Potomac Basin Large River Environmental Flow Needs

PREPARED BY

James Cummins, Claire Buchanan, Carlton Haywood, Heidi Moltz,
Adam Griggs
The Interstate Commission on the Potomac River Basin
51 Monroe Street Suite PE-08
Rockville, Maryland 20850

R. Christian Jones, Richard Kraus
Potomac Environmental Research and Education Center
George Mason University
4400 University Drive, MS 5F2
Fairfax, VA 22030-4444

Nathaniel Hitt, Rita Villella Bumgardner
USGS Leetown Science Center
Aquatic Ecology Branch
11649 Leetown Road,
Kearneysville, WV 25430

PREPARED FOR

The Nature Conservancy of Maryland and the District of Columbia
5410 Grosvenor Lane, Ste. 100
Bethesda, MD 20814

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Interstate Commission on the Potomac River Basin
51 Monroe St., PE-08
Rockville, MD 20852

or call 301-984-1908.

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Front cover: the Potomac River from South Mountain, downstream of Harpers Ferry. Photo by Jim Palmer, ICPRB.

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EXECUTIVE SUMMARY

The purpose of this Potomac River environmental flows analysis is to identify the hydrologic needs of flow-dependent species and communities in segments of the mainstem Potomac and selected large tributaries. This work provides a foundation for a collaborative, multi-jurisdictional dialogue on developing flow recommendations for the river that would protect its flow regime. These recommendations can be made operational by state and local jurisdictions through the development of decision support tools to help guide water and land use planning and management.

Environmental flow is defined as seasonally and inter-annually variable flow of water that sustains healthy river ecosystems and the goods and services that people derive from them. A river's flow regime – the magnitude, frequency, duration, timing, and rate of change of water in the river – is regarded by river scientists to be a "master variable" that influences all other aspects of riverine ecosystems, from water quality to habitat availability to energy supply to biotic interactions. Aquatic species and natural communities have evolved in concert with naturally variable flows, and the ecological health of a river system depends on an intact hydrologic regime.

The Potomac is the fourth largest river along the U.S. Atlantic coast and the second greatest source of freshwater flow to the Chesapeake Bay. The river travels 383 miles through a 14,670 square mile watershed of six million people, most of whom live in the Washington D.C. metropolitan region. The Potomac provides more than 500 million gallons of freshwater daily to those living in its watershed, as well as other critical environmental services such as wastewater assimilation, irrigation, and power plant cooling water.

Compared to other large eastern U.S. river systems, the Potomac River is relatively intact, with few large dams regulating its flows. For this reason, the Potomac presents a rare opportunity to be proactive in defining a hydrological baseline of the flows required to sustain its natural diversity and ecosystem functions while meeting the needs of a growing regional human population. The opportunity is timely considering the watershed jurisdictions' development of state water management plans and policies, increased demand for consumptive use of river water, and the potential for increased incidence of droughts or catastrophic floods with global climate change. Continued population growth in the watershed is expected to convert forest and farmland into developed and hardened landscapes, increasing demand for water and electricity and increasing levels of runoff and pollution to the river and the Bay.

This large river-focused report is part of a broader effort to identify, protect, and, where necessary, restore the Potomac watershed's environmental flows – the Middle Potomac Watershed Assessment, a U.S. Army Corps of Engineers (USACE) project partnered with the Interstate Commission on the Potomac River Basin (ICPRB) and The Nature Conservancy (TNC). The U.S. National Park Service provided funding for this portion of that larger effort. In conjunction with the work represented in this report, ICPRB is also defining quantitative flow alteration-ecological response relationships for classes of smaller tributary stream systems in the basin. While the official geographic scope of the watershed assessment is the Middle Potomac River basin (**Figure 1**), many of the overall project analyses are watershed-wide in scope. This report focuses on an evaluation of six selected river reaches using a modification of the *Ecologically Sustainable Water Management* approach described in Richter et al. (2006). The purpose of this evaluation is to identify ecological flow needs for these river reaches and their representative species and natural communities to provide guidance for future decisions about water uses and development in the Potomac watershed that may affect flows.

This draft report was conducted by a research team from ICPRB, TNC, Aquatic Ecology Branch of the USGS (USGS), and the Potomac Environmental Research and Education Center of George Mason University (GMU). It includes a comprehensive literature review, assessment of large river flow needs, flow hypotheses, and draft flow recommendations. Over 480 sources of information were collected, reviewed, and organized into a searchable on-line database. The draft report will serve as a foundation for a Potomac large river environmental flows workshop, to be held September 22-23, 2010, at the National Conservation Training Center, Shepherdstown, WV. At the workshop, hydrologists, biologists, engineers, water resource managers, and regional and national experts on flow and river ecology will discuss the report findings and recommendations put forth in this draft report. The final report will include the findings and recommendations from the workshop. In conjunction with the concurrent Middle Potomac Watershed Assessment, this work can support the development of decision support tools that will enable water and land use managers to consider the ecological implications of land and water use decisions across non-Coastal Plain portions of the Potomac watershed.

Two Potomac sub-basins and three mainstem segments were selected for this study because of the high count and severity of risk factors that can lead to altered hydrology. These were:

1) Potomac mainstem from the confluence of the Shenandoah River to Point of Rocks
2) Potomac mainstem from Point of Rocks to Great Falls
3) Potomac mainstem from Great Falls to Chain Bridge (Potomac Gorge or Fall Zone)
4) Monocacy River mainstem
5) Opequon Creek mainstem

The Potomac River Gorge is of special concern because of its relatively unique and rare biological communities. One charge to the study was to re-examine the 100 million gallon per day (mgd) (155 cfs) minimum flow-by requirement established for the Gorge in the 1978 Potomac River Low-Flow Allocation Agreement. The tidal fresh Potomac estuary from Chain Bridge to Occoquan Bay was also examined for flow alteration effects.

Four plant communities, twelve fish indicator species, and sixteen native mussel species were selected and used to represent the diversity of species, the flow ecology relationships, and the flow needs of communities found in the large, free flowing rivers of the basin. Sufficient research and empirical data to define thresholds of acceptable hydrologic change applicable to the Middle Potomac River study area were not found. The research team used the available literature and professional judgment to develop 5 general flow-ecology hypotheses that apply to a broad range of species/communities and 18 specific flow-ecology hypotheses tailored to selected indicator organisms.

Phytoplankton, aquatic grasses, zooplankton, and benthic invertebrate communities, and four fish species were used to represent key aspects of tidal freshwater ecology and its responses to low freshwater flows in the tidal fresh estuary. In general, the ecological impacts of flow into the Potomac tidal fresh estuary are to deliver nutrients and pollutants and to determine the location of the salinity gradient which governs structure and function of biological communities along the entire length of the estuary. Low flow effects on estuarine biota are for the most part indirect and realized as a change in salinity, or the volume proportions of fresh and salt water. Flow alteration as a factor affecting the Potomac tidal fresh biological communities is presently far outweighed by the effects of poor water quality and other stressors. Seven general flow-ecology hypotheses for the tidal fresh estuary are presented.

Key points that shaped the team's flow recommendations

1) The Potomac River has only minimal flow regulation, and that only at very low flows. There are no dams regulating flow on Opequon Creek or Monocacy River. Thus, high and mid range flow magnitude, and frequency and duration of events, are not subject to operational management.
2) Except for low flows from Great Falls to Little Falls, the observed distribution of flows appears to be the result of weather, climate, and land use factors.
3) Evidence suggests that there have been changes in flow distributions over the past 100 years but additional analysis is required to determine the roles of climate, land use, or other factors, in those changes.
4) Intra- and inter-annual variability in flows is high.

5) For aquatic species, the only studies found in the literature that provided quantitative measures of flow needs were expressed as velocity requirements at the individual organism scale. These requirements could not be translated to stream discharge values. The literature and expert judgment did provide qualitative descriptions of flow needs.
6) No documented evidence of species impairment due to flow management was found.
7) Low flows in the Great Falls to Little Falls reach are lower than they would otherwise be due to drinking water withdrawals at, and above, Great Falls. A 100 mgd (155 cfs) minimum flow-by at Little Falls and 300 mgd (464 cfs) from Great Falls to Little Falls recommendation has been observed since the early 1980s. During that time flows have rarely been that low. In 2002, when flows were approaching these levels, field observations did not identify any stressed communities and there did not seem to be a significant loss of habitat in these reaches.
8) The flow "needs" of most freshwater species in the tidal fresh river segment are typically a reflection of their salinity preferences and tolerances. High river flows can benefit taxa and life stages that prefer freshwater while low flows can benefit taxa and life stages that prefer salt water.
9) Eutrophication and sedimentation of the tidal Potomac River have significantly changed many estuarine flow-ecology relationships. The flow needs identified for tidal fresh biota do not consider the very significant confounding influence of the tidal fresh Potomac River's poor water quality. Nor do they consider the flow needs of higher salinity taxa such as oysters, young-of-year menhaden, and older, resident striped bass.
10) Future impacts on flow from climate change are uncertain but studies have suggested that impacts in the middle Atlantic region of the U.S. will be lower in magnitude than elsewhere and may result in both higher precipitation and higher temperatures.

Considering these points, the team's approach has been less a question of determining what flows are required to restore these river sections, and more a matter of defining and characterizing how existing flows are functioning to maintain ecological values. Tables 12-16 provide that characterization. Tables 12 and 13 relate the flow hypotheses listed at the end of Chapters 2 and 3 to flow needs, grouped into high, mid-range, and low flow categories and, within categories, addressing magnitude, frequency and duration of events. In Table 14, a set of flow metrics, or statistics, are proposed to "capture" the ecological needs identified in Tables 12-13. Table 15 provides a cross reference showing which flow statistics are relevant to the flow needs of each biotic community.

Table 16 shows values computed for each flow statistic for the five large river reaches (the Opequon Creek mainstem, the Monocacy River mainstem, and three Potomac River mainstem segments between the Shenandoah River confluence and Little Falls) selected for this study. The flow statistics for each reach were calculated from daily mean flows recorded at US Geologic Survey gages between 1984 and 2005. Freshwater inflow to the upper tidal estuary can be represented by either the Little Falls or Great Falls flow statistics. Most of the drinking water withdrawn above Little Falls is returned to the tidal fresh estuary at Blue Plains as treated wastewater. Since Great Falls flow equals Little Falls flow plus drinking water withdrawals, the Great Falls flow is a better measure of total Potomac River contribution to the entire tidal fresh zone. Little Falls flow is the better measure of Potomac River contribution to the portion of the tidal river above the confluence with the Anacostia River. Table 16 includes first and third quartile values, in addition to medians, in order to indicate variability associated with these measures.

Draft Flow Recommendations

1) General flow recommendation: Maintain current flow characteristics.
2) Extreme floods: Where possible, impervious surface cover should be reduced and vegetative cover increased to reduce extreme floods.
3) Small Floods: No observed major problems, recommend maintain current flow characteristics.
4) Low Flows - Potomac Mainstem Harpers Ferry to Point of Rocks: There are no discernable problems in this reach, therefore, recommend maintain current flow characteristics.

5) Low Flows - Point of Rocks to Great Falls: Withdrawals should be managed so that Potomac river flows do not fall below those experienced in the 1999 and 2002 droughts. It is recommended also that a gage be installed to measure low flow levels at the Great Falls weir.
6) Low Flows - Great Falls to Little Falls: A prior (1978) recommendation for a 300 mgd minimum flow should be continued.
7) Low Flows - Little Falls to Chain Bridge (tidal river): A) maintain the existing 100 mgd minimum flow-by, and also B) maintain the variability in extreme low flows observed in 1999 and 2002.
8) Low Flows - Chain Bridge to Occoquan Bay: Water quality is the major determinant of biological health, not freshwater flow. Recommend maintaining current flow characteristics.
9) Low Flows - Monocacy River and Opequon Creek: Current low flow statistics should be maintained and withdrawal volumes not be allowed to push flows below those observed in 1999 and 2002.

Information Gaps and Research Recommendations

1) Monitoring and data analysis gaps identified in 2004 and 2005 Potomac low flow workshops should be addressed, including: Studies to better understand the "normal" variation of species populations and ranges; and studies to better understand the effects of extreme low flows on species and their habitat.
2) Mussels are an excellent group to use for studying impacts of low flows because they are sessile and more likely to become stranded. These species were *Elliptio complanata, Pyganadon cataracta, Utterbackia imbecillis, Lampsilis sp,* and possibly *Strophitus undulatus and Alasmidonta undulata.*
3) Recommend research on fish species which live near drinking water intake pipes; a focus on short life span, rather than long life span, fish species.
4) Research recommendations for other species groups:
    a. Macroinvertebrates may be useful but large river study protocols are not well developed. Crayfish may be an important group because they are an important food source.
    b. Amphibians and reptiles are difficult to study because they are mobile.
    c. Cormorants are important as fish predators, but they are mobile, part time residents, and population changes may be due to factors other than river flow and fish (prey) abundance.
5) Monitoring recommendations:
    a. For most of the species discussed in this report, there simply is not enough information with which to define the normal variability in population and distribution.
    b. Additional monitoring or analysis may be helpful to define acceptable levels of hydrologic change, or what the acceptable thresholds of deviation from current conditions.
    c. Some of that analysis is being done for the Middle Potomac Watershed Assessment project. After that study is complete, it will be appropriate to revisit this issue to propose new monitoring that is targeted at measuring change in a few key flow measures and for potential disruptions to key biotic communities.

Participants of the September 22-23, 2010, workshop will discuss and refine the flow hypotheses and information gaps and research recommendations.

CHAPTER 1: INTRODUCTION

Summary

This study accomplishes the first step in an Ecologically Sustainable Water Management (ESWM) process focused on the Potomac River. A literature survey and technical synthesis identified the flow needs of native species and natural ecosystem functions in large rivers of the Middle Potomac River study area (**Figure 1**). This report and the findings of a September 22-23, 2010 workshop support a companion ongoing effort, the Middle Potomac Watershed Assessment, to quantify environmental flows and facilitate long-term sustainable water management in the river basin. The Potomac River, with relatively few dams, offers a rare opportunity to examine the flow regime of a Mid-Atlantic river with relatively unregulated hydrology. Average monthly precipitation in the basin is approximately the same across the year, but high evapotranspiration rates from May to October result in lower summer and autumn flows and higher winter and spring flows. Inter-annual variability in precipitation results in a two orders of magnitude difference between minimum and maximum daily mean flows throughout the year (**Figure 2**). During droughts, summer flows in the Potomac mainstem can approach the total amount withdrawn to supply drinking water to the large Washington metropolitan area. A suite of hydrologic indicators was used to characterize components of environmental flow. A preliminary analysis (Category and Regression Tree) of 35 Potomac sub-basins and 5 mainstem segments identified natural features, land uses and water uses that can potentially alter hydrology. A simple cumulative risk index calculated for each sub-basin and segment (**Table 1**) pinpointed the following nontidal river reaches as having the highest count and severity of risk factors:

1) Potomac mainstem from the confluence of the Shenandoah River to Point of Rocks
2) Potomac mainstem from Point of Rocks to Great Falls
3) Potomac mainstem from Great Falls to Chain Bridge (Potomac Gorge or Fall Zone)
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The Potomac River Gorge located between Great Falls and Little Falls is of special concern because of its relatively unique and rare biological communities. One charge of the study and workshop is to re-examine the 100 million gallon per day (mgd) (equivalent to 155 cfs) minimum flow-by requirement established for the Gorge in the 1978 Potomac River Low-Flow Allocation Agreement. The tidal fresh Potomac estuary from Chain Bridge to Occoquan Bay was also examined for flow alteration effects.

Appendix A lists flow metrics calculated by the Indicators of Hydrologic Alteration software. Appendix B has a detailed description of the CART analysis; Appendix C has additional information about watershed geology, land use, and long term trends in streamflow; Appendix F has information on how to access and use the online database of literature reviewed for this report.

Background

Environmental flows needs can be defined as the quality, quantity and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide multiple goods and services to people. We assume that least-disturbed watersheds meet most of the environmental flow needs of a river's ecosystem.

This report provides the findings of a study to identify the flow needs of native species and natural ecosystem functions in large river reaches of the Potomac basin. This large river environmental flow needs assessment, which was supported by funding from The Nature Conservancy and the U.S. National Park Service, accomplishes the first step in the Ecologically Sustainable Water Management (ESWM) approach described by Richter et al. (2003) and the study's findings provide a baseline against which flow changes resulting from human impacts (water use and watershed changes) and climate change can be evaluated. More information about ESWM is provided at http://www.nature.org/initiatives/freshwater/misc/art16771.html.
In a companion study, the Interstate Commission on the Potomac River Basin (ICPRB), The Nature Conservancy (TNC), and the U.S. Army Corps of Engineers (USACE) are conducting a watershed assessment of the Middle Potomac River basin (**Figure 1**) to describe current and future conditions that are likely to have significant impacts on human and ecological flow needs within the basin. Work conducted for the watershed assessment (see Assessing Risk of Hydrologic Alteration, pp 12-16) , helped inform the selection of river reaches evaluated in this large river environmental flow needs assessment. For further information about the Middle Potomac Watershed Assessment, due to be completed in February 2012, visit http://www.potomacriver.org/cms/.

The ESWM process was developed by TNC and described in Richter et al. (2003). Flow-ecology relationships are identified by relating critical life history traits of river communities to categories of events in the flow regime, or Environmental Flow Components (EFCs) (Richter et al. 2005, Postel and Richter 2003). Critical life history aspects of aquatic biota include fish spawning times and habitat requirements and the return interval of floods needed to inundate and maintain riparian areas and disperse seeds. The EFC's categories used in this study are low-flows, mid-range flows, and high flows. This process provides an analytical framework to relate flows with the ecological needs of river-based species and communities. Next steps, to be done as part of the separate Middle Potomac Watershed Assessment project, are: a) development of empirically testable relationships between flow alteration and ecological responses using the Ecological Limits of Hydrologic Alteration (ELOHA) approach, and b) an assessment of human impacts on water flows. The former identifies quantitative thresholds of environmental degradation due to flow alteration, and the latter identifies existing water uses that are incompatible with the river ecological needs, and facilitates development of solutions to resolve the incompatibilities.

Flow-ecology research and management in this country and throughout the world have focused on restoring natural flow regimes to highly regulated rivers where large dams capture large volumes of water, resulting in abrupt and overt changes to the flow regime and negatively altering the river ecology. The Potomac River is one of the least dam-regulated large river systems in the Eastern United States. The combined storage capacity of all major impoundments in the basin upstream of Washington, DC makes up less than 7% of median flow. Consequently, this river offers a rare opportunity to characterize the flow regime of a relatively unregulated hydrology. Despite this distinction, the Potomac's flow regimes are at risk from population growth. Population growth accelerates loss of forest and farmland, hardens surfaces, increases demand for water, and can increase levels of runoff and pollution to the Potomac River and Chesapeake Bay. Urbanization can significantly alter a river's flow regime, impacting river ecosystems and the people depending on them (Lettenmaier 1999; Poff 2002; Palmer 2007). A study of the Potomac River's present flow regime is timely in light of the fact that several basin jurisdictions are presently developing state water management policies.

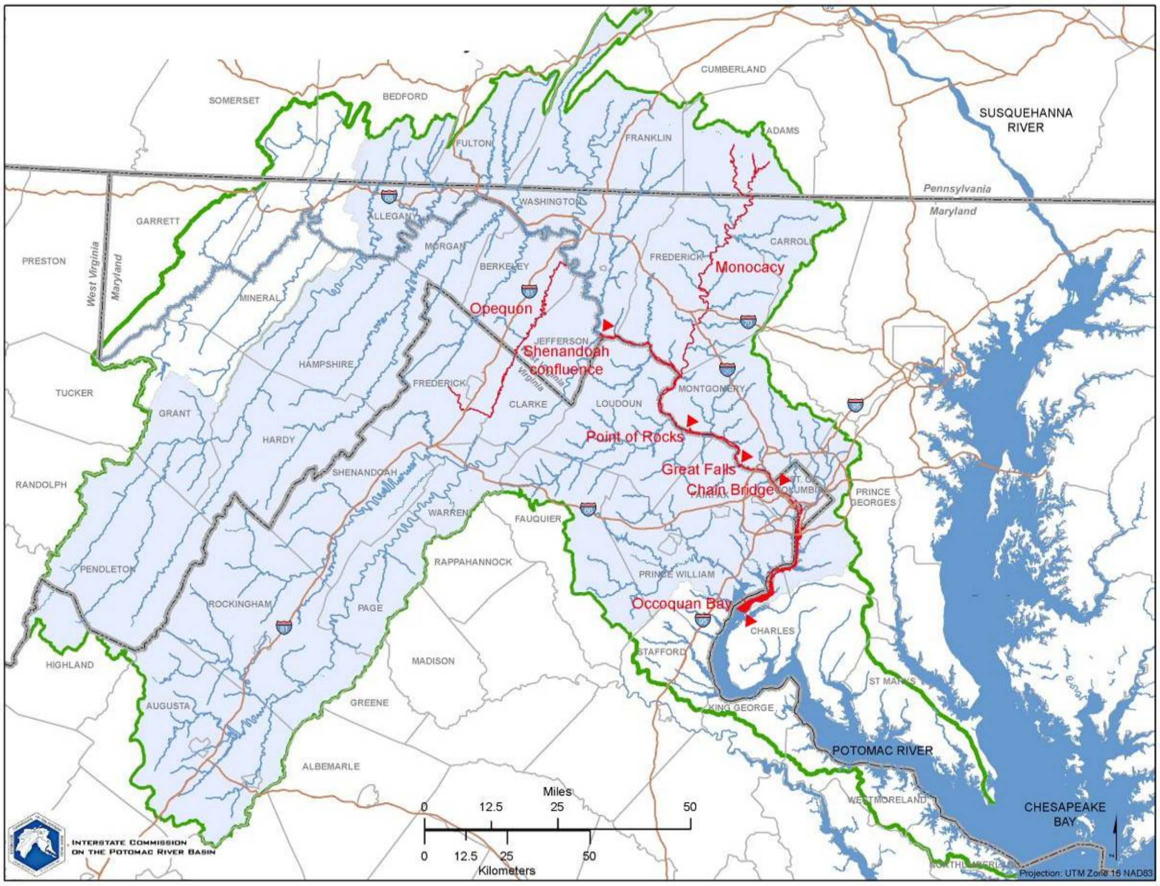


Figure 1. Middle Potomac River study area and the study's large river segments.
Red lines and triangles identify river segments identified as areas of special interest in this study. Light blue shading indicates the Middle Potomac watershed study area. Green line is the Potomac River basin boundary.

Methodology

ICPRB and TNC collaborated with the Aquatic Ecology Branch of the U.S. Geologic Survey (USGS) and the Potomac Environmental Research and Education Center of George Mason University (GMU) to conduct a literature search for information relevant to environmental flow requirements for the Potomac River and its ecological components. This search included information on small streams as well as large river environments so that the information also could be a resource for aquatic ecological assessments throughout the Potomac watershed. Over 480 sources of information were collected, reviewed, and organized into a searchable on-line database (see Appendix F). Five nontidal river reaches and one tidal region were selected for focused study based on an assessment of risk of hydrologic alteration. Using information from the literature review and professional judgment, the research team selected large river indicator species or communities known to be dependent upon specific flow conditions during one or more aspects of their life cycle. Then the research team developed flow-ecology hypotheses that link specific environmental flow components (low flows, mid-range flows, and high flows) with the needs and tolerances of these species or communities, as well as key river processes. A preliminary assessment of the current hydrology, i.e. distribution of flows, was then used to help characterize how period-of-record hydrologic changes might be affecting these indicator species and communities. A draft set of flow recommendations was developed based on the flow-ecology hypotheses and current hydrology, and recommendations made to fill information gaps. The information assembled in this report is intended to serve as background material for a Potomac Large River Flow Workshop, to be held September 22-23, 2010 at the National Conservation Training Center, Shepherdstown, WV. At the workshop, scientists, engineers, water resource managers, and regional and national experts on flow and river ecology will review the report and draft flow recommendations. The workshop findings will be used to further the ESWM process in the Potomac basin and facilitate ecologically sustainable water management for the long term in the basin's jurisdictions. The final report will combine this draft report with the results of the flow workshop.

Hydrologic Indicators

Metrics that characterize flow regimes and hydrological events such as floods and droughts are called hydrologic indicators. They are used to evaluate different Environmental Flow Components (EFCs), or repeating patterns in a hydrograph that are ecologically relevant. Five types of EFCs can be calculated from mean daily flows using the Indicators of Hydrologic Alteration (IHA) software developed by The Nature Conservancy. They are low flows, extreme low flows, high flow pulses, small floods, and large floods (Appendix A). Thresholds for identifying each EFC type are set according to the software user's preferences, which can be based on literature reviews or data analyses. The different flow components trigger important reproductive and migratory behaviors in the correct seasons, affect the diversity and abundance of plants and animals, and shape the river's structure. Poff et al. (2010) and other researchers believe the full spectrum of flow conditions represented by these five types of flow events must be maintained in order to sustain riverine ecological integrity.

The flow-ecology relationships in the main body of this report are initially qualitative. For example, "high flow" events cue fish migrations in certain months and "low flow" years increase growth and reproduction of submerged aquatic vegetation (SAV). Quantitative flow thresholds for key EFCs were subsequently developed from these flow-ecology relationships and used to evaluate and compare river flow regimes (Chapter 4). Flow, or the volume of water moving through a river cross-section per unit of time, is calculated from multiple velocity measurements made in a cross-section of known dimensions. In some cases, the literature identifies optimal or preferred flow velocities for a species' growth or survival. Velocity is dependent on several factors, including the energy gradient (slope), depth, and roughness. It "varies from one part of a given cross section to another and is the integrated result of complex interaction of water moving at different speeds in different parts of the channel" (Leopold et al. 1964). Velocity is thus useful in evaluating local stream habitat conditions but not entire stream or river reaches.

Figures 2 (log scale) and **3** (linear scale) are annual hydrographs that show the seasonal cycle of flows and annual variability at the Point of Rocks gage. (Flow units are shown as million gallons per day, or mgd. To obtain cubic feet per second, multiply million gallons per day by 1.547.) Of the Potomac mainstem gages, this one has the least amount of consumptive withdrawals in its upstream watershed (1.66% of median flows). Generally speaking, flows in the spring are about five times higher than flows in late summer, but year to year variability is such that 1.5 - 2.0 orders of magnitude separates peak and minimum flows for each day of the year. Both hydrographs show that, over the past 113 years, floods with mean daily flows greater than 100,000 mgd (154,700 cfs) have occurred in almost every month. No long-term record of flows with similar magnitudes prior to the mid 1800s is available. The gage record also documents three extended droughts in the Potomac River: 1930-1931, 1965-1966, and 1999-2002. Annual hydrographs for the other large river reaches considered in this report show a similar annual cycle.

Lorie and Hagen (2007) used the Palmer Drought Severity Index estimates derived from Potomac basin tree rings to reconstruct annual minimum flows dating back to 367 A.D. By their estimates, twenty-one *annual* minimum flows have been lower than the all time low flow observed in 1966 at the gage. Long-term moving averages (10-yr, 50-yr) of the reconstructed annual minima imply that prolonged periods of low flows (droughts) more severe than those in the gage record probably occurred in the past 1650 years (**Figure 4**). The basin was mostly forested until clear-cutting and agricultural practices in the 18th, 19th

and 20th centuries significantly altered the landscape and effectively changing its evaporation and plant transpiration properties.

