and fall a decrease in low flows may reduce fitness and growth of crayfish[A13]**

- Under low flow conditions, crayfish carapace length was reduced (Taylor 1982, Acosta and Perry 2001).

●**During summer and fall, a decrease in extreme low flows may decrease crayfish habitat (depth, velocity, available cover) resulting in a shift in biomass or assemblage [A14].**

- Stream permanence had a significant effect on crayfish community density and composition. Predation interactions (presence of fish) were thought to also influence densities in permanent systems (Flinders and Magoulick 2003)
- Maintenance of shallow margin habitats (18 to 30 cm) provided optimal conditions for crayfish growth and refuge from predators (Centrarchids) as compared to deep pools (Flinders and Magoulick 2007).

●**During summer and fall, a decrease in flow magnitude may contract the hyporheic zone or disconnect it from surface waters. Low mobility, small-home range species within glaciated river types may be most sensitive to this change [G4].**

- The hyporheic zone acts as refuge for early instars and stream invertebrates during extreme conditions including drought. Exchange between surface water and the hyporheic zone occurs in response to variations in discharge and bed topography (Boulton et al. 1998).
- In an Appalachian headwater stream, abundance and taxa richness varied more with depth into the hyporheic zone than among seasons or sites. However, epibenthic and hyporheic community structure varied most among season. Abundance and taxa richness were positively correlated with interstitial flow, especially during the late summer/fall when stream flow was lowest (Angradi et al. 2001).
- Crayfish were found in the hyporheic zone during seasonal summer drying; they did not migrate downstream to avoid desiccation. Hyporheic burrows served as refuge for other invertebrates (DiStefano 2009).

Maintain water quality and transport of organic matter and fine sediment

●**During summer and fall, a decrease in high flow events may result in cumulative thermal and water quality stress (dissolved oxygen) and reduce export of coarse particulate organic matter [W1].**

- In a survey of three headwater catchments in the central Appalachian, most FPOM export occurred during high discharge summer events (Wallace et al. 1991).
- During summer and fall temperature and dissolved oxygen in surface and subsurface waters – headwater streams most sensitive (Angradie et al 2001)

●**During summer and fall, a decrease in low flow magnitude in proximity to a point source discharge would reduce dilution capacity which may exacerbate existing water quality impairments or result in new impairments [W2].**

- Assimilative capacity for streams is calculated using the 7Q10. Using a set of index gages, the **7Q10 condition occurs between the summer (J, A, S) Q99.5 and Q93, with most relationships falling between the Q96 and Q98** (USGS, unpublished data; IHA Analysis).

- In 1983, USACE conducted a study comparing water quality benefits of varying release scenarios from Kinzua dam to the Allegheny River. The existence of storage and regulation reduces water quality extremes. Appendix C of the report includes water quality duration curves associated with each scenario (Hadley et al. 1983).

●**During summer and fall, a decrease in flow magnitude would decrease capacity to assimilate TDS (salt) changing osmotic potential. Warm water streams would be most sensitive [W4].**

- In August and September 2010, hot, dry conditions caused DO and temperature violations and algae blooms in the upper Ohio River. Minimum flows in **August were at Q90 with the majority of days falling below Q60**. Minimum flows in September were at Q95 with the majority of days falling below Q70 (ORSANCO 2011, USGS unpublished data; IHA Analysis).
- A summary of water quality data collected 6 times a year at each of the tributary mouths and along the Ohio river finds trends for the PA portion of the Ohio include increasing Cl-, Mg, and NO2,3 and N, and decreasing metals (Al, Fe, Zn) and no trend on TSS or NH3-N (ORSANCO 2008).
- Headwater reservoirs in the Monongahela watershed are operated to mitigate low dissolved oxygen, high temperature and increasing total dissolved solids during the low flow months (USACE 2011, Renner 2009)

Maintain stable hibernation habitat for reptiles and amphibians

●**From fall through spring, a decrease in seasonal flow magnitude may decrease water temperatures or dewater individual or communal hibernacula for aquatic and semi-aquatic reptiles in stream banks (e.g. wood turtle) [H1].**

- During the hibernation period, map and wood turtles need flowing waters (that generally do not freeze) and high DO concentrations (Graham and Forseberg 1991; Crocker et al. 2000)
- Wood turtles are only capable of small and slow movements to avoid freezing or poor water quality conditions during the overwinter period (Graham and Forseberg 1991).

●**From fall through spring, a decrease in low flow magnitude may decrease water temperatures or dewater individual or communal hibernacula for aquatic and semi-aquatic reptiles in stream beds (e.g. spiny softshell, map turtle, wood turtle) [H2].**

- Wood turtles were surveyed and radio-tracked to monitor location of hibernacula and describe movement during the hibernation period. Wood turtles hibernated on the riverbed at a depth of approximately 1 m and approximately 1m from the riverbank. While air temperatures fluxtuated between 10.5 and -40 C, thermal buffering provided by flowing water maintained turtle body temperatures near 0 from December through April (Greaves and Litzgus2007, Greaves and Litzgus 2008).
- Reptiles and amphibians have several behavioral and physiological adaptations to survive freezing temperatures during the hibernation period. Most species rely on hibernation sites capable of buffering winter air temperatures (aquatic) (Storey and Storey 1992).

