North Branch, Little Salmon River – Scott Prindle, NYSDEC Region 7

Flow Recommendations for the Tributaries of the Great Lakes in New York and Pennsylvania

A report submitted to
New York State Department of Environmental Conservation by
The Nature Conservancy

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Foreword

The Nature Conservancy acknowledges the scientific rigor, skill, and creativity of our partners in the New York Cooperative Fish and Wildlife Research Unit in the completion of this project. The knowledge, expertise, and analytic capability of Dr. Jason Taylor are fully on display in this final report. We thank Dr. William Fisher, Associate Professor and Unit Leader, for his leadership and guidance.

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Flow Recommendations for the Tributaries of the Great Lakes in New York and Pennsylvania

A report submitted to the New York State Department of Environmental Conservation by The Nature Conservancy

In order to make recommendations for management of water withdrawals and water use at a regional scale, this project focuses on defining and quantifying the ecological processes necessary to maintain intact aquatic ecosystems in streams ranging from headwaters to large rivers. The goal of these recommendations is to avoid cumulative adverse impacts to the waters and water-dependent natural resources, while providing the water necessary for human needs. In pursuit of this goal, we recommend the following guidelines for water withdrawal policy for streams of different types:

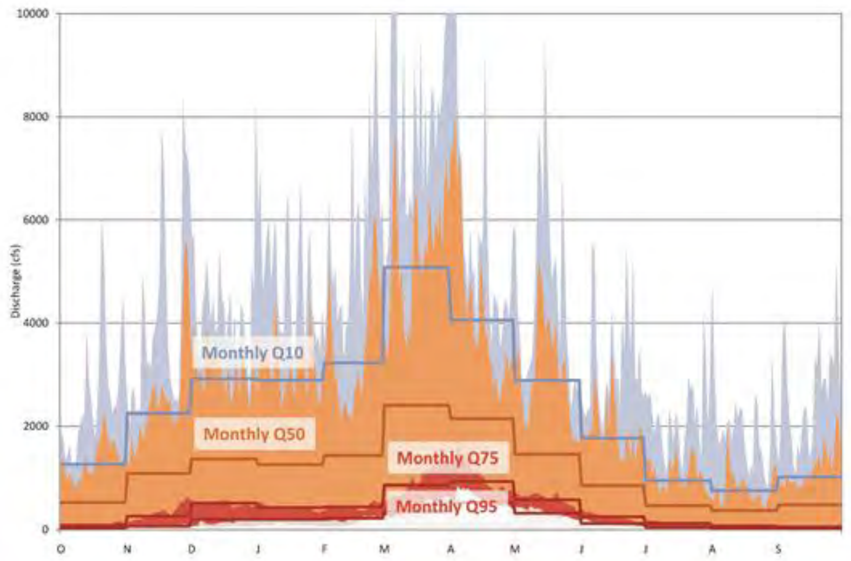
High flows	**All habitat types**	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, frequency and duration of channel forming (1 to 2-year) events	
	All habitat types	**All seasons** • < 10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})	
Seasonal flows	**Headwaters and creeks**	**All seasons:** <10% change to upper flow range (between monthly Q_{10} and Q_{50}) **Summer - Fall:** No change to monthly Q_{50}; no change to lower seasonal range below Q_{50} **Winter-Spring:** <10% change to Q_{50}; <10% change between monthly Q_{50} and Q_{70}	
	Small rivers, 50 - 200 sq.mi.	**<10% change** to monthly Q_{50}, to upper seasonal range monthly $Q_{10} – Q_{50}$, and to lower seasonal range monthly Q_{50} - Q_{70} (summer-fall) or monthly $Q_{50} – Q_{80}$ (winter-spring)	
	Major tributaries, 200 - 1,000 sq.mi.	**<15% change** to monthly Q_{50}, to upper season range monthly Q_{10} to Q_{50}, and to lower seasonal range monthly Q_{50} to Q_{70} (summer-fall) or monthly Q_{50} to Q_{80} (winter-spring)	
	Large rivers, >1,000 sq.mi.	**<20% change** to monthly Q_{50}, to upper seasonal range Q_{10} to Q_{50} , and to lower seasonal range monthly Q_{50} to Q_{75}	
Low flows	**Headwaters and Creeks**	**No change** to low flow range monthly Q_{50} to Q_{99} (summer-fall) or monthly Q_{70} to Q_{99} (winter-spring)	
	Small rivers and Major tributaries	**No change** to low flow range monthly Q_{70} to Q_{99} (summer-fall) or monthly Q_{80} to Q_{99} (winter-spring	
	Large rivers	**Summer-Fall (July – Oct)** • <20% change to low flow range (monthly $Q_{75} – Q_{85}$) • No change to lowest flow range ($Q_{85–99}$)	**Winter-Spring (Nov – June)** • <20% change to low flow range (monthly $Q_{75} – Q_{90}$) • No change to lowest flow range (Q_{90-99})

To implement these recommendations in actual practice, we further recommend the use of two tools for water management: passby flows, to preserve the vital minimum flows during periods (and seasons) of low water; and withdrawal limits, to preserve the natural variability in seasonal flows so necessary for diverse aquatic life. The combination of these two tools meets the needs of a diverse array of target aquatic organisms:

Stream Type	Policy Tool	Summer/Fall (July-October)	Winter/Spring (November-June)
Class 1 Streams:	WD	10% of Q_{50}	10% of Q_{50}
Headwaters and Creeks	PB	Q_{50}	Q_{70}
Class 2a Streams:	WD	10% of Q_{75}	10% of Q_{75}
Small Rivers	PB	Q_{70}	Q_{80}
Class 2b Streams:	WD	15% of Q_{75}	15% of Q_{75}
Major Tributaries	PB	Q_{70}	Q_{80}
Class 3 Streams:	WD	20% of Q_{75}	20% of Q_{75}
Large Rivers	PB	Q_{85}	Q_{90}

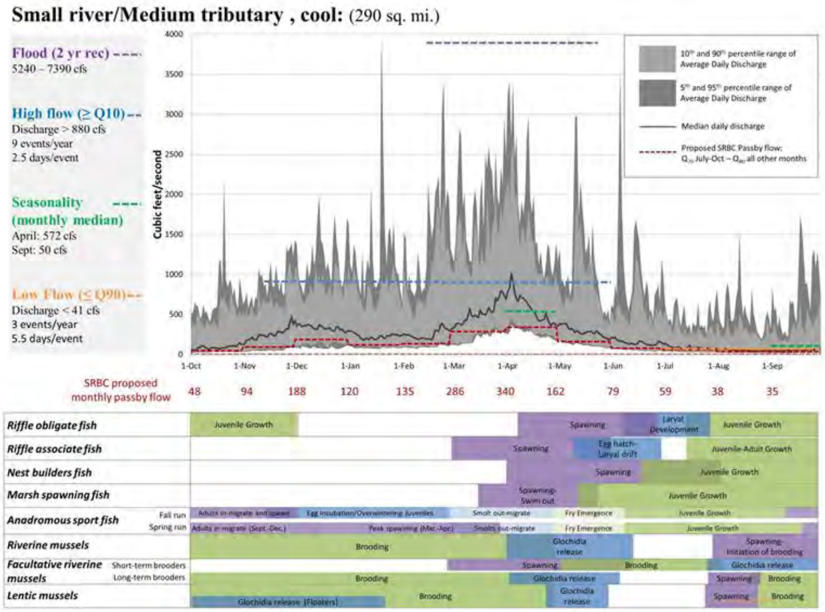
This table presents an example of the combination of monthly withdrawal limits (WD) and passby flows (PB) for streams of different types. In this example, during July-October for Class 1 (headwaters < 50 square miles) streams, the potential withdrawal limit above the passby flow is 10% of the monthly Q50, and this withdrawal limit is combined with a passby flow that would halt further withdrawals once the monthly Q50 level has been reached.

In order to develop recommendations for management of water withdrawals in the Great Lakes watershed, we engaged a 28-member Technical Advisory Team, composed of natural resource professionals from the NYSDEC, USGS, USFWS, EPA, and scientists from regional universities. To facilitate identification of vital ecological processes, we defined flow components to highlight specific portions of the hydrograph. The color coding in this diagram defines high flows, seasonal flows (light orange), and low flows – the flow components whose ecological importance was the focus of analysis and discussion in this project. We used monthly flow exceedance values (Q_{ex}) to quantify these flow components and permit examination of responses by flow-sensitive biota to different degrees of flow alteration.

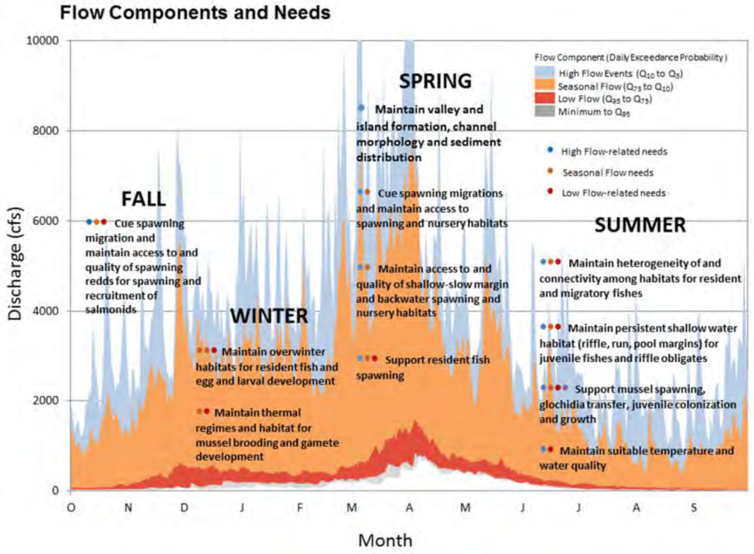


In consultation with the advisory team, we selected a representative sample of 43 species of flow-sensitive fish and mussels, and 5 guilds of other aquatic organisms to serve as targets for analysis of the impacts of different degrees of hydrologic alteration. The sensitivity of these target fish, mussels, and aquatic invertebrates to flow variables enabled us to focus analysis on a few species that are representative of the range of aquatic vertebrate and invertebrate organisms.

We combined the life history requirements of these target species with the typical hydrographs for streams of different types to frame 54 hypotheses of how these species would respond to specific alterations in the flow components.



We aggregated these hypotheses into 11 general flow needs, and used a *weight of evidence* approach to evaluate the support for these flow needs in the scientific literature. Over 300 scientific publications on responses of the target fish and mussels to flow alterations were synthesized in this evaluation.



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Section 1: Introduction

1.1 Background and Concepts of Environmental Flows

Environmental flows can be defined as the flow of water in a river or lake that sustains healthy ecosystems and the goods and services that humans derive from these ecosystems. Hydrologists have developed a number of measures for quantitatively describing the flow of water in a water body: *magnitude*, the amount of water flowing in a river (expressed as cubic feet per second or some other unit) or the water level of a lake; the *duration* of a hydrologic condition, such as flow events of high or low magnitude; the *timing* of these flow events during the year; the *frequency* of occurrence of particular hydrologic conditions; and the *rate of change* between one type of hydrologic condition and another. Each of these measures can be characterized by a range of historic variability over annual or inter-annual intervals.

The process of defining environmental flows seeks to preserve or restore enough of the variability in these hydrologic measures to protect the ecologic functions essential to diverse aquatic communities. Natural, seasonal patterns of rising and falling water flows provide essential cues to fish for migration and spawning; influence the reproductive success of fish, mussels, and aquatic insects; shape the channels and floodplains of riparian habitats; distribute seeds, allow a diverse array of plants to survive and germinate; and in general define the optimal functioning of rivers, lakes, and estuaries. Section 4, and Appendix 2, of this report provide detailed documentation of the flow needs of representative fish and other aquatic organisms within the Great Lakes watershed of New York and Pennsylvania.

Alteration of the patterns of flow - through water withdrawals, damming, diversions, shoreline hardening or channelization - can have myriad and cumulative effects on the survival of aquatic organisms and the functioning of riparian ecosystems. Water withdrawals that suppress seasonal flood events, for example, may eliminate the cues to fish to ascend a river and spawn, and isolate the floodplain that is essential to the life cycles of other fish and insects. On the other hand, water releases from a dam that exceed the frequency and magnitude of historic floods may scour the rocky substrate of the eggs of nest-building fish. Stabilization of flows – removing both flood and low water events – favors a few organisms adapted to the new regime, at the expense of many others.

Globally, and in New York and Pennsylvania, the extent of hydrologic alteration in riverine habitats has made aquatic organisms the most endangered segment of the natural world (Stein et al. 2000), threatening the irreplaceable benefits and services we derive from freshwater ecosystems. At the same time, our needs for water, both locally and globally, will only increase.

This apparent tension poses a key question – how can we continue to use water resources without endangering the ecosystems and ecosystem services on which we depend? This project will focus on this question by synthesizing existing scientific information on the flow needs of representative fish and other aquatic organisms, and framing flow recommendations for watersheds of different sizes that accommodate both human and ecosystem needs for water.

A number of mechanisms are available for managing the use of water. Examples include *pass-by flows*, which prescribe the minimum magnitude or quantity of flow that must be maintained immediately downstream from withdrawals of water; *reservoir or dam releases*, which attempt to mimic natural flooding conditions for fish spawning or floodplain maintenance; and *withdrawal limits*, which seek seasonally adjusted limits on the rate at which water can be withdrawn, based on the historic variability in flows in a particular stream. Pass-by flows are an important tool for assuring sufficient water for aquatic life under low-flow conditions, while withdrawal limits seek to preserve as much of the natural patterns of flow as possible. This report will recommend a combination of pass-by flows and withdrawal limits.

Prescriptions for environmental flows, which seek to balance ecological and economic needs, have been developed for a number of river systems around the globe (Annear et al. 2003, Tharme 2003, King and Brown 2006). These river-specific approaches have been very useful, but the global pace of modification of the flow regimes of rivers, and the dire state of aquatic biota, demand a new framework that can develop flow recommendations for the rivers of an entire region.

The Ecological Limits of Hydrologic Alteration (ELOHA) framework seeks to fill this need, beginning with *classification* of streams to facilitate generalizations that can apply to all the streams within a class; and *formulations of hypotheses of hydrologic alteration and ecological response,* which propose testable relationships “that can serve as a starting point for empirically based flow management at a regional scale”(Poff et al. 2010). The ELOHA framework incorporates best professional judgment with quantitative analysis, and has been applied at the watershed level for the Susquehanna, Connecticut, and Potomac Rivers, and at the statewide level in Massachusetts, Michigan, Maine, and Florida.

The results of these river-specific and regional approaches have led to the proposal of a “presumptive standard” to provide a starting point and “rules of thumb” for discussions of regional water management (Richter et al. 2011). For example, *less than 10 per cent* alteration in the pattern of daily flows will maintain the natural structure and function of an ecosystem with minimal changes to its native biota; *11-20 per cent* alteration in daily flows may result in measurable changes in species structure, but minimal changes in ecosystem functions; *greater than 20 per cent* alteration in the historic hydrograph of a river is more likely to result in moderate or greater changes to structure and function. This project has examined the extent to which this proposed standard can be applied to the organisms, aquatic communities, and streams of the Great Lakes drainage in New York and Pennsylvania.

1.2 The Great Lakes Compact and Environmental Flows

Passage of the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Compact (the "Great Lakes Compact") by the legislatures of the Great Lakes states was a landmark event that will protect the lakes and their watersheds from large-scale diversions of water to other states and countries. At the same time, the Compact commits the states to a sequence of water conservation and management measures to achieve full implementation of the Compact's protections.

Perhaps the most far-reaching of the Compact's provisions is the commitment that each state will manage the waters (including tributaries, connecting channels, and ground-water) of its jurisdiction in such a way that new or increased withdrawals "will result in no significant individual or cumulative adverse impacts to the quantity or quality of the Waters and Water Dependent Natural Resources and the applicable Source Watershed". The states are committed to achieve this standard within five years of the effective date of the Compact, December 8, 2008.

This standard raises several questions:

- how will the ecological impacts of withdrawals be evaluated?
- how will natural resource professionals know when thresholds of "significant … adverse impacts to … Water Dependent Natural Resources" are being approached?
- How much water does a tributary need – and when – to avoid "cumulative adverse impacts" to flow-dependent natural resources?

Sections 4 and 5 of this report will review the documented requirements of representative flow-dependent biota, and formulate and test hypotheses of the responses of these biota to different types and degrees of alteration in flows.

1.3 Project Objectives and Implementation

We have followed several steps, based on the ELOHA framework, to formulate ecologically-based flow recommendations that can be incorporated into the implementation of New York's Water Resources Protection Act:

1. We assembled a 28-member Technical Advisory Team, composed of natural resource professionals and scientists from local universities, from regional and central offices of NYS Department of Environmental Conservation (NYSDEC), and from federal agencies

   such as US Fish and Wildlife Service and US Geological Survey. This advisory team has guided each step in this project. We conferred with these expert advisors through three workshops in June 2011, June 2012, and December 2012, and a webinar in February 2013 (see project time-line in 1.4).

   Basic Principles for Management   The discussions in these workshops reaffirmed several basic premises identified in previous river-specific or regional water management efforts:

   - The entire flow regime, including high, median, and low flows for each season, and the natural variability among these flow components, is important for maintaining the diversity of species in streams;
   - Smaller streams, such as headwater streams, benefit from greater levels of flow protection;
   - Streams of various sizes are more vulnerable to the impacts of flow alteration during low-flow months (typically the summer months), so water management needs to be seasonally adjusted;
   - It is possible to minimize adverse ecological impacts through careful water management, and still provide the water necessary for economic uses.

2. In consultation with the advisory team, we selected a representative sample of flow-sensitive fish, mussels, and other aquatic organisms to serve as targets for analysis of the impacts of different degrees of hydrologic alteration.   The sensitivity of these target fish, mussels, and aquatic invertebrates to flow variables enabled us to focus analysis on a few species that are representative of the range of aquatic vertebrate and invertebrate organisms.
3. A regional approach to recommendations for water management must group the various kinds of streams into categories that permit extrapolation of information and data across the streams in the same class. We tested various methods for classifying streams, and opted for the simple and straightforward method now used by the NYSDEC of classes based on watershed size, with groupings for small, headwater streams (watersheds less than 50 square miles), small (50 – 200 square miles) rivers, medium (200 – 1,000 square miles) rivers, and large rivers.
4. We summarized the scientific literature on the flow requirements of the each of the target species and species guilds, setting the stage for identification of flow needs that apply to the range of aquatic organisms.
5. As a cost-effective and efficient way to derive broadly applicable flow needs from the voluminous scientific literature on aquatic organisms, we used the detailed information on flow requirements of target species in (4) to formulate hypotheses of ecological responses to different types and degrees of flow alteration. This process of hypothesis

formulation was aided by similar work for the Susquehanna and Ohio River basins (references), and is a step outlined by Apse et al (2008).

6. To test these hypotheses, we used a structured approach to evaluate the scientific literature, Causal Criteria Analysis (Norris et al. 2012, see Appendix 3 for detailed discussion of the application of this method). This method focuses on assembling and quantifying the weight of evidence in the literature in support of a particular hypothesis. Section 5 provides a detailed description of the method and the results of its application in this project.
7. Once the weight of evidence for the various hypotheses was assessed, it was possible to aggregate hypotheses that related to the same flow component (high flows or floods, or median flows for a particular season, for example), to the same season (fall, winter, spring, summer), to particular flow-sensitive life stages (spawning, egg survival, larval development), or to ecosystem processes (maintenance of floodplains, channel sinuosity). By aggregating similar hypotheses with strong scientific support, we derived general *flow needs* (see section 5.3, and Box 5.1) that provided the basis for the recommendations on management of flows in the different classes of streams in the Great Lakes watershed. We present the flow needs identified through this process in section 5, followed by recommendations for flow management in section 6.
8. In order to apply these flow recommendations in actual practice, we propose limitations on the rate at which water can be withdrawn from a stream (section 6.1). These proposed water withdrawal limits take the form of recommended limits on the degree to which particular flow parameters may be allowed to change. For example, the weight of evidence on the hypothesized response of fish inhabiting cold, headwater streams leads to the recommendation that cumulative withdrawals from such streams be limited to 10 per cent of the median flows during the spring. Section 6 provides detailed recommendations on withdrawal limits.
9. Finally, in section 6.2 of this report, we use several test cases to examine how withdrawal limits might interact with low-flow protections (the pass-by flows the NYSDEC plans to employ in implementing the Water Resources Development Act), and with actual examples of current water withdrawals. We ask the question: will limits on the rate of water withdrawal – designed to preserve enough natural variation in flows for diverse aquatic life – combined with minimum low flows allow enough water in different types of streams to accommodate actual human uses of water? The examples in section 6.2 demonstrate that, with careful management, sufficient water exists to maintain diverse aquatic life and intact ecosystems, while allowing for current and future human needs in the study area. This does not mean, however, that new water management policy mechanisms would allow for "business-as-usual" operations for all water users. For example, the low flow protections in the form of passby flows that we

modeled within this report would limit water withdrawals in all types of streams, under drought conditions (see Table 6-10). These restrictions would be particularly noticeable in headwaters creeks and small rivers (50-200 square mile watersheds).

1.4 Project Time-line

Figure 1.1 outlines the sequence of steps toward the flow recommendations for Great Lakes tributaries that are the focus of this report. As mentioned above, this project benefitted from expert consultation with a Technical Advisory Team, which has guided this project since its inception in June 2011. The following sections of this report describe the steps depicted in Figure 1.1 and include:

- Summaries of the life histories of flow-sensitive fish, mussels, and other aquatic organisms, and discussion of the impacts of different flow components in each season on the growth, survival, and reproductive success of these biota;
- The flow statistics used to describe the changes in flow components, such as high flows, median (seasonal) flows, and low flows for each season, and to define the flow needs of target organisms;
- Flow needs, by season, of the target organisms, based on the detailed review of the scientific literature on their life histories summarized in section 4;
- Flow recommendations for headwaters streams, small rivers, medium rivers (200-1,000 square miles), and large rivers that will avoid adverse impacts to these natural resources;
- An examination of how these flow recommendations can accommodate current and future needs for water.

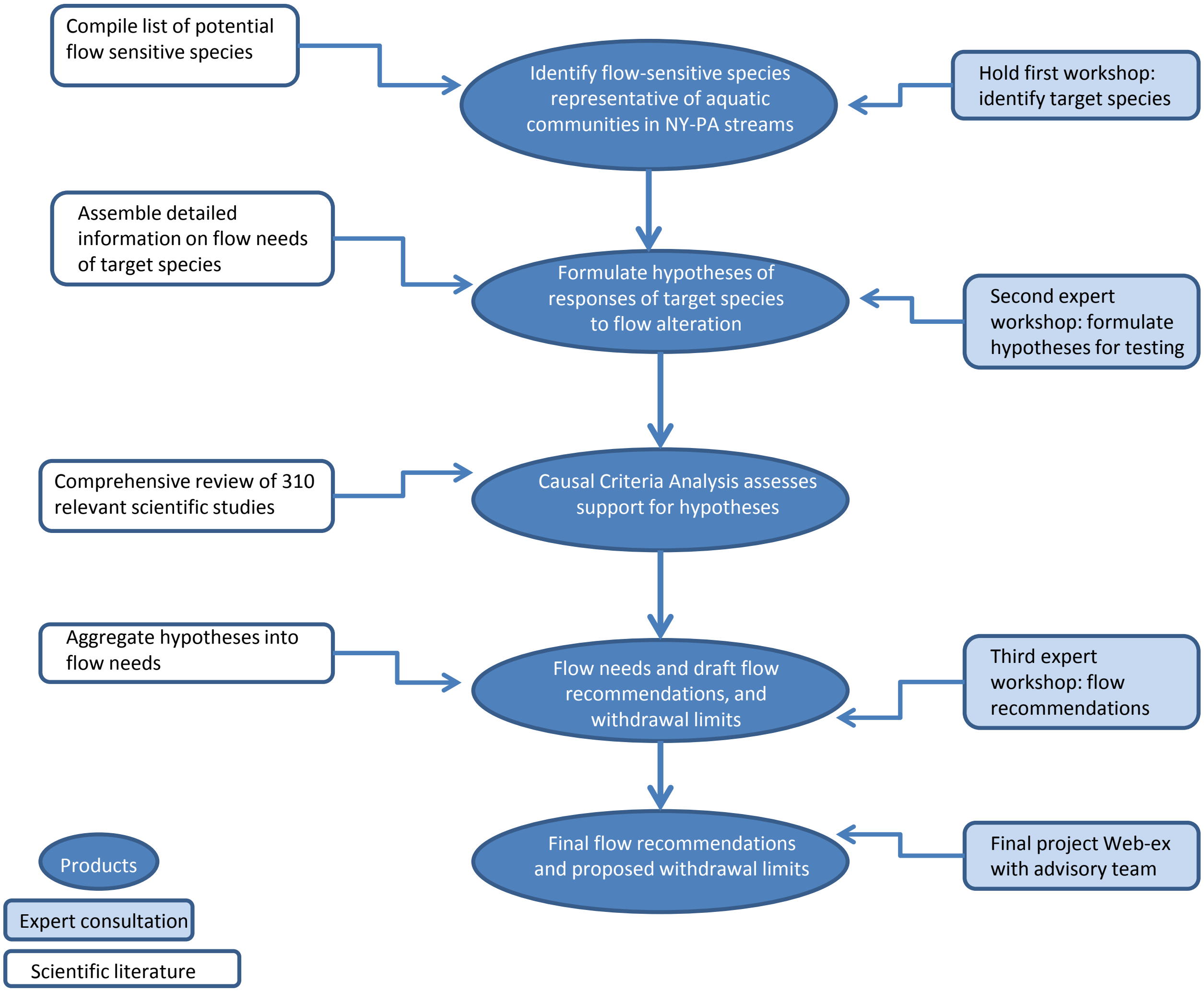
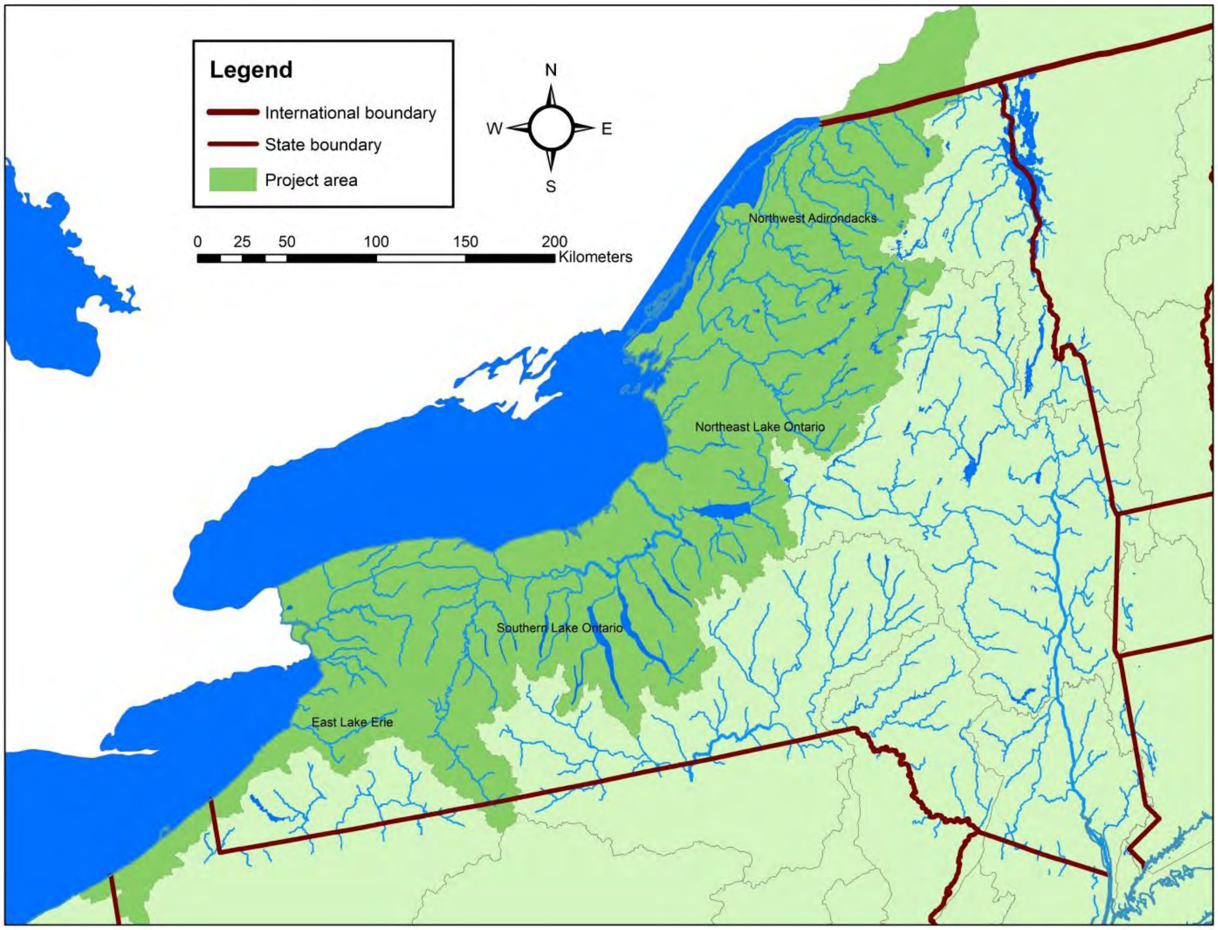


Figure 1.1: **The process for development of the flow recommendations** in this report. Final and interim products are represented by dark ovals, and the multiple information sources and expert consultation that were integrated into these recommendations are also indicated. Expert consultation occurred throughout the project, and was organized around three workshops at the Welch-Allyn Lodge in Skaneateles, New York. This figure is modeled on the similar figure in DePhilip and Moberg 2013.

Section 2: Basin Geography and Water Use

2.1 Geographic Scope of the Project

As mentioned above, this project focuses on the watersheds of the Great Lakes in New York and Pennsylvania, and Figure 2.1 outlines the geographic scope. This area covers 21,077 square miles, with a population over 3.9 million people. Major cities include Buffalo, Rochester, and Syracuse in New York, and Erie, Pennsylvania.



A previous ecoregional assessment of the Great Lakes by The Nature Conservancy (2001) grouped the streams of this portion of the Great Lakes watershed in four ecological drainage units (EDUs), as depicted in Figure 2.2. EDU 1 consists of the Genesee River and watershed, the Finger Lakes and Seneca River watershed, and the low-gradient lake-plain streams that characterize the Lake Ontario coastal zone west of Rochester. Such low-gradient streams also occur east of Rochester, and include the river mouths of Sodus Bay and other embayments. The small watersheds of these streams are influenced by broad, low ridges of glacial origin and by other glacial features. Many of these low-gradient streams flow directly to Lake Ontario;

others, such as Black Creek in Genesee County, flow to the Genesee River. The southern portions of the Genesee River watershed in the High Allegheny Plateau include numerous high-gradient cold headwater streams, such as Canaseraga and Keshequa Creeks.

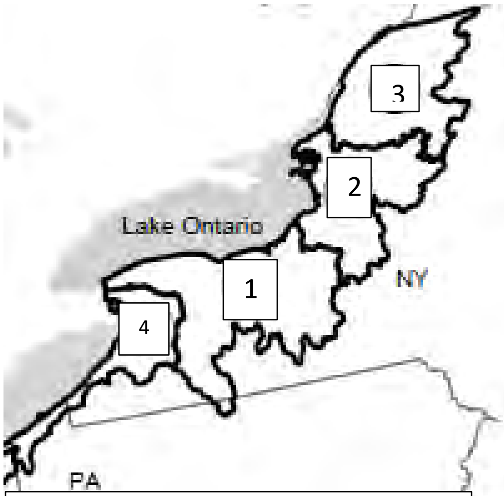


Figure 2.2: Ecological Drainage Units

The second major EDU in this region is the Seneca River, which drains seven of the Finger Lakes and joins the Oneida River to form the Oswego River a short distance south of Lake Ontario. Expansion of the New York State Canal System in the early part of the 20th century followed the course of the Seneca River and its major tributary to the east, the Clyde River, and altered their flows with 11 locks and dams for commerce and flood control. The Canal System has altered the hydrology of the Seneca and Clyde Rivers, and of many of the low gradient coastal streams along the remainder of the southern coast of Lake Ontario, in complex ways.

Tributaries to the Finger Lakes are typically short, high gradient streams that have cut steep ravines through the predominantly limestone bedrock. Prior to European settlement, Atlantic salmon ascended the Oswego and Seneca Rivers to spawn in these streams.

The northern third of EDU 2 consists of the alluvium-filled valley of the Black River, which drains the eastern Adirondacks and enters Lake Ontario in Black River Bay near Watertown. The southwestern portion of this unit drains to the Oneida River via Oneida Lake through high-gradient surface-water streams. The streams of the eastern third begin as high gradient surface-water streams on bedrock of the Tug Hill highlands and flow through the till of the lake plain to form the barrier beach ecosystem of eastern Lake Ontario. Prevailing winds from the west over Lake Ontario bring considerable precipitation – average annual snowfalls exceed 20 feet – to the Tug Hill region.

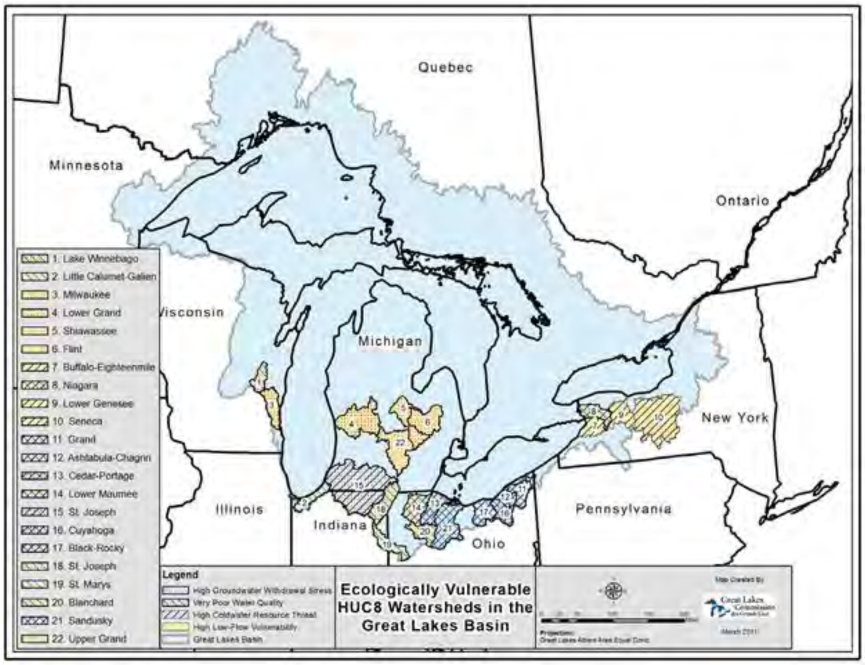
EDU 3 is characterized by low-gradient streams that flow to the St. Lawrence River through the lacustrine sands, clays, and peat deposits of the St. Lawrence lowlands, the broad, flat plain that follows the river from its origin at Lake Ontario. Many of the streams in this unit originate as cold headwaters in the hills of the northern Adirondack region; examples include the Oswegatchie and Raquette Rivers.

Cattaraugus Creek, the largest stream in EDU 4, originates in the moraine of the Cattaraugus Highlands and has cut through the shale of these highlands to flow through a very narrow lake plain to Lake Erie. Several smaller streams, such as Chautauqua Creek and 18-mile Creek, have also formed shale gorges in their flow to the lake. The southwestern portion of this unit is characterized by small tributary streams flowing directly to Lake Erie.

2.2 Assessments of current hydrologic vulnerability

Estimates of the level of withdrawals and other water uses, as of 2005, are available for each U.S. HUC-8 watershed in the Great Lakes Basin through 5-year compilations by USGS (Mills and Sharp 2010). Total estimated daily surface and groundwater withdrawals for the 24 HUC-8 watersheds in New York and Pennsylvania are nearly 4.253 billion gallons per day. (It must be noted that this total does not include the watersheds in NY that join the St. Lawrence River below the Moses-Saunders Dam at Massena. These are sparsely populated watersheds.) Thermoelectric power and public water supplies together are estimated to account for over 90 per cent of this total withdrawal.

The Great Lakes Commission, in a related study (Pebbles and Bradley 2011) that modeled the impact of further energy development on each of the 100 HUC-8 watersheds of the Great Lakes, has rated the vulnerability of the aquatic organisms native to each watershed to further alteration of low flows and thermal conditions, using methods described by Bain (2011). Under this assessment, four of the HUC-8 watersheds in the NY-PA project area – Seneca River, Lower Genesee River, Buffalo River-18 Mile Creek, and Niagara River – emerge as highly vulnerable to further alterations of low flows and of thermal conditions. The streams and creeks of two other watersheds – Oak Orchard/12 Mile Creeks, and Salmon River/Sandy Creek – display moderate vulnerability to low-flow alterations. Figure 2.3 is a map from the GLC study showing the ecologically vulnerable watersheds.

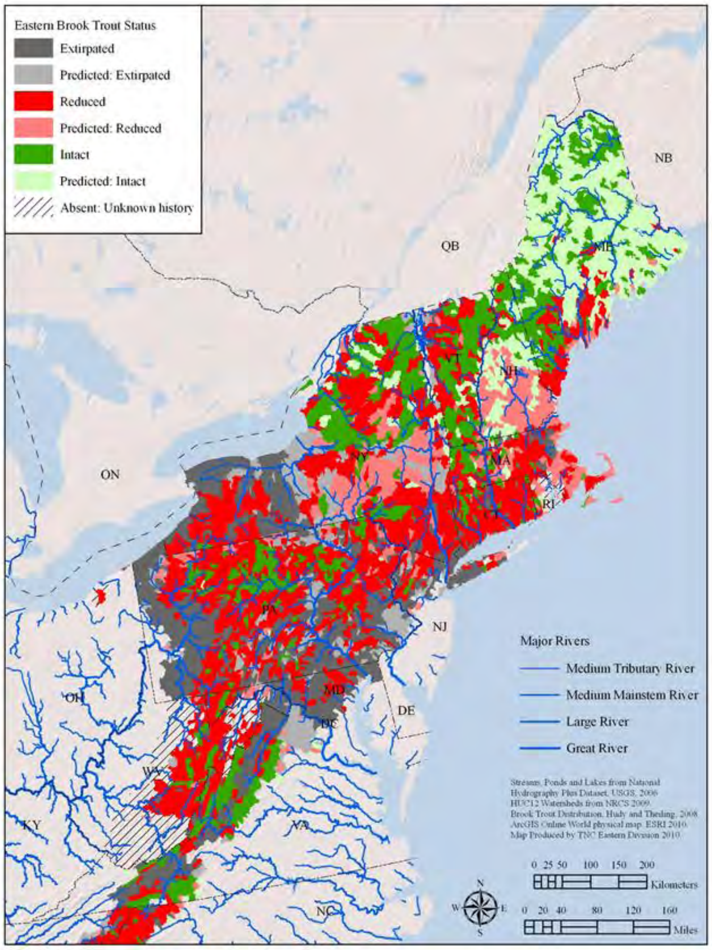


2.3 Condition of watersheds and Biota

In addition to direct withdrawals of water, many other types of human impact can alter water flows. Changes in land use, density of impervious surfaces, damming, and density of road-stream crossings can all alter the magnitude, timing, and duration of flows. A recent study of the status of fish, wildlife and natural habitats in the Northeast provides a different geographic context for the NY-PA portion of the Great Lakes watershed (Anderson and Olivero Sheldon 2011).

In general terms, this study found that gages on streams and rivers in New York and New England displayed higher percentages of diminished minimum flows (with principal effects on headwaters and creeks) and diminished maximum flows (principally affecting larger rivers) than the neighboring mid-Atlantic region. Diminished minimum flows limit further the habitat for aquatic biota under low flow conditions, with particular impacts to headwaters and coldwater tributaries. Diminished maximum flows may impact the condition and connectivity of floodplains, with likely impacts to fish communities.

When predicted status of brook trout, a species dependent on coldwater habitats and smaller streams (see section 4 for documented flow needs of this species) is added as an additional indicator of the condition of small watersheds, the low-flow and thermal vulnerability of much of the project area is demonstrated again. The Tug Hill region emerges as the most ecologically intact portion of the Great Lakes watershed in New York and Pennsylvania, while habitat conditions in other portions of this watershed are much less suitable for this highly flow-sensitive species. Figure 2.4 presents predicted brook trout status in the Northeast, based on analysis of habitat conditions.



Streams, Ponds and Lakes from National Hydrography Plus Dataset, USGS, 2006
HUC12 Watersheds from NRCS 2009
Brook Trout Distribution, Hudy and Theiling, 2008
ArcGIS Online World physical map, ESRI 2010
Map Produced by TNC Eastern Division 2010

Figure 2.4: Predicted distribution of Brook Trout in the northeast

Both the analyses by the Great Lakes Commission and by Anderson and Olivero-Sheldon (2011), employing different methodologies, have highlighted the vulnerability of the Great Lakes region in New York and Pennsylvania as a region already under hydrologic impairment. These analyses point to the need for careful management of new surface water withdrawals, and it is the objective of this report to make recommendations that will aid in managing further hydrologic alterations and avoid adverse impacts to water-dependent natural resources.

Section 3: Flow Components and Hydrologic Characterization

To integrate this project's flow recommendations with other regional environmental flow recommendations developed or in development for the adjacent Susquehanna, Ohio and Delaware River basins, we follow DePhilip and Moberg (2010, 2013) in defining three ecological flow components that include: high flows[1], "typical" seasonal flows, and low flows. The flow statistics used in this study are also consistent with those used in these other basin studies (see Table 3.1).

3.1 Flow Components

Mathews and Richter (2007) discuss the concept of environmental flow components and their application to environmental flow standard setting. Drawing examples from around the world, they describe the major flow components that are often considered ecologically important in a broad spectrum of hydro-climatic regions: extreme low flows, low flows, high flow pulses, small floods, and large floods.[2] 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. This section briefly describes the ecological importance of each flow component. We also define and illustrate these flow components for rivers within the Great Lakes basin 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 (Sections 4 and 5). We also organize our flow recommendations, which are presented in Section 6, around these components.

High flows and floods. In the New York and Pennsylvania rivers draining into Lake Erie and Ontario, as well as the St. Lawrence River, high flow events and floods provide cues for fish migration, maintain channel and floodplain habitats, inundate submerged and floodplain vegetation, and transport organic matter and fine sediment. 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). 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.

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[1] 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).

[2] Much of the text and several of the figures of this section are taken directly, or adapted from, DePhilip and Moberg 2013, who have applied the concepts of Mathews and Richter 2007 to the rivers of the northeast.

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; 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. 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. These flows are sometimes referred to as “baseflows,” but we chose not to use this term because it is potentially confused with the groundwater component of streamflow.

Low flows. Low flows provide habitat for aquatic organisms during dry periods, maintain floodplain soil moisture and connection to the hyporheic zone, and maintain water temperature and dissolved oxygen conditions. 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.

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 state 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 3.1, 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 *(from DePhilip and Moberg 2010, 2013)*

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

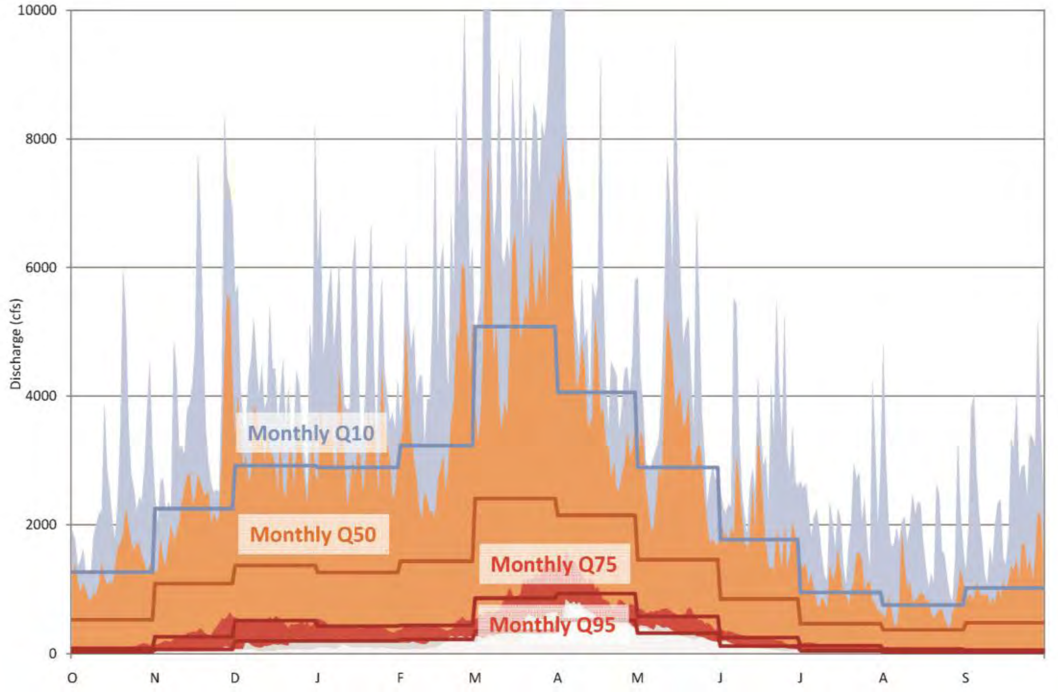

Table 3.1 **Flow statistics used to track changes to high, seasonal, and low flow components.**

Flow Component	Flow Statistic
High flows	
Annual / Interannual (>= bankfull)	
Large flood	Magnitude and frequency of 20-year event
Small flood	Magnitude and frequency of 5-year event
Channel forming events	Magnitude and frequency of 1 to 2-year high flow event
High flow pulses (< bankfull)	
Frequency of high flow pulses	Number of events > monthly Q_{10}
High pulse magnitude	Monthly Q_{10}
Seasonal flows	
Monthly magnitude	Monthly Q_{50}
Typical monthly range	Area under monthly flow duration curve between Q_{75} and Q_{10} (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 Q_{75} Monthly Q_{90}

**We initially quantify low flow magnitude based on deviation in monthly Q_{75} or Q_{90} flows but during the 3rd flow recommendations workshop, participants felt more comfortable presenting low flow recommendations in terms of what Q_{value} they felt no change should occur vs. % alteration to a fixed Q_{75} or Q_{90}.*

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: Q_{10}, Q_{50}, Q_{75}, and Q_{90}.

We define large and small floods as the **20-year and 5-year events**, respectively, based on studies within the basin and in similar systems that indicate these events are commonly associated with floodplain maintenance and channel maintenance, bank and island morphology and maintaining various successional stages of floodplain vegetation (Burns and Honkala 1990, Auble et al. 1994, Abbe and Montgomery 1996, Walters and Williams 1999, Zimmerman and Podniesinksi 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 (approximately every 1-2 years) and, over time, is responsible for moving the most sediment and defining channel morphology. Mulvihill et al. (2009) published recurrence intervals and regression equations for bankfull events within the basin. Based on this study, we selected the **1 to 2-year event** to represent the bankfull flow.

High flow pulses that are less than bankfull flows flush fine sediment, redistribute organic matter, moderate stream temperature and water quality, maintain aquatic and riparian vegetation, and promote ice scour during winter (Nanson and Croke 1992, Abbe and Montgomery 1996, Hakala and Hartman 2004). 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 Q_{10}** magnitude to represent high flow pulses and also include counts of Q_{10} events to measure frequency. Most of the high flow pulses occur as peak events above the monthly Q_{10}. In Great Lakes tributary streams, the frequency of these events (that is, the number of pulses above the monthly Q_{10}) is particularly important in fall when these flows maintain water quality and temperature and transport organic matter and fine sediment from spawning areas for fall spawning salmonids.

We use the **monthly Q_{50} flow** as the primary statistic representing 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). However, the median is a measure of central tendency, and does not reveal much about the distribution of flows around the median. Therefore, 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[3], which are flow duration curve-based indices used to evaluate overall impact of streamflow regulation on flow regimes (Vogel et al. 2007, Gao et al. 2009). 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).

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[3] 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).

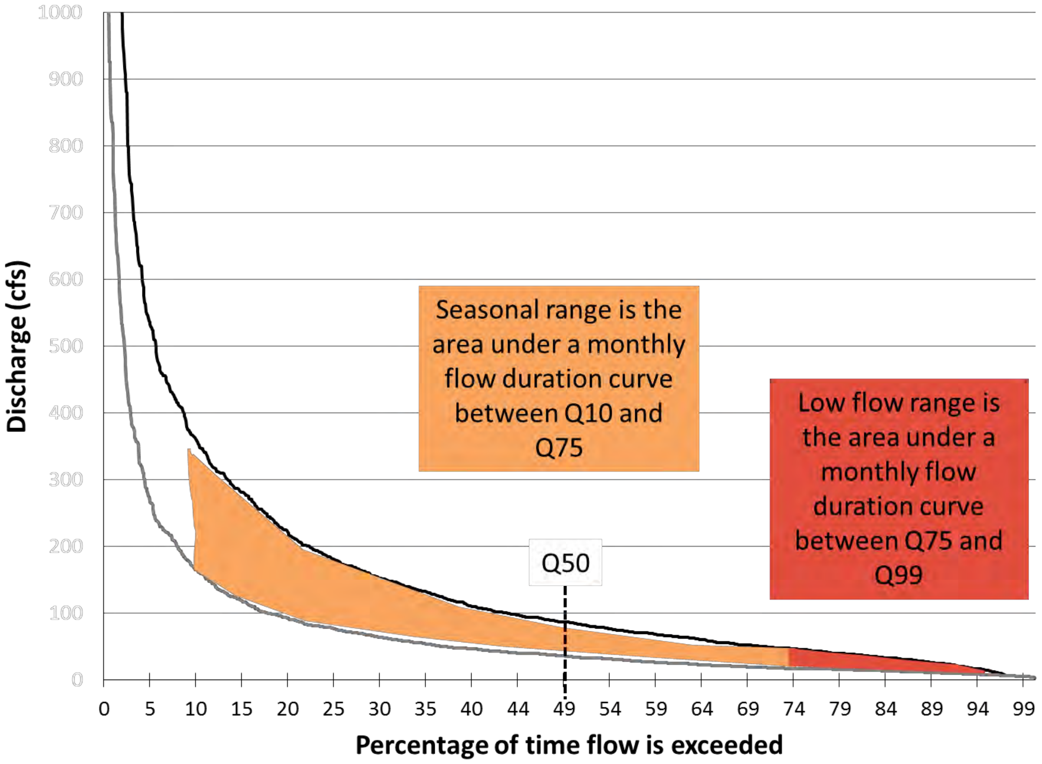


Figure 3.1 Seasonal range and monthly low flow range statistics. The black line represents unregulated conditions and the gray line represents regulated conditions. The colored area represents the difference in area between portions of the two curves.