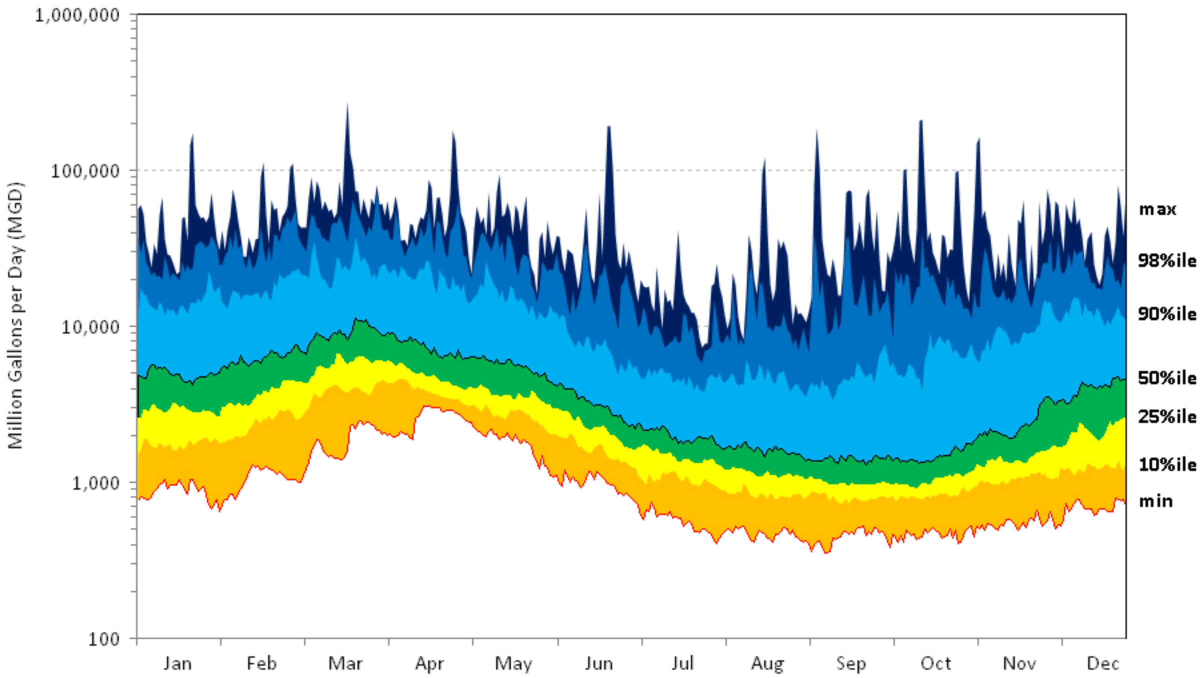


Figure 2. Logarithmic projection of the distribution of daily mean flows at the Point of Rocks, MD gage for each day of the year (data from 2/1/1895 – 9/30/2008).

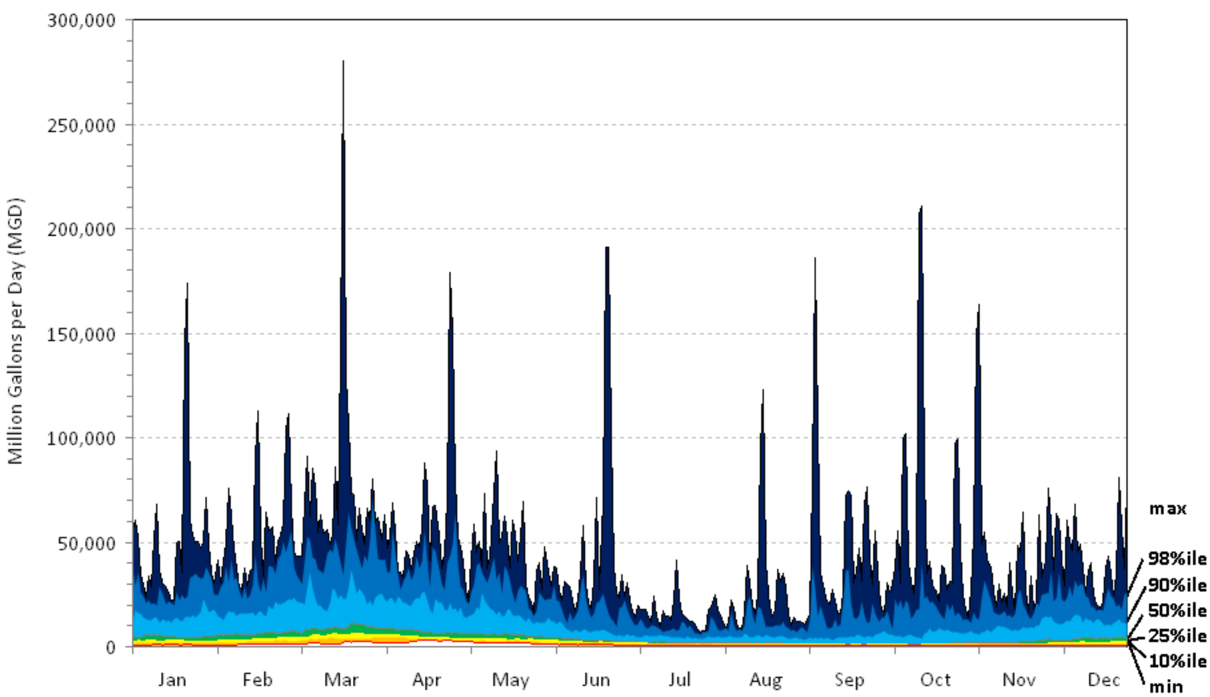


Figure 3. Linear projection of the distribution of daily mean flows at the Point of Rocks, MD gage for each day of the year (data from 2/1/1895 – 9/30/2008).

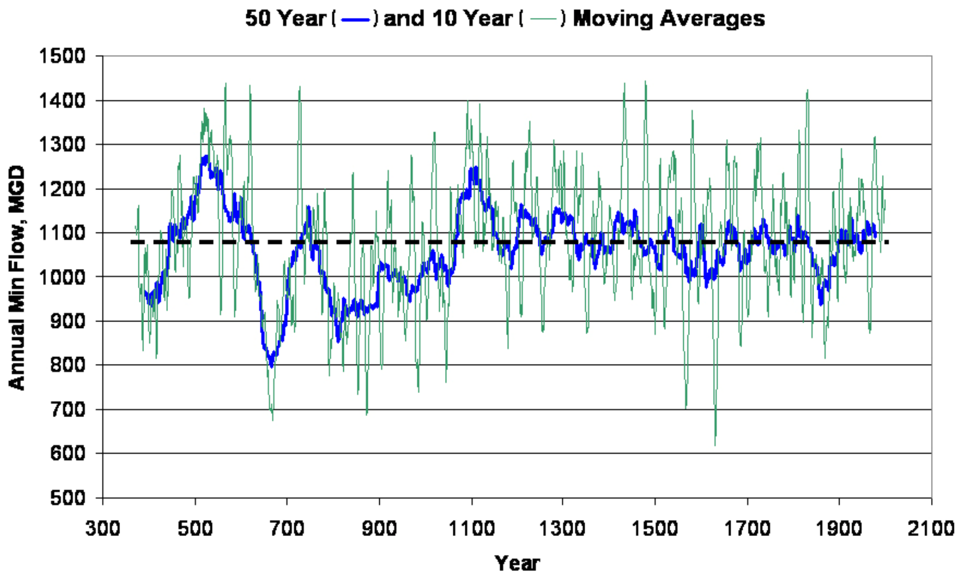


Figure 4. Reconstructed annual minimum flows from tree-rings (from Lorie and Hagen 2007). Dashed line is average annual minimum flow. Multiply by 1.547 to obtain cfs.

Factors Influencing Potomac River Hydrology

The hydrology of the Potomac River, like all rivers, is defined by watershed topography, geology, climate, and vegetation. Each of these factors poses some level of "risk" of altering the natural hydrology of a river. Karst geology more closely connects surface and groundwater flows (Waele et al. 2009; Legrand and Stringfield 1973) and was shown to increase low surface flows and decrease high surface flows during the course of this study. Forests have complex hydrologic effects including higher infiltration rates, which may sustain baseflows during low flow conditions, and consumptive use of soil water and shallow groundwater by evapotranspiration (Dunne and Leopold, 1943). Human activities in the watershed—population growth (urbanization), agriculture, mining, water withdrawals, and dams—can further alter the river's hydrology. Agricultural land uses are associated with increased run-off, erosion, and nutrients (Novotny and Harvey, 1993). Increases in urban land cover and imperviousness increase the volume of surface run-off and storm peaks while decreasing the time to hydrograph peak among other hydrologic impacts (Dunne and Leopold, 1943; Novotny and Harvey, 1993). Impoundments can have widely varying impacts on downstream hydrology depending on their size and operations. Both surface and groundwater withdrawals may limit the availability of water resources for instream uses, both human and ecological. Human consumptive use is of particular interest because the withdrawn water is not returned to the waterway and is effectively lost to downstream uses.

Topography and Geology

Starting as a spring at the Fairfax Stone in West Virginia, the Potomac River flows approximately 385 miles to the Chesapeake Bay. Its tributaries drain areas of West Virginia, Maryland, Pennsylvania, Virginia, and all of the District of Columbia. The Potomac River is the Chesapeake Bay's second largest tributary, with a mouth nearly 10 miles wide. It crosses five major physiographic provinces or Level III ecoregions (Woods et al. 1999) from headwaters to mouth (**Figure 5**). Each province has a distinct topography and geology that affects river structure and flow.

The Central Appalachian Plateau is a high elevation, deeply dissected plateau with shallow soils and nearly horizontally bedded shales and sandstones of Upper Devonian and Mississippian ages. Coal mining has altered natural drainage patterns and negatively influenced water quality. The Potomac watershed in this province receives the watershed's greatest precipitation, has a shorter growing season and, with its low permeability, has the greatest surface runoff per unit of area. None of the plateau is included in the Middle Potomac River assessment study area but its flows significantly influence the Potomac River when they enter the study area near Oldtown, MD.

The Ridge and Valley makes up much more of the basin area than any other province. It is composed of intensely folded and, in many cases, faulted sedimentary rocks formed between the Cambrian and Devonian ages. All large rivers in this province flow northeast or southwest until they meet the Potomac River mainstem, which arcs from northwest to southeast across the province (**Figure 5**). The western two-thirds of the province have narrow ridges and valleys, with shales predominating in the valleys and more resistant sandstones generally forming the ridges. The area is mostly forested, but also has fairly high runoff rates due to low permeability. The easterly one-third is a broad limestone ("karst") valley, sometimes called the Great Valley, which is drained by the Shenandoah River in the south and Conococheague Creek in the north. This valley has well developed subsurface drainage and widespread solution cavities. It is heavily farmed because of its fertile soils.

The Blue Ridge is a narrow mountain belt separating the Great Valley from the Piedmont. In general, it is a single, erosion-resistant ridge composed of steeply dipping quartzites and slates of Cambrian age on the west and pre-Cambrian greenstones, schist, and granite on the east. The Blue Ridge remains largely forested, but there are areas of recent urban growth. Its shallow soils and steep slopes do not support much agriculture.

The Piedmont province slopes eastward from the Blue Ridge to the Coastal Plain. In the western half of the province, erodible sandstones and shales underlay the broad, flat Leesburg and Frederick valleys. To the east, the Piedmont becomes a plateau characterized by rounded hills and V-shaped valleys cut in pre-Cambian schists and gneisses with many intrusions of younger igneous rocks. An eastern remnant of the Blue Ridge mountain range is the monadnock Sugarloaf Mountain. Deep zones of soil are common in Piedmont valleys which were once predominantly agricultural. The region is becoming increasingly urban as the greater metropolitan Washington area expands.

The Coastal Plain province in the Potomac River basin (called the Southeastern Plains ecoregion in Woods et al. 1999) is a low elevation, dissected, hilly plain underlain by irregular, stratified, and unconsolidated beds of gravel, sand, clay and marl. These deposits rest upon crystalline rocks which lie at depths which vary from a few feet at the western boundary to 2,000 feet or more at the mouth of the Potomac River estuary. The area was once heavily agricultural and now faces urban development. Only the small section of Coastal Plain adjacent to Washington, DC is included in the Middle Potomac River assessment study area (**Figure 1**).

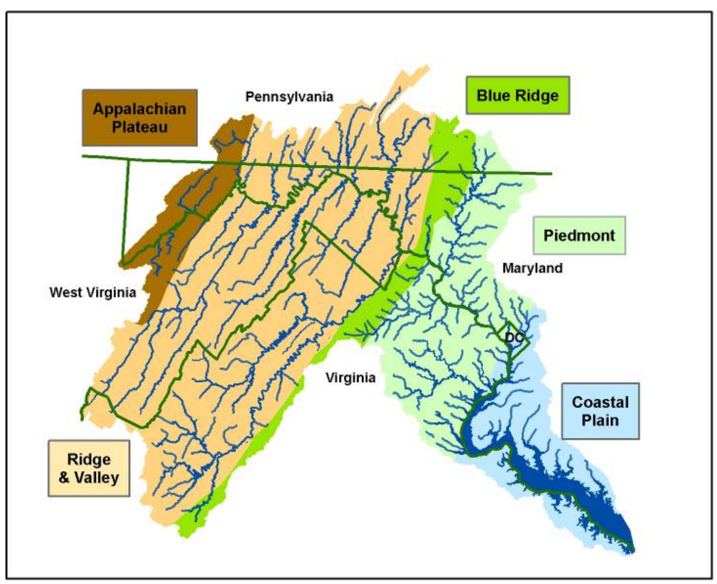


Figure 5. Physiographic provinces of the Potomac River basin, based on Woods et al. (1999). See text for details.

In the Central Appalachian Plateau, Ridge and Valley, and Blue Ridge provinces, locations of the Potomac's larger rivers have remained relatively unchanged because their channels were cut into bedrock when geologic uplifting formed the Appalachian Mountains more than 250 million years ago. River down-cutting formed V-shaped valleys as the mountains eroded, and glaciers never scoured the basin during the Pliocene-Quaternary ice ages. The wetted, or active, mainstems are usually wide and shallow and often constrained by bedrock. River bottoms have thin alluvial sediment layers interspersed with rock ledges and rock beds. There is typically a single thalweg divided occasionally by islands, some of which are long (over a mile) and wide (over 500 feet).

River channels in Piedmont province have shifted over time. Fluctuating sea level, especially during the ice ages, and differential uplifting of the Piedmont relative to the Coastal Plain are responsible for most of the shifts in the Piedmont (Reed 1981). Rivers located in the broad, flat valleys of the western Piedmont are wide, shallow and slow with large flood plains. In the eastern Piedmont, rivers have eroded wide, steep-sided valleys which confine their flood plains. The Potomac River settled into its present position in the Piedmont about 2 million years ago. Active down-cutting during the Pleistocene ice ages formed the river's Great Falls gorge which is located on a zone of flexure or distributed faulting (Fall Line) at the Coastal Plain boundary.

From a geologic perspective, the path of the tidally-influenced Potomac River has changed course often as it crossed the Coastal Plain physiographic province. Evidence of this is visible in topographic maps of the area between Washington, DC and Occoquan Bay (e.g., folio map 2 of the Environmental Atlas of the Potomac River Estuary, Lippson et al. 1979). Tributaries draining the Coastal Plain as sea level fell during each ice age would often down-cut new paths through the unconsolidated sediments to reach the developing Chesapeake Bay and Atlantic Ocean. The province is presently undergoing cycles of post-glacial isostatic rebound, tilting, and subsidence as the earth's crust recovers from the weight of the last ice sheet.

Climate and Vegetation

The Potomac watershed has a temperate climate but summer temperatures can exceed 105°F in the southeastern portions and winter temperatures go below -30 °F in its western mountains. The projected 3°C increase in mean temperature related to climate change which will make September temperatures more like those in June in 2050 (O. Devereux, pers. comm.). Much of the basin currently receives between 35"-45" of precipitation per year, with a basin-wide average of about 39" per year. There are areas with notable differences, the headwaters of the North Branch average approximately 52"/yr while an area of the South Branch south of Petersburg, WV averages only 30"/year, a difference of 22"/yr of rainfall occurring over a distance of less than 30 miles. This abrupt difference is due to a rain shadow effect caused by the mountain system which includes Spruce Knob.

Unlike the western United States, average precipitation in the eastern mid-Atlantic is more evenly spread across the year and rivers are less dependent on snow-melt for their flow. Monthly rainfall averages in the Potomac River basin range from 2.54" in February to 4.13" in May (**Figure 6**). Median flow of the river varies 16-fold, however, with highs typical in late winter and lows in late summer (**Figures 2** and **3**). Seasonal differences are primarily due to increased evaporation and plant transpiration during the warmer months of the growing season, between March and September. Evaporation and plant transpiration redirect almost 60% of the basin's annual precipitation away from surface flows in spring and summer. Surface flows usually reach their annual minimum in late summer even though monthly precipitation is slightly above average. Transpiration and evaporation decrease in the autumn with leaf-senescence

Figure 6. Monthly rainfall averages for the Potomac River basin (U.S. Weather Service).

and cooler temperatures, and surface flows return to relatively high median levels in December. Snow melt increases the median slightly in March and April.

Most of the plant transpiration is due to forests which cover ~63% of the river basin above Washington, DC. Some is due to agricultural crops in the basin. While substantial plant transpiration directly reduces spring and summer surface flows, a vegetated watershed also reduces the number of high pulses resulting from rainfall events, dampens the peak flows of major events, and distributes high flows across more days. This allows more groundwater recharge and better retention of soil and organic material in the watershed.

In a global analysis of the potential effect of climate change on river basins, Palmer et al. (2008) found that the northeast region of the United States would have generally low level of stress and postulated that free-flowing rivers would require less management interventions than rivers impacted by dams. The USGS evaluated whether droughts have increased over recent decades in the United States in response to climatic conditions (Lins 2005), and found that stream flows have been increasing since 1940. The Mid-Atlantic is among those regions experiencing the most increase. Increases were most prevalent in the low and moderate percentiles of stream flow, and the trends were dominated by increases in the months of September through December. Flow increases occurred as a sudden rather than gradual change around 1970, suggesting the Mid-Atlantic climate shifted to a new regime. A regime shift from one set of conditions to another indicates that the new conditions are likely to persist until the next sudden shift occurs. The rapidity of the shift indicates the changes are due to variability in climate whereas a slow, gradual trend implies a pattern that is likely to continue into the future (Lin 2005). The USGS concluded that what this may mean for future variations and changes in U.S. stream flow will only be revealed with time but that it should be expected that these rivers and streams will continue to be characterized by both short- and long-term variations.

Water Uses

Most of the Potomac River basin is rural and about 80 percent of its residents live in the Washington, DC metropolitan area (**Figure 7**). The basin's average population density is around 400/mi², which is roughly five times the national average of 84 people/mi². By jurisdiction, the population densities in the Potomac River basin range from West Virginia's 60/mi² to the District of Columbia's 8,290/mi², with Maryland averaging about 540/mi², Virginia about 460/mi², and Pennsylvania about 120/mi².

Freshwater withdrawals in 2005 averaged 3,871 cfs (2,502 mgd) in the Potomac River basin above Little Falls and 2,314 cfs (1,496 mgd) in the Coastal Plain watersheds below Little Falls (database assembled in 2009 by Jim Palmer, ICPRB). The available information suggests 78.5% is for power generation, 18.28% for drinking and domestic uses, 2.12% for industry, 0.92% for mining and 0.18% for agriculture. The total withdrawal of 6,185 cfs (3,998 mgd) represents 43.3% of the estimated 14,300 cfs of surface freshwater entering the estuary from all streams and rivers in the basin (from Lippson et al. 1979). Hydrologic impacts of upper basin withdrawals on the estuary are not large because 97.5% are from surface waters and most are returned to surface waters. An exception is the free-flowing Potomac River directly above the estuary head-of-tide. An average 574 cfs (371 mgd) was taken from this stretch of the river in 2005-2008 to supply the Washington, DC metropolitan area (pers. comm. S. Ahmed, ICPRB) and returned to the estuary rather than the river. During dry periods, these withdrawals have a large impact on river flows in the several miles between the water supply intakes and the estuary head-of-tide, but do not substantially alter the total freshwater flow to the tidal fresh zone. The basin's population is expected to continue to increase, requiring more water and greater services from the river and its tributaries. Demand for clean drinking water will increase proportionally with population growth. Recent gains in river water quality will be reversed if more and better "best management practices" are not implemented to better control runoff from the additional urban areas as well as from agriculture, silviculture, and mining. Urban development without major advances in stormwater control will add impervious surfaces that increase stormflow peaks, frequency, and duration, as well as pollution loads. Fewer forests will lessen

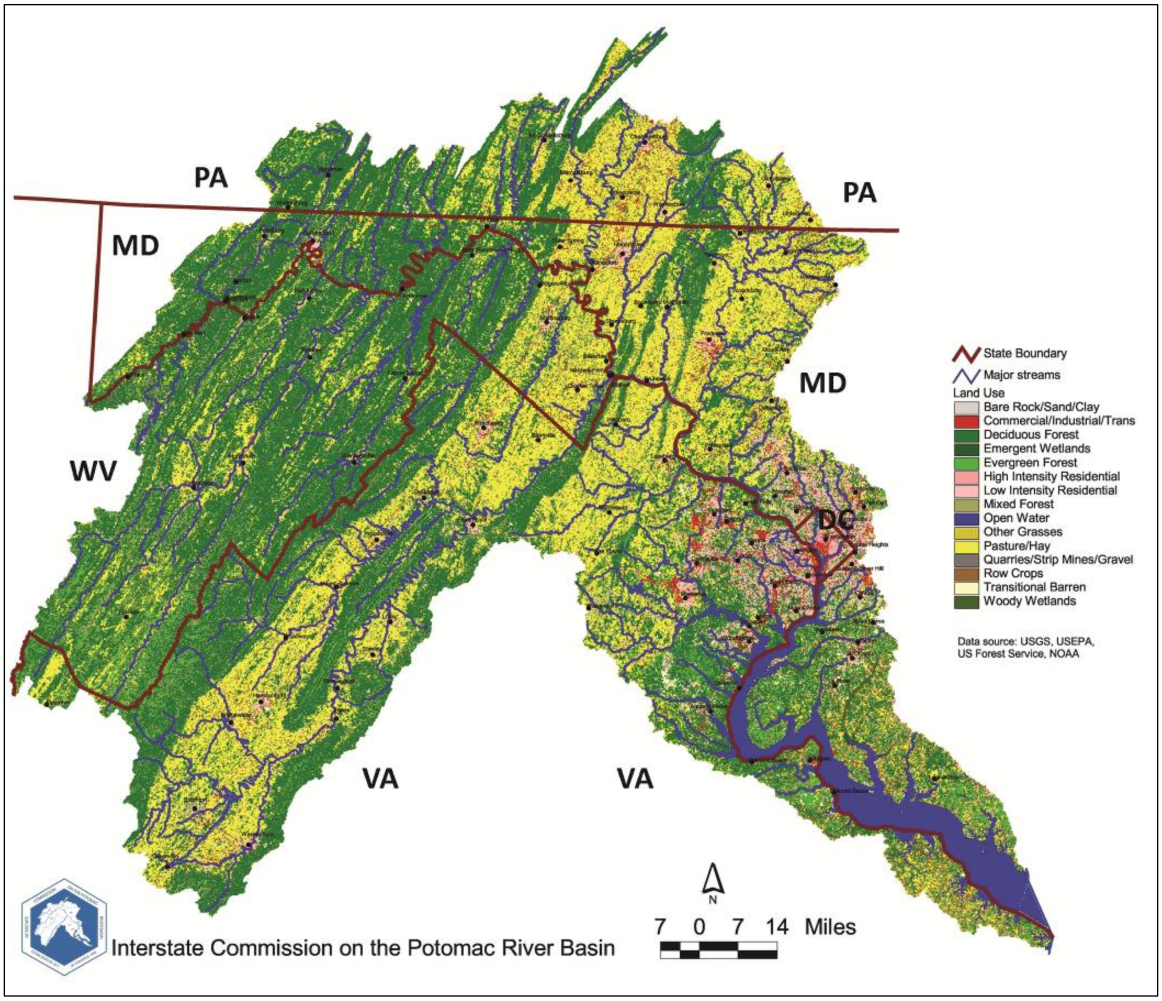


Figure 7. Land use in the Potomac River basin.

groundwater recharge, ultimately reducing mid-range and low flows and adding to drought stress for humans and wildlife. Affecting and probably exacerbating all of these impacts is climate change.

Current water supply demand in the Washington, DC metropolitan area is about 778 cfs (502.7 mgd), and continued population growth in the metropolitan area is expected to increase demand for water to 891 – 941 cfs (576.2 – 608.2 mgd) by the year 2025, or an additional 14.6 – 21.0% (ICPRB 2010). Roughly 76% of the water comes from the Potomac River, with other withdrawals made from local reservoirs and the Patuxent and Occoquan rivers. Estimates vary depending on demographic forecasts and predictions about future water use behavior. For the Potomac River basin as a whole, population is projected to increase 18.34% between 2010 and 2025 [O. Devereux, per. comm.]. Final water demand estimates are not available for the basin; however demand is expected to increase proportionally and will include a factor for change in the %withdrawal per person over time.

In 2005, the ICPRB CO-OP section considered climate change in projecting future water demand and supply for the Washington, DC metropolitan area to the year 2025 (Kame'enui, A. et al., 2005). This “Demand Study” concluded that even with a higher-than-expected growth scenario, the water supply system developed twenty-five years ago is adequate to meet 2025 demand under a repeat of the worst meteorological and stream flow conditions on record. The study also concluded that "despite these optimistic results, a scenario which stressed the supply system was the 2025 climate change scenario."

The climate change scenario in the ICPRB Demand Study included a temperature change component (Kame'enui, A. and E. R.Hagen, 2005) based on two Global Climate Models for the Northeastern United States. The confidence level associated with these projected changes was considered "high" for temperature (Najjar et al., 2000; Neff et al., 2000). Higher temperatures due to climate change resulted in relatively modest changes in modeled demand. The data did show a clear warming trend for July and August. While these positive trends may be entirely related to the heat island effect of increasing urbanization or other climate variability factors in the Washington, DC metropolitan area, they are clear indications that the climate in the region has in fact changed during the last century. July, August, and September average demand in a drought year in 2025 is projected to be 1063 cfs without climate change, and 1080 cfs assuming higher temperatures due to climate change, a difference of 23 cfs.

The ICPRB Demand Study used a 10% reduction of streamflow as a sensitivity analysis in the climate scenario. Although entirely arbitrary, the 10% reduction was conservative and based on an interest in testing the vulnerability of the system to a given threshold rather than on any specific scientific evidence. Another investigation of regional climate change included assessment of long-term streamflow records (Neff et al., 2000) and did not yield evidence of a 10% decrease. However, that research reflected modeled changes in average conditions, and did not attempt to model extreme event hydrology like droughts. The Demand Study concluded that with the high degree of uncertainty associated with the streamflow reduction scenario, additional research is needed to investigate how climate change might affect the resource (streamflow) itself rather than demand alone. The USGS is currently conducting a study on how climate change is affecting the Chesapeake Bay.

Land Uses

Land uses can directly alter stream and river hydrology. Impervious surfaces increase stormflow peaks, frequency, and duration, impart greater erosive power to the water, and forcefully reshape stream contours. Low flows sustained by groundwater are reduced when urban and agricultural landscapes interfere with groundwater recharge. Heavy deforestation, such as that experienced over a 100 years ago in the upper basin, substantially increases the proportion of rainfall running off the landscape instead of seeping into the ground where it can be taken up by plants or enter the groundwater. Multiple indicators of hydrologic alteration significantly change as forest cover is replaced with agricultural and urban landscapes, including the annual flow minima, mean, maxima, low pulse duration, high pulse count, high pulse duration, rise rate, and number of reversals.