WINTER

Maintain overwinter habitats for resident fish

●**During winter, a reduction in seasonal flows may reduce deep pool refugia for adult migratory residents, increasing bioenergetic costs to seek suitable habitats [F4].**

- During winter, frazil ice poses direct physiological effects (attaching to gills) in addition to restricting available physical habitat. In the fall, trout began to aggregate in deep pools with high cover and low velocity. Trout aggregations were found in areas where groundwater buffered temperatures by 2-6 degrees C (Brown et al. 1993).
- During winter spawning, burbot need connectivity to upstream spawning habitats and maintenance of pools and runs for overwintering (D. Fischer, personal communication, 2012).

●**During winter, a decrease in low flow magnitude may decrease availability and access to riffle habitats needed by riffle obligate fishes [F5].**

- Population size for mottled sculpin is regulated by overwinter habitat availability. Juveniles and adults directly compete for refuge (Rashleigh and Grossman 2005).

●**During winter, a decrease in streamflow and groundwater contributions may decrease depth and temperature encouraging ice infiltration of salmonid eggs leading to impaired development or reduced survival [F3].**

- An observational study found that persistent groundwater upwelling (from spawning through incubation) was critical in protecting redds from infiltrating surface water and ice and maintaining dissolved oxygen levels. Survival was lowest (6%) in the redd with the lowest proportion of groundwater contribution and lowest temperatures (Curry et al 1995).

Maintain overwinter thermal regimes for mussels

●During gametogenesis (winter), a decrease in seasonal flow magnitude may reduce temperatures, shifting thermal regimes that cue **gamete development and release. Long-term brooders may be particularly sensitive** [M1].

- Reproductive success of long-term brooders may be influenced by overwinter flow magnitude (R. Villella, personal communication, 2010).
- Temperatures less than 10 C (and greater than 30 C) limit individual growth (Spooner and Vaughn 2008).
- Both field and lab studies suggest that thermal regimes are important cues for the timing of gamete development and potentially for gamete release. For all species, timing of reproduction was correlated with the number of accumulated degree days (Galbraith and Vaughn 2009).

●**During winter months, in riffles and runs, a decrease in low flow magnitude may cause anchor ice formation and scour mussel habitat [M2].**

Support winter emergence of aquatic insects and maintain overwinter habitat for macroinvertebrates

●**During winter, a decrease in seasonal flows may reduce access to and quality of habitats and reduce abundance of winter emerging aquatic insects [A2].**

- Decreased winter flows have been correlated with anchor ice formation and reduction or elimination of winter emerging stonefly taxa (Clifford 1969, Flannigan 1991).

●**During winter, a decrease in low flows may reduce macroinvertebrate abundance and result in a shift in assemblage [A3].**

- A withdrawal of >90% of fall and winter baseflow resulted in a reduction in macroinvertebrate density (-51%) and richness (-16%), and an assemblage dominated by tolerant species (Rader and Belish 1999).

Maintain ice scour events and floodplain connectivity

●During winter, a decrease in seasonal flows may reduce the extent of shoreline ice scour, reducing the maintenance of disturbances that support substrate and light conditions for the riverine scour vegetation community [V2].

- The riverine scour vegetation community is found throughout the Ohio watershed on all stream orders. They are dependent on ice scour, floods and high water velocities. Five high quality examples of the river scour community occur at the elevation that would be scoured above the February Q48 to the Q66. These examples occur on French Creek, the Allegheny, Beaver, and Monongahela rivers (Zimmerman and Podniesinski. 2008, USGS 2012, IHA Analysis).

SPRING

Support resident fish spawning

●**During spring and summer, an increase in the magnitude of high flows may reduce availability of suitable spawning riffles or impair egg and larval development for riffle obligates [F7].**

- Increased high flows in spring and summer increased relative abundance of deep-fast habitat and decreased the relative abundance of percids (Etheostoma and Percina). This may represent a habitat limitation for successful reproduction (Bowen et al. 1998).

●**During spring and summer, an increase in the magnitude or frequency of high flows can scour nests or damage developing eggs. River chub may be particularly sensitive to this change in tributaries and large rivers and hornyhead chub in headwaters and small rivers [F17].**

- Strongest smallmouth bass year class observed when June flows were within 40% of the long-term mean, peak recruitment was observed when June flows were within 4% of the long-term mean, years when mean June flow was more than 40% above the mean resulted in near year class failures (Smith et al. 2005).
- Graham and Orth 1986; Lukas and Orth 1993; Lukas and Orth 1995

●During spring and summer, if high flow magnitude or frequency increase, eggs and larvae developing in riffles may be scoured and/or physically damaged. [F19]

- Survival of walleye larvae were directly related to the frequency of high flow events with low survival during years with multiple events during the spring (Mion et al. 1998).
- Suitable habitat for young-of-year was predicted by conditions including high pulse magnitude, duration and rate of change (Freeman et al. 2001).

●During summer, increased frequency, magnitude or duration of high flow events may shift species assemblage [F20].

- Increased frequency of summer storm flows were related to decreased richness of endemic, cosmopolitan and sensitive fish species (Roy et al. 2005).

●During spring, a decrease in seasonal flow magnitude may result in deposits of fine sediment and suffocation of salmonid eggs [F6].

- Increased sand bed load (4 to 5 times baseline) resulted in decreased survival of eggs and juveniles and a 50% decline in overall population. (Alexander and Hansen 1986).
- Substrate dominated by fine sediments reduced intragravel permeability, dissolved oxygen and survival of brook trout eggs and larvae (Argent and Flebbe 1999).
- Fine organic sediment decreased salmonid embryo survival. Fish in the high-sediment treatment did not postpone emergence in response to predator odour and had reducing swimming ability (Louhi et al. 2011).