Monthly low flow magnitude can be represented using either the **monthly Q_{90} or monthly Q_{75}**, depending on drainage area. We recommend using the Q_{75} in headwater streams with drainage areas less than 50 square miles and Q_{90} for larger streams and rivers. For headwater streams, we propose the Q_{75} because there are several studies in small streams that document ecological impacts when flows are reduced to below the Q_{75} and/or extreme sensitivity of taxa within headwater habitats (Hakala and Hartman 2004, Haag and Warren 2008, Walters and Post 2008, Walters and Post 2011). Also, analysis of streamflow at index (minimally-altered) gages showed that monthly Q_{90} 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 (Q_{75}) is needed to ensure that these flow values are outside of the measurement error of the streamflow gage. However, during the 3rd "flow recommendations"

Calculating Flow Statistics *(adapted from DePhilip and Moberg 2010, 2013)*

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 Michele DePhilip (mdephilip@tnc.org) or Tara Moberg (tmoberg@tnc.org).

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.

workshop, participants preferred to make low flow recommendations based on judgment of the Q_{value} necessary to avoid cumulative adverse impacts instead of prescribing a per cent alteration to a fixed Q_{75} or Q_{90}. Recommendations for low flows in sections 6 are presented in this format. We also define the **monthly low flow range** as the area under the monthly flow duration curve between Q_{75} and the Q_{value} at which participants felt no change should occur (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.

3.3 Hydrologic Characteristics of Major Habitat Types

We used flow data from 28 index gages on New York or Pennsylvania streams within the Great Lakes 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 28 index gages encompass three out of four major stream habitat types. There were no index gages on Class 3 streams (Large Rivers > 1000 sq. mi.) within the study area.

We used all available water years available for each index gage to define interannual variability of these statistics. While standardized time periods representing a significant number of years across all gages is ideal for comparison purposes (DePhilip and Moberg 2013), the limited number of gages within the project area that met this criteria required more flexibility to increase representation across the stream habitat classes. A minimum of 20 years of data is recommended to reduce variability in flow metrics (Richter et al. 1997, Huh et al. 2005). All gages had at least 10 years of data with the majority (24 out of 28) ranging from 24-74 years of data.

We used the Indicators of Hydrologic Alteration to calculate flow duration statistics, including the Q_{10}, Q_{50}, Q_{75}, and Q_{90} for each index gage (see Appendix 1). 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 monthly high (Q_{10}), seasonal (Q_{50}), and low flow statistics (Q_{75} and Q_{90}) are included in Appendix 1.

Class 1: Headwaters and creeks (<50 sq miles)

- Compared to larger streams, magnitude of flows in headwaters and creeks is relatively low throughout the year.
- In summer and fall, 91% of monthly Q_{50} flows are less than 10 cfs; 100% are less than 50 cfs.
- In winter and spring, 28% of monthly Q_{50} flows are less than 10 cfs; 83% are less than 50 cfs.
- In summer and fall, 100% of monthly Q_{75} values are less than 10 cfs.
- In winter and spring, 45% of monthly Q_{75} values are less than 10 cfs; 93% are less than 50 cfs.

Class 2a: Small rivers (50-200 sq miles)

- Monthly Q_{50} flows range from a low of 6 cfs in August to 780 cfs in April.
- In summer and fall, 73% of monthly Q_{50} flows are less than 50 cfs.
- In winter and spring, 94% of median monthly flows are greater than 50 cfs
- In summer and fall 44% of monthly Q_{90} values are less than 10 cfs; 90% are less than 50 cfs.
- In winter and spring, 35% of monthly Q_{90} values are less than 50 cfs with 3% less than 10 cfs.

Class 2b: Major tributaries (200-1000 sq. miles)

- Monthly Q_{50} ranges widely from 32 cfs in the fall to more than 2065 cfs in the spring.
- In summer and fall, 100% of monthly Q_{50} flows are greater than 10 cfs; 71% are greater than 50cfs
- In winter and spring, 100% of monthly Q_{50} flows are greater than 50 cfs.
- In summer and fall, 67% of monthly Q_{90} values are less than 50 cfs.
- In winter and spring, 90% of monthly Q_{90} values are greater than 50 cfs.

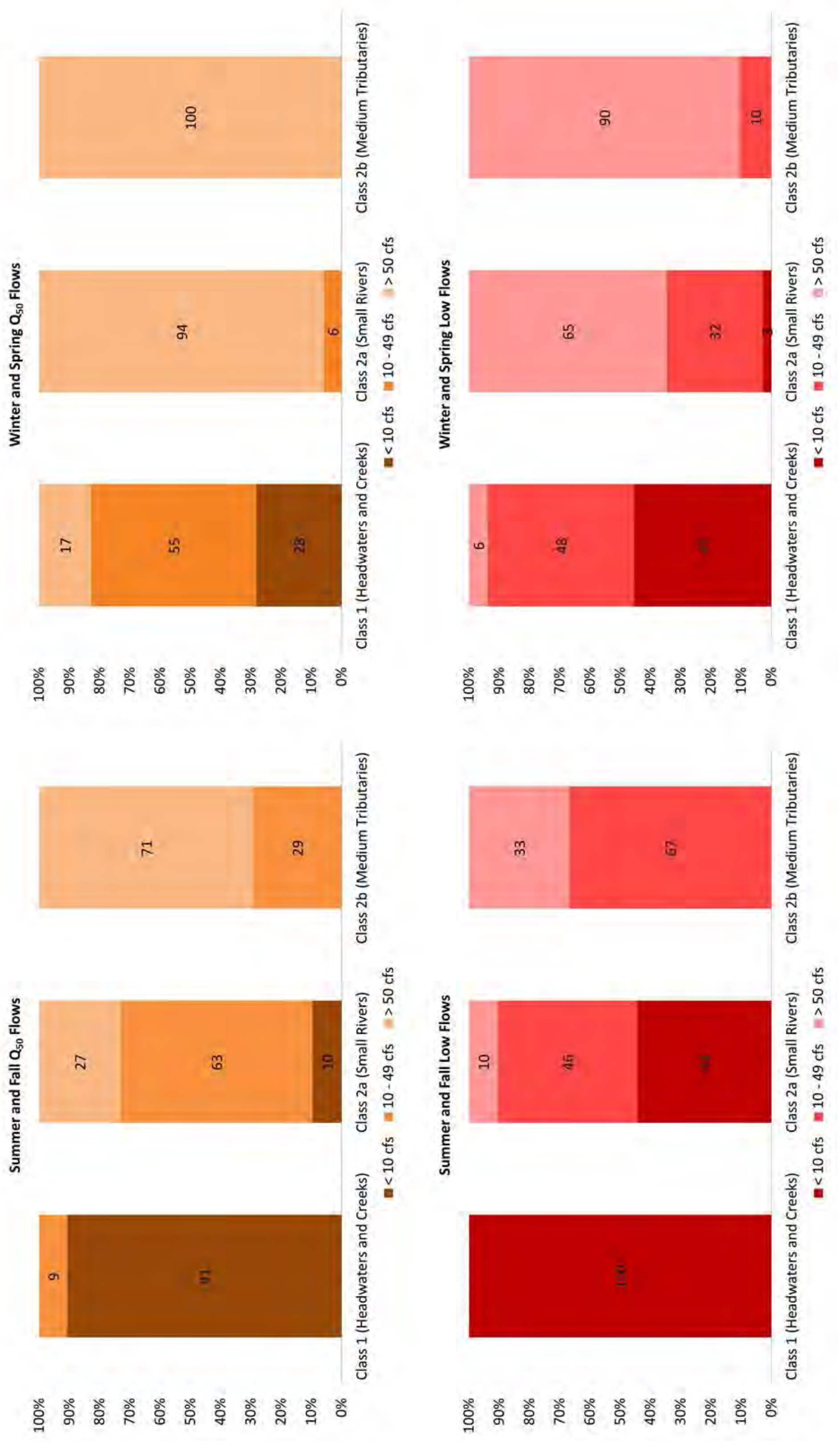


Figure 3.2. **Results of analysis using the Indicators of Hydrologic Alteration (IHA) to compute the flow duration statistics** for streams that contain index gages, and represent three of the four stream size classes discussed in this report. For each stream size class, flow exceedance values are grouped within the intervals discussed in the text above.

Section 4: Flow sensitive taxa and ecological processes

The starting point for this project was the selection of flow-sensitive species to serve as the targets of analysis and modeling. The documented flow requirements of these species formed the basis for hypotheses of the responses of aquatic biota to different types and degrees of hydrologic alteration. Section 5 of this report will explain in greater detail how hypotheses were aggregated into 11 general flow needs, based on similarity of season, flow variables or components, or life stages of organisms. In this section, and in greater detail in Appendix 2, we present the categories of target organisms we considered and information about vulnerable life stages and other flow sensitivities. Our first project workshop with the Technical Advisory Team identified flow sensitive taxa. Hypothesis generation in workshop 2 focused on fish and mussels, and we present below short summaries of fish and mussel target groups and species. Please refer to Appendix 2 for an in depth review of target groups and the flow and habitat associations of individual target species. Additionally, we included floodplain and channel maintenance as important ecological process targets related to maintaining natural flow regimes.

4.1 Fish

The inland waters of New York that flow into Lake Erie, Lake Ontario, and the St. Lawrence River **(Figure 2.1)** support a rich fish fauna with 139 species reported from within the project area (Smith 1985, Carlson and Daniels 2004). Twelve species and two hybrids were introduced through intentional game fish stocking or canal systems and associated shipping traffic, and are non-native to New York waters (Carlson and Daniels 2004). An additional 7 species have been introduced to the basin through transfers from NY basins outside the project area, and 17 species have had range extensions through basin transfers within the project area (Carlson and Daniels 2004a). There are ten fish species with distributions within the project area that are currently listed as threatened or endangered by the State of New York. Threatened species include lake sturgeon (*Acipenser fulvescens*), mooneye (*Hiodon tergisus*), lake chubsucker (*Erimzon sucetta*), longear sunfish (*Lepomis megalotis*), and eastern sand darter (*Ammocrypta pellucida*). Endangered species include silver chub (*Macrhybopsis storeina*), pugnose shiner (*Notropis anogenus*), round whitefish (*Prosopium cylindraceum*), and two lake dwelling sculpins (*Cottus ricei*, *Myoxocehaplus thompsonii*). Additional species of special concern known from the project area include redfin shiner (*Lythrurus umbratilis*) and black redhorse (*Moxostoma duquesnei*).

From this total list of species, the Technical Advisory Team selected a subset of flow-dependent species whose needs are representative of the requirements of the entire range of aquatic biota in the Great Lakes drainage. With an additional literature review, we documented temperature, habitat, and flow needs for various life history stages of these species (see Table 4.1 and Appendix 2), and grouped these species into 6 guilds based on similar life history traits (body size, fecundity, home range, habitat associations, feeding habits, flow-velocity tolerances) and the timing and location of

Table 4.1. Flow ecology target species groups of fish based on key life history traits.

Group	Key Traits and Hydrological associations	Species
Cold Headwater	Similar needs defined by temperature thresholds • Groundwater discharge areas serve as spawning habitats and maintain red conditions throughout winter • High seasonal flows keep redds sediment free • Scour events can flush eggs/larvae from redds • Low flows increase temperature and limit habitat quality and availability	Brook trout, brown trout, sculpins.
Riffle obligates	Small bodied, flow-velocity specialists who spend most of their life in riffle/run habitats • High to moderate velocity riffle and run habitats are limited by low flow periods	Longnose dace, central stoneroller, rosyface shiner, stonecat, darters
Riffle associates	Species with moderate-sized home range that migrate in the spring to spawn and need access to, and connectivity between, riffle habitats • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats • Low flows can limit drift and limit survival of larvae	Lake sturgeon, silver lamprey, American brook lamprey, suckers, white bass, walleye
Nest builders	Similar timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy (includes true nests, mound construction and ledge spawners) • High discharge events after spawning scour nests	Brown bullhead, River chub, Fallfish, Creek chub, Rock bass, sunfishes, smallmouth bass
Marsh spawners	Large-bodied fish that rely on spring flows to flood emergent vegetation for spawning • Rely on spring high flows to flood and maintain backwater marsh areas for spawning, egg and larval development, and swim up.	Bowfin, Northern Pike, Muskellunge
Anadromous sport fish	Salmonid species that use lake habitats for adult growth and stream habitats for spawning and juvenile growth • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats	Atlantic salmon, rainbow trout

flow-sensitive life history stages. Our six species groups (Table 4.1) differ from the five proposed by DePhilip and Moberg (2010) by the inclusion of a marsh spawning group, and the replacement of a diadromous group with a more specific anadromous sport fish group (both native and non-native salmonid species that occur in land-locked populations). These changes are based on recommendations made by the Advisory Team during the first workshop. Detailed descriptions of each flow ecology target species group (Table 4.1) with supporting information on temperature, habitat and flow needs and relationships between important life history events and representative hydrographs can be found in Figures 4.1 – 4.3, and Appendix 2. General life history activities for each target fish group in relation to natural hydrographs is summarized for each stream type in Figs. 4.1 - 4.3.

4.2 Mussels

Freshwater mussels are among the most threatened taxonomic groups in North America (Stein et al 2000). The inland waters of New York that flow into Lake Erie, Lake Ontario, and the St. Lawrence River (Figure 2.1) historically supported a mussel fauna that included 41 or 42 confirmed species (Strayer and Jirka 1997). Current records estimate the regional species pool to include 28 to 32 species. State endangered species with historic records from within the project area include the **fat pocketbook** (*Potamilus capax*) with two historic records from the Niagara River/Buffalo area, and potentially the **pink mucket** (*Lampsilis abrupta*). Both of these species are likely extirpated from the basin. State threatened species confirmed from the basin include the **wavy-rayed pocketbook** (*Lampsilis fasciola*), with a few historic records from the Niagara River, and the **green floater** (*Lasmigona subviridis*), with historic records from the Genesee and Oswego River basins but currently only known from a tributary of Oneida Lake (Strayer and Jirka 1997).

We initially identified 25 mussel species as possible candidate target species for developing flow ecology hypotheses based on current distributions, habitat preferences, and potential flow needs. Based on input from expert breakout groups during the New York Sustainable Flows Project workshop (June 29, 2011) no additions or deletions were made to the list of mussel flow targets. We aggregated these species into three groups (Table 4.2) defined by a combination of hydraulic habitat associations (velocity, depth, substrate and impoundments) and tolerance to changes in streamflow (DePhilip and Moberg 2010). Detailed descriptions of each flow ecology target species group (Table 4.2) with supporting information on temperature, habitat and flow needs and relationships between important life history events and representative hydrographs can be found in Appendix 2. General life history activities for each target mussel group in relation to natural hydrographs are summarized for each stream type in Figs. 4.1-4.3.

Table 4.2. Flow ecology target mussel species groups based on general habitat associations.

Group	Key Traits	Species
Riverine	Primarily associated with riffle habitats. Use a wide variety of fish hosts, including small-bodied riffle obligate species. • Primary habitat may be de-watered during low flow periods • Host species interactions may be limited by access to shallow habitat during low flow periods • Susceptible to increased predation during low flow periods	**Elktoe**[B], snuffbox[B], **creek heelsplitter**[B], **fluted shell**[B], eastern pearlshell[?], hickory nut[B], **creeper**[B]
Facultative riverine	Use slow to moderate current, including backwaters and standing water habitats. Utilize both lotic and lentic fish hosts. • Sensitive to physical and chemical changes in habitat conditions including temperature, DO and velocity • Sensitive to increased predation with shallower depths during low flow periods	Triangle floater, slippershell[B?], three-ridge[T], **eastern elliptio**[T], **spike**[T], **Wabash pigtoe**[T], yellow lampmussel, pocketbook[B], **eastern lampmussel**[B?], **fat mucket**[B], **black sandshell**[B], **pink heelsplitter**[B], **rainbow**[B]
Lentic-pool	Associated with slow-moving river habitats, including channel margins and pools. Use a wide variety of fish hosts. • May become stranded in margin habitat during low flow periods	**Cylindrical papershell**[B], **eastern pondmussel**[B], eastern floater[B], **floater**[B], Lilliput[B]

Reproductive strategy

[B] Bradytictic: glochidia overwinter in the marsupial demibranch of female- winter breeders

[T] Tachytictic: fertilization, larval development, and parasitic period all occur in the same calendar year- summer breeders

4.3 Floodplain and Channel Maintenance

Valley and channel morphology, associated vegetation and sediment distributions are dependent on natural flow regimes within the Great Lakes basin. High flow events during winter and spring move sediment, maintain substrate size distributions, and maintain riffle/pool sequences. High flow events also initiate large woody debris recruitment and transport which contributes to instream habitat cover as well as stream geomorphology and riparian forest patch dynamics (Abbe and Montgomery 1996, Roghair et al. 2002). Winter and spring flooding and associated ice scour events influence the distribution and composition of floodplain vegetation assemblages (Auble et al. 1994, Johnson 1994, 1998, Townsend 2001, Cowell and Dyer 2002, Bowen et al. 2003, Elderd 2003, Ahn et al. 2004, Zimmerman and Podniesinksi 2008), as well as seed dispersal and seedbed preparation for propagules of many floodplain and riparian vegetation species.

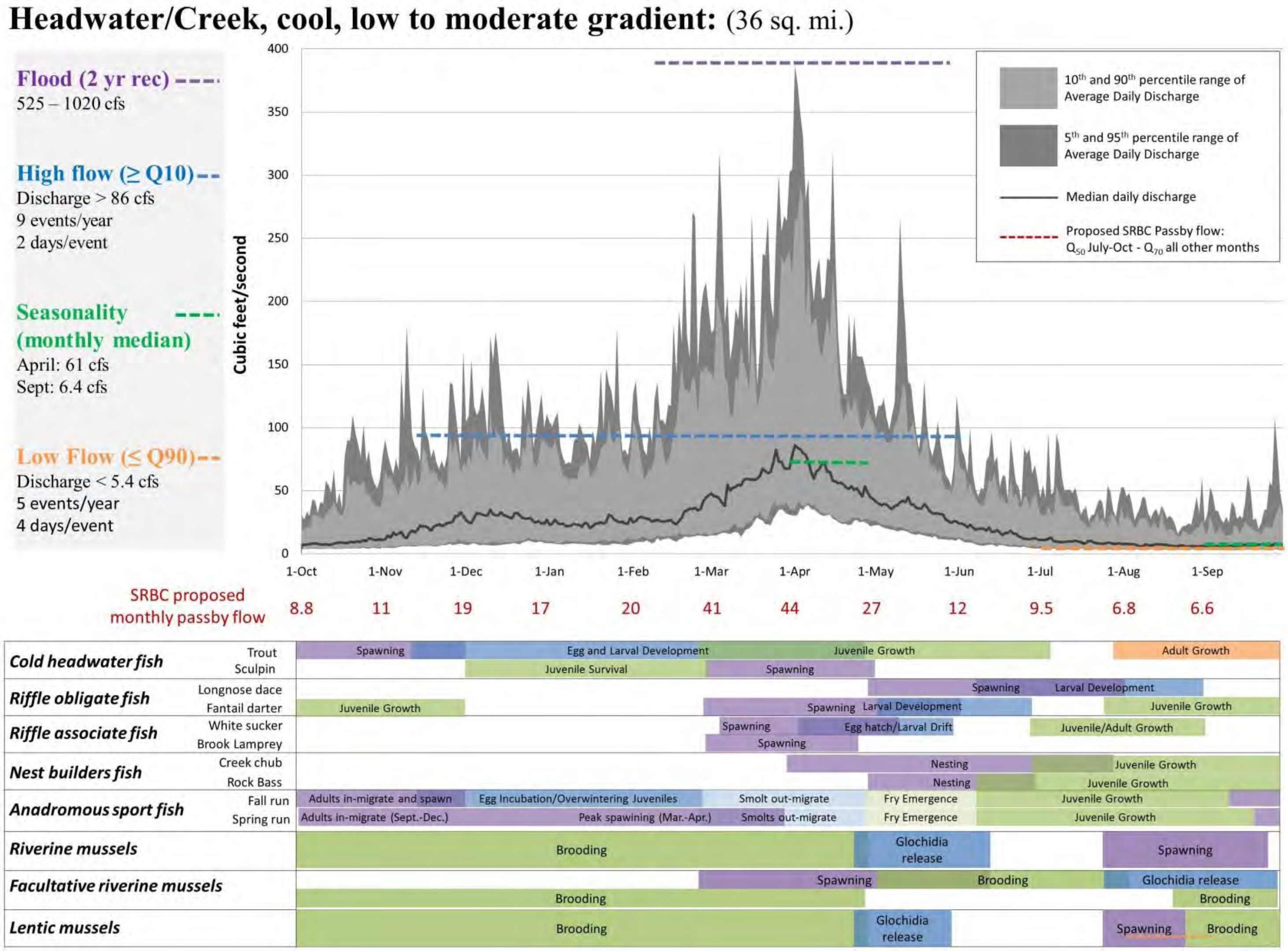


Figure 4.1. Representative un-altered hydrograph from a headwater/creek in the Great Lakes basin (NY) with associated life history phenology for fish and mussel targets.

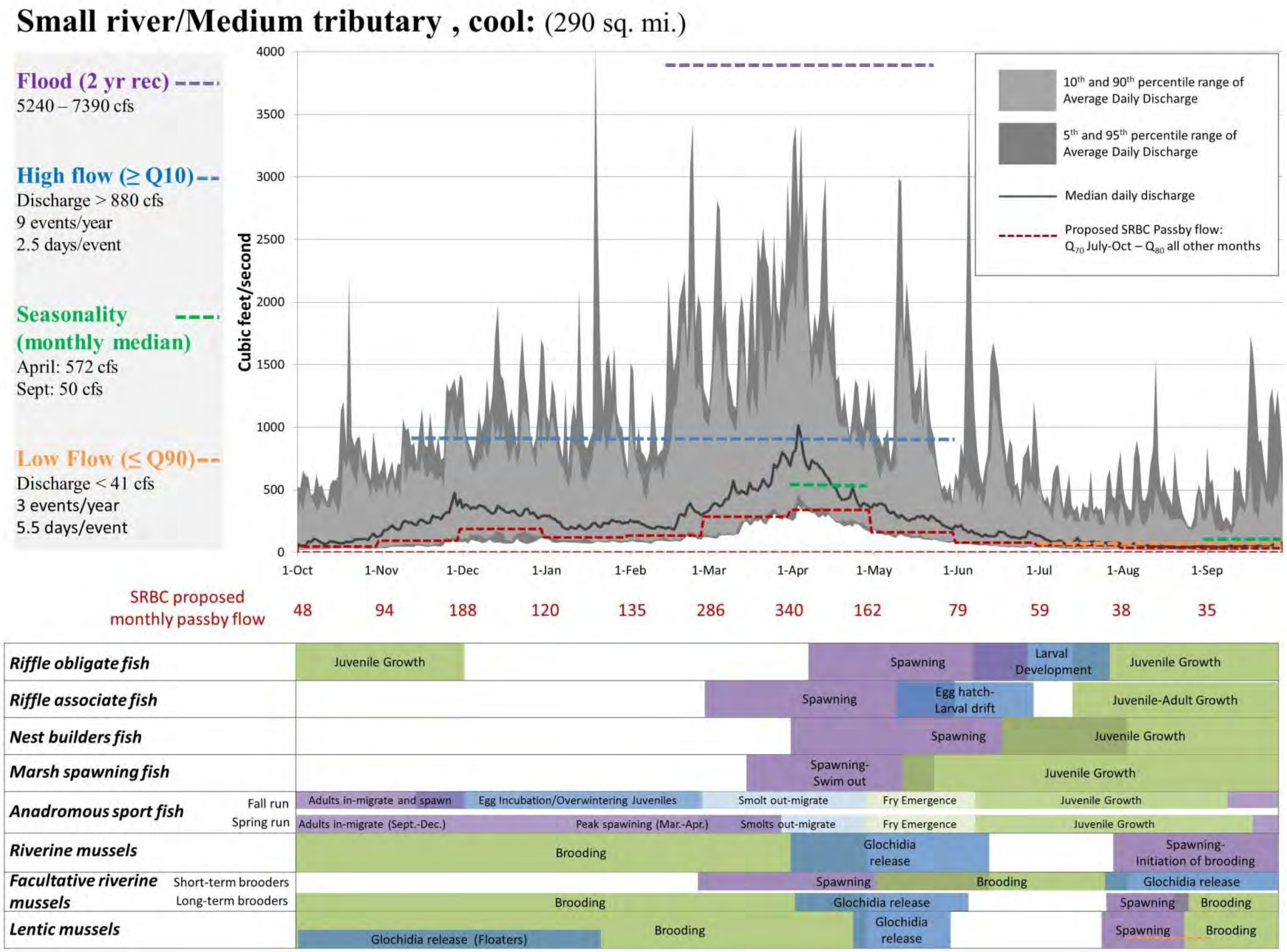


Figure 4.2. Representative un-altered hydrograph from a small river in the Great Lakes basin (NY) with associated life history phenology for fish and mussel targets.

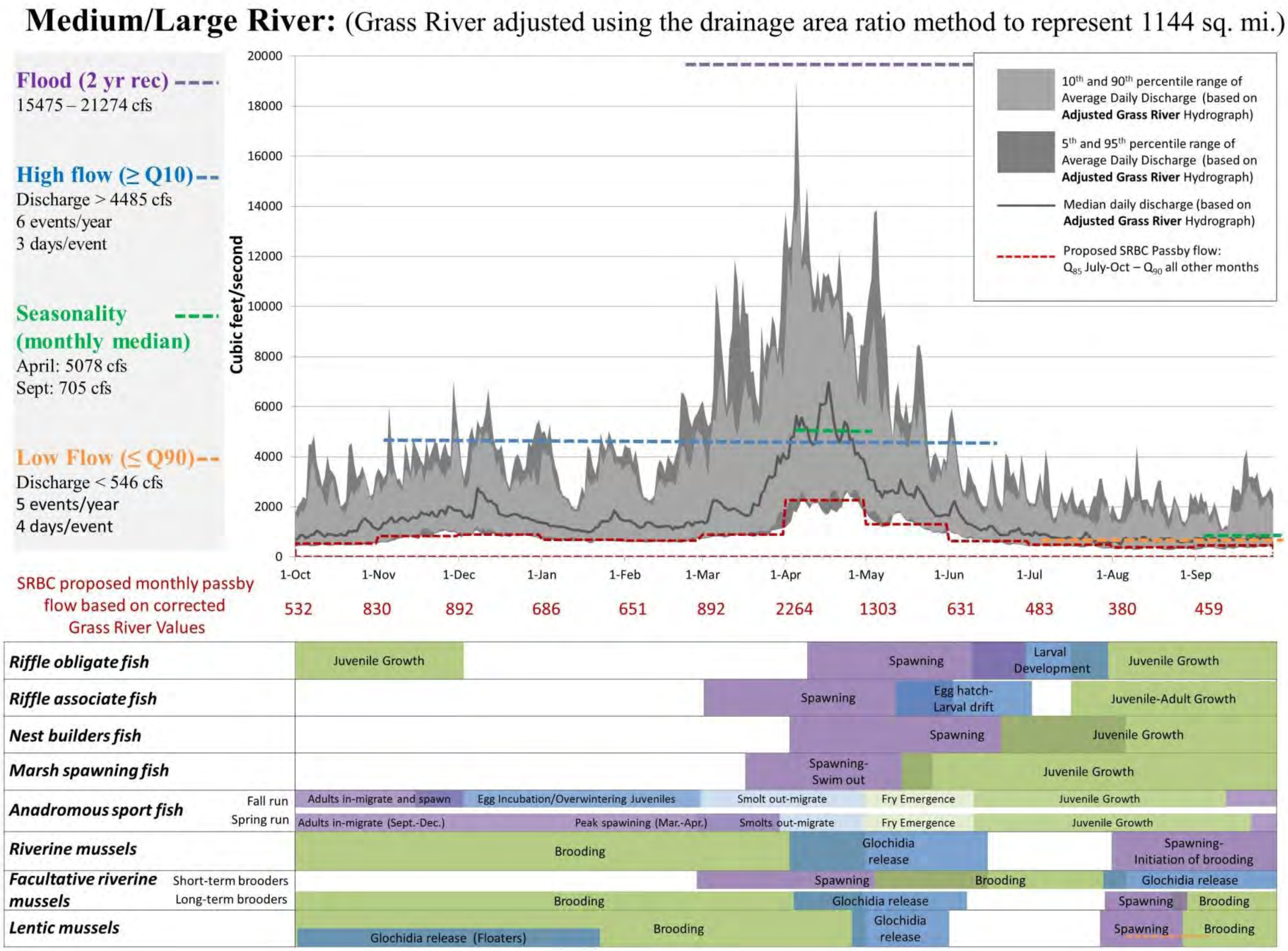


Figure 4.3. **Representative un-altered hydrograph from a large river** in the Great Lakes basin (NY) with associated life history phenology for fish and mussel targets.

Section 5: Identification of Flow Needs

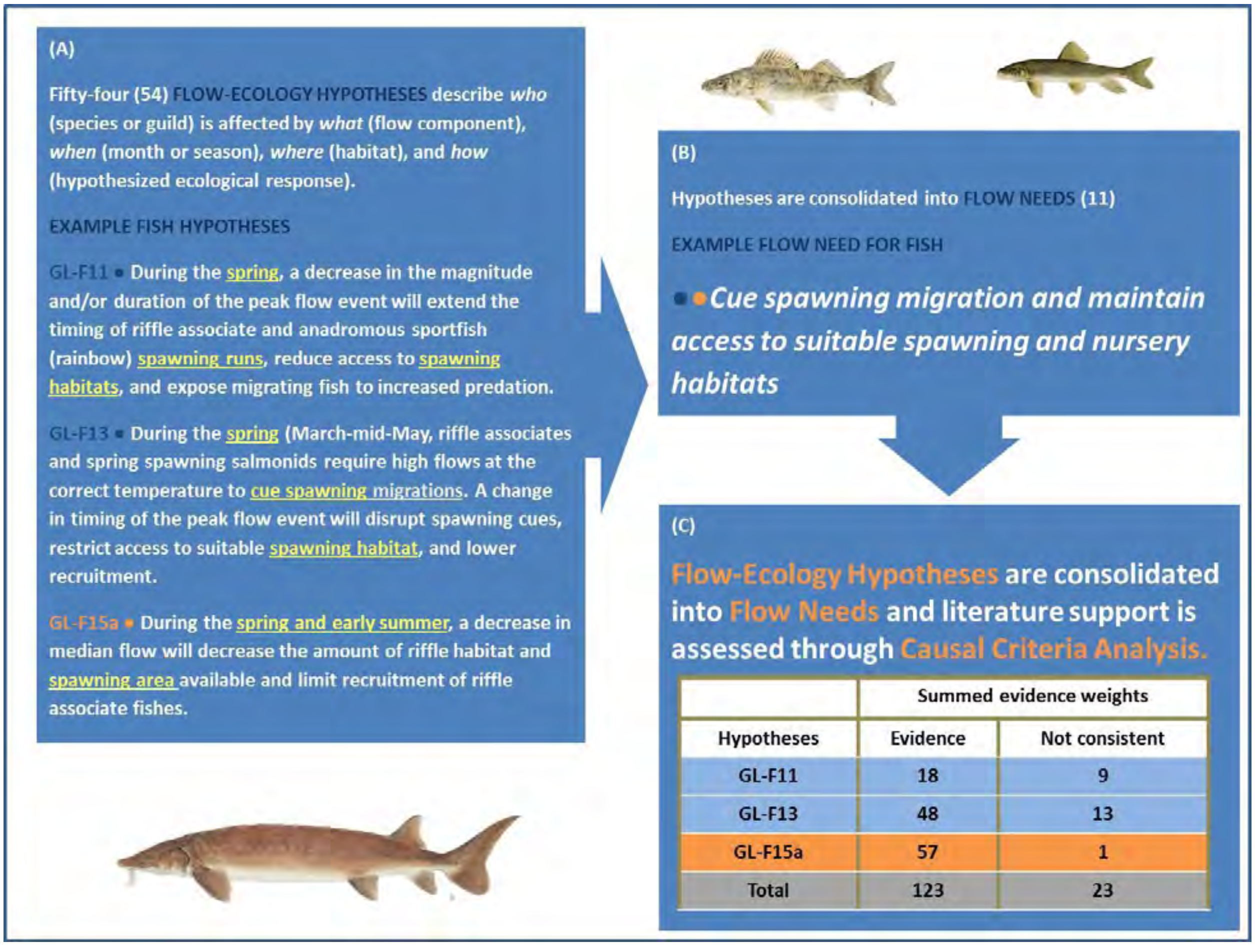
5.1 The eco-evidence framework to evaluate hypotheses

To frame eventual flow recommendations, we consulted with the Technical Advisory Team to define 54 working hypotheses that describe anticipated ecological responses by guilds of target species (section 4) to changes to natural flow regimes. Then, we aggregated related hypotheses into a set of 11 flow needs that combine one or more responses of a specific taxonomic group or multiple groups to a change in flow conditions within a particular season (Figs. 5.1-5.2). This provided the structure for using a weight-of-evidence approach to document the degree to which scientific literature supports each flow hypothesis, the cluster of related hypotheses aggregated as a flow need, and ultimately the flow recommendations that constitute the goal of this project. The weight-of-evidence approach is built on the idea that one can seldom infer cause and effect from individual ecological studies (Downes et al. 2002). However, evidence to support a hypothesis may come from a wide range of ecological studies including observational studies, repeated studies of similar hypothesized relationships in different environments with different study designs and methods, or experimental results from small-scale manipulations in the laboratory or field. None of these types of evidence may be convincing by themselves, but using a causal-criteria analysis, together they can provide numerous lines of evidence that result in strong support for a hypothesis (Norris et al. 2012).

Here, we use the *Eco Evidence* approach, a form of casual criteria analysis, to transparently assess the level of support for a list of flow ecology hypotheses generated by the Technical Advisory Team. Our approach differs slightly from Norris et al. (2012) in that our goals were not necessarily to establish causality for specific hypotheses, but rather to establish and measure support for overall flow needs and associated flow components. Thus, our goals were to: 1) articulate flow needs through hypothesis generation; 2) use hypotheses to structure a systematic literature review that assessed support for flow needs; and 3) use results to make conclusions about the importance of each flow need and provide important context for developing flow recommendations at our third and final project workshop.

The *Eco Evidence* framework is organized around three phases that include: 1) *Problem formulation*; 2) *Literature review*, and 3) *Weighting evidence and judging support*. Our problem formulation phase involved the series of project workshops with the Technical Advisory Team that identified target species (Section 4) and generated 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) (Fig. 5.1). These hypotheses were used to identify 11 ecosystem flow needs (Fig. 5.2) and served as a framework for conducting a systematic literature review during the 2nd phase of the *Eco Evidence* analysis. The final phase involves weighting literature based on study robustness (design and sample size) and tallying results for and against individual hypotheses which can be used to summarize support for flow needs or seasonal flow components. This approach has been successfully applied to water resource questions related to stream riparian sediments and flooding regimes (Greet et al. 2011, Norris et al. 2012, Webb et al. 2012). Detailed methods for each step and a list of generated hypotheses are presented in Appendix 3. In some cases it also was possible to associate biological responses in the literature with relevant Q statistics used in our recommendations through post-hoc analysis of gage data associated with a particular scientific study. We generally used two approaches to do this. For sources that published an observed biological response to specific hydrologic conditions that could be paired

Figure 5.1. Flow ecology hypotheses are formulated during expert workshops and grouped based on similar characteristics (A), and consolidated into flow needs (B). Support for flow needs and underlying hypotheses are then assessed using existing literature in a causal criteria analysis framework where each paper is weighted based on its study design and summed for (evidence) or against (not consistent) the associated flow need or hypothesis. See Appendix 3 for more details.



(A)

Fifty-four (54) FLOW-ECOLOGY HYPOTHESES describe *who* (species or guild) is affected by *what* (flow component), *when* (month or season), *where* (habitat), and *how* (hypothesized ecological response).

EXAMPLE FISH HYPOTHESES

GL-F11 ● During the spring, a decrease in the magnitude and/or duration of the peak flow event will extend the timing of riffle associate and anadromous sportfish (rainbow) spawning runs, reduce access to spawning habitats, and expose migrating fish to increased predation.

GL-F13 ● During the spring (March-mid-May, riffle associates and spring spawning salmonids require high flows at the correct temperature to cue spawning migrations. A change in timing of the peak flow event will disrupt spawning cues, restrict access to suitable spawning habitat, and lower recruitment.

GL-F15a ● During the spring and early summer, a decrease in median flow will decrease the amount of riffle habitat and spawning area available and limit recruitment of riffle associate fishes.

(B)

Hypotheses are consolidated into FLOW NEEDS (11)

EXAMPLE FLOW NEED FOR FISH

●● ***Cue spawning migration and maintain access to suitable spawning and nursery habitats***

(C)

Flow-Ecology Hypotheses are consolidated into Flow Needs and literature support is assessed through Causal Criteria Analysis.

	Summed evidence weights	
Hypotheses	Evidence	Not consistent
GL-F11	18	9
GL-F13	48	13
GL-F15a	57	1
Total	123	23

with a near-by stream gage (e.g. Bowman 1970), we used IHA to characterize the hydrologic conditions under which that response occurred in terms of a Q value. For sources that published an observed biological response to a gradient of alteration (e.g. Freeman and Marcinek 2006), we interpreted the alteration gradient in the context of regional hydrology using Great Lakes reference gages. This additional information was used to characterize ranges along the Q statistics scale in which biological responses have been observed, and help inform flow recommendations in Section 6. Instances where we applied either of these approaches are indicated by "IHA analysis" associated with citations in sections 5 and 6.

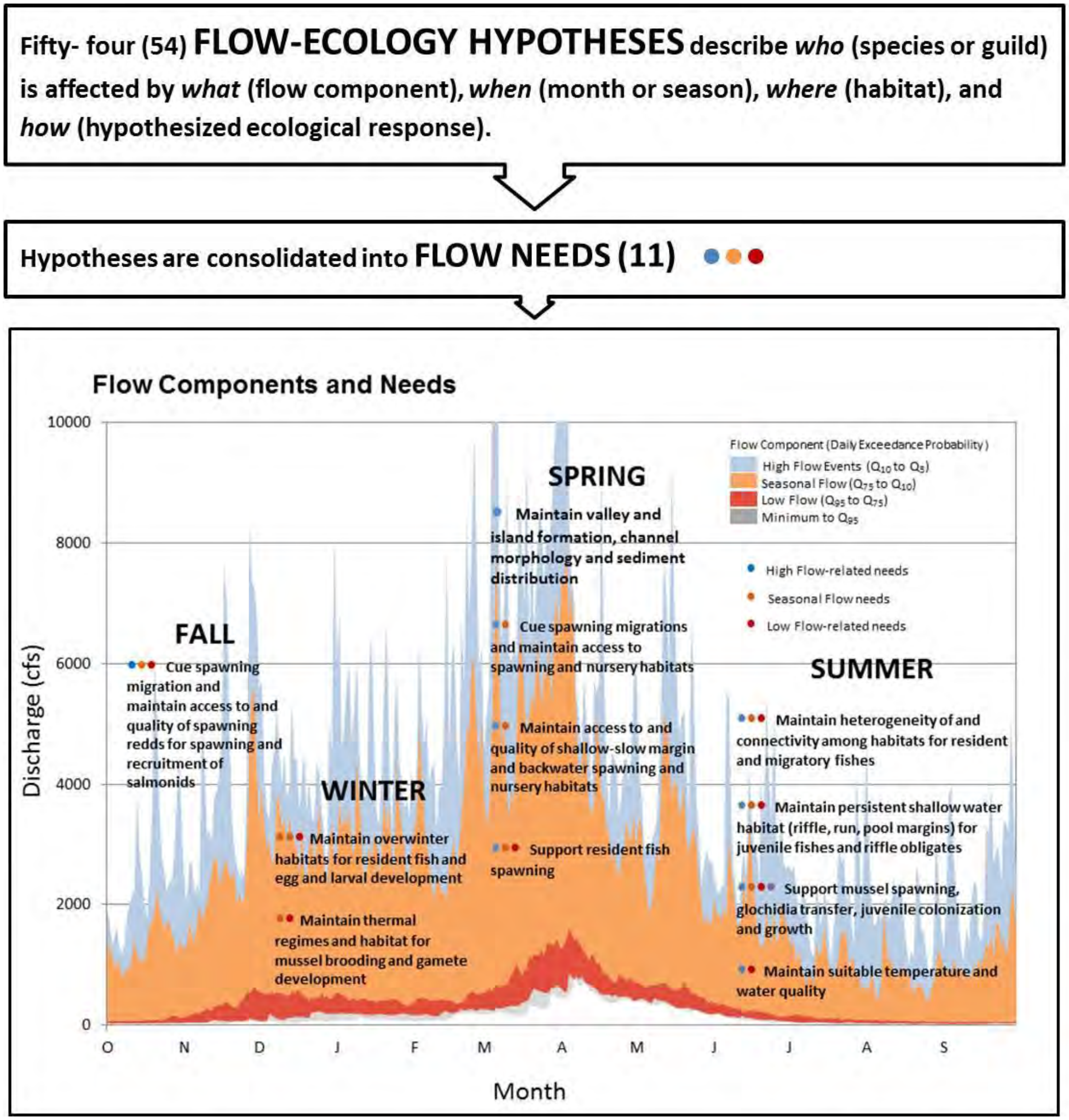


Figure 5.2. Conceptual model of seasonal flow needs for fish and mussels in Great Lakes rivers and streams based on flow ecology hypotheses generated during by this project's Technical Advisory Team.

5.2 Support for Hypotheses and Flow Needs

We examined 310 papers and extracted 265 pieces of evidence for or against our flow ecology hypotheses from 228 relevant publications. Fish were the most represented taxa with 204 pieces of evidence evenly distributed across high, seasonal and low flow components (Fig. 5.3). We found fewer pieces of evidence for hypotheses related to mussels (34), vegetation (23), and habitat (4), which is not surprising given that the systematic literature review focused on fish and more research has been conducted on fish in general. The majority of the literature for mussels focused on low flows, whereas vegetation and habitat literature primarily focused on high flows (Fig. 5.3).

Thirty three of the 54 individual hypotheses were well supported by the literature with an additional 19 hypotheses having some literature support (Appendix 3, Table A3.4). There were no hypotheses with inconsistent support or support for an alternative hypothesis, although one hypothesis (GL-F17) related to the effects of decreased seasonal flows on trout habitat approached inconsistent support criteria (Appendix 3 Table A3.4). Multiple flow ecology hypotheses supported each flow need, except for winter mussel needs. With the exception of fall low flows and fall and winter rate of change components, every flow component within every season had at least one supported flow-ecology hypothesis.[4] Additionally, when results are presented in terms of flow needs, there is clear support for all flow needs with the exception of flow need 3 regarding thermal regimes for mussel brooding and gamete development (Table 5.1). There are also clear patterns of support for high and seasonal flows in the fall, all flow components in the winter, seasonal and high flow components in the spring, and all flow components in the summer (Table 5.1; Fig. 5.4). Overall, these results suggest a high degree of support for a large number of flow ecology hypotheses generated by the Technical Advisory Team and corresponding support for the majority of identified flow needs.

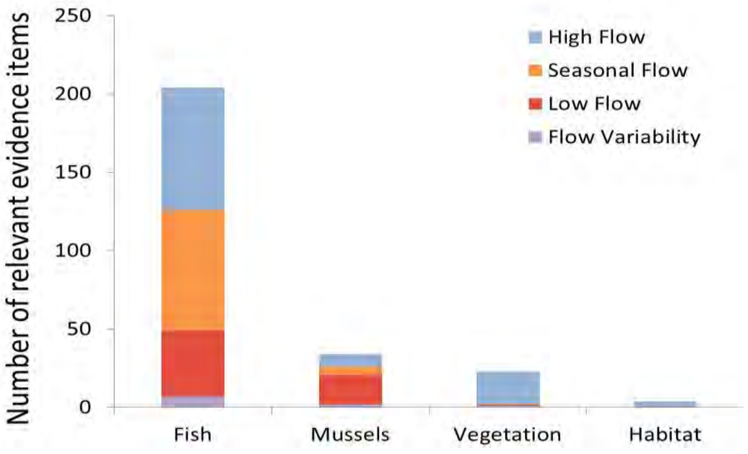


Figure 5.3. Number of individual pieces of information (relevant evidence items) used to build support for flow needs within each taxon and flow component. Information for fish dominated the analysis with high, seasonal and low flow needs all represented well.

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[4] The reader is referred to Appendix 3, Tables A3.1 and A3.4 for complete listing of hypotheses and individual Eco Evidence ratings. Further citations of individual hypotheses in this section refer to these tables.

Table 5.1. Summary of evidence scores (for/against) for flow needs and associated flow components across seasons. Total evidence scores combined across seasons are presented in the right hand column. Bold values represent scores that exceed >20 criteria across seasons and for total scores.

Flow Needs and Associated Flow Components	**Evidence Score by Season**				**Evidence Score**	
	Fall	**Winter**	**Spring**	**Summer**		
	S O N	**D J F**	**M A M**	**J J A**	**Yes**	**No**
FN 1: Cue spawning migration and maintain access to and quality of spawning redds for spawning and recruitment of salmonids	**125/9**	2/0		**35/0**	**125**	**9**
High Flow	**24/0**	2/0		13/0	**24**	**0**
Seasonal Flow	**92/9**			18/0	**92**	**9**
Low Flow	9/0			4/0	9	0
FN 2: Maintain overwinter habitats for resident fish and egg and larval development		**111/9**			**111**	**9**
High Flow		**39/0**			**39**	**0**
Seasonal Flow		**36/9**			**36**	**9**
Low Flow		**36/0**			**36**	**0**
FN 3: Maintain thermal regimes and habitat for mussel brooding and gamete development	5/0	5/0	5/0	5/0	5	0
Seasonal Flow	5/0	5/0	5/0	5/0	5	0
FN 4: Maintain valley and island formation, associated floodplain/riparian vegetation, channel morphology and sediment distribution	**101/0**	**133/0**	**176/0**	**75/0**	**176**	**0**
High Flow	**88/0**	**133/0**	**163/0**	**62/0**	**163**	**0**
Low Flow	3/0	3/0	3/0	3/0	3	0
Rate of Change	10/0		10/0	10/0	10	0
FN 5: Cue spawning migrations and maintain access to spawning and nursery habitats			**119/10**	7/0	**119**	**10**
High Flow			**63/9**	7/0	**63**	**9**
Seasonal Flow			**56/1**		**56**	**1**
FN 6: Support resident fish spawning	**28/0**	**65/9**	**278/9**	**146/0**	**291**	**9**
High Flow	4/0	4/0	**115/0**	**71/0**	**115**	**0**
Seasonal Flow	16/0	**48/9**	**110/9**	**35/0**	**123**	**9**
Low Flow			**22/0**	13/0	**31**	**0**
Rate of Change	8/0	13/0	**31/0**	**27/0**	**31**	**0**
F 7: Maintain access and quality of shallow-slow margin and backwater and nursery habitats	2/0	**5/0**	**148/0**	**71/0**	**153**	**0**
High Flow		5/0	**127/0**	**59/0**	**130**	**0**
Seasonal Flow	2/0		**21/0**	12/0	23	0

Table 5.1 continued.

Flow Needs and Associated Flow Components	**Evidence Score by Season**				**Evidence Score**	
	Fall	**Winter**	**Spring**	**Summer**		
	S O N	**D J F**	**M A M**	**J J A**	**Yes**	**No**
FN 8: Maintain suitable temperature and water quality	8/9		**63/9**	**84/18**	**84**	**18**
Seasonal Flow			11/9	11/9	11	9
Low Flow	8/9		52/0	73/9	73	9
FN 9: Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes	**44/0**		9/0	**150/0**	**150**	**0**
High Flow	**30/0**		9/0	**30/0**	**30**	**0**
Seasonal Flow	1/0			**44/0**	**44**	**0**
Low Flow	13/0			**76/0**	**76**	**0**
FN 10: Maintain persistent shallow water habitat (riffle, run, pool margins) for juvenile fishes and riffle obligates	**56/0**		5/3	**149/3**	**149**	**3**
High Flow	14/0			14/0	14	0
Seasonal Flow	**23/0**		5/3	**55/3**	**55**	**3**
Low Flow	19/0			**80/0**	**80**	**0**
FN 11: Support mussel spawning, glochidia transfer, juvenile colonization and growth	10/0	**77/0**	**135/0**	**135/0**	**159**	**0**
High Flow		**24/0**	**31/0**	**31/0**	**55**	**0**
Seasonal Flow		18/0	18/0	18/0	18	0
Low Flow		**25/0**	**76/0**	**76/0**	**76**	**0**
Rate of Change	10/0	10/0	10/0	10/0	10	0

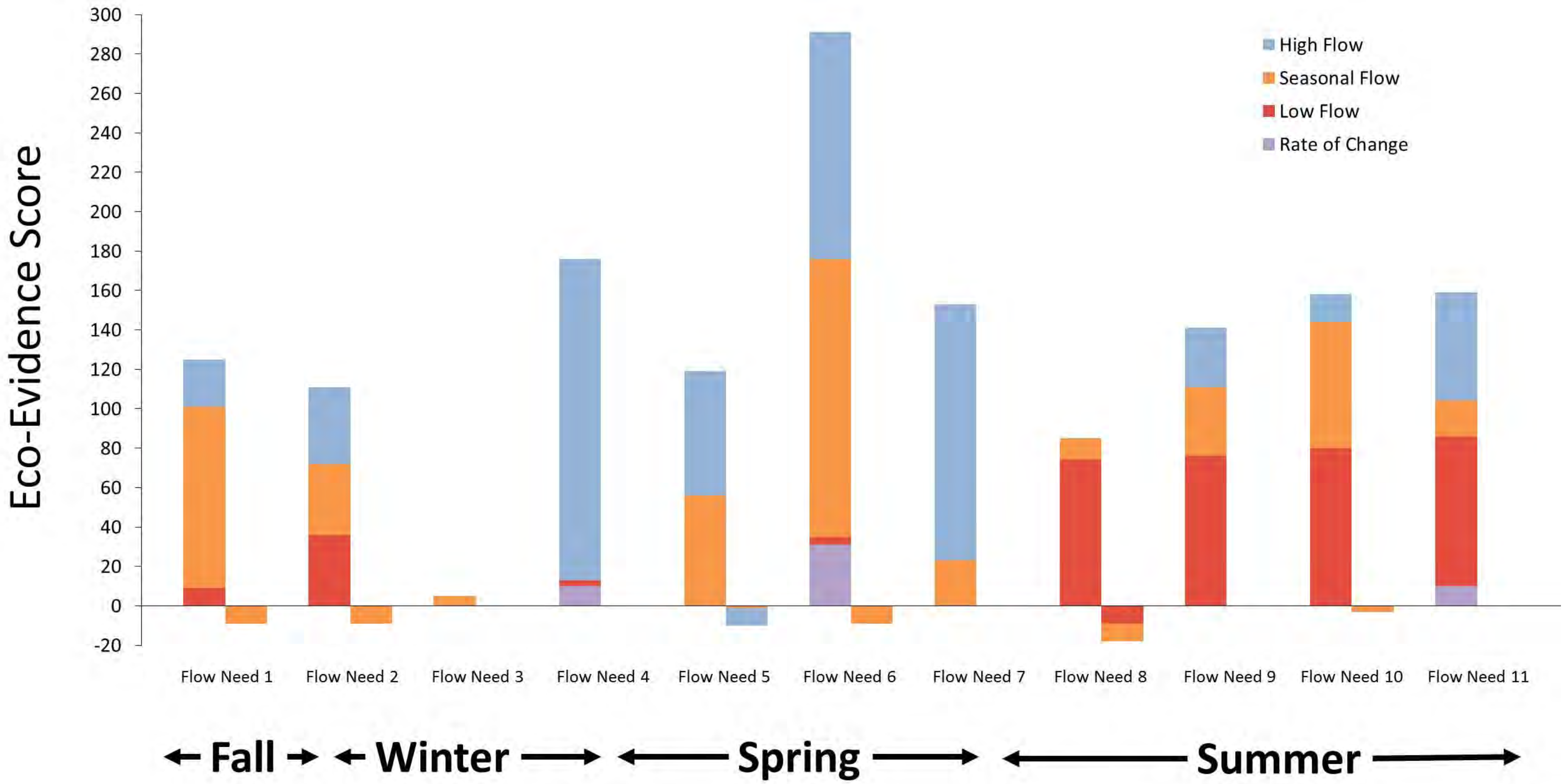

Figure 5.4. Summed eco-evidence scores for each flow need. Colors represent contribution of support for flow needs from papers representing hypotheses related to different flow component. Eco-evidence scores are computed based on the sum of weighted paper scores that provide support for (positive) or against (negative) flow needs.