An understanding of the changing landscape is often confounded by short-term “environmental memory”. A good example concerns forest cover. The region’s original forests had many mature trees, with trunk diameters up to fourteen feet for oaks, ten feet for cedars, and eight feet for chestnut trees. Some of the trees were so large that once felled and sectioned they were too large to move, and they had to be "split" with blackpowder or dynamite to reduce them to manageable sizes. Wood from a single tree was enough to fill a train (Clarkson, 1964). These forests were largely destroyed by slash-and-burn agriculture, by logging to make charcoal for the production of steel, railroad ties, lime and potash, for lumber and heating fuel, for bark used in tanning, or just to "conquer the wild". By the 1890s, approximately 60%-70% of the original forest cover was gone from the Chesapeake Bay basin (**Figure 8**, from Sprague et al. 2006). Starting in the late 1800s, marginal agricultural lands were abandoned and young forest began to reestablish. The new forest helped restore ecological and hydrological functions, and new forest management practices reduced logging impacts. Forest increases continued until the late 1900s, when expanding urbanization began to reverse that trend.

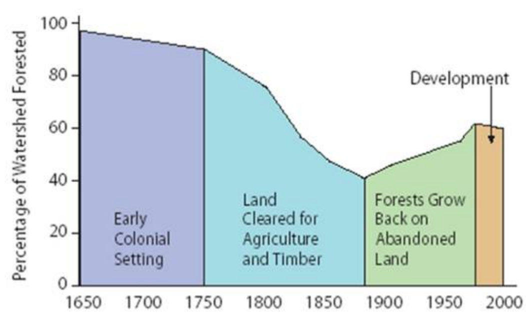


Figure 8. Changes in Chesapeake forest cover.

The young forests perform poorly compared to their ancestors. Wasteful logging and farming practices of the 18th and 19th centuries eroded huge amounts of forest soils, washing them downstream while simultaneously eroding stream banks, filling valleys, and altering stream channels (**Figure 9**). The young forests grew on stonier, nutrient-deprived landscapes with remnants of farming activity such as diverted and incised streams, and sediment-filled mill and ice ponds behind low dams. The forests now have less capacity to slow runoff, reduce flooding, or store water and ameliorate droughts. Important water storage and filtration functions of wetlands were also lost. For example, the estimated 1.2 million acres of wetlands that existed in Maryland before European settlement have been reduced to 600,000 acres, of which more than half (51%, or 342,000 acres) are nontidal palustrine wetlands (Tiner, 1987). Maryland averaged a loss of over 600 wetland acres per year between 1955 and 1995 (Thompson, et al, 1999).

The stream gage records analyzed for this study, the earliest of which started in the 1890s, will reflect these landscape changes. The landscape was far from pristine in the period from 1880 to 1930, and many changes in flow have occurred since the gages were installed. Just how those changes may have affected flows will be examined in the next sections.

CBP Watershed Model Results

The cumulative effects of more people and increased water demands on the Potomac River basin's hydrology and the counter effects of watershed restoration and protection will not be easy to forecast. Comparisons of hydrologic indicators measured in heavily impacted watersheds and in least-disturbed (reference) watersheds are beginning to quantify changes that might be expected if conditions improve. The Chesapeake Bay Program (CBP) Phase 5 Watershed Model is being used in the Middle Potomac Watershed Assessment Project to generate synthetic flow time series for different scenarios in which watershed characteristics are changed. A "current conditions" scenario simulating current land uses was compared to an "all forest" scenario in which 100% of land cover was forest. Annual mean and minimum flows are about 8% and 140-146% higher, respectively, for the "current condition" scenario than for the "all forest" scenario (Moltz per. comm. 2009). This reflects the forest's capacity to absorb and transpire water. Also higher in the "current" scenario are high flow pulse count (~20%) and number of flow reversals (~33%). The duration of low flow pulses is shorter (about -71%).

Figure 9. Effects of deforestation.
Top, erosion after the forest harvests of 1880-1920 (ICPRB photo archives); bottom, burnt post-logging landscape in Grant County of the North Branch sub-basin, early 1900s (photo by H. A. Allard).

Assessing Risk of Hydrologic Alteration

A preliminary assessment of the combined risk of hydrologic alteration from multiple factors was conducted on the Potomac sub-basins and mainstem segments. Ten risk factors were selected for evaluation based on their ability to influence one or more Indicators of Hydrologic Alteration (IHAs). The factors are: the percentages of urban, forest, and agricultural land cover; the expected change in urban land use (2010-2030); total withdrawals as a percentage of median flows (includes both surface and groundwater withdrawals); surface water withdrawals as a percentage of 10th percentile flows;

impoundments as a percentage of median flows; consumptive use as a percentage of median flows; percent impervious surface; and percent karst geology. The ten risk factors were categorized as low, medium, high, and severe risk based on results of a Classification and Regression Tree (CART) analysis, on literature values, and on the frequency of risk factor values in the basin.

Cumulative Risk Index

A Cumulative Risk Index for the 35 sub-basins and 5 mainstem segments was developed from the analysis results. Risk posed by each of the ten factors was categorized and scored (low risk=0, medium risk=2, high risk =4, severe risk=6) and the scores summed to obtain a Cumulative Risk Index for each sub-basin and mainstem segment. The index does not reflect the actual cumulative impact of the risk factors as much as it does the *count* of risk factors impacting each sub-basin, weighted by the relative severity of each factor. Thus, the highest index values correspond to a high count of high and severe risk factors. A detailed description of the CART analysis and index development can be found in **Appendix B**. A complete list of sub-basins, risk scores, and Cumulative Risk Index values is provided in **Table 1**. **Figure 10** shows the spatial distribution of Cumulative Risk Index values in the Potomac Basin.

Several sub-basins appear to be at very high risk of hydrologic alteration from an array of current land uses, water uses, impoundments, and/or geology as well as future land use changes. They include Monocacy River and Opequon Creek in the upper basin and Occoquan River and Aquia Creek on the Coastal Plain (**Table 1**). Slightly less at risk are Antietam, Conococheague, and Goose creeks in the upper basin and Mattawoman Creek and Saint Marys River on the Coastal Plain. The Cumulative Risk Index values for the mainstem Potomac River rise slightly as the river flows across the Piedmont towards the Potomac River Gorge and Washington, DC. This is primarily due to the greater level of agricultural land use in the Piedmont as well as the potential for future urban growth in the region.

Regions of Special Interest

Two sub-basins and four river segments were identified as regions of special interest for this study: Opequon Creek, Monocacy River, and three nontidal segments and one tidal segment of the Potomac River. The reasons these reaches were selected vary. The Opequon Creek watershed is heavily farmed, experiences significant withdrawals (surface and ground) and consumptive uses, lies in the developing U. S. Interstate 81 corridor, and sits largely on porous karst (limestone) geology. The very heavily farmed Monocacy River and Potomac mainstem from the Shenandoah River confluence to Point of Rocks are located in the Piedmont physiographic province in an area that is also becoming an ex-urb of Washington, DC. Like the Opequon, the Monocacy watershed experiences significant withdrawals (surface) and consumptive uses. The Potomac mainstem flowing from Point of Rocks to the tidal head-of-tide in Washington, DC crosses one of the most rapidly urbanizing regions in the United States. It is experiencing significant increases in surface water withdrawals to supply the Washington metropolitan area, and the resulting treated wastewater is return to the river more than 20 miles downstream. The unique and special habitats of the Potomac Gorge, or Fall Zone, between Great Falls and Chain Bridge (**Figure 1**) are located in this rapidly urbanizing region. The estuarine river segment from Chain Bridge to Occoquan Bay is the tidal fresh portion of the river's estuary and its much degraded condition in 1960s and 1970s was one motivation of the 1972 Clean Water Act. Most of the water withdrawn from the Potomac River and its tributaries to supply the Washington, DC metropolitan area returns to the river's tidal fresh segment as treated wastewater. This tidal segment is presently recovering from two centuries of eutrophication, sediment accumulation, and overfishing.

Table 2 summarizes the major land and water uses in the six regions of special interest and contrasts these with the rest of the basin upstream of the regions. **Figure 11** shows the watershed areas immediately bordering each of the four Potomac River mainstem segments, as well as the area upstream

Table 1. Risk factor scores and Cumulative Risk Index values for 35 sub-basins and 5 mainstem segments of the Potomac River.

Sub-Basin	Location	Urban	Agriculture	Forest	Urban Change ('10-'30)	Imperviousness	Impoundments	Karst	Total Withdrawals	Surface Withdrawals	Consumptive Use	Cumulative Risk Index
Occoquan	Coastal	2	4	2	6	4	6	0	6	6	6	42
Aquia	Coastal	2	2	0	4	2	6	0	4	6	6	32
Mattawoman	Coastal	4	2	0	6	2	0	0	4	4	6	28
Saint Marys	Coastal	2	2	2	6	2	4	0	4	2	4	28
Accotink	Coastal	6	0	4	2	6	4	0	0	2	0	24
Cameron Run	Coastal	6	0	6	2	6	4	0	0	0	0	24
Anacostia	Coastal	6	2	6	0	6	2	0	0	0	0	22
Rock	Coastal	6	2	6	0	6	2	0	0	0	0	22
Piscataway	Coastal	4	2	2	4	4	0	0	2	0	0	18
Potomac Creek	Coastal	0	2	0	6	0	2	0	2	4	2	18
Wicomico	Coastal	2	2	2	4	0	2	0	2	0	2	16
Quantico	Coastal	2	0	0	2	2	6	0	0	0	0	12
Saint Clements	Coastal	2	4	2	4	0	0	0	0	0	0	12
Machodoc	Coastal	0	2	0	4	0	0	0	0	0	0	6
Yeocomico	Coastal	0	4	2	0	0	0	0	0	0	0	6
Monocacy	**Upper**	**2**	**6**	**4**	**4**	**2**	**2**	**2**	**2**	**4**	**4**	**32**
Opequon	**Upper**	**2**	**4**	**2**	**4**	**2**	**0**	**6**	**4**	**2**	**4**	**30**
Potomac @ Point of Rocks*	**Upper**	**0**	**4**	**0**	**2**	**0**	**2**	**2**	**6**	**6**	**4**	**26**
Potomac @ Little Falls*	**Upper**	**0**	**4**	**0**	**2**	**0**	**2**	**2**	**6**	**6**	**4**	**26**
Goose	Upper	0	6	2	4	0	2	0	4	4	4	26
Conococheague	Upper	0	6	2	4	2	2	4	2	2	2	26
Antietam	Upper	2	4	2	4	2	0	6	2	2	2	26
Potomac @ Shepherdstown*	Upper	0	2	0	0	0	4	2	6	6	4	24
Potomac @ Paw Paw*	Upper	0	2	0	0	0	4	2	6	6	4	24
Potomac @ Hancock*	Upper	0	2	0	0	0	4	2	6	6	4	24
North Branch	Upper	0	2	0	0	0	4	2	6	6	4	24
Seneca	Upper	4	4	4	4	4	4	0	0	0	0	24
South Fork Shenandoah	Upper	0	4	0	2	0	2	4	2	4	4	22
North Fork Shenandoah	Upper	0	4	0	2	0	2	4	2	2	0	16
Catoctin, VA	Upper	0	6	2	4	0	0	0	0	2	0	14
Catoctin, MD	Upper	2	4	2	4	0	0	0	0	0	0	12
Back	Upper	0	2	0	2	0	2	2	0	0	0	8
Licking	Upper	0	2	0	0	0	2	2	0	0	0	6
Sleepy	Upper	0	2	0	0	0	2	0	0	2	0	6
South Branch	Upper	0	2	0	0	0	2	0	0	2	0	6
Tonoloway	Upper	0	4	0	0	0	0	2	0	0	0	6
Town	Upper	0	2	0	0	0	0	2	0	0	0	4
Cacapon	Upper	0	2	0	0	0	0	0	0	0	0	2
Little Cacapon	Upper	0	2	0	0	0	0	0	0	0	0	2
Sideling Hill	Upper	0	2	0	0	0	0	0	0	0	0	2

Sub-basins and segments of special interest are bolded. Risk categories: low (0), medium (2), high (4), and severe (6). The Cumulative Risk Index is the sum of the 10 risk factor scores. The lowest (best) possible score is 0, the highest (worst) possible score is 60. Location: Coastal, the Coastal Plain physiographic province; Upper, the Potomac River basin west of the Coastal Plain province, including the Piedmont, Blue Ridge, Ridge & Valley, and Central Appalachian physiographic provinces. *, risk factors are based on the *entire* upstream contributing area.

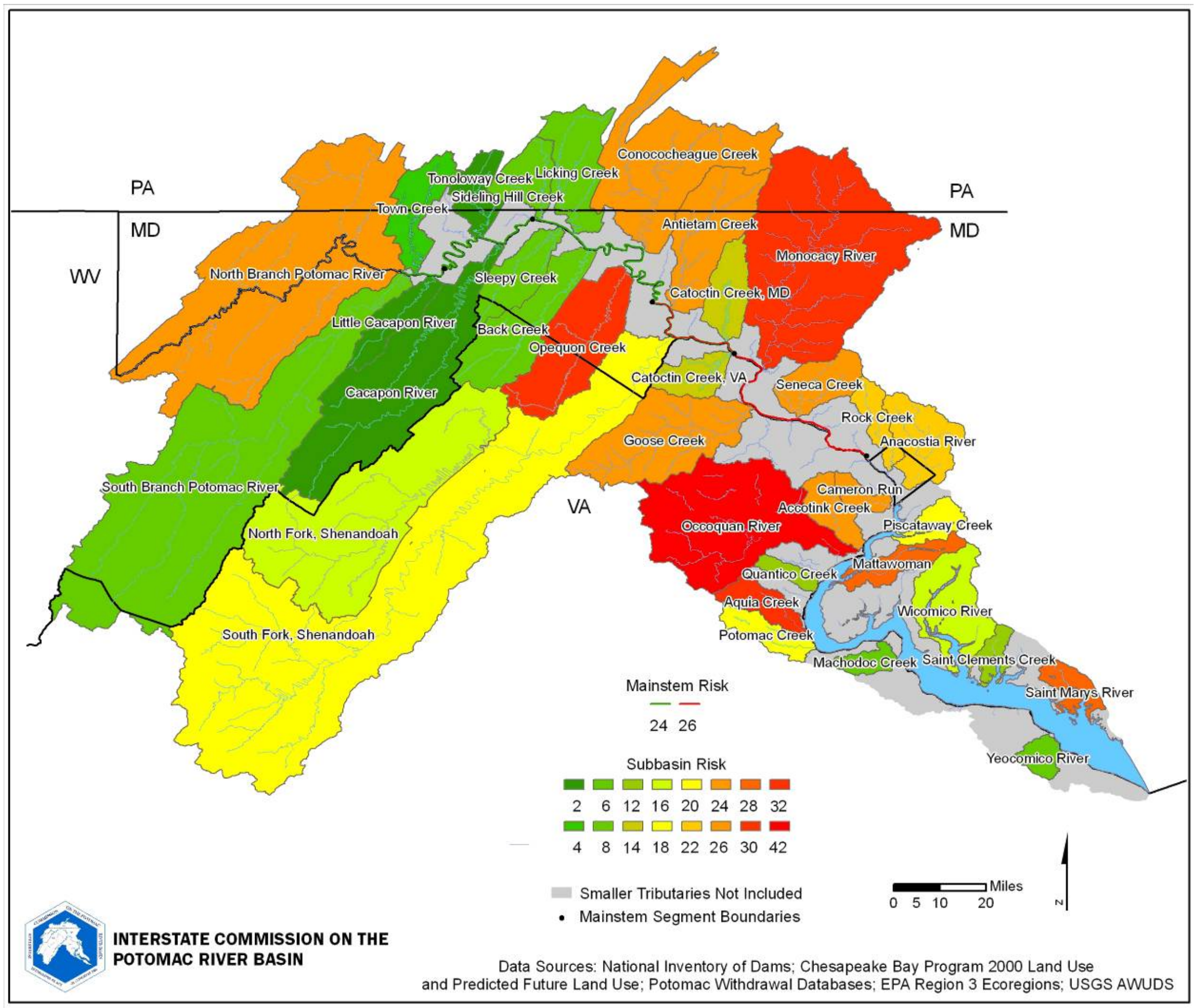


Figure 10. Cumulative Risk Index values for 35 sub-basins and 5 mainstem segments in the Potomac Basin. Gray areas drain directly into the Potomac mainstem and were not included in the large river analyses.

of the Shenandoah River confluence with the Potomac mainstem. Further descriptions of these regions of special interest are presented in **Appendix C**. Closer examination the regions' risk factors and their hydrologic indicators (presented later in the Flow Recommendations section) is a workshop task. The results can have broad application to the management of other rivers in the basin, and may have immediate bearing on state and basin-scale water planning, protection, restoration, and management actions in these regions.

The Potomac River Gorge and Flow-By Requirement at Little Falls

The Potomac River Gorge, located in the Great Falls to Chain Bridge segment, has been an area of interest for many years, and is home to rare species and communities. The National Park Service, a primary landowner in the area (Chesapeake and Ohio Canal National Historical Park and the George Washington Memorial Parkway), and The Nature Conservancy have long-standing interests in the site's extraordinary biological diversity. Working collaboratively, the two organizations completed the Potomac Gorge Site Conservation Plan in November 2001.

Table 2. Land and water uses in Opequon Creek, Monocacy River, and the areas laterally bordering each of the four Potomac River mainstem segments of interest and the upstream basin (shown in Figure 11).

	Area of bordering watershed, mi^2	Agri-culture area, mi^2 (%)	Urban area, mi^2 (%)	Forest area, mi^2(%)	Total withdrawal, billion gallons per year	Consump. use, billion gallons per year
Opequon & Monocacy Watersheds						
Opequon Creek	344	128 (37%)	38 (11%)	165 (48%)	7.3	2.0
Monocacy River	965	455 (47%)	144 (15%)	309 (32%)	16	4.4
Potomac River Mainstem Segments						
Basin upstream of Shenandoah River confluence	9,360	2,108 (23%)	605 (6.5%)	6,507 (70%)	570	30
Shenandoah River confluence to Point of Rocks	288	126 (44%)	32 (12%)	125 (44%)	0.81	0.23
Point of Rocks to Great Falls	1,796	778 (43%)	336 (19%)	618 (34%)	340	47
Great Falls to Chain Bridge (Little Falls)	119	8.6 (7%)	72 (61%)	33 (28%)	1.6	0.44
Chain Bridge (Little Falls) to Occoquan River confluence	1,397	206 (15%)	584 (42%)	504 (36%)	114	8.7

Values were obtained as follows: area or volume/year calculated for the entire basin above the upstream end of each segment is subtracted from that calculated for the entire basin above the downstream each of each segment.

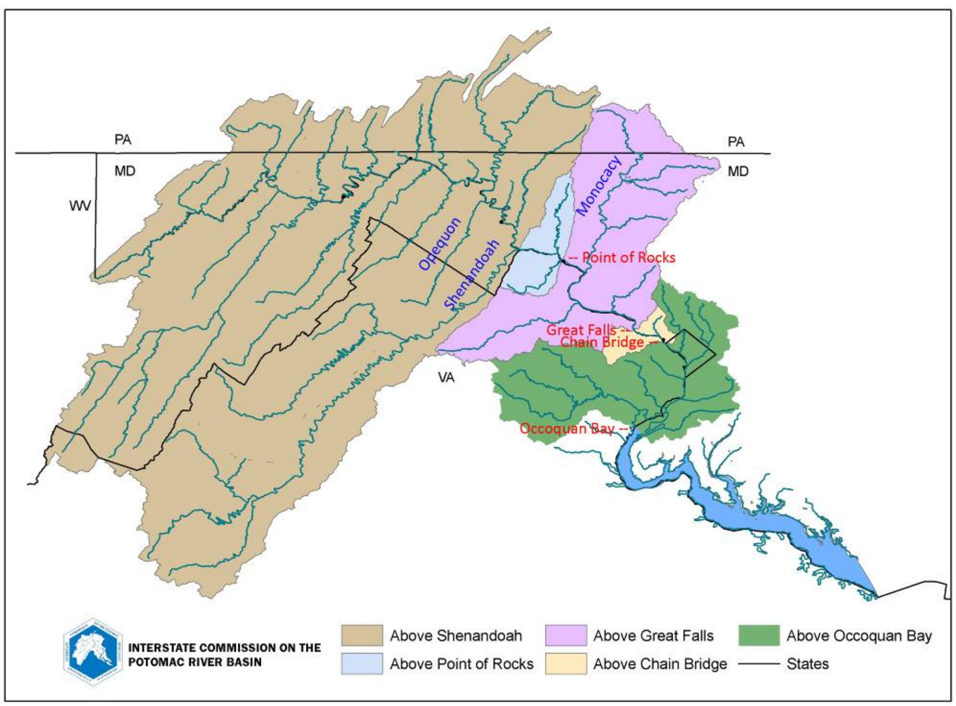
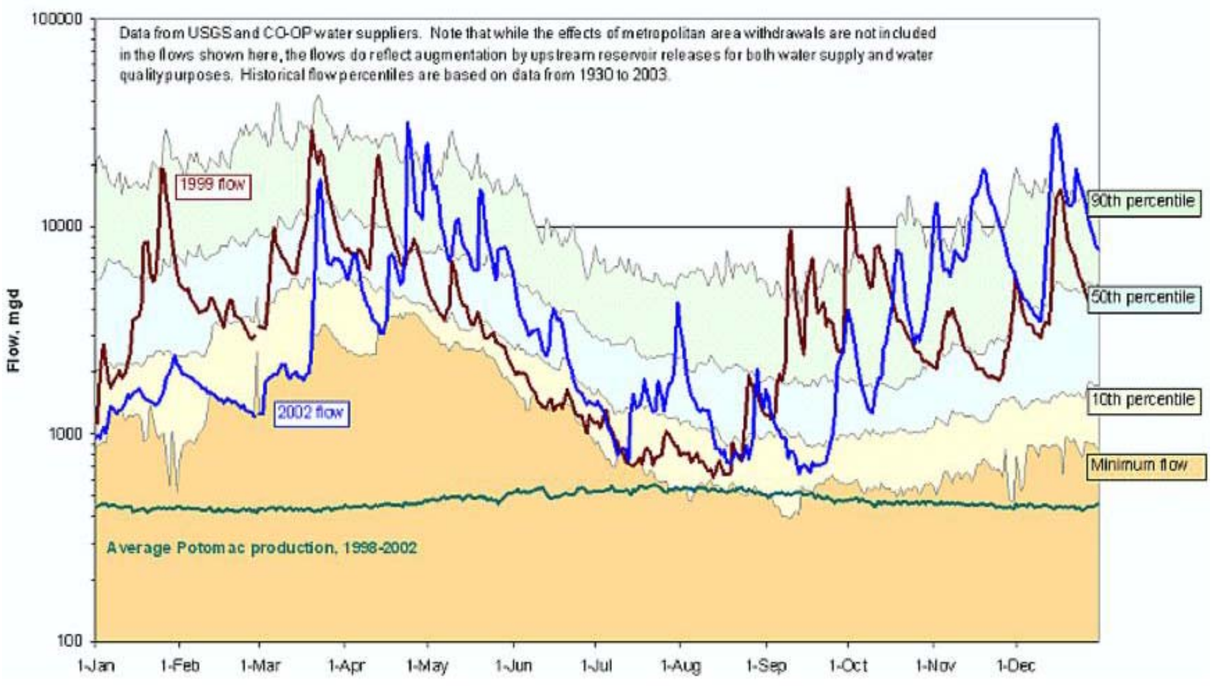


Figure 11. Areas bordering the four Potomac River segments which are regions of special interest.

Concern for the Gorge ecosystem was also a principal motive for establishing Potomac River flow-by requirements for Little Falls, along with concern about drinking water supplies during droughts. The severe extended drought in the 1960s demonstrated that the water supply needs of the Washington DC metropolitan area were reducing flows to the point that the river was nearly running dry between Great Falls and the tidal river (**Figure 12**). The 1978 Potomac River Low-Flow Allocation Agreement, signed by Virginia, Maryland, the District of Columbia and the Federal Government, led to the establishment of the current Potomac River minimum environmental flow requirement of 100 mgd at Little Falls and a recommended operational guideline of 300 mgd flow-by at Great Falls. The construction of the Jennings Randolph and Seneca Dams and a cooperative management approach has met the human water needs of the utilities in subsequent droughts while also exceeding the environmental flow-by requirements.

The 1999 drought raised concerns that the environmental flow requirements and recommendations for this river section could be too low because they were developed in a 1981 study for a period that did not have extreme low flows. The requirement and associated recommendations can be reevaluated using new scientific methods and low-flow information. The Maryland Department of Natural Resources (MDDNR) formed a Potomac Flow-by Committee, which included resource agencies, environmental organizations, water utility representatives, and other parties, to provide guidance for this reevaluation. During the drought of 2002, MDDNR's Power Plant Research Program assembled teams of biologists from their staff and Versar, Inc, and with assistance from Montgomery County, Maryland, and the Interstate Commission on the Potomac River Basin (ICPRB) performed habitat assessments during low flow conditions (Versar 2003).

Figure 12. Adjusted Potomac River flows at Little Falls gage in drought years.



The lower green line is the average water withdrawals for the drought years of 1999 and 2002, which was greater than overall average withdrawals due primarily to more residential lawn watering. Annual flows of the two most severe recent drought years, 1999 and 2002, are seen in brown and blue lines, respectively. The water volume between the green line and the 1999/2002 hydrographs is what actually flowed over Little Falls (unadjusted flow). The 100 mgd flow-by requirement at Little Falls means there must be at least 100 mgd between the water withdrawal line and the flow line at any given moment. There was a short period in mid-August 1999 when the flow-by volume was close to 100 mgd. That period was brief, even during this multi-year drought which had much greater water demand than the 1966 drought. Flow was variable—not a flat line—during the drought and typically many mgd's above the 100 mgd requirement. This was mostly due to isolated storm events in the basin which delivered small pulses of flow. It was also due to caution on the part of Washington, DC water suppliers who made several releases from the main water supply reservoir, Jennings Randolph, when they anticipated drops below the 100 mgd requirement. Jennings Randoph is over 200 miles from Washington, DC and releases take 7-9 days to reach Little Falls.

In 2003, ICPRB and MD DNR convened a workshop with a special panel of nationally recognized experts on habitat assessment methods to investigate and develop a method to evaluate the environmental flow-by requirements. At this workshop, members of the special panel collectively considered and debated the various methodologies applicable to the Potomac River. Five principle recommendations came from that workshop:

1. Define the desired hydrologic regime (i.e., natural ranges of flow).
2. Collect background (hydrologic, biologic) data.
3. Develop a biological community-habitat conceptual model.
4. Collect data and conduct simulations to fill the gaps.
5. Evaluate and refine management targets (an adaptive management approach).

In 2004 and 2005, ICPRB carried forward the process by convening two smaller update workshops. Also in 2005, ICPRB, the MD DNR's Power Plant Research Program, and Versar conducted supplemental physical habitat measurements during a low-flow period (< ~1400 cfs) downstream of Little Falls. A significant amount of additional hydrologic and biologic information was still needed. The update workshops prescribed next steps for a Potomac flow-by evaluation, including:

* Develop a list of fish and mussel species and low-flow habitat preferences as possible indicator species.
* Develop a conceptual model of the ecological relationship between species and their habitat.

This study on the Potomac's large rivers and the larger ELOHA study were initiated as a result of the 2004 and 2005 workshops. Information on the findings of those workshops, studies and various Potomac low-flow issues can be found at the MD DNR's Power Plant Research Program's website http://esm.versar.com/pprp/potomac/.

Confounding Factors

The effects of hydrologic alteration on stream and river biological communities are easily masked by other environmental factors. These confounding factors are important to recognize when pursuing the objective of identifying flow-ecology relationships and making flow recommendations. Two important confounding factors in the Potomac River basin are introduced below and discussed in more detail in the following chapters.