●During spring, a reduction of seasonal flows may alter spawning cues (temperature and flow) and reduce connectivity to upstream spawning riffles for riffle associates (redhorses) and potadromous fish (specifically walleye, sauger and Escocids) [F13]

- White sucker, creek chub, northern hogsucker, and black redhorse partition spawning timing and longitudinal position. Stream alterations that affect temperature, flow regimes, substrate or connectivity may reduce niche diversity impacting catostomid species composition (Curry and Spacie 1984).

●During spring and early summer, a decrease in median flows may reduce fish movement to, and availability of, preferred spawning habitats. Fish spawning in riffles are especially sensitive and they vary in body-size and river types (eg darters, redhorses, paddlefish) [F8].

- A decrease in the magnitude of median daily flows in spring results in an assemblage shift, reducing the number of spring spawners and increasing the number of summer spawners (Freeman et al. 2001).

Maintain access to and quality of shallow-slow margin and backwater habitats

●**During spring and summer, a reduction in high flow events may limit connectivity to and quality of oxbow and backwater habitats reducing fish production and species diversity [F16].**

- Within oxbow habitats, fish assemblage structure was associated with both macrohabitat features (depth, temperature, conductivity) and the frequency of floods that connected backwater habitats to the channel. Six species that were collected in oxbow lakes were never collected in river channel surveys and several species that were rare in river channel surveys were abundant in oxbows (Zeug et al. 2005).

●**During the spring and early summer, a reduction in high flow magnitude may restrict access to floodplains (backwaters and oxbows), reducing successful reproduction (egg laying and larval migration to channel) for great river species including longnose gar and bigmouth buffalo [F15].**

- From spring to summer, in an unregulated system, the distribution, location and size of shallow-slow habitat followed an annual pattern tied to the seasonal hydrograph: patches in side channels and tributary backwaters remained connected, migrating to the main channel during recession and benefitting larvae with poor swimming abilities and reliance on zooplankton and detritus as primary food sources (Bowen et al. 2003).
- For several populations of paddlefish, spawning success and year-class strength have been associated with years of high sustained spring discharge (Paukert and Fisher 2001).
- Firehammer and Scarnecchia (2007) find that in years of moderate discharge, site-fidelity may be as influential as spring flow in determining the reaches to which paddlefish ascend. Annual distance in ascent distance over the study period was not detected despite annual differences in spring flow regimes.

●**During spring and summer, a decrease in seasonal flows may reduce the availability of or connectivity to shallow-slow habitats (margins and backwaters) from the main channel, reducing successful larval development for migratory residents (walleye) and riffle associates (suckers). [F14]**

- From spring to summer, in an unregulated system, the distribution, location and size of shallow-slow habitat followed an annual pattern tied to the seasonal hydrograph: patches in side channels and tributary backwaters remained connected, migrating to the main channel during recession and benefitting larvae with poor swimming abilities and reliance on zooplankton and detritus as primary food sources (Bowen et al. 2003).

Provide sufficient flow for streamside amphibians

●From winter through early spring, if the frequency, duration or magnitude of high flow events decreases, inundation **of vernal pools and intermittent stream beds will decrease, reducing the hydroperiodand and success of egg and larval development for amphibians** (streamside and mole salamanders) [H5].

- Environmental conditions act as a cue for amphibian breeding. Under dry conditions, it is estimated that 90% of mole salamanders may skip a breeding year (Kinkead 2007).

●**During spring, if seasonal flow magnitude is reduced, streamside salamander eggs may be desiccated [H8].**

- Nesting sites of Desmognathus are generally found in aquatic habitats including cascading waterfalls, streambeds, stream banks and seepage areas. During a drought (1980), nests were found in high elevation seepages. The clutches were likely laid during flowing water, but lacked flowing water in the brooding chambers when collected. The breadth of viable nesting habitat is greatly increased during average precipitation and hydrologic years (Trauth 1988).

Support establishment and growth of floodplain, riparian and aquatic vegetation

● During the growing season, if high flow magnitude, duration or frequency are reduced, water availability (inundation days and soil saturation) and disturbance intensity may be reduced, causing a shift in floodplain and riparian community assemblage [V1]

- Seasonal flood magnitude and frequency on the Allegheny River were reduced by construction and operation of a flood control dam. Researchers found that spring scour is now insufficient to open sites for colonization and later stages of succession are more widely represented. Light regime one of a closed canopy favoring species with life history characteristics atypical of the pre-dam environment (Cowell and Dyer 2002).
- Using a flood inundation model derived from radar imagery, researchers quantified relationships between forest composition and flooding gradients on the Roanoke River floodplain. They find that **spring high flows are important in driving competitive sorting** especially during the establishment/early succession by limiting competitive advantage of early-season seedlings. Annual hydroperiod affects relative dominance. The elimination of flooding events would promote a homogenization of community composition. Flooding throughout the year, including the dormant period has been demonstrated to affect the ability of plants to maintain the stored reserves that are crucial to survivorship (Townsend 2001).
- The flood regime of the Illinois river has shifted due to regulation, reducing the magnitude and frequency of flood events. This has resulted in a shift in plant communities, including reduced abundance and diversity of many moist-soil species. They use a non-steady state hydraulic model to simulate annual hydrographs of river under different management scenarios to predict moist-soil plant success (Ahn et al. 2004)
- Reservoir operations and irrigation diversion have reduce flood magnitude, frequency and duration, causing sharp declines in pioneer woodland species. Under new hydrologic regime, a model projects replacement communities will be dominated by later successional woodland or grassland species. **A 25 to 50% reduction in spring high flows and mean annual flows** results in riparian encroachment into former channels (Johnson et al. 1998, Johnson et al. 1994).
- Silver maple and Sycamore floodplain forest communities have a high scour disturbance fidelity. Streams with high quality examples of silver maple and sycamore floodplain forest communities occur at elevations **between the Annual .5 and the 62** (Zimmerman and Podneisinski 2008, USGS 2012 and IHA Analysis).
- Comparing free-flowing to regulated rivers, find that both vegetation community composition and structure changed in response to and altered hydrologic regime. Regulated reaches had increased leaf litter and grass thatch composition compared to naturally flowing reaches. There was also an increased woody species canopy coverage as distance from the stream increased altering light conditions and reducing successful establishment of rare species in the floodplain (Eldered et al. 2003).