5.3 Seasonal Flow Needs

Flow ecology hypotheses and environmental flow needs provide a framework for: 1) articulating what we are trying to protect with environmental flow recommendations and 2) building support from the scientific literature for linkages between flow regimes and aquatic organisms and ecological processes. While support for specific flow needs tends to center around particular seasons, there is considerable overlap across seasons for supported hypotheses and flow needs (Table 5.1, Appendix 3 Table A3.4). In section 6, we provide flow recommendations for specific flow components within specific seasons. Here we summarize the literature for each season based on key flow needs and hypotheses, but also quantify support for each flow component within seasons by taking into account overlap between seasons, flow needs and hypotheses (Table 5.1). Figures 5.4 through 5.7 represent support from the literature summarized by flow component for each season, after accounting for literature support that extended into additional seasons. Additionally, bold citations in the text below indicate scientific studies where quantitative flow statistics were reported, or where flow statistics could be derived by follow up analysis using Indicators of Hydrologic Alteration (IHA) analysis of data from nearby gages.

5.3.1 Fall

Key Elements

- **Many flow needs typically associated with summer extend into early fall when low flow discharges continue into September. For example, maintaining heterogeneity of, and connectivity among, habitats for resident and migratory fishes (Flow Need # 9) continues to be important during early fall months.**
- **High flow pulses combined with an increase in seasonal flows during the fall trigger spawning migrations for salmonids and provide access to tributary spawning habitats.**
- **After spawning events, stable surface and groundwater flows are necessary for maintaining redds throughout fall and into winter.**

The Technical Advisory Team defined fall as the months of September, October, and November. There was considerable support for high, seasonal and low flows during fall months, with high and seasonal flows representing the majority of support (Fig. 5.5). Late summer low flow conditions continue into early fall and can contribute to warm temperatures and low dissolved oxygen. Because early fall is an extension of summer flow conditions and juvenile fish development is still occurring, many supported flow needs for summer also apply to fall (Table 5.1). As fall progresses, flows generally increase in relation to decreasing evapotranspiration as summer vegetation growth period ends.

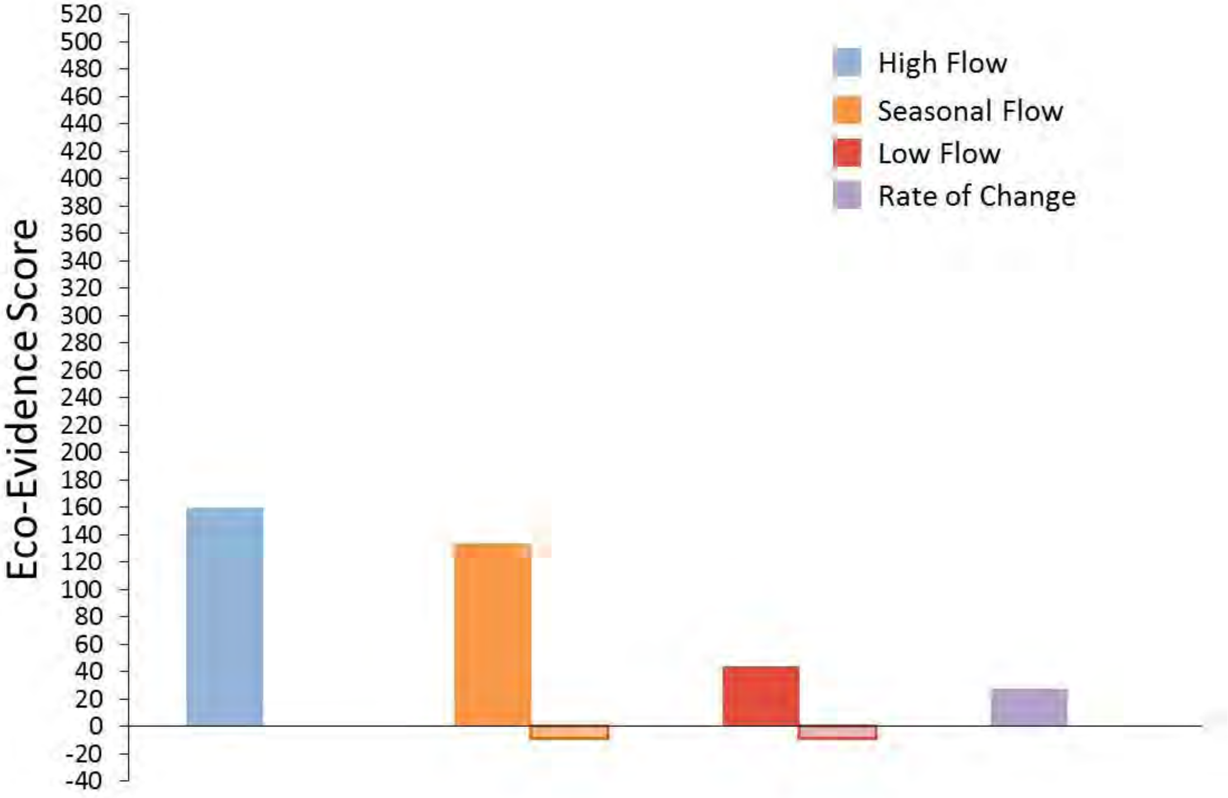

Figure 5.5. **Eco-evidence scores tallied across flow components for fall months.** Values include scores from papers representing flow needs from other seasons that extend into fall.

Fall marks the beginning of the spawning season for the majority of native and introduced salmonids within Great Lakes tributaries. There is good support from the literature for the role of **high flow pulses** in triggering migratory runs (GL-F1) (Huntsman 1948, Maccrimmon and Gordon 1981, Trepanier et al. 1996, Taylor et al. 2010). However, New York land-locked salmon likely cue on the relative difference in flow between September and October (Russ McCulloch, personal communication, workshop 2), and we found considerable support in the literature for **seasonal flow magnitude** in initiating salmonid runs and providing access to spawning habitats (GL-F3). This has been observed for European populations, where increases from low to moderate flows in late summer/early fall stimulate salmonid migration, but increases in flow from September to October when flows were higher have little effect (Jonsson and Jonsson 2002, Jonsson et al. 2007). Changes in seasonal flow may trigger movements but also increase access to spawning habitats. For example, in a separate study, Jonsson et al. (1991) observed a positive relationship between mean annual discharge (MAD) and mean body length of ascending Atlantic salmon, suggesting that river flow influences the ascent of larger fish in smaller streams. Fall seasonal flows are a significant factor in explaining New York's Salmon River YOY catches in spring. There is a strong positive correlation between mean flow during the first three weeks of October and spring peak YOY Chinook salmon catches. Using this relationship combined with IHA analysis of the Salmon River hydrograph, **spring YOY catches are predicted to be twice as high during years when October median flows are above the period of record (POR) median compared to years when flow is below the (POR) median (Bishop et al. 2008, IHA analysis) (Fig. 5.6)**. Positive relationships between fall-spawning discharge (in addition to density dependent factors) and age 0 densities have also been observed for a stream resident brown trout population in Pennsylvania (Carl 2006), but similar observations were not made for a western population (Spina 2001). There was some evidence that **extended low flows** in the fall prevent access to upstream spawning habitat for trout, although it was related to navigating artificial fish ladders (GL-F7). These studies demonstrated that low flows during the fall can prevent brown trout from moving through fish ladders to upstream spawning habitats - support for the hypothesis that low flows limit access to upstream habitats (Jensen and Aass 1995, Arnekleiv and Kraabol 1996).

In addition to providing access to spawning habitats, stable fall seasonal flows are also important for maintaining redds during and after salmonid spawning. A **decrease in seasonal groundwater or surface water flows** reduces quality of spawning habitats (O-F1). Several studies have observed relationships between brook trout spawning and groundwater seepage areas or the use of high groundwater fed streams for spawning (Hazzard 1932, Witzel and Maccrimmon 1983, Curry and Noakes 1995, Petty et al. 2005). Baxter and McPhail (1999) observed a similar relationship for bull trout in western streams. In addition to groundwater contribution, depth and velocity are also important aspects of spawning habitats. **A regional IFIM study from Pennsylvania predicted a 10% spawning habitat loss for withdrawals of 11 to 14% of the November median (Denslinger et al. 1998, IHA analysis, DePhilip and Moberg 2013).** **Declines in seasonal flows or increased flow variability** during the spawning season can have negative effects on recruitment (GL-F4). Nelson (1986) observed that high flow variation during the fall spawning season resulted in lower brown trout year class strength. Spawning habitat models below dams also indicate that flow reductions associated with hydropower operations can reduce Atlantic salmon spawning habitat considerably (60-90%) and Hatten et al. (2009) found that Chinook salmon were more likely to spawn in areas that maintained stable flows.

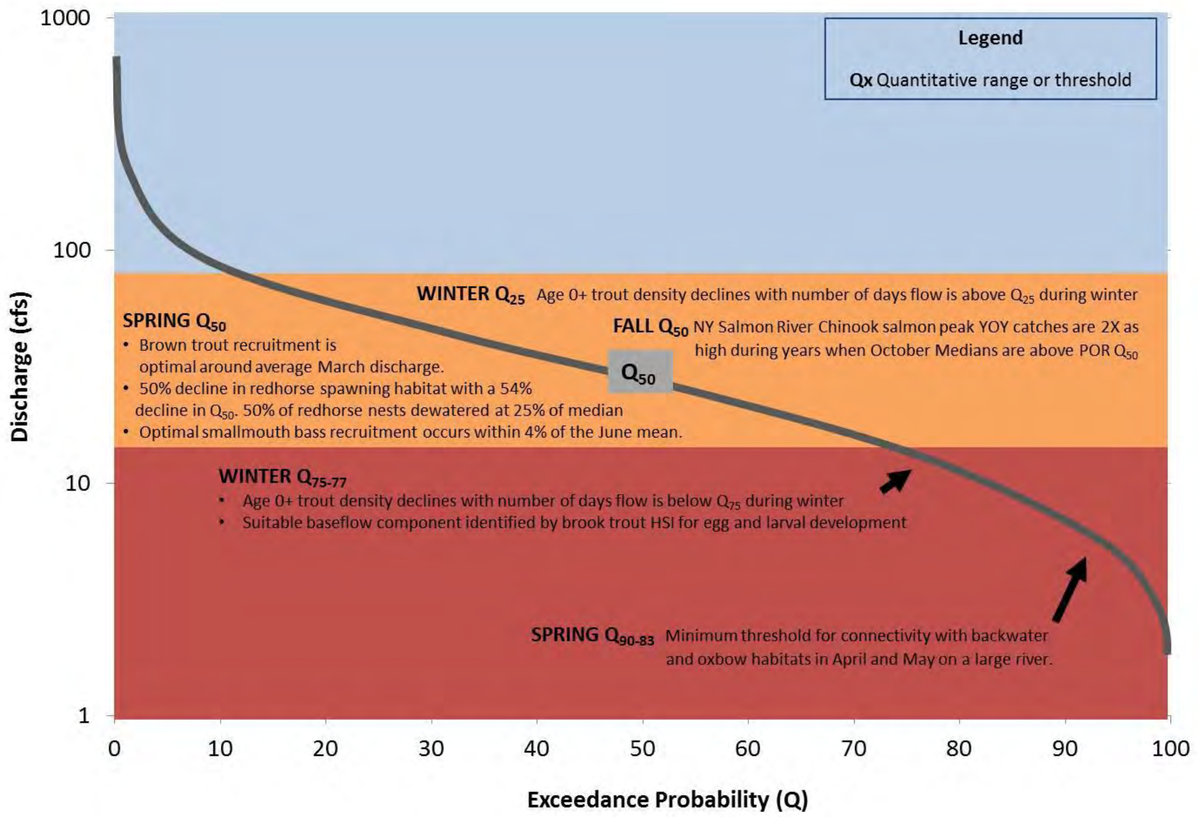

Figure 5.6. **Observed ecological responses** from the scientific literature in reference to points along the flow duration curve during fall, winter, and spring seasons.

5.4.2 Winter

Key Elements

- **Recruitment success of fall spawning salmonids is limited by egg and larval mortality related to winter high flow events.**
- **Low flow influences egg and larval incubation environments.**
- **Bioenergetic costs associated with movement may impact fish during cold periods due to low metabolic activity.**
- **Stable flows and ice cover buffer stream temperatures.**
- **Ice scour events are important for maintaining shoreline vegetation communities.**

Winter is defined as the months of December, January and February. Winter is recognized as a critical time for many fish and mussel species, as well as processes that maintain riparian and floodplain vegetation. Relatively little is known about species-specific overwinter habitat requirements. However, based on winter flow needs identified during our project workshops and needs that carry over from other seasons, we found considerable support for maintaining high, seasonal and low flows within natural ranges of variation during the winter (Fig. 5.7).

Eggs and larvae of salmonids that spawned in the fall (brook trout, Atlantic salmon) are sensitive to changes in both high flow and low flow components and thus overwintering flow conditions are critical to successful recruitment. **Increased frequency or magnitude of high flow events** (bankfull or above) can increase egg and larval mortality rates due to scouring of redds and larval habitat (GL-F8). Loss of an entire brook trout year class was attributed to flooding (**peak flows ranged from 5 to 25 year recurrence interval**) that scoured brook trout redds in January (Carline and McCullough 2003). Brown trout YOY densities have been negatively associated with peak discharge or the number of days above the Q_{25} flow during the winter incubation period (Spina 2001, Alonso-Gonzalez et al. 2008). Cunjak et al. (1998) and Cunjak and Therrien (1998) observed the lowest Atlantic salmon egg to age-0 survival rates during a year in which the stream experienced severe streambed disturbance due to a midwinter thaw. One of the best predictors of Chinook salmon return rates in Pacific coastal streams is the magnitude of floods experienced during the egg incubation period (Greene et al. 2005). While all of these studies represent natural high flow events, they demonstrate that increased frequency and magnitude of high flow events could have negative population consequences on fall-spawning salmonids.

Salmonid egg and larval mortality can also be influenced by **extreme low flows** that may increase freezing and anchor ice formation within redds (GL-10). **Based on temperature and velocity habitat suitability models, stream flow during the brook trout egg and incubation period should be greater than 25% of average daily flow (AFD) to maintain suitable incubation conditions (Raleigh 1982). This represents flows above Q_{77} to Q_{95} for Class 1 streams within the Great Lakes Basin (IHA analysis). Alonso-Gonzalez et al. (2008) observed a negative relationship between age-0 densities and the number of days below the Q_{75} flow during the incubation period for a brown trout population (Fig. 5.6).** Very low egg to age-0 survival during winters with extreme low flows has been reported for at least two Atlantic salmon populations (Gibson and Myers 1988, Cunjak et al. 1998, Cunjak and Therrien 1998). Groundwater contribution to winter low flows helps maintain stable incubation conditions (see OF-1). Persistent groundwater upwelling is critical in protecting brook trout redds from infiltrating surface water and ices and maintaining dissolved oxygen. Curry et al. (1995) observed significant reductions in egg to age-0 survival in redds with low versus high groundwater contributions, and other studies have observed similar results, particularly

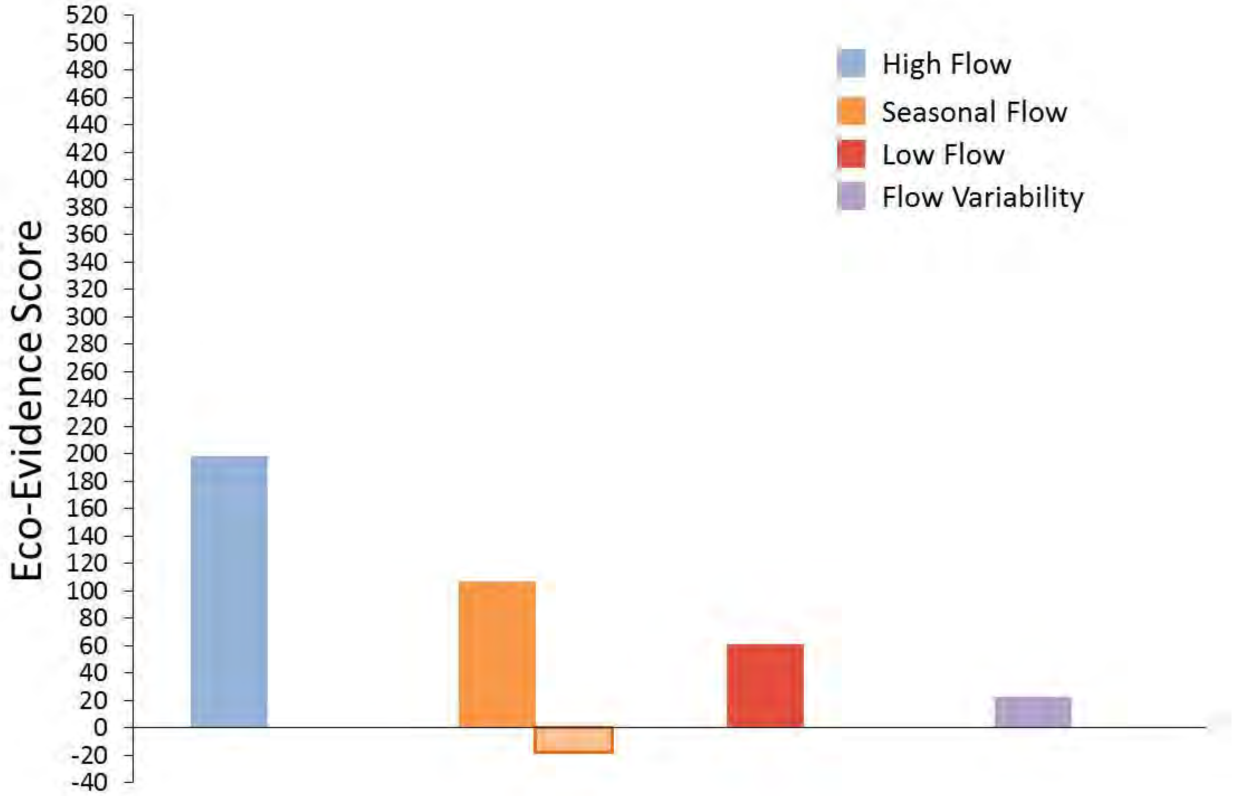

Figure 5.7. **Eco-evidence scores tallied across flow components for winter months.** Values include scores from papers representing flow needs from other seasons that extend into winter.

when surface water flows and temperatures are reduced (Fraley and Decker-Hess 1987, Baxter and McPhail 1999, Calles et al. 2007). **Decreasing low flow conditions** can also limit riffle habitat for other coldwater fishes and older age classes of salmonids (O-F5). Juvenile and adult mottled sculpin directly compete for winter refuge in crevices between gravel and cobbles and population size is regulated by overwinter habitat availability (Rashleigh and Grossman 2005). Cunjak et al. (1998) and Cunjak and Therrien (1998) found positive relationships between mean winter discharge and age 0 to 1 and age 1 to 2 survival of Atlantic salmon.

During winter, fish have limited mobility due to high bioenergetics costs. Increased magnitude of seasonal flows can increase energy expenditure to hold positions in flow water habitats, leading to decreased survival or condition of fish (GL-F9). Experimental evidence suggests that rainbow trout and rosyside dace have decreased swimming abilities at higher velocities during winter and increasing velocities increase metabolic activity in rainbow trout (Facey and Grossman 1990). A study by Brenden et al. (2006) that compared habitat use of muskellunge in a regulated river across winter and summer found that fish movements occurred when discharge was greater than the median for the period of record. Fish moved more during winter suggesting that fish use more energy to move in response to flow increases when energy reserves are lowest. Two different studies demonstrate that warmer temperatures and higher flows have negative consequences on growth and condition of overwintering Atlantic salmon (Murphy et al. 2006, Davidson et al. 2010). This may also be due to the effects of flow on the timing and duration of ice cover which shelters the stream from winter environments and factors that can effect fish movement. Frazil ice poses direct physiological effects (attaching to gills) in addition to restricting available physical habitat for trout (Brown et al. 1993). Prevention of surface ice formation by higher flows combined with extreme temperatures can result in frazzle ice and force frequent and long distance fish movements to avoid unsuitable habitat conditions (Simpkins et al. 2000).

During winter, **decreased seasonal flow magnitude** may reduce temperatures and shift thermal regimes that are critical during mussel gametogenesis (O-M1). 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; DePhilip and Moberg 2013). 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 one study, the timing of reproduction was correlated with the number of accumulated degree days (Galbraith and Vaughn 2009).

5.4.3 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 of fish, vegetation recruitment and geomorphic 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.**
- **Migration and movement of spring-spawning fishes frequently coincides with high flow events that are synchronized with temperature and other cues. Maintaining frequency and magnitude of high flow events is essential to provide opportunities for migration when other conditions are suitable.**
- **High flow pulses followed by stable, high seasonal flows are key to spawning success for many fish species.**
- **Larval transport to slow-moving habitats (after spawning) is essential for spring-spawning fishes, including walleye and northern pike.**
- **Spring spawning fishes can be negatively affected by both extreme high and extreme low flow events; flows that are too high or too low can affect spawning success.**

Spring is defined as the months of March, April and May, but many spring flow needs can extend into early summer (June). Peak flows generally occur in spring and are critical for maintaining stream geomorphology, substrate distributions and shoreline vegetation. Spring is also a biologically active season when the reproductive periods of many aquatic organisms are tied to flow conditions. High flow needs are particularly important and are well supported for spring, but flow needs representing seasonal and low flow components were also well supported (Fig. 5.8).

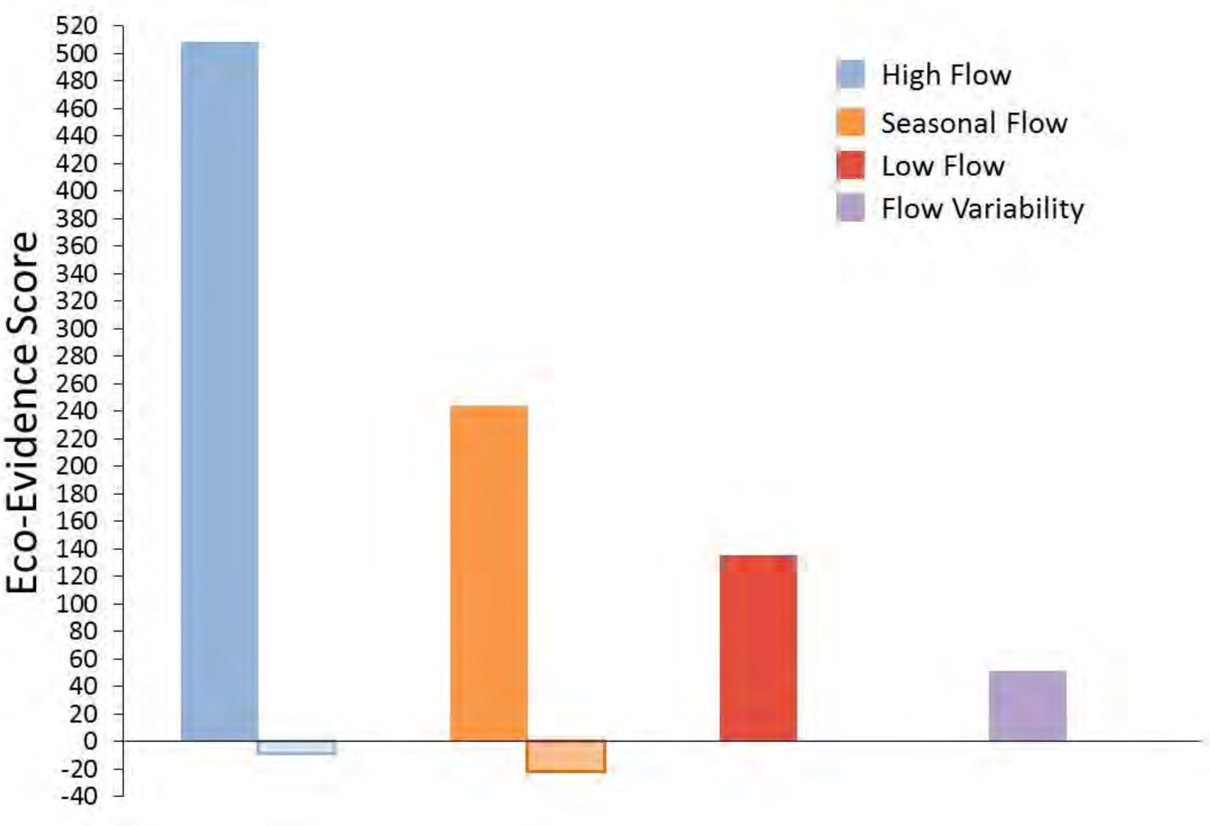

Figure 5.8. **Eco-evidence scores tallied across flow components for spring months.** Values include scores from papers representing flow needs from other seasons that extend into spring.

High flow events during winter and spring maintain valley and channel morphology, associated vegetation and sediment distributions. **Decreasing magnitude, duration or frequency of high flow events** can eliminate habitat forming processes that increase riffle embeddedness and aggrade channel morphology (GL-H3). Flooding can increase the number of riffles and pools, and increase overall substrate size (Roghair et al. 2002). Channel maintenance is associated with 1-5 year flood events (Nanson and Croke 1992). A decrease in magnitude or **shift in**

timing of peak flow events can also reduce complexity of pool habitat cover by eliminating ice scour events (GL-H4). Flood events transport large woody debris which contributes to fish cover and flow refugia, as well as influencing stream geomorphology and riparian forest patch dynamics (Abbe and Montgomery 1996, Roghair et al. 2002). **Winter and spring flooding and associated ice scour** events also influence the distribution and composition of floodplain vegetation assemblages (O-V1). Many studies have observed a shift in floodplain vegetation communities from those with a high fidelity for flood disturbance (silver maple and sycamore forest) to those dominated by late successional woodland or grassland communities, characterized by more homogeneity and woody species encroachment in the riparian zone, and a reduction in successful recruitment of rare species in the floodplain (Auble et al. 1994, Johnson 1994, 1998, Townsend 2001, Cowell and Dyer 2002, Bowen et al. 2003, Elderd 2003, Ahn et al. 2004, Zimmerman and Podniesinksi 2008). **High flow events** influence seed dispersal and prepare seedbeds for propagules of many floodplain and riparian vegetation species (O-V2). Seeds of riparian trees like American sycamore, river birch, and silver maple, depend on high flows for dispersal (Burns and Honkala 1990) and winter flows are important for maintaining species richness by remobilizing and transporting propagules (Gurnell et al. 2008)). Jansson et al. (2000) found that regulated reaches had a higher proportion of species with generalist dispersal mechanisms. Altered high flow regimes can lead to recruitment failure, narrower bands of seedling establishment, and lower quality habitats for establishment of riparian species (Fenner et al. 1985, Walters and Williams 1999, Shafroth et al. 2002). **Declines in low flow magnitude** during the growing season can decrease inundation and groundwater elevation. This may stress riparian plant and forest assemblages resulting in species more adapted to mesic conditions (O-V8). A shift from facultative wetland species to facultative upland and upland species occurs along a gradient of high to moderate/low inundation. Sites with high inundation potential (seasonal inundation during spring median flows) support greater ground-layer species richness, biomass, and cover and a relatively distinct wetland flora compared to mesic floodplains (Williams et al. 1999). Similarly, in headwater settings, Hanlon et al. (1998) observed a shift in species composition from wetland to upland assemblages with more woody species across an inundation gradient.

The **magnitude and duration** (GL-F11) and **timing** (GL-F13) of **high flow events** serve as cues for the reproductive cycles of riffle associate fishes during the spring. Increased walleye and white sucker activity and confirmed spawning have been observed after spring high flow pulses (Dustin and Jacobson 2003, Doherty et al. 2010), and DiStefano and Hiebert (2000) observed discrete upstream movement of walleye during peaking operations below a dam during the spring spawning season. Koel and Sparks (2002) observed that fish assemblages with high proportions of white bass were significantly associated with the magnitude and duration of the spring flood, and a meta-analysis of three studies representing southeastern and Great Lakes streams found a positive relationship between YOY fish density and the 10-day maximum discharge during the spring spawning period (Craven et al. 2010). While these studies provide some evidence for the role of high flow magnitude in spring spawning runs, there was considerably more evidence from studies that included additional cues such as temperature and day length in addition to high flow pulses (GL-F13). Several studies have observed relationships between lake sturgeon spawning runs, flow and temperature. In general, lake sturgeon spawning is initiated on the receding limb of high flow pulses once adequate temperature thresholds have been reached; spawning may be limited during low water years with no pulses, or during springs with extreme flood events (LaHaye et al. 1992, Auer and Baker 2002). Recent work by Forsythe et al. (2012a, 2012b) demonstrated that spawning activity of lake sturgeon, including initiation of migration and timing of arrival at spawning sites, is driven by a complex combination of factors including genetic subpopulation differences, stream temperature, discharge, and lunar phase. Overall, the study reveals that declining flow rates (receding limbs) and increasing temperatures are important cues for lake sturgeon. Studies on other sturgeon species (genus *Acipenser*) that spawn in the spring have also identified temperature and high flow pulses as important factors in spawning migrations (Paragamian et al. 2001, Paragamian and Wakkinen 2002, Heise et al. 2004, Paragamian and Wakkinen 2011). Sucker spawning migration runs have also been associated with increasing temperature and the receding limbs of high flow pulses, but temperature cues can be overridden by flows that are too high or too long where spawning runs are delayed until the receding limb (Curry and Spacie 1984, Reid 2006). Additional evidence also supports the influence of temperature and high flow pulses on spawning of white bass and rainbow trout (Quist et al. 2002, Holecek and Walters 2007).

Higher seasonal flows during the spring spawning period also influence recruitment of riffle associate fishes by influencing the amount of spawning habitat available (GL-F15a). Total walleye larval production is positively associated with mean discharge on estimated spawning days (Johnston et al. 1995). Saugeye recruitment is also positively associated with discharge leading up to spawning (Sammons and Bettoli 2000). Kelder and Farrell (2009) found that depth was a key factor in predicting walleye egg deposition in a Lake Ontario tributary and as flow increases margin and riffle areas become wetted, increasing amounts of shallow water habitat. Not many papers link lake sturgeon spawning to average flows, but Duong et al. (2011) demonstrated that higher discharge during the spawning and larval development period decreases time spent in the vulnerable larval development stage. An analysis for a similar species (white sturgeon) shows that YOY catch rate is positively associated with weighted usable area during the spawning period, which is influenced by discharge (Beamesderfer and Farr 1997). Low flows during the spring can reduce redhorse spawning habitat significantly. (Bowman 1970) documented significant decline in overall available spawning habitat and mean size of individual male territories within a black redhorse spawning shoal. **Discharge during a low flow year (-64% of April median) reduced available spawning habitat by 50% compared to**

a more typical flow year (-11% of April median)(Bowman 1970, IHA analysis, see Fig. 5.6). Several studies provide evidence for positive associations between white bass recruitment and seasonal flow conditions during the spawning period, suggesting that higher spring flows provide more access to spawning habitat in tributary streams (Beck et al. 1997, Sammons and Bettoli 2000, DiCenzo and Duval 2002, Willis et al. 2002). Underwood and Bennett (1992) reports that the highest rainbow trout year class was associated with high, relatively constant flows from April to June during the spawning, incubation, and emergence period. Two years with low flows had much lower year class strengths.

A **decline in seasonal flows** can limit survival of riffle associate fishes during the larval drift stage by decreasing drift dispersal rates to juvenile rearing habitats (GL-F18). A larval transport survival model based on published relationships demonstrated that walleye larval drift survival is more a function of velocity than temperature at distances less than 80 km but temperature becomes more important at longer distances. High velocities or low velocities with high temperatures lead to increased mortality (Jones et al. 2003). Larval lake sturgeon drift occurs at daily temperatures above 16 C and discharge between 182 and 259 cfs (Smith and King 2005). Year class strength of lake sturgeion in the St. Lawrence system is positively associated with June flow from the Des Prairies River and the May-June increase in temperature in the St. Lawrence. June is a period of larval drift and higher flows may decrease predation and increase dispersal (Nilo et al. 1997).

While high flow pulses are important for instream habitat and floodplain maintenance and serve as cues for riffle associate spawning runs, **increased magnitude and frequency of high flow events** during later spring and early summer months can scour eggs and larvae and limit recruitment of fish (Appendix 2, Table 1, GL-F14). Reduced survival of walleye larvae has been associated with high discharge during the hatching period in a Lake Erie tributary and lake data combined with modeled current velocities suggest that weak recruitment years are linked to current velocities capable of dislodging eggs from substrate (Mion et al. 1998, Zhao et al. 2009). We found considerable support for the impact of spring high flows on fall-spawning salmonids. Peak flows during the spring can result in near bed displacement velocities for newly emerged Atlantic salmon (Gibbins and Acornley 2000). A **large spring flood ($< Q_1$)** in a New York stream was followed by a shift in dominance from fall-spawning (brook and brown trout) to spring-spawning (rainbow trout) spawners (Warren et al. 2009, IHA analysis). Several other studies have observed brook and brown trout recruitment failures in response to large spring floods (Latterell et al. 1998, Letcher and Terrick 1998, Smith and Atkinson 1999, Roghair et al. 2002). However, rapid re-colonization and high growth rates can lead to full recovery in 2-4 years, suggesting that spring flood events at natural frequencies do not have long term effects on populations. Zorn and Nuhfer (2007) observed a negative relationship between brown trout density and high flow conditions (magnitude of deviation from average spring flows) at or near the time of fry emergence and models based on long term datasets at several streams predict that **brown trout year classes are eliminated when March discharge is 45% above the mean** (Lobón-Cerviá 2004, Lobón-Cerviá 2007, 2009) (Fig. 5.6). There was considerable support for nest-building fish recruitment being sensitive to high flow events in the spring as well. Higher spring flows are associated with lower bass year class strength (Bonvechio and Allen 2005). **Very high June flows (> 40% of POR mean)** are associated with near year class failure for smallmouth bass in a Virginia river (Smith et al. 2005), and population models for the same species **predict a >42% decline in densities in response to a 25% increase in mean spawning/rearing discharge** (Peterson and Kwak 1999). These relationships with increases in mean flow are presumably driven by increased frequency and magnitude of high flow events as several studies have reported nest abandonment, failure, and termination of spawning season due to flooding events, especially repeated events (Winemiller and Taylor 1982, Graham and Orth 1986, Lukas and Orth 1995). Similar effects of flood events on rock bass and sunfish nests with high flow events **(as low as Q_{12})** destroying nests have been noted (Noltie and Keenleyside 1986, 1987, Lukas and Orth 1993, Jennings and Philipp 1994, IHA analysis). Despite high flow impacts, overall annual nest success can be relatively high in most years, but frequent floods **(five Q_3 events in one season)** can result in low recruitment (Jennings and Philipp 1994). Nest-builders may adapt to flooding regimes and increase reproductive success by nesting earlier and more often to avoid floods or have more opportunities to re-nest after floods (Noltie and Keenleyside 1986). Lower **seasonal flows** may limit recruitment of nest building fishes as well (GL-F16). Smith et al. (2005) observed that **optimal smallmouth bass recruitment occurs during years within 4% of the POR mean** for a Virginia river (Fig. 5.6).

Seasonal flows also provide shallow riffle habitat for riffle obligates (GL-F15b). Frequency of occurrence of catostomids and darters in Midwestern streams is positively associated with lower flow variability and higher discharges in spring (Koel and Peterka 2003). Freeman et al. (2001) found that YOY abundance was frequently correlated with persistence of shallow-fast habitat in spring at unregulated sites. At regulated sites, seven species were positively correlated with spring shallow water habitat persistence and 5 out of 6 species were significantly less abundant in regulated sites that had less persistent shallow water habitat in the spring. Microhabitat use by 4 riffle obligates below a dam was influenced most by stream hydrology, but no single flow regime adequately protected all 4 species, emphasizing the need to preserve long-term median flows and the inter-annual variability around them (Brewer et al. 2006). Spring seasonal flows also influence trout species during the early rearing phase in shallow riffle habitats. Several studies based on a 20 year dataset have demonstrated that, when flows were below the March average, a positive relationship between brown trout recruitment and March mean flow existed. **Both brown trout recruitment and spawner density the following year are predicted to decline by 10% with a 5% decrease in March mean flow. Year class failure is expected when March discharge is 45% below average (Lobón-Cerviá**

2004, Lobón-Cerviá 2007, 2009)(Fig. 5.6). Arthaud et al. (2010) found a positive relationship between May flow (time of early rearing) and egg-trap/trap-smolt transition rates in a river subject tow water withdrawals.

Rapid decreases or increases in flow can limit recruitment of fish species that use shallow habitats for nesting or juvenile development by de-watering nests, stranding or flushing larvae from rearing habitats along margins (GL-F19). Fifty percent of robust redhorse nests on a shoal in a large river were de-watered or at near zero flow conditions for several days due to flow fluctuations around the POR unaltered median. **De-watering of redhorse nests occurred when flow fluctuations decreased discharge by 25% of the POR May median (Grabowski and Isely 2007, IHA analysis)(Fig. 5.6).** Flow variation associated with hydropower dams has been linked to changes in species composition associated with persistance of shallow water habitats that maintain nursery function for fluvial specialists. Persistence of native fish in flow-regulated streams depends on seasonal occurrence of stable shallow water habitat conditions that facilitate reproduction and YOY survival, and fluvial fish abundance, relative abundance of suckers, and mean fish density all increase with decreasing daily fluctuations in shallow water habitats (Kinsolving and Bain 1993, Travnichek and Maceina 1994, Scheidegger and Bain 1995, Bowen et al. 1998, Freeman et al. 2001). Additionally, in a 5-year study of largemouth bass spawning and catches of YOY, low cohort strenght was observed in a year when flow and water levels dropped dramatically during the spawning period (Raiblet et al. 1997). Several repeated experiments in an experimental channel demonstrated that brown trout YOY stranding increases with dewatering rate (Halleraker et al. 2003).

Salmonid redds and larval emergence in the spring can be impacted by deposition of fine sediments when **magnitude of seasonal flows declines** during the incubation period (fall-spring) (O-F6). Significant declines (50%) in brook trout abundance and population changes associated with decreased survival rates, particularly in the egg to fry and fry to fall fingerling stages with relatively small increases in sediment loads have been experimentally demonstrated (Alexander and Hansen 1986). Sediment impacts to salmonid redds can begin as early as summer. Two studies in brook trout streams observed that drought flows in the summer resulted in significant increases in sand and silt within substrates in the fall (Hakala and Hartman 2004, Grossman et al. 2012). **Hakala and Hartman (2004) observed significant increases in fine sediments within spawning substrates of seven brook trout streams when summer/fall monthly medians were reduced to flows comparable to Q_{83} to Q_{95} (based on a local downstream gage, IHA analysis).** Increasing levels of fine sediment during incubation reduces survival of brook and brown trout during early development stages. In experimental brook trout redds, intra-gravel permeability and dissolved oxygen declined with increasing fine sediments, and survival at each development stage generally declined with increasing fine sediment (Argent and Flebbe 1999). Franssen et al. (2012) observed that increasing sediment during incubation decreases egg to emergence survival of brook trout regardless of interstitial flow and dissolved oxygen levels within redds. Increasing fine sediment during incubation can decrease brook trout fry weight (Argent and Flebbe 1999). Increased fine organic sediment also decreases survival by inhibiting predator cue responses related to emergence behavior and resulted in brown trout fry with larger yolk sacs which increases vulnerability to predation or displacement through decreased swimming ability (Louhi et al. 2011). Declines in percent survival to hatching (Levasseur et al. 2006) and emergence (Lapointe et al. 2004) in response to increases in fine sediments have also been reported for Atlantic salmon, and high sediment treatments altered emergence patterns of rainbow trout fry in experimental redds (Fudge et al. 2008). Several of these studies highlight the role of stream flow in maintaining low sediment conditions in redds. Comparison of seasonal patterns of silt and very fine sand in redds indicated that periods of low transport corresponded with periods of infiltration (Levasseur et al. 2006) and can return to pre-spawning conditions within 25 days based on measured deposition rates (Acornley and Sear 1999). A comparison of spring Chinook salmon YOY densities and mean stream velocity across sites among 3 Great Lakes streams found that streams with velocities below critical mean current velocities necessary for moving sand and clay particles did not support salmon reproduction, but YOY densities increased with mean current velocities in streams that maintained flows above critical values (Carl 1982). Research on measured deposition rates during high flow events suggest that while deposition can be substantial and reduce interstitial flows, changes in interstitial flows were still well above thresholds for salmon egg/larvae survival (Zimmermann and Lapointe 2005). Maintaining higher low flow conditions results in less sediment accumulation in redds, and periodic small high flow pulses likely flush redds and maintain sediment conditions below thresholds necessary for egg and larvae survival (Acornley and Sear 1999, Levasseur et al. 2006, Franssen et al. 2012). Overall, the literature provided strong evidence for negative effects of sedimentation on salmonid egg and larvae survival, and positive effects of higher seasonal flows on reducing sediment deposition rates. Additionally, maintaining natural magnitude and frequency of high pulses likely provide additional sediment removal functions.

During the spring, a **decrease in magnitude and duration of peak flow events** will reduce connectivity and maintenance of floodplain wetland habitat which is critical for spawning and fry development, and limit recruitment of pike (GL-F12). **Maintaining high water levels that flood shallow emergent marshes for 4 weeks until fry swim-up period is a critical hydrologic function for northern pike recruitment success**. Using a spatial-temporal habitat model and hydrology from 1960-2000, Mingelbier et al. (2008) demonstrated that loss of flooded sedge habitat occurred frequently and impacted up to 78% in the most exposed region of the St. Lawrence River. Loss of seasonally flooded sedge habitat results in northern pike using deeper spawning habitats than expected. Spawning in deeper habitats is not ideal due to colder temperatures and slower development rates, and competition with YOY muskellunge (Farrell

2001). Estimated growth rates in preferred versus alternative habitats suggest that pike eggs require more degree days to hatch and enable larvae to reach swim-up stages in alternative habitats (Cooper et al. 2008). Simulations that compared northern pike early life history processes and YOY production among preferred sedge and deeper alternative habitats demonstrated that earlier spawning and warmer spring temperatures in flooded tributary habitats yielded higher mean daily survival and higher net YOY production (Farrell et al. 2006). Smith et al. (2007) developed a model that related year class strength of northern pike to environmental variables. High spring flows, high winter and spring water levels, and low variability in spring water levels were important predictors of strong year classes. Hudon et al. (2010) also observed positive associations between spring water level and temperature and pike year class strength. In European systems, investigators have observed positive relationships between juvenile phytophilic species abundance and duration of flooded vegetation in manmade floodplain ponds, and periodic strategists including northern pike and magnitude and duration of flooding (Janac et al. 2010, Gorski et al. 2011).

A **reduction in seasonal flow limits availability and connectivity** of shallow-slow habitats which are important for development of juvenile fishes (O-F14). Reduction in natural spring flows in a regulated river reduced the amount of available shallow slow water habitats by 3-3.5 times during a normal and dry water year. Freeman et al. (2001) observed positive correlations between persistence of shallow-slow habitat and YOY fish abundance. Fish communities with higher overall richness and more rheophilic forms were observed in off-channel habitats that were wet more often and for longer durations (Flinn et al. 2008). Growth rates and survival of brassy minnows using backwaters were significantly lower during dry years. Survival was higher among cohorts that utilized large backwater areas that dried more slowly (Falke et al. 2010). In small streams, longnose and blacknose dace fry segregate based on shallow margin habitat. Loss of margin habitat during lower flow periods can put these two species in direct competition (Gibbons and Gee 1972).

High flow events increase fish productivity and species diversity by maintaining connectivity to and quality of oxbow and backwater habitats (O-F16). Large numbers of species utilize floodplain habitats. **Fish movement (with a high proportion of juveniles) between river and oxbow habitats was positively correlated with discharge on a large river (Class 3) during intermediate flood periods and required a minimum discharge that corresponded to Q90, Q83, Q62, Q32 and Q15 flows for April, May, June, July, and August respectively ((Kwak 1988), IHA analysis)(Fig. 5.6).** Pool area (a surrogate for duration) was positively associated with fish richness in 19 floodplain pools and total fish production in five pools increased with duration of stream connectivity (Halyk and Balon 1983). Several studies have reported higher YOY diversity, production and transport in relation to magnitude and duration of flooding (Jurajda et al. 2004, Martin and Paller 2008, Janac et al. 2010, Gorski et al. 2011). Nest building species that will leave the channel during flooding can also benefit from flooding. Increased growth of redbreast sunfish was associated with wet years characterized by greater flows in April through June (Sammons and Maceina 2009), and Raiblet et al. (1997) observed a positive relationship between largemouth bass cohort strength and days above flood stage on the Illinois River (large river). Increasing connectivity between oxbow lakes and rivers shifts fish assemblages from equilibrium or opportunistic strategists (primarily lentic) to periodic strategists that include more rheophilic species (fluvial specialists) and results in higher richness (Galat et al. 2004, Zeug et al. 2005, Górski et al. 2010, Miyazono et al. 2010). In contrast, loss of connectivity due to lack of flooding can lead to increased gar density within oxbow lakes which can impact juvenile fish densities and change assemblage structure if annual flooding is not restored (Bonvillain et al. 2008).

5.4.4 Summer

Key elements

- **Stable flows and warmer temperatures make summer the peak season for growth of many species, but coldwater species can be limited by warm temperatures during low flow periods.**
- **The combination of low flows and temperature during summer influence species abundances and assemblage composition.**
- **Diversity of hydraulic habitats including riffles, runs, habitat cover in 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 juvenile establishment after excystment.**

Summer is defined as the months of June, July, and August. Many biological processes that begin in spring, including fish spawning, juvenile rearing, and vegetation establishment, extend into summer months. As a result, there is still considerable support for high flow needs in the summer (Fig. 5.9). However, scientific studies also have demonstrated the importance of seasonal and low flows, with particular attention to low flow needs (Fig. 5.9). In general, flows decrease over summer, often leading to stressful conditions related to increasing temperatures and decreasing dissolved oxygen. Low flows also limit habitat availability and increase biological interactions. However, during optimal summer flow conditions, warm temperatures and high food availability make summer the growing season for many species.

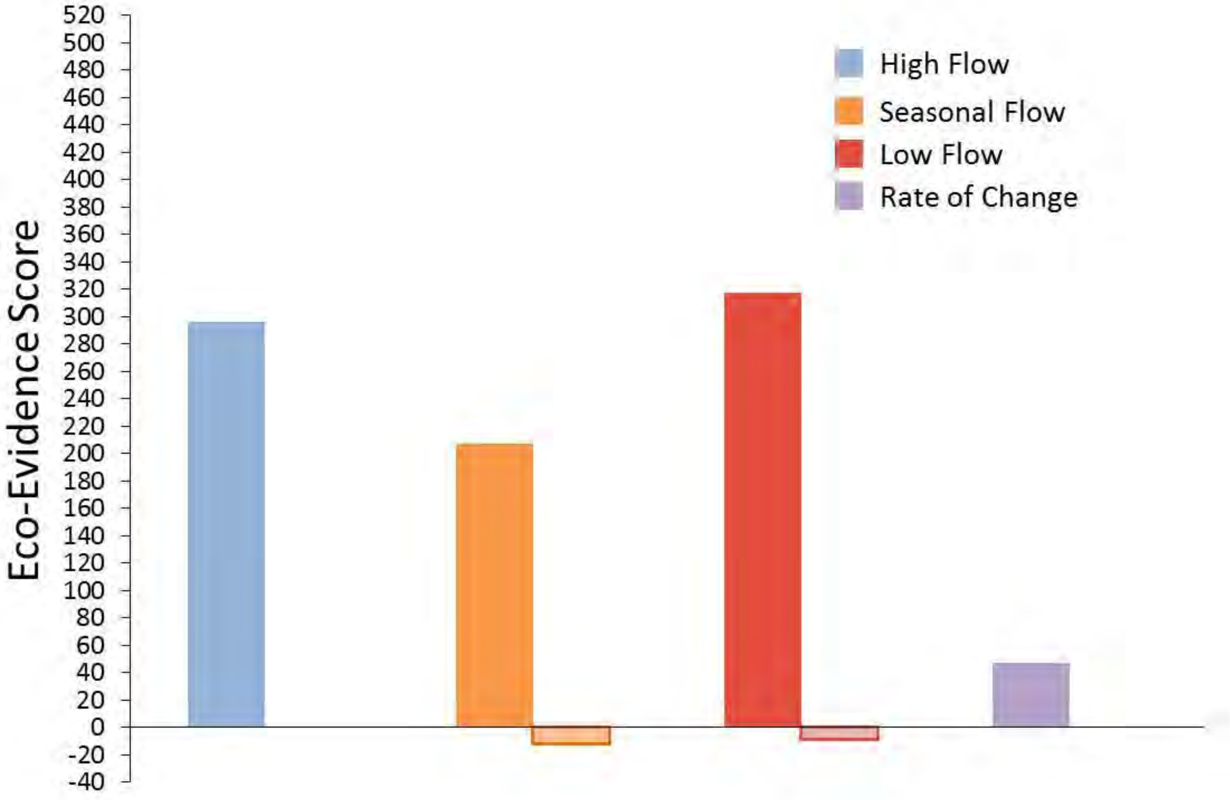

Figure 5.9. **Eco-evidence scores tallied across flow components for spring months.** Values include scores from papers representing flow needs from other seasons that extend into summer.