Figure 13. Pictures of the Potomac estuary during the 1960s and 1970s. Top left, factory outfall; bottom left, fish kill; right, the dock at Mt. Vernon [photos from ICPRB archives].

Wastewater and Pollutant Removal

Quality rather than quantity was the predominant water issue of the Potomac River during the 20th century (**Figure 13**). Huge fish kills during the 1960s prompted President Johnson to declare the Potomac River a "national disgrace." Following the enactment of the Clean Water Act in 1972, a concerted effort to reduce pollution resulted in tertiary wastewater treatment, the partial ban of phosphate-rich

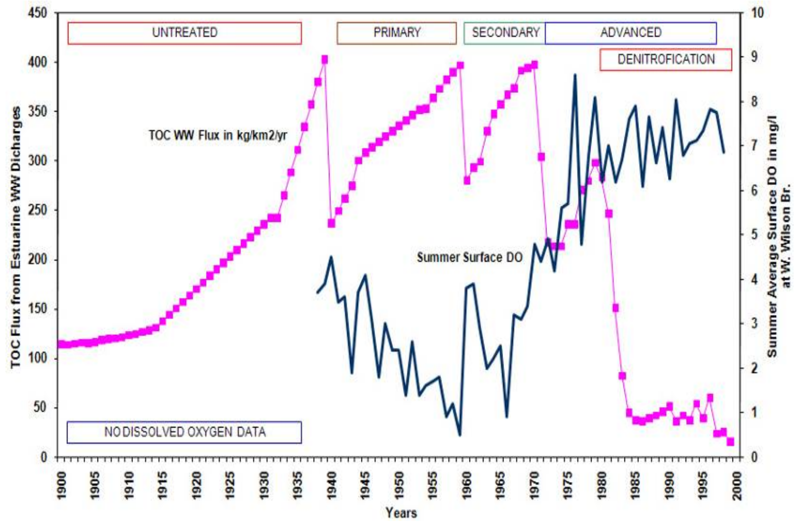


Figure 14. Total organic carbon from wastewater treatment plants and surface dissolved oxygen concentrations in the Potomac River tidal fresh estuary, at the Woodrow Wilson Bridge (Jaworski et al. 2007).

detergents, improved agriculture, silviculture, mining, urban stormwater management, and other nonpoint source management practices. Total organic carbon loads to the tidal fresh estuary have decreased to a tenth of their peak 20th century levels, and summer dissolved oxygen concentrations in the tidal fresh river have returned to levels that support most designated uses (**Figure 14**). For example, very low dissolved oxygen concentrations occurred in the tidal fresh mainstem during the 1965-1966 drought and inflicted severe respiratory stress on aquatic communities whereas dissolved oxygen concentrations rarely went below 5 mg/liter during the similarly dry 1999-2002 drought.

Water quality issues still remain. Nutrients and sediments in agricultural runoff are problematic in the Conococheague in Pennsylvania, the Shenandoah in Virginia, the Monocacy in Maryland, and in the lower Potomac. There are increasing concerns about emerging contaminants such as estrogen mimics. Acid mine drainage from abandoned coal mines is still a problem on the North Branch, and treatment of wastewater from Marcellus Shale gas extraction ("fracking") is not expected to adequately or fully protect the quality of the receiving waters. Urban stormwater runoff and wastewater flows are expected increase with development, and although the technologies to remove nutrients and sediments from these waters have improved enormously, the projected population increases may outstrip the ability of the technology to keep pace.

Introduced Species

Over the last four hundred years, humans have changed the biological communities of the basin directly through introductions and harvesting or indirectly through habitat impacts. Notable aquatic species introduced to Potomac waters include the northern snakehead, largemouth and smallmouth basses, carp, channel and blue catfishes, rainbow, brown, lake and cutthroat trouts, Asiatic clam, hydrilla, Eurasian millfoil, and Japanese knotweed. In the process of developing recommendations for protective environmental flows, the effects of flow on both the natural and introduced biological components should be considered. Encouraged flow levels should not unduly attract or benefit introduced species considered harmful to the Potomac ecosystem. Conversely, unnatural flows may be required to restrict the growth and/or distribution of undesired introductions.

CHAPTER 2: RIVERINE ECOLOGICAL INDICATORS

Summary

This chapter describes the multiple direct and indirect ways that flow regime affects ecological functions and biological communities in large, nontidal rivers. The pathways by which flow regimes affect riverine communities are described, first for aquatic ecosystems in general and then in particular for riparian plant communities, fishes, and mussels. These taxonomic groups were selected in part because of the availability of information to investigate their flow needs in the Potomac River basin.

Riparian plant communities have varying flow requirements which, in un-regulated rivers, are principally factors of elevation and frequency of inundation or exposure. Variation in flow is needed to maintain ecological complexity since floods and droughts have differential effects, each adversely affecting some community or species while benefitting others. Flow ecology relationships for four large-river plant community groups are assessed:

1) In-stream – usually inundated all year with some seasonal exposure along the edges.
2) Bank and Bar – the zone from the mean-water mark to bank-full.
3) True Floodplain – the zone typically affected by small floods
4) Flood Terrace - this zone is inundated only by extreme floods with a return interval (RI) of >10 years.

Two additional representative rare plant communities for the Potomac Gorge also were assessed:

1) Piedmont/Central Appalachian Riverside Outcrop Prairie – found in True Floodplain.
2) Bedrock Terrace Oak-Hickory Forest – found in alluvial areas of Flood Terrace.

The Potomac River basin supports approximately 102 fish species, of which 56 occur in large rivers and were considered in this report. Multivariate ordination techniques identified three clusters: large-bodied, flow velocity generalists (e.g., sturgeons); medium-sized fishes with moderate-sized, flow velocity specialists; and small-bodied, flow velocity specialists. Twelve indicator species were selected from the three groups and used to represent the diversity of fish species traits and flow needs in large Potomac rivers.

Sixteen native mussel species are found in the Potomac basin and represent a variety of habitat and reproduction requirements. All 16 were used to explore mussel flow-ecology relationships.

Sufficient research and empirical data to define thresholds of acceptable hydrologic change applicable to the Middle Potomac River study area are not available. As part of on-going companion project, ICPRB will be attempting to identify quantitative thresholds of biotic degradation that can be linked to the direct alteration of river flow by impoundments and withdrawals, as opposed to urban and agricultural land uses, topography, and geology, but those results will not be available until 2011. The research team used the available literature and professional judgment to develop 5 general flow-ecology hypotheses that apply to a broad range of species/communities and 18 specific flow-ecology hypotheses tailored to selected indicator organisms. Participants of the September 22-23, 2010 workshop will discuss and refine the hypotheses.

The Riverine Habitat and Biological Communities

Researchers use ecological indicators that are sensitive to flow to develop meaningful flow-ecology hypotheses and propose defensible environmental flow recommendations (Arthington et al. 2006; Poff et al. 2010). Riverine ecological indicators from three biotic assemblages, riparian plants, fishes, and mussels, were selected for in-depth evaluation and used to develop flow-ecology hypotheses in the Middle Potomac study area. Other taxonomic groups, for example some benthic macroinvertebrate taxa (see Bunn and Arthington 2003), can be sensitive to flow variability and alteration but sufficient results from large rivers in the Potomac basin were not available to make a similar detailed evaluations. The flow recommendations included in Chapter 4 for benthic macroinvertebrates, amphibians and reptiles are based primarily on information from other rivers.

Flow-ecology hypothesis is a testable explanation for a suspected or observed relationship between river flow and the needs and tolerances of the river's biological species and communities.

Flow regimes affect riverine communities through multiple direct and indirect pathways (**Figure 15**). In each pathway, flow timing, duration, and magnitude will alter the suitability of local environmental conditions as well as the availability of colonists for immigration within regional source populations. As such, flows affect river communities across spatial and temporal scales and have a fundamental role for conservation of freshwater biodiversity (Poff et al. 2003). A river's flow regime therefore is regarded as a "master variable" because it influences nearly every aspect of stream structure and function (Poff et al. 1997).

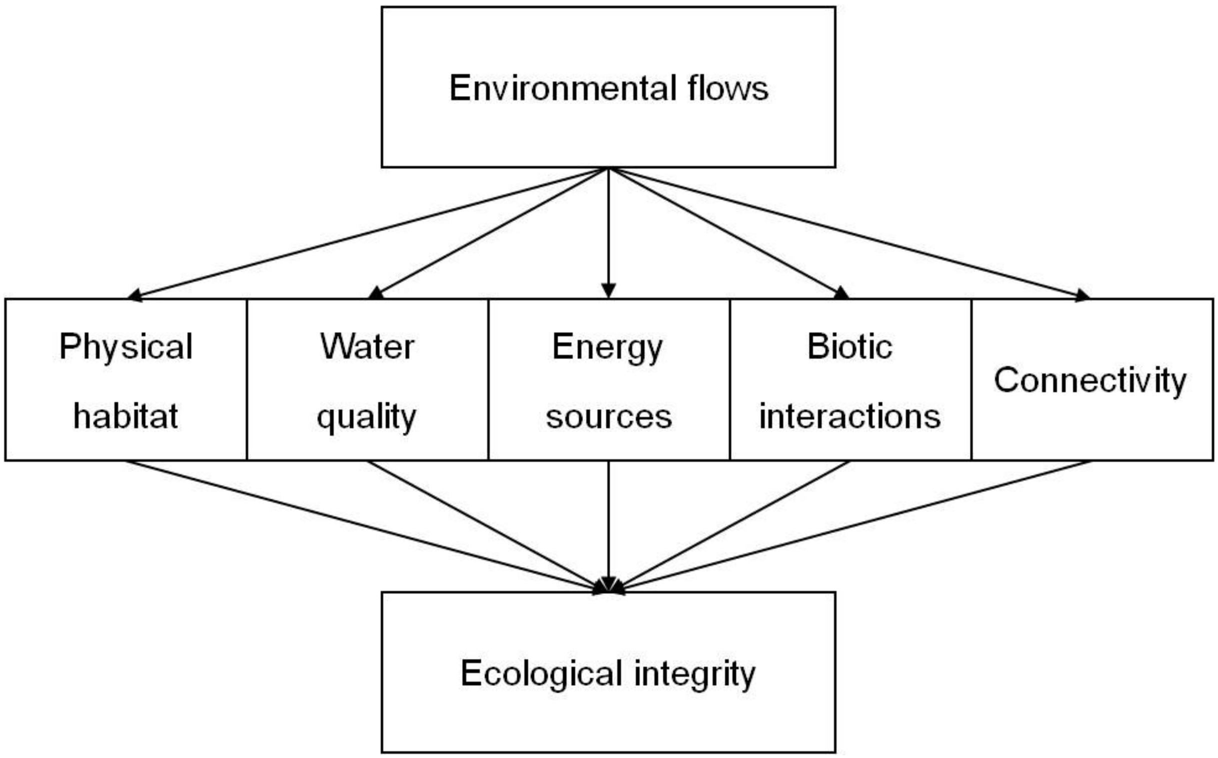


Figure 15. Conceptual relationships between flow regimes and ecological integrity. Adapted from Poff et al. (1997).

Direct effects include the physical forces of sheer stress and scouring during high-flow events. Flash floods may cause adult and juvenile fish mortalities (e.g., Schlosser 1985). High-flows may also exclude species from colonizing some rivers. For example, rainbow trout (*Oncorhynchus mykiss*) have been introduced in rivers across the globe, but locally-reproducing populations appear to be limited to areas where high spring flows do not scour spawning nests (Fausch et al. 2001). Similarly, Marchetti et al. (2004) recommended that restoration of natural flow regimes may help restore native fish communities by creating unsuitable conditions for invasive species.

Flow regimes indirectly affect biota through altering physical habitat in rivers and streams. High-flows reorganize substrates, as determined by sheer stress, particle size, and channel gradient (Galay 1983). Such events are important but rare. For example, Galay (1983) estimated that 99% of the river substrates that moved during a year did so during the highest flow events, encompassing 1% of the time. In extreme high-flows, debris torrents may scour substrates to bedrock, resulting in a loss of habitat (e.g., Jackson et al. 1989). High-flows also recruit large woody debris into stream channels where it promotes pool development (Naiman et al. 2000). Low flow events also affect physical habitat by limiting the volume of stream, which is particularly important for organisms with low vagility such as freshwater mussels.

Water quality is related to environmental flows. Nutrients are recruited into the stream during high-flow events (Likens et al. 1970). For example, phosphorous bound to sediment particles is entrained into the stream during floods. Floods may also increase delivery of nutrients through increased surface runoff from urban and agricultural areas, as well as combined sewer overflows (Zipper et al. 1998). Contaminant concentrations may be lower during high flows (due to dilution) but the total load is greatest during floods. This affects biota through direct effects on physiological function (primarily respiration) and indirect effects through altered food-webs (e.g., algal blooms) and feeding efficiency (e.g., water turbidity affects feeding rate).

Flows affect energy sources for freshwater biota. Coupled with nutrient effects, flows also will affect primary productivity in streams by regulating the abundance of algae. On one hand, high-flows may reduce algal production by scouring substrates and decreasing solar incidence to substrates (Cushman 1985). On the other hand, high-flows may increase algal production by supplying nutrients and “new” substrates for colonization by algae. Moreover, high-flows will recruit organic materials into the stream channel, providing a source for fungal and bacterial at the base of stream food-webs (Webster and Meyer 1997). Flows also affect the production of benthic macroinvertebrates, where high flows may crush benthic macroinvertebrates and low flows may increase competition for optimal feeding locations (e.g., hydropsychid caddisfly larvae).

Biotic interactions are influenced by flow regimes. Competition for feeding or breeding may be greatest when flows are lowest. Visual predators may also be less efficient during high-flows due to increased turbidity. Connell (1978) described an “intermediate disturbance hypothesis” such that the greatest production and diversity of biological systems occurs in ecosystems with an “intermediate” level of disturbance to reduce competitive pressures. Although Connell (1978) focused on marine and rainforest ecosystems, flow regimes provide some basis for the applicability of this hypothesis in riverine ecosystems.

Flow regimes affect physical and biological connectivity in streams and rivers. High-flows trigger outmigration in alosids and American eel (*Anguilla rostrata*) (Smogor et al. 1995). Chapman (2006) also reported increased fish movement rates during high flow-events. Physical connectivity may also be influenced by flow regimes because low flows may disconnect pool-riffle-run sequences or may alter substrate deposition dynamics at stream confluences (Benda et al. 2004). In addition, barriers to fish movement at low flows may be passable at high-flows. For example, Great Falls on the Potomac River may be permeable for fishes when the Falls are submerged (e.g., Garrett and Garrett 1987).

Water Quality and Drought in the Potomac River Mainstem

Water quality and clarity should hypothetically improve during droughts because there is less surface runoff and thus less sediment, nutrients, and other pollutants entering the river. Flow inputs are primarily from groundwater which can have better water quality than surface water due to natural filtering by soils and rock layers. Increased water clarity and greater penetration of sunlight allow better growth of submerged aquatic vegetation (SAV) and enhance habitat and food resources for invertebrates, fishes, and other aquatic animals. All of these conditions characterized the 1999-2002 drought period in the Potomac River basin. Loss of habitat through de-watering and reduction in depth can lead to crowding and/or forced migrations which increases exposure to diseases, competitors, and predators. The generally good water quality and healthy submerged aquatic vegetation beds observed in the nontidal Potomac River mainstem during the 1999-2002 drought apparently countered these potential problems.

The 1999-2002 drought conditions are in stark contrast to the water quality during the major droughts of the 1930s and 1960s, before most pollution reduction efforts had begun. During the 1930-1931 drought, “one outstanding and persistent trouble in all affected states [of the mid-Atlantic] was the prodigious algal growth in streams and storage basins with the accompanying organic load and the resulting nauseating tastes and odors. In many cases there were no known means of relieving the condition (Tisdale 1931).”

The public health crisis brought on by the drought led to the creation of the West Virginia State Water Commission and the Maryland Water Resources Commission, both of which were established to limit sewage and industrial pollution and start reclamation programs (Tisdale, 1931). Water quality improvements did not keep up with the region's strong population growth in the mid 20th century, especially in and around Washington, DC. In the late 1950s, US Public Health Service officials described the tidal Potomac near Washington, DC, as "malodorous . . . with gas bubbles from sewage sludge over wide expanses of the river . . . and coliform content estimated as equivalent to dilution of 1 part raw sewage to as little as 10 parts clean water." Dissolved oxygen concentrations were typically below 1 mg/liter during summer low flows (Stoddard et al, 2002). When drought returned in the 1960s, the poor water quality resulted in massive fish kills. National attention on the river's condition helped motivate political action, resulting in the 1972 Clean Water Act.

Even with today's much improved waste water treatment capabilities, the river's assimilative capacity, or ability to "absorb pollution," is still reduced when flows decrease. Lower flows result in less dilution of discharges and less aeration and algal blooms can occur at trouble spots below discharge points. Significant water quality problems due to erosion and pollutants also occur after droughts. Heavy rains from large storms such as hurricanes frequently end droughts in the Mid-Atlantic region in late summer or early fall. Watersheds are particularly susceptible to erosion at this time because drought-stressed vegetation has a reduced ability to absorb water and hold soil. Non-point source pollutants that build up during the drought, including underutilized residential and agricultural fertilizers, manure, sludge applications, and vehicle toxins, are delivered to the river in big slugs.

Water temperature can be of concern during drought periods. The mainstem Potomac River is relatively wide and shallow, and therefore water temperatures are strongly influenced by air temperature and solar inputs. Groundwater inputs are cooler than air temperatures in summer and early fall and ameliorate atmospheric warming. Habitat and water quality evaluations performed from Seneca to Chain Bridge during the severe drought summer of 2002 (Versar 2003) found the highest river temperatures coincided with the highest air temperatures rather than the lowest flows at Little Falls. River temperatures also responded quickly to diurnal air temperature cycles and became cooler at night. The cascading sections of the river, especially in the stretch between Great Falls to Chain Bridge, helped keep dissolved oxygen levels above stress levels, with only slight dips below the Maryland 5 mg/liter dissolved oxygen standard in the longest and deepest pools of the Potomac Gorge. (One pool is almost 100' deep and needs more study because at such depths there are likely times when temperature stratification creates stressful dissolved oxygen levels in the deeper waters.)

Riparian Plant Communities

Floodplain forests and other riparian vegetative communities have varying flow regime requirements which in un-regulated rivers are principally factors of elevation. Ecological gradients develop from the fully inundated river bottom to the frequently flooded river benches to the occasionally flood-affected hill tops. Within each gradient, temporal variation is important to maintain ecological complexity. Where floods and droughts have differential effects, each adversely affects some communities while benefitting others. For instance, submerged aquatic plants in the Potomac experience their greatest growth and reproductive potential during years with lower flows. If flows are low during the growing season, less sediment and nutrients run off the landscape and there is greater substrate stability, resulting in increased water clarity and plant production. Conversely, aquatic plants tend to grow poorly during wet summers when flows are more turbid and erosive. Up from the river's edge, duration and frequency of floods upon landforms of different elevation is the most important factor determining riparian vegetation communities along rivers (e.g. Hupp and Osterkamp 1985). Consequently, species richness of riparian plants increases with topographic complexity of the floodplain (Everson and Boucher 1998). Bar formation and growth associated with flood peaks provides recruitment sites for pioneer species. Tree falls caused by floods promote diversity by providing openings in the canopy, creating opportunities for pioneer species that do not occur during dry years. Floodplain plants depend on floods to disperse their seeds, to maintain floodplain surfaces and enrich soils through sediment deposition, to exclude potential upland competitors, and to provide adequate moisture conditions for germination and growth (Dixon 2003).

Over 1,100 taxa that are influenced by flow have been identified on the Virginia side of the Potomac Gorge (Fleming 2006), and there are over 580 plant species and communities considered as rare, threatened or endangered in the Potomac watershed (Fleming 2007). To simplify the complexity of highly diverse ecosystems and capture ecological gradation, plant ecologist often group plant species into communities which occupy zones within a gradient, in this case flooding (e.g. Thompson, et al. 1999; Lea, 2000; Fleming, 2006). Plant ecologists are then better able to characterize and assess environmental interactions. For this study it was deemed sufficient to sort plant species into four groups, defined by the generally recognized, large-scale inundation zones where they are found, plus two special categories to address unique plant communities found in ecologically rare areas such as the Potomac Gorge. The four, large-river plant community groups, in ascending vertical-zone order, are:

1. **In-stream** – the most river-active area which is usually inundated all year with some seasonal exposure along the edges.
2. **Bank and Bar** – the zone from the mean-water mark to bank-full, with a flood event recurrence interval (RI) of between 0.5-2 years.
3. **True Flood Plain** – the zone affected by floods with 2-10 year RI. Due to frequent flooding, this area is not typically farmed because it becomes too wet and therefore is generally left wild, but has some use, mostly as shaded pasture, although with substantial fence maintenance issues.
4. **Flood Terrace** - this zone is inundated only by extreme floods, with an RI of >10 years. Silt, nutrients and moisture delivered by these floods produces excellent agricultural soils. Good soils with lower flood frequency have resulted in much of this zone's low-slope land conversion to prime farmland. Natural cover is rare, occurring most typically where slope has precluded agricultural use. This zone also tends to have more human structures which are compromised during floods.

Two additional plant communities for the Potomac Gorge, selected in consultation with Chris Lea, a National Park Service plant ecologist familiar with the Gorge, are:

> Piedmont/Central Appalachian Riverside Outcrop Prairie – found in the True Flood Plain. Adapted to floods but, because they are in areas of rock outcrops, seasonally become very dry due to thin soils. Characteristic flora: Virginia pine, white ash, post oak, eastern red cedar, prairie plants. 2.5-7 year RI.
>
> Bedrock Terrace Oak-Hickory Forest – found in alluvial areas of the Flood Terrace. In the Gorge these are relic populations. Thin soils on rock outcrops are due to scour of 100-year floods.

Figure 16 and associated **Table 3** present a conceptual flow-ecology model which visually links the river hydrograph with life-stage flow requirements and timing of these four plant groups.

Climate warming can potentially alter Potomac River floodplain species composition. The Potomac River is near the southern range limit of northern species such as *Acer saccharinum*, *Acer saccharum*, *Quercus bicolor*, *Quercus palustris*. It is near the northern range limit of many southern floodplain species including *Celtis laevigata*, *Fraxinus profunda*, *Nyssa aquatica*, *Taxodium distichum*, *Ulmus alata*, and the southern bottomland oaks, among other southern floodplain species. Since species composition is likely to change most quickly near current range limits and the Chesapeake Bay to the east is a dispersal barrier, the Potomac River could be at the forefront of floodplain species range shifts, with the potential for dramatic increases in species diversity (C. O. Marks, pers. comm., June 9, 2010, The Nature Conservancy).

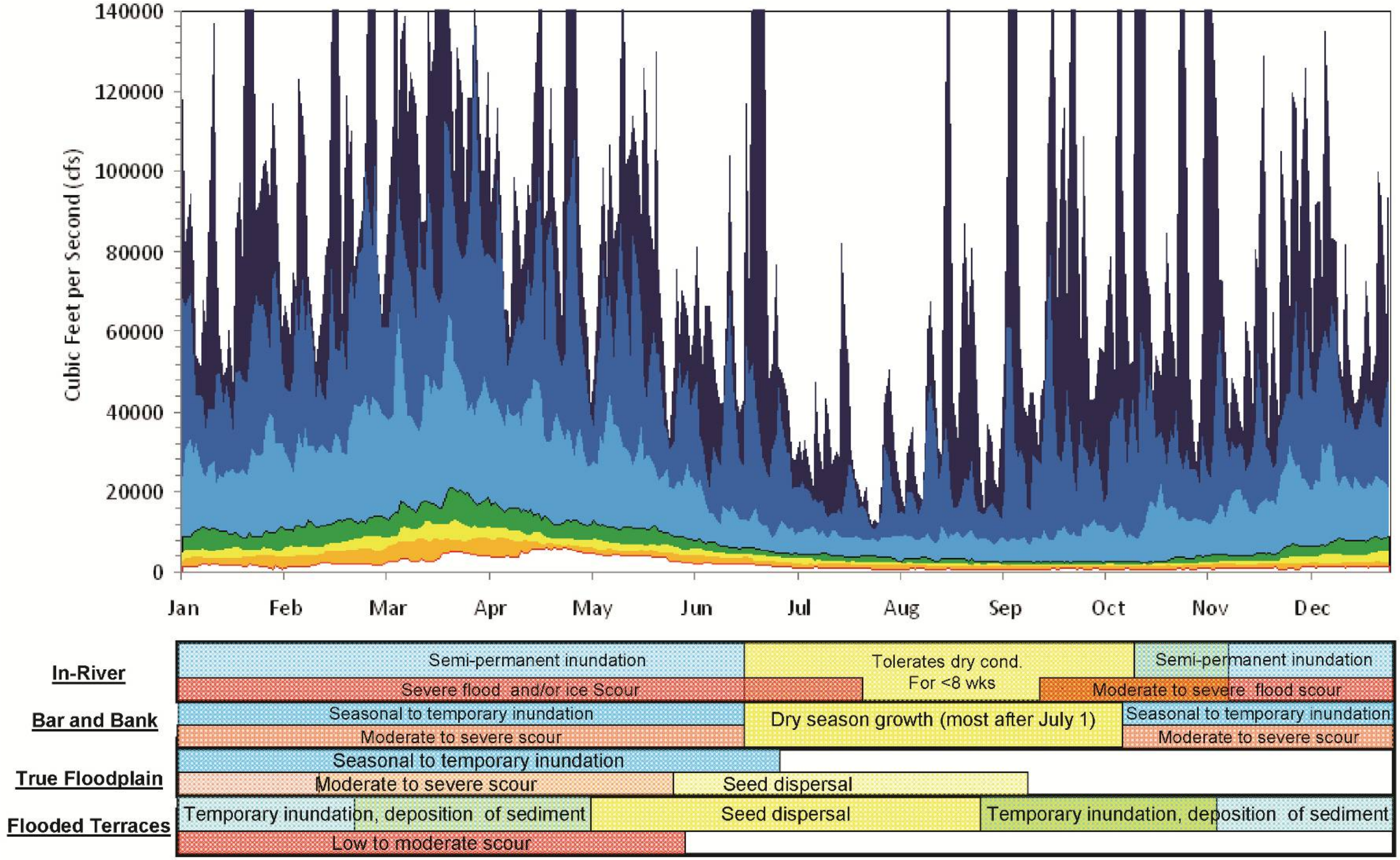


Figure 16. Riparian plant community relations to flow in the Potomac River.
The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Little Falls (adjusted), 3/1/1930 – 12/31/2008, are shown in the upper panel.

Table 3. Riparian plant community zones.