- Regulation of a large river (Salt River, AZ) decreased the frequency and magnitude of overbank floods and changed the seasonal timing of flows with high flows in the summer which reduced the quality of habitat available for Populus regeneration (Fremont cottonwood).(Fenner at al. 1985).
- Riparian assemblages in large rivers are particularly sensitive to changes to the minimum flow and high flow events (Auble et al. 1994).
- Plant communities were arrayed along a hydrologic gradient with the Salix community occurring on surfaces with a recurrence interval < 2.2 years and Betula and Alnus on sites between 2.2 and 4.6 years, or **between the bankfull flood and small flood** (1 in 5 year recurrence interval) (Friedman and Auble 1999).

●**During late winter and early spring, a reduction of high flow magnitude and duration will reduce extent of water-dispersed seeds and scour and preparation of seed beds reducing availability and moisture of bare mineral soil. [V2]**

- Regulated high flows on the Allegheny River have altered the flow regime and led to failure in recruitment of Silver Maple and American sycamore along that portion of the river (Walters and Williams 1999).
- Comparison of riparian and floodplain vegetation communities between a regulated and unregulated river in western Arizona. Recent seedling establishment (saplings established since the 1980's when the dam was constructed) occurred over a wider band along the unregulated stream than the regulated. The 1 in 10 year flood has decreased from 1397 to 148 m3/s (Shafroth et al 2002).
- Comparing presence of vascular plants with different dispersal mechanisms between free-flowing and regulated river reaches. Find that regulated reaches had a higher proportion of wind-dispersed species and species with generalist dispersal mechanisms (Jansson et al. 2000**).**
- River bank and bed propagule samples were taken to determine whether species abundance of plant propagules varies in space and time (seasonally) and to what extent patterns of deposition can be attributed to fluvial processes. Highest depostied propagule species richness in late autumn and winter, followed by spring implicates the importance of winter high flows for remobilizing and transporting propagules (Gurnell et al. 2008)
- Seeds of riparian trees including American sycamore, river birch and silver maple, depend on high flows for dispersal (Burns and Honkala 1990).

●**During fall and winter, an increase in the frequency and magnitude of high flows may scour SAV and emergent seed beds (at a time when roots are dormant) resulting in a local loss of seedbank (may redistribute elsewhere) [V3]**

- Quantification of the effects of sediment mobilization and extended inundation on box elder saplings. Two stressor threshold functions from inundation and shear stress. Box elders were either killed by > 85 days of inundation or by shear stress that mobilizes the underlying sediment particles (**Friedman and Auble 1999).**

●From spring to fall, during the growing season, increased flashiness may increase decomposition rates and associated nutrient availability and enhance establishment and persistence of non-native species [V7]

- Major hydrologic changes due to regulation led to a reduction of inter-annual variability and a reduction in peak flows and periodic low flows, leading to a dampening of 30 to 40 year water cycles. An invasive plant (Typha) benefits from increased summer water levels (Farrell et al. 2010).

●During the growing season, if seasonal flow magnitude is decreased, groundwater storage may decrease, lowering the water table and resulting in stress to riparian plant and forest communities. [V8]

- In headwater and small stream settings in Pennsylvania, examined the influence of inundation potential (high, moderate or low probability of seasonal inundation) and forest overstory on species richness, biomass and cover of the summer groundlayer (vascular plants) at six riparian sites. Richness and biomass were significantly greater for high inundation sites. Obligate and facultative wetlands species occurred most often at high inundation sites. Facultative upland, and upland species occurred most often in moderate to low inundation sites. High inundation sites were subject to seasonal inundation (during March and May) and high flow pulses; moderate inundation periodic inundation during seasonal high flows; beyond the influence of normal high stream flows. Sites with high inundation potential support great ground-layer species richness, biomass and cover and a relatively distinct wetland flora compared to mesic floodplains (Williams et al. 1999).
- In a headwater setting, nineteen geomorphic site combinations were grouped according to inundation class (frequent, moderate and low inundation) to determine the influence of flood frequency on seedbank composition. Species composition by growth and form varied across inundation classes. Forbs dominated seed bank composition for frequently inundated sites. Graminoids and forbs were codominant in the seed banks of moderately inundated sites. Low inundation sites were similar to moderate inundation sites with the addition of woody species. For the extant vegetation, there was a significant difference in occurrence of wetland and upland species across inundation classes with wetland species occurring most often at frequently inundated sites (Hanlon et al. 1998).