Decreasing seasonal flows during the spring and summer limit salmonid growth by increasing temperatures (GL-F17). Summer growth of juvenile Atlantic salmon was lowest during years with higher maximum temperature and lower discharge. Spring growth increases with temperature when flows are high, but decreases with temperature during low flow years (Davidson et al. 2010). Additionally, Alonso-Gonzalez et al. (2008) observed a negative correlation between age1 trout mean fork length and the **number of days flow was below Q_{75} discharge** during the late spring and early summer. Age 1 brook trout density and growth was negatively associated with summer temperatures in a model based on 51 years of modeled temperature and discharge data (Grossman et al. 2012). While Hakala and Hartman (2004) did not observe temperature exceeding critical ranges for brook trout when **summer monthly median flows were reduced to Q_{83} - Q_{95} flows (IHA analysis)(Fig. 5.10)**, they did observe reductions in overall brook trout population size and lowered body condition. Waco and Taylor

(2010) did not observe temperature changes > 1 C in response to modeled increasing withdrawals for high baseflow streams, but impacts might be greater in lower baseflow headwater streams. Survival of rainbow trout and Atlantic salmon have also been linked to high temperatures associated with lower flows. Trout survival was negatively related to time that water temperature exceeded 20 C and was more sensitive to higher water temperatures. Models predicted that additional discharge was needed to maintain suitable temperatures that occurred prior to urban development (Runge et al. 2008). Cowx et al. (1984) observed an Atlantic salmon year class failure during a summer with low flows that led to extreme temperatures (26 °C).

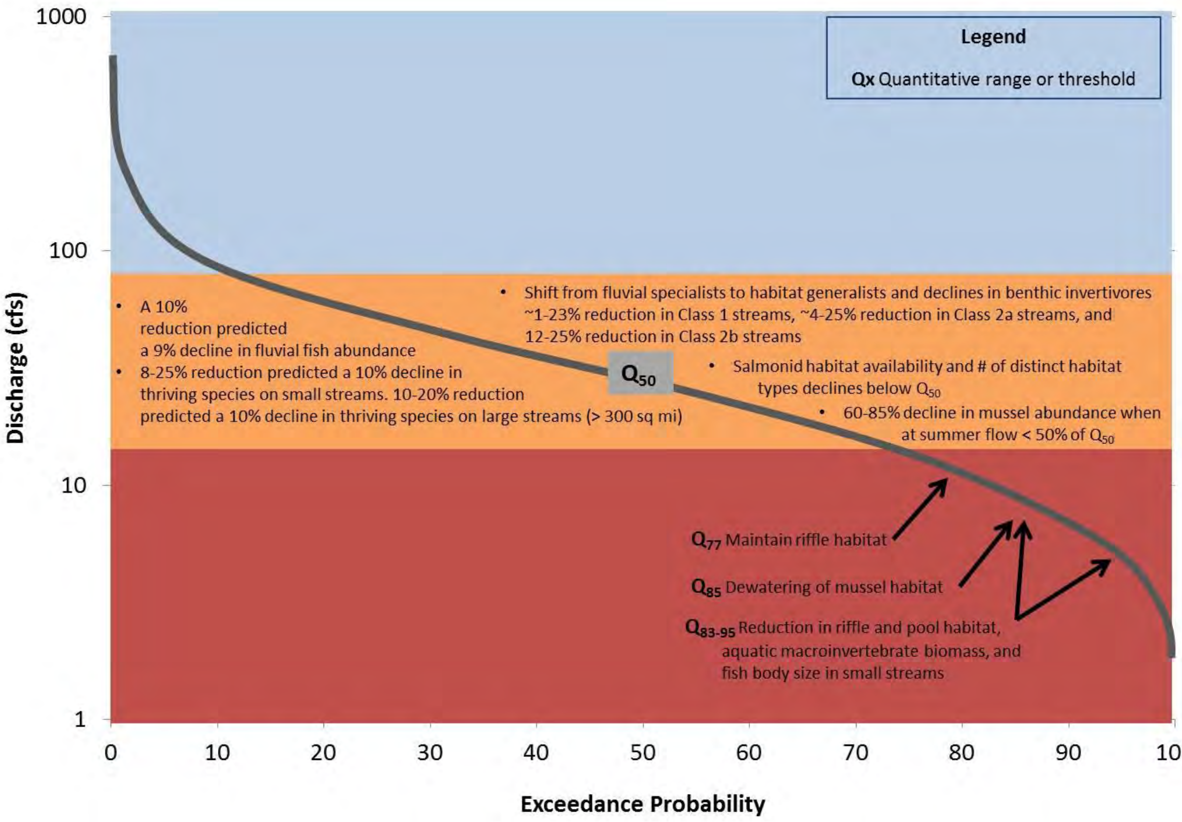

Figure 5.10. Observed ecological responses from the scientific literature in reference to points along the flow duration curve during the summer.

Increasing temperatures associated with **decreasing magnitude of low flows** during summer and fall may reduce fitness of thermally sensitive mussel species (O-M8). Decreased velocity, disconnected habitats, and increased water temperatures during low flow events resulted in higher mortality rates of thermally sensitive mussel species. Thermal stress associated with low water levels was one of the proximate causes of decline in mussel species density, abundance and diversity (Galbraith et al. 2010). Sublethal stress associated with higher temperatures during low flow periods may also impact thermally sensitive species. Muckets catabolize glycogen stores, increase respiration, and reduce nutrient processing when temperatures exceed 30 C, and stressful conditions that cause mussels to catabolyze glycogen can impact reproduction in later months (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. Declines in dissolved oxygen associated with **decreasing low flows** and increasing algal production can also impact mussel and fish populations (GL-H7). Diel dissolved oxygen swings increase with declining discharge, particularly in large rivers (Garvey et al. 2007, Valenti et al. 2011). Johnson et al. (2001) increased mussel mortality when velocity fell below 0.1 m/s and DO below 5 mg/L. Mussel mortality associated with thermal stress results in tissue decay and nutrient pulses that cause algal blooms and lower DO, resulting in further mortality (Galbraith et al. 2010). Loss of surface flows and groundwater connectivity resulted in significant declines in mussel richness and abundance (Golladay et al. 2004).

Changes in frequency or magnitude of high flows during the summer can cause shifts in fish assemblages (O-F20). Altered storm flow in summer and autumn are associated with decreased richness of endemic, cosmopolitan, and sensitive species as well as decreased abundance of lentic species (Roy et al. 2005). Grossman et al. (1998) identified significant clusters in fish assemblage structure associated with drought conditions. When frequency of high flow events was reduced during droughts, shifts in assemblages due to increased abundance of water column species occurred. Fish richness, diversity and index of biotic integrity (IBI) scores all decreased with increased magnitude and frequency of high flow events (Helms et al. 2009, Coleman et al. 2011).

Reduced magnitude of **seasonal** or **low flows** decreases flowing water habitat availability for riffle obligates and other flow-dependent species (GL-F21). A national study found that the likelihood of biological impairment doubled with increasing severity of diminished streamflows (Carlisle et al. 2011). Dominance within fish assemblages transitioned from fluvial specialists to mobile lentic species that preferred slow-moving currents, fine-grained substrates. (Roy et al. 2005) observed an increase in tolerant lentic species with increased duration of low flows during late summer and early autumn. Likewise, (Freeman and Marcinek 2006) observed shifts in fish assemblages from those characterized by fluvial specialists to habitat generalists when withdrawals exceeded **50% of the 7Q10 flow for streams.** Similarly, **benthic invertivores decline by an estimated 10% when withdrawals were 50% of 7Q10 in Connecticut streams (Kanno and Vokoun 2010)**. **These values represent a decrease in August medians ranging from 1-23% for Class 1 streams, 4-25% for Class 2a streams, and 12-25% for Class 2b streams, based on Great Lakes reference gages (StreamStats/IHA Analysis)(Fig. 5.10)**. Estimated species richness and fish density were greatest when seasonal flows approached the median and lowest at 7Q10 flows across all stream types. In a Massachusetts study, **10% to 20% reduction in August Q_{50} flow reduced fluvial fish relative abundance by 9% and 17% respectively (Armstrong et al. 2011)**. Loss of riffle habitat in response to **reductions in low flows below August Q_{77} flows, shifted fish assemblages from fluvial specialist species to habitat generalists (Fig. 5.10).** Riffle obligate habitat is optimal around summer median flows (Leonard and Orth 1988) and as a result, species that used fast-flowing habitats are one of the groups expected to experience the greatest negative effects of diminished summer flows (McCargo and Peterson 2010). Declining flows during the summer reduce riffle habitat for darters, madtoms, and juvenile catfishes. As a result, darter species may move to suboptimal habitats that result in declines in survival and recruitment (Schlosser and Toth 1984), or decrease habitat breadth and partitioning which induces more competition (Kessler et al. 1995, Stauffer et al. 1996). On the Allegheny River, **flows above Q_{80} maintained habitat partitioning among darter species (Stauffer et al. 1996, IHA analysis; Dephilip and Moberg 2013).** Stonecats are susceptible to habitat limitation during low flow periods (Brewer and Rabeni 2008).

Reduced magnitude and increased duration of low flows also impacts adult pool-dwelling fish species by limiting habitat complexity (GL-F23). Pool dwelling fish need cover that includes undercut banks and overhanging vegetation, large woody debris and aquatic vegetation. This habitat becomes less available when water recedes away from banks (Armstrong et al. 2001). Sunfish use complex habitat along shorelines. Model simulations demonstrated that river stage reductions of 0.3 m in a coastal stream reduced preferred habitat for spotted sunfish by 20 to 70% (Dutterer and Allen 2008). McCargo and Peterson (2010) observed that fish species with large adult body sizes, low tolerance, and deepwater habitat species were negatively affected by drought flows. For coldwater fish, declining year class strength and adult biomass in relation to wetted stream area and loss of pool habitat have been observed for brown trout (Elliott 2006, James et al. 2010). Additionally, **declining low flow magnitude** can limit access to thermal refugia for coldwater fish (Tables A3.1, A3.4, O-F25). Access to, and use of, areas of groundwater discharge are critical for thermoregulation, particularly for brook trout (Baird and Krueger 2003), and brook and brown trout will move considerable distances to access coldwater refugia (Petty et al. 2012).

Increased frequency and magnitude of high flow events can flush juvenile fish from rearing habitats and decrease year class strength of all target fish groups (GL-F20/GL-F2). Young of the year abundances have been negatively associated with magnitude of 1 hour maximum flows during the summer (Freeman et al. 2001). Smallmouth bass year class failure was observed during a year with summer flooding and sustained high flows (Wathen et al. 2011). Repeated flooding in a Great Lakes tributary influenced the longitudinal distribution and partitioning of habitat between glides and pools for juvenile Coho salmon, and there was a 50% decline in densities within glide habitats by the end of the study (Lonzarich et al. 2009). Despite the impacts of high flow events on juvenile fish habitat, long term effects are minimal when natural frequencies are maintained. Few detectable changes in composition of the fish community were observed 11 months after major flooding with pre and post flood densities of 11 species falling within the natural range of variation for an Appalachian stream (Dolloff et al. 1994).

A decline in seasonal median or low flows reduces habitat for all fish groups using riffle, run, or pool habitats (GL-F5). **On headwater and small streams, a 10% decline in thriving species abundance was predicted between 8 and 25% reduction in August Q_{50} along a temperature gradient from cold-transitional to warm. On large rivers (> 300 sq. mi.), a 10 to 20% reduction in August Q_{50} was predicted to impact thriving species by 10% (Zorn et al. 2008) (Fig. 5.10).** Armstrong et al. (2011) observed significant declines in fluvial fish abundance associated with percent depletion or increase of August median flow with abundance predicted to be 55% lower in depleted streams. Grossman et al. (2006) observed that sculpin YOY density increased with mean daily flow during drought years. **Salmonid habitat availability and number of distinct habitat types declines with summer flows below the Q_{50}** (Heggenes et al. 1996, Grossman et al. 2010)(Fig. 5.10). Higher summer flows likely increase size and suitability of fish habitat by maintaining riffle connectivity and pool depth. Grantham et al. (2012) observed positive relationships between juvenile steelhead survival in coastal streams and the magnitude of summer Q_{90} flows. Likewise, rainbow trout growth has been positively associated with water depth and distance downstream, suggesting that higher flows provide more depth and more habitat, reducing density dependent interactions (Harvey et al. 2005). Summer drought **flows less than monthly Q_{83} significantly reduced riffle and pool habitat for brook trout (Hakala and Hartman 2004). An experimental 90% reduction in summer flows resulted in a 62% reduction in brook trout abundance in run habitats compared to 20% in control sections (Kraft 1972).** Age 1 brown trout growth was positively associated with summer flow magnitude (Carline 2006), and studies on Atlantic salmon document summer drought conditions explaining variation in year class strength and returning female and egg densities (Cowx et al. 1984, Elliott et al. 1997).

Juvenile fish requirements for shallow-slow margin habitats continue in the summer. **Declining low flows** can limit growth and survival of juvenile fish by decreasing margin habitat availability (GL-F22). Young of the year fish abundance is correlated with availability of shallow habitat in the summer (Freeman et al. 2001). Persistence of this habitat is maintained by adequate flows. Freeman et al. (2001) found that suitable conditions could be predicted by median daily flows. Multiple studies have shown positive responses in abundances of juvenile fish and fluvial specialists to setting minimum flows below dams (Travnichek et al. 1995), based on comparisons between regulated and unregulated rivers (Bain and Finn 1988, Freeman et al.

2001), and on periods when regulation ceased and shallow slow habitats were more persistent (Bowen et al. 1998).

Declining low flows can also reduce access to, and abundance of, food resources for insectivores and omnivores (O-F28). Schlosser (1998) demonstrated that low flows increase effects of density on fish growth. When flows were experimentally reduced in stream mesocosms, a decline in capture of macroinvertebrate prey corresponded with a decline in growth of creek chub. Low flow conditions **(< Q83)** during a drought, restricted habitat availability and increased competition for limited food resources, resulting in individual fish (brook trout) having significantly lower body condition relative to non-drought periods (Hakala and Hartman 2004). Large decreases in riffle habitat and reduced flow velocities combined to limit food availability. Walters and Post (2011) observed that biomass of aquatic insects declined after experimentally diverting flows to an estimated **Q_{90}-Q_{95} flow**. The authors observed a corresponding decline in fish body length for large bodied (30-40%) and small bodied (10%) fishes (Walters and Post 2008). Low growth for brook trout may also be explained by habitat strategies that minimize risk and energy costs rather than maximizing forage gain during low flows. Sotiropoulos et al. (2006) demonstrated that brook trout habitat preferences did not change during low flow periods, and reduced prey drift rates in low flow environments resulted in lower gut fullness for brook trout. Similarly, microhabitat foraging quality for YOY Atlantic salmon is positively associated with growth, but declines with discharge (Nislow et al. 2004).

Increased magnitude and frequency of high flow events may increase velocity and shear stress and inhibit successful colonization of juvenile mussels (O-M6). Model estimates of survival, recruitment and population growth rates for 3 federally endangered species, indicate that mussel survival was negatively related to high flows during the summer (Peterson et al. 2011). High flows increase water column velocity and shear stress, inhibiting juvenile settlement after excystment from fish host and likely limit recruitment (Holland-Bartels 1990, Layzer and Madison 1995, Hardison and Layzer 2001). Using a particle distribution model, Morales et al. (2006) determined that shear stress ratios < 1 are necessary for juvenile colonization and timing of annual peak flow events likely limits the availability of colonization habitats. Increased magnitude and frequency of high flow events can eliminate flow refuges and reduce abundance of mussel populations (O-M13). Large flood events (> 50-100 year return intervals) can significantly decrease the abundance and distribution of unionids, particularly in reaches that lack flow refuges (Hastie et al. 2001, Fraley and Simmons 2006). Smaller flood events (3-30 year floods) can also redistribute bedload and unionids and individuals are 5 to 15 times more likely to occur within flow refuges than outside of them (Strayer 1999). Increased velocity and shear stress associated with **increasing high** and **seasonal flow magnitudes** can also reduce abundance, richness, or individual growth (O-M4). Increased frequency and magnitude of high flows and increased shear stress were factors that contributed to reduced diversity and abundance of mussels below a dam (Vaughn and Taylor 1999). Growth for some mussel species has been negatively correlated with increasing May and June medians and high pulse counts (number of events > Q25) (Rypel et al. 2009).

Rapid declines in stream flow can result in mussel stranding, particularly in margin habitats (O-M14). In addition to limiting factors of high flows (shear stress), persistent suitable habitat for mussels is also impacted by low flow velocities and restricted depth (Maloney et al. 2012). Mussels can move to avoid loss of habitat during declining low flow periods, but movements are slow and they are not adapted to follow receding water levels when low flows change quickly (Layzer and Madison 1995).

Maintaining suitable conditions for host fish-mussel interactions during reproduction periods is critical to recruitment processes. **Decreased magnitude of low flows** may reduce the potential for host fish to reach mussels and for successful glochidia transfer (O-M5). Maintenance of hydrology for host fish interactions may be most critical for highly mobile species (riffle associates) that are not obligated to a specific hydrologic condition (Layzer and Madison 1995). Layzer (2009) found that dam releases that increased flow during the spring and summer resulted much higher recruitment success of Lampsilinae and Ambleminae mussels. Presence of host fish and suitable conditions for juvenile survival and growth were factors necessary for success of *Actinonaias ligamentina* (Moles and Layzer 2008). Dispersal by host fish affects the abundance and distribution of mussels. Flows that ensure host fish-mussel interactions and connectivity between populations maintain metapopulation structure (Schwalb et al. 2011). Mussels associated with shallow riffle or margin habitats may be subject to increased predation or desiccation if **low flow magnitude declines** during baseflow months. Flows less than 50% of median conditions lead to losses of riffle habitat, disconnected pools, and drying of stream margins (Haag and Warren 2008). Mussel mortality increases with decreasing depth (Galbraith et al. 2010), and lower flows can result in mussel emersion and increased predation, particularly for smaller mussels (Johnson et al. 2001). Low flow on French Creek in the late summer of 1988 **(minimum flow = August Q_{90}, median flow = August Q_{85})** dewatered margin habitats and exposed mussels (Pers Comm, Charles Bier 2012, IHA Analysis; DePhilip and Moberg 2013). Decreasing low flow magnitudes during baseflow months may have greater impacts on mussel populations in creeks and small streams than on larger rivers. **Haag and Warren (2008) measured a 60-85% decline in mussel abundance when summer median monthly flows declined by 50% (Fig 5.10).** Loss of species occurred in smaller streams (4-105 sq. mi.) but larger river habitats maintained connectivity and flow refuges, and mussel assemblages survived (Haag and Warren 2008). Johnson et al. (2001) also observed higher habitat impacts (loss of connectivity, temperature and DO stress) in small streams verses larger tributaries. Occupancy modeling results suggest that mussel species were on average 4 times less likely to be present following a severe drought, but negative effects declined rapidly with increasing stream size (Shea et al. 2013).

Seasonal and low flows can also influence riparian, submerged aquatic and emergent vegetation. **Increases in low flow magnitude** may increase inundation and inhibit colonization of riparian species (O-F12). Plant communities organize along hydrologic gradients with *Salix* assemblages occurring on frequently inundated surfaces (< 2.2 year recurrence interval) and *Betula* and *Alnus* on sites with longer recurrence intervals (2.2-4.6 years) (Friedman et al. 2006). **Declines in low flow magnitude** during the growing season may also reduce growth and survival of submerged and emergent aquatic vegetation (GL-V9). Plant bases of a submerged aquatic plant that grows in riffles and runs were exposed during a low flow year where August flows were below **August Q87 flows** (Munch 1993, IHA anlaysis). Additionally, seasonal flow variation can be important in maintaining submerged and emergent aquatic vegetation. A **reduction in seasonal flow variation** during the summer can replace submerged aquatic vegetation and emergent vegetation with cattails (*Typha*) which degrades optimal spawning habitat for northern pike (GL-V7). Major hydrologic changes due to regulation of inter-annual variability and reduction in peak flows and periodic low flows have led to a dampening of water cycles and a corresponding encroachment of invasive cattails (Farrell et al. 2010).

Section 6: Flow recommendations for Great Lakes streams

Previous sections of this report have aimed to provide the background for water management recommendations that consider the spectrum of natural variability in flows necessary to support healthy riverine ecosystems.

In section 3, we identified key components of the natural flow regimes of different classes of streams, grouped by size of watershed. The five flow components identified in section 3 – large and small floods, high flow pulses, seasonal flows, and low flows – can readily be quantified, and can provide a statistical framework for describing the variability of flows and the impact of various kinds and degrees of flow alteration. Large floods, for example, are defined as those flows that occur only once in 20 years; seasonal flows span the middle range of flows between Q_{10} and Q_{75}, and so on.

Section 4 describes the process followed by the Technical Advisory Team to select six groups of fish species and three groups of mussels whose sensitivities to flow include the full range of flow components in different seasons of the year. Because these fish and mussels are flow-sensitive, they were selected to represent the flow requirements of all aquatic biota and to serve as the focal points for examining the ecosystem impacts of different degrees of flow alteration.

Having selected target species for analysis, and having assembled the information in the scientific literature about the interactions between water flows and the life history traits of these species, we turned in section 5 to conceptual models, or hypotheses, of how these species will respond to changes in the frequency, timing, duration, and magnitude of flow components. By assessing the degree of support in the scientific literature for the 54 hypotheses proposed by the advisory team, and for the 11 flow needs into which the hypotheses were aggregated, section 5 provides a framework for water management decisions that preserve aquatic ecosystems while providing water for human needs.

6.1 Flow recommendations

Building on previous sections of this report, we now present the flow recommendations for four different classes of streams, defined by watershed size. We highlight scientific studies from section 5 that are particularly useful for supporting recommendations for a given size class. These recommendations are guided by five principles, in common with principles previously framed by DePhilip and Moberg 2010, 2013:

1. **Flow recommendations address high, seasonal, and low flows for each season**. The flow needs summarized in section 5 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, increased frequency or magnitude of high flow pulses can also have negative effects on many species during the summer. Conversely, spring is a wet season, but low flow conditions during spring can limit access among habitats during fish spawning migration.

2. **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, seasonal flow, and low flow-related statistics. Individual recommendations will likely be applicable to a variety of water uses, 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 release rules on regulated rivers, or through stormwater management measures in watersheds where increased frequency and magnitude of high flow events could negatively affect instream habitat.
3. **Recommendations are expressed in terms of (1) acceptable limits of change from estimated natural flow statistics to capture naturally-occurring variability and in terms of (2) no-change thresholds to allow streams to vary naturally during critical low flow periods.** We use the flow statistics described in Section 3.2 as a starting point for making recommendations. Recommendations related to flow magnitude are expressed in terms of acceptable deviation (i.e., percent or absolute change to distribution) from natural flow statistics (i.e. reference conditions) for a particular site rather than prescribing a specific volumetric flow rate (i.e., cubic feet per second or cfs/square mile). The exception is low flow recommendations which take the form of passby (no alterations below a particular Q value) recommendations. Because our flow recommendations are expressed in terms of acceptable variation from natural flow, we are able to apply the same recommendations to multiple streams within a stream class. In other words, although the *relative* (percent) change to a particular statistic may be similar between two streams, the absolute change in terms of volumetric flow rate may be different.
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., lower percent change):

   - To Class 1 streams compared to Class 3 rivers (e.g, no change to monthly Q_{50} in headwaters, <10% change in small rivers, and <15% change in medium tributaries, and <20% change in large rivers).
   - In dry seasons compared to wet seasons (e.g., no change to monthly Q_{50} in summer and fall vs. monthly Q_{70} in winter and spring – for Class 1 streams).

- For low flow conditions compared to median or high flow conditions. (e.g., <20% change to monthly median and no change to monthly low flow magnitude for large rivers).

5. **Recommendations are designed to protect the most sensitive taxa within a season.** In most cases, there are many species and natural communities that benefit from a particular flow condition. In developing these recommendations, we used information on the most sensitive taxa to establish the recommendation. For example, spring is a critical period for fish spawning and because of the importance of seasonal flows in maintaining access to and connectivity among spawning habitats, fish are more likely than aquatic insects to be sensitive to changes in streamflow.

6.1.1 Class 1 Streams: Headwaters and Creeks (< 50 sq miles)

Headwaters and creeks represent a continuum from small ephemeral or intermittent streams to groundwater-fed cool-water streams. This size class represents 90% of the total mapped stream miles within the study area. Hydrologic processes in headwater drainages control the storage and movement of water throughout landscapes. These important hydrological functions coupled with biogeochemical processes that control solute transport in watersheds play a significant role in downstream water quantity and quality (Alexander et al. 2007). Headwater streams are generally considered less biologically diverse than larger streams, but cumulatively support a disproportionate amount of freshwater biodiversity and contribute substantially to regional biodiversity pools (Meyer et al. 2007, Finn et al. 2011). Headwater streams and creeks may have poorly defined stream channels, and the stream network can be highly dynamic, expanding and contracting depending on season and precipitation. Relatively few headwater streams have stream gages; in the Great Lakes basin of New York and Pennsylvania, there are only 8 index stream gages on headwaters and creeks less than 50 square miles. Consequently, caution dictates a conservative approach to water management in streams of this class. Flow recommendations for headwaters and creeks are presented in Table 6.1.

Table 6.1. Ecosystem Flow recommendations for Class 1 streams (headwaters and creeks, < 50 square miles)

	Summer	Fall	Winter	Spring
High flows *Annual / Interannual (>= bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, frequency and duration of channel forming (1 to 2-year) events			
High flow pulses (< bankfull)	**All seasons** • < 10% change to the magnitude of high flow pulses (monthly Q10) • No change to the frequency and duration of high flow pulses (monthly Q10)			

Seasonal flows	**All seasons** • < 10% change to upper seasonal flow range (between monthly Q_{10} and Q_{50})	
	Summer and Fall (July – Oct) • No change to monthly Q_{50} • No change to lower seasonal flow range below monthly Q_{50}	**Winter and Spring (Nov – Jun)** • < 10% change to Q_{50} • < 10% change to lower seasonal flow range (between monthly Q_{50} and monthly Q_{70})
Low flows	**Summer and Fall (July – Oct)** • No change to low flow range (between monthly Q50 to Q99)	**Winter and Spring (Nov – Jun)** • No change to low flow range (between monthly Q70 to Q99)

Recommendations for headwater streams are based on analysis of hydrology and sensitivity to flow alteration (Section 3); on literature that emphasizes a wide range of supported flow needs (Section 5); on recommendations provided by the technical working group; and on scientific studies that quantify responses to flow alteration or experimental manipulation. 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 portions of the flow volume and measure the biological response.

The **high flow recommendations** (both above and below bankfull flow) are intended to maintain flows that balance the role of large woody debris recruitment and channel morphology maintenance with short term impacts to stream communities or populations. Roghair et al. (2002) provides evidence for the positive role that floods play in manipulating habitat in headwater systems, but high flow events can also have negative impacts on headwater stream populations. For example, large winter floods (5 to 25 year recurrence intervals) can scour redds and significantly reduce age 0 brook trout densities (Carline and McCullough 2003, IHA analysis[5]) and floods (> Q_1) during the early spring larval emergence periods can impact brook and brown trout recruitment (Warren et al. 2009, IHA analysis). While there are few studies that document the threshold of flow alteration that would impair or eliminate habitat forming processes or cause long term impacts to headwater stream communities, there is clear evidence that increases in magnitude and frequency of high flow events in small streams (due to changes in landscape condition and stream channelization) can change fish assemblage structure (Roy et al. 2005). Recognizing that these are natural disturbance events that provide important energy transport and habitat maintenance functions

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[5] The senior author (J. Taylor) conducted follow-up analysis, using a nearby stream gage and the Indicators of Hydrologic Alteration (IHA) software, to convert the stream-flow values of a cited scientific study to the “Q” values that are used in this report to delineate different points in the hydrograph.

with short term impacts on fish populations (Smith and Atkinson 1999, Roghair et al. 2002) , **the technical working group recommended maintaining the magnitude and frequency and duration of high flow events (bankfull events and higher) within their expected naturally-occurring range** (Table 6.1). Additionally, withdrawals in Class 1 streams can remove enough flow volume to reduce the magnitude of high flows (i.e., monthly Q_{10}) during some seasons (DePhilip and Moberg 2010). Recognizing that any size withdrawal will necessarily result in minor changes in Q_{10} flows we recommend that withdrawals **avoid decreasing the magnitude of monthly Q_{10} flows beyond 10% of their natural range.**

Seasonal flow recommendations (Q_{10} to Q_{75}) are intended to maintain habitat and adequate temperatures within headwater streams (< 50 square miles), particularly for coldwater fish targets. Several studies have documented impacts to headwater fish populations or assemblages with declining seasonal flows, particularly in the summer. Loss of fish species, declines in fluvial fish abundance with assemblage shifts to habitat generalists, and declines in benthic invertivores are expected when August median flow is reduced by 8 to 25% for streams spanning a size gradient from headwaters to small rivers (Freeman and Marcinek 2006, Zorn et al. 2008, Kanno and Vokoun 2010, Armstrong et al. 2011). Salmonid habitat availability and number of distinct habitat types decline below Q_{50} flows (Gosselin et al. 2010, Gosselin et al. 2012).

Additionally, maintaining seasonal surface and groundwater flows is important for providing access to spawning habitats for migratory and resident salmonids in small streams. A regional IFIM study from Pennsylvania predicted a 10% spawning habitat loss for withdrawals of 11 to 14% of the November median flow (Denslinger et al. 1998, DePhilip and Moberg 2013). Given the low discharges and uncertainty across regional reference gages for summer median flows (Fig. 3.2) and documented relationships between relatively small flow alterations and changes in stream habitat and fish assemblages, the technical working group **recommended no change to summer and early fall Q_{50} flows and below and no more than 10% change to the seasonal flow range between the Q_{10} and Q_{50}** (Table 6.1). The Technical Advisory Team recommended extending the same level of protection across all seasons for headwater streams, primarily to protect developing salmonid eggs and larvae from temperature and potential anchor ice impacts during winter. However, the few published studies on winter flow conditions and salmonid recruitment point to impacts related to extreme winter conditions occurring at much lower flows (Gibson and Myers 1988, Cunjak et al. 1998, Cunjak and Therrien 1998). Alonso-Gonzalez et al. (2008) observed a negative relationship between age-0 densities and the number of days below the Q_{75} during the winter incubation period for a brown trout population. National brook trout habitat suitability indices recommend that stream flow during the brook trout egg and larval development period be greater than 25% of the average daily flow (ADF) to maintain suitable incubation conditions. This translates to Q_{75} to Q_{90} flows for

Class 1 stream reference gages within the Great Lakes project area (Raleigh 1982, IHA analysis). Given: 1) higher Q_{50} flows across the majority of streams in winter and spring (Fig. 3.2); 2) documented or predicted impacts at winter flows below Q_{75}, and; 3) recognizing uncertainty associated with literature based values, we recommend **no change to winter and spring Q_{70} flows, and no more than 10% change to the Q_{50} and the seasonal flow range above and below the Q_{50} (Q_{10}–Q_{50}, Q_{50}-Q_{70})** (Table 6.1).

The goal of our **low flow recommendations** is not to prevent low flow periods, but to buffer aquatic communities against additional stressors during naturally stressful low flow conditions. To be consistent with seasonal flow recommendations, we recommend **no change to the monthly low flow range for all months, including the area under the duration curve between the Q_{50} and Q_{99} (July-Oct) and Q_{70} and Q_{99} (Nov-Jun)**. Note that all index gages for headwater streams had Q_{75} flows below 10 cfs (Fig. 3.2).

Multiple studies point to the need to protect low flows in headwater systems. Experimental diversions from an estimated Q_{75}-Q_{95} flow reduced aquatic insect density, species composition, and available habitat in headwater streams, and the authors observed a corresponding decline in fish body length for large bodied (30-40%) and small bodied (10%) fishes (Walters and Post 2008, Walters and Post 2011). Responses to natural variation in low flows have also been observed for small coldwater headwater streams. Low flow conditions (< Q83) during a drought restricted habitat availability and increased competition for limited food resources, resulting in individual fish (brook trout) having significantly lower body condition relative to non-drought periods (Hakala and Hartman 2004).

6.1.2 Class 2a Streams: Small Rivers (50-200 sq miles)

Compared to headwaters and creeks, there are more studies on small rivers that quantify some type of biological response to change in streamflow. These studies include multiple taxa groups and a variety of biological and habitat responses, including assemblage shifts, habitat loss, loss of assimilative capacity, and desiccation. This is likely because most stream sampling occurs in small (wadeable) streams and these metrics are typically used in such assessments. Table 6.2 contains the flow recommendations for small rivers.

High flow events in small rivers perform many ecological functions including habitat forming processes such as channel maintenance and large woody debris recruitment, maintaining disturbance regimes (ice scour) that sustain dynamic floodplain vegetation communities, and serving as cues for riffle associate reproductive cycles. As in headwater systems, high flows can also impact recruitment, particularly in late spring after many fish have spawned. Impacts to nest builder success have been observed in the late spring after flood events > Q_{12}, or when June median flows were 25 to 40% above period of record median (Peterson and Kwak 1999, Smith et al. 2005). Additionally, increased frequency of high flow events can result in shifts in the fish community (Roy et al. 2005). As described under the headwaters section, **we recommend maintaining the magnitude, frequency, and duration of high flow events based on their expected naturally-occurring range for small rivers and not decreasing the magnitude of Q_{10} flows beyond 10% of their natural range.**

Table 6.2. Ecosystem Flow recommendations for Class 2a streams (small rivers, 50-200 square miles)

	Summer	Fall	Winter	Spring
High flows *Annual / Interannual (>= bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, frequency and duration of channel forming (1 to 2-year) events			
High flow pulses (< bankfull)	**All seasons** • < 10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})			
Seasonal flows	**All seasons** • < 10% change to upper seasonal flow range (between the monthly Q_{10} and Q_{50}) • < 10% change to monthly Q_{50}			
	Summer and Fall (July – Oct) • < 10% change to lower seasonal flow range (between monthly Q_{50} and Q_{70})		**Winter and Spring (Nov – Jun)** • < 10% change to seasonal flow range between monthly Q_{50} and monthly Q_{80})	
Low flows	**Summer and Fall (July-Oct)** • No change to low flow range (between monthly Q_{70} and Q_{99})		**Winter and Spring (Nov-Jun)** • No change to low flow range (between monthly Q_{80} and Q_{99})	

Several studies have documented impacts to small river fish populations or assemblages with declining **seasonal flows**, particularly in the summer. As above, loss of fish species, declines in fluvial fish abundance with assemblage shifts to habitat generalists, and declines in benthic invertivores are expected when August median flow is reduced by 8 to 25% in streams spanning a size gradient from headwaters to small rivers (Freeman and Marcinek 2006, Zorn et al. 2008, Kanno and Vokoun 2010, Armstrong et al. 2011).

Higher seasonal flows are also important in the fall, as they stimulate movement and maintain access to upstream spawning habitats for migratory salmonids (Jonsson et al. 1991, 2002, 2007). Spring young of year (YOY) catches are predicted to be twice as high during years when October median flows are above the POR median compared to years when flow is below the POR median on the Salmon river (Bishop et al. 2008, IHA analysis). Several studies document positive relationships between recruitment of riffle associates in the spring and seasonal flows; follow up IHA analysis on Bowman 1970[6], indicates that discharge during a low flow year (-64% of April median) reduced available spawning habitat by 50% compared to a near-average year (-11% of April median). For all seasons we recommend limiting change to the Q_{50} **and upper seasonal flow range (Q_{10}-Q_{50}) to less than 10%; we recommend less than 10% change to the lower seasonal flow range (Q_{50}-Q_{70} for July-Oct and Q_{50}-Q_{80} for Nov-June).**

Our recommendation of no change to summer or fall Q_{70} and below is based on Armstrong et al. (2001), who observed loss of riffle habitats and a shift from fluvial specialists to habitat generalists at August Q_{77} flows across several sites within a small river in Massachusetts.

Low flow recommendations for summer are supported by loss of riffle habitat at Q_{77} flows (Armstrong et al. 2001)), dewatered margin habitats and exposed mussels during a low flow summer (August Q_{50} = Q_{85}) (Pers Comm, Charles Bier 2012, IHA Analysis, DePhilip and Moberg 2013), and large mussel declines when monthly median flows declined by 50% (Haag and Warren 2008). Consistent with seasonal flows recommendations **we recommend no change in the summer and fall Q_{70} and below**. Q_{75} values are higher for small rivers in winter and spring than summer and fall (Section 3). Therefore, **we recommend a less than 10% change to the winter and spring low flow range down to the Q_{80}, and no change to the Q_{80} and below.**

6.1.3 Class 2b Streams: Major Tributaries (200-1000 sq miles)

Flows in major tributaries and large rivers are primarily influenced by precipitation, large infrastructure, cumulative impacts of water use and discharges, and by land cover changes that affect basin water budgets. Large reservoirs potentially affect magnitude and frequency of high flow events and may also either augment or reduce flows during dry seasons. While larger systems tend to incur more impacts, a few studies that have investigated drought conditions on fish and mussel communities report reduced impacts with increasing size (Johnson et al. 2001, Haag and Warren 2008, McCargo and Peterson 2010, Shea et al. 2013), suggesting that major tributaries and large rivers should be more resistant than smaller streams to minor changes in natural flow conditions. Table 6.3 provides flow recommendations for major tributaries.

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[6] Like the previous IHA analysis, J. Taylor used a nearby gage and the IHA software to calculate the Q_{50} for the period of record at the site used in Bowman's study.

Table 6.3. **Ecosystem Flow recommendations for Class 2b streams** (major tributaries, 200-1000 square miles)

	Summer	Fall	Winter	Spring
High flows *Annual / Interannual (>= bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, frequency and duration of channel forming (1 to 2-year) events			
High flow pulses (< bankfull)	**All seasons** • < 10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})			
Seasonal flows	**All seasons** • < 15% change to upper seasonal flow range (between monthly Q_{10} and Q_{50}) • < 15% change to median (monthly Q_{50})			
	Summer and Fall (July – Oct) • < 15% change to lower seasonal flow range (between monthly Q_{50} and Q_{70})		**Winter and Spring (Nov – Jun)** • < 15% change to lower seasonal flow range (between monthly Q_{50} and monthly Q_{80})	
Low flows	**Summer and Fall (July-Oct)** • No change to low flow range (between monthly Q_{70} and Q_{99})		**Winter and Spring (Nov-June)** • No change to low flow range (between monthly Q_{80} and Q_{99})	

In addition to many of the ecological functions previously mentioned for smaller systems, **high flow events** become particularly important in medium tributary systems where wider floodplains support off channel habitats that are important spawning, rearing and feeding habitats for riverine fishes. Maintaining water levels in early spring high enough to flood shallow emergent marshes for 4 weeks allows for the spawning, larval development, and fry swim-up periods critical to northern pike recruitment success in tributary rivers (Mingelbier et al. 2008, Farrel 2001, Cooper et al. 2008, Farrel et al 2006, Smith et al 2007). High flow events also maintain connectivity between river and oxbow lake habitats which can positively affect fish production and species diversity (Halyk and Balon 1983, Jurajda et al. 2004, Martin and Paller 2008, Górski et al. 2010, Janac et al. 2010, Miyazono et al. 2010, Gorski et al. 2011). To preserve these important functions, **we recommend maintaining the magnitude, frequency, and duration of high flow events based on their expected naturally-occurring range for medium tributary rivers. We also recommend limiting decreases in the magnitude of Q_{10} flows to 10% or less of their natural range.**

Recommendations for **seasonal flows** generated for the original Class 2 (50-1000 sq mi) during the flow recommendations workshop ranged from < 20% change to the monthly Q50 for spring, to < 5-15% change in summer to no change in fall and winter (Appendix Table x). This wide range of allowable alteration across seasons was generated primarily from concern for potential impacts to streams on the smaller end of the gradient. Information behind recommendations for smaller sized streams and medium tributaries address these concerns by: 1) assigning recommendations for seasonal flows based on subclasses (50-200 sq mi, 200-1000 sq mi) for Class 2 streams, 2) supporting information that identifies winter impacts associated with declining flows occurring at lower flow ranges (i.e. **< Q_{75}**) in smaller streams (Gibson and Myers 1988, Cunjak et al. 1998, Cunjak and Therrien 1998, Alonso-Gonzalez et al. 2008), and 3) the general pattern of decreased flows impacting aquatic assemblages in smaller streams in warmer months reported by (McCargo and Peterson 2010, Shea et al. 2013). Following this rationale, **we recommend limiting changes in Q_{50} and upper (Q_{10}-Q_{50}) and lower (Q_{50}-Q_{80}) winter and spring seasonal ranges to less than 15% for major tributaries**. **During summer and early fall (July-Oct) we also recommend less than 15% change to the lower seasonal range (Q_{50}-Q_{70}),** due to the fact that a significant portion of streams in this size range can still experience low flow discharges below 50 cfs during drier months (Fig. 3.2).

Low flow recommendations for summer are carried over from Class 2a streams and are intended to prevent increased duration or frequency of low flow events that can result in loss of riffle habitat at Q_{77} flows (Armstrong et al. 2001), dewatering of margin habitats that can expose mussels (August Q_{50} = Q_{85}) (Pers Comm, Charles Bier 2012, IHA Analysis[7], DePhilip and Moberg 2013) in smaller size classes. Due to the uncertainty associated with lack of published information on low flow impacts in larger streams that still support shallow water habitats **we recommend carrying low flow recommendations from Class 2a over to Class 2b streams (Table 6.2-6.3)**. Compared to smaller habitat types, combining seasonal recommendations for major tributaries with low flow protections used for small rivers, allows for flexibility for water use and management while protecting against significant habitat loss during low flow periods.

6.1.4 Class 3 Streams: Large Rivers (> 1000 sq miles)

There are no large river systems within the Great Lakes basin of New York and Pennsylvania that retain a natural hydrologic regime and very few USGS gages throughout the state of New York measure flows that remain relatively un-altered. Large rivers receive the cumulative impacts of large infrastructure, water use and discharges, and land cover changes that affect

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[7] The IHA analysis was performed by DePhilip and Moberg, based on information from Charles Bier.

basin-wide water budgets. The potential for magnitude and frequency of high flow events to be affected by large reservoirs is also great in large river systems where flood control is important for protecting people and commerce. Despite this, maintaining or restoring as much hydrologic function in larger river systems is important for maintaining functional networks of stream ecosystems by providing connectivity and dispersal routes for all taxa including spawning migrations of riffle associate and anadromous fish, as well as providing habitat for large river dependent taxa. We present flow recommendations for large rivers in table 6.4.

Table 6.4. **Ecosystem Flow recommendations for Class 3 streams** (large rivers, > 1000 square miles).

	Summer	Fall	Winter	Spring
High flows *Annual / Interannual* *(>= bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, frequency and duration of channel forming (1 to 2-year) events			
High flow pulses *(< bankfull)*	**All seasons** • < 10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})			
Seasonal flows	**All seasons** • < 20% change to upper seasonal flow range (between monthly Q_{10} and Q_{50}) • < 20% change to monthly median (Q_{50}) • < 20% change to lower seasonal flow range (between monthly Q_{50} and Q_{75})			
Low flows	**Summer and Fall (July-Oct)** • < 20% change to low flow range (between monthly Q_{75} and Q_{85}) • No change to lowest flow range (between monthly Q_{85} and Q_{99})		**Winter and Spring (Nov-June)** • < 20% change to low flow range (between monthly Q_{75} and Q_{90}) • No change to lowest flow range (between monthly Q_{90} and Q_{99})	

We recommend maintaining the magnitude, frequency and duration of high flow events to the extent possible. Restoring some hydrologic function associated with managed high flow events is feasible in large river systems and has been demonstrated in other regions (Konrad et al. 2012). However, restoration of components of high flow regimes will likely have to be addressed on a river by river basis.

There is considerably more water available in large river systems throughout the year, and the impacts of reduced flows are expected to decline with increasing stream size (Johnson et al. 2001, Haag and Warren 2008, McCargo and Peterson 2010, Shea et al. 2013). While adverse impacts to aquatic biota of reduced flows can still occur, these will likely occur at higher levels of alteration. For example, in a large temperate river in Georgia, de-watering of redhorse nests occurred when flow fluctuations decreased discharge by 25% of the POR May median (Grabowski and Isely 2007, IHA analysis). Additionally, fish movement (with a high proportion of juveniles) between river and oxbow habitats was positively correlated with discharge on a large river in Illinois during intermediate flood periods. A minimum discharge necessary for connectivity and movement of juvenile fishes corresponded to Q_{90}, Q_{83}, Q_{62}, Q_{32} and Q_{15} flows for April, May, June, July, and August respectively (Kwak 1988, IHA analysis).

Analysis of reference gage data for a minimally altered Class 3 stream in southern NY shows that a 20% reduction in monthly Q_{50} corresponds to a ~ Q_{62} stream flows during April-June and should maintain natural frequency and duration of connectivity between the river channel and unobstructed floodplain habitats during spring. **We recommend limiting change to the Q_{50} and the seasonal range above and below the Q_{50} to 20 %**.

Low flow recommendations follow a pattern of less conservative protection on large streams than on smaller streams. **During winter and spring, we recommend less than 20% change to the low flow range down to Q_{90}, and no change below Q_{90}**. Because water quality impacts associated with assimilative capacity of waste discharges increases with declining flow and increasing temperature (Garvey et al. 2007, Valenti et al. 2011), **during summer and fall, we recommend less than 20% change to the low flow range down to Q_{85},and no change below Q_{85}**.

Flow recommendations for large rivers are designed to allow more water to be taken for out-of-river purposes, (providing withdrawals do not conflict with other goals, including designated uses, water quality and temperature) and to minimize impacts on naturally-occurring hydrologic variation. However, large river systems receive the cumulative effects of multiple factors influencing both flow and water quality, more so than in smaller sized streams. As a result, it is may be necessary to make reach-specific flow recommendations along large rivers to account for existing impairments and water quality or habitat impacts, additional objectives or uses, and interactions among these factors. The recommendations presented here represent a starting point that can be used for developing reach-specific recommendations or goals for flow restoration in altered large river systems where feasible.

6.2 Test Application of Flow Recommendations

Implementing flow recommendations described in section 6.1 will require developing policy that incorporates full consideration of other uses and complies with state and federal law. To help inform any future policy[8], which will need to take into account a range of factors beyond the scope of this report, we provide an example of a potential withdrawal policy to act as a starting point for discussion. This example policy would meet the recommendations presented in section 6.1 by establishing passby flow limits to protect the low flow component and withdrawal rate limits (withdrawal caps) to protect the seasonal flow ranges of natural hydrographs (Table 6.5).

A **passby flow** is the quantity of streamflow that must be allowed to pass downstream of a water withdrawal point to support downstream usages. We define passby flows in this example withdrawal policy to meet recommendations of no change to low flow ranges, quantified as monthly flow duration statistics[9] calculated from a long period of record for each stream type (Tables 6.1-6.4). Passby flows are designed to protect streams during low flow periods and are implemented by halting withdrawals when streamflow falls below the prescribed flow value (i.e. passby limit) (Fig. 6.1A). Passby flows can play a vital role in managing water during low flow periods, but are not sufficient to address the range of flow variability above these limits.

Withdrawal caps (or limits) are designed primarily to protect the seasonal flow component of natural hydrographs and represent the maximum withdrawal allowable on a stream based on a percentage of a particular flow duration statistic (for example 10% of monthly Q_{50}; Fig 6.1A). Values presented in table 6.5 represent limits that are easy to compute from streamflow data over the period of record, prevent any major deviations from long term Q_{50} patterns and meet all other seasonal flow range recommendations (Fig. 6.1).

Table 6.5. A possible combination of monthly withdrawal limits (WD) and monthly passby flows (PB) for Great Lakes streams in NY and PA. During July-October for Class 1 (headwaters < 50 square miles) streams, the potential withdrawal limit above the passby flow is 10% of the monthly Q50,; and this withdrawal limit is combined with a passby flow that would halt further withdrawals once the monthly Q50 level has been reached.

Stream Type	Policy Tool	Summer/Fall (July-October)	Winter/Spring (November-June)
Class 1 Streams: Headwaters and Creeks	WD PB	10% of Q_{50} Q_{50}	10% of Q_{50} Q_{70}
Class 2a Streams: Small Rivers	WD PB	10% of Q_{75} Q_{70}	10% of Q_{75} Q_{80}
Class 2b Streams: Major Tributaries	WD PB	15% of Q_{75} Q_{70}	15% of Q_{75} Q_{80}
Class 3 Streams: Large Rivers	WD PB	20% of Q_{75} Q_{85}	20% of Q_{75} Q_{90}

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[8] Given water allocation policy is primarily determined at the state level, it is anticipated that any implementation will be at the state scale through regulation and/or guidance documents that may incorporate regionally varying standards.

[9] Flow duration statistics relate stream flow to the percent probability that the monthly flow over a long period of record (> 20 years) will be exceeded (example: Q_{70} flow is exceeded 70 % of the time.