Vegetation communities (geomorphic area, flood inundation frequency)	Representa-tive types (in ascending altitude order)	Special community types in Potomac Gorge	Representative / dominant species in the zone (in ascending altitude order)	Seed dispersal/ Establishment: Timing & dispersal	Seed dispersal/ establishment: Substrate	Seedling inundation tolerance	High flow magnitude	High flow duration	High flow frequency	Drought cond.: magnitude, frequency, duration	Other notes
In-stream (inundated or seasonally exposed)	Submerged Aquatics Water willow rocky bar and shore		Submerged: water stargrass. Emergent: water willow	seeds dispersed by current, wildlife rhizomes enlarge beds, fragment dispersal with floods	variable, generally silt/sand generally porous, course. Silt/sand/w/gravel/ cobble.		Subject to flood scour Subject to flood scour and rare ice scour	Full-time Turbidity delays & reduces growth	Inundated all year Edges exposed during low-flows	Does well in droughts/clear water. Condition rapidly declines after 8 weeks of dessication, less if with a subsequent dessication event	
Bank and Bar (mean-water edge to Bank Full), 0.5-2 year flood RI	Flood-Battered Hardwood-shrubwood Switch Grass/ Carolina Willow/ Sycamore/ River Birch	Generally there are no notable special types. At Chain Bridge Flats – swamp white oak, low prairie below true flood plain. Typically a couple of m wide, but broad at Ch Br Flats.	big bluestem, switchgrass, willow, river birch, silver maple, green ash, ruderal species on open woodland: some herbaceous species, with stunted trees.	perennial warm-season grass	sand mixed with cobble, rapidly draining soils		Big floods help create bars, renew the bar's land surface. 10 yr floods.		Seasonal to temporary flooding	Green ash: does well in seasonally dry places (ie, Chain Bridge Flats), or might be benefitting from ponding.	Look into seed bank viability, b/c timing less critical if they can bank seeds. Long period of seed dispersal, more tolerant of flow changes.
True Flood Plain (small floods, 2-10 year RI). Due to frequent flooding, this area is not typically farmed, generally left wild, but some use, more as shaded pasture, but has fence maintenance issues.	Sycamore/ silver maple/ pawpaw/ green ash/ boxelder	Piedmont / Central Appalachian Riversie Outcrop Prairie. Adapted to seasonal drying. Riverside prairies, VA pine. High prairie – white ash, post oak, flooded by seasonally very dry. eastern red cedar, prairie plants. 2.5-7 year RI	Silver maple/ sycamore, green ash, box elder, paw paw, American elm. More upland sycamore – less battered.	Paw paw – animal dispersal. Clonal – pioneers in flood disturbed areas. Virginia pine – upper flood plain, lower flood terrace: shallow rooted, don't tolerate inundation. But, reproduce well in exposed, dry areas, fast-growing. post oaks can sprout.	Sycamore regenerate better on sand and coarser substrates. See Susq report details.		Delivers moisture, nutrients, sand and gravels as well as silt, soils are fairly well draine., Sand inputs help sycamores		opens canopy which promotes mosaic of plant communities .	Seeds require multi-year absence of prolonged inundation. For Gorge communities, Virginia pine – drought tolerant old field spp. does fine in nutrient poor areas. Oaks and hickories, xeric sp. on BI terrace.	
Flood Terrace (Extreme floods, >10 year RI). Natural cover is rare in low-slope land in this infrequently inundation zone, has largely been converted to farmland .	Mixed mesophytic forests with a few floodplain species like boxelder, cove/rich forests. Toe slope communities in R&V.	Potomac River Bedrock Terrace Oak-Hickory Forest. In alluvial areas in the Gorge, these are relic population. Lower BI, lower Offutt Isl.	Boxelder stands, sugar maple, white ash, basswood, bitternut hickory (alluvial), some N. red oak, tulip poplar, cove species like blue cohosh. Special types: Pignut hickory (special/Gorge), Virginia pine, red cedar, post oak,	For special communities in Gorge, these are pretty isolated population. May be its own gene pool?	Sugar maple – seed dispersal Sept. to Nov., germinate following spring. Although sugar maple seed is not flow dependent, can help re-establish stands.. White ash: Seed dispersal Sept to Dec, disperse following spring.	White ash: wet alluvium, more tolerant to inundation than sugar maple.	Periodic inundation enhances, delivers silt, moisture and nutrients. Special types like zeric conditions, but floods can open canopy for them	Less than 2 weeks inundation Sycamore seedlings will die if inundated > 2 wks		Virginia pine – needs large scouring floods to keep open canopy to allow it to compete.	This type is more of restoration concern. Many are gone or early successional so dispersal is important for them. Monitoring question – is sugar maple in areas that are intact with right flood interval?

Fishes

The Potomac River basin supports approximately 102 fish species, comprising 61 native upland species, 30 introduced species, and 11 diadromous species (Jenkins and Burkhead 1994). Of these, 56 species occur in the mainstem (**Table 4**) and are considered in more detail below. The zoogeographic history of the basin is characterized primarily by the river's drainage to the Atlantic Ocean. This isolation from the interior continental rivers probably has reduced the overall diversity of the system compared to other river basins of the same size (Sheldon 1988). However, fish dispersal among Atlantic slope basins occurred periodically when basins were connected during low sea-level periods (i.e., ice ages) (Jenkins and Burkhead 1994). Moreover, the headwaters of the Potomac basin have "captured" stream systems from the interior Monongahela River basin (Thompson 1939; Schwartz 1965; Cincotta et al. 1986, Hocutt 1979), presumably increasing species richness in the Potomac River basin.

Freshwater fish communities have changed substantially over time. Localized extirpations of fish taxa have been reported in the lower Potomac River basin (Starnes 2002) and probably have occurred in upstream areas. Stocking programs have also added several fish species to the River. Jenkins and Burkhead (1994) estimated that 33% of the fish species in the basin are introduced, a higher proportion than for other mid-Atlantic drainages. The historical absence of some popular game fishes and the presence of multiple federal fish hatcheries near Washington, DC may explain the relatively high level of stocking in the basin. Starnes (2002) estimated that of the 30 non-native fishes introduced into the Potomac, 22 probably remain. This report is focused on native riverine species, with one exception, smallmouth bass (*Micropterus dolomieu)*, which, although introduced, represents an important management species.

Fishes of the Potomac River basin exhibit a wide range of habitat use and life history strategies. Although most species are small-bodied (i.e., < 25 cm TL) several species may achieve adult body sizes of greater than 1 meter (**Figure 17 A**). These large-bodied fishes typically exhibit diadromous migrations to and from marine environments (i.e., sturgeons, eel, striped bass) (**Table 4**). Age of maturity and longevity also show skewed distributions, with most taxa showing relatively young ages of female maturity (i.e., < 3 years, **Figure 17 B**) and short longevity (i.e., < 5 years, **Figure 17 C**). Such associations among life history traits are expected and have been demonstrated elsewhere (e.g., Winemiller and Rose 1992). Fecundity expressed as log-transformed value exhibits a unimodal distribution among riverine species, wherein most species exhibit an intermediate fecundity level (**Figure 17 D**). Spawning season length expressed as the cumulative proportion of each month when spawning occurs (Frimpong and Angermeier 2009) showed an intermediate pattern among river fishes of the Potomac (**Figure 17 E**). Most Potomac River fishes were considered to be flow velocity specialists (i.e., flow range = 1, **Table 4**), not generalists (**Figure 17 F**).

Multivariate ordination techniques were used to explore the relationships among species traits and to evaluate the selection of indicator species[1]. Several groups of species may be recognized from the ordination results (**Figure 18**). For heuristic purposes, three groups are highlighted. "Group A" consists of large-bodied, flow-velocity generalists (e.g., sturgeons). "Group B" species consists of medium-sized fishes with moderate flow-velocity specialization. This group includes taxa with large and small home

[1] Non-metric multidimensional scaling (NMS) techniques were used to ordinate species by the life history variables presented in Table 4 (Frimpong and Angermeier 2009). Bray-Curtis distances (Bray and Curtis 1957) were used for NMS ordinations in PC-ORD version 5.0. A 2-dimensional NMS ordination explained 96.6% of the variation in fish species traits (Figure 18). The first NMS axis partitioned species based on body size, age of maturation, longevity, and fecundity. As expected, small-bodied fishes tended to exhibit earlier ages of maturation, shorter life-spans, and less fecundity than large-bodied fishes. The second NMS axis primarily reflected a gradient of flow velocity specialists and generalists. The first NMS axis explained a much larger proportion of the total variance explained than the second NMS axis (96.4% and 0.2%, respectively). However, the cumulative variance explained in the ordination was high and the final stress was low (2.9), enabling an interpretation of NMS axes as gradients of species traits.

Table 4. Potomac River fish list and species traits.

Family	Scientific name	Common name	Total length (cm)	Age of Female maturity	Longevity	Log-fecundity	Spawning season length	Flow range
Acipenseridae (Sturgeons)	*Acipenser brevirostrum**	Shortnose sturgeon	143.0	10.0	67.0	5.3	2.5	2
	*A. oxyrhynchus**	Atlantic sturgeon	267.0	18.0	60.0	6.6	1.8	2
Amiidae (Bowfins)	*Amia calva*	Bowfin	109.0	4.0	25.0	4.8	2.8	1
Anguillidae (Eels)	*Anguilla rostrata**	American eel	152.4	12.3	43.0	6.4	0.0	3
Aphredoderidae (Pirate perches)	*Aphredoderus sayanus*	Pirate perch	14.0	2.0	4.0	2.2	3.0	1
Catostomidae (Suckers)	*Carpiodes cyprinus*	Quillback sucker	66.0	4.0	10.0	4.8	1.0	2
	Catostomus commersoni	White sucker	64.0	3.0	8.0	4.7	1.8	3
	Erimyzon oblongus	Creek chubsucker	36.0	2.0	5.5	4.9	2.3	1
	Hypentelium nigricans	Northern hogsucker	61.0	3.0	11.0	4.5	1.5	2
	*Moxostoma macrolepidotum**	Shorthead redhorse	75.0	3.5	12.0	4.6	1.3	3
Centrarchidae (Sunfishes)	*Lepomis auritus**	Redbreast sunfish	30.5	2.0	6.0	4.0	2.3	1
	L. gibbosus	Pumpkinseed sunfish	40.0	2.0	8.0	4.1	7.0	1
	*Micropterus dolomieu**	Smallmouth bass	69.0	3.5	15.0	4.4	2.3	1
	Perca flavescens	Yellow perch	50.0	4.0	12.0	5.0	1.8	1
Clupeidae (Herrings)	*Alosa aestivalis**	Blueback herring	40.0	4.0	9.0	5.5	1.0	2
	A. mediocris	Hickory shad	40.0	3.0	5.5	5.5	1.0	1
	*A. pseudoharengus**	Alewife	40.0	3.0	5.5	5.5	1.0	1
	*A. sapidissima**	American shad	76.0	4.0	7.0	5.7	2.0	2
	Dorosoma cepedianum	Gizzard shad	60.0	2.0	6.0	5.7	1.5	1
Cottidae (Sculpins)	*Cottus girardi*	Potomac sculpin	14.0	2.0	5.0	2.1	2.0	2
Cyprinidae (Minnows)	*Campostoma anomalum*	Central stoneroller	22.0	2.5	5.0	3.7	2.5	2
	*Cyprinella analostana**	Satinfin shiner	11.0	1.5	4.0	3.6	2.8	2
	C. spiloptera	Spotfin shiner	12.0	2.0	5.0	3.9	2.8	1
	Exoglossum maxillingua	Cutlips minnow	16.0	2.0	4.5	3.1	1.0	2
	Hybognathus regius	Eastern silvery minnow	12.0	1.5	3.0	3.8	3.0	1
	Luxilus cornutus	Common shiner	18.0	2.0	6.0	3.3	2.0	2
	Nocomis leptocephalus	Bluehead chub	26.0	1.5	2.5	2.9	1.5	3
	N. micropogon	River chub	32.0	2.0	5.0	3.0	1.5	2

Family	Scientific name	Common name	Total length (cm)	Age of Female maturity	Longevity	Log-fecundity	Spawning season length	Flow range
	Notemigonus crysoleucas	Golden shiner	30.0	1.0	8.0	3.7	3.5	1
	Notropis amoenus	Comely shiner	11.0	1.0	2.5	2.7	3.0	2
	N. buccatus	Silverjaw minnow	9.8	1.5	3.0	3.2	3.5	2
	N. hudsonius	Spottail shiner	15.0	1.5	4.5	3.6	1.3	1
	N. procne	Swallowtail shiner	7.2	2.0	3.0	3.4	3.0	1
	N. rubellus	Rosyface shiner	9.0	1.5	3.0	3.2	3.0	2
	Pimephales promelas	Fathead minnow	10.0	0.5	2.0	4.0	3.3	1
	Rhinichthys cataractae[*]	Longnose dace	22.5	2.5	5.0	4.0	2.0	1
	Semotilus corporalis	Fallfish	51.0	2.5	9.0	4.1	1.0	2
Esocidae (Pikes)	*Esox americanus*	Redfin pickerel	37.6	2.5	7.0	3.7	3.0	1
	E. niger	Chain pickerel	99.0	2.0	9.0	3.9	2.0	1
Fundulidae (Killifishes)	*Fundulus diaphanus*	Banded killifish	10.0	1.0	4.0	2.4	6.0	1
Ictaluridae (Catfishes)	*Ameirurus catus*	White catfish	95.0	3.5	11.0	3.6	1.3	1
	A. natalis	Yellow bullhead	47.0	2.5	7.0	3.8	1.5	1
	A. nebulosus	Brown bullhead	55.0	2.5	11.0	4.1	1.3	1
	Noturus gyrinus	Tadpole madtom	13.0	1.5	4.0	2.6	4.0	1
	N. insignis[*]	Margined madtom	15.0	2.0	4.0	2.3	2.0	3
Lepisosteidae (Gars)	*Lepisosteus osseus*	Longnose gar	200.0	5.0	26.0	4.9	1.5	1
Moronidae (Striped bass)	*Morone americana*	White perch	49.5	3.5	12.0	5.2	0.5	1
	M. saxatilis	Striped bass	200.0	4.5	30.0	6.7	0.5	1
Poeciliidae (Livebearers)	*Gambusia holbrooki*	Eastern mosquitofish	5.0	0.1	1.0	2.5	5.5	1
Petromyzontidae (Lampreys)	*Petromyzon marinus*	Sea lamprey	120.0	5.0	8.0	5.5	1.3	3
Percidae (Perches)	*Etheostoma caeruleum*	Rainbow darter	7.7	1.0	4.0	3.2	3.0	2
	E. flabellare	Fantail darter	8.4	1.0	4.0	2.7	2.0	1
	E. olmstedi	Tessellated darter	11.0	1.0	3.0	3.2	3.0	1
	E. vitreum	Glassy darter	6.6	1.0	3.0	2.7	1.5	3
	Percina notogramma	Stripeback darter	8.4	1.5	3.0	1.3	3.0	2
	P. peltata	Shield darter	9.0	2.0	3.0	2.6	2.0	3

Traits data are from Frimpong and Angermeier (2009). Riverine indicator species are indicated with an asterisk (*)

range sizes (e.g., blueback herring [*Alosa aestivalis*] and redbreast sunfish [*Lepomis auritus*]) and for this reason Alosids are distinguished from non-Alosids. "Group C" species include small-bodied flow velocity specialists (e.g., margined madtom [*Noturus insignis*]).

Based on this analysis, twelve indicator species, distributed across these three Groups, were selected to represent the range of fish species trait diversity in the Potomac River mainstem: Atlantic sturgeon (*Acipenser oxyrhynchus*), shortnose sturgeon (*Acipenser brevirostrum*), American eel (*Anguilla rostrata*), smallmouth bass (*Micropterus dolomieu*), shorthead redhorse (*Moxostoma macrolepidotum*), redbreast sunfish (*Lepomis auritus*), blueback herring (*Alosa aestivalis*), alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), longnose dace (*Rhinichthys cataractae*), margined madtom (*Noturus insignis*), and satinfin shiner (*Cyprinella analostana*).
Flow regimes may influence fish life history groups in different ways. Striped bass and white perch (Group A, **Figure 18**) are influenced by flow with respect to habitat suitability during spawning and migration, and they may use flow to cue movement and spawning behaviors (**Figure 19**; **Table 5**). Out-migrations of American eel are closely linked to high flow events and the associated turbidity. The timing of alosid migrations as well as habitat suitability for spawning and overwintering are affected by flow (**Figure 20**, **Table 6**). Flow regimes influence non-migratory fishes primarily through their influence on local habitat quality (**Figure 21-22**; **Table 7-8**). For example, smallmouth bass recruitment can be limited by high flow events that scour nests, reducing recruitment.

Several critical uncertainties remain with respect to fish relations to environmental flows in the Potomac River. For example, although several studies have identified "optimal" flow and depth conditions for fishes, it remains unknown whether or not exposure to suboptimal conditions would affect individual physiology, behavior, or reproduction. In addition, interactive effects of flow with water temperature often prevent the resolution of flow-specific factors. Instead, it is emphasized here that variation in flow regime is coupled with regional and local habitat quality through the multiple direct and indirect pathways shown in **Figure 15**.

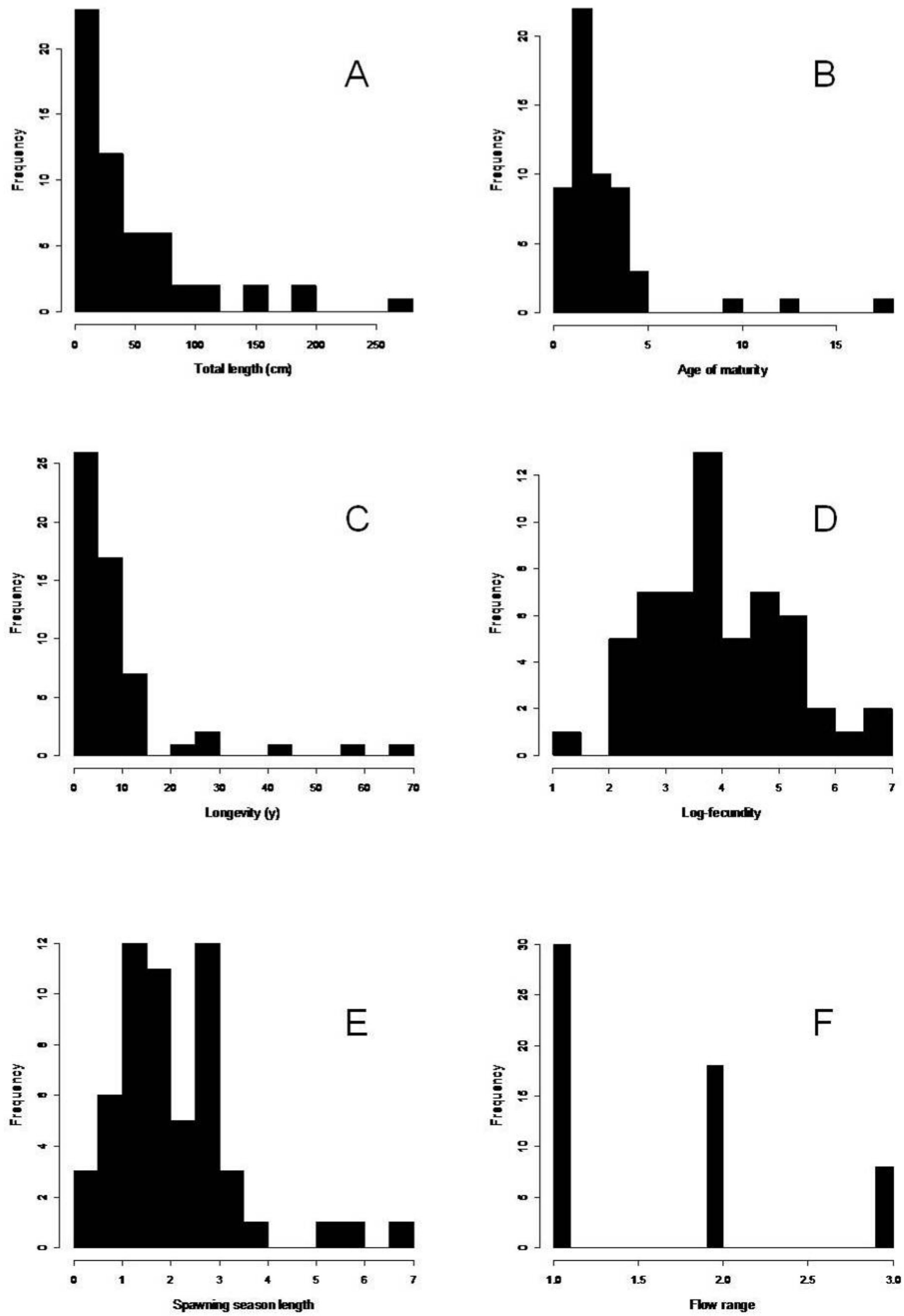
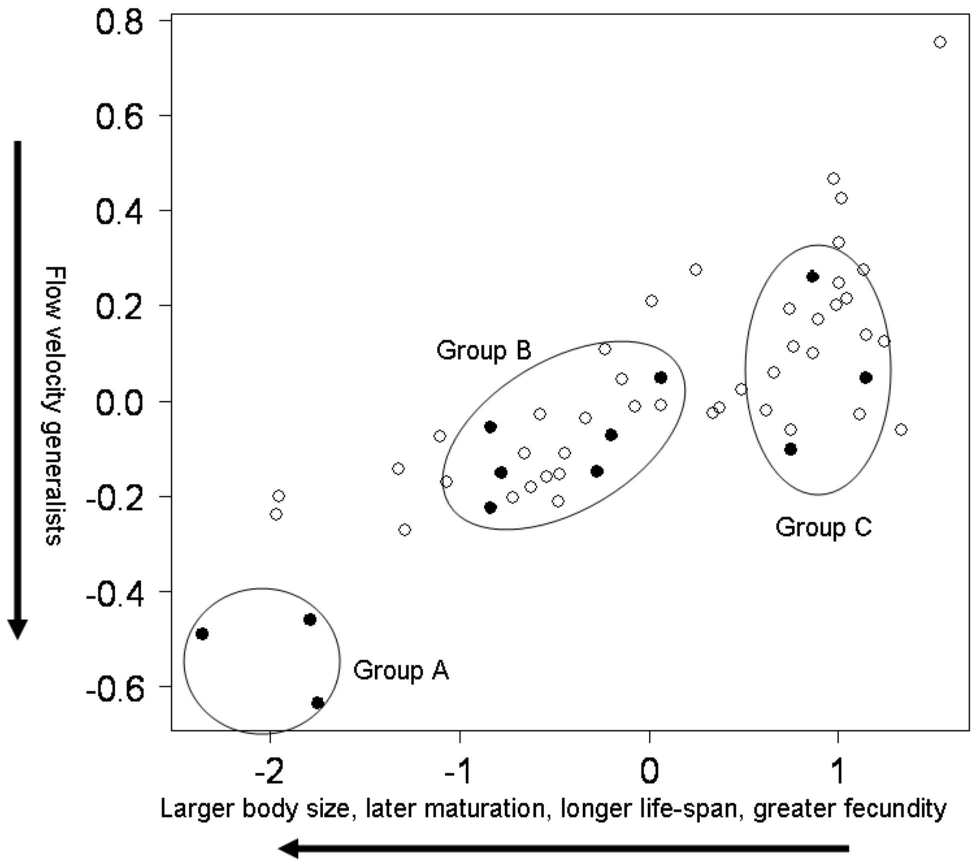


Figure 17. Species trait histograms.
A – total length, B – Age of female maturity, C – Longevity, D – Fecundity (log-transformed), E – Spawning season length, F – Flow tolerance range.



Variable	NMS I	NMS II
Body size	-0.97	-0.65
Age of maturity	-0.74	-0.73
Longevity	-0.79	-0.72
Fecundity	-0.61	-0.46
Spawning season length	0.40	0.55
Velocity tolerance	0.01	-0.14

Figure 18. Non-metric multidimensional scaling (NMS) ordination of fish species traits for the Potomac River. Data are presented in Table 4. Variable loadings are presented in table above. Group A, B, and C fishes are further described in the text .

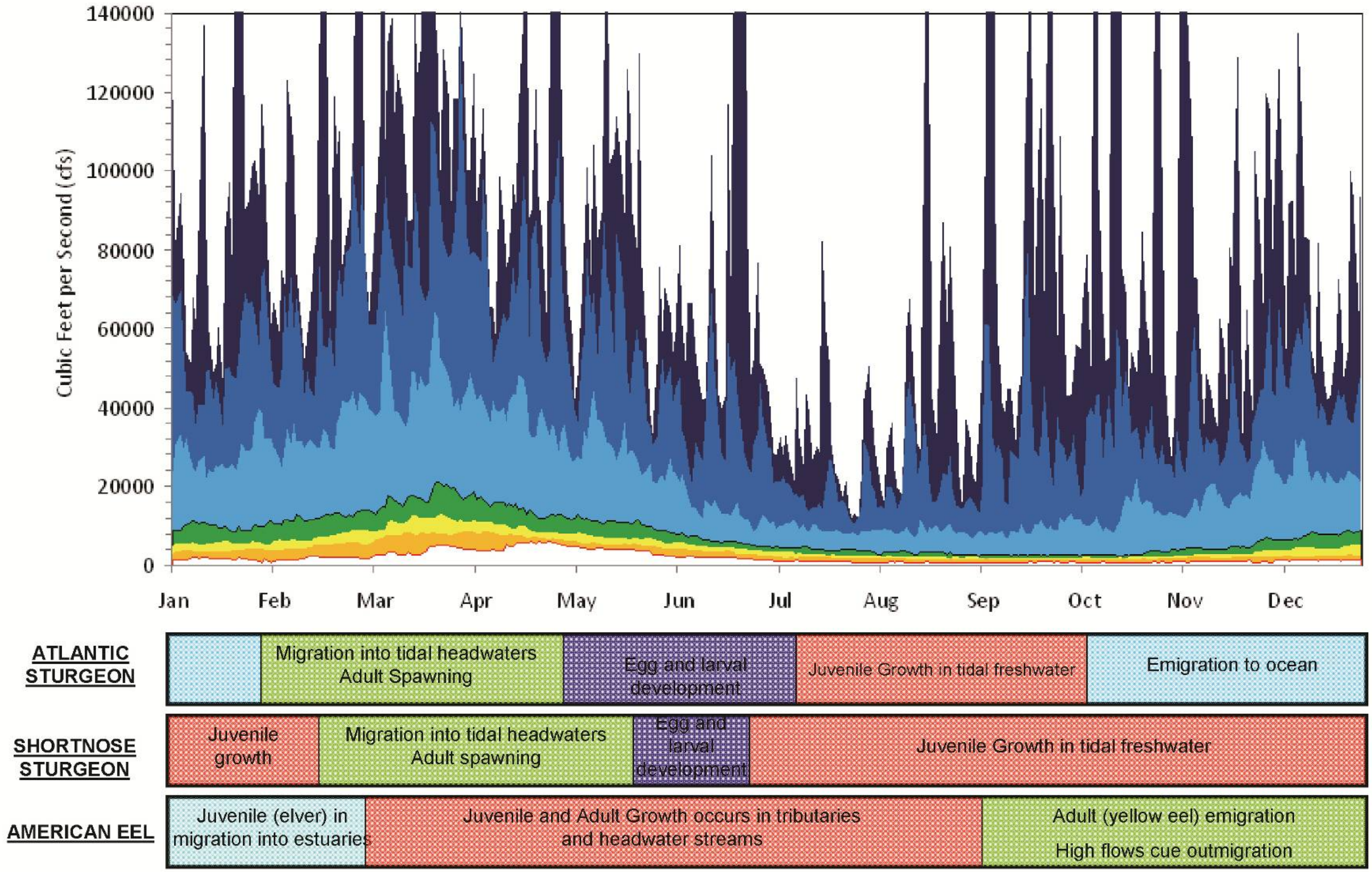


Figure 19. Group-A fish relations to Potomac River flow regime.
Groups are defined in Figure 18 and in text. The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Little Falls (adjusted), 3/1/1930 – 12/31/2008, are shown in the upper panel.

Table 5. Group-A fish data (use with Figure 19). Groups are defined in Figure 18 and in text.