●From spring to fall, during the growing season, a decrease in low flow magnitude may reduce growth and survival of submerged and emergent aquatic vegetation. [V9]

- Podostemum grows in fast riffles and runs of relatively undisturbed and unpolluted streams. On the Allegheny, the plant bases of an area of Podostemum were exposed during a low flow year (August of 2000). The majority of flows during the month were below the August Q87 (Munch 1993, USGS 2012, IHA Analysis).

●Year-round, a decrease of high flow frequency and duration may alter nutrient biogeochemistry and floodplain soils, mychorrhisal activity and decomposition rates [V12]

- Measured litterfall, leaf breakdowns and floodplain litter before and after a flood at twelve sites (inundated and non-inundated). The flood was characterized as a 1 in 5 year flood. Found the flood increased leaf breakdown of all species (families Acer, Plantanus, Juglans and Carpinus). Additionally it transported leaves from the floodplain to the river via entrainment (Netrour 2004).

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

- Low flows can reduce aquatic prey availability for birds of prey and wading birds (Brauning 1992).
- Low flows can create land bridges between mainland and island habitats, introducing predators which may threaten rookeries and breeding success (PGC and PFBC 2005).
- Small mammals including the southern water shrew and many bat species require continuous localized access to an abundance of aquatic insects (Merritt 1987, PNHP 2009).

● Maintain valley and island formation, channel morphology, island formation, and sediment distribution

- The **number of river islands on the Upper Ohio river has been reduced from 14 to 6 in the last 50 years** (-67% of island shoreline habitat) as a result of dredging, erosion ad changes to river elevation and hydrology (Fortney et al. 2001).
- **Flood events transport large woody debris**, specifically 'key member' logs which initiate formation of stable bar apex and meander jams that alter the local flow hydraulics leading to pool and bar formation. Individual **jams provide interim stability, bank protection and refugia for local forest patches and influence pool intervals and depth** (Abbe 1996).
- **1 in 5 year high flow events are associated with channel maintenance and overbank events** (Nanson and Crook 1992).
- Regression equations to estimate bankfull discharge for streams in Pennsylvania fall within the 1 in 2 year recurrence interval (Chaplin et al. 2005).
- Sediment in spawning redds increases under low flow conditions: Hakala and Hartman (2004), Dewson (2007)

Appendix 7: Methods for a Weight-of-Evidence Approach to Assessing Support for Regionally-Specific Flow Ecology Hypotheses, Needs and Recommendations

An understanding of the causal relationships between stressors and ecological responses is required to make informed decisions in natural resource management. Inherent in demonstrating cause-effect relationships in natural systems are the difficulties of designing a study that minimizes confounding influences, includes sufficient replication, control and reference sites, and accounts for natural variability. In light of these complications, few individual studies result in a design with the rigor to infer a cause-effect relationship with reasonable confidence (Downes et al. 2002). While individual studies may not provide evidence to infer causation, Norris et al. (2012) recognized that multiple lines of evidence within the extensive ecological literature may cumulatively provide strong support for a cause-effect relationship. To this end, Norris et al. (2012) developed the Eco Evidence framework to transparently review and weight evidence to characterize support for a given hypothesis.

The Eco Evidence framework is an 8-step process to systematically review the evidence to assess the level of support for the overall question. The process can be grouped into three phases: *Problem formulation, Literature review,* and *Weighting evidence and judging support*. This approach has been successfully applied to aquatic stressor response relationships including the influence of accumulation of fine sediments on macroinvertebrate assemblages and the influence of flow regimes on riparian, wetland and floodplain vegetation (Harrison 2010, Greet et al. 2011, Norris et al. 2012, Miller et al. 2012 and Webb et al. 2012). Our approach differs slightly from Norris et al. (2012) in that our goals were not only to characterize support for causality for each specific hypothesis, but to summarize that support for flow needs and recommendations.

Problem Formulation

The goal of this project is to develop a set of ecologically based flow recommendations that can be applied to instream flow protection within the Upper Ohio River basin. Therefore, the broad, overarching question is, "*what are the flows needed to support stream ecosystems within the Upper Ohio River basin?*"

In order to apply the Eco Evidence method to this broad question, we hypothesized flow-ecology relationships for each stream type. We summarized the hydrology of the basin's habitat types in relation to the life histories of the biota they support in a series of flow ecology diagrams and life history tables (Appendix 2). Our problem formulation involved using the flow-ecology diagrams and life history information in an expert workshop setting to generate flow ecology hypotheses that describe ***who*** (species or guild), is affected by ***what*** (flow component), ***when*** (month or season), ***where*** (habitat), and ***how*** (hypothesized ecological response). Experts defined approximately 80 working hypotheses that describe anticipated ecological responses to changes to the flow regime (Appendix 4). We aggregated related hypotheses into a set of 20 flow needs that combine one or more responses of a taxa group to a change in flow conditions (Appendix 5). This provided the structure to use a weight-of-evidence approach to document the degree to which literature supports the flow hypotheses, flow needs and ultimately the recommendations.

Targeted Literature Review

The Eco Evidence framework requires that a systematic and documented method for retrieving literature be used to reduce subjectivity and bias of the reviewer (Greet et al. 2011). Key words (*who, what, when, where, how*) from flow ecology hypotheses were used to develop the literature search and review to test hypotheses and support identified needs for the region. In addition to using key words from the hypotheses we used references documented in recent flow-ecology literature reviews including Zimmerman and Poff (2010), DePhillip and Moberg (2010), McManamy et al. (2011) and Taylor et al. (*in review*).