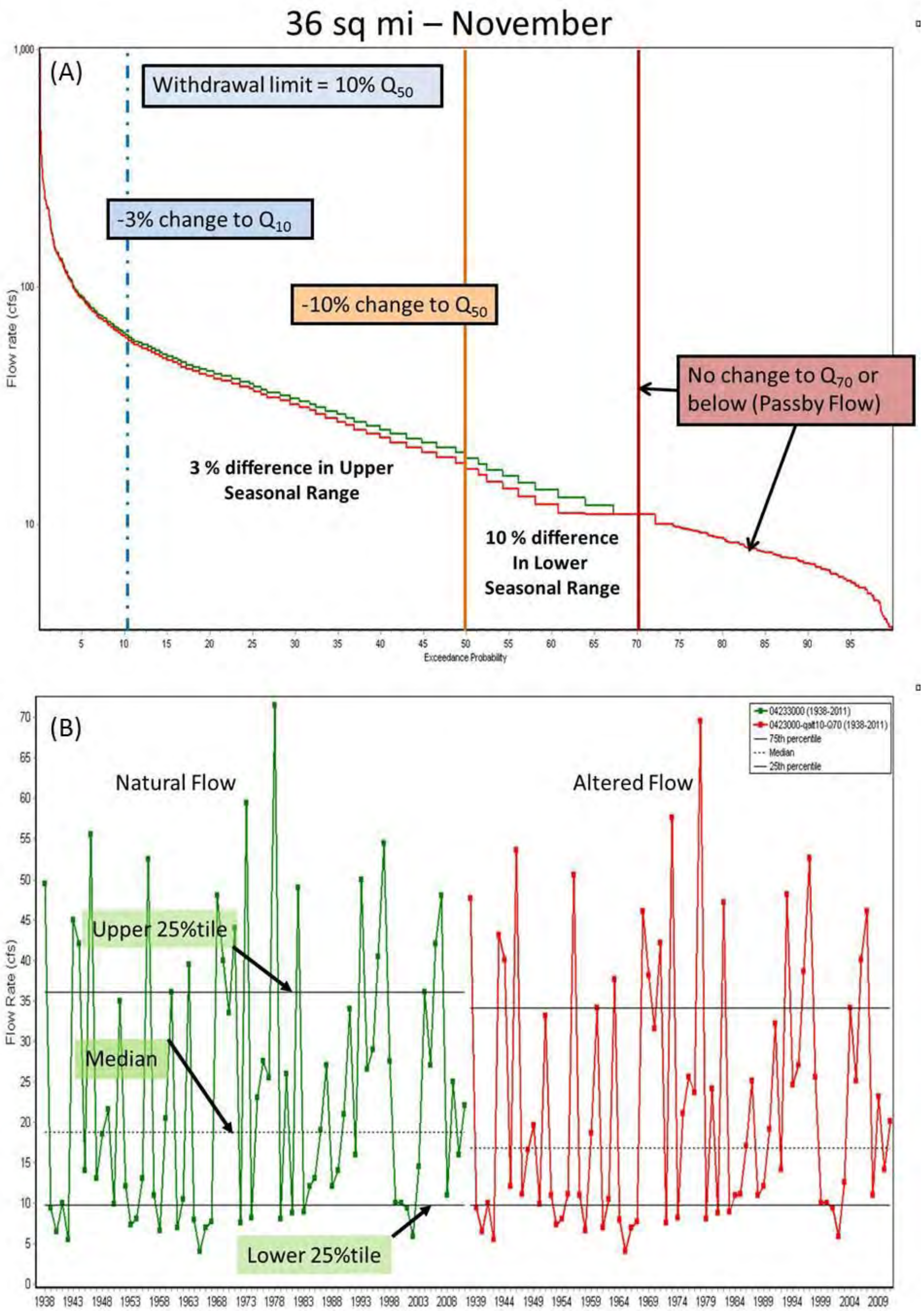


Figure 6.1. (A) Flow duration curves for natural hydrographs (green) and hydrographs altered by the maximum water withdrawals under flow protections proposed in Table 6.5, which are designed to protect seasonal flows (withdrawal limits) and low flows (passby). The x axis represents the probability that a streamflow value (y axis) will be exceeded. This flow duration curve demonstrates that the flow recommendations of Table 6.1 for headwaters streams can be achieved by applying the proposed withdrawal limit and passby flows outlined in Table 6.5. **(B) Annual variation in November Q_{50} values for natural (green) and altered (red) hydrographs.** The altered

hydrograph displays the results of applying the withdrawal limits and passby flows of Table 6.5 to this stream. Results for both A. and B. are calculated from flow data measured by a least altered reference gage located on Cayuga Inlet near Ithaca, NY (USGS Gage # 0433000).

6.2.1 Demonstration of passby and withdrawal cap concepts

To demonstrate how passby flow limits, withdrawal limits, and the combination of the two approaches can protect seasonal and low flow regimes, we calculated flow duration statistics for the period of record using data from a reference gage (USGS gage # 04243500) located on a 113 mi^2 stream in the Great Lakes basin (Oneida Ck. at Oneida, NY). We combined this information with data on water withdrawals that had been collected by New York Department of Environmental Conservation (NY DEC) Division of Water and provided confidentially to the analysis team as a courtesy. The water withdrawal data we used consisted of average daily withdrawal rates representing a relative large public water supply diversion. Rates varied across months based on seasonal water use patterns, ranging from 4.35 to 5.11 mgd. We then calculated expected alteration (Equation 6.1) due to this withdrawal pattern under the assumption that it was a direct withdrawal from surface water (i.e., no storage) using each policy tool (Table 6.6). We performed the following calculations for each approach:

1. Passby approach: We subtracted the example average daily withdrawal rate from the natural daily flow when stream flow was greater than the passby (July-Oct = Q_{70}, Nov-June = Q_{80}) for the period of record;
2. Withdrawal cap approach: We subtracted the example average daily withdrawal rate from the daily natural flow up to the withdrawal cap (10% of Q_{75});
3. Passby Withdrawal cap combination: We subtracted the example daily average withdrawal rate from the daily natural flow up to the withdrawal cap when stream flow was greater than the passby.

Equation 6.1: Percent alteration = ((Flow $\text{statistic}_{\text{altered}}$/Flow $\text{statistic}_{\text{natural}}$)/-1)*100

Table 6.6 shows the flow protection that each of the three policy tools would provide from this water withdrawal, individually and in combination. Passby flow protections prevent alteration to the low flow range, typically considered the most sensitive portion of the natural hydrograph to withdrawals, but do not prevent withdrawals from excessively altering the Q_{50} and lower seasonal flow range. In contrast, withdrawal caps prevent withdrawals from exceeding recommended limits of alteration to the Q_{50} and lower seasonal flow range, but low flow range recommendations are exceeded in all but the wettest months (March, April). A combination of passby flow limits and withdrawal caps maintains both seasonal and low flow components of the flow regime within the recommended limits of alteration proposed in section 6.1 for Class 2a streams (see Table 6.6).

Note that there is considerable room for more water to be withdrawn in certain months or higher flow years and still meet all proposed recommendations. Thus, in this example, a regulatory authority might consider withdrawal limits default standard and investigate additional proposed withdrawals on a case-by-case basis when limits are reached. Based on our recommendations, the combination of these two approaches should prevent adverse impacts to aquatic natural resources (Fig. 6.1) while still making a significant amount of water available for societal needs. In the following section we explore how four examples of typical water withdrawal patterns reported to NYS DEC Division of Water would be affected by our potential water withdrawal policy.

Table 6.6 illustrates the application of the passby and withdrawal limits proposed in table 6.5, which are designed to achieve the flow recommendations of Table 6.2. For a stream of this size class, passby restrictions would occur when stream flow falls below monthly Q_{70} (July-Oct) or Q_{80} (Nov-June). The withdrawal cap would limit withdrawals to 10% of monthly Q_{75} flows. When either passby limits or withdrawal caps are used separately, flow recommendations are exceeded. Used in combination, the two tools are consistent with recommendations based on analysis of the flow needs of target aquatic organisms.

Table 6.6. **Percent by which a 4.35-5.11 mgd withdrawal would alter seasonal and low flows** for a 113 square mile stream (Class 2a) under 3 different potential water withdrawal policies. Dark grey shading represents alteration values that exceed flow recommendations in Table 6.2 of section 6.1.
The three columns represent impacts to high seasonal flows (measured by change to Q_{50} flow); low seasonal flows (see endnote at the bottom of table); and low flows. For a stream of this size class, Table 6.2 recommends that seasonal flows (Q_{50} and the low seasonal flow range) be altered by no more than 10%. Table 6.2 also recommends limits to the amount of change of key flow statistics for low seasonal and low flows. Based on flow data from a least-altered reference gage located on Oneida creek at Oneida, NY (USGS Gage # 04243500).

Policy Tool	Month	Median Flow % alteration	Lower Seasonal Flow Range[a] % alteration	Low Flow Range[b] % alteration
Passby	Oct	-14	-11	0
	Nov	-6	-8	0
	Dec	-5	-6	0
	Jan	-6	-7	0
	Feb	-6	-6	0
	Mar	-3	-4	0
	Apr	-3	-3	0
	May	-6	-7	0
	Jun	-11	-11	0
	Jul	-16	-11	0
	Aug	-21	-11	0
	Sep	-20	-10	0

Withdrawal Cap	Oct	-7	-8	-12
	Nov	-5	-8	-14
	Dec	-5	-8	-11
	Jan	-6	-8	-13
	Feb	-6	-9	-11
	Mar	-3	-8	-7
	Apr	-3	-8	-6
	May	-6	-9	-11
	Jun	-7	-9	-13
	Jul	-7	-8	-12
	Aug	-7	-8	-12
	Sep	-8	-9	-12
Passby and Withdrawal Cap	Oct	-7	-7	0
	Nov	-5	-7	0
	Dec	-5	-6	0
	Jan	-6	-7	0
	Feb	-6	-6	0
	Mar	-3	-4	0
	Apr	-3	-3	0
	May	-6	-7	0
	Jun	-7	-8	0
	Jul	-7	-7	0
	Aug	-7	-6	0
	Sep	-8	-6	0

[a]Jul-Oct:Q_{50}-Q_{70}/Sep-Jun:Q_{50}-Q_{80} **[b]Jul-Oct:Q_{70}-Q_{99}/Sep-Jun:Q_{70}-Q_{99}**

6.2.2 Results of Test Application of Passby Flows and Withdrawal Caps

In the previous section we demonstrated how incorporating two tools, passbys and withdrawal caps, into a water withdrawal policy can protect seasonal and low flow components within the recommended limits of alteration presented in section 6.1. Here, we expand our analysis to examine:

1) how much water would be available to water users under our proposed withdrawal caps from four sample streams representing all four stream size classes;
2) how a sample of current withdrawals (using data reported to NYSDEC), representing a range of water volumes withdrawn from tributaries within the Great Lakes basin, would meet or exceed recommended limits of alteration to seasonal flow statistics if each withdrawal were applied to a typical stream in each of the size classes discussed in section 6.1; and
3) for each stream size class, the number of days that passby flow requirements would limit some portion of these withdrawals across a range of flow conditions (low and high flow months, dry and wet years, etc.) .

We selected four streams that represented our stream classes and had least altered reference gages with a long period of record located on the stream (Table 6.7). To examine the amount of water available under the monthly withdrawal caps presented in section 6.1, we:
1) calculated the appropriate monthly Q_{values} (Class 1= Q_{50}: all others = Q_{75}) for each stream; 2) calculated the recommended percent alteration for each stream class (Table 6.5), and: 3) converted that result to million gallons per day (mgd). We used reported withdrawal data provided by NY DEC Division of Water for typical withdrawal types within the Great Lakes basin, selecting rates that represented a real-world range of values. Specific details about these withdrawals – including whether they are from groundwater or surface water and whether they are associated with storage or not—are unknown to the authors.

The current withdrawals represent a range of users and withdrawal volumes including small withdrawals associated with seasonal golf course irrigation, small and large public water supplies, and a large industrial water supply (Table 6.8). We calculated percent alteration to Q_{50} statistics for each combination of stream class and withdrawal type following methods presented in 6.2.1. Stream class and withdrawal information are presented in tables 6.7 and 6.8. We did not conduct a similar analysis for low flow statistics because passby flow limits prevent alteration to low flow statistics. However, passby flows have the potential to limit water withdrawals, and thus water available to users if no storage is available. To explore this, we counted the number of days for each month that passby flows were initiated across all years, and calculated percentile statistics to quantify how passby limits varied across drought, dry, average, wet, and very wet years (5th, 25th, 50th, 75th, and 95th percentile of years for the period of record, respectively). We based passby calculations on appropriately sized withdrawals for each stream class (i.e. small streams = small withdrawal and large streams = large withdrawal).

Table 6.7. Background information for four sample streams, representing each of the watershed size classes examined in this report. Data from these streams are used in this section to examine water availability for each withdrawal type under proposed water policies.. Each of these streams is relatively unaltered.

USGS Gage ID	Stream Class	Stream Name	Drainage Area	Period of record
04233000	Class 1	Cayuga inlet near Ithaca, NY	35.5	1938-2011
04243500	Class 2a	Oneida Creek at Oneida, NY	113	1950-2011
04254500	Class 2b	Moose River at McKeever, NY	366.7	1906-1970
01512500*	Class 3	Chenango River near Chenango Forks, NY	1482	1914-2011

*This gage is not in the Great Lakes basin. There are no Class 3 stream reference gages within the basin.

Table 6.8. Average daily withdrawal rates, by month, for each of the withdrawals used to examine the two-part policy explored in this report. These withdrawals are recorded in cubic feet per second (cfs), and converted to million gallons per day (mgd) for the test cases discussed in this section. WD1 is a golf course, WD2 and WD3 are municipal water supplies, and WD4 is an industrial withdrawal.

WD	Units	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep
WD1	CFS	0.03	0.01	0.00	0.00	0.00	0.00	0.30	0.10	0.10	0.19	0.11	0.10
WD2		1.05	1.02	1.05	1.10	1.11	1.09	1.14	1.18	1.17	1.21	1.12	1.15
WD3		6.73	7.00	6.89	7.90	7.80	7.35	6.75	7.22	7.60	7.72	7.70	7.30
WD4		15.92	15.84	15.27	10.27	12.63	11.79	13.88	15.80	17.54	26.55	25.60	18.80
WD1	MGD	0.02	0.01	0.00	0.00	0.00	0.00	0.19	0.06	0.06	0.12	0.07	0.06
WD2		0.68	0.66	0.68	0.71	0.72	0.70	0.74	0.76	0.76	0.78	0.72	0.74
WD3		4.35	4.52	4.45	5.11	5.04	4.75	4.36	4.67	4.91	4.99	4.98	4.72
WD4		10.29	10.24	9.87	6.64	8.16	7.62	8.97	10.21	11.34	17.16	16.54	12.15

Under the example withdrawal cap policy, considerable water is available from streams when flows are above passby limits, particularly in Class 2b (200 – 1000 sq. mi.) and Class 3 (> 1000 sq. mi.) streams (Table 6.9). There are clear patterns of water availability across stream classes and seasons. Minimum water availability occurs in August or September and ranges from less than 0.5 mgd for the Class 1 stream to greater than 30 mgd for the Class 3 stream. It should be noted that there are considerably larger Class 3 streams within the basin than the one modeled (> 4000 sq mi), with proportionately more water available. There is significant seasonal variation in water available after the example withdrawal caps are applied. In fact, there is almost 4 mgd available in March and April in the Class 1 stream and over 350 mgd available in the Class 3 stream. This represents considerable volumes of water that could be collected and stored for use during drier months. Overall, this analysis indicates that a withdrawal cap would not be extremely limiting to water availability among stream classes across the basin. However, it is critical to note that these example water availability values represent **cumulative upstream withdrawal amounts (i.e. not necessarily single but multiple upstream user amounts)** that would meet the recommended limits of alteration to downstream systems.

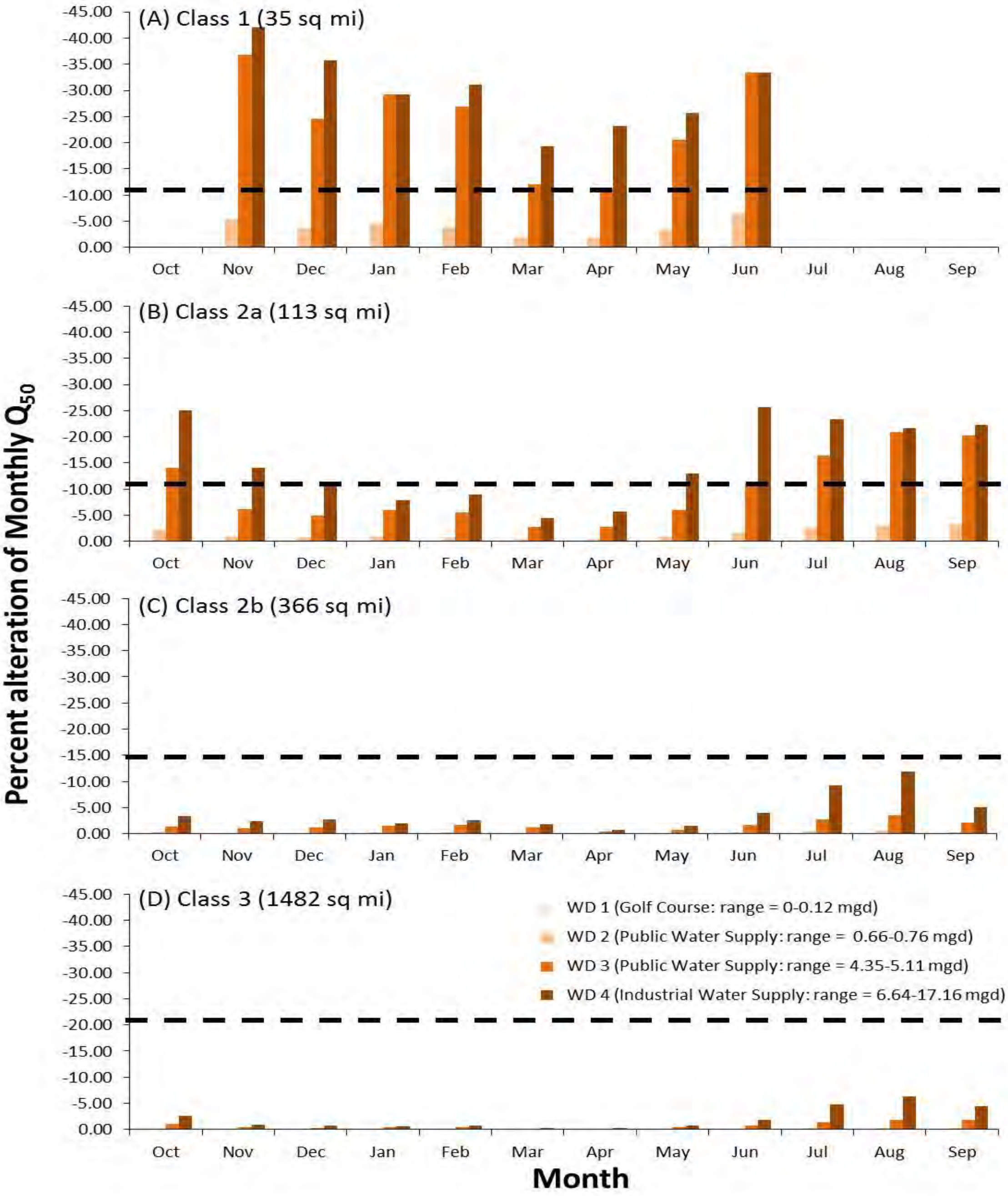
Table 6.9. Amount of water available for withdrawal, in million gallons per day, from each of the sample streams identified in table 6.7, **with the example withdrawal limits in place, and when the flow in each stream is above the passby limits. (see** Table 6.5**).** These amounts available for withdrawal meet the flow recommendations of Tables 6.1-6.4.

Month	Class 1 Example (35 mi^2) availability (mgd)	Class 2a Example (137 mi^2) availability (mgd)	Class 2b Example (366 mi^2) availability (mgd)	Class 3 Example (1482mi^2) availability (mgd)
October	0.57	2.39	34.12	40.33
November	1.23	8.79	42.17	108.32
December	1.81	10.47	39.94	168.03
January	1.55	7.11	35.87	129.25
February	1.87	7.11	32.96	129.25
March	3.94	10.99	41.30	271.43
April	3.88	18.69	115.12	358.03
May	2.26	6.33	64.37	158.98
June	1.16	2.33	29.66	75.48
July	0.63	0.9	18.32	47.63
August	0.45	0.63	14.64	35.03
September	0.42	0.78	25.11	33.99

The extent to which a range of typical withdrawal rates within the Great Lakes basin would affect median flows varies with stream class and season (Fig. 6.2). In general, larger withdrawals on smaller stream classes (Class 1 and Class 2a) will exceed recommended limits of flow alteration. Seasonal flow statistics for summer and fall low flow months would not be impacted by withdrawals in Class 1 streams because of the recommended high passby values (Q_{50}). Winter and spring estimated Q_{50} alteration varies with withdrawal type on Class 1 streams. In our example, golf course (WD1) and small public water supplies (WD2) did not alter seasonal flow statistics beyond the recommended limit of alteration but our larger public water supply and industrial user examples exceed limits in most months (Fig. 6.2A). Slightly larger streams (Class 2a) may support the larger withdrawal types during the wettest months (Jan-April), but these withdrawals (WD3, WD4) exceed recommended limits of alteration during the low flow and transition months (May-Oct) (Fig 6.2B). Class 2b and Class 3 streams can support all types of withdrawals during all months (Fig 6.2C-D).

Figure 6.2 and Table 6. 9 indicate that large stream classes can support large withdrawals while maintaining stream flows within our recommended limits of alteration (Tables 6.1-6.4). These results also highlight the potential for large withdrawals to occur on smaller streams during the wetter winter months, without impacts to our recommended flow alteration limits. Water users with seasonal water needs or the ability to store water (e.g., in an off-stream pond or tank) may be able to utilize small streams during winter without significantly impacting natural flow regimes.

Fig 6.2. Percent by which each example withdrawal listed in Table 6.8 would alter the median flow (monthly Q_{50}) of a typical stream in each Class. In general, the smaller the withdrawal or the larger the stream, the less the withdrawals would alter its Q_{50}. Class 1 streams are assumed to have pass-by flow requirements that preclude alteration of monthly Q_{50} during July through October. Bold black lines represent recommended limits of alteration. Equation 6.1 was used to compute per cent alteration of Q_{50} for each month, using least-altered reference-gage data for the period of record for each stream.



While our previous results demonstrate that there is substantial water availability even when withdrawals are capped to protect seasonal flow components, low flow regime protection is dependent on passby flow limits. Regional hydrology varies with long-term fluctuations in weather patterns. Depending on stream flows during any given month in a given year, water users may be limited during low flow periods.

Table 6.10 presents the number of days that these hypothetical water users would be limited and/or prevented from taking a withdrawal for each month. Results are presented across a percentile range for the period of record that qualitatively represents drought, dry, average, wet, and very wet years. Trends in the data suggest that no stream classes would be limited in very wet and wet years. In average years, smaller (Class 1 and Class 2a) streams would be significantly limited by passby flows during the low flow months and moderately limited during wetter months. Class 2b streams are likely to be limited by up to one week per month, particularly low flow months during an average year. Class 3 streams are not limited by passby flows during average years. Class 1- Class 2b streams are likely to experience significant passby limitations in dry years with Class 3 streams likely being moderately limited. During drought years, all stream classes would be limited by passby flows for the majority of the month. Overall, these results mirror trends reported in our previous analyses: in addition to more water availability, large streams will be limited less than small streams by passby restrictions. However, passby flow restrictions could present significant challenges to all water users during dry and drought periods and would require additional considerations, and possibly site-specific standards, to meet minimum consumptive water needs while limiting hydrologic impacts during these times.

Table 6.10. Number of days per month when water users would be subject to passby flow restrictions under a gradient of hydrologic year types (drought to very wet). Drought, dry, normal, wet, and very wet correspond to 5th, 25th, 50th, 75th and 95th percentiles of water availability based on reference flow conditions, respectively. Numbers reported are number of passby days per month across years over the period of record. It is crucial to note that columns do not represent single years. Instead, water availability was determined for each month over the period of record. A month during one year that fell at the 5% point in the period of record <u>for that month</u> could be followed by a much wetter month with few restrictions.

Stream Class / Withdrawal	Month	Drought[a]	Dry[b]	Normal[c]	Wet[d]	Very Wet[e]
Class 1 (35 sq mi) **WD 1** **Golf Course** **Withdrawal Range = 0-0.12 mgd**	October	31	28	17	1	0
	November	29	21	6	0	0
	December	31	18	4	0	0
	January	30	20	6	0	0
	February	25	15	8	0	0
	March	25	15	8	2	0
	April	27	15	7	3	0
	May	29	18	8	1	0
	June	28	17	6	0	0
	July	31	26	17	4	0
	August	31	26	20	5	0
	September	30	25	18	5	0
Class 2a (113 sq mi) **WD 2** **Public Water Supply** **Withdrawal Range = 0.66-0.76 mgd**	October	31	21	4.5	0	0
	November	24	13	3	0	0
	December	25	14	2	0	0
	January	29	12	3	0	0
	February	27	9	2	0	0
	March	25	11	4	0	0
	April	20	8	4	0	0
	May	19	11	5	0	0
	June	24	1	5	0	0
	July	31	19	11	3	0
	August	31	22	13	0	0
	September	30	18	9	0	0
Class 2b (366 sq mi) **WD 3** **Public Water Supply** **Withdrawal Range = 4.35-5.11 mgd**	October	29	18	7	1	0
	November	22	10	3	0	0
	December	27	11	1	0	0
	January	31	12	0	0	0
	February	28	13	0	0	0
	March	27	13	1	0	0
	April	17	10	5	1	0
	May	24	13	5	2	0
	June	25	12	3	0	0
	July	26	18	6	0	0
	August	27	19	7	0	0
	September	26	12	7	4	0
Class 3 (1482 sq mi) **WD 4** **Industrial Water Supply** **Withdrawal Range = 6.64-17.16 mgd**	October	29	7	0	0	0
	November	21	2	0	0	0
	December	23	3	0	0	0
	January	23	0	0	0	0
	February	17	2	0	0	0
	March	14	5	0	0	0
	April	14	4	1	0	0
	May	16	5	0	0	0
	June	17	4	0	0	0
	July	27	5	0	0	0
	August	30	6	0	0	0
	September	24	6	0	0	0

6.3 Summary and comments

In this section of the report, we have proposed ecosystem flow recommendations (Tables 6.1 – 6.4) for the streams and rivers of the Great Lakes Basin in NY and PA. These recommendations were based on thorough analysis of the needs of flow-sensitive fish and mussels, species that were selected to represent the needs of healthy aquatic ecosystems. Section 5 of this report presents numerous examples (see in particular figures 5.6 and 5.10), drawn from the scientific literature, of the impacts of altered flows on these representative taxa at critical points in their life cycles. The flow recommendations proposed in Table 6.1 are based on these documented flow needs, and on the professional judgments of the scientists and natural resource professionals on our Technical Advisory Team.

To implement these flow recommendations through water withdrawal policy and guidance, we have examined two policy tools, separately and in combination. Our assessment of the passby flow approach demonstrated that it prevents alteration to the low flow component which can be stressful for aquatic organisms (Table 6.6). However, passby flows did not prevent alteration, beyond recommended limits, to seasonal flows, which represent the typical conditions to which many organisms are adapted. The second approach, withdrawal caps, prevented excessive alteration to seasonal flows, but was not protective of low flows when used alone. Our analysis indicated that using a combination of passby flows and withdrawal caps would meet the ecosystem flow recommendations presented in tables 6.1 – 6.4 for both seasonal and low flow components.

To further examine the application of these two tools, we tested four withdrawals, ranging from a small seasonal golf course withdrawal to a large daily industrial withdrawal, using actual streamflow data representing the four watershed size classes. Figure 6.2 illustrates the effect of applying both water policy tools to each withdrawal in each stream. The two largest stream classes (tributaries with watersheds 200 – 1,000 square miles, and large rivers over 1,000 square miles) can easily accommodate each of the four withdrawals. For the small tributary, representative of watersheds of 50 – 200 square miles, recommended limits of median flow alteration would be exceeded by the two largest withdrawals during several months. For the headwaters stream, alteration limits would be exceeded by the two largest withdrawals in every month, but a smaller public water supply (e.g., drawing 660,000 – 760,000 gpd) could be accommodated in all months except July – October. All of these test examples assumed direct withdrawal from a river or stream, and therefore the real life flexibility that might be afforded by use of storage, conjunctive use with groundwater, nearby return flows, use of multiple supplies, etc. was not modeled. The analysis also only assumes one withdrawal on each stream or river to that point. In the real world, the complexity of water resource management issues would undoubtedly increase, but so would the opportunity for creative approaches to meet ecosystem flow recommendations.

Water availability increases with watershed size. Avoidance of adverse impacts to aquatic resources becomes difficult when large withdrawals are taken from small watersheds, particularly without use of storage. Conversely, adverse impacts can easily be avoided by directing large withdrawals to large rivers, as long as cumulative withdrawals and return flows are accounted for.

Of the two policy tools analyzed in Section 6.2, passby flows are most restrictive of water use in low flow periods; nevertheless the need for such protection emerges clearly in our review of the scientific literature. Likewise, science clearly demonstrates the need to maintain the variability of seasonal flows, and figure 6.1A illustrates the benefits of using withdrawal caps as the tool to maintain this protection.

Section 7: Conclusion

In order to address issues of flow management at a regional scale, this project has focused on defining and quantifying the ecological processes necessary to maintain intact aquatic ecosystems in streams ranging from small headwaters watersheds to large rivers. We have adapted the ELOHA framework in pursuit of recommendations for statewide management of river and stream flows that avoid "cumulative adverse impacts" (in the words of the Great Lakes Compact) to water-dependent natural resources.

We began by identifying six guilds of fish and four guilds of mussels and aquatic insects, comprising a total of 43 species, whose fluvial dependencies are clear and well-documented. We selected these species as target organisms to represent all aquatic organisms and communities. Next, we defined components of the flow regime that would facilitate discussion of the flow needs of the target organisms and of the management steps necessary to meet these needs. We have been guided in the identification of these flow components – which include various degrees of high, seasonal, and low flows, and the statistics that define them – by considerable previous work, including flow recommendations for the Susquehanna Basin (Dephilip and Moberg 2011), the Ohio River watershed in Pennsylvania (DePhilip and Moberg 2013), and the basic discussion of flow components by Mathews and Richter (2007).

Documentation of the associations between the critical life stages of the target organisms and particular flow components (sections 4 and 5, and Appendix 2) enabled the Technical Advisory Team to frame hypotheses of how these organisms (and the wider aquatic ecosystems they represent) will respond to altered flow regimes. Framing and evaluating these hypotheses enabled us to match the reproductive success of target organisms with variations in flow components and to provide the scientific basis for the flow recommendations in the preceding section.

To evaluate the hypotheses of response to flow alteration, we employed causal-criteria analysis of the scientific literature, a structured approach for assessing the support a given study provides to a particular hypothesis. The use of this method, in place of quantitative testing of hypotheses, is an interim step made necessary by the lack of region-wide hydrologic simulations of unaltered flows and by limited streamflow gage data. We grouped hypotheses that address similar reproductive phases or flow components into generalized flow needs so that our flow recommendations efficiently address ecological processes that affect many different species simultaneously.

These steps, guided by the Technical Advisory Team and the experience of similar projects, have led to the flow recommendations presented in Section 6. These recommendations address a dual need – to safeguard low flows, particularly during the drier periods of the year, and to preserve the elements of hydrologic variability above these low flows that are essential for reproduction and other life cycles needs of the diverse array of organisms that characterize aquatic ecosystems. To address the dual need, we recommend the use of two policy tools: passby flows for protection of low flows, and withdrawal limits to preserve the essential elements of hydrologic variability. The analyses in section 6 demonstrate that each tool is necessary but not sufficient by itself to preserve flow-dependent natural resources. We have taken the further step of testing the impact of these recommendations on a range of typical withdrawals in four streams representing the four stream size classes. The two policy tools acting in combination result in flow regimes that meet our flow recommendations, and thereby meet the documented flow needs of aquatic ecosystems.

This project has assembled considerable information about the life cycles of the target fish, mussels, and aquatic macroinvertebrates. The information provided in Section 4 and Appendix 2, when combined with equivalent documentation assembled in the Susquehanna and Ohio River projects, constitutes a useful database for other states or large watersheds in the Northeastern U.S. or Great Lakes Basin, since many of the species are common to both of these regions.

This project has shared with the Ohio River study (DePhilip and Moberg 2013) the same methodology to frame and evaluate hypotheses of response to flow alteration and to aggregate these hypotheses into flow needs. These flow needs, and the documented evaluation of their constituent hypotheses, provide a framework with broad applicability for flow management in the Northeast and Great Lakes.

We have attempted in this report to frame flow recommendations that are science-based and also practical to apply in an actual water regulatory program. The flow recommendations employ hydrologic statistics that can readily be computed for each stream or stream reach, given information on simulated unaltered flows and current water withdrawals. At the moment, such information is only available for the Pennsylvanian portion of the project study area. Full application of the recommendations, within the Great Lakes and throughout New York State, will be achievable with the Streamflow Estimator Tool (SET), now nearing completion by the USGS Water Sciences Center in Troy. The SET will simulate the unaltered hydrograph for each stream in New York State, providing agency staff with desktop access to the flow management statistics used in this report. We believe this new tool, and the recommendations in this report, provide the basis for a water regulatory program that is science-based, transparent, and protective of aquatic ecosystems.

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Appendix 1: Flow statistics of reference gages

Appendix Table 1.1. Monthly Q_{50} statistics (cubic feet per second) for 28 Great Lakes reference gages within the project area. Dark orange and light orange shading denotes site x month combinations where stream flow is < 10 cfs and < 50 cfs, respectively. NYSET ref refers to gages currently being used to develop the NY Streamflow Estimator Tool by the U.S. Geological Survey NY Water Office.

GAGE_ID	Drainage Area sq. mi.	State	NYSET Ref	Stream Class	October Q_{50}	November Q_{50}	December Q_{50}	January Q_{50}	February Q_{50}	March Q_{50}	April Q_{50}	May Q_{50}	June Q_{50}	July Q_{50}	August Q_{50}	September Q_{50}
4213040	2.6	PA	N	1	0.6	2.1	2.9	2.0	2.2	3.7	2.9	1.4	0.5	0.2	0.2	0.3
4213075	4.5	PA	N	1	2.4	4.3	5.1	5.0	5.4	7.7	6.8	3.9	2.1	1.4	1.1	1.4
4216500	24.2	NY	Y	1	0.9	3.7	15.0	14.0	19.0	44.0	43.0	16.0	4.1	1.6	1.0	0.8
4235150	31	NY	Y	1	3.4	15.0	20.0	16.0	18.0	63.5	50.0	33.0	10.0	4.2	2.3	2.1
4265100	32.6	NY	Y	1	12.0	43.0	35.0	22.0	26.0	49.0	88.0	33.0	11.0	6.0	6.7	7.3
4245200	32.8	NY	Y	1	14.0	33.0	42.0	39.0	40.0	72.0	81.0	42.0	21.0	12.0	8.8	8.8
4233000	**35.5**	**NY**	**Y**	**1**	**8.8**	**21.0**	**29.0**	**24.0**	**29.0**	**59.0**	**60.0**	**36.0**	**18.0**	**9.5**	**6.8**	**6.6**
4232100	43	NY	Y	1	9.9	41.0	59.5	49.0	52.0	110.0	92.5	46.0	16.0	6.6	4.7	4.6
4216418	75.9	NY	N	2a	34.0	74.0	101.5	84.0	90.0	149.5	139.0	63.0	38.0	21.0	18.0	20.5
4256000	89.7	NY	N	2a	110.0	181.5	156.0	120.0	101.0	160.0	398.0	183.0	99.0	60.0	51.0	64.0
4258700	94.8	NY	Y	2a	66.0	182.5	160.0	103.0	110.0	194.5	619.5	140.0	53.0	23.0	21.0	26.0
4215000	96.4	NY	Y	2a	18.0	67.0	105.0	80.0	85.0	190.0	140.0	51.0	20.0	8.4	6.6	7.0
4235250	102	NY	Y	2a	10.0	40.0	62.0	50.0	50.0	160.0	150.5	65.5	27.0	11.0	6.2	6.8
4243500	113	NY	Y	2a	48.0	113.0	142.0	130.5	140.0	263.5	241.0	121.5	68.5	47.0	37.0	36.0
4215500	135	NY	Y	2a	42.0	137.0	190.0	145.0	150.0	313.0	244.5	110.0	51.0	27.0	21.0	22.0
4250750	**137**	**NY**	**Y**	**2a**												
4214500	142	NY	Y	2a	38.0	108.0	164.0	130.0	130.0	278.0	217.0	96.0	49.0	26.0	20.0	22.0
4217000	171	NY	Y	2a	39.0	106.0	180.0	147.0	151.5	346.0	294.0	132.0	58.0	31.0	23.0	23.0
4268800	171.4	NY	N	2a	200.0	280.0	240.0	180.0	170.0	240.0	779.5	378.0	215.0	146.0	123.0	128.0
4213000	175.8	OH	Y	2a	39.0	166.0	229.0	175.0	198.5	312.0	239.0	107.0	45.0	25.0	20.0	18.0
4269500	182	NY	Y	2a	91.0	159.0	140.0	118.0	120.0	180.0	567.0	195.0	92.0	60.0	60.0	63.0
4230500	200	NY	Y	2b	39.0	75.0	154.5	160.0	185.0	410.5	372.0	188.0	88.0	54.0	41.0	36.0
4217500	231	NY	Y	2b	48.0	132.5	250.0	170.0	200.0	495.5	415.5	169.0	78.0	44.0	33.0	32.0
4221000	289.9	NY	N	2b	84.5	244.0	333.0	222.0	230.0	505.0	599.0	286.5	146.5	86.0	54.0	55.0
4221500	308	NY	Y	2b	52.0	167.5	235.0	210.0	190.0	600.0	675.0	347.0	135.0	70.5	47.0	38.0
4265000	333.4	NY	Y	2b	275.0	464.0	499.0	350.0	370.0	660.0	1435.0	706.0	337.0	219.0	194.0	206.0
4218000	349	NY	Y	2b	81.0	212.0	380.0	300.0	360.0	698.5	617.5	249.5	115.0	60.5	51.0	45.0
4254500	**366.7**	**NY**	**N**	**2b**	**439.5**	**611.0**	**620.0**	**490.0**	**430.0**	**560.0**	**2065.0**	**944.0**	**435.5**	**238.5**	**195.5**	**350.0**

Bold denotes reference gages used in flow recommendations analysis in Section 6.2

Appendix Table 1.2. Monthly Q_{75} and Q_{90} statistics (cubic feet per second) for 28 Great Lakes reference gages within the project area. Dark orange and light orange shading denotes site x month combinations where stream flow is < 10 cfs and < 50 cfs, respectively. NYSET ref refers to gages currently being used to develop the NY Streamflow Estimator Tool by the U.S. Geological Survey NY Water Office.

GAGE_ID	Drainage Area sq. mi.	State	NYSET Ref	Stream Class	October		November		December		January		February		March	
					Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}
4213040	2.6	PA	N	1	0.3	0.2	1.0	0.5	1.7	1.1	1.2	0.7	1.3	0.8	2.3	1.4
4213075	4.5	PA	N	1	1.5	1.1	2.5	1.6	3.3	2.0	3.0	1.9	3.1	2.0	4.7	3.4
4216500	24.2	NY	Y	1	0.6	0.3	0.9	0.6	7.2	0.7	8.7	1.0	11.0	6.8	25.0	15.8
4235150	31	NY	Y	1	0.8	0.4	3.0	1.7	9.2	4.5	7.4	3.5	9.8	6.0	33.0	17.0
4265100	32.6	NY	Y	1	6.9	5.1	22.0	12.0	21.3	12.0	13.0	9.6	16.0	9.7	24.0	14.0
4245200	32.8	NY	Y	1	8.5	6.6	16.0	10.0	28.0	18.0	26.5	18.0	28.0	21.0	45.5	32.0
4233000	**35.5**	**NY**	**Y**	**1**	**5.7**	**4.4**	**9.6**	**6.9**	**16.0**	**9.7**	**15.0**	**9.6**	**19.0**	**14.0**	**37.0**	**23.5**
4232100	43	NY	Y	1	4.1	2.1	16.0	6.5	35.0	16.0	33.0	19.0	36.0	27.0	64.0	43.0
4216418	75.9	NY	N	2a	20.0	14.0	41.0	23.0	68.0	40.0	58.0	42.7	60.0	46.0	90.0	70.0
4256000	89.7	NY	N	2a	67.0	43.0	120.0	82.0	110.0	90.0	84.5	66.0	80.0	60.9	98.0	70.0
4258700	94.8	NY	Y	2a	26.8	14.0	108.8	53.8	114.0	98.2	86.0	76.0	77.0	68.0	104.0	80.2
4215000	96.4	NY	Y	2a	6.2	3.4	25.0	8.2	56.0	27.0	48.0	26.0	50.0	32.0	102.0	67.0
4235250	102	NY	Y	2a	4.1	1.4	12.0	5.0	27.0	11.0	26.0	12.0	20.5	18.0	79.0	45.3
4243500	113	NY	Y	2a	33.0	26.0	58.0	41.0	95.0	63.0	90.0	60.0	100.0	74.0	160.0	110.0
4215500	135	NY	Y	2a	20.0	12.0	65.0	30.0	120.0	76.0	95.0	66.0	96.0	68.0	175.0	114.0
4250750	**137**	**NY**	**Y**	**2a**	**37.0**	**18.0**	**136.0**	**72.9**	**162.0**	**119.0**	**110.0**	**93.2**	**110.0**	**84.0**	**170.0**	**108.6**
4214500	142	NY	Y	2a	20.0	12.0	50.0	28.0	100.0	56.0	86.0	50.0	88.0	60.0	160.0	102.0
4217000	171	NY	Y	2a	17.0	11.0	44.0	22.0	100.0	56.0	92.0	62.0	98.0	68.0	198.3	134.0
4268800	171.4	NY	N	2a	124.0	101.4	204.3	160.0	170.0	130.0	135.0	100.0	135.0	110.0	150.0	130.0
4213000	175.8	OH	Y	2a	18.0	9.2	64.0	21.0	125.5	70.0	95.0	65.0	110.0	70.0	180.0	105.0
4269500	182	NY	Y	2a	68.0	56.3	115.0	89.0	92.0	79.0	96.0	80.6	94.0	74.0	115.5	92.0
4230500	200	NY	Y	2b	28.0	23.0	35.0	24.0	74.0	39.0	93.0	58.0	120.0	73.3	236.5	170.0
4217500	231	NY	Y	2b	26.0	17.0	59.8	31.0	150.0	92.0	120.0	86.0	130.0	88.0	270.0	170.0
4221000	289.9	NY	N	2b	41.8	30.0	110.0	50.0	210.0	107.5	130.0	91.0	149.8	96.0	320.0	207.0
4221500	308	NY	Y	2b	31.0	23.0	62.0	36.0	140.0	74.5	110.0	72.0	108.3	73.1	314.8	159.0
4265000	333.4	NY	Y	2b	186.0	144.0	322.0	242.0	350.0	260.0	250.0	200.0	260.0	190.0	350.0	260.0
4218000	349	NY	Y	2b	39.0	23.0	82.0	41.0	200.0	100.1	180.0	121.0	213.5	125.0	400.0	293.1
4254500	**366.7**	**NY**	**N**	**2b**	**337.0**	**262.9**	**425.0**	**305.0**	**470.0**	**359.3**	**370.0**	**290.0**	**350.0**	**290.0**	**400.0**	**350.0**

Bold denotes reference gages used in flow recommendations analysis in Section 6.2

Appendix Table 1.2 continued. Monthly Q75 and Q90 statistics (cubic feet per second) for 28 Great Lakes reference gages within the project area. Dark orange and light orange shading denotes site x month combinations where stream flow is < 10 cfs and < 50 cfs, respectively. NYSET ref refers to gages currently being used to develop the NY Streamflow Estimator Tool by the U.S. Geological Survey NY Water Office.

GAGE_ID	Drainage Area sq. mi.	State	NYSET Ref	Stream Class	April		May		June		July		August		September	
					Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}	Q_{75}	Q_{90}
4213040	2.6	PA	N	1	1.8	1.1	0.7	0.4	0.2	0.1	0.1	0.0	0.1	0.02	0.1	0.03
4213075	4.5	PA	N	1	4.5	3.3	2.5	1.9	1.4	1.0	1.0	0.7	0.7	0.5	0.9	0.6
4216500	24.2	NY	Y	1	26.0	16.0	9.4	5.4	2.6	1.5	0.9	0.4	0.5	0.3	0.4	0.3
4235150	31	NY	Y	1	32.0	21.0	22.0	14.0	6.5	4.2	2.4	0.9	0.8	0.2	1.0	0.4
4265100	32.6	NY	Y	1	54.5	39.0	23.0	17.9	7.3	5.4	4.0	3.0	3.7	3.0	5.0	4.0
4245200	32.8	NY	Y	1	57.0	45.0	28.0	21.0	14.0	10.0	7.7	5.9	6.0	4.7	6.3	4.8
4233000	**35.5**	**NY**	**Y**	**1**	**41.0**	**31.0**	**24.0**	**17.0**	**11.0**	**7.8**	**6.5**	**4.4**	**4.7**	**3.7**	**4.5**	**3.4**
4232100	43	NY	Y	1	58.0	42.0	31.0	18.0	9.6	5.9	4.0	2.8	2.9	1.7	2.6	1.8
4216418	75.9	NY	N	2a	91.0	66.9	40.0	30.0	23.8	17.0	15.0	10.0	11.0	7.5	13.0	8.0
4256000	89.7	NY	N	2a	240.0	168.0	122.0	90.0	66.0	47.0	42.0	33.0	35.0	28.0	42.0	31.0
4258700	94.8	NY	Y	2a	352.0	219.8	90.0	64.3	33.0	22.0	12.0	6.5	12.0	8.2	12.0	7.2
4215000	96.4	NY	Y	2a	81.0	51.0	28.0	18.0	11.0	6.3	4.1	2.2	2.9	1.5	3.3	1.3
4235250	102	NY	Y	2a	86.0	57.9	41.0	29.0	17.0	11.0	5.8	2.9	3.0	1.5	2.5	0.6
4243500	113	NY	Y	2a	161.0	121.0	84.0	65.0	50.0	39.0	34.0	26.0	27.0	21.0	27.0	21.0
4215500	135	NY	Y	2a	148.0	105.0	67.0	48.0	32.0	21.0	16.0	11.0	12.0	8.5	13.0	8.6
4250750	**137**	**NY**	**Y**	**2a**	**289.3**	**179.8**	**98.0**	**64.6**	**36.0**	**24.0**	**14.0**	**8.4**	**9.7**	**6.2**	**12.0**	**5.9**
4214500	142	NY	Y	2a	134.0	95.0	62.0	46.0	31.0	19.0	16.0	11.0	12.0	8.3	13.0	8.4
4217000	171	NY	Y	2a	186.0	128.9	8.0	57.0	37.0	25.0	20.0	12.0	13.0	9.0	13.0	8.0
4268800	171.4	NY	N	2a	485.3	314.9	272.0	210.4	144.0	102.9	97.0	75.0	81.5	64.0	88.0	68.0
4213000	175.8	OH	Y	2a	135.0	92.0	60.0	41.0	28.0	18.0	13.0	8.7	11.0	6.5	9.4	5.6
4269500	182	NY	Y	2a	357.5	238.0	138.0	104.0	71.0	59.0	48.0	42.0	46.0	34.3	50.0	44.0
4230500	200	NY	Y	2b	249.0	177.0	132.0	101.0	61.0	50.0	43.0	37.0	34.0	28.0	28.0	23.0
4217500	231	NY	Y	2b	259.0	180.0	109.0	79.0	50.0	36.0	28.0	20.0	23.0	17.0	21.0	12.0
4221000	289.9	NY	N	2b	379.0	273.9	183.0	122.5	87.0	56.9	54.0	35.0	33.0	23.0	31.0	23.0
4221500	308	NY	Y	2b	440.0	288.0	203.8	131.0	82.0	56.0	43.0	30.5	28.8	20.0	25.0	18.0
4265000	333.4	NY	Y	2b	936.0	660.0	508.0	381.6	248.0	184.9	156.0	125.0	132.0	102.0	154.0	116.0
4218000	349	NY	Y	2b	383.0	271.9	170.0	120.0	70.8	47.9	41.0	29.0	30.0	21.0	26.0	16.0
4254500	**366.7**	**NY**	**N**	**2b**	**1200.0**	**699.7**	**661.3**	**481.8**	**292.5**	**217.8**	**163.8**	**129.0**	**144.0**	**117.0**	**272.8**	**181.8**

Bold denotes reference gages used in flow recommendations analysis in Section 6.2

Appendix 2

TARGET SPECIES GROUPS AND DOCUMENTED FLOW-ECOLOGY RELATIONSHIPS IN SUPPORT OF DEVELOPING INSTREAM FLOW RECOMMENDATIONS FOR THE GREAT LAKES BASIN TRIBUTARIES OF NEW YORK AND PENNSYLVANIA

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[2]United States Geological Survey

Project background

The Great Lakes Compact protects the waters of the Great Lakes Basin from diversion, and also places obligations on the states for water management. The Compact instructs each state to create a management program for new or increased withdrawals and consumptive uses (beyond current uses, which are the Compact baseline) within 5 years of the effective date of the Compact, December 2008. Such water management programs should prevent "significant individual or cumulative adverse impacts to the quantity or quality of the Waters and Water-Dependent Natural Resources" of the Great Lakes Basin from further water withdrawals or consumption. Michigan has defined "adverse impacts" as those that impair a stream's ability to support characteristic fish communities, and the legislature has defined levels of species loss that constitute impairment. The New York State Senate has joined the Assembly in passing the Water Resources Protection Act, which authorizes the New York State Department of Environmental Conservation (DEC) to develop quantitative stream-flow standards that maintain aquatic life consistent with the policy objectives of the act. The goal of the New York-Pennsylvania Great Lakes Sustainable Flows (NYPAFLOs) project is to provide the DEC with the scientific foundation to work with stakeholders in defining such stream-flow standards for streams draining into Lake Erie and Ontario **(Figure 1)** and fulfilling one of the state's major obligations under the Compact. To achieve this goal, we are consulting with experts to establish clear links between degrees of hydrologic alteration and ecological impacts through literature and documentation on the needs of target species, natural processes, and habitat data analysis; classify streams so that limited data can be applied across the streams of the same type; and develop flow alteration-ecological response curves based on available data to support spatially and temporally specific flow recommendations for the basin.

Defining environmental flows and developing recommendations

Environmental flows can be defined as the flow of water in a natural river or lake that sustains healthy ecosystems and the goods and services that humans derive from them (Poff et al. 1997). A number of measures have proven useful for quantitatively describing the flow of water in a water body: *magnitude* or the amount of water flowing, in cubic feet per second, or some other unit of measure; *duration* of a hydrologic condition, such as high or low flow events; *timing* of flows; *frequency* of occurrence; and the *rate of change* between one type of flow and another. Each of these measures can be characterized by a range of natural variability, with particular emphasis on inter-annual variability.