Species	Life stage	Timing		Hydro-ecological relationships
		Months	**Cue**	
Atlantic sturgeon (*Acipenser oxyrhynchus*)	Egg and larval development	May-July	Water temperature at 20°C	Observed in depths from 9.1-19.8 m Substrate scouring from major floods can cause egg and larval mortality.
	Juvenile growth	All months for 1-6 years	Outmigration typically occurs near age-IV and may be triggered by seasonal high-flow events	Observed in depths from 2-27 m Flow velocity may affect food availability (indirect effect on physiology and growth) and energetic costs of feeding (direct effects on physiology and growth). Small body size may permit flow refugia access.
	Adult growth and migration	in rivers from Mar-Oct, then overwinter in saltwater	Adult migration may be triggered by water temperature changes	Observed in depths from 1.5-60 m Adult use of deep pools during extreme low-flows, and near-bank habitats during extreme high-flows (i.e., flow refugia).
	Spawning	April-May	Water temperature at 20°C	Optimal flow velocity reported at 0.2-0.8 m/s; Unsuitable flow velocity reported at < 0.06 m/s and > 1.1 m/s Observed in depths from 3-27m, optimal depths reported from 2.4-8.0 m
Shortnose sturgeon (*Acipenser brevirostrum*)	Egg and larval development	May-July	High flow events. Water temperatures from 9-15 °C	Optimal flow velocity reported from 15-45 cm/s. Eggs and larvae observed in depths from 4.6-12.0 m.
	Juvenile growth	July-February	NA	Flow velocity may affect food availability (indirect effect on physiology and growth) and energetic costs of feeding (direct effects on physiology and growth). Small body size may permit flow refugia access.
	Adult growth and migration	Migration most common during spring months, but also observed during fall months; migration earlier in southern regions	Migrations occur during increased flows	Adult body size smaller than *A. oxyrhynchus* and therefore may permit access to smaller flow refugia.
	Spawning	Mar-May	High flow events. Water temperatures from 9-15 °C	Observed in depths from 37-125 cm/s. Lee et al. (1980) report that spawning typically occurs during peak flows in brackish river reaches.

Species	Life stage	Timing		Hydro-ecological relationships
		Months	Cue	
American eel (*Anguilla rostrata*)	Egg and larval development	NA	NA	NA
	Juvenile growth and immigration	Enter rivers mid-December to April	Unknown	Tolerant of 25 cm/s but optimal flow velocities unknown. Juveniles are commonly observed in fine-substrate environments; Large winter flows (i.e., rain on snow events) may impede upstream migrations.
	Adult growth (yellow eel)	May to October	NA	Occur in high and low flow velocities.
	Emigration for spawning (silver eel)	Mid-September to December	Emigration may be triggered by a combination of high-flow events, turbidity, and (possibly) lunar phase.	Research from Shenandoah River shows greatest emigration rates over dams during high-flow events.

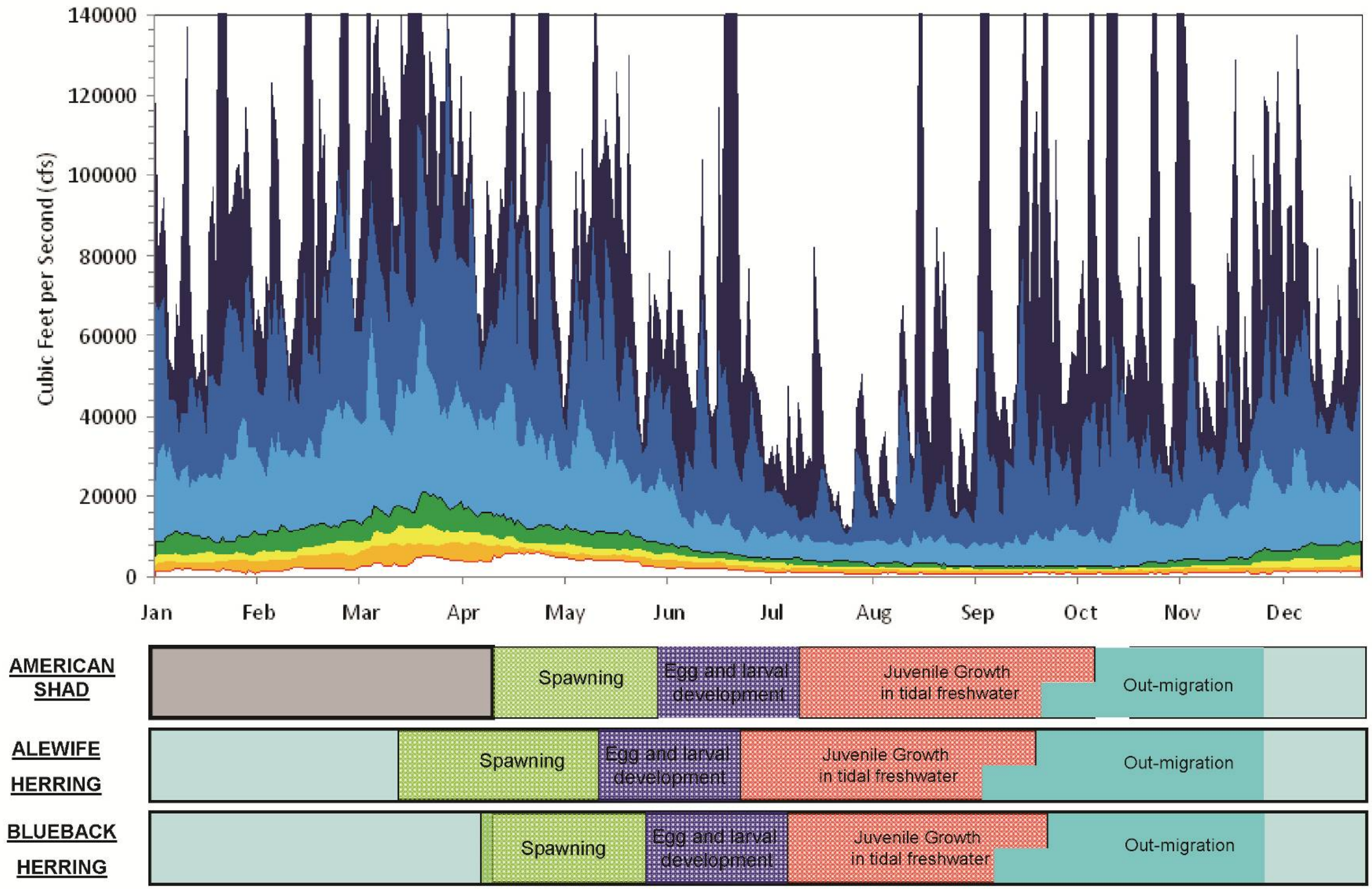


Figure 20. Group B1 fish relations to Potomac River flow regime.
Groups are defined in Figure 18 and in text.The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Little Falls (adjusted), 3/1/1930 – 12/31/2008, are shown in the upper panel.

Table 6. Group B1 fish info (Alosids) (use with Figure 20). Groups are defined in Figure 18 and in text.

Species	Life stage	Timing		Flow-ecology relationships
		Months	Cue	
American shad (*Alosa sapidissima*)	Egg and larval development	Early April to late May	Development time after fertilization, correlated inversely to temperature	Optimal flow velocity 0.3 to 0.9 m/s (0.98 to 2.95 ft/s) but reported in lower velocities. Higher flow velocities may cause scour and egg mortality. Optimal depths reported from 1.5 to 6.1 m. Yolk sac larvae observed deeper in benthic habitats in tidal environments. Riverine-tidal flow interactions important for larval development via salinity-influenced osmoregulation.
	Juvenile growth and emigration	Emigration late October to late November	Emigration cue likely a combination of temperature and lunar cycle; juveniles can't tolerate a change +/- 1 to 4 C from ambient	Optimal flow velocities reported from 0.1 - 0.8 m/s (0.33 to 2.62 ft/s). High low velocity may instigate downstream movements. Observed depths reported from 0.46-15.4 m. Optimal depths reported from 1.5 to 6.1 m.
	Adult growth	Adults return to sea and migrate to summer feeding grounds after spawning.	Adults remain in ocean 2 to 6 years before sexual maturity (male average. 4.3, and female 4.6 years) return to spawn in natal river.	NA
	Migration and spawning	Begin to enter freshwater in winter, gonad development early March-April. Spawning peak in early May (Delaware River).	Temperature 13-20 C in Connecticut River. Substantial inter-annual variation in water temperature reported.	Flow velocity may be more important than water temperature for migration and spawning cues. Optimal flow velocities reported from 0.3 to 0.9 m/s (1.0 to 3.0 ft/s). Observed in depths from 0.46-15.4 m. Optimal depths reported from 1.5-6.1 m. Spawning observed in runs with shallow water and moderate current.
Alewife (*Alosa pseudoharengus*)	Egg and larval development	Range 2 to 15 days after spawning, most often 3 to 5 days after	Development time after fertilization is inversely correlated to water	High velocity limits egg and larval survival rates. Reproducing successfully in some dam tailwater environments (Virginia) from stocking in reservoirs as a forage fish.

Species	Life stage	Timing		Flow-ecology relationships
		Months	Cue	
		spawning	temperature.	
	Juvenile growth and emigration	Growth March-October, Emigration November	Changes in flow, photoperiod, temperature, lunar phase hypothesized to cue emigration.	Juveniles avoid high flows and narrow channels where velocity > 10 cm/s. Enters streams earlier than *A. aestivalis* and may be subject to more rain-on-snow events. Landlocked populations known from northeastern U.S. and Virginia. Some downstream emigration observed before mass-migration (i.e., some emigration may be weakly related to specific environmental cues).
	Adult growth	After spawning, adults return to estuary and feed until migrating to wintering grounds	Sexual maturity occurs at a minimum age of 2, spawning populations 3 to 8 in the Chesapeake Bay.	NA (but note that A. *pseudoharengus* typically occupies deeper habitats than *A. aestivalis*).
	Migration and spawning	Enter freshwater in March and April, spawning begins 2 to 3 wks earlier than shad (late April)	Most predictably temperature, may also be triggered by high flow periods.	Spawning occurs in slow flow velocities and low depths (observed from 15 cm to 3 m depth, but typically < 1 m). Spawning occurs in lentic-type habitats including river margins, ponds, backwaters. Fecundity of landlocked populations is much less than in Anadromous populations (e.g. 22,000 eggs vs. 360,000 eggs, respectively; see Jenkins and Burkhead 1994).
Blueback herring (*Alosa aestivalis*)	Egg and larval development	June-July	Egg incubation time is temperature dependent.	Eggs require low-flow refugia for development (i.e., fertilized eggs settle in low-flow velocity reaches). High flows and low water temperatures from flood control discharges resulted in lower numbers of *A. aestivalis* larvae (observed in South Carolina and Virginia). *A. aestivalis* larvae exhibit diel movements to surface waters at night and to midwater depths during day. In the Potomac River, juveniles select pelagic main channel portion of tidal waters.
	Juvenile growth and emigration	March-August	Emigration is thought to be temperature-dependent (Connecticut River emigration peaked with temperatures	In laboratory studies, *A. aestivalis* juveniles avoided velocity > 10 cm/s. Landlocked populations show similar growth rates as Chesapeake Bay anadromous populations in age 1 and 2 (Kerr Reservoir, Virginia).

Species	Life stage	Timing		Flow-ecology relationships
		Months	**Cue**	
			14-15 C). However, other cues could include increased high flows, photoperiod, and lunar phase.	
	Adult growth			NA
	Migration and spawning	March-April Early April for the lower tributaries and Late April for the upper tributaries (Chesapeake Bay); 3-4 weeks after alewife, early to mid-May for Susquehanna River	Water temperature 14 °C coincides with spawning run initiation.	*A. aestivalis* immigrates into freshwater approximately 1 month later than *A. pseudoharengus* and therefore may be less subject to stochastic spring flow variation (e.g., rain-on-snow events).

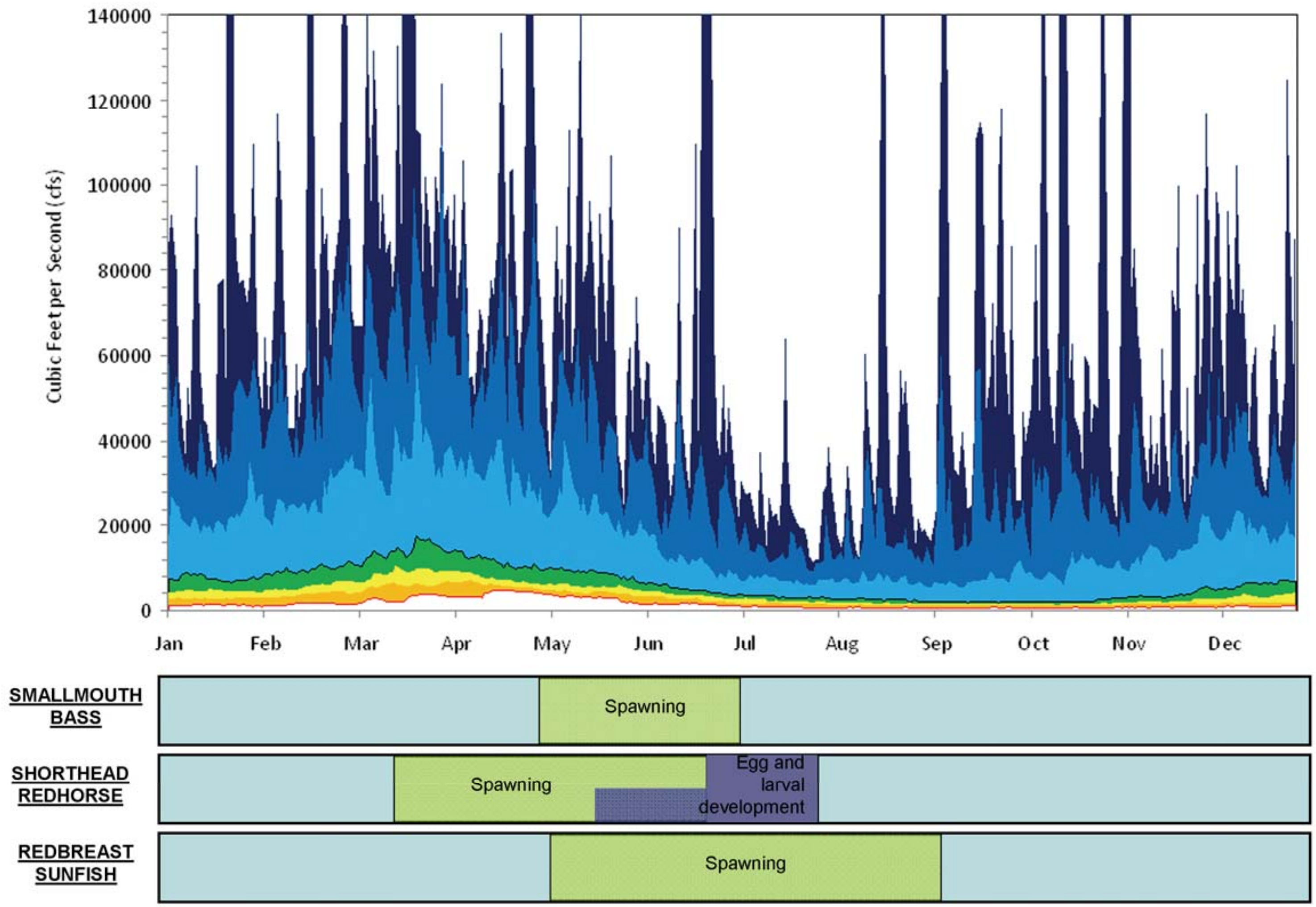


Figure 21. Group-B2 fish relations to Potomac River flow regime at Point of Rocks.
Groups are defined in Figure 18 and in text. The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Point of Rocks. 2/1/1895 - 9/30/2008, are shown in the upper panel.

Table 7. Group B2 fish information (non-Alosids) (use with Figure 21). Groups are defined in Figure 18 and in text.

Species	Life stage	Timing		Flow-ecology relationships
		Months	Cue	
Smallmouth bass (*Micropterus dolomieu*)	Egg and larval development	April – July		Flow velocity for egg and larval development requires low-flow refugia (i.e., < 0.2 m/s). Floods after spawning will reduce survival rate if substrate scouring occurs. Eggs and larvae observed at depths of 0.3-0.9 m. Eggs and larvae observed in pools and downstream side of bedrock ledges. Bedrock ledges provide important flow refugia for eggs and larvae. Males guard nests for several days after eggs hatch.
	Juvenile growth	June – September		Floods may decrease juvenile survival and growth rates (e.g., strongest year classes observed when June flows are relatively low). Dispersal from nesting habitat exposes juveniles to more variation in flow than in larval stages. Movement strategies may permit access to flow refugia in large woody debris, undercut banks, and large pools (but predation risks are probably highest in pool habitats).
	Adult growth			Movement to large woody debris, undercut banks, and pools is crucial for accessing flow refugia. *M. dolomieu* in northern regions (i.e., southern Canada) typically live longer than in southern regions (i.e., Potomac River basin) but adult body sizes are similar.
	Spawning	April-July	Spawning observed during descending limb of hydrograph and corresponds with water temperature increases.	Spawning observed in depths from 0.3-0.9 m.
Shorthead redhorse (*Moxostoma macrolepidotum*)	Egg and larval development	April-June		Egg development in gravel and cobble substrates is subject to flow-scouring.
	Juvenile growth	October-February		Optimal flow velocity reported from 0.8-3.4 ft/s. Juveniles observed at depths of 1.5-3.0 ft.
	Adult growth			Optimal growth rates reported from 1.5-4.3 ft/s. Adults are habitat generalists, occupying lotic and lentic environments in rivers and reservoirs.
	Migration and spawning	March-June	15°C water temperature	Spawning observed in flow velocities from 0.6-0.9 m/s. Spawning observed in depths from 30-60 cm. *M. macrolepidotum* exhibit upstream spawning migration runs.

Species	Life stage	Timing		Flow-ecology relationships
		Months	Cue	
				Spawning occurs primarily on gravel, cobble substrate (and occasionally sand) in pool tail-outs and runs. Flow maintenance of clean substrate spawning substrate is important.
Redbreast sunfish (*Lepomis auritus*)	Egg and larval development	August-September		High flows may cause males to desert nests, thus exposing eggs and larvae to increased predation rates. Optimal egg development reported at flow velocities from 0-0.3 ft/s. Stable water levels are important for egg adhesion. Flow refugia are important for egg development.
	Juvenile growth	September-May		Optimal flow velocities for juvenile growth reported from 0.4-0.6 ft/s. Optimal depths for juvenile growth reported from 0.5-5.2 ft.
	Adult growth			Optimal flow velocities for adult growth reported from 0.5-0.8 ft/s optimal. Optimal depths for adult growth reported from 2.0-6.1 ft. Adults often observed in pools and backwater areas. Adults are habitat generalists, occurring in ponds, reservoirs, streams, and rivers. However, *L. auritus* is more common in stream habitats than other *Lepomis* sunfishes and less common in ponds, suggesting adaptations to fluvial environments.
	Spawning	May-August	Peak spawning reported from 20-28 °C.	Nest construction and spawning occurs in shallow depths without siltation. Nests are often associated with large woody debris or other structural near pool margins. Substantial variation in spawning flow velocities has been reported. Spawning in slightly brackish water has been reported but occurrences in tidal zones are very rare.

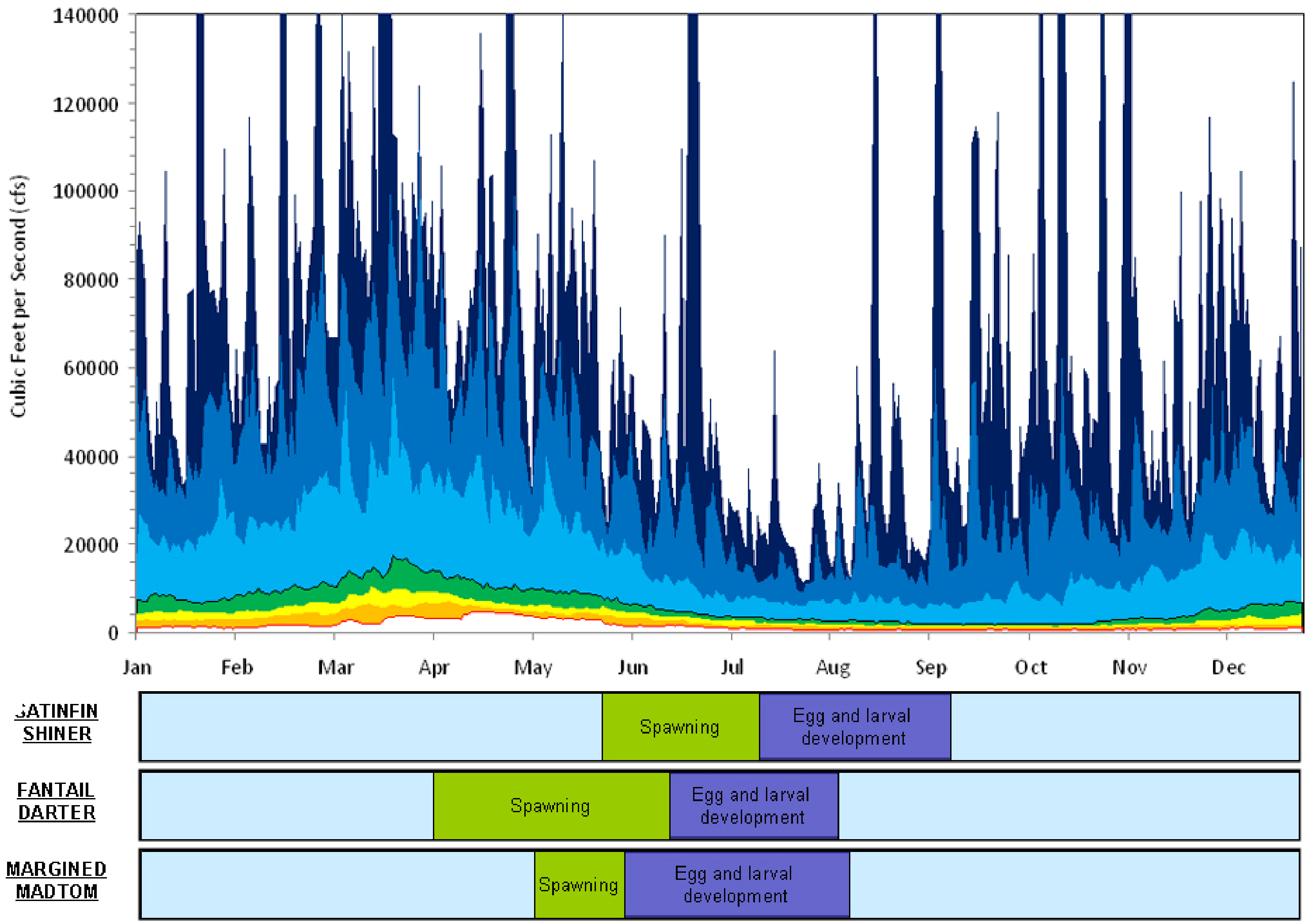


Figure 22. Group-C fish relations to Potomac River flow regime.
Groups are defined in Figure 18 and in text. The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Point of Rocks. 2/1/1895 - 9/30/2008, are shown in the upper panel.

Table 8. Group-C fish information (use with Figure 22). Groups are defined in Figure 18 and in text.

Species	Life stage	Timing		Flow-ecology relationships
		Months	**Cue**	
Margined madtom (*Noturus insignis*)	Egg and larval development	May-August	Incubation 7-10 days at 15.6 °C yolk sac absorbed 7 days after hatch	Cavity spawning behavior reduces egg exposure to substrate scour during peak flows.
	Juvenile growth	July-September		Juveniles observed in cobble substrate (not gravel) presumably for flow and predation refugia.
	Adult growth	Mature at age 2. Maximum longevity is 4 years		Adults exhibit diel behavior (i.e., active predators during night, hiding during day) so flow-induced turbidity is probably unimportant for predation efficiency.
	Spawning	May-June	?	Slow velocities preferred for spawning. Spawning occurs under flat rocks or in cavities. K-selected reproductive strategy invests in parental care (i.e., few, large eggs). Spawning may occur earlier in piedmont streams and later in montane streams in the Potomac River basin.
Satinfin shiner (*Cypinella analostana*)	Egg and larval development	July-September		Cavity spawning behavior reduces egg exposure to substrate scour during peak flows.
	Juvenile growth	August–June		?
	Adult growth	Maturation in 1-2 years		During winter months, observed in pools at 1.0-1.3 m. Observed in pools, backwaters, and runs. Occurs in tidal fresh waters, may be more saline-tolerant than other headwater fishes.
	Spawning	June-July	?	*C. analostana* are crevice spawners, often depositing eggs in woody debris. Females are fractional spawners (i.e., many spawn multiple times in a season), thus potentially avoiding year-class failure if scouring occurs. Males are territorial and behaviors/communication may be influenced by flow volume/turbidity.
Fantail darter (*Etheostoma flabellare*)	Egg and larval development	May-July: Hatch one month behind spawning (30 to 35 days at 17-20 C)	14-16 days at 23 °C	
	Juvenile growth	July-November		?

Species	Life stage	Timing		Flow-ecology relationships
		Months	Cue	
	Adult growth		Mature at age 1 or 2	Adults occupy shallow riffles.
	Spawning	April-June	Correlated with temperature (15-24°C)	*E. flabellare* is an egg-clusterer, attaching eggs to undersides of flat rocks in runs and slow riffles. Egg attachment may provide flow-refugia from floods (and may help explain the widespread distribution of this tolerant species). Egg attachment also may diminish effects of predation and siltation. Females are fractional spawners (i.e., many spawn multiple times in a season), thus potentially avoiding year-class failure if scouring occurs.

Mussels

Sixteen native mussel species are recognized in the Potomac River basin, and encompass a variety of traits related to habitat use and reproduction (**Figure 23** and **Table 9**). A 2009 map produced by M. Cannick (TNC) shows the known distribution of common and rare species (**Figure 24**). As with fishes, the Potomac River basin generally supports fewer freshwater mussel species than rivers draining into the interior basins (i.e., Mississippi River) (Ortmann 1913; Taylor 1985). In Atlantic-slope basins, mussel communities suggest colonization among rivers, perhaps to due fish host dispersal (Sepkoski and Rex 1974). The focus here is on brood length, adult size, fish hosts, substrate preference, and flow-velocity preference to explore flow-ecology relations.

"Brood length" indicates an important aspect of mussel reproductive biology, the amount of time between fertilization and release of immature offspring (i.e., glochidia). "Short-term brooders" complete this cycle within 1 year whereas "long-term brooders" typically overwinter after fertilization before releasing glochidia (O'dee and Watters 2000). In the Potomac River basin, the *Elliptio* species (*E. complanta, E. fisheriana, E. lanceolata*) are short-term brooders and other taxa are long-term brooders. The implication for environmental flow management is that reproduction of long-term brooders may be influenced by flow regimes over more seasons than short-term brooders. Conversely, summer flow dynamics may be more important for successful reproduction and recruitment in short-term brooder species. In addition, study of short-term brooders presents research challenges because females typically are gravid only in early summer and thus may be more difficult to use in field surveys and experiments.

Potomac basin mussels exhibit important differences in adult size and associated habitat use. The three smallest species (< 75 mm) are *Alasmidonta undulata* (triangle floater), *A. varicosa* (brook floater), and *Lasmigona subvirdis* (green floater). Conversely, *Lampsilis* species are the largest mussels in the Potomac basin (>150 mm), including *L. cariosa* (yellowlamp mussel), *L. cardium* (plain pocketbook), *L. radiata* (eastern lampmussel), and *L. ovata* (pocketbook). Intermediate-sized mussels (75-150 mm) include the *Elliptio* taxa as well as species within 6 other genera (**Table 9**). Adult size relates to flow dynamics through direct and indirect pathways. Direct effects include the physical effects of flow on large and small-bodied mussels (e.g., sheer stress and wetted habitat); indirect effects include the flow-mediated effects of substrate sizes.