Each paper was reviewed to determine its relevance to the hypothesis. We reviewed two types of evidence, papers that provided qualitative support and papers that provided quantitative support. We developed relevance criteria for each type, recognizing that quantitative findings should be transferred within a more specific hydogeographic context. The specific criteria for each type are discussed in Section 5.1. Generally, criteria for relevance included a combination of geographic proximity, similar environmental characteristics (i.e., temperate river systems), and similar causal agents (flow component, target species groups). Relevant publications related to temperate streams of North America that had similar target species or functional groups.

Because we were looking at questions related to variation in the natural flow regime and how organisms respond, we reviewed studies that documented responses to human impacts to flow regimes as well as observations of target species or species groups to natural variation in the flow regime (e.g., responses to drought or flood events). We also considered unpublished regional data and observations from our expert group. When possible, we put observations in the context of long-term hydrology by retrieving local index gage data and calculating long-term statistics using the Indicators of Hydrologic Alteration.

Each relevant paper provides evidence to support a hypothesis. In general, each paper is considered one piece of evidence. However, some papers document more than one flow-ecology relationship. For example, a paper may document responses of multiple taxa to hydrologic alteration or the response of a species in more than one season. In these cases, a paper may provide evidence for more than one cause-effect hypotheses. We summarized findings of more than 150 flow-ecology publications relevant to Ohio basin species groups and habitats. Only studies or observations relevant to the hypotheses were weighted as described below.

Weighting Evidence and Judging Support

Following the Eco Evidence framework, we used a rule-based approach to weight individual studies based on the tenet that studies that better account for environmental variation or error should carry more weight in the overall analysis than studies with less robust designs (Norris et al. 2012). For example, inclusion of control or reference sampling units, or data collected before the hypothesized disturbance, as well as the use of gradient-response models, all improve a study's inferential power (Downes et al. 2002). Additional replication provides an estimate of variability around a normal condition, further adding weight to the findings of any difference between treatments or time periods caused by the hypothesized causal agent (Downes et al. 2002). For each relevant study, we evaluated the quality of the evidence based on three attributes:

1. Study design type
2. Number of independent sampling units used as controls
3. Number of potentially impacted independent sampling units

We assessed these three attributes using the scoring criteria presented in Table 1. The combined weights based on all attributes are summed to give an overall study weight for each piece of evidence identified from a study. For example, if a reference vs. impact study had 1 reference site and 2 impact sites, the overall study weight would be 2 (design) + 1 (reference site) + 2 (impact site) = 6 (based on criteria in Table 1). In addition to the criteria presented in Table 1, we scored studies that published observational results confirming the relationship between and ecological response and a component of the flow regime. Observational studies were given a weight of 1 (similar to the after impact only score). The weights reflect previously elicited expert opinions about the number of consistent results from high and/or low quality studies that is needed to confidently support a hypothesis (Norris et al. 2005).

Table 1. Weights applied to study types and the number of sampling units (Nichols et al. 2011). B= before, A= after, C= control, R= reference, I= impact, M= multiple. Overall evidence weight is the sum of design weight and replication weight (Norris et al. 2012).

Study design component	Weight
Study design type	
After impact only	1
Reference/control vs impact with no before data	2
Before vs after with no reference/control location(s)	2
Gradient response model	3
BACI, BARI, MBACI, or beyond MBACI	4
Replication of factorial designs	
Number of reference/control sampling units	
0	0
1	2
>1	3
Number of impact/treatment sampling units	
1	0
2	2
>2	3
Replication of gradient-response models	
<4	0
4	2
5	4
>5	6

After assembling and weighting evidence from each relevant paper, we combined it to assess evidence of support for each hypothesis. More than 150 papers were reviewed and weighted to characterize support.

The method of causal criteria analysis presented by Norris et al. (2012) relies on the causal criterion of the repeated observation of an association between cause and effect under different conditions and assessed using different methods or 'consistency of association' (Hill 1967).

A default threshold of 20 summed study weight points delineates the point at which sufficient evidence exists for the hypothesis. The default 20-point threshold means that ≥ 3 independent, high quality studies are sufficient to conclude that a hypothesis is supported. However, the same conclusions can be met with ≥ 7 low quality studies or a combination of high and low quality studies. The threshold is somewhat analogous to the use of a *p*-value of 0.05 to ascertain statistical significance, and while based on numerous trials and extensive consultation, should be considered more as a convenient division of a continuous score, rather than an unmovable threshold (Norris et al. 2012). We also developed categories to characterize the support for hypotheses with a score of < 20 as moderate support (10 to 20) and some support (1 to 10) (Table 2).

Table 2. Three levels of support as adapted from Norris et al. (2012)

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

Appendix 8. Application of recommendations to the Great Lakes and Potomac River basins

The Nature Conservancy has also been a partner on flow studies for the Great Lakes and Potomac River basins, through our New York and Maryland chapters. In our scope of work for the Upper Ohio study, Pennsylvania DEP also asked us to address the Great Lakes and Potomac River basins within Pennsylvania.

In this appendix we

1) summarize the status and draft conclusions of concurrent Great Lakes and Potomac basin flow studies; and
2) discuss how the recommendations from the Upper Ohio flow study could apply in these basins based on similarities in habitat types and flow-sensitive species.