The process of defining environmental flows seeks to preserve enough of the natural variability in these hydrologic measures to protect the ecological functions essential to diverse, healthy communities of aquatic organisms. For example, natural floods are necessary to scour river channels, maintain floodplains, and provide access to floodplains to organisms that depend on them; on the other hand, aquatic biota may not be adversely impacted with some reduction in the natural frequency and duration of flooding. Development of prescriptions for environmental flows, which seek to balance ecological and economic needs, have been developed for a number of river systems around the globe, including the partnerships between Army Corps of Engineers and TNC for the Savannah River and other rivers included in the Sustainable Rivers Project.

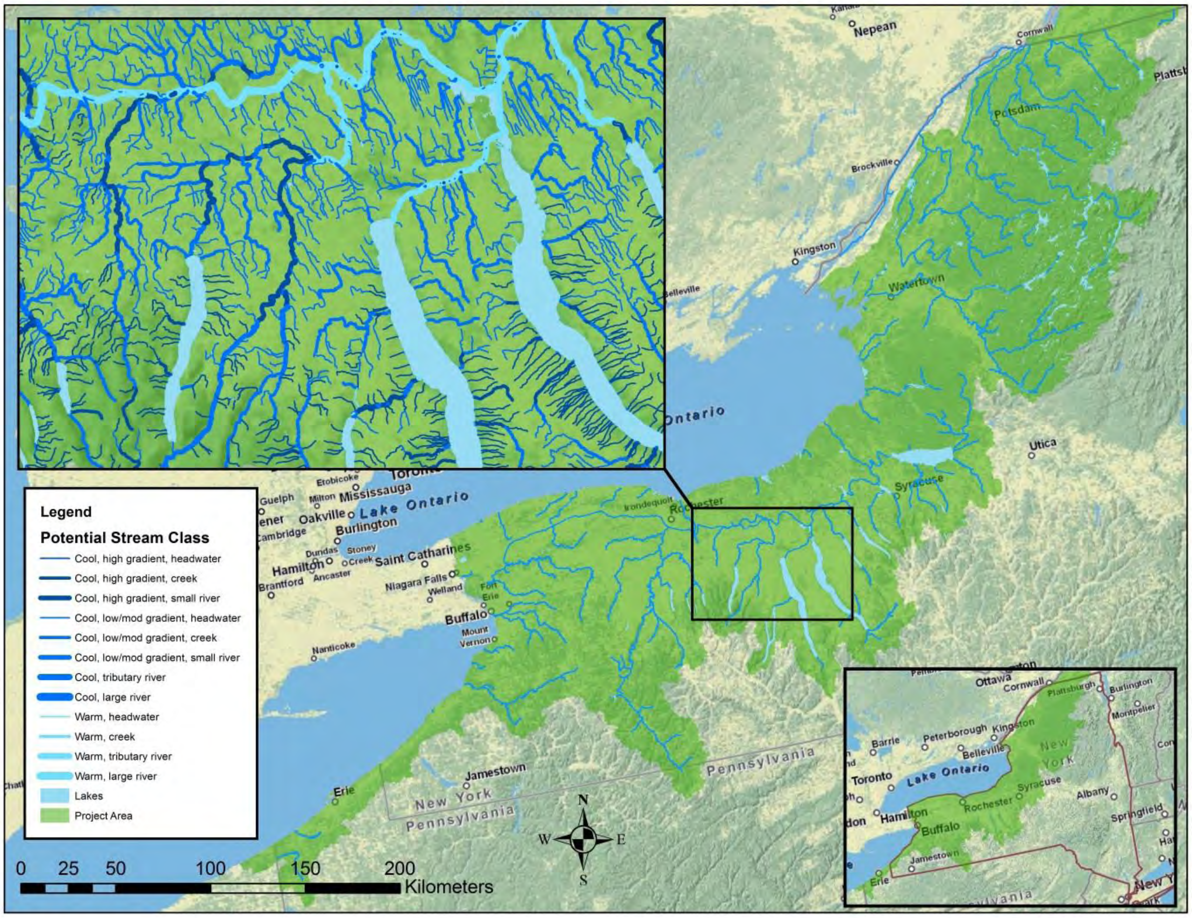


Figure 1. Map of project area representing Lake Erie, Lake Ontario, and St. Lawrence River drainages in NY and PA.

These river-specific approaches have been very useful, but the global pace of human modification of the flow regimes of rivers, and the dire state of aquatic biota across the globe, demand a new framework that can develop flow recommendations for the rivers of an entire region. The Ecological Limits of Hydrologic Alteration (ELOHA) framework seeks to fill this need, beginning with *classification of streams* to facilitate generalizations that can apply to all the streams within a class; and *formulation of hypotheses of hydrologic alteration and ecological response,* which provide testable relationships “that can serve as a starting point for empirically based flow management at a regional scale” (Poff et al. 2010). This framework incorporates best professional judgment with quantitative analysis, and has been applied at the watershed level for the Susquehanna, Connecticut, and Potomac rivers, and at the statewide level in Massachusetts, Michigan, Maine, and Florida.

Most recently, the results of these river-specific and regional approaches has led to the proposal of a “presumptive standard” (Richter et al. 2011) to act as the starting point for discussions of regional water management: 1) *less than 10 per cent* alteration in daily flows will maintain the natural structure and function of an ecosystem with minimal changes; 2) *11-20 per cent* alteration may result in measurable changes in species structure, but minimal changes in ecosystem functions; and 3) *greater than 20 per cent* alteration is more likely to result in moderate or greater changes to structure and function. The examination of whether this proposed standard applies to a specific region must begin with the formulation and testing of hypotheses based on set of target species that represent the fluvial needs of the region. This report presents results from the initial target fish species selection with subsequent refinement based on expert review at a NYPAFLOs workshop, and additional documentation of specific flow needs through a review of existing scientific literature.

Target fish: species descriptions

The inland waters of New York that flow into Lake Erie, Lake Ontario, and the St. Lawrence River **(Figure 1)** support a rich fish fauna with 139 species reported from within the project area (Smith 1985, Carlson and Daniels 2004). Twelve species and two hybrids were introduced through intentional game fish stocking or canal systems and associated shipping traffic, and are non-native to New York waters (Carlson and Daniels 2004). An additional 7 species have been introduced to the basin through transfers from NY basins outside the project area, and 17 species have had range extensions through basin transfers within the project area (Carlson and Daniels 2004). There are ten fish species with distributions within the project area that are currently listed as threatened or endangered by the state of NY. Threatened species include lake sturgeon (*Acipenser fulvescens*), mooneye (*Hiodon tergisus*), lake chubsucker (*Erimzon sucetta*), longear sunfish (*Lepomis megalotis*), and eastern sand darter (*Ammocrypta pellucida*). Endangered species include silver chub (*Macrhybopsis storeina*), pugnose shiner (*Notropis anogenus*), round whitefish (*Prosopium cylindraceum*), and two lake dwelling sculpins (*Cottus ricei*, *Myoxocehaplus thompsonii*). Additional species of special concern known from the project area include redfin shiner (*Lythrurus umbratilis*) and black redhorse (*Moxostoma duquesnei*).

We examined fish traits among species combined with input from experts attending the first NYPAFLOs Project workshop (June 29, 2011) and literature review to select a subset of flow-dependent species that represent six target fish species groups. Initially a subset of species was selected as potential fluvial targets based on exhibiting at least one fluvial dependent temperature, velocity, or habitat preference. Through breakout groups during the workshop, experts made suggestions for 15 species additions and recommended removing 4 species. With an additional literature review, we documented temperature, habitat, and flow needs for various life history stages of several species **(Appendix Tables 1-6)**, removed functionally redundant species, and grouped the remaining 27 species/species complexes based on similar life history strategies, habitat niches, or other characteristics that make them sensitive to hydrologic alteration. We modified existing groups developed by the Susquehanna River Ecosystem Flow Study which are based on similar life history traits (body size, fecundity, home range, habitat associations, feeding habits, flow-velocity tolerances) and the timing and location of flow-sensitive life history stages (DePhillip and Moberg 2010). Our six species groups **(Table 1)** differ from the five proposed by (DePhillip and Moberg 2010) by the inclusion of a marsh spawning group, and the replacement of a diadromous group with a more specific anadromous sport fish group (both native and non-native salmonid species that occur in land-locked populations). These changes are based on recommendations made by the project team during the June 2011 workshop.

Table A2.1. Flow ecology target species groups based on key life history traits.

Group	Key Traits	Species
Cold Headwater	Similar needs defined by temperature thresholds	Brook trout, brown trout, sculpins.
Riffle obligates	Small bodied, flow-velocity specialists who spend most of their life in riffle/run habitats	Longnose dace, central stoneroller, rosyface shiner, stonecat, darters
Riffle associates	Species with moderate-sized home range that migrate in the spring to spawn and need access to, and connectivity between, riffle habitats	Lake sturgeon, silver lamprey, American brook lamprey, suckers, white bass, walleye
Nest builders	Similar timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy (includes true nests, mound construction and ledge spawners)	Brown bullhead, River chub, Fallfish, Creek chub, Rock bass, sunfishes., smallmouth bass
Marsh spawners	Large-bodied fish that rely on spring flows to flood emergent vegetation for spawning	Bowfin, Northern Pike, Muskellunge
Anadromous sport fish	Salmonid species that use lake habitats for adult growth and stream habitats for spawning and juvenile growth	Atlantic salmon, rainbow trout

Target species groups will be used in conjunction with a hydrologic habitat classification to identify testable flow-ecology hypotheses and develop flow alteration-ecological response curves that will be the basis for flow recommendations for the project area. We will link each species group to one or more habitat types identified in the next step of the project (hydrologic habitat classification). It is important to recognize that every species within a group may not be present in each habitat type. Utilizing DEC datasets, we will crosswalk individual species, within target groups, with future hydrologic habitat classes to identify which species should be used to develop flow ecology relationships between target groups and distinct hydrologic habitats. The following sections provide detailed descriptions of each flow ecology target species group **(Table 1)** with supporting information on temperature, habitat and flow needs **(Appendix Tables 1-6)** and relationships between important life history events and representative hydrographs **(Figures 2-7)**.

Cold Headwater Fish

While Atlantic salmon enter tributary streams from lake and marine environments for spawning, **brook trout** (*Salvelinus fontinalis*) represent the only native salmonid that permanently resides in New York streams. **Brown trout** (*Salmo trutta*) were first introduced to NY waters in 1883, have similar stream habitats requirements to, and can displace brook trout (Smith 1985). Brook trout are limited by temperature and habitat conditions within NY streams, preferring cold stream temperatures, gravel substrates for spawning, and adequate cover for adult habitats **(Appendix Table 1)**. All aspects of the life history of brook trout are influenced by stream flow and its interaction with other limiting factors **(Figure 2)**. In New York, male and female brook trout seek out spring-fed headwater streams or tributaries in October with peak spawning activity occurring in in gravel substrates associated with groundwater flow at the beginning of November (Hazzard 1932) **(Figure 2)**. Sediment accrual in redds can limit recruitment (Alexander and Hansen 1986, Argent and Flebbe 1999) and high seasonal flows leading up to spawning are important for maintaining sediment free spawning redds (Hakala and Hartman 2004). Egg and larvae develop through the late fall and early winter **(Figure 2)**. Stable baseflows are important for protecting redds from sedimentation, infiltrating surface water and ice (Curry et al. 1994, Curry et al. 1995), whereas scour events can destroy redds during incubation or flush fry during swim-up periods (Raleigh 1982, Curry et al. 1994, Curry et al. 1995, Denslinger et al. 1998, Kocovsky and Carline 2006, Hudy et al. 2008, Warren et al. 2009). Temperature and habitat are the primary factors limiting adult brook trout. Brook trout use localized coolwater areas to lower their body temperature below that of the water column, and loss of groundwater discharge areas within pools and tributary confluences can impact populations (Baird and Krueger 2003). Reduction in surface water discharge during summer months significantly reduces brook trout habitat quality and availability, including a reduction in riffle habitats, spatially-limited food resources, and increased fine sediment within spawning habitats **(Figure 2)**. Juveniles and adults exhibit diurnal differences in habitat use during summer and autumn. Juveniles in particular, inhabit higher velocity areas during the day but utilize slower currents at night (Johnson et al. 2011). Adult abundance and biomass in run habitats decline with flow reduction and carrying capacity is likely limited by available pool area during low flow periods (Kraft 1972, Hakala and Hartman 2004, Walters and Post 2008).

Sculpins (family Cottidae) frequently co-occur with trout and are common in cooler streams and lakes. Mottled sculpins (*Cottus bairdi*) and slimy sculpins (*Cottus cognatus*) can be found in cool water streams within Lake Ontario drainages (Smith 1985). Sculpin population size is density dependent (Grossman et al. 2006) and influenced by intraspecific competition between juveniles and adults. Fish select for microhabitats where macroinvertebrate prey abundance is high (Petty and Grossman 1996), but juveniles are restricted to shallower microhabitats by adults who prefer deeper areas dominated by erosional substrata (cobble, boulder) (Freeman and Stouder 1989, Grossman and Ratajczak 1998) **(Appendix Table 2)**. Winter baseflow may limit habitat availability for populations by increasing intraspecific habitat competition between juveniles and adults, which can impact overall population size (Rashleigh and Grossman 2005) **(Figure 2)**. Spawning occurs in early spring when temperatures reach 40 – 60 F (Smith 1985) and spring flows may influence reproductive success **(Figure 2)**. There is evidence for nest guarding within the genus with Bailey (1952) reporting that *Cottus* males build nests on large substrates and attend eggs while they incubate (21-28 days) and during the fry stage (~ 14days) (Bailey 1952) (Table 2). Sculpins have a relatively small home range (< 15 m) making them vulnerable to localized disturbance (Hill and Grossman 1987). However, flow may influence density dependent movement, as juveniles that move during low flow periods in response to high adult densities have higher growth rates (Petty and Grossman 2004).

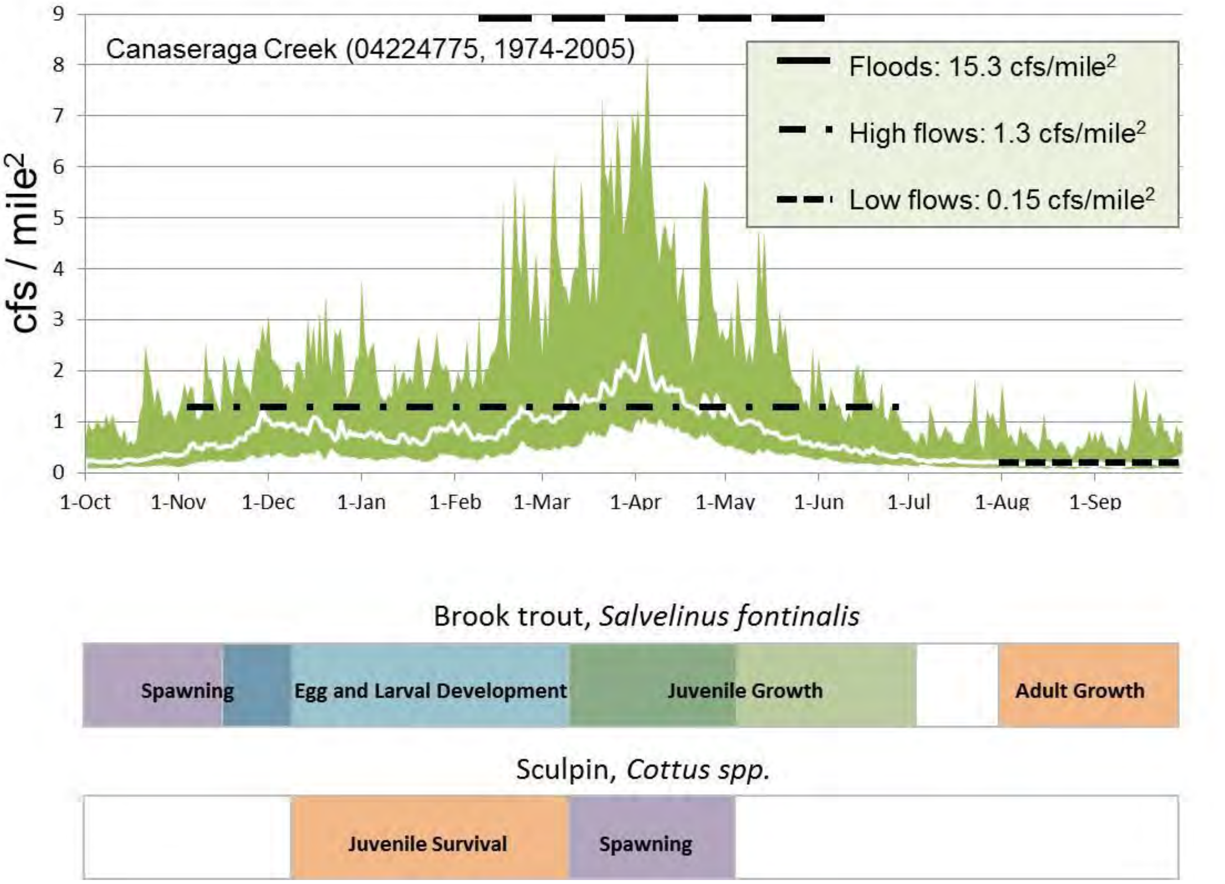


Figure 2. Representative un-altered hydrograph from a small trout supporting stream, Canaseraga Creek in western New York, with associated life history phenology for target coldwater target species.

Riffle Obligate Fish

Small-bodied fish that occupy riffles with moderate to fast currents over course substrate are common in a wide range of stream types, ranging from cold headwater streams to mainstem rivers. Moderate and fast velocity riffle and run habitats become scarce or absent during low flow periods and are particularly vulnerable to withdrawals. This makes riffle obligates an important ecological target when developing flow recommendations (Leonard and Orth 1988, Aadland 1993). Presence, as well as, persistence of riffle habitats is important for several species **(Appendix Table 2, Figure 3)**. **Longnose dace** (*Rhinichthys cataractae*) adults occupy shallow, fast riffle habitat (> 45 cm S^{-1}) while fry are generally found along stream margins during summer months (Gibbons and Gee 1972, Aadland 1993). There is evidence for intraspecific competition for high flow habitats with juveniles occupying higher velocity habitats when adults are not present (Mullen and Burton 1998). Adult longnose dace over-winter in crevices beneath cobble substrates in slightly deeper, fast moving water (Cunjak and Power 1986). **Rosyface shiner** (*Notropis rubellus*) prefer high velocity habitats at the base of riffles in moderate to large-sized streams but over-winter in pools (Reed 1957, Smith 1985). Spawning occurs at the head of

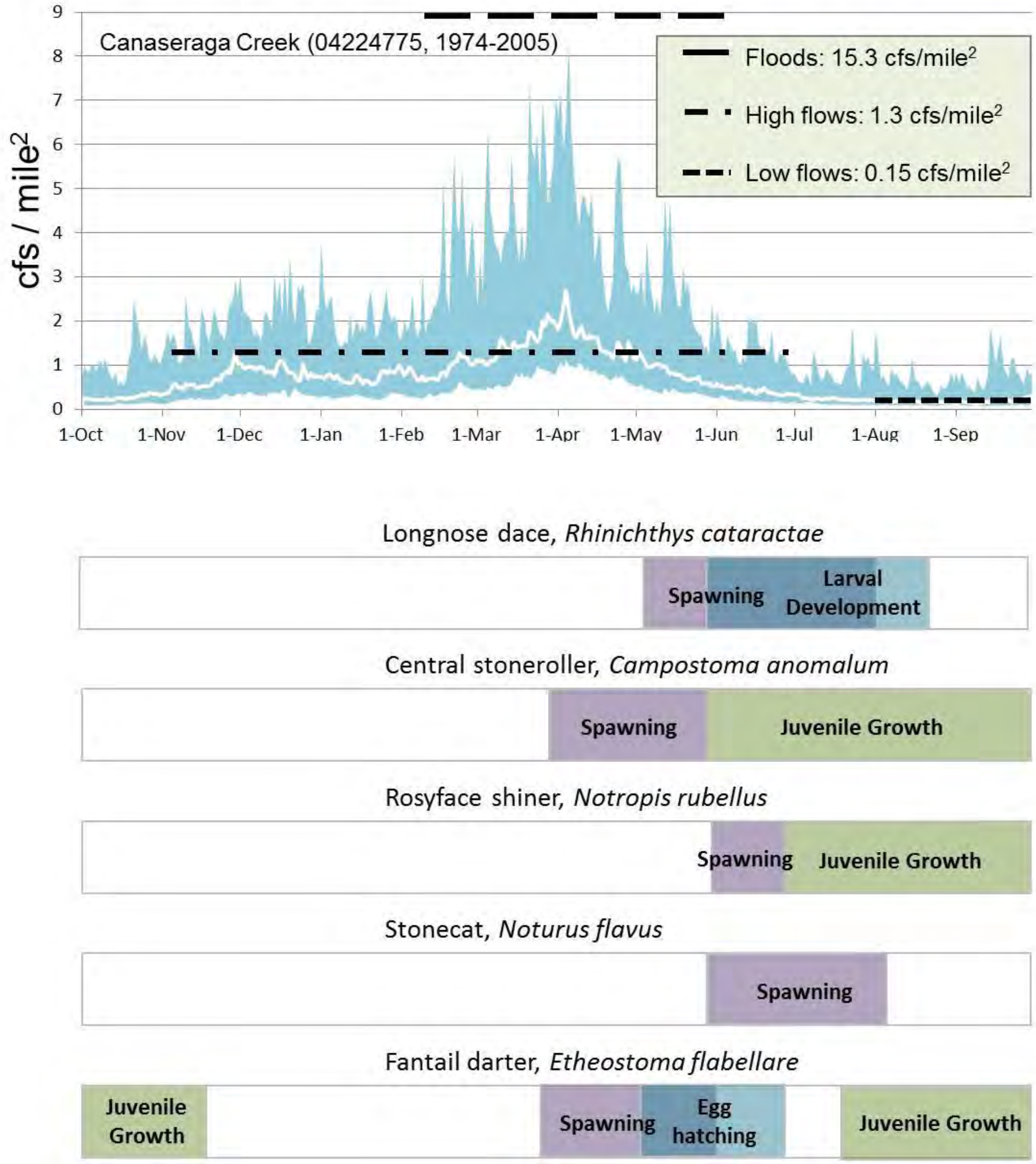


Figure 3. Representative un-altered hydrograph from a small stream, Canaseraga Creek in western New York, with associated life history phenology for target riffle obligate target species.

pools in June (Pfeiffer 1955). Central stonerollers (*Campostoma anomalum*) also prefer shallow, flowing waters over hard substrates on the margins of riffle habitat. Stonerollers can occupy pools during low flow periods but are more susceptible to predation (Power and Matthews 1983). **Stonecat** (*Noturus flavus*) juveniles and adults use shallow riffle habitats in autumn, but adults potentially use deeper habitats in the summer to spawn (Brewer et al. 2006, Brewer and Rabeni 2008). **Rainbow darters** (*Etheostoma caeruleum*), **Fantail darters** (*Etheostoma flabellare*), and **Greenside darters** (*Etheostoma blenniodes*) all prefer large substrates in riffle habitats (Schlosser and Toth 1984, Smith 1985, Chipps et al. 1994). Rainbow darter spawning activity has been reported from March through June, while fantail and greenside darters spawn from April through June (Smith 1985) **(Appendix Table 2, Figure 3)**. Males of fantail darters tend nests during egg incubation. Schlosser and Toth (1984) found that rainbow darters move in to sub-optimal habitats (deeper, slower) during low flow periods, which contributes to increased variation in population size.

Riffle Associate Fish

Riffle associates comprise a group of species that rely on access to, or connectivity between, riffle habitats during spawning and larval stages. Spawning runs begin in early spring with **walleye** (*Stizostedion vitreum*), followed by **white sucker** (*Catostomus commersoni*), and continues into late spring with runs of **american brook lamprey** (*Lampetra appendix*), **silver lamprey** (*Ichthyomyzon unicuspis*), **white bass** (*Morone chrysops*), and several species of suckers including **northern hogsucker** (*Hypentelium nigricans*) and members of the **redhorse** group (*Moxostoma anisurum, M. duquesnei, M. macrolepidotum, M. valenciennesi*) **(Appendix Table 3, Figure 4)**. Spawning occurs in shallow habitat with coarse substrates (primarily gravel and cobble) and moderate-fast flows for spawning, and is followed by a pelagic larval drift phase for most species (D'Amours et al. 2001). **Lake sturgeon** (*Acipenser fulvescens*) were historically abundant but are currently threatened in NY waters and the subject of restoration efforts (Carlson 1995, Chalupnicki et al. 2011). Lake sturgeon exhibit similar habitat preferences and timing of spawning and larval drift activities (LaHaye et al. 1992, Auer 1996, Auer and Baker 2002, Bruch and Binkowski 2002, Peterson et al. 2006) and we group them with riffle associates, despite being larger bodied and migrating considerably farther distances (Peterson et al. 2006) **(Figure 4)**. **Sea lamprey** (*Petromyzon marinus*) have spawning requirements similar to silver lamprey, and within the same timeframe as other riffle associate fish. Balancing the flow needs of riffle associate species with management concerns about sea lamprey will likely complicate developing flow prescriptions for this group.

Stream hydrology can influence riffle associate spawning runs through several mechanisms. First, successful recruitment requires sediment free substrates, and high flow events in late winter or early spring are necessary for removing fine sediment from spawning habitats. Second, peak flow events combined with rising temperatures may serve as cues for some species to migrate (Curry and Spacie 1984, Quist et al. 2002, Kelder and Farrell 2009). However, additional high flow events after spawning runs have commenced can decrease recruitment success by dislodging fertilized eggs and larvae (Mion et al. 1998) or terminate spawning activities for redhorse species (Kwak and Skelly 1992). Third, higher baseflows increase connectivity and availability of high quality spawning habitats for riffle associate species (Curry and Spacie 1984, DiCenzo and Duval 2002, Quist et al. 2002). The larval phase of many

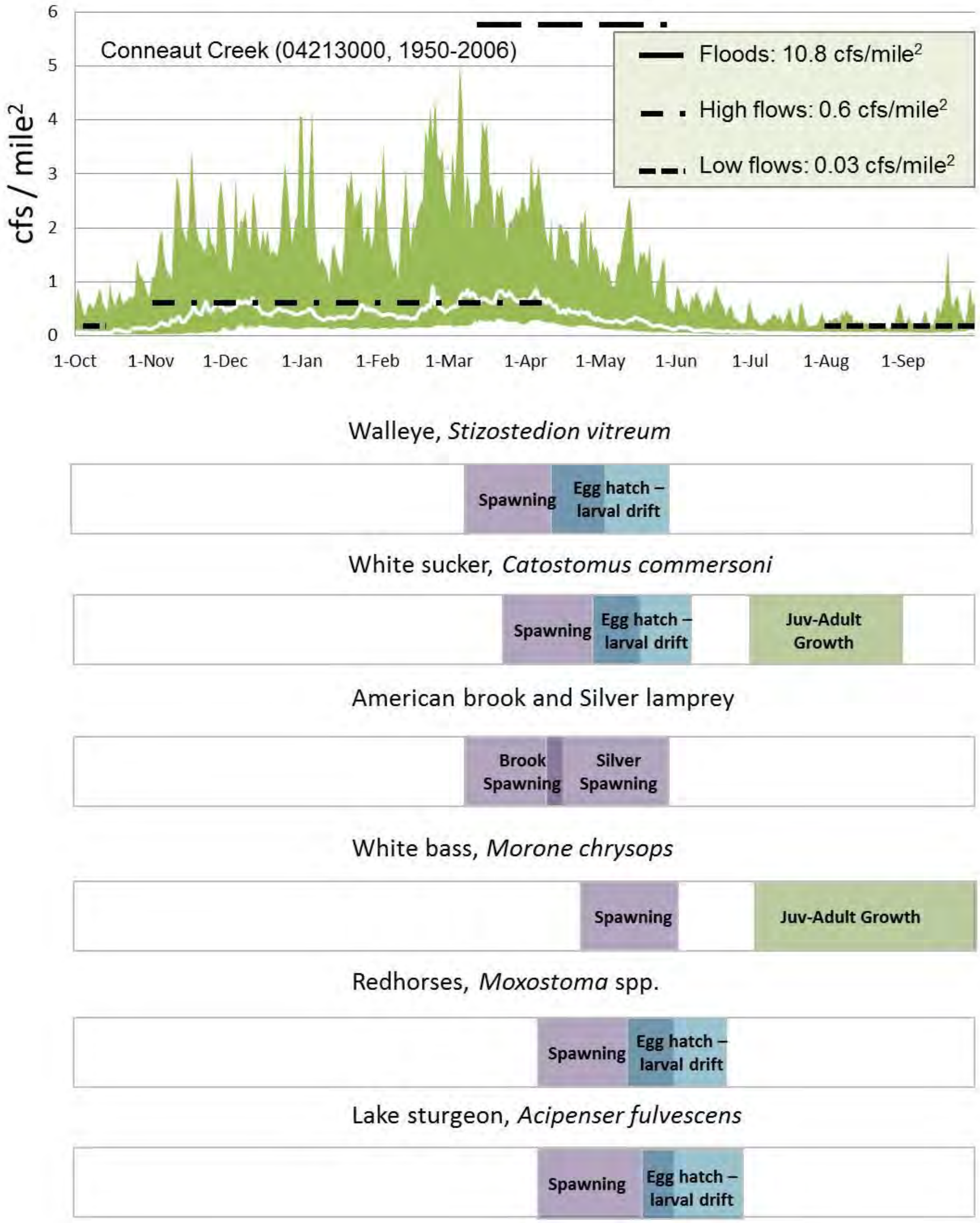


Figure 4. Representative un-altered hydrograph from a medium-sized Lake Erie tributary stream with associated life history phenology for riffle associate target species.

riffle associate species is dependent on appropriate stream flow as well. Larvae emerge from the substrate and drift primarily at night toward juvenile nursery habitats in May and June **(Figure 4)**. This period is important for metamorphosis and larvae are vulnerable to flow and temperature changes, especially species drifting considerable distance to lentic nursery habitats (walleye, white bass, lake sturgeon). The duration of the drift stage is flow dependent (Corbett and Powles 1986, Auer and Baker 2002) and low discharge combined with high temperatures may lead to rapid yolk metabolism and starvation of walleye larvae, with discharge being more important at distances less than 100 km (Mion et al. 1998, Jones et al. 2003). This effect likely influences other riffle associate species success as well. Conversely, while high flow events increase drift densities (Smith and King 2005), associated sediment loads can physically damage larvae (Mion et al. 1998), but higher flows with some turbidity may increase survival by limiting predation or decrease completion among larvae through greater dispersion (Nilo et al. 1997). Overall, high flow pulses in early spring, coupled with higher but stable flows throughout the spawning and larval drift period (April-June) likely improve recruitment of riffle associate fish. In fact, size of spawning runs and year class strength for lake sturgeon and white bass have been positively associated with higher spring flows (Auer 1996, Nilo et al. 1997, Sammons and Bettoli 2000, DiCenzo and Duval 2002, Willis et al. 2002).

Nest building fish

Nest building species exhibit a variety of nesting strategies but are grouped based on nest success being tied to stable flows during the late spring-early summer reproductive season **(Appendix Table 4, Figure 5)**. Target species within this group include **fallfish** (*Semotilus corporalis*), **creek chub** (*Semotilus atromaculatus*), **river chub** (*Nocomis micropogon*), **brown bullhead** (*Ictalurus nebulosus*), **rock bass** (*Ambloplites rupestris*), **sunfish** (*Lepomis gibbosus*, *L. macrochirus*, *L. megalotis*), and **smallmouth bass** (*Micropterus dolomieu*) **(Table 1)**. Nests may be built in riffles, channel margins, or pools. Regardless of nesting habitat, stream discharge during and immediately after spawning is critical to nest success and recruitment. High discharge can scour nests or force guarding parents to abandon the nest and nest failure for rock bass, sunfish, and smallmouth bass has been linked to high flow events during the nesting period (Graham and Orth 1986, Noltie and Keenleyside 1986, Lukas and Orth 1993, Jennings and Phillipp 1994, Lukas and Orth 1995) **(Figure 5)**. Use of shade or debris for cover can lead to nests being built in channel margins for some species, making nests susceptible to rapid decline in discharge which can desiccate eggs and strand larvae (DePhillip and Moberg 2010). At lower more stable flows nest success is more associated with biotic interactions and positively related to guarding male size (Noltie and Keenleyside 1986, Jennings and Phillipp 1994, Dauwalter and Fisher 2007). Size of guarding males is also related to recruitment success during seasons with high flow variability, as larger individuals make earlier attempts and have more re-nesting opportunities (Noltie and Keenleyside 1986, 1987, Lukas and Orth 1995). In general, stable moderate flows during the nesting and early development periods are associated with recruitment success of this group (Noltie and Keenleyside 1986, Lukas and Orth 1995, Smith et al. 2005) **(Figure 5)**. Nests constructed by this group are necessary for the recruitment of other species as well. For example, 27 minnow species use nests constructed by the genus *Nocomis*, either simultaneously or once abandoned (Sabaj et al. 2000). In addition to spawning activities, juvenile *Lepomis* sp. utilize aquatic vegetation for foraging and cover from predation (Mittelbach 1984). Scour events may limit macrophyte habitat for sunfishes during the summer growth period.

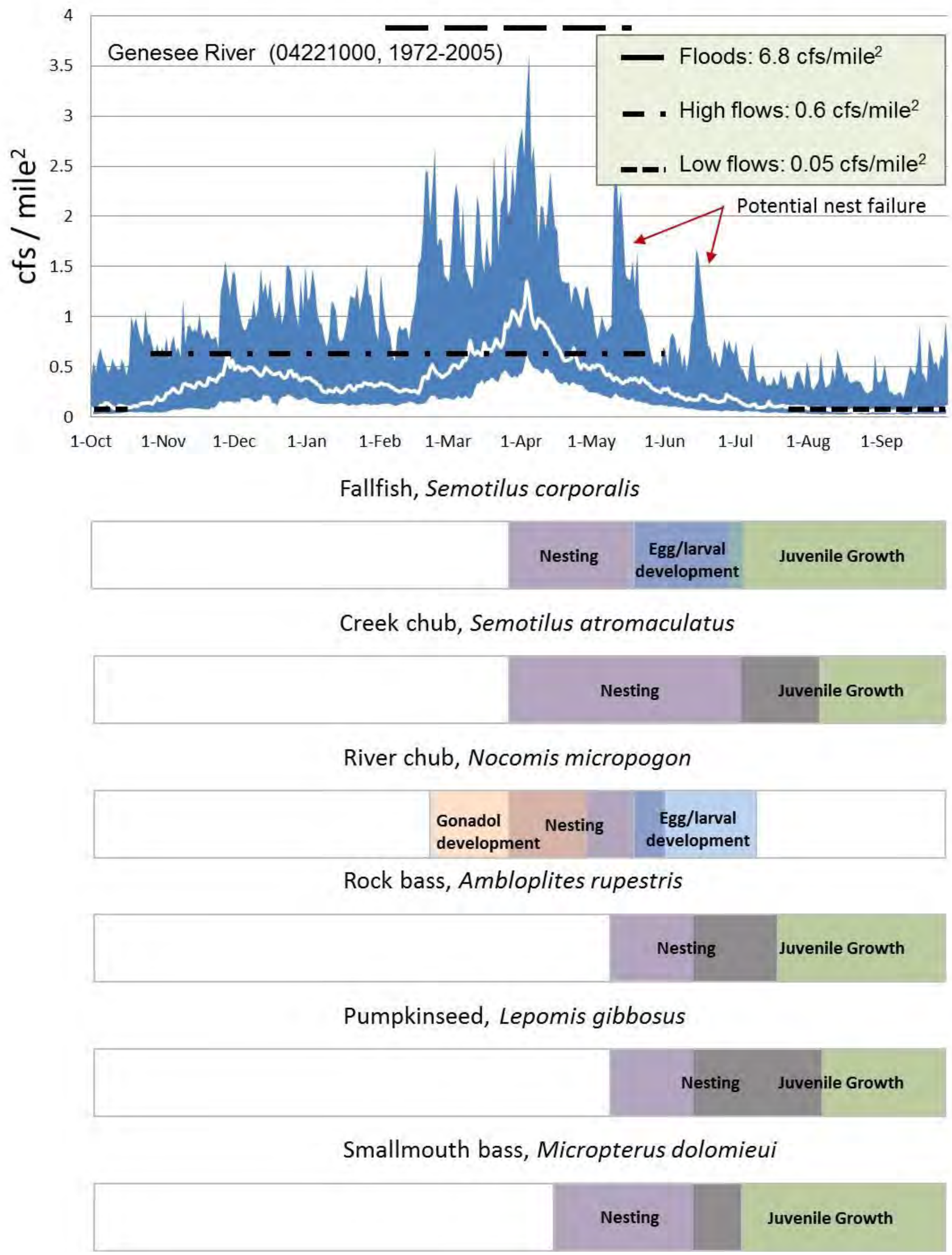


Figure 5. Representative un-altered hydrograph from a large river in western New York with associated life history phenology for nest building target species.

Marsh spawning fish

Temperature during early life stages is an important predictor of year class strength in **northern pike** (*Esox lucius*) and water levels influence the spatial and temporal availability of optimum spawning habitat (Farrell et al. 2006b, Smith et al. 2007, Mingelbier et al. 2008) **(Appendix Table 6)**. Successful pike recruitment is tied to water level and temperature because of sensitive spawning and nursery requirements associated with aquatic vegetation (Craig 2008). Northern pike will utilize three different types of habitat spanning the littoral gradient of lakes; tributary marshes, shallow bays, and deep littoral habitats. Shallow tributary habitats are preferred because they provide warmer temperatures earlier in the spring, which is predicted to contribute to higher survivorship and overall pike production (Farrell et al. 2006b). Shallow tributary marsh habitats are warmer and more abundant at higher discharge during early spring (Mingelbier et al. 2008), and Smith et al. (2007) demonstrated that spring water levels are positively associated with pike year class strength. Success of early life stages depends not only on availability of shallow tributary marsh habitats for egg deposition, but also the probability that those habitats will not be lost to dewatering during egg incubation and fry stages (Mingelbier et al. 2008). The highest quality habitats (shallow sedge marshes) are the first spawning habitats to be affected by dewatering. After spawning, these areas need to remain wetted for approximately 4 weeks to allow egg incubation and fry to reach swim-up size (20 mm) and avoid being trapped in vegetation during dewatering (Fortin et al. 1982). Thus, spring flood amplitude and duration are important for maintaining optimal spawning and nursery habitats for northern pike **(Figure 6)**. Altering the frequency and amplitude of spring water levels through discharge and/or lake level regulation as well as geomorphic changes (dredging and shoreline development) will affect spawning and overall productivity of northern pike (Cohen and Radomski 1993, Farrell et al. 2006b, Smith et al. 2007, Hudon et al. 2010). It should be noted that water levels in most spawning habitats will be a function of both instream flows as well as lake outlet flows which may be controlled by additional water management activities (dams, locks).

Summer low flows may influence pike success through direct effects on growth and indirect effects on vegetation composition in marsh spawning habitats. Summer temperatures during the first year of development are important to pike recruitment success (Craig and Kipling 1983). Higher depths during the juvenile stage are associated with lower water temperatures which may limit growth (Smith et al. 2007). Lower summer growth rates have negative consequences including increasing length of exposure to size-specific predation risks (Smith et al. 2007) and not meeting sufficient size for winter survival (Kipling 1983). Historic emergent wetland habitat is maintained by interannual variability, peak flows and periodic low flow periods. Saturation of shallow marsh habitat throughout the summer growing season replaces diverse mixed emergent plant assemblages (high quality spawning habitat) with dense cattail *(Typha* spp.) stands. Overall, periodic summer low water periods combined with higher winter and spring water levels regulate cattail density and maintain healthy pike spawning and nursery habitats (Farrell et al. 2010) **(Figure 6)**. Lack of access to suitable spawning habitat associated with low water levels in the spring or increased cattail density push northern pike into deeper spawning habitats typically used by **muskellunge** (*E. masquinongy*). Despite considerable overlap with muskellunge and higher egg deposition rates for northern pike, overall survivorship and predicted pike production from these habitats is low (Farrell 2001, Farrell et al. 2006b). Poor recruitment success of northern pike in deepwater spawning habitats favors muskellunge production during years where favorable pike spawning habitat is not available (Cooper et al. 2008).

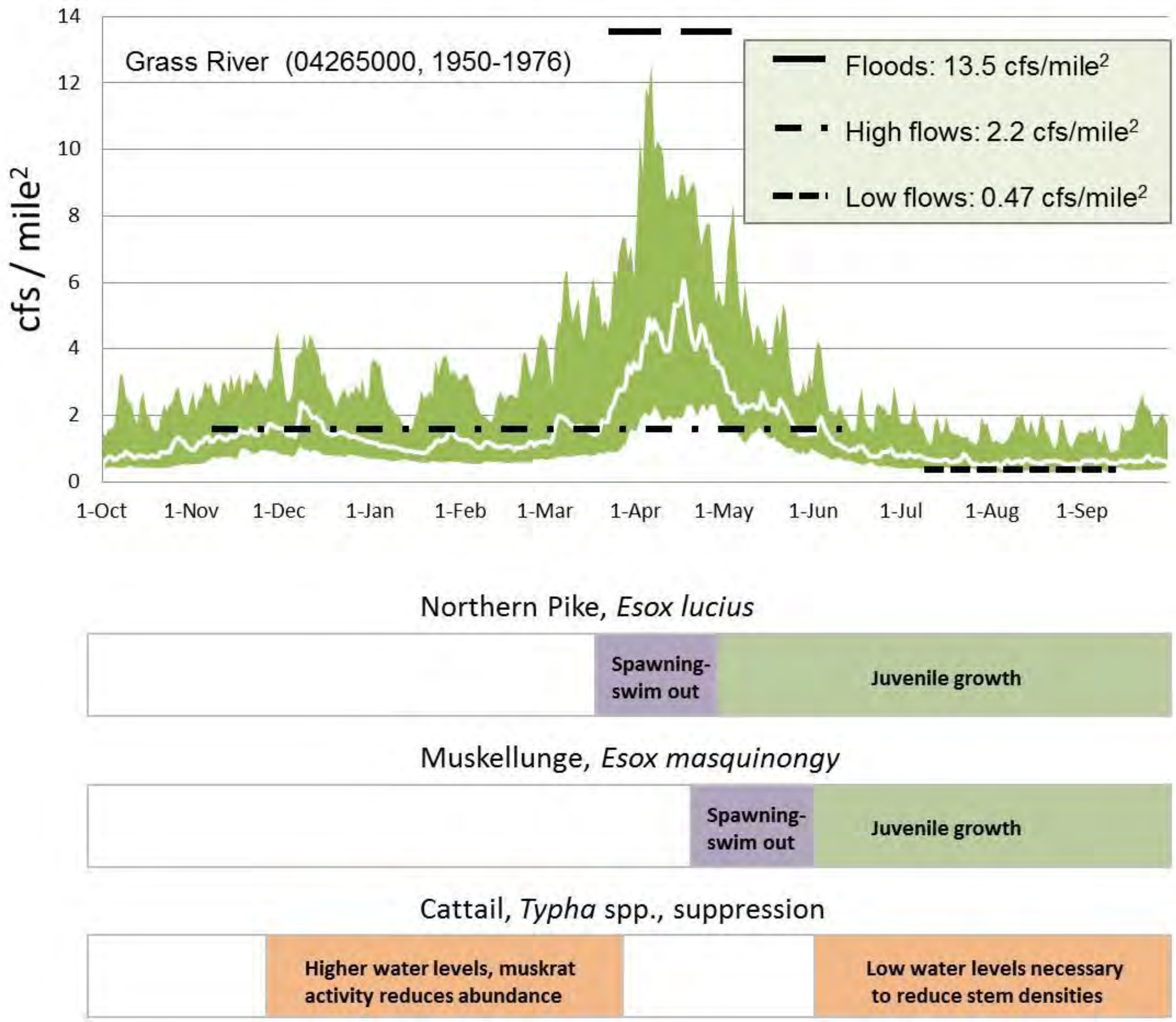


Figure 6. Representative un-altered hydrograph from a medium-sized St. Lawrence River tributary stream with associated life history phenology for marsh spawning target species and invasive plant control target periods.

Anadromous sport fish

Atlantic salmon were once an important component of the historical native fish community with spawning runs occurring in every major Lake Ontario tributary, as well as sustainable populations in the Finger Lakes (Webster 1982). Overfishing, construction of mill dams, habitat destruction, pollution, and nonnative species introductions led to the collapse of this native salmonid fishery by the late 1800s (Christie 1974, Webster 1982). Attempts to reestablish naturally reproducing populations through stocking of Adirondack progenitor stock within the Finger Lakes and Lake Ontario have had limited success, largely due to the 'Cayuga syndrome,' a non-infectious disease that kills all yolk-sac fry (Fisher et al. 1995). Cayuga syndrome is the result of thiamine deficiencies linked to high thiaminase activity in nonnative alewives (*Alosa pseudoharengus*), the primary forage fish of current lake dwelling salmonids

(Fisher et al. 1996, Ketola et al. 2000). However, there is recent evidence of natural reproduction of atlantic salmon in the Salmon River, near Puluski, NY (J. H. Johnson, personal communication). In addition, other Lake Ontario and Erie tributaries currently support a reproducing salmonid sport fishery for Pacific salmonids including chinook salmon (*Oncoryhynchus tshawytscha*), coho salmon (*O. kisutch*), and especially **rainbow trout** (*O. mykiss*), which also occur in several Finger Lakes systems. Competition between atlantic salmon and nonnative salmonids for juvenile rearing habitat (Johnson and Wedge 1999, McKenna and Johnson 2005), as well as, spawning habitat (Scott et al. 2003), may hamper future native salmonid restoration efforts. Despite this, flow requirements for native and non-native salmonids are similar and maintaining ecological flow components that support salmon spawning runs and juvenile nursery habitat for the current migratory salmonid fishery is important because: 1) salmon runs contribute to overall ecosystem function by potentially providing an important influx of lake-derived nutrients (Schuldt and Hershey 1995, Gende et al. 2002), and 2) pacific salmon runs support a popular sport fishery with substantial recreational and economic benefits to the state.

Fall-run salmonids include atlantic salmon, chinook salmon, coho salmon, and lake-dwelling brown trout. Peak spawning occurs in November for atlantic salmon with adults moving up-stream in greater numbers on the descending limb of high flow events (Trepanier et al. 1996) **(Appendix Table 6)**. Increased flows, combined with declines in temperature and day length encourage movement onto spawning areas and redd construction (Enders et al. 2009) **(Figure 7)**. Chinook and cohos have a similar spawning phenology, generally entering Great Lake tributary streams in October, peaking in mid to late November (Carl 1983). However, spawning phenology for fall-run migratory salmon is slightly different for NY streams, with atlantic salmon moving into tributaries as early as July-August followed by chinooks and cohos in early and mid-September, respectively (J. H. Johnson, personal communication) **(Figure. 7)**. In NY streams, salmon spawn in October thru November, with migratory brown trout spawning slightly later (J. H. Johnson, personal communication). Fall flows influence spawning success and recruitment, with a strong relationship between fall flows (mean Oct 1-21), and YOY Chinook produced in subsequent springs in the Salmon River, NY (Bishop et al. 2008). Stable low flow conditions in winter are necessary for incubation of eggs and overwintering of juveniles (Enders et al. 2009) **(Figure 7)**. Winter spates are negatively correlated with egg-to-fry survivorship of both Atlantic and Pacific salmonids (Gibson and Myers 1988, Greene et al. 2005). Autumn rainbow trout migrations can occur from September to December, with fish overwintering in streams or returning to the lake until spawning. A three week spawning period for rainbow trout generally occurs during peak flows associated with snowmelt in early March to late April (Biette et al. 1981) **(Figure 7)**. Fry for all species emerge during the declining limb of the hydrograph in May/June and reside in streams until the following April, except for Chinook, which move to lake habitats immediately in NY streams (Carl 1983, Enders et al. 2009) **(Figure 7)**. Smolts (atlantic and coho salmon, rainbow trout) representing previous year's cohorts may use spring freshets to out-migrate to lake environments, avoiding predation in higher flows with increased turbidity (Enders et al. 2009). Stable baseflows in winter and summer are necessary for survival and growth of Atlantic salmon juveniles, which are likely positively correlated with baseflow discharge during these periods (Gibson and Myers 1988, Nislow et al. 2004, Enders et al. 2009).

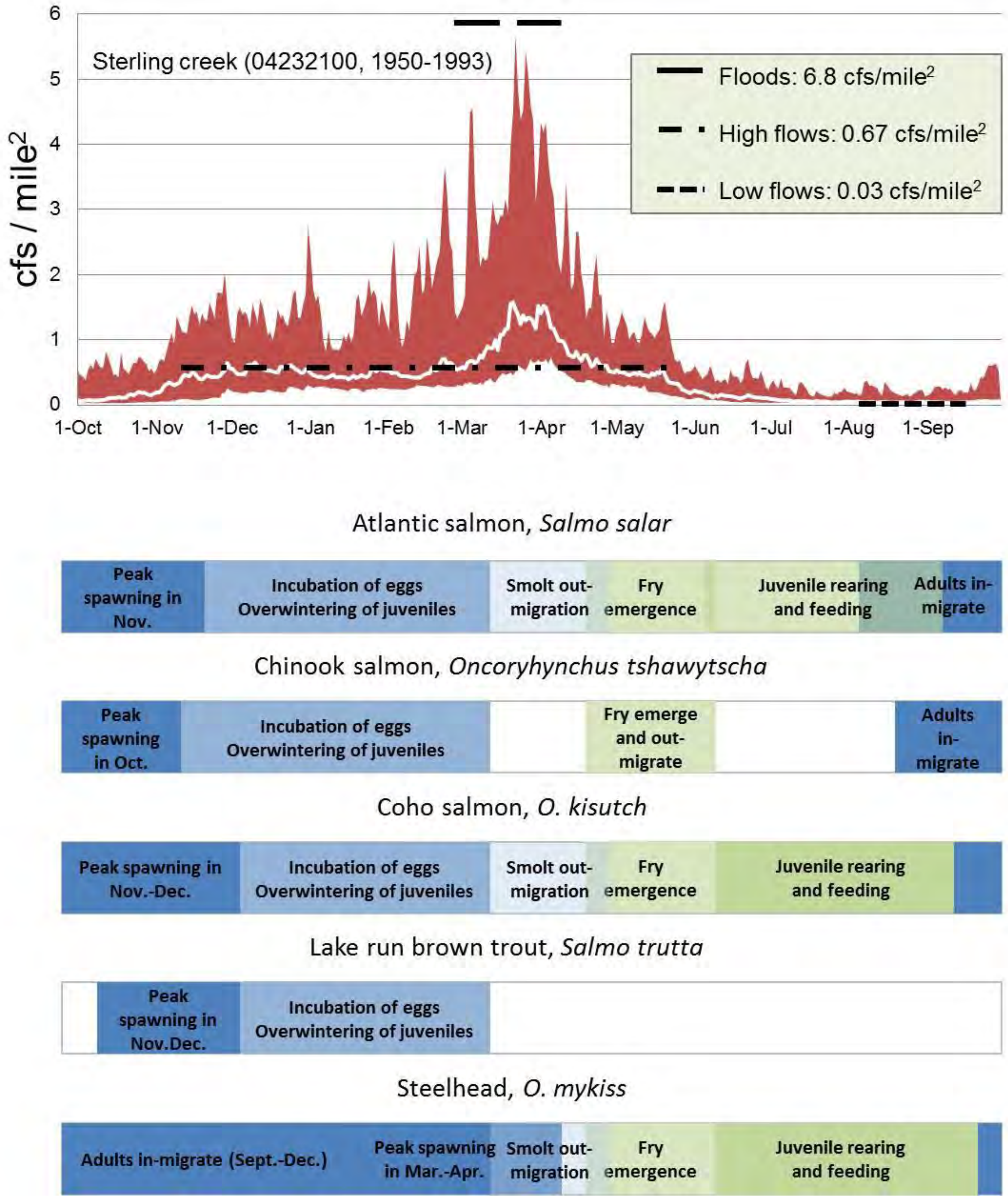


Figure 7. Representative un-altered hydrograph from a small Lake Ontario tributary stream with associated life history phenology for anadromous sportfish target species.