Substrate size preferences include specialists and generalists using silt, sand, and gravel (**Table 9**). Most mussel species in the Potomac basin are found in multiple substrate types. For example, only 1 of the 16 Potomac basin mussels occurs in only 1 substrate type: *Utterbackia imbecillis* (paper pondshell) occurs in silt substrates (**Table 9**). In contrast, all other species prefer sandy substrates, and a greater number of species exhibit an affinity for gravel over silt (i.e., 11 vs 9). Most mussels in the Potomac basin are not substrate specialists per se. 3 of the 16 species are found in all substrate types: *Anodonta implicata* (alewife floater), *E. complanata* (eastern elliptio), and *Ligumia nasuta* (eastern pondmussel) may occur in silt, sand, or gravel substrates. Moreover, 11 species are known to occur in gravel and sandy conditions and 8 are known from silt and sand-dominated habitats (**Table 9**). High flows will reorganize the distribution of substrate sizes (Benda et al. 2004) and thus may affect mussels with different substrate size preferences differently.

Potomac basin mussels exhibit considerable variation in their tolerance of flow velocities. Seven species do not exhibit flow preferences but are found in slack water, slow, moderate, and fast velocities (**Table 9**). These velocity-generalists include members of the genera *Alasmidonta*, *Elliptio*, *Lampsilis*, and *Strophitus*. Conversely, 5 species occur within a single flow-velocity category, primarily slack-water or slow-water specialists. Slack-water and slow-water taxa include Utterbackia imbecillis (paper pondshell), Pyganodon cataracta (eastern floater), *Anodonta implicata* (alewife floater), and *Lasmigona subvirdis* (green floater). No species were fast-water specialists, but 7 species occur in fast-water as well as slow-water (e.g., *Elliptio complanata*). Although the specialist slack-water species (i.e., *Utterbackia imbecilis*)

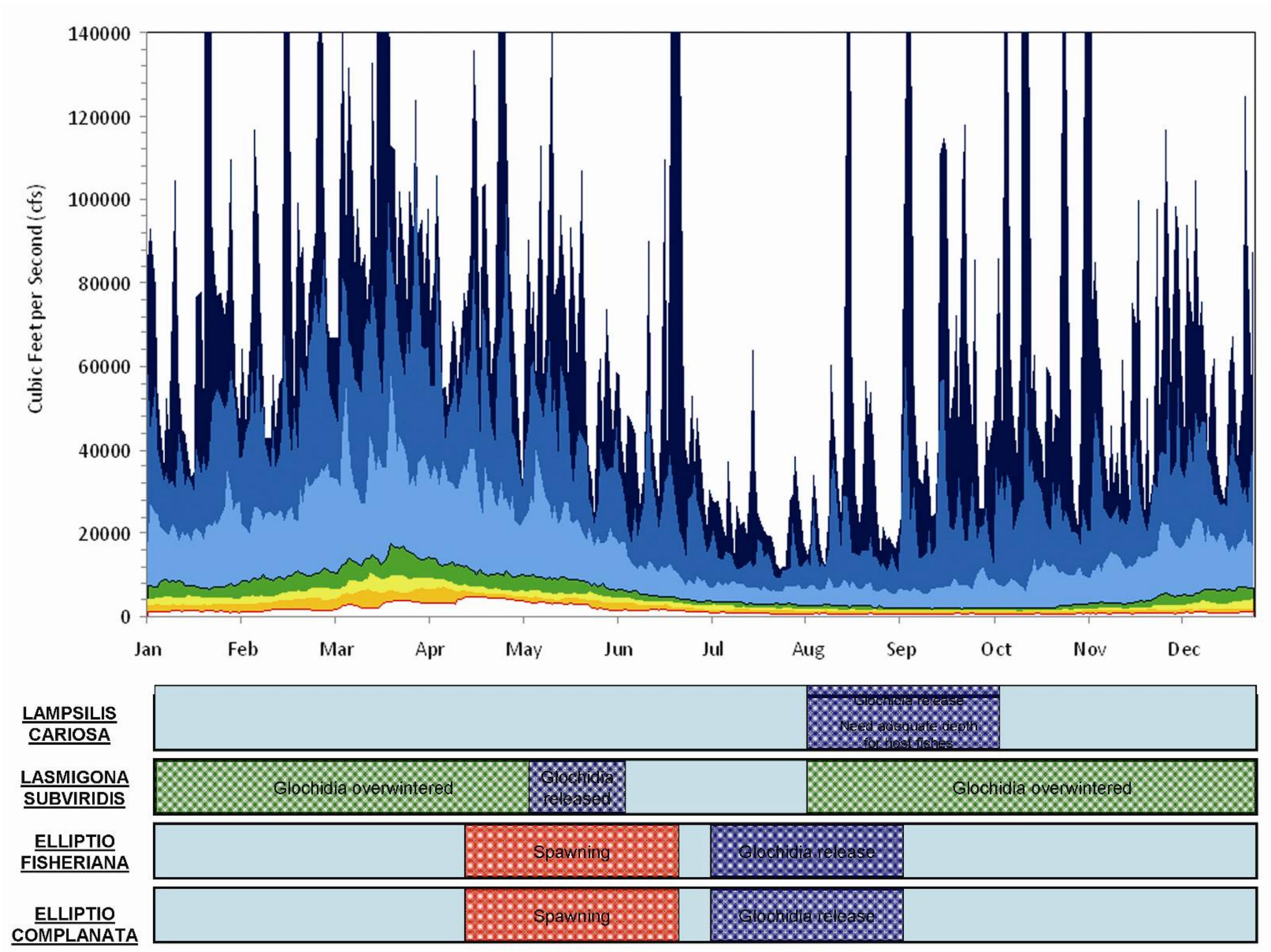


Figure 23. Mussel relations to Potomac River flow regime.
The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows for Point of Rocks. 2/1/1895 - 9/30/2008, are shown in the upper panel.

Table 9. Potomac River basin mussel list and species traits. Riverine indicator species are indicated with an asterisk (*).

Scientific name	Common name	Reproductive strategy		Adult size (mm)			Substrate preference			Flow velocity preference			
		Short-term brooder	Long-term brooder	< 75	75 - 150	> 150	Silt	Sand	Gravel	Slack	Slow	Moderate	Fast
Alasmidonta undulata	Triangle floater		X	X				X	X	X	X	X	X
Alasmidonta varicosa	Brook floater		X	X				X	X		X	X	
Anodonta implicata	Alewife floater		X		X		X	X	X	X			
Elliptio complanata *	Eastern elliptio	X			X		X	X	X	X	X	X	X
Elliptio fisheriana *	Northern lance	X			X		X	X			X		
Elliptio lanceolata	Yellow lance	X			X		X	X			X		
Lampsilis cariosa *	Yellow lampmussel		X			X		X	X		X	X	
Lampsilis cardium	Plain pocketbook		X			X		X	X	X	X	X	X
Lampsilis radiate	Eastern lampmussel		X			X		X	X	X	X	X	X
Lampsilis ovata	Pocketbook		X			X		X	X	X	X	X	X
Lasmigona subviridis *	Green floater		X	X				X	X	X	X		
Leptodea ochracea	Tidewater mucket		X		X		X	X		X	X		
Ligumia nasuta	Eastern pondmussel		X		X		X	X	X	X	X	X	X
Pyganodon cataracta	Eastern floater		X		X		X	X		X			
Strophitus undulates	Creeper		X		X		X	X	X	X	X	X	X
Utterbackia imbecillis	Paper pondshell		X		X		X			X			

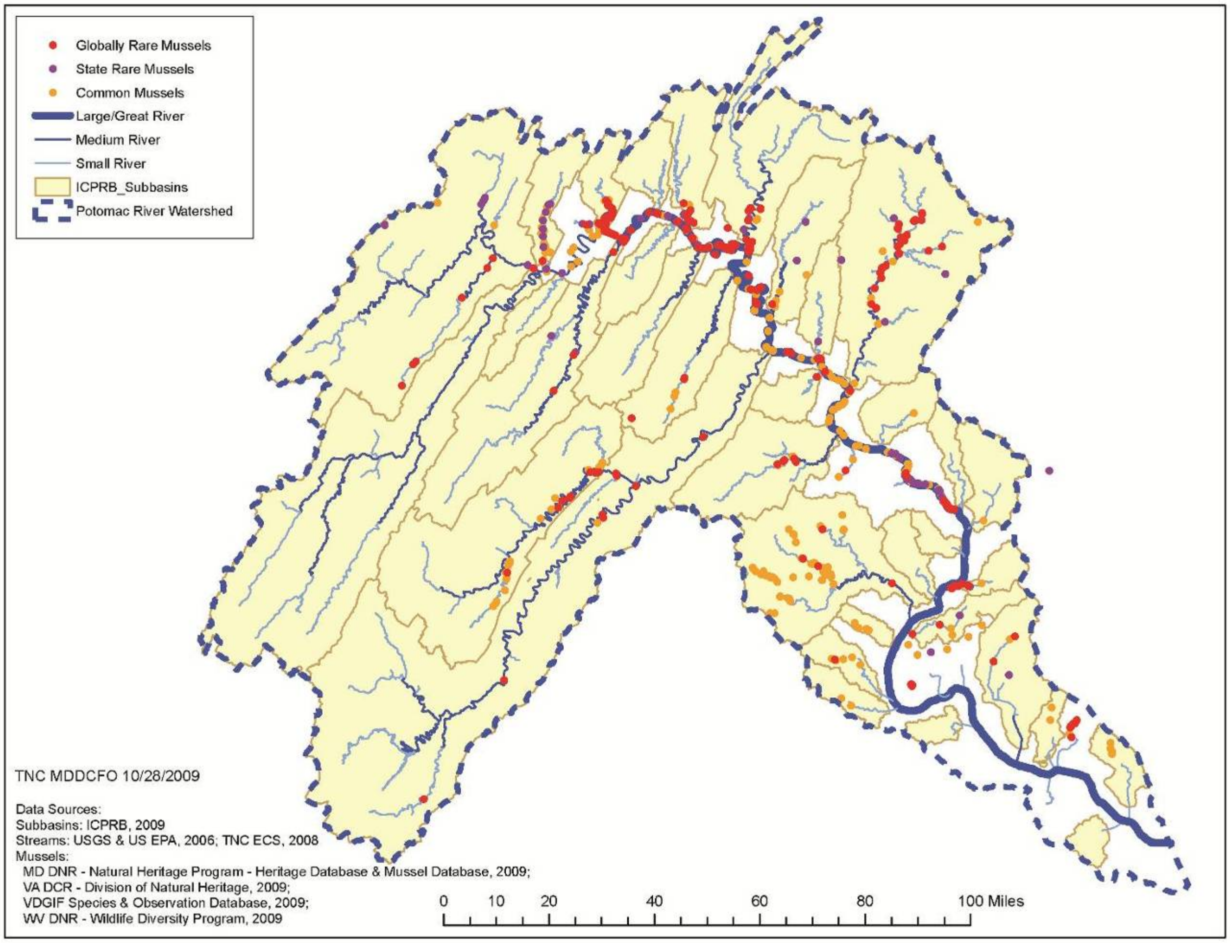


Figure 24. Known distribution of mussels in the Potomac River basin.
Map created in 2009 by M. Cannick (TNC). Common species are *Elliptio angustata*, *Elliptio complanata*, and *Pyganodon cataracta*. Species rare in Potomac basin states are: *Alasmidonta undulata*, *Anodonta implicata*, *Elliptio fisheriana*, *Lampsillis radiata*, *Ligumia nasuta*, *Strophitus undulatus*, and *Utterbackia imbecillis*. Globabally rare species are: *Alasmidonta heterodon*, *Alasmidonta varicosa*, *Elliptio lanceolata*, *Elliptio producta*, *Lampsillis cariosa*, *Lasmigona subviridis*, and *Leptodea ochracea*.

occur in lentic habitats are probably not strongly linked to riverine flow management, flow-velocity generalists such as *Strophitus undulatus* (creeper) have been observed in mainstem Potomac collections (R. Villella, USGS, personal observation). Also, *Alasmidonta varicosa* (brook floater) is typically found in small stream habitats, but a recent survey near Shepherd Island revealed fresh shells this species, indicating a high probability of mainstem-reproducing population (R. Villella, USGS, personal communication).

Flows also affect mussels indirectly through influencing behavior of fish hosts for glochidia dispersal. Experimental trials have revealed fish-host relations for several mussel species found in the Potomac Basin. For example, *Lampsilis cariosa* fish hosts may include white perch (*Morone americana*), yellow perch (*Perca flavescens*), white sucker (*Catostomus commersoni*), and smallmouth bass (*Micropterus dolomieu*) (Kneeland and Rhymer 2008). *Elliptio fisheriana* may utilize centrarchids (bluegill, largemouth bass), cyprinids (white shiner), and darters (Johnny darter) for dispersal and transformation of glochidia (O'dee and Watters 2000). In some cases, amphibians may also serve as hosts for glochidial dispersal (Watters and O'dee 1998). Fish movements are often linked to variation in flow regimes (Fausch et al. 2002) and fishes of the mid-Atlantic highlands exhibit distinct dispersal-grain signatures (Hitt and Angermeier 2008). However, no research was identified directly linking fish dispersal behaviors and mussel spatial population structure and this is recognized as an important research need.

Species traits should be considered not as independent quantities, but instead as ‘packages’ of traits (e.g., Winemiller and Rose 1992). For Potomac basin mussels, the short-term brooders (*Elliptio* species, *n* = 3) tend to be intermediate in adult size (75-150 mm), and occupying a range of substrate types and flow velocities. In contrast, the large-bodied *Lampsilis* species tend to exhibit a preference for gravel and/or sand under but no clear preference for flow velocity, whereas the small-bodied *Lasmigona subvirdis* (green floater) exhibits a preference for slow-water velocities (**Table 9**). Four focal species were chosen to represent the range of variation in mussel species traits in **Figure 23**: *Lampsilis cariosa*, *Lasmigona subviridis*, *Elliptio fisheriana*, and *Elliptio complanata*.

Flow-Ecology Hypotheses for Potomac Nontidal River Communities

A significant body of scientific literature about flow-ecology relationships was assembled and reviewed for this report. Research and empirical data to define thresholds of acceptable hydrologic change and make quantitative environmental flow recommendations are lacking for large mid-Atlantic river systems. For example, many studies of the ecological needs of fish and aquatic insects identify water velocity requirements, not flow requirements, which make direct correlations of flow and ecology difficult. Velocity measurements (distance per unit time) necessitate micro-habitat studies conducted across transects at various flows in a river reach and are relatively rare whereas flow measurements (volume per unit time) are routinely made at multiple gage sites in the Potomac River basin and published by the US Geological Survey. As part of the related Middle Potomac Watershed Assessment project, ICPRB is using the Ecological Limits of Hydrologic Alteration (ELOHA) approach to identify quantitative thresholds of biotic degradation that can be linked to flow alteration, but results from that analysis are not available at this time.

The research team for this literature-based study developed the following set of flow-ecology hypotheses to help bridge the gap, recognizing that they are largely based upon interpretation of literature, personal observation, and professional judgment. There are two categories: general hypotheses that apply to a broad range of aquatic species and/or communities and specific hypotheses tailored to selected indicator organisms. These hypotheses are meant to serve as a starting point for discussion at the workshop.

<u>General hypotheses</u>

1. Species richness will peak at intermediate levels of flow variability (*sensu* Connell 1978).
    a. Too many low-flows will extirpate riverine biota due to a cascade of flow-induced effects on water quality, connectivity, biotic interactions (i.e., predation and competition).
    b. Too many high-flows will extirpate some riverine biota through sheer-stress effects and habitat loss.
    c. An “intermediate” level of flow variability will increase riverine species richness by creating habitat features and limiting competition.
2. Low and high flow effects will be mediated by the spatial proximity and abundance of flow refugia and organismal vagility.
3. The mechanisms of flow-effects will vary across spatial and temporal scales.
    a. Spatial
        i. At local-scales (i.e., within 1-10 mile-long river reaches), flows affect riverine biota primarily through physiological and behavioral pathways.
        ii. At regional-scales (i.e., more than 10 mile-long river reaches), flows affect riverine biota primarily through recruitment and metapopulation dynamics.
    b. Temporal
        i. Over short time periods (i.e., hours-days), flows affect riverine biota primarily through physiological and behavioral pathways (e.g., sheer stress).

ii. Over long time periods (i.e., years-decades), flows affect riverine biota primarily through habitat-forming processes (e.g., substrate organization and mesohabitat structure).

4. Behavioral, phenotypic, and physiological species traits will predict organismal and population sensitivity to flow regimes.

<u>Specific hypotheses</u>

Plant Communities

5. Submerged aquatic plants experience their greatest growth and reproduction during years with lower flows during the growing season due to increased water clarity and greater substrate stability.
6. Floodplain plants depend on floods for seed dispersal, deposition of sediment to maintain floodplain surfaces and enrich soils, removal of debris and potential competitors from germination sites, and to provide adequate moisture conditions for germination and growth.
7. Flooding-caused tree falls promote diversity by providing openings in the canopy and opportunities for pioneer and understory species that do not occur during dry years.
8. Duration and frequency of floods upon different fluvial landforms is the most important factor determining riparian vegetation communities.
9. Species richness of riparian plants increases with topographic complexity of the floodplain.

Fishes

10. Out-migrations of American eel (*Anguilla rostrata*) and alosids are triggered by high-flows and associated water quality conditions (i.e., turbidity).
11. Fishes exhibiting K-selected reproductive strategies with fewer, longer-living offspring will be more vulnerable to stochastic high-flows and floods than R-selected species with many shorter-living offspring (e.g., margined madtom, *Noturus insignis* versus white sucker, *Catostomus commersoni*, respectively).
12. Pelagic fishes will be influenced by stochastic flow variability more than benthic fishes.
13. Fishes exhibiting simple lithophilic spawning strategies (i.e., no parental care, gravel-spawning species) will be influenced by stochastic flow variability more than other reproductive strategies.
14. Riverine fishes exhibit a bimodal distribution of body sizes in response to natural flow regimes (i.e., regulated rivers will exhibit unimodal distributions).
15. Spring peak-flows regulate smallmouth bass (*Micropterus dolomieu*) recruitment.
16. Bedrock-dominated river reaches will be more prone to high-flow extirpations than freestone-dominated river reaches (i.e., microhabitat refugia).
17. River reaches containing stream-river confluences will be less-subject to flow-induced extirpations than river reaches without such stream network connectivity (i.e., macrohabitat refugia).

Mussels

18. Winter flow conditions will influence recruitment in long-term brooding mussel species (represented by *Lampsilis* sp.) more than in short-term brooding species (represented by *Elliptio* sp.).
19. Recruitment in short-term brooding mussel species will be influenced by stochastic effects of peak-flows more than long-term brooders.
20. Deep-water mussel species will be less subject to drought than shallow-water species.
21. Mussel populations exhibit patch dynamics at the meso-habitat scale such that isolated riffles are more vulnerable to flow-induced extirpations than "connected" riffles.
22. Mussel fish host generalists are less subject to flow-induced extirpation than fish host specialists.

CHAPTER 3: FRESHWATER ESTUARINE ECOLOGICAL INDICATORS

Summary

This chapter discusses the impacts of low freshwater flow on the habitat and biota of the Potomac tidal freshwater estuary between Chain Bridge and Occoquan Bay. This reach is longer and shallower than it was three centuries ago. Enormous sediment loads from the basin have filled in the reach and changed the estuary's average residence time, circulation patterns, and location of the salt front. Semidiurnal tides mix out-flowing freshwater with intruding salt water from the ocean, creating a salinity gradient which governs structure and function of biological communities along the entire length of the estuary. Salinity is generally recognized as a surrogate for flow in the tidal freshwater reaches of estuaries, with low flows reducing the volume of the tidal freshwater habitat and high flows increasing it. In years with low freshwater flow, the smaller volume of freshwater correlates with lower production of freshwater zooplankton and the juvenile fish that utilize tidal fresh habitats during early life stages. Conversely, brackish water species do better. Contrary to the usual pattern, low freshwater flows degrade rather than improve water quality in the Potomac tidal fresh estuary because of significant nutrient loads from sources in the metropolitan Washington area.

Several community indicators were employed to represent key aspects of tidal freshwater ecology and its responses to low freshwater flows, namely the phytoplankton (algae suspended in the water), SAV, zooplankton, and benthic invertebrates. Four fish species that inhabit freshwater for part or all of their life cycle were also examined. A wide variety of behavioral, morphological, and physiological adaptations allows most estuarine organisms to temporarily withstand or avoid the negative effects of high or low flow conditions. Low flow effects on estuarine biota are for the most part indirect and realized as a change in salinity, or the proportions of fresh and salt water. Flow alteration as a factor affecting the Potomac tidal fresh biological communities is presently far outweighed by the effects of poor water quality and other stressors. Seven general flow-ecology hypotheses are presented. Participants of the September 22-23, 2010 workshop will discuss and refine the hypotheses.

Appendix D provides additional information about the Chesapeake Bay Program's Estuarine Health Indicators. Appendix E contains detailed information about the geometry of the estuary.

The Tidal Freshwater Habitat and Biological Communities

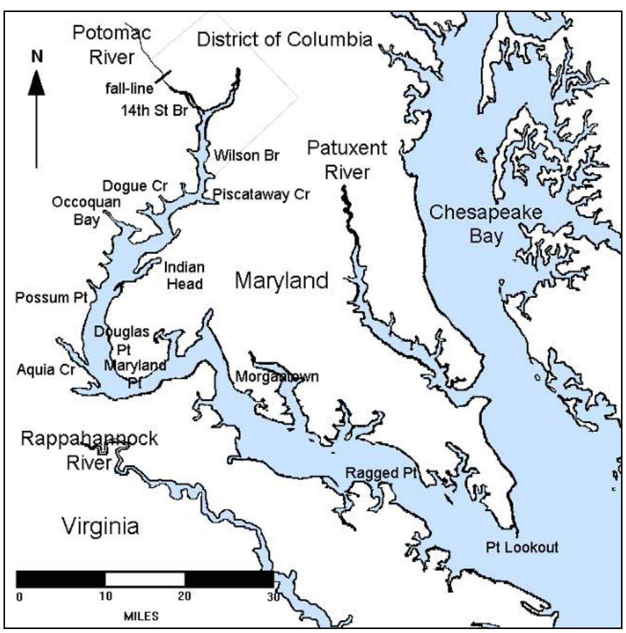


Figure 25. The Potomac River estuary.

The 113 mile long, tidally-influenced portion of the Potomac River is the smaller arm of the bifurcated Chesapeake Bay estuary (**Figure 25**). The Potomac estuary is ~200 ft wide near its head-of-tide above Washington, DC and broadens to nearly 10 miles at its mouth. Mean annual discharge at the mouth is 14,300 cfs with ~78% of freshwater flow coming from above the Piedmont fall-line and ~22% coming from numerous small to moderately sized Coastal Plain tributaries (Lippson et al. 1979). Semidiurnal tides mix out-flowing fresh water with intruding salt water from the ocean, creating a salinity gradient which governs structure and function of biological communities along the length of the estuary.

Freshwater flow to the estuary is highly variable from year to year, and multi-year wet and dry periods occur. Discharge near the fall-line has been measured at the Little Falls USGS gage 01646502 since March 1930 and at the Point of Rocks USGS gage 01638500 since 1895. Low flow periods occurred in 1930-1931, 1965-1966, and 1999-2003 in the gage records. Lorie and Hagen (2007) found a higher frequency of severe minimum flow periods (droughts) in time series constructed for the pre-Colonial period from tree-ring analysis and the Palmer Drought Severity Index (**Figure 4**).

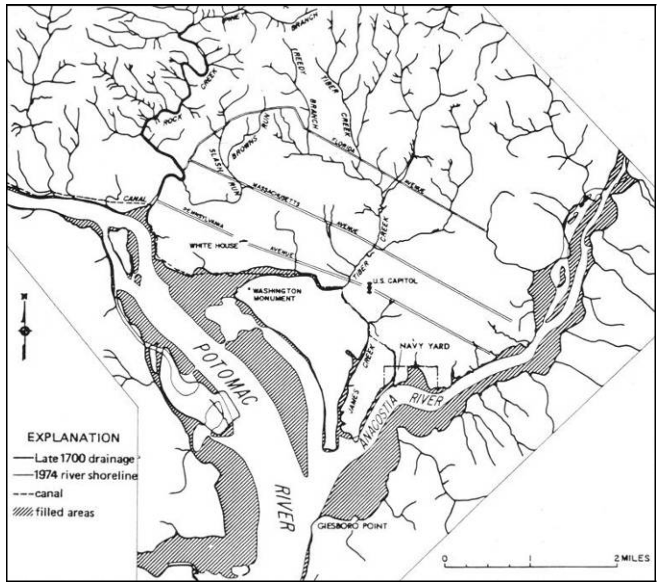


Figure 26. Stream network and river shorelines of Washington, DC in the late 1700s as compared to 1974. Selected reference streets and points and the 19th century canals are shown (map from ICPRB archives).

Naturally occurring dry periods and low freshwater flows do not change the mean water level in the Potomac estuary, which is at sea level. Flow regulates the downstream location of the estuary's salinity gradient and thus the volume of the tidal fresh habitat available to migratory fish and freshwater species. Low flow allows brackish water to intrude upstream and enables strong winds and tides to deeply mix the surface layer. High flow pushes brackish water downstream and, where the estuary widens below Morgantown, forces brackish water to spill out on top of the saltier bottom layer and form a pycnocline, or sharp vertical gradient in salinity. The salt wedge is usually found between statute river mile (RM) 81 at the mouth of Mattawoman Creek and 47 at Morgantown (see **Appendix E**). It typically advances up the mainstem between these boundaries in summer and fall, and down the mainstem in winter and spring, reflecting seasonal differences in flow. It advances downstream rapidly in response to large flow events, which can occur in any season. Monitoring data show that the estuary mainstem above Dogue Creek has been persistently fresh in the 20th century (www.chesapeakebay.net). The tidal fresh reach now has a volume of about 52.83 billion gallons (200 x 10^6 m^3) or less during dry periods with prolonged low flows. Very high seasonal flows and floods can expand it to upwards of 264.2 billion gallons (1 billion m^3) (calculated from Lippson et al. 1979).

Impacts of historic land and water uses on the river's flow regime were compounded by the enormous changes in the estuary's morphology that occurred after European settlement. The wide and deep tidal fresh Potomac River mainstem and tributaries of pre-Colonial times have filled in with upland and Coastal Plain sediments. The once "drowned river valley" formed after the Pleistocene ice age is now a drowned river flanked by broad shallows and shoals on either side (Buchanan 2008). Evidence of this is clearly seen in comparisons of the Potomac River boundaries near Washington, DC from the late 1700s and 1974 (**Figure 26**). Heavy sediment inputs from the watershed have affected the estuary's residence time, circulation patterns, location of the salt front or "salt wedge," and the habitat characteristics of tidal fresh water available to anadromous spawners.

Early accounts of the Washington, DC area refer to animals such as dolphins, and possibly sharks, which favor saltwater. The average location of the salt wedge, or 0.5 ppt isocline, is now 34 miles downstream of the District near Douglas Pt. (**Figure 27**), corresponding to a tidal fresh reach volume of about 146.4 billion gallons (554.2 x 10^6 m^3). The tidal fresh reach of the estuary is longer and shallower than it once was. It is not clear if the same *volume* of tidal fresh habitat has been maintained since Pre-Colonial days. If the same volume was present then, its reach downstream would have been substantially shorter.