Summary of concurrent studies in Great Lakes and Potomac River basins

Great Lakes Basin

In 2011, the Conservancy, the New York State Department of Environmental Conservation (DEC), and Cornell University's New York Cooperative Fish and Wildlife Research Unit began an 18-month project to provide information that supports development of sustainable water management policies for **Great Lakes surface and ground-waters in New York and Pennsylvania**. The project supports a series of water conservation and management measures underway in New York that are tied to implementation of the Great Lakes Water Resources Compact and statewide improvements to water management. This project to develop Instream Flow Recommendations for the Great Lakes Basin of New York and Pennsylvania (referred to as NYPAFLO) followed a very similar process and timeline as the Upper Ohio basin study. A Cornell post-doctoral research associate led technical aspects of the project, which included engaging technical advisors from agencies and universities to develop hypotheses of ecological responses to flow alterations, testing these hypotheses, compiling supporting information and making flow recommendations that avoid adverse impacts to aquatic resources. We collaborated closely with NYPAFLO project staff to identify representative species and species groups and to develop the weight-of evidence methods for strength of support. We also reviewed each other's interim products and helped facilitate each other's workshops. The NYPAFLO project used stream types based on New York's existing state classification and focused primarily on fish. Flow recommendations are currently in draft and will be in a similar form to the Upper Ohio recommendations. We expect them to be completed in spring 2013, shortly after completion of this report.

Potomac River Basin

In May 2009, the USACE-Baltimore District, the Interstate Commission on the Potomac River Basin (ICPRB), and the Conservancy began collaborating on the Middle Potomac River Watershed Assessment (MPRWA). The goal was to assess streamflows in the **mainstem and tributaries to a large portion of the Potomac River.** The study addressed key ecological needs related to streamflow, existing and future impacts of human activities on flow, and the potential effects of climate change on watershed hydrology. Two of the project's five components provide information relevant to the Pennsylvania portion of the Potomac River basin: (1) a large river environmental flow needs assessment; and (2) a stream and small rivers environmental flow needs assessment.

Large rivers. The Potomac Basin Large River Environmental Flow Needs assessment was developed by a research team from the ICPRB, USGS Leetown Science Center, the Potomac Environmental Research and Education Center of George Mason University (GMU) and the Conservancy. It included a comprehensive literature review, development of flow hypotheses, assessment of large river environmental flow needs, statistics proposed to track those flow needs, and recommendations for additional research, monitoring, and analysis to improve understanding of flow needs (Cummins et al. 2011[1]). Even though the large rivers addressed are outside of Pennsylvania (i.e., Potomac and Monocacy Rivers), some Riverine Ecological Indicators presented in the report are relevant to Pennsylvania's tributaries because Pennsylvania streams contain the same species or species with similar traits. Cummins et al. (2011) recommended:

> *"In the large rivers included in this study, based on currently available information, there has been no discernible adverse ecological impact on focal species due to human modification of flows. As a precautionary measure, the team recommended that the current large river flow regime be maintained for the entire range of flows as defined by 20 flow statistics based on a 21-year period of record (1984-2005)."*

Streams and small rivers. For the streams and small rivers assessment, the project team developed flow alteration-ecological response relationships using modeled flow data and a basinwide benthic macroinvertebrate dataset. The hydrologic modeling was done using the Chesapeake Bay Program's watershed model and the Virginia Department of Environmental Quality's Online Object Oriented Meta-Model (WOOOMM) routing module. Current and baseline flow time series were simulated for 747 macroinvertebrate sampling locations. The baseline flow time series was simulated by removing the influence of water withdrawals, impoundments, and land cover change. More than 170 flow metrics were considered but six flow metrics were ultimately selected to represent different aspects of the flow regime and to relate flow alteration to biological status, represented by seven biological metrics, including both macroinvertebrate indices and trait-related metrics.

Watershed factors that alter flow in the Middle Potomac study area were related most often to urban development, particularly impervious surface area. Flashiness was shown to increase when impervious surface in a watershed exceeded about one percent.

The project team did not recommend limits to hydrologic alteration that could be applied to management of water withdrawals or reservoirs. They did conclude that the quantitative relationships between flow alteration (especially alteration to high flows and flashiness-related metrics) and macroinvertebrate indices could be applied to set thresholds for watershed development that would maintain or improve ecological conditions.

The final report is expected in spring or summer 2013.

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[1] http://www.potomacriver.org/2012/sustainableflows/large_riv_flow_needs.pdf

Application to Great Lakes and Potomac basin streams and rivers

In addition to the Great Lakes and Potomac studies, there is potential to apply some of the flow recommendations from the Upper Ohio study to streams and rivers in these basins that:

a) share similar habitat types and associated species; and
b) are likely to have similar hydrological and ecological responses to changes in streamflow.

Table A9.1 summarizes the habitat types that likely occur in the Great Lakes and Potomac basins. We follow with a description of similarities and differences in basin physiography, which flow recommendations would likely apply, and a list of steps that would further strengthen the basis for applying these recommendations in the Great Lakes and Potomac River basins.