Target mussels: species descriptions

Freshwater mussels are among the most threatened taxonomic groups in North America (). The inland waters of New York that flow into Lake Erie, Lake Ontario, and the St. Lawrence River **(Figure 1)** historically supported a mussel fauna that included 41 or 42 confirmed species (Strayer and Jirka 1997). Current records estimate the regional species pool to include 28 to 32 species. State endangered species with historic records from within the project area include the **fat pocketbook** (*Potamilus capax*) with two historic records from the Niagara River/Buffalo area, and potentially the **pink mucket** (*Lampsilis abrupta*). Both of these species are likely extirpated from the basin. State threatened species confirmed from the basin include the **wavy-rayed pocketbook** (*Lampsilis fasciola*), with a few historic records from the Niagara River, and the **green floater** (*Lasmigona subviridis*), with historic records from the Genesee and Oswego River basins but currently only known from a tributary of Oneida Lake (Strayer and Jirka 1997).

We initially identified 25 mussel species as possible candidate target species for developing flow ecology hypotheses based on current distributions, habitat preferences, and potential flow needs. Based on input from expert breakout groups during the New York Sustainable Flows Project workshop (June 29, 2011) no additions or deletions were made to the list of mussel flow targets. We aggregated these species into three groups **(Table 2)** defined by a combination of hydraulic habitat associations (velocity, depth, substrate and impoundments) and tolerance to changes in streamflow (DePhillip and Moberg 2010).

Table A2.2. Flow ecology target species groups based on general habitat associations.

Group	Key Traits	Species
Riverine	Primarily associated with riffle habitats. Use a wide variety of fish hosts, including small-bodied riffle obligate species.	**Elktoe**^{B}, snuffbox^B, **creek heelsplitter**^{B}, **fluted shell**^{B}, eastern pearlshell$^?$, hickory nut^B, **creeper**^{B}
Facultative riverine	Use slow to moderate current, including backwaters and standing water habitats. Utilize both lotic and lentic fish hosts.	Triangle floater, slippershell$^{B?}$, three-ridge^T, **eastern elliptio**^{T}, **spike**^{T}, **Wabash pigtoe**^{T}, yellow lampmussel, pocketbook^B, **eastern lampmussel**$^{B?}$, **fat mucket**^{B}, **black sandshell**^{B}, **pink heelsplitter**^{B}, **rainbow**^{B}
Lentic-pool	Associated with slow-moving river habitats, including channel margins and pools. Use a wide variety of fish hosts.	**Cylindrical papershell**^{B}, **eastern pondmussel**^{B}, eastern floater^B, **floater**^{B}, Lilliput^B

Reproductive strategy

^{B} Bradytictic: glochidia overwinter in the marsupial demibranch of female- winter breeders

^{T} Tachytictic: fertilization, larval development, and parasitic period all occur in the same calendar year- summer breeders

Mussels are highly sensitive to localized physical and chemical changes in habitat conditions including dissolved oxygen (DO), temperature, depth, and velocity. There limited mobility during both juvenile and adult stages makes them more susceptible to changes in local habitat conditions resulting from altered flow regimes (). For example, significant declines in mussel communities have been observed during severe drought conditions characterized by reductions in flow and DO in southeastern streams, (Layzer and Madison 1995, Johnson et al. 2001, Golladay et al. 2004, Haag and Warren 2008). There is evidence from tag-recapture model estimates of three federally-endangered mussel species from the southeast that high flow events in the summer may negatively influence survival while overall decreased instream flows in the spring and summer may negatively impact recruitment. Simulations of population parameters based on these models under historic (pre-irrigation), current, and future water use scenarios indicated that the probability of extinction under current conditions was 8 times greater than under historic hydrologic conditions, and the probability of extinction would increase with increased water withdrawals (Peterson et al. 2011).

Primarily riverine species

This species group is most associated with riverine habitats with good stream flow. Species with widespread distributions within the project area include **elktoe** (*Alasmidonta marginata*), **creek heelsplitter** (*Lasmigona compressa*), **fluted shell** (*Lasmigona costata*), and **creeper** (*Strophitus undulatus*). Other less abundant riverine species whose instream flow needs may be met by the development of flow recommendations include **snuffbox** (*Epioblasma triquetra*), **eastern pearlshell** (*Margaritifera margaritifera*), and **hickory nut** (*Obovaria olivaria*). All species listed in this group exhibit a bradytictic or long-term brooding reproductive strategy. Spawning occurs between July and September, followed by females remaining gravid throughout the fall and winter, and releasing glochidia during mid to late spring (Watters et al. 2009). This reproductive strategy potentially creates year-round sensitivity to changes in streamflow as long-term brooders are in a different reproductive stage each season (DePhillip and Moberg 2010). Reproductive success may be influenced indirectly by sensitivities of host fish species to changes in flows. This target group utilizes a wide range of fish hosts, including several small-bodied riffle obligate species and larger bodied riffle associate species. Reduction of habitat for riffle obligate hosts or loss of access to spawning habitats for riffle associate hosts during the spring glochidia release period due to reduced magnitude of spring flows could influence reproductive success for primarily riverine mussel species. Increased magnitude during the same period may have negative effects on mussel reproduction as well, by decreasing the concentration of host fish and likelihood of glochida infestation or by limiting the display of lures for host attraction (Layzer 2009). Natural flow regimes also regulate mussel habitat by influencing the distribution of preferable substrates for this group, including maintaining adequate riffle/run areas with sand and gravel substrates.

Eastern pearlshell may have utility as a unique coldwater stream mussel target. Primarily a northeastern species, it is limited to soft coldwater trout streams not usually occupied by mussels, and is probably widespread in streams draining the Adirondacks (Strayer and Jirka 1997). Maturity is not reached until 12-13 years and 200 year old individuals have been reported (Young and Williams 1984, Mutvei and Westermark 2000). Glochidia are released in July-October (Smith 1976, Young and Williams 1984), and may overwinter on salmonid hosts (Young et al. 1987, Hoggarth 1992). Juveniles may spend 10 or more years buried in the substrate (Bauer 1986). The overall slow pace of the **eastern pearlshell** life cycle suggests that they may be particularly sensitive to changes in flow outside of natural ranges of variation.

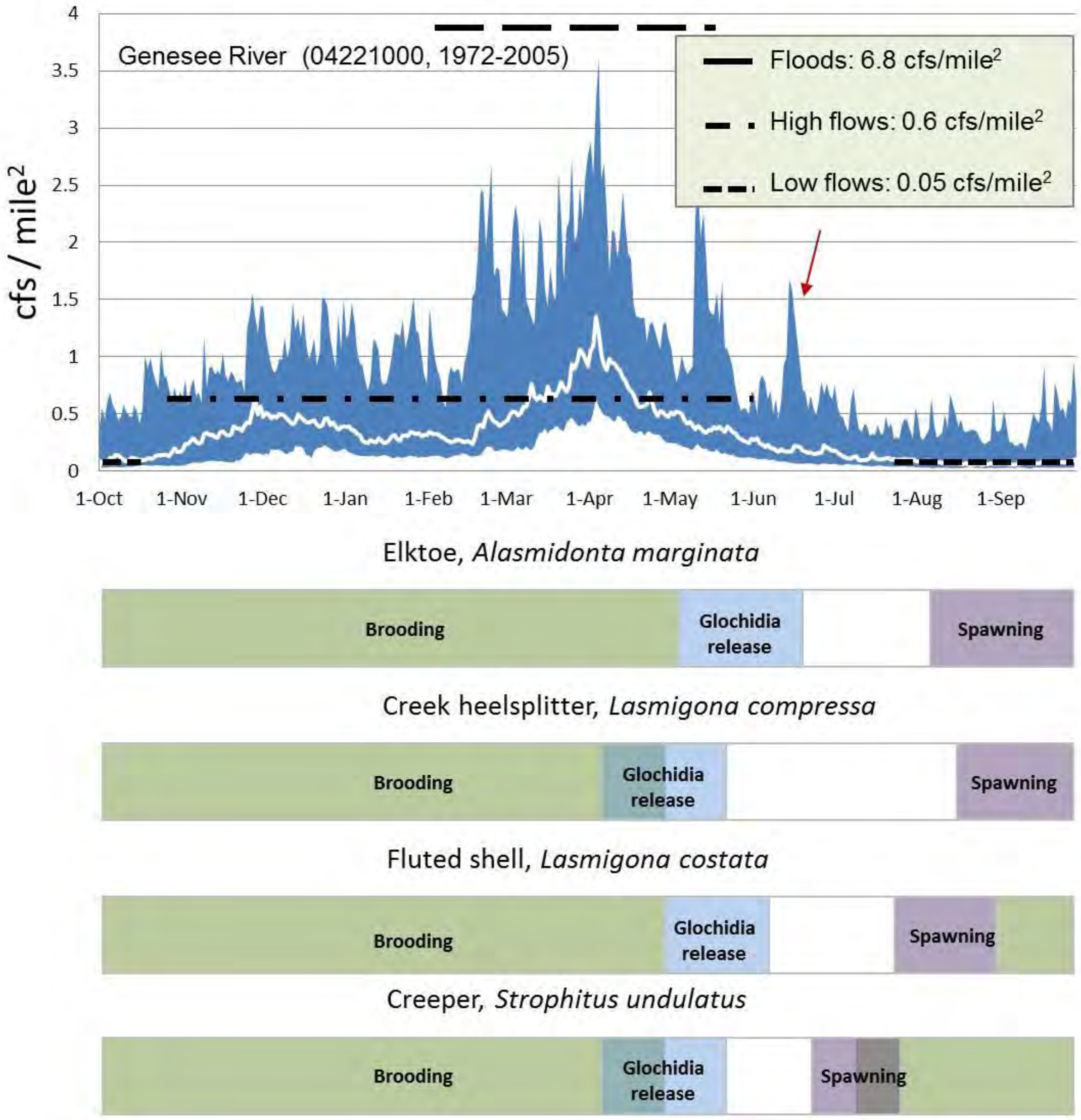


Figure 8. Representative un-altered hydrograph from a large river in western New York with associated life history phenology for riverine mussel targets.

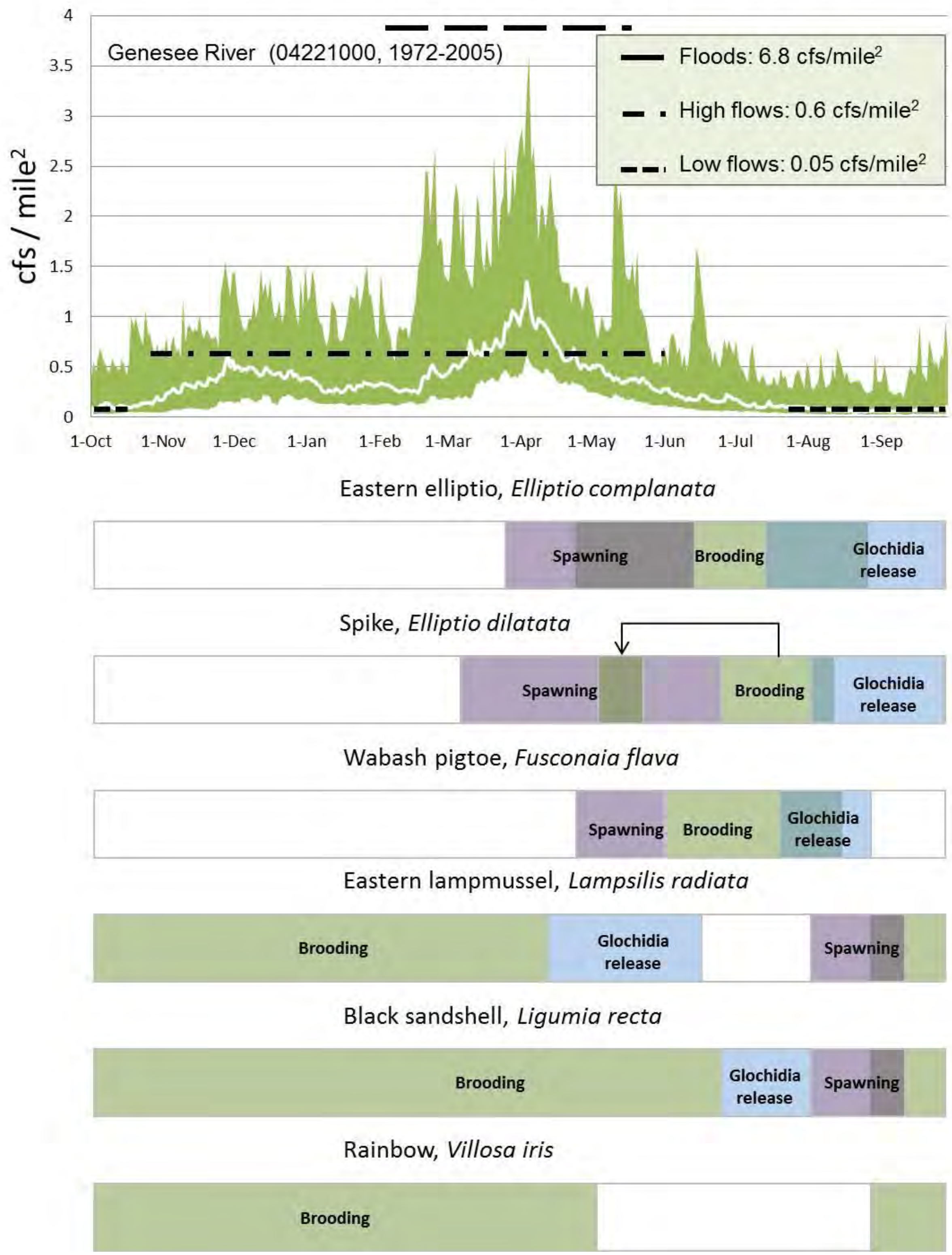


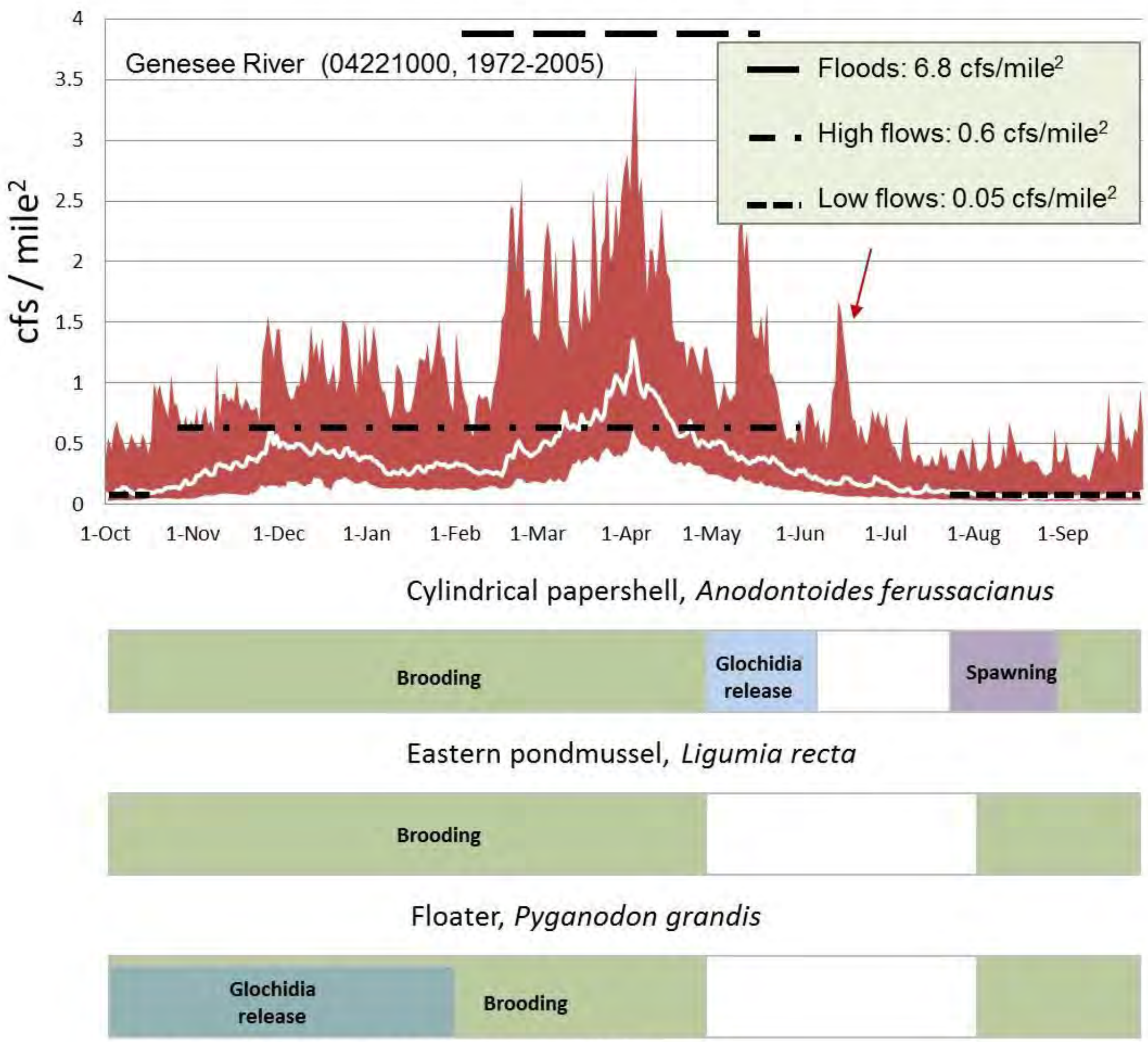
Figure 9. Representative un-altered hydrograph from a large river in western New York with associated life history phenology for facultative riverine mussel targets.

Facultative riverine species

This species group is found in a wide range of habitats from small streams to large rivers and lakes and can utilize a variety of substrates. Species that are abundant or have a widespread distribution within our study region include **eastern elliptio** (*Elliptio complanata*), **spike** (*Elliptio dilatata*), **Wabash pigtoe** (*Fusconaia flava*), **eastern lampmussel** (*Lampsilis radiata*), **fat mucket** (*Lampsilis siliquoidea*), **black sandshell** (*Ligumia recta*), **pink heelsplitter** (*Potamilus alatus*) and **rainbow** (*Villosa iris*). Some species such as the **fat mucket** are two insensitive to habitat and flow to be useful for developing flow-ecology hypotheses, while other less abundant facultative riverine species instream flow needs may be met by the development of flow recommendations for more common species. These include **triangle floater** (*Alasimidonta undulata*), **slippershell** (*Alasimidonta viridis*), **three-ridge** (*Amblema plicata*), **yellow lampmussel** (*Lampsilis cariosa*), and **pocketbook** (*Lampsilis ovata, L. cardium*) mussels. Three abundant species (**eastern elliptio, spike, Wabash pigtoe**) within this group exhibit a short-term brooding strategy with spawning occurring in late spring, followed by a short incubation period and glochidia release during summer low flow periods. Increased magnitude of summer low flows may have negative effects on mussel reproduction for these species by decreasing the concentration of host fish and likelihood of glochida infestation or by limiting the display of lures for host attraction (Layzer 2009). The remaining abundant species within this group (**eastern lampmussel, black sandshell, pink heelsplitter, rainbow**) are all likely long-term brooders with a similar reproductive phenology to riverine target species. The **black sandshell** is an exception, having an extended brooding period with glochidia release occurring in July as the summer low flow period begins. Additionally, **spikes** have two brooding and glochidia release periods and **pink heelsplitter** are thought to breed year round with overlapping brooding periods. With multiple events throughout the year, reproduction for these two species may be less susceptible to flow alteration.

Primarily lentic species

Abundant examples of lentic species within the study area region include **cylindrical papershell** (*Anodontoides ferussacianus*), **eastern pondmussel** (*Ligumia recta*), and **floater** (*Pyganodon grandis*) mussels. Other less abundant species that likely have similar flow requirements include **eastern floater** (*Pyganodon cataracta*) and **lilliput** (*Toxolasma parvum*). Species within this group are fast growing, are host generalists, and tolerate a wide range of substrates found in standing water habitats including channel margins. All three species are long term brooders but **eastern pondmussels** may breed year round. Among the three groups, lentic species are the most tolerant of disturbed conditions and can tolerate impoundment (Strayer and Jirka 1997, Nedeau et al. 2000). However, changes in flow that result in loss of backwater and slow-moving habitats in large rivers, or rapid changes in margin habitat for in smaller streams (**cylindrical papershell**), could have negative effects on species within this target group.



Cylindrical papershell, *Anodontoides ferussacianus*

Eastern pondmussel, *Ligumia recta*

Floater, *Pyganodon grandis*

Watters and O'Dee observed glochidia release at 5°C from Oct. to Feb. in Ohio. Glochida likely overwinter on hosts.

Figure 10. Representative un-altered hydrograph from a large river in western New York with associated life history phenology for lentic mussel targets.

Macroinvertebrate target group descriptions

Macroinvertebrates constitute an important functional component of stream ecosystems (Wallace and Webster 1996) and are widely recognized as a useful measure of ecological integrity in freshwater environments (Doledec and Statzner 2010). While a few studies are species specific, most macroinvertebrate responses to flow alteration have been described by aggregating taxa into groups that share **functional traits** (Poff et al. 2006) or by using **assemblage metrics** (e.g., species richness, % tolerant) (Table 3). A few studies have linked changes in functional traits or assemblage metrics to flow.

Table A2.3. Documented response of macroinvertebrate functional traits and assemblage metrics to low flow conditions (modified from DePhilip and Moberg 2010).

Responsive Traits and Metrics		**Response to Withdrawal or Low Flow**	**Citations**
Functional Traits (from Poff et al. 2006)			
Life history	Voltinism	Increase in taxa that are multivoltine	Brittian and Salveit 1989 Apse et al. 2008
	Desiccation tolerance	Persistence or increased 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 Apse et al. 2008
	Attachment	Increased abundance of free-ranging taxa	Walters 2011
Ecology	Rheophily	Increase in abundance and number of obligate depositional taxa	Lake 2003
		Decrease in number and abundance of rheophilic taxa	Wills et al. 2006 Brooks et al. 2011
	Trophic habit	Decreased diversity in grazers and shredders	McKay and King 2006
		Decreased abundance of scrapers and shredders	Richards et al. 1997
		Decreased densities and size of collector-filterer taxa	Walters and Post 2011
		Decreased 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 abundance of stenothermal (cold water) taxa	Lake 2003
General Assemblage Metrics			
	Abundance	Decrease in total number of individuals	Rader and Belish 1999 McKay and King 2006
		Decrease in biomass	Walters et al. 2010 Blinn et al. 1995 Dewson et al. 2007b
	Species richness	Decrease in taxonomic richness	Boulton and Suter 1986 Englund and Malmqvist 1996 McElravey et al. 1989 Rader and Belish 1999 Wood and Armitage 1999
		No change in taxonomic richness	Wood and Armitage 2004 Armitage and Petts 1992 Cortes et al. 2002 Dewson et al. 2003
	HBI	Increase in tolerant taxa	Bednarcek and Hart 2005 Kennen et al. 2009 Rader and Belish 1999 Apse et al. 2008 Walters 2010
	EPT richness	Decrease in density of EPT taxa	Bednarcek and Hart 2005 Kennen et al. 2009 Miller et al. 2007 Wills et al. 2006 Dewson et al. 2007b

alteration through experimental withdrawals and diversions (Dewson et al. 2007, Brooks et al. 2011, Walters 2011, Walters and Post 2011), experimental reservoir releases (Bednarek and Hart 2005), and correlative studies across gradients of hydrologic alteration or monitoring during extreme hydrologic conditions (Boulton et al. 1992, Kennen et al. 2009, Carlisle et al. 2011). These studies from other rivers systems can help set expectations for macroinvertebrate response to flow alteration and potential mechanisms in Great Lakes tributary streams.

Lotic insect functional traits

Poff et al. (2006) published a synthesis of 20 **functional traits** for 70 North American lotic insect families. A traits based approach can provide a mechanistic link to understanding or predicting macroinvertebrate responses to varying environmental conditions by summarizing the response of groups of species based on their similarities in life histories, and physiological and morphological requirements and adaptations (Vieira et al. 2006). DePhilip and Moberg (2010) identified a subset of traits that are expected to be most sensitive to changes in hydrology within the Susquehanna River basin (Table 3). We use this subset of functional traits here to describe potential mechanisms underlying expected responses of macroinvertebrate communities to flow alteration in Great Lakes tributary streams.

Duration of aquatic insect life cycles ranges from less than 2 weeks to more than 2 years, and are catergorized as univoltine, bivoltine, trivoltine, multivoltine to describe species with 1, 2, 3, or multiple generations per year (Fig. 11). Semivoltine species take two years to develop and longer lived species are described as merivoltine (Wallace and Webster 1996). Life cycles can further be described as slow seasonal, fast seasonal and nonseasonal life cycles for aquatic insects in temperate streams (Hynes 1970). Multivoltine, nonseasonal life cycles characterized by short development times, may be an adaptation to disturbance prone environments (Taylor and Kennedy 2006) and have been shown to increase along gradients of increasing water withdrawals or other flow alterations (Brittain and Saltveit 1989, Apse et al. 2008). Previous research has indicated that low flow conditions can also favor the persistence and increased abundance of desiccation-adapted taxa (Resh et al. 1988, Delucchi and Peckarsky 1989, Williams 1996, Lytle and Poff 2004). Behavioral adaptations that convey desiccation resistance include species that burrow into the hyporeic zone and aestivate as larvae (Harper and Hynes 1970), or have an egg diapause period (Williams 1996) during periods of unfavorable conditions. These behavioral adaptations to desiccation usually result in fast seasonal life cycles (rapid growth after long egg or larval diapause) which confer some resistance to seasonal low flow periods but may be negatively impacted by changes in the duration and timing of low flow periods. Additionally, species with limited desiccation tolerance were late colonizers of dewatered reaches once rewetted (Boulton 2003).

Increased frequency or magnitude of extreme high or low flow conditions may select for aquatic insect taxa with high mobility. Insects may avoid unfavorable flow conditions by drifting to more suitable habitats, or use drifting behavior to recolonize from upstream refugia after flow disturbances (Minshall and Winger 1968, Gore 1977, Brittain and Eikeland 1988, Boulton 2003). Lytle et al. (2008) observed positive rheotaxis (movement toward source of flow) in desert macroinvertebrates during stream drying events, and several species have also been observed using rainfall cues to exit stream channels or seek refuge under stable substrates in anticipation of flood events in desert streams (Lytle and White 2007). Highly mobility may also indirectly aid species in coping with increased biotic interactions (predation) associated with low flow conditions (Miller et al. 2007, Walters 2011).

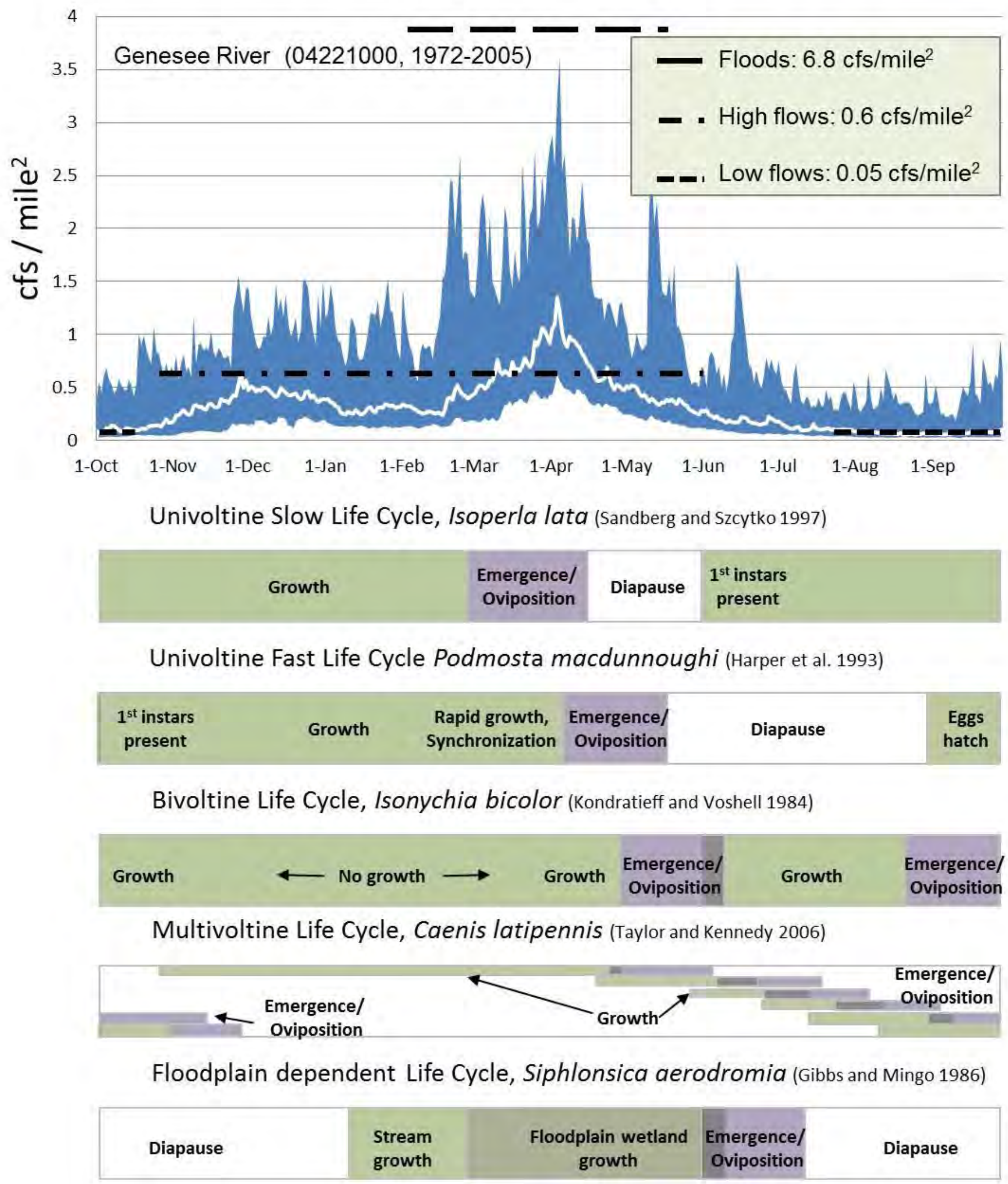


Figure 11. Representative un-altered hydrograph from a large river in western New York with examples of univoltine, bivoltine, and multivoltine aquatic insect life cycles.

Size of maturity is a morphological trait that has been linked to changes in stream flow. Taxa with a larger size at maturity, such as Perlodid stoneflies, may become less frequent or abundant and smaller bodied taxa persist with decreasing flows (Rader and Belish 1999, Apse et al. 2008). However, small aquatic insect size at maturity is closely associated with rapid growth rates, and it may be that faster growing organisms that are likely to exhibit multivoltine asynchronous life cycles are more adapted to unpredictable conditions in altered flow environments (Brittain and Saltveit 1989, Brittain 1990)(Brittain and Saltveit 1989). Taxa with sessile attachment stages, such as case-building caddisflies, are disproportionately associated with low flow environments (Richards et al. 1997). However, Walters (2011) provided evidence that body armoring, including cased organisms, may provide protection from increased predation during low flow conditions.

Ecological traits including rheophily, trophic habit, and thermal preference may also be sensitive to changes in hydrology. Rhelophily, or the degree to which taxa prefer flowing water, is categorized into depositional (pools), depositional/erosional (pools and riffles), and erosional (riffles) trait states (Vieira et al. 2006, Poff et al. 2006). Decreased velocity and loss of riffle habitat associated with lower flow magnitudes can lead to declines in erosional taxa and increased abundance of obligate depositional taxa (Lake 2003, Wills et al. 2006, Brooks et al. 2011). Aquatic macroinvertebrates can be broken up into five functional feeding groups or trophic habits that include collector-gatherers, collector-filterers, herbivores, predators, and shredders (Cummings and Klug 1979). Loss of persistent riffle and pool habitats with declining seasonal flows can alter trophic composition, including declines in densities of filter-feeding and grazing insect taxa and increases in predator species' abundance (Richards et al. 1997, McKay and King 2006, Wills et al. 2006, Miller et al. 2007, Apse et al. 2008, Walters 2011).

Assemblage metrics

Macroinvertebrate responses to hydrologic alteration have also been detected using many of the common assemblage metrics used to assess water quality impacts in streams. These include species abundance, species richness, the Hilsenhoff Biotic Index (HBI), and EPT richness (Table 3). Declines in density, biomass, and total counts have been associated with decreasing flow magnitudes (Rader and Belish 1999, McKay and King 2006). Declines in species richness, HBI, and EPT richness have also been associated with decreasing flow magnitudes or drought conditions (Williams 1996, Apse et al. 2008). Decreases in overall macroinvertebrate density, number of EPT taxa, and available habitat in response to experimental withdrawals confirm many of these associations (Blinn et al. 1995, Dewson et al. 2007, Walters and Post 2011)(Blinn et al. 1995, Dewson et al. 2007, Walters and Post 2011). Additionally, while most withdrawal impacts are thought to occur during summer low flow periods, Rader and Belish (1999) demonstrated that constant withdrawals on small streams reduced stream flow by 90% through fall and winter. Decreased flows during the fall and winter reduced invertebrate density, richness and shifted the community to one dominated by tolerant taxa. Bednarek and Hart (2005) demonstrated that macroinvertebrate richness increased and % of pollution tolerant species decreased after dam operations were modified to increase minimum flows and dissolved oxygen (DO). Percent EPT increased following dam and DO modifications. EPT richness was not affected by flow but increased after flow and DO modifications. Carlisle et al. (2011) found that decreased flow magnitudes were primary predictors of biological integrity in streams, with likelihood of impairment doubling with increasing severity of diminished flow. However, several studies have also failed to associated changes in assemblage metrics with flow alteration (Table 3) or have observed variation in the response of assemblage metrics and functional traits to flow alteration (Poff and Zimmerman 2010). While the magnitude of flow alteration has been positively associated with ecological change using such measures, the use of aggregate measures can be relatively insensitive to synchronous threshold declines of numerous individual taxa, and fail to detect community threshold responses across alteration gradients (King and Baker 2010). A potential alternative anaylsis framework that may improve our ability to detect macroinvertebrate responses to flow alteration as well as underlying mechanisms, involves identifying the responses of individual taxa to flow alteration, followed by a comparison of functional traits between declining and increasing species groups (King and Baker 2010, Baker and King 2010, Stanley et al. *in press*).

High flows and floodplain dependent taxa

Most studies have focused on low flow alteration impacts on macroinvertebrate communities, but flooding also plays an important role in regulating distribution, abundance, and coexistence of benthic macroinverts. Floods reduce macroinvertebrate densities with the degree of reduction related to flood magnitude Robinson et al. 2004). Flood magnitude influences the drift and deposition of seston and macroinvertebrates in water column and riparian environments with catastrophic drift occurring during flood conditions capable of physically disturbing substrate (Brittian and Eikeland 1988, Robinson et al. 2004). As such, increased frequency and magnitude of high flow events can result in higher abundance of tolerant taxa (Kennen et al. 2009). However, absence of high flow events may also impact communities. A large variety of macroinvertebrates including the mayflies *Siphlonsica aerodromia*, *Siphloplecton basale*, *Siphlonurus mirus*, *Siphlonurus alteranatus*, *Leptophlebia cupida*, *Leptophlebia nebulosa*, *Ephemerella temporalis*, *Ephemerella subvaria*, chironomids (midges), *Limnephilus* caddisflies, aquatic beetles, hemipterans, and amphipods are commonly found in high abundance within inundated floodplain wetlands (Gibbs and Mingo 1986). *Siphlonsica aerodromia* are floodplain dependent and utilize floodplain wetlands to rapidly accrue biomass and emerge (Clifford Gibbs and Mingo 1986, Gibbs and Seibenmann 1996) (Fig. 11). Movement from stream to wetland habitats occurs during spring high flow events following snowmelt, and timing of seasonal emergence from wetlands is dependent on maximum air temps and persistence of standing water in the floodplain (Gibbs and Seibenmann 1996).

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Life history summary tables.

Table A2.4. Summary of timing, habitat, and hydro-ecology relationships for different life stages of cold headwater fish target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Brook trout (Brown trout)	Egg and Larval development	November through April: Fry emergence-28 to 165 days depending on temperature		10-40 cm; eggs buried in gravel, presence of fines limits development	range 14.8 to 2.8 C, warmer temperatures decrease development time		Range: 0 -0.88 ft/s, Opt.: 0-0.38 ft/s	Range: 0.38-2.88 ft, Opt: 1.13-1.88 ft		embryo development maximized at v 30 to 60 cm/s, fry overwinter in shallow areas with low velocity (0.984 to 1.96 ft/s), flux in flow can influence groundwater flow around egg during incubation
	Juvenile Growth	Cool months (March-June)		use gravel substrate (10-40 cm) as winter cover			Range: 0 to 1.63 ft/s, Opt: 0 to 0.88 ft/s; 0.26-0.78 ft/s	Range: 0.63-2.88 ft, Opt: 1.13-1.88 ft	margins; shallows	Use higher velocity habitats during the day but switch to low velocity habitats at night.
	Adult Growth	Aug-Dec: most critical period during baseflow (lowest flows of late summer to winter	sexual maturity varies, as early as age '0', usually age 1 or 2	rocky	cold, range: 0 to 24C, with optimal range 11-16 C, most limiting factor in suitable habitat		Range: 0 -0.25 ft/s, Opt: 0 -0.38ft/s	Range: 0.63-5 ft, Opt: 1.13-2.63 ft	riffle-run areas with 1:1 pool-riffle ratio including areas of slow, deep water	
	Spawning	October and November	temp. 3 to 10 C	redds built in gravel, sometimes sand		inter-gravel 0_2 concentration important for spawning success	Range: 0 -0.88 ft/s, Opt.: 0-0.38 ft/s	Range: 0.38-2.88 ft, Opt: 1.13-1.88 ft	strong preference for areas of groundwater upwelling; found in all habitat types, higher tendency in downstream end of pools	Sediment accrual in redds can limit recruitment
Mottled sculpin	Egg and Larval development	Eggs incubate 21-28 days followed by 14 day fry stage								
	Juvenile Survival	Dec-February: population size regulated by overwinter density-dependence among juveniles and adults						shallow habitats	margins and shallow riffles, specific habitat is dependent on adult sculpin density	Juveniles that move during low flow periods in response to high adult densities have higher growth rates
	Adult Growth		Mature by age 2	use interstitial spaces in substrate for cover, cobble and boulder	tolerate warm water		habitat specialist with regard to velocity (fast), 25 cm/s	deeper habitats than juveniles	riffles	
	Spawning	Mid-March and April	small home range, average recapture distance 12.9 m		40-60 F				males select cavity beneath a rock in a stream riffle, eggs laid on underside of stones	

References: (Hazzard 1932, Raleigh 1982, Cooper 1983, Smith 1985, Hill and Grossman 1987, Denslinger et al. 1998, Van Snik Gray and Stauffer 1999, Rashleigh and Grossman 2005, Grossman et al. 2006, Kocovsky and Carline 2006, Hudy et al. 2008, Johnson et al. 2011)

Table A2.5. Summary of timing, habitat, and hydro-ecology relationships for different life stages of riffle obligate fish target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Longnose dace	Egg and Larval development	3-4 days at 21 C	Larval dev. takes 110 days				within 6 weeks move to swift water (> 45 cm/s)		fry abundant in protected margins of quite shallow water	
	Juvenile Growth						> 45 cm/s	<0.3 m, rarely > 1m	riffles	juveniles and adults adapted to high velocity areas
	Adult Growth		mature at age 2, live up to 5 years				45-60 cm/s, as high as 182 cm/s	<0.3 m, rarely > 1m		small home range, average recapture distance 13.4 m
	Spawning	As early as May, late as Aug., peak from June/early July	when daily maximum temp exceeds 15 C	gravel and rock smaller than 20 cm diameter	Optimum 14-19 C			<0.3 m, rarely > 1m		
Central stoneroller	Egg and Larval development									
	Juvenile Survival									
	Adult Growth		Mature in 1 to 5 years	hard bottomed streams			30-59 cm/s	< 60 cm	runs and riffles, shoreline in large rivers, males commonly school over Nocomis nests	small home range size (35 m stream length)
	Spawning	April to May		males dig pits in shallow-gravel bottomed areas, may maintain spawning pits in close proximity	58-75F, spawning ceases at < 50 F		slow to moderate	8-24 inches	heads of riffles	
Rosyface shiner	Egg and Larval development	Eggs hatch in ~ 8 days							base of riffles	
	Juvenile Survival									
	Adult Growth						high velocity	shallow	base of riffles in moderate to large streams, overwinter in pools	Males grow faster in year 1, Females year 2-3
	Spawning	June		small gravel	76-84F			1-3 inches	base of riffles	
Stonecat	Egg and Larval development			Cobble/rock slabs						
	Juvenile Survival			Cobble/rock slabs						
	Adult Growth			Cobble/rock slabs			>0.2 m/s in autumn	shallow depths (0-0.2m at night)	riffle in larger streams	
	Spawning	Early June-Late August		flat rocks	27-29 C			may spawn in deeper habitats	pools/riffles	

Table A2.5 continued.

	Life Stage	**Timing**		**Habitat**			**Hydro- Ecology Relationships**			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Rainbow Darter	Egg and Larval development	Eggs hatch 10-11 days, larval stage ends ~47 days after hatching			17-18.5 C					
	Juvenile Growth									reach 37-42 mm by first fall
	Adult Growth			gravel cobble			> 60 cm/s	< 60 cm	riffles of small creeks to moderate sized rivers	move to deeper slower water during low flow periods- increases pop. Variability
	Spawning	March-June		small gravel				4 inch-2 ft		
Greenside Darter	Egg and Larval development	eggs hatch 18 days after fertilization, yolk sac adsorbed 6 days later			55-60 F					
	Juvenile Growth									
	Adult Growth			cobble			26 cm/sec	< 60 cm	deeper riffles in moderate-large sized streams	
	Spawning	April through June	temp	algae attached to cobbles	> 51 F					
Fantail Darter	Egg and Larval development	May-July: Hatch one month after spawning (30-35 days at 17-29 C), larval stage lasts ~ 27 days	14-16 days at 23 C							
	Juvenile Growth	Mid July-November							pools and slack water areas	
	Adult Growth		Mature at age 1 or 2	abundant in streams with slabs of limestone or shale: many stones and rocks for cover	cool and warm streams		10-17 cm/sec	31-44 cm	riffles or along shallow banks	
	Spawning	April to Mid-June	correlated with temp		temps 15 to 24 C				runs and slow riffles, including shallows	

References: (Pfeiffer 1955, Miller 1964, Cooper 1979, Edwards et al. 1983, Schlosser and Toth 1984, Smith 1985, Walsh and Burr 1985, Mundahl and Ingersoll 1989, Aadland 1993, Chipps et al. 1994, Mullen and Burton 1998, Brewer and Rabeni 2008)

Table A2.6. Summary of timing, habitat, and hydro-ecology relationships for different life stages of riffle associate fish target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Lake sturgeon	Egg and Larval development	Eggs hatch 8-14 days, larvae emerge 11-19 days later and drift 45 km in 25-40 days (flow dependent), drift during month of June	drift triggered temp > 16 C	newly hatched larvae are pelagic	60-64 F				streams	Larval drift period vulnerable/flow regulates drift speed which is also an important period of metamorphosis/higher drift densities after peak flows
	Juvenile Growth	protracted period of high growth rate (12-27 years)		sand/gravel/rock					lake/large river	Higher June Flows and daily rate of temp. increase in May/June are positively correlated with year class strength (this has also been observed for white sturgeon and Russian sturgeon
	Adult Growth			sand/gravel/rock					lake/large river	
	Spawning	Mid April to early June	temp and gradual decrease in flow	coarse gravel and cobble	10-15 C, 11.5-16 C		0.5-1.3 m/sec		high gradient reaches of large rivers	
Silver lamprey	Egg and Larval development									
	Juvenile Survival	4-7 years, transform in the fall, overwinter and out-migrate in Spring.		sand/mud					depositional areas of moderate sized streams	
	Adult Growth			pelagic					Large rivers/Lakes	Adults are parasitic on a variety of species including trout, whitefish, smelt, pike, white sucker, black buffalo, brown bullhead, carp, rock bass, walleye, paddlefish, sturgeon and gars
	Spawning	Mid April to early June	temp	sand/gravel	7.6-16.9 C				riffles of moderate sized streams	Have similar life history and spawning behavior to sea lamprey so protecting silvers also protects sea lampreys and vice versa.