Table A9.1 Habitat types in the Great Lakes and Potomac basins

	Great Lakes	**Potomac**
Upper Ohio Basin Flow Study habitat types	Lake Erie • Headwaters • Cool/cold creeks • Warm creeks • Small Rivers – glaciated Lake Ontario (Genesee watershed) • Headwaters • Cool/cold creeks • Small Rivers – glaciated[2]	• Headwaters • Cool/cold creeks • Warm creeks • Warm small rivers • Cool-cold small rivers • Warm tributary[3]
Northeast Aquatic Habitat Classification System (NAHCS)	• Cool-cold	• Cool-cold • Warm
Pennsylvania Chapter 93 Designated Uses	Lake Ontario • Cold Water Fishes • HQ Cold Water Fishes Lake Erie • Cold Water Fishes • HQ Cold Water Fishes • Warm Water Fishes	• Cold Water Fishes • HQ Cold Water Fishes • Warm Water Fishes • Exceptional Value • Trout Stocking (TSF)

The Great Lakes basin in Pennsylvania is within the Central Lowlands and Appalachian Plateaus Provinces. The Lake Erie streams (Erie and Crawford County) are primarily within the Eastern Lake Section, which consists of a series of parallel low-relief ridges made up of unconsolidated surficial

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[2] There is only one short reach approximately 3 km long near confluence of Middle and West Branches of Genesee River where the drainage area is > 40 mi^2 before the Genesee River flows into New York.

[3] There is a short reach of Conococheague Creek downstream of confluence with Back Creek that is > 200 mi^2 drainage area.

materials, mainly sands and gravels, deposited after the most recent glaciation. Most streams flow within steep-sided, narrow valleys that cut through these ridges into the underlying shales and siltstones and flow into Lake Erie. Drainage pattern is typically parallel and streams are oriented perpendicular to the Lake Erie shoreline. Many of these streams begin on the Northwestern Glaciated Plateau Section, which is the same section that underlies the headwaters, creeks and small glaciated rivers in the French Creek and Beaver River watersheds. In this section, the valleys are often wide and the unconsolidated material beneath the valley floor is quite deep. Dendritic drainage patterns are common. Although glaciated, the Lake Erie tributaries do not have the same broad glacial valleys and extensive groundwater contributions that were some of the defining characteristics of similar-sized rivers in the Upper Ohio basin.

The small portion of the Lake Ontario watershed is within the High Plateau Section. The underlying geology, landforms, and drainage pattern are very similar to the tributaries to the Upper Allegheny River and streams that flow into the West Branch of the Susquehanna River (including the headwaters of Pine Creek and the Cowanesque River).

The Potomac River basin in Pennsylvania is primarily within the Ridge and Valley Province; there is a small section of the Monocacy watershed that is in the Piedmont Province. Streams in the Potomac River basin share more characteristics – in terms of underlying geology, landform and drainage pattern – with streams in the Susquehanna River basin than with streams in the Ohio River basin. Potomac streams also share similar fauna with Susquehanna streams.

The NAHCS classifies all Pennsylvania streams in the Great Lakes basin as cool-cold. The Potomac basin includes both cool-cold and warm streams. There are both cold and warm water fishes in both basins according to the Chapter 93 designated uses. The Pennsylvania Aquatic Community Classification (PACC) also indicates cold and warmwater fish communities in both basins.

Based on the Chapter 93 designations, the PACC, physical characteristics of these watersheds, we expect headwaters (< 4 mi^2), and warm and cool-cold creeks (4 to 40 mi^2) to occur in both Great Lakes and Potomac basins. Both basins also have small rivers (40-200 mi^2). In the Potomac basin they are unglaciated; in the Great Lakes basin, they are glaciated, although they do not share many characteristics with glaciated small rivers in the Upper Ohio basin. The Potomac basin has one short reach of (warm) tributary that is >200 mi^2.

Additional considerations:

- Although the individual species will differ among basins, we expect representatives of most of the fish and mussel groups to be present in all three basins, with some exceptions noted below.
- The overall species diversity in the Upper Ohio basin is higher than either the Great Lakes or Potomac River basin.
- The Pennsylvania portions of Great Lakes basin and the Potomac basin do not include any great river fish. However, the Lake Erie basin streams would include Great Lakes migratory fish that have not been considered in the Upper Ohio basin but that were addressed as part of the NYPAFLO project.

The life history needs for these species reveals additional flow sensitive periods, especially related to migratory cues, timing of migration and spawning habitat quality.

Because the Great Lakes and Potomac River basins share similar habitats types and species groups with the Upper Ohio basin, we would expect the following recommendations to be sufficient to protect the ecosystems in the Great Lakes and Potomac basins and could be used as a starting point for water management in the Pennsylvania portion.

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

We have outlined several fairly simple **steps that would strengthen the basis for applying these recommendations** in the Potomac and Great Lakes basins:

- **Confirm habitat types in each basin.** Are the habitat types listed above actually present? Are there any other types that occur in these basins that do not occur in the Upper Ohio that and would warrant different recommendations? Confirm the presence of both warm and cool-cold creeks and small rivers. The recommendations for warm and cool habitat types are the same for each size class, but the temperature designations influences which species are likely to be present and therefore which species the recommendation is intended to protect.

- **Review species lists for each basin.** We did not have or use species lists for these two basins to confirm that all the taxa groups we believe to be present are actually present. There are several good sources of information that could be used to confirm which species groups are present, the species that represent each group, and which additional species that are not present in the Upper Ohio are present in the Potomac and Great Lakes.
- **Conduct hydrologic characterization.** Calculate monthly exceedence values using minimally altered gages in these reaches.
- **Incorporate any new information or any basin-specific studies** that have been completed.
- **Review recommendations with basin experts.** Incorporate observed ecological responses to changes in flow conditions during the period of record.
- **Once the Great Lakes recommendations are finalized, do a side-by-side comparison** of recommendations for the Great Lakes, specifically for headwaters, creeks and small rivers.