Table A2.6 continued.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
American brook lamprey	Egg and Larval development	eggs hatch 9 days after fertilization			at 20 F					
	Juvenile Growth	4-5 years		medium-fine substrate/organic matter						
	Adult Growth	I year								no growth-just spawning
	Spawning	late March-April	temp	gravel	7 C				upstream of head of riffles	
***Moxostoma* group** (Black redhorse, Golden redhorse, Shorthead redhorse, Greater redhorse)	Egg and Larval development	April-late June: 1 to 2 weeks after fertilization	larvae drift last among riffle associates (late June)		hatched at mean temp. of 15.6 C					Spawning may be terminated by rain events (is this rain or discharge related?)
	Juvenile Growth	Oct-Feb					0.75-3.4 ft/s optimal	1.5-3 ft		
	Adult Growth						1.5-4.3 ft/s optimal	2-12 ft,1-6 ft		
	Spawning	Mid April to early June	temp	coarse mixed substrate, gravel and cobble	10-21 C		0-0.5 ft/s	30-60 cm, 1-2 ft		all species spawn during spring but segregate out by depth/flow/gravel size/timing
***Catostoma* group** (Longnose sucker, White sucker	Egg and Larval development	May-July (eggs hatch ~ 16 days but larvae don't drift for another 11-13 days), drift late may-early June	embryo development temperature dependent		max hatching success 15 C		Opt: 30-60 cm/s			Drift at night when water is high and turbid
	Juvenile Growth	Max growth occurs July-Aug.							pools: HIS Opt: 30-60% pools	
	Adult Growth	Max growth occurs July-Aug.			geographically dependent, wide ranging	optimal 6-10	moderate current, migration can be impeded by swift currents		deep connected pools and slow runs (10-19 cm/s), Max abundance in low to moderate gradient streams (2.8-7.8 m/km, Pools: 30-60% (HIS)	growth inhibited during gonadal development and spawning
	Spawning	April to June	upstream migration triggered by temp (50 F) or stream flow	gravel (2 to 16 mm), can have clean sand but gravel necessary	range 6-24 C, Opt: 12-16 C, migration ceases > 18 C		spawning selection influenced primarily by water velocity, depth, and substrate type, HIS riffle velocity Opt: 30-60 cm/s	shallow waters, HIS Range: 4-45 cm, Opt 15-27 cm	migrate from stream pools to riffles of small creeks and rivers	migration distance ranges from a few 100 m to 6.4 km

Table A2.6 continued.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Northern hogsucker	Egg and Larval development	April-late May	estimated 2 weeks to hatch another 1 to 2 wks. for yolk sac adsorption	hatch in 10 days at mean temp 17.4 C						eggs and small young predated by other fish
	Juvenile Growth									disturb bottom sediment, sympatric relationship with fish following to take advantage of insect drift
	Adult Growth		mature at age 2-4	gravel/cobble streams				feeds and rests in very shallow riffles		rests on bottom of stream in shallow riffles
	Spawning	late March through early May		gravel; gravel and sand	60 F		0.4-0.9 m/sec	30-60 cm		move from larger streams to smaller headwaters to spawn, over riffles, like other suckers
White bass	Egg and Larval development	eggs hatch in 4.5 (14 C) to 1 (26 C) days	Larvae part of ichthyoplankt on May-June							larvae spend time in riverine environments
	Juvenile Growth	Summer/Fall							lakes/big rivers	Year class strength is positively associated with spring flow
	Adult Growth	Summer/Fall							lakes/big rivers	
	Spawning	May-June (earlier farther south)-season can last 25 days	temp/inflow	sand/gravel/cobble	14-20 C				lower reaches of streams	higher flows provide more access to high quality spawning habitat/also potentially associated with increased nutrient loading and production by lower trophic levels
Walleye	Egg and Larval development	Eggs hatch ~ 19 days and drift (hatch duration ~ 29 days), drift mid-May	Flow rate and temp important/dependent on distance to nursery habitat	pelagic	low discharge combined with high temp may lead to rapid yolk metabolism and starvation effects on drifting larvae				lakes/big rivers	Egg dislodgement due to high flows decreases recruitment. Flow during drift period critical: too fast = physical damage/ too slow = starvation
	Juvenile Survival								lakes/big rivers	
	Adult growth			cobble gravel			moderate current (riverine residents)	1.25-1.8 m (riverine residents)	lakes/big rivers	
	Spawning	Early spring, just after ice breakup-often concurrent with White Suckers	temp	sand/gravel	35-44 F		require moderate to fast-flowing water	< 2ft, not > 4	gravel bars in streams/shoals in lakes	Respond to riffle restoration

References: (Beamish and Lowartz , Ruelle 1977, McCormick 1978, Curry and Spacie 1984, Twomey et al. 1984, Smith 1985, Corbett and Powles 1986, Paragamian 1989, Kwak and Skelly 1992, LaHaye et al. 1992, Cochran and Marks 1995, Matheney and Rabeni 1995, Nilo et al. 1997, Mion et al. 1998, Sammons and Bettoli 2000, D'Amours et al. 2001, Auer and Baker 2002, Bruch and Binkowski 2002, DiCenzo and Duval 2002, Guy et al. 2002, Quist et al. 2002, Willis et al. 2002, Dustin and Jacobson 2003, Jones et al. 2003, Cochran and Lyons 2004, Smith and King 2005, Peterson et al. 2006, Reid 2006, Zhao et al. 2009)

Table A2.7. Summary of timing, habitat, and hydro-ecology relationships for different life stages of nest building fish target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
River chub	Egg and Larval development	Eggs hatch in 5-6 days at 21 C	Larval dev. Complete in 57 days	gravel			slow to moderate current			
	Juvenile Survival		mature at age 2-3							
	Adult Growth	March-April: gonadal development			13 C (during gonadal development)		tolerant to high flows in early spring		riffles in high gradient streams of moderate size; medium to large tributaries, pools, runs, and riffles	
	Spawning	Apr-May	temp > 20 C, 17-26.7 C	gravel	Range 17-26.7 C		slow to moderate current (bigmouth chub)	> 15 cm, a nest height at center recorded as 10 cm		27 minnow species recorded to be nest associates of Nocomis
Fallfish	Egg and Larval development	eggs hatch in 5-6 days, fry emerge 9-11 days after hatching and drift downstream at night			incubation occurs between 16-18 C					
	Juvenile Survival	Warm months							juveniles occur in smaller streams than adults	Long-lived (up to 11 years), larges minnow east of the Rockies, constructs the largest stone mound nest known
	Adult Growth		Reach maturity at age 4 (as early as 2)	Sand and gravel	warmest water temperatures, range 5-27 C, Opt:10-20 C, seldom occur > 28 C		tolerant to high flows in early spring		clear gravel bottomed streams, commonly found near cascades and falls	Turbidity < 30 NTUs
	Spawning	April-June	temperature		Throughout spawning season Range: 15-18, Opt: 16.5-17.5, spawning may cease if temps drop below 15 C		5-69 cm/s	Avg. depth across stream Opt: <0.5m	move into smaller streams to spawn, prefer habitats with overhead cover	Selects spawning grounds based on abundance of instream cover over preferred substrate
Creek chub	Egg and Larval development	Eggs hatch in 6 days at 18 C			15-20 C	5 mg/L; some studies have shown tolerance to low DO	Opt < 10 cm/s	30-100 cm	fry-edges of stream margins	
	Juvenile Growth	Warm months					10 cm/s	<1m	prefer small, clear, cool streams with moderate to high gradient, well defined riffles and pools (greatest abundance in gradients 7-13.4 m/km, 45-60% pools)	Cover is an important component of habitat quality
	Adult Growth		Mature between ages 2-5	gravel	average temp. 18-22 C, always < 32 C			<1m avg. depth		
	Spawning	April-July	temperature		temp 14 C		<1.25 cfs, 20-60 cm/s in riffle areas	>100 cm	immediately up or downstream of riffles in shallow water	

Table A2.7

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Rock bass	Egg and Larval development	Males guard nests for 14 days								
	Juvenile Survival									
	Adult Growth			boulder,cobble,gravel-rootwads			prefer considerable current		moderate sized streams	
	Spawning	Mid May-mid July (Ontario)	temp	gravel	13-31 C			45-138 cm		can spawn multiple times-nest success associated with low flows
***Lepomis* group** (Pumpkinseed, Bluegill, Longear)	Egg and Larval development	Eggs hatch in 3 days, Males guard fry for > 1 week								
	Juvenile Survival						no/low flow		habitat generalists	
	Adult Growth						no/low flow		habitat generalists	
	Spawning	Late spring-August	temp	often near aquatic veg.	60 F			6-12 inches deep	near shore	
Smallmouth bass	Egg and Larval development	up to 1 month past spawn		nests built on sand, gravel or rock	15-25 C		< 0.2 m/s, flood after spawning reduces survival if scouring occurs	0.3-0.9 m	pools, successful nests closer to the stream bank	
	Juvenile Survival	June flows have significant influence on survival, growth during warm months		no clear pref.			strongest year classes when June flows within 40% of the long-term mean			
	Adult Growth			no clear pref- cwd cover/boulder	21-27 C in summer		10 cm/s or less	Intermediate depths	pools	
	Spawning	mid April-July	mean daily water temp most important variable (as it interacts with discharge), tend to spawn during receding limb of a high flow event	nests built on sand, grave, or rock almost always under protection of cover	> 12.5 C and < 25 C		slow current, a flood event can split the spawning season in 2	0.3-0.9 m	pools, protected areas, very strongly prefer areas of abundant shade and cover	Temp and flow are good predictors of spawning activity

References: (Reed 1971, Buynak and Mohr 1979, Cooper 1980, Probst et al. 1984, Blumer 1985, Smith 1985, Graham and Orth 1986, Noltie and Keenleyside 1986, 1987, Todd and Rabeni 1989, Bain et al. 2008)

Table A2.8. Summary of timing, habitat, and hydro-ecology relationships for different life stages of marsh spawning fish target species.

	Life Stage	**Timing**		**Habitat**			**Hydro- Ecology Relationships**			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Northern Pike	Egg and Larval development	Eggs hatch in 12-14 days and fry remain attached to veg. for 6 days		vegetation		need high DO			vegetated margins/shallow temp. marshes	high depth variability or de-watering during egg larval stage has negative effects
	Juvenile Growth	Summer								Year class strength best when June water levels high
	Adult Growth									Loss of marsh habitat moves spawning to deeper water (musky)- this can be due to too little water or too much water (increased *Typha*)
	Spawning	April/May	temp/ice breakup	prefer shallow emergent veg	40-52 F			shallow, often < 1 ft	vegetated margins/shallow temp. marshes	May require spring high flows to flood marshes/higher flows enable earlier spawning in tributary marshes = protracted spawning period along littoral gradient = larger year class
Muskellunge	Egg and Larval development	Eggs hatch in 8-14 days/yolk sac takes several days to absorb (for 7-14 days to swim up)		important that eggs are off bottom/water circulation	12-16.7 C	need high DO	> 0.1 m/s	1.3-4 ft	large river/cool lake	Rising spring water levels correlated with repr. Success
	Juvenile Survival	Summer		shoreline vegetation				<1.5 m (0.65 m)	large river/cool lake	
	Adult Growth			structure (veg/cwd/ledges)					large river/cool lake	
	Spawning	Early May-mid June		vegetation (*Chara*)	10-18 C		>0.1 m/s	1.3-4 ft	large river/cool lake	Decreasing springtime water level strands spawners and young, exposes eggs

References: (Smith 1985, Cook and Solomon 1987, Farrell 2001, Farrell et al. 2006a, Farrell et al. 2006b, Smith et al. 2007, Cooper et al. 2008, Craig 2008, Mingelbier et al. 2008, Farrell et al. 2010, Hudon et al. 2010)

Table A2.9. Summary of timing, habitat, and hydro-ecology relationships for different life stages of anadromous sportfish target species.

	Life Stage	**Timing**		**Habitat**			**Hydro- Ecology Relationships**			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Atlantic salmon	Egg and Larval development	Eggs incubate from Dec-May-fry emerge May June	Fry emergence associated with decreasing flow conditions	gravel					Streams	Habitat requirements for Atlantic Salmon should also cover non-native Coho and Chinooks: Atlantic salmon do not die after spawning and may live 9 years
	Juvenile growth	June-Oct	Warmer temps	Juveniles prefer gravel/Parr prefer larger substrates				< 15 cm/ not less than 20 cm (Parr)	Runs of streams	growth may be influenced by summer flow (habitat availability)
	Smolts	April	Rapid increase in flow (snowmelt) combined with increasing temp and day length	Pelagic					Streams	Smolts for all species, including rainbows out-migrate at this time
	Spawning	November peak	increased flow, declining temp. and day length/ descending limb of peak flow cues migration	gravel			30-50 cm/s	< 30 cm	Streams	
Rainbow trout (Steelhead)	Egg and Larval development	Shorter egg incubation (18- days at 15 C) with similar fry emergence to Fall spawning salmonids	Fry emergence associated with decreasing flow conditions	gravel					Streams	
	Juvenile growth	June-Oct	Warmer temps						Streams	Juvenile habitat requirements similar to Atlantic Salmon, habitat segregation depending on time of year
	Adult migration-overwintering	Sept-Dec: Early migrations can occur with some adults overwintering in streams							Streams	
	Spawning	March-late April	Peak flows associated with snowmelt	gravel	50-60 F				Streams	

References: (Warner 1962, Biette et al. 1981, Carl 1982, 1983, Rimmer et al. 1983, Hearn and Kynard 1986, Gibson 1993, Trepanier et al. 1996, Nislow et al. 2004, McKenna and Johnson 2005, Enders et al. 2009)

Table A2.10. Summary of timing, habitat, and hydro-ecology relationships for different life stages of riverine mussel target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Elktoe	Spawning	August-September	Temperature	Sand, gravel, and cobble					Riffle/run areas of Small creeks to medium rivers	Requires high water quality, Indv grow quickly for 3-4 years then very slow, **hosts** include common shiners, blacknose dace, longnose dace, rock bass, white sucker, northern hogsucker, warmouth, and shorthead redhorse
	Brooding	September-May	Temperature							
	Glochidia release	May-June	Temperature							
Creek heelsplitter	Spawning	September	Temperature	Stable sand coarse gravel,and cobble			Moderate (1.2 ft./sec) to swift (1.7 ft/sec) bottom current	2 “ – 2’	Moving water/riffles in large creeks and rivers	Indv. Grow quickly in 2-3 years, large indv (70mm) may be 10-15 years old; **hosts** include *Cottus* and *Percina* spp.
	Brooding	September-April/May	Temperature							
	Glochidia release	April/May	Temperature							
Fluted shell	Spawning	August	Temperature	Sandy mud, sand and gravel with cobble			Often in moving water		Large creeks and small rivers, some lakes	Indv grow quickly in years 2-3, then slowly, grow to 150 mm and live to ~ 20years; two types of glochida with the 2nd type possibly allowing this species to forgoe parasitic stage; **hosts** include a wide variety of fishes
	Brooding	August-May	Temperature							
	Glochidia release	May	Temperature							
Creeper (Squawfoot)	Spawning	July	Temperature	Sand and mud, Sand and gravel, even bedrock crevices			Wide range of velocities		Intermittent creeks to large rivers	Indv grow very quickly for 2-3 years, then slow, max size/age is 120 mm at 15 years old; hosts include a wide variety of fish species
	Brooding	July-May	Temperature							
	Glochidia release	April-May	Temperature							

References: (Baker 1928a, Ortmann 1919, Watters, etal. 2009, Strayer and Jirka 1997, Spoo 2008, Barnhart etal 1998a,

Table A2.10. Summary of timing, habitat, and hydro-ecology relationships for different life stages of facultative riverine mussel target species.

	Life Stage	Timing		Habitat			Hydro- Ecology Relationships			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Eastern elliptio	Spawning	April-mid june	>20 °C	Fine gravel or sand/gravel mix			Tolerate wide range of current		Brooks to large rivers	Grow slowly, max size 130 mm at 20 years old; Adults may migrate to form aggregate beds and increase spawning success; **hosts** include primarily centrachids; usually very abundant
	Brooding	Spring-late summer	Temperature							
	Glochidia release	1 month after spawning	Temperature							
Spike	Spawning	March-July	Temperature	Sand and cobble				Wide ranging, up to 25'	Creeks, rivers, and large lakes	Slow growing, max size 130 mm at 25 years old; hosts include rock bass, banded sculpin, gizzard shad, rainbow darter, yellow perch, white and black crappie, flathead catfish, and Sauger
	Brooding	May and July/August (2 periods)	Temperature							
	Glochidia release	August/Sept and again in Nov.	5 and 19°C							
Wabash pigtoe	Spawning	May	Temperature	Nearly all substrates			Fast to no flow		Creeks, rivers, and lakes	Slow growing with max size 110 mm and age > 25 years; hosts include bluegill, silver shiner, white crappie, black crappie, and creek chub
	Brooding	June to August	Temperature							
	Glochidia release	July to August	Temperature							
Eastern lampmussel	Spawning	Late summer	Temperature	Sand and gravel			Slow to moderate		Small to medium sized rivers and lakes	
	Brooding	Late summer-spring	Temperature							
	Glochidia release	Spring	Temperature							
Black sandshell	Spawning	August	Temperature	Both hard and soft substrates			Swift current to slackwater habitats		Widespread but sporatic in rivers and lakes, less common in streams	Grows quickly for 6 years before slowing, max size/age = 180mm/30 years;hosts include a variety of large bodied fishes
	Brooding	September-July	Temperature							
	Glochidia release	July	Temperature							
Pink heelsplitter	Spawning	May breed year round	Temperature	Silty sand and mud			Slackwater		Impoundments and rivers, rarely in small streams	Morphological variation based on flow environment; Grow rapidly for 2-4 years then slow; max size/age = 190mm/15 years; freshwater drum may be a host but metamorphosis has not been observed on any host
	Brooding	Potential overlapping broods; June –October and May to July	Temperature							
	Glochidia release		Temperature							
Rainbow	Spawning		Temperature	Sand and cobble			Moving water		More common in small creeks	Grows quickly 1st 2-4 years, max size/age=

	Brooding	September to following May	Temperature							80mm/15 years; appears to be a host generalist
	Glochidia release		Temperature							

References: (Watters, etal. 2009, Strayer and Jirka 1997, Spoo 2008, Ortmann 1919, Fichtel and Smith 1995, Matteson 1948, Amyot and Downing 1998, Jirka and Neves 1992, Watters and O'Dee 1998c, Heath et al. 1998, Watters 1996d),

Table A2.11. Summary of timing, habitat, and hydro-ecology relationships for different life stages of lentic mussel target species.

	Life Stage	**Timing**		**Habitat**			**Hydro- Ecology Relationships**			
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit	Comments
Cylindrical papershell	Spawning	August	Temperature	Substrate generalist from packed cobble to silty mud and clay			slow		Primarily headwater species, found near margins	Fast growing, shortlived species, max size/age= 100m/7 years; appears to be a host generalist
	Brooding	September-May	Temperature							
	Glochidia release	May	Temperature							
Eastern pondmussel	Spawning			Mud, fine gravel, or sand/gravel mix			Slow		Slackwater areas of slow flowing streams and medium-sized rivers, also lentic habitats	Live +10 years and grow to 120mm; No host known
	Brooding	August-May (may breed year round)								
	Glochidia release									
Floater	Spawning			Nearly every type of substrate			Often in standing waters but known from rough waters and riffles		Wide range of habitats across all stream types	Grow quickly 1st few years to a max size of 210mm, short life span < 10 years; host generalist
	Brooding	Gravid females recorded from August – May (conflicts with bellow								
	Glochidia release	October – February	5°C							

References: (Ortmann 1919, Watters, etal. 2009, Strayer and Jirka 1997, Spoo 2008, Watters and O'Dee 1998c),

Appendix 3: Eco-evidence Framework and Methods for Evaluation of Hypotheses

To evaluate the hypotheses of biotic responses to varying degrees, types and timing of hydrologic alteration (generated by the Technical Advisory Team during our second project workshop in June 2012), we have used the *Eco Evidence* approach, a form of casual criteria analysis. This approach provides a transparent assessment of the level of support for each hypothesis in the scientific literature. Our approach differs slightly from Norris et al. (2012) in that our goals were not necessarily to establish causality for specific hypotheses, but rather to establish and measure support for overall flow needs and associated flow components. Thus, our goals were to: 1) articulate flow needs through hypothesis generation; 2) use hypotheses to structure a systematic literature review that assessed support for flow needs; and 3) use results to make conclusions about the importance of each flow need and to provide important context for developing flow recommendations at our third and final workshop.

We organized our analysis around the 8 step framework presented by Norris et al. 2012 (Fig. A3.1). The *Eco Evidence* framework is a form of systematic review of the scientific literature, with steps 1 through 4 and 6 representing problem formulation. Step 5 consists of the literature search and systematic review, with the option to reconsider the conceptual model in light of the literature review, and revise steps 1-4 (Step 6). Finally, in steps 7 and 8 the reviewer weights, combines and considers the evidence to assess the level of support for and against each hypotheses identified at Step 4. Results for all the cause-effect hypotheses are then assessed collectively to inform the original overall question (Norris et al. 2012). These 8 steps can be grouped into three phases that include *Problem formulation*, *Literature review*, and *Weighting evidence and judging support*. This approach has been successfully applied to water resource question related to stream sediments and riparian flooding regimes (Harrison 2010, Greet et al. 2011, Norris et al. 2012).

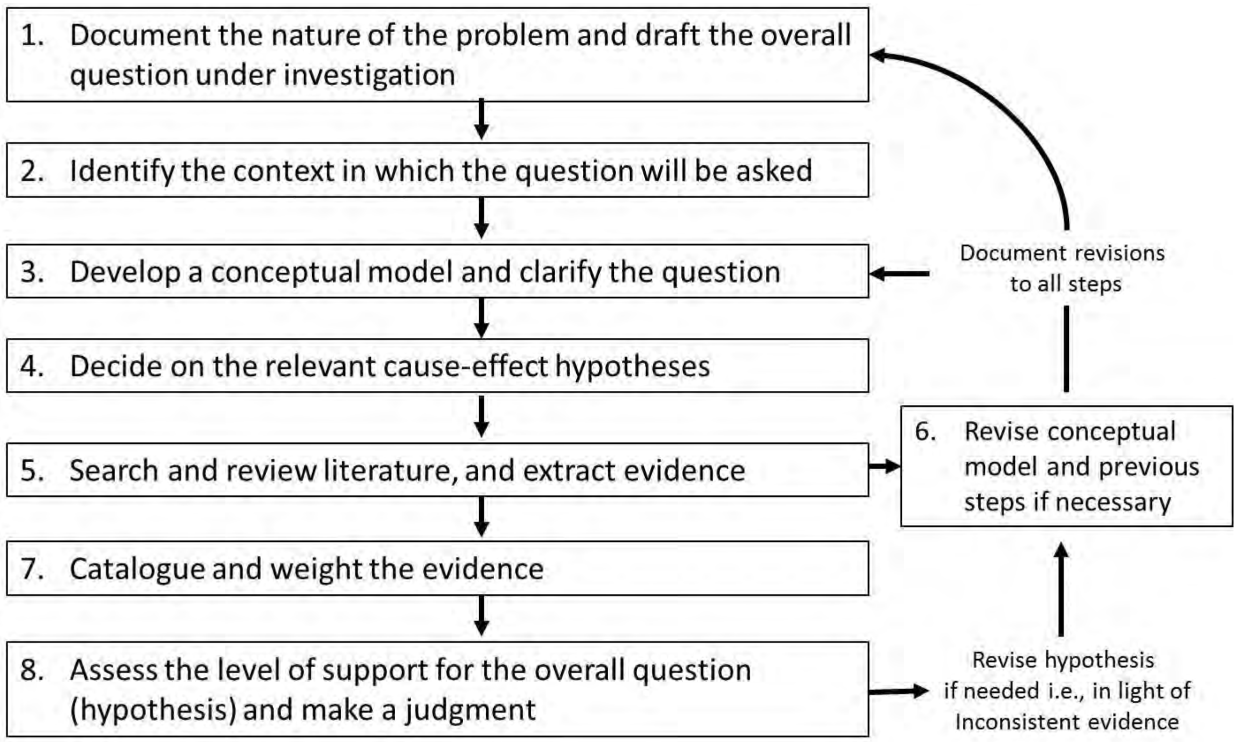


Figure A3.1. *Eco Evidence* framework flow diagram (Norris et al. 2011).

A3.1 Problem formulation

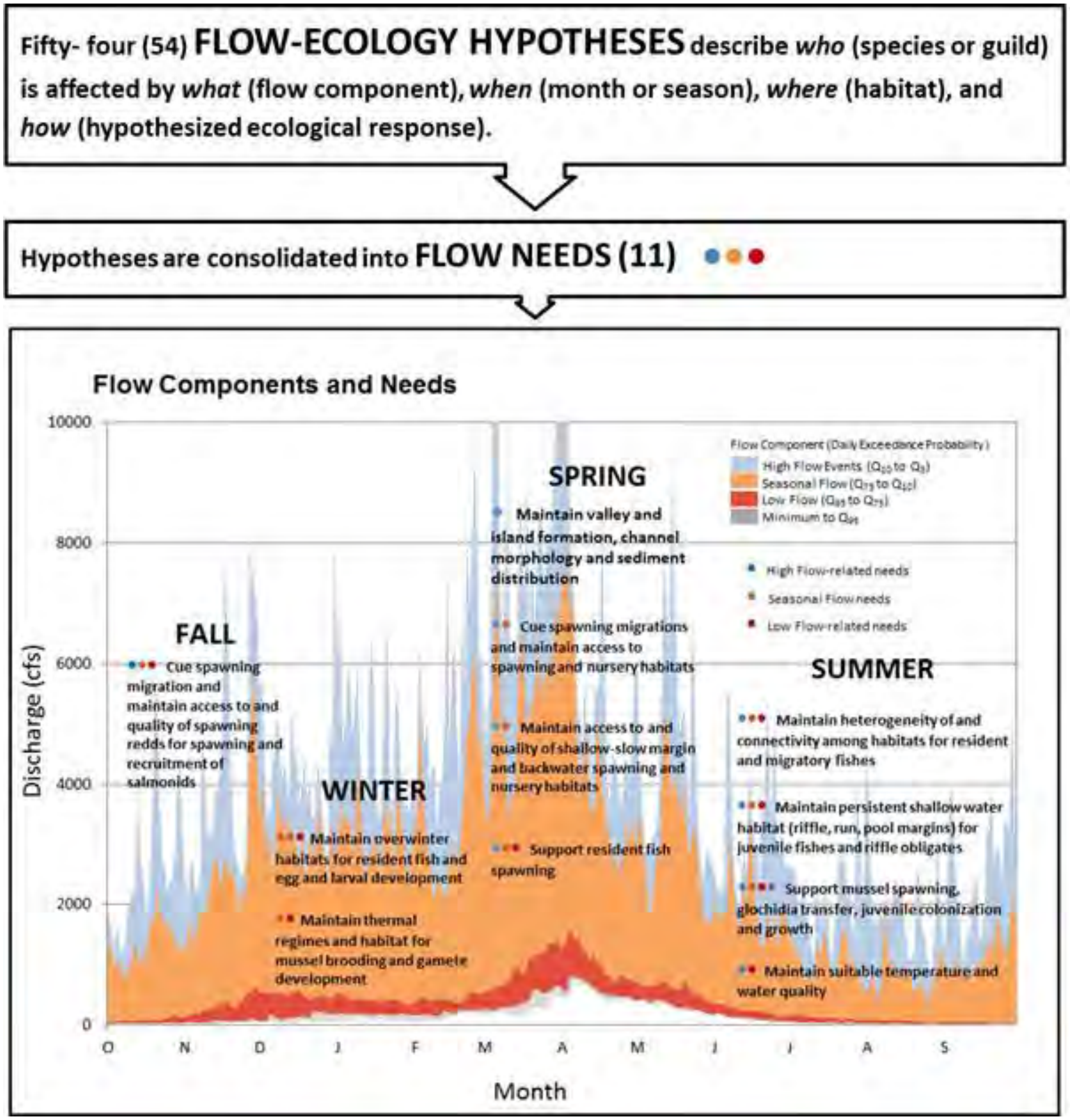
The NYPAFLOs project aims to provide the DEC with the foundation to define stream-flow standards that are scientifically defensible, can be efficiently applied, and are easily understood, in fulfillment of one of the state's major obligations under the "Great Lakes Compact." Thus *steps 1 and 2* are defined by the project. The overall question is "*what are the flows needed to protect stream ecosystems within the Great Lakes region of New York and Pennsylvania?*" A literature-based approach probably cannot answer this question. However, in order for policy makers to make informed decisions related to the flow needs of Great Lakes stream ecosystems, we need to articulate and build support for what it is we are trying to protect, during what season, and based on what component of the flow regime. Here we use a slightly modified version of the *Eco Evidence* approach to answer those questions. Our problem formulation *steps 3 and 4* involved generating 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). We then used these hypotheses to develop a conceptual model of general flow needs represented by different seasons and flow components.

A3.1.1 Flow Ecology Hypothesis Workshops

During our second project workshop in June 2012, two breakout groups refined and drafted hypotheses about potential responses to flow conditions based on synthesis of life history information presented in Section 4, and in more detail in Appendix 2 (Figs 1-3). Discussions focused on four seasons during three 45 minute breakout sessions. Participants were provided with flow ecology diagrams (conceptual models – see section 4 and Appendix 2) linking important life history periods for guilds of flow-sensitive species with natural hydrology of different stream types within the region. Breakout discussion groups focused on drafting hypotheses for targets, stream types and seasons. Workshop participants developed over 49 working hypotheses, with the majority (24) of hypotheses generated for fish. Reviewing flow ecology hypotheses generated by this project and by the Upper Ohio River project (a project that has followed the same ELOHA approach) revealed considerable overlap between lists of hypotheses, as well as a few hypotheses generated by the Upper Ohio Project that were applicable to this project. We supplemented notes from our second workshop with additional fish, mussel, and vegetation hypotheses generated in cooperation with the upper Ohio River Basin ELOHA project. Very few specific hypotheses (2) were generated for aquatic macroinvertebrates. After removal of redundant hypotheses and consolidation with Ohio River Basin hypotheses, we generated a total of 33 fish flow ecology hypotheses representing high, seasonal and low flow components for assessment using the *Eco Evidence* approach (Table 1). In cooperation with Tara Moberg of TNC's Pennsylvania chapter, we focused the *Eco Evidence* analysis on fish hypotheses and supplemented results with *Eco Evidence* analyses for 11 mussel and 7 vegetation hypotheses.

A3.1.2 From Hypotheses to Flow Needs

We consolidated flow-ecology hypotheses into general flow needs that form a conceptual model delineating what aspects of fish and mussel life histories, and instream and floodplain habitat processes, are supported by particular flow components (high flows, seasonal flows, and low flows, as defined in section 3) during particular times of year (Fig. A3.2). Our 54 hypotheses were aggregated into 11 flow needs (please see Table 5.1, and Table A3.1). Aggregating related hypotheses by timing, flow-sensitive life stages and ecosystem function into a set of flow needs provides structure for using a weight-of-evidence approach to document the degree to which the flow hypothesis, associated flow needs and future recommendations are supported in the literature. Key words (*who, what, when, where, how*) from flow ecology hypotheses were used in *step 5* to search the scientific literature for relevant studies, and to assess the support for individual hypotheses and general flow needs.



Fifty- four (54) **FLOW-ECOLOGY HYPOTHESES** describe *who* (species or guild) is affected by *what* (flow component), *when* (month or season), *where* (habitat), and *how* (hypothesized ecological response).

Hypotheses are consolidated into **FLOW NEEDS (11)** ●●●

Figure A3.2. Conceptual model of seasonal flow needs for fish and mussels in Great Lakes rivers and streams based on flow ecology hypotheses generated during project workshops.

Table A3.1. Flow needs and associated flow-ecology hypotheses.

Hyp. #	Taxa	Flow Component	Timing	Hypothesis
Flow Need 1: Cue spawning migration and maintain access to and quality of spawning redds for spawning and recruitment of salmonids				
GL-F1	Fish	High	Sept-Nov	During the fall (mid-September-November), anadromous and resident salmonids require high flow pulses that trigger spawning migrations from lake to stream habitats or streams to headwater habitats (brook trout). If the magnitude and duration of high flows is reduced, the size of spawning runs may be reduced and recruitment limited
GL-F3	Fish	Seasonal	Sept-Nov	During the fall (mid-September-November), anadromous and resident salmonids require sustained elevated flow after high flow events to provide access to spawning habitats and prevent stranding in shallow stream habitats. If the magnitude of seasonal flows is reduced, spawning and recruitment may be limited because fish can't reach suitable spawning habitat and/or are more susceptible to predation.
GL-F4	Fish	Seasonal	Oct-Apr	From fall to spring, anadromous and resident salmonids need stable flows to maintain spawning redds. A decline in seasonal median flows, would increase egg and larvae mortality, thereby reducing recruitment.
O-F1	Fish	Seasonal	Sept-Nov	During fall, a decrease in seasonal groundwater or surface flows may reduce quality of redds during salmonid spawning
GL-F7	Fish	Low	Sept-Nov	Low flows in the fall prevent access for salmonids to spawning habitats and fail to flush redds prior to spawning. A shift in the timing and duration of low flow events from summer to fall would limit recruitment of fall-spawning salmonids in streams.
Flow Need 2: Maintain overwinter habitats for resident fish and egg and larval development				
GL-F8	Fish	High	Dec-Mar	During the winter, increased frequency and magnitude of high flow events (bankfull or above) will increase salmonid egg and larval mortality due to scouring of redds and larval habitat.
GL-F9	Fish	Seasonal	Dec-Apr	During the winter, an increase in seasonal median flows will require more energy for fish to hold position in flowing habitats, leading to decreased survival or condition of fish.
GL-F10	Fish	Low	Dec-Mar	A decrease in magnitude of extreme low flows (below Q90) during winter, will result in anchor ice formation and increase freezing, egg and larval mortality of river-dwelling fish and fall-spawning salmonids in headwater streams to medium rivers.
O-F5	Fish	Low	Dec-Mar	During winter, a decrease in low flow magnitude may decrease availability and access to riffle habitats needed by riffle obligate fishes.

Table A3.1 continued.

Hyp. #	Taxa	Flow Component	Timing	Hypothesis
FN 3: Maintain thermal regimes and habitat for mussel brooding and gamete development				
GL-M1	Mussel	Seasonal	Dec-Aug	From winter through summer, during gametogenisis, a decrease in seasonal flow magnitude may alter temperatures, shifting thermal regimes that cue gamete development and release. Long-term brooders may be particularly sensitive.
GL-M2	Mussel	Low	Dec-Mar	During winter, a decrease in low flow magnitude may cause anchor ice formation and scour mussel habitat.
FN 4: Maintain valley and island formation, associated floodplain/riparian vegetation, channel morphology and sediment distribution				
GL-H3	Habitat	High	March-April	During the spring, a decrease in the magnitude, duration, and frequency of high flow events will eliminate habitat forming processes (removing silt from spawning habitats) necessary for maintaining flowing habitat structure for riffle obligates and associates, and salmonids.
GL-H4	Habitat	High	March	During the spring, a decrease in the magnitude or shift to a later timing of peak flow event will eliminate ice scour events and reduce complexity of pool habitat structure (LWD, cut banks) for adult fish (nest builders/salmonids, riffle associates).
O-V1	Veg.	High	Dec-April	During winter and early spring (prior to leaf out), flood flows and associated ice scour support the distribution and composition of vegetation communities with a high fidelity for flood and scour disturbance. A decrease in seasonal flood flow magnitude and frequency may transition communities to those less dependent on and adapted to conditions supported by flood and scour events.
O-V2	Veg.	High	Oct-April	From fall through spring, many floodplain and riparian vegetation species rely on seasonally high flows for seed dispersal and to prepare the seedbed for propagules. Change to the timing or magnitude of high flows may reduce seed dispersal and recruitment.
O-V3	Veg.	High	Nov-April	During winter and spring, herbaceous species, such as buttonbush, need low intensity, moderate duration flood events that sustain the length of inundation to promote establishment. 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.
O-V7	Veg.	HIgh	May-Oct	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.

O-V8	Veg.	Seasonal	May-Oct	From spring to fall, during the growing season, particularly in headwater settings, a decrease in groundwater elevation or overbank inundation may encourage a transition from mesic toward xeric communities
O-V9	Aquatic Veg.	Low	May-Oct	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.
O-V12	Veg.	Low	June-Oct	During summer and fall, an increase in low flow magnitude may increase inundation and inhibit colonization of riparian species

Hyp. #	**Taxa**	**Flow Component**	**Timing**	**Hypothesis**
FN 5: Cue spawning migrations and maintain access to spawning and nursery habitats				
GL-F11	Fish	High	Mar-Apr	During the spring, a decrease in the magnitude and/or duration of the peak flow event will extend the timing of riffle associate and anadromous sportfish (rainbow) spawning runs, reduce access to spawning habitats, and expose migrating fish to increased predation.
GL-F13	Fish	High	Mar-May	During the spring (March-mid-May, riffle associates and spring spawning salmonids require high flows at the correct temperature to cue spawning migrations. A change in timing of the peak flow event will disrupt spawning cues, restrict access to suitable spawning habitat, and lower recruitment.
GL-F15a	Fish	Seasonal	Mar-Jun	During the spring and early summer, a decrease in median flow will decrease the amount of riffle habitat and spawning area available and limit recruitment of riffle associate fishes.
FN 6: Support resident fish spawning				
GL-F14	Fish	High	April-June	During the spring and summer, after spawning, an increase in the magnitude and frequency of later high flow events will scouring eggs and developing larvae from previous spawning events and limit recruitment of riffle obligate, riffle associate, and nest building fishes
GL-F15b	Fish	Seasonal	Mar-Jun	During the spring and early summer, a decrease in median flow will decrease the amount of riffle habitat and spawning area available and limit carrying capacity and recruitment of riffle obligate.
GL-F16	Fish	Seasonal	Apr-Jun	During the spring and early summer, a decrease in median flow will limit recruitment of nest building fishes by decreasing the amount of margin habitat available for spawning.
O-F6	Fish	Seasonal	Oct-May	During fall through spring, a decrease in seasonal flow magnitude may result in deposits of fine sediment and suffocation of eggs.
GL-F18	Fish	Low	Apr-Jun	During the spring, a decline in low flows (or seasonal flows) will limit survival of riffle associate (walleye, suckers, redhorse, sturgeon) larval stage by decreasing drift disperal rates to juvenile rearing habitat and increased predation.

GL-F19	Fish	Variability	April-Jun	During the spring and early summer, a sudden decrease in flows will limit recruitment of nest building and riffle obligate fish by de-watering nests and stranding larvae in margin habitats. A sudden increase in flow will flush larvae into channel habitats, exposing them to increased predation.

Hyp. #	**Taxa**	**Flow Component**	**Timing**	**Hypothesis**
F 7: Maintain access and quality of shallow-slow margin and backwater and nursery habitats				
GL-F12	Fish	High	Mar-Apr	During the spring, a decrease in magnitude and duration (4-5 weeks) of peak flow event necessary for connectivity and maintenance of floodplain wetland habitat for marsh spawners egg laying and fry development will result in low recruitment for pikes, bowfin, and yellow bullhead.
O-F15	Fish	High	Mar-June	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.
O-F16	Fish	High	Mar-June	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.
O-F14	Fish	Seasonal	May-Sept	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 riffle associates (walleye and suckers).
FN 8: Maintain suitable temperature and water quality				
GL-H5	Habitat	HIgh	Jun-Sept	During the summer, a reduction in magnitude and frequency of high flow events will decrease water quality and habitat for all fish targets by allowing increased primary production and nuisance algal growth.
GL-F17	Fish	Seasonal	May-Sept	During the spring and summer, decreased seasonal flows limit brook trout populations by limiting habitat, drift encounter rates, and potentially increasing temperature,
GL-F24	Fish	Low	Jun-Sept	During the summer, a decrease in magnitude or increase in duration of low flows could increase temperatures, potentially putting coldwater fish in contact with competitor species with higher temperature tolerances or warm water fish species.
GL-H7	Habitat	Low	Jun-Sep	During the summer, reduced magnitude and increased duration of low flows will increase temperature and presence of algae, which can increase the range of diel dissolved oxygen swings outside the range of tolerance for sensitive fish species.
GL-M11	Mussels	Low	Aug-Sep	During the baseflow months, a decrease in low flow magnitude may significantly increase algal production, decreasing DO and resulting in reduced growth or mortality for individuals, and reduced abundance and richness of populations.

GL-M8	Mussels	Low	Jun-Sep	In summer and fall, during the baseflow months, a decrease in low flow magnitude may increase temperatures, reducing fitness of thermally sensitive species.

Hyp. #	Taxa	Flow Component	Timing	Hypothesis
FN 9: Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes				
O-F20	Fish	High	June-Sept	During summer, increased frequency, magnitude or duration of high flow events may shift fish species assemblage composition.
O-F24	Fish	Seasonal	June-Sept	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.
GL-F21	Fish	Low	Jun-Sept	During summer, reduced magnitude of low flows will reduce carrying capacity of flowing water habitats for riffle obligates.
GL-F23	Fish	Low	Jun-Sept	During summer, reduced magnitude and increased duration of extreme low flows reduce habitat complexity by moving water away from undercut banks and overhanging vegetation, and dewatering aquatic vegetation and large woody debris which will decrease growth and condition of adult pool-dwelling fishes.
O-F25	Fish	Low	Jun-Oct	During the summer and early fall, a decrease in low flow magnitude may result in reduced access to thermal refugia and cause a shift in species assemblage
FN 10: Maintain persistent shallow water habitat (riffle, run, pool margins) for juvenile fishes and riffle obligates				
GLF20/ GL-F2	Fish	High	June-Nov	During the summer and early fall, increased magnitude or frequency of high flow events could flush juvenile fish from rearing habitats and decrease year-class strength of all target fish groups.
GL-F5	Fish	Seasonal	Jun-Nov	During the summer and fall, a decline in seasonal median flows, would reduce habitat for all fish groups using riffle, run, or pool margin habitat.
GL-F22	Fish	Low	Jun-Sept	During summer, juvenile fish require flows that maintain shallow margin habitats. If the magnitude of low flows is reduced, available shallow margin habitat will be reduced limiting the growth, survival, and dispersal of juvenile fishes.
O-F28	Fish	Low	Jun-Sep	During 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 (central stoneroller, hornyhead and river chub would be particularly sensitive)
Hyp. #	**Taxa**	**Flow Component**	**Timing**	**Hypothesis**
FN 11: Support mussel spawning, glochidia transfer, juvenile colonization and growth				
O-M6	Mussels	High	June-Oct	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.
O-M13	Mussels	High	All month	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.
O-M4	Mussels	Seasonal	Mar-Nov	From spring to fall, an increase in seasonal flow magnitude may increase velocity and associated shear stress, reducing abundance, richness, or individual growth
O-M5	Mussels	Low	Apr-Nov	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.
O-M9	Mussels	Low	Jun-Sep	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 may be subject to increased predation or desiccation.
O-M10	Mussels	Low	Jun-Sep	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 rivers.
O-M14	Mussels	Variability	All months	Any time of year, a rapid decrease in stream flow may decrease depth and result in mussel stranding, particularly in margin habitats

A3.2 Literature Review

The *Eco Evidence* framework requires that a systematic and documented method for retrieving literature be employed 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 in *step 5* to develop the literature search and review to test hypotheses and support identified needs for the region. We developed standardized search strings for each key word and combined search strings to represent specific hypotheses. Overall we generated 105 different search strings representing the 33 fish flow ecology hypotheses. We used the Web of Knowledge (© 2012 Thompson Reuters) which simultaneously searches several citation index databases including Web of Science (1900-present), BIOSIS Citation Index (1926-present), BIOSIS Previews (1926-present), CABI: CAB Abstracts (1910-present), FSTA-the food science resource (1969-present), MEDLINE (1950-present), and the Zoological Record (1864-present). For each search string we generated anywhere from 1 to > 10,000 hits in the Web of Knowledge search engine. We sorted records by relevance and reviewed at least the first 500 abstracts to determine if identified papers were relevant to a hypothesis. In general, justification for relevance can include a combination of geographic proximity, similar environmental characteristics (i.e. temperate river systems), and similar causal agents (flow component, target species). While our problem was limited to a fairly small region representing streams within the New York and Pennsylvania portions of the Great Lakes watershed, papers were not limited to our study region. We expanded the area of which papers could come from to include temperate streams of North America that had similar target species or functional groups, but this was dependent of the hypotheses being reviewed. Additionally in a few cases (hypotheses related to fall spawning salmonids or floodplain fish communities) we also included papers from temperate rivers in Europe, as we considered it likely that these specific targets would respond similarly to flow alteration in European rivers. Additionally, because we were looking at questions related to variation in the natural flow regime and how organisms respond, we did not limit our analysis to studies that only investigated human impacts to flow regimes. We also included observed target organism responses to natural variation in the flow regime (i.e. differences in recruitment between wet years vs dry years). Evidence extraction involved recording whether study findings supported the hypothesis, the type of experimental or survey design used, and the number of replicates. This information was used to weight the evidence in *step 7*.

A3.2.1 Weighting evidence and judging support

Following the *Eco Evidence* framework, we used a rule-based approach to weight individual studies (*step 7*) based on the philosophy 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 A3.2. 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) + 2 (reference site) + 2 (impact site) = 6 (based on criteria in Table A3.2). The weights (and thresholds presented in Table A3.3) 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 A3.2 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.

Study design component	Weight
Study design type	
After impact only or published observation	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 for each hypothesis, we combined it to assess evidence of support for each hypothesis (*step 8*). 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). This is measured simply by comparing the sum of weights for supporting evidence for the hypothesis against the sum of weights against the hypothesis. A default threshold of 20 summed study weight points delineates the point at which sufficient evidence for (or against) 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). Table A3.3 presents a range of possible outcomes from the analysis. *Support for a hypothesis* requires both a high level of support (i.e. ≥20 points for evidence of response) and a lack of non-supporting evidence (<20). *Support for an alternative hypothesis* represents a falsification of a hypothesis, as does *inconsistent evidence* (both columns score above 20).

In these cases, new or revised hypotheses should be developed. Finally, hypotheses that were concluded to have *insufficient evidence* represent knowledge gaps in the literature (Norris et al. 2012). We used this framework to assess support from the literature based on three different scales of questions: 1) individual hypotheses; 2) overall flow needs; and 3) seasonal flow components. Individual hypotheses were assessed based on possible outcomes presented in Table A3.3, whereas support for flow needs and seasonal flow components were assessed based on combined scores of associated hypotheses and Table A3.3 values may not represent relevant thresholds for assessing support at the roll up level. However, the *Eco Evidence* weighting criteria and scoring thresholds still serve as a useful way to quantify support for seasonal flow needs based simply on the relative difference between evidence weights for the supporting and non-supporting columns.

Table A3.3 Possible outcomes of an *Eco Evidence* analysis, using the default 20-point threshold of summed evidence weights (Norris et al. 2012).

Summed evidence weights		
Evidence of response	Non-supporting evidence	Conclusion
≥ 20	< 20	Support for hypothesis
< 20	< 20	Insufficient evidence
≥ 20	≥ 20	Inconsistent evidence
< 20	≥ 20	Support for alternative hypothesis

Flow Need and Associated Hypotheses	***Evidence Score by Season***												**Evidence Score**	
	Fall			***Winter***			***Spring***			***Summer***				
	S	***O***	***N***	***D***	***J***	***F***	***M***	***A***	***M***	***J***	***J***	***A***	**Yes**	**No**
FN 1: Cue spawning migration and maintain access to and quality of spawning redds for spawning and recruitment of salmonids	***125/9***			*2/0*						***35/0***			**125**	**9**
High Flow	***24/0***			*2/0*						*13/0*			**24**	**0**
Seasonal Flow	***92/9***									*18/0*			**92**	**9**
Low Flow	*9/0*									*4/0*			9	0
Gl-F1	***24/0***			*2/0*						*13/0*			**24**	**0**
GL-F3	***54/9***									*18/0*			**54**	**9**
GL-F4	*11/0*												11	0
O-F1	***27/0***												**27**	**0**
GL-F7	*9/0*									*4/0*			9	0
FN 2: Maintain overwinter habitats for resident fish and egg and larval development				***111/9***									**111**	**9**
High Flow				***39/0***									**39**	**0**
Seasonal Flow				***36/9***									**36**	**9**
Low Flow				***36/0***									**36**	**0**
GL-F8				***39/0***									**39**	**0**
GL-F9				***24/9***									**24**	**9**
GL-F10				***42/0***									**42**	**0**
O-F5				*6/0*									6	0
FN 3: Maintain thermal regimes and habitat for mussel brooding and gamete development	*5/0*			*5/0*			*5/0*			*5/0*			5	0
Seasonal Flow	*5/0*			*5/0*			*5/0*			*5/0*			5	0
O-M1	*5/0*			*5/0*			*5/0*			*5/0*			5	0
O-M2													0	0

Table A3.4 Results of Eco Evidence analysis of support in scientific literature for individual hypotheses listed in Table A3.1. Bold entries identify hypotheses for which support in specific scientific studies surpassed the >20 threshold, indicating significant support. Results are presented as: rating of studies in support/rating of studies with inconclusive data or support for alternate hypotheses. Ratings for flow components are summations of the ratings for relevant hypotheses.

Flow Need and Associated Hypotheses	**Evidence Score by Season**				**Evidence Score**	
	Fall	**Winter**	**Spring**	**Summer**		
	S O N	**D J F**	**M A M**	**J J A**	**Yes**	**No**
FN 4: Maintain valley and island formation, associated floodplain/riparian vegetation, channel morphology and sediment distribution	**101/0**	**133/0**	**176/0**	**75/0**	**176**	**0**
High Flow	**88/0**	**133/0**	**163/0**	**62/0**	**163**	**0**
Low Flow	3/0	3/0	3/0	3/0	3	0
Rate of Change	10/0		10/0	10/0	10	0
GL-H3	4/0	4/0	10/0	10/0	10	0
GL-H4	9/0	9/0	15/0	15/0	15	0
O-V1		**63/0**	**63/0**		**63**	**0**
O-V2	**29/0**	**29/0**	**29/0**		**29**	**0**
O-V3	9/0	9/0	9/0		9	0
O-V7	10/0		10/0	10/0	10	0
O-V8	18/0		18/0	18/0	18	0
O-V9			3/0	3/0	3	0
O-V12	19/0	19/0	19/0	19/0	19	0
FN 5: Cue spawning migrations and maintain access to spawning and nursery habitats			**119/10**	7/0	**119**	**10**
High Flow			**63/9**	7/0	**63**	**9**
Seasonal Flow			**56/1**		**56**	**1**
GL-F11			16/0		16	0
GL-F13			**47/9**	7/0	**47**	**9**
GL-F15a			**56/1**		**51**	**1**

Flow Need and Associated Hypotheses	**Evidence Score by Season**				**Evidence Score**	
	Fall	**Winter**	**Spring**	**Summer**		
	S O N	**D J F**	**M A M**	**J J A**	**Yes**	**No**
FN 6: Support resident fish spawning	**28/0**	**65/9**	**278/9**	**146/0**	**291**	**9**
High Flow	4/0	4/0	**115/0**	**71/0**	**115**	**0**
Seasonal Flow	16/0	**48/9**	**110/9**	**35/0**	**123**	**9**
Low Flow			**22/0**	13/0	**31**	**0**
Rate of Change	8/0	13/0	**31/0**	**27/0**	**31**	**0**
GL-F14	4/0	4/0	**113/0**	**69/0**	**113**	**0**
GL-F15b			**41/0**	18/0	**41**	**0**
GL-F16			6/0	6/0	6	0
O-F6	16/0	**48/9**	**57/9**	13/0	**70**	**9**
GL-F18			**22/0**	13/0	**22**	**0**
GL-F19	8/0	13/0	**39/0**	**27/0**	**39**	**0**
F 7: Maintain access and quality of shallow-slow margin and backwater and nursery habitats	2/0	**5/0**	**148/0**	**71/0**	**153**	**0**
High Flow		5/0	**127/0**	59/0	**130**	**0**
Seasonal Flow	2/0		**21/0**	12/0	**23**	**0**
GL-F12			**52/0**		**52**	**0**
O-F16		5/0	**75/0**	**59/0**	**78**	**0**
O-F14	2/0		**21/0**	12/0	**23**	**0**
FN 8: Maintain suitable temperature and water quality	8/9		**63/9**	**84/18**	**84**	**18**
Seasonal Flow			11/9	11/9	11	9
Low Flow	8/9		**52/0**	**73/9**	**73**	**9**
GL-F17	8/9		11/9	**23/18**	**23**	**18**
GL-H5					0	0
GL-H7				9/0	9	0
GL-M11			**22/0**	**22/0**	**22**	**0**
GL-M8			**30/0**	**30/0**	**30**	**0**

Flow Need and Associated Hypotheses	**Evidence Score by Season**												**Evidence Score**	
	Fall			**Winter**			**Spring**			**Summer**				
	S	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**Yes**	**No**
FN 9: Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes	**44/0**						9/0			**150/0**			**150**	**0**
High Flow	**30/0**						9/0			**30/0**			**30**	**0**
Seasonal Flow	1/0									**44/0**			**44**	**0**
Low Flow	13/0									**76/0**			**76**	**0**
O-F20	**30/0**						9/0			**30/0**			**30**	**0**
O-F24										**23/0**			**23**	**0**
GL-F21	12/0									**60/0**			**60**	**0**
GL-F23										**31/0**			**31**	**0**
O-F25	2/0									6/0			6	0
FN 10: Maintain persistent shallow water habitat (riffle, run, pool margins) for juvenile fishes and riffle obligates	**56/0**						5/3			**149/3**			**149**	**3**
High Flow	14/0									14/0			14	0
Seasonal Flow	**23/0**						5/3			**55/3**			**55**	**3**
Low Flow	19/0									**80/0**			**80**	**0**
GL-F20/GL-F2	14/0									14/0			14	0
GL-F5	**37/0**									**86/0**			**86**	**0**
GL-F22										**24/0**			**24**	**0**
O-F28	5/0						5/3			**25/3**			**25**	**3**
FN 11: Support mussel spawning, glochidia transfer, juvenile colonization and growth	10/0			**77/0**			**135/0**			**135/0**			**159**	**0**
High Flow				**24/0**			**31/0**			**31/0**			**55**	**0**
Seasonal Flow				18/0			18/0			18/0			18	0
Low Flow				**25/0**			**76/0**			**76/0**			**76**	**0**
Rate of Change	10/0			10/0			10/0			10/0			10	0
O-M6				**24/0**			**31/0**			**31/0**			**31**	**0**
O-M14	10/0			10/0			10/0			10/0			10	0
O-M4				18/0			18/0			18/0			18	0
O-M5				**25/0**			**25/0**			**25/0**			**25**	**0**
O-M9							**25/0**			**25/0**			**25**	**0**
O-M10							**26/0**			**26/0**			**26**	**0**
O-M13													**24**	**0**

Appendix 4:

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