In years with low freshwater flow, the smaller tidal fresh reach correlates with low production of juveniles of fish species that utilize tidal fresh habitats during early life stages but favors species that prefer brackish water (Wood and Austin 2009). Inter-annual variability in flow appears to be a key factor

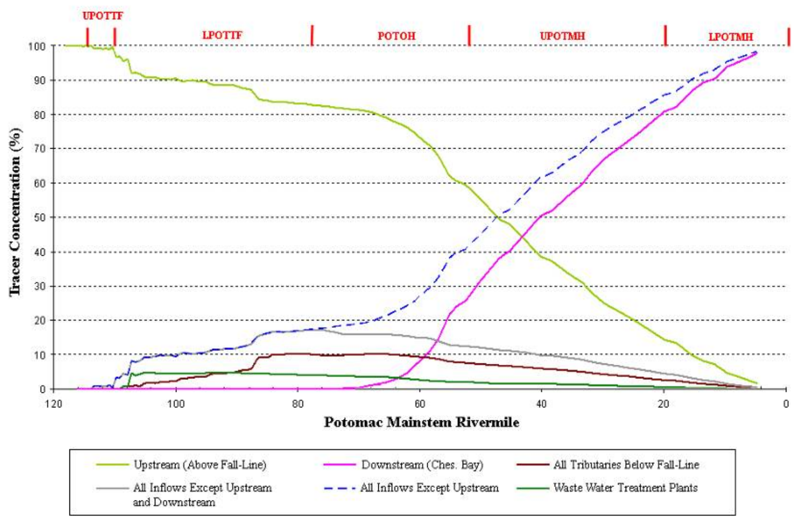


Figure 27. Potomac estuary salinity model results.
Potomac estuary salinity model results showing the relative impacts on a conservative tracer (salinity) of *average* flow from upstream (above fall-line), downstream (Chesapeake Bay), all Coastal Plain tributaries (below fall-line), and wastewater treatment plants (adapted from LimnoTech 2007). The upper boundary of Chesapeake Bay's influence ends at river mile 70, corresponding to Douglas Pt.

influencing biological communities throughout the estuary. Flow also affects circulation patterns in brackish waters and alters critical habitats and migratory paths for bottom fish species. If a strong pycnocline develops in Potomac mesohaline waters (>5 ppt salinity) following high flows, oxygenated waters in the upper layer cannot circulate downward past the pycnocline and respiration of abundant heterotrophs in the saltier bottom layer depletes oxygen faster than it can be replenished (Mann & Lazier 2006). This situation intensifies in summer and leads to hypoxia (<2 mg DO/liter) that persists in the bottom layer throughout summer (Kemp et al. 2005), especially when spring freshwater flows are high and bring additional nutrients into the estuary. Hypoxia impairs bottom habitats and blocks fish migration routes, and the chronic occurrence of hypoxia in bottom waters is a significant problem in the Potomac and in estuaries worldwide (Diaz 2001).

Small freshwater zones are also found in the tidal tributaries located between Morgantown and the Potomac's confluence with the Chesapeake Bay. Freshwater flow into tidal embayments is tidally mixed with brackish water intruding from the Potomac mainstem. The location of the tidal tributary salinity gradients reflects a balance between incoming freshwater and the relative strength of the tidal incursions from the mainstem.

Anthropogenic Impacts on Freshwater Flow to the Estuary

Surface and Groundwater Withdrawals

Freshwater withdrawals in 2005 averaged 3,871 cfs (2,502 mgd) in the Potomac River basin above Little Falls and 2,314 cfs (1,496 mgd) in the Coastal Plain watersheds below Little Falls (database assembled in 2009 by Jim Palmer, ICPRB). The combined total of 6,185 cfs (3,998 mgd) represents 43.3% of the estimated average 14,300 cfs (from Lippson et al. 1979) of surface freshwater flow entering the estuary from all streams and rivers in the basin. Overall, hydrologic impacts of upper basin withdrawals on the estuary are not large because 97.5% are from surface waters and much is returned to the basin's streams and rivers. An exception is the free-flowing Potomac River directly above the estuary head-of-tide. An average 574 cfs (371 mgd) is taken from this stretch of the river to supply the Washington, DC metropolitan area (2005-2008, pers. comm. S. Ahmed, ICPRB) and is returned to the estuary rather than the river. During dry periods, these withdrawals have a large impact on river flows in the several miles between the water supply intakes and the estuary head-of-tide, but do not substantially alter the total freshwater flow into the tidal fresh zone. The Potomac estuary also receives freshwater from an inter-basin transfer. Approximately 49 mgd withdrawn from the Patuxent River watershed is used to supply the Washington metropolitan area and most is released to the Potomac estuary.

In the Coastal Plain, the proportion of total withdrawals coming from surface waters ranges from 0% to 100% in individual watersheds. Groundwater withdrawals represent 80% - 100% of total withdrawals in the Piscataway, Machodoc, Wicomico, St Clements, Yeocomico, and St Marys watersheds. Freshwater flows to the estuary from these watersheds are thus significantly enhanced by discharges from groundwater sources, especially during dry periods. Groundwater is drawn from a stacked series of confined aquifers that slope gently downward to the east under the Coastal Plain (Vroblesky and Fleck 1991). Aquifer recharge areas parallel the east bank of the Potomac estuary, from WashingtonDC. to beyond Maryland Pt. Local water suppliers, state agencies, and the USGS are sensitive to the possibility of overdrawing the aquifers locally and of contaminating the waters that recharge the aquifers with chemical pollutants (e.g., Klohe and Kay 2007).

Consumptive Uses

Theoretically, water lost to consumptive uses could shift the average location of the estuarine salinity gradient upstream. Consumptive uses are water withdrawals that are "evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (USGS 1998). They are estimated to be less than a sixth of the average flow at any point throughout the upper basin (Steiner et al. 2000) and about 3.22% of the median flow at Little Falls (Appendix B **Table B-1**). Under drought conditions, consumptive use removes a greater proportion of the flow and can increase the frequency and duration of low flows at Little Falls (Steiner et al. 2000), which would tend to shift the salinity gradient upstream.

With one exception, estimates of consumptive use in the Coastal Plain fall between 0.02% (Yeocomico R., VA) to 4.78% (Mattawoman Cr., MD) of the tributary median flow. Consumptive use in the Occoquan R., VA, watershed, which straddles the Piedmont and Coastal Plain and which has a dam and water supply reservoir near its mouth, is 8.10% of the tributary median flow (Appendix B **Table B-1**). The percentages are greater under drought conditions when flow is low. Consumptive water losses in Coastal Plain watersheds can potentially affect tributary flow regimes and the location of the salinity gradient in tidal embayments. However, losses to surface flow in some tributaries are significantly ameliorated by additions from groundwater withdrawals.

Land Uses

Land uses in the areas immediately bordering the Potomac estuary have little, if any, effect on the amount of freshwater in the mainstem or the direction of water movement. Land uses above the reach of tides, however, affect hydrologies of the free-flowing waters that eventually drain into the estuary. Urbanization and the closely aligned percent of impervious surface decrease the duration of both high and low flow pulses and increase the high pulse count and the frequency of extreme lows. Forest cover increases low pulse duration, reduces high pulse count but increases high pulse duration, and reduces number of reversals. In Coastal Plain watersheds in and around the Washington, DC metropolitan area, urbanization, imperviousness, and forest loss are the most significant land uses affecting nontidal hydrologies. Land use impacts on nontidal riverine hydrology are being investigated in another ICPRB project, and final results are due in early 2012.

Water Quality

High freshwater flows into Chesapeake Bay and its major rivers usually carry higher concentrations of suspended sediments and nutrients than moderate or low flows (Boynton et al. 1995; Sprague et al. 2000). In the Potomac, suspended sediments tend to settle out in the freshwater and oligohaline reaches of the mainstem and sub-estuaries (Brush and DeFries 1981, DeFries 1986), although they can later be re-suspended and moved further downstream during high flow periods. Nutrients entering tidal waters that are not taken up by plants and bacteria continue to flow downstream and eventually mix with and enrich incoming salt water.

Water quality in the Potomac estuary mainstem is particularly impacted by freshwater flow due to the fact that the heavily urbanized Washington, DC metropolitan area is located at the estuary head-of-tide. Concentrated nutrients and sediment flow into the tidal fresh river from impervious surface runoff, combined sewer overflows, and waste water treatment plants. The effects on estuarine water quality of these direct loads under different flow conditions can be seen in longitudinal plots through the estuary (**Figure 28-31**). Water quality data for the indicated period of record were first split into three flow classes before station-specific medians were calculated. The three flow classes are seasonal, tributary specific flow characterizations based on the distribution of daily mean flows experienced during a baseline period with a wide range of flow conditions (Olson 1999). High flow is flow >67th percentile of the flow distribution for the season in a given tributary, moderate is 33rd–67th percentile, and low is <33rd percentile.

Low river flow results in a peak in nitrate (NO_3), the major component of total nitrogen, in the tidal fresh reach because less river water is diluting metropolitan area loads. High flow dilutes the NO_3 peak and pushes it downstream to the middle estuary (**Figure 28**). A longitudinal plot of ortho-phosphate (PO_4), or dissolved inorganic phosphorus, shows peaks at the fall-line and the middle estuary which are flattened by high flow. PO_4 concentrations under low flow conditions tend to be lower overall but not by much (**Figure 29**). Water clarity (Secchi depth), governed to a larger extent by suspended sediments and dissolved substances rather than phytoplankton photopigments (expressed as chlorophyll *a*), is poorer under low flow conditions in the Potomac (**Figure 30**). This is at odds with the usual case of high flows bringing higher sediment concentrations to tidal waters. It may be related to differences in the sources of turbidity under dissimilar flow conditions; it does not appear to be caused in a consistent manner by high concentrations of phytoplankton expressed as chlorophyll *a*. Bottom dissolved oxygen (DO) levels in the river's deep mid-channel during summer (June – September) shows similar longitudinal patterns under different flow regimes (**Figure 31**). In the tidal fresh, summers with low flow are associated with slightly lower DO levels, possibly reflecting the poorer water clarity in this reach which would impede photosynthesis and reduce daily oxygen production. As photosynthesizing organisms, phytoplankton and SAV are most directly impacted by the combined influences of nutrient concentrations and light conditions. Benthic macroinvertebrates, zooplankton, and fish are more affected by dissolved oxygen.

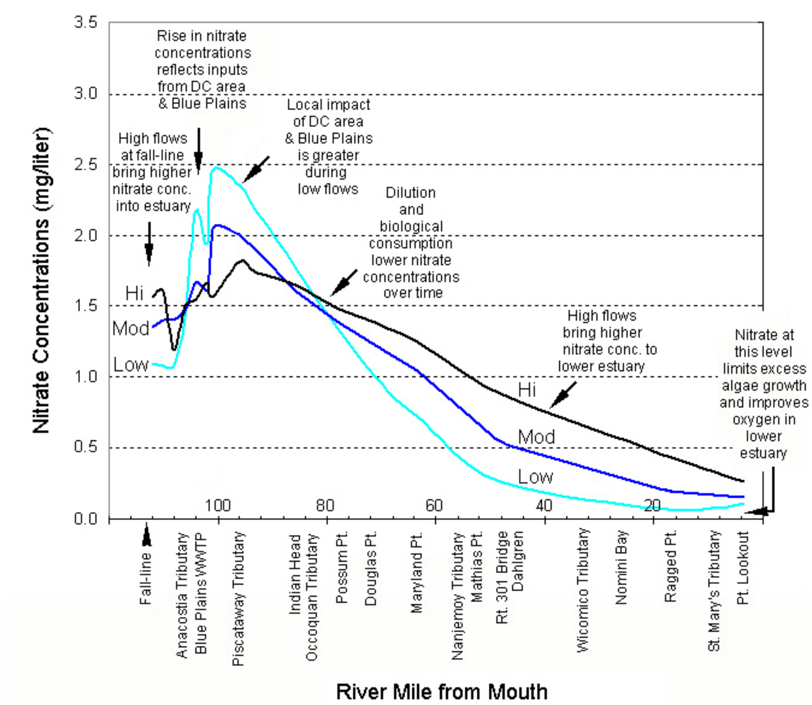


Figure 28. Average nitrate (NO3) concentrations in high, moderate and low freshwater flow conditions.

All seasons, 1990 – 1996, before Biological Nutrient Reduction (BNR) was incrementally implemented at the Blue Plains Wastewater Treatment Plant. Hi, seasonal Potomac freshwater flow is greater than the 67th percentile for the season; Mod, seasonal flow is between 33rd and 67th percentiles for the season; Low, seasonal flow is less than the 33rd percentile for the season. [Note: The large Blue Plains Wastewater Treatment Plant, located at the southern boundary of Washington, DC, incrementally implemented "Biological Nutrient Reduction" (BNR) between October 1996 and January 2005, significantly reducing effluent total nitrogen concentration from 14.6 to 5.6 mg/liter and nitrate from 13.0 to 3.3 mg/liter (data from Discharge Pt #2). Flow effects on river nitrogen concentrations can not be accurately determined yet for the post 2005 period.]

Water quality in Potomac tidal tributaries feeding into the river mainstem reflects a balance between Coastal Plain watershed nutrient and sediment loads and the quality of the adjacent mainstem water that is driven into the tributaries by tidal forces. Information about tidal embayment water quality can be gained by analyzing the states' fixed station monitoring data (available at www.chesapeakebay.net or the states' web sites), and the recently available "dataflow" data collected along multiple transects while the boat is underway and the continuous monitoring data collected at fixed sites at 15 minute intervals (http://www2.vims.edu/vecos/ and http://mddnr.chesapeakebay.net/newmontech/contmon/index.cfm.) An analysis of the 2004 – 2008 continuous monitoring data show that embayments can differ significantly from each other and from the adjacent Potomac mainstem (e.g., Buchanan 2009, Jones and Buchanan 2009). All embayments failed the states' instantaneous minimum dissolved oxygen criteria at some point in the 2004 – 2008 period, usually in summer. Many exceeded the instantaneous maximum pH criteria at some point, usually in spring. These failures and exceedances are linked directly or indirectly to eutrophication (nutrient enrichment) by the states in their 303(d) reports to the U. S. Environmental Protection Agency (Maryland Department of the Environment 2008, Virginia Department of Environmental Quality 2008).

Phytoplankton

These drifting, microscopic plant-like organisms inhabit surface waters of all open water environments and are usually the dominant primary producers supporting aquatic food webs. The short generation times of phytoplankton allow their populations to rapidly respond to changes in the surrounding water quality. Phytoplankton blooms in tidal fresh and estuarine waters have been linked to increased nutrientloadings resulting from higher flows (Bennett et al. 1986; Malone et al. 1988; Harding et al. 1999; Sellner and Fonda-Umani 1999).

Buchanan et al. (2005) examined the water quality responses of Chesapeake phytoplankton under different seasonal flow levels in order to determine if flow trumps the importance of water

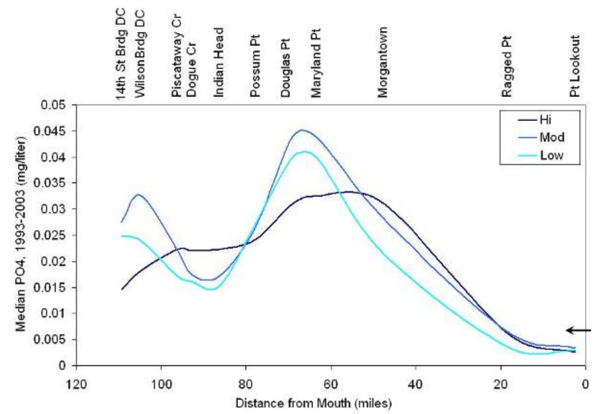


Figure 29. Median ortho-phosphate (PO_4) concentrations in high, moderate and low freshwater flow conditions.
April-October, 1993 – 2003. Arrow indicates threshold below which excess phytoplankton growth, or formation of algal blooms, is limited. See Figure 28 heading for details.

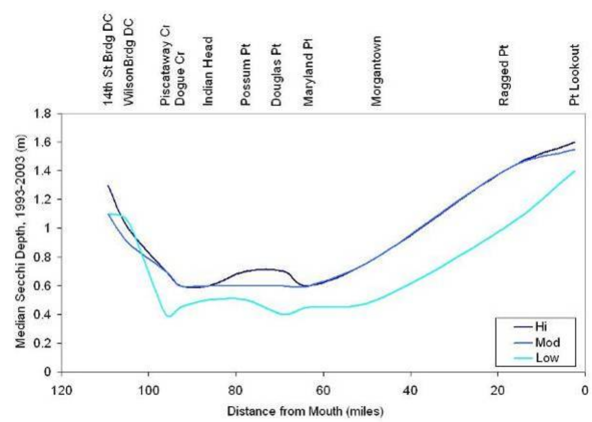


Figure 30. Median Secchi depths in high, moderate and low freshwater flow conditions.
SAV growing period (April-October), 1993 – 2003. See Figure 28 heading for flow details.

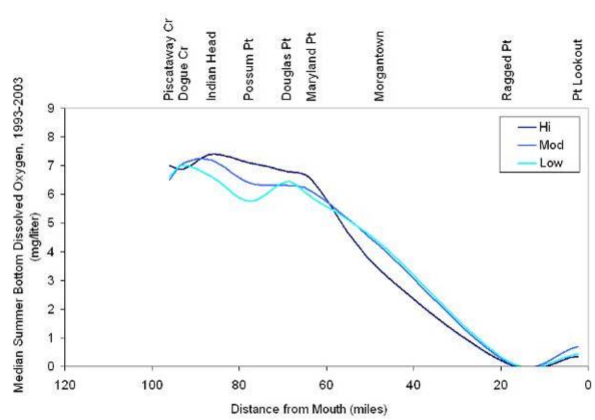


Figure 31. Median bottom dissolved oxygen concentrations, 1993 – 2003.
Summer (June-September), 1993 – 2003. See Figure 28 heading for flow details.

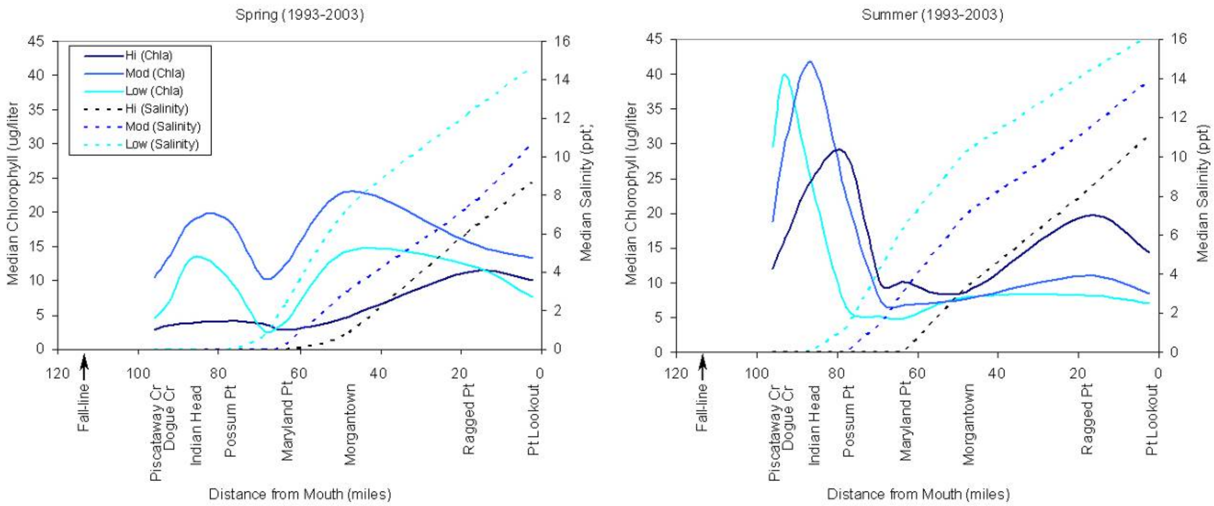


Figure 32. Median Spring and Summer Chlorophyll a (solid lines) and salinity (dashed lines), 1993-2003. Spring (March – May) and Summer (June – September).

quality. Estuarine species are normally found across wide ranges of salinity and temperature. However, seasonally distinct freshwater and brackish water communities occur. To reduce variability not related to water quality and flow, records were grouped by season and salinity zone. In each group, phytoplankton data were binned into one of six water quality categories depending on PO_4 and dissolved inorganic nitrogen (DIN) concentrations and Secchi depth. Within each season and salinity zone group, the chlorophyll *a* concentrations in the water quality categories were in most cases statistically different. Data in each season-salinity zone-water quality category were further split into five flow classes: very high, high, moderate, low, and very low flow. The five flow classes are seasonal, tributary specific flow characterizations based on the distribution of daily mean flows experienced during a baseline period with a wide range of flow conditions (Olson 1999). Very high is flow >90th percentile of the flow distribution for the season in a given tributary, high is 67th–90th percentile, moderate is 33rd–67th percentile, low is 10th–33rd percentile, and very low is <10th percentile.

In the mesohaline (5-18 ppt) and polyhaline (>18 ppt) salinity zones of the Chesapeake system, flow per se had little or no direct effect on phytoplankton abundance, expressed as chlorophyll *a* (chl *a*) concentration. Median chl *a* concentration in 85% of the flow classes varied less than 2 μg/1 from the overall medians for each respective season-salinity zone-water quality categories (Buchanan et al. 2005). In these high salinity zones, freshwater flow appeared to indirectly influence chl *a* by changing the water quality conditions and flow did not alter the actual phytoplankton responses to water quality. In tidal fresh reaches, flow effects on phytoplankton and chl *a* were more evident. Median and maximal (95th percentile) chl *a* concentrations were lower regardless of water quality category when flow was high, and peaks were located further downstream. This reflects the hydraulic force and dilution potential of freshwater flow pushing tidal fresh water rapidly downstream.

The Chesapeake Bay Program rates status of phytoplankton communities with the Phytoplankton Index of Biotic Integrity (PIBI). The index is comprised of between 5 and 9 phytoplankton community metrics sensitive to water quality condition, one of which is chlorophyll *a* (**Figure 32**). Others include the ratio of chlorophyll *a* to carbon (an indicator of low light stress), pheophytin, and the biomasses of important taxonomic groups. Metrics are scored on a scale of 1 – 5 according to how similar they are to a season- and salinity-specific reference (least-impaired) community, and the PIBI is the average of the metric scores. The CBP goal is for all PIBI index scores to pass 3 or better on the scale of 1 – 5 (CBP) 2009a). Since 1985, the Potomac PIBI has shown a lot of variability but no consistent trend (**Figure 33**).

PIBI scores tend to reflect flow-driven changes in the frequencies of the six water quality categories used to characterize phytoplankton habitat (above), although hydraulic forcing in the tidal fresh reaches and weather variables such as available sunshine also affect the scores. Categories representing desirable phytoplankton habitat conditions have concentrations of one or more nutrients low enough to limit algal bloom formation and water clarity that is adequate for unstressed photosynthesis. Undesirable conditions have excess nutrient concentrations and poor water clarity. Cells in this habitat type have increased their chlorophyll content to compensate for the overall poorer light environment and, because of high nutrient concentrations, can rapidly form "blooms" when currents incidentally expose them to higher light levels. The blooms are often composed of opportunistic species that produce toxins or offer marginal food quality to grazers. Worst conditions are the extreme case, where water clarity is so poor it can depress phytoplankton abundance. Timing of high flow events is important and can affect annual PIBI scores. Of the six "wet" years indicated in **Figure 33**, 1993, 1994, 1998, 2003, and 2004 had high flows in one or more seasons and the frequency of passing PIBI scores were lower, ranging from 9.1% - 36.4%. In 1996, every season except spring had record high flows, and all PIBI scores failed that year in the tidal fresh reach.

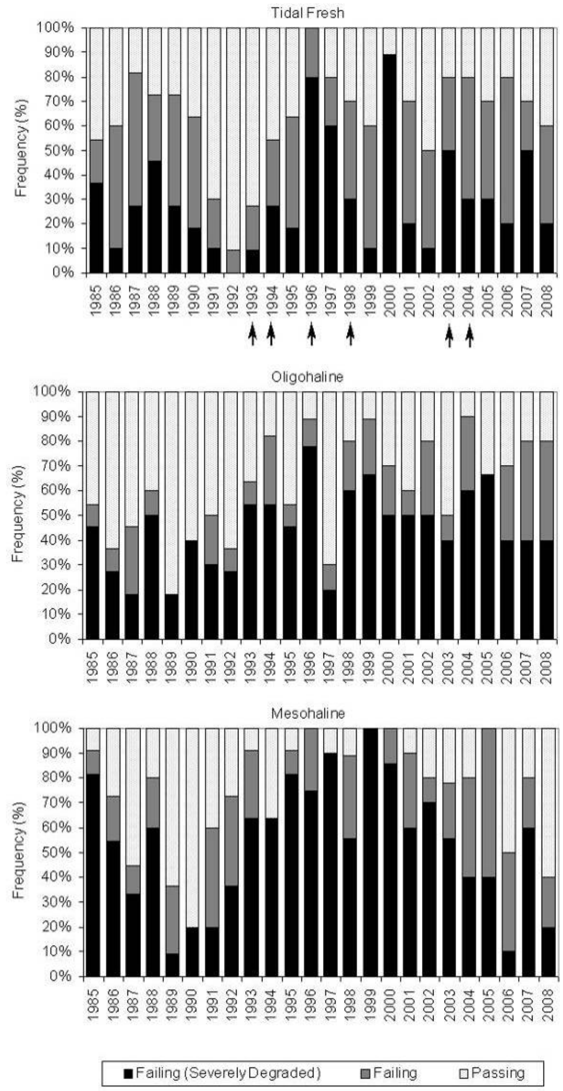


Figure 33. Time series of the Phytoplankton Index of Biotic Integrity (PIBI), 1985 – 2008.
Phytoplankton Index of Biotic Integrity (PIBI), 1985 – 2008, expressed as percent of Potomac River estuary phytoplankton community passing or failing an index score of 3 on a scale of 1-5. Samples are collected at three fixed stations: tidal fresh station TF2.3 (Indian Head); oligohaline station RET2.2 (Maryland Pt); mesohaline station LE2.2 (Ragged Pt). Arrows indicate wet years. Drought occurred 1999-2002.

Desirable phytoplankton habitat conditions tend to prevail in the swift-moving Washington, DC stretch of the river under low seasonal flows. This is primarily due to relatively low PO_4 concentrations—a result of the 1980s phosphorus bans—and good water clarity in the free-flowing river upstream under low flow conditions. Moderate and high flows increase nutrient and sediment concentrations in the free-flowing river above the fall-line and significantly reduce the frequency of desirable phytoplankton habitat conditions in Washington, DC. Below the District, desirable conditions rapidly disappear regardless of flow as first nitrogen and then PO_4 concentrations climb and water clarity degrades (**Figures 28-30**). Undesirable and worst habitat conditions prevail in the stretch between Piscataway Creek and the tidal fresh downstream boundary.

Management actions to reduce nutrient and sediment loads entering the Potomac estuary are changing the longitudinal profiles. Theoretically, flow alteration in the form of less river water entering the estuary might at some point increase the frequency of desirable habitat conditions for phytoplankton in the tidal freshwater reach near present-day Washington, DC and possibly reduce the frequency of "worst" conditions along the length of the estuary. Countering these potential benefits would be the loss of freshwater volume as the average salinity gradient shifts upstream. Tidal fresh phytoplankton abundances increase with growth and reproduction as cells drift downstream from D.C. Peak abundances typically occur 5-20 miles upstream of the salt wedge. A persistent loss of freshwater flow will reduce the importance of the tidal fresh phytoplankton community relative to the brackish water community located below the salt wedge. The impact of such a shift on the estuarine food web is not clear, but may not be important given the salinity tolerances of certain estuarine species that graze on phytoplankton, such as the zooplankter *Eurytemora affinis*.

Submerged Aquatic Vegetation (SAV)

The 20 or so SAV species reported in the tidal Chesapeake system are responsive to the same factors governing phytoplankton, namely light and nutrients. They are also regulated by temperature, salinity, substrate (sediment) type, water currents in their shallow environments, periphyton growth on their leaves, and grazers (Batiuk et al. 1992). The plants emerge each year from rhizomes, tubers, and seeds overwintering in nearshore sediments (Hurley 1991). Most SAV species grow best in low salinities (<6 ppt) but can tolerate exposures as high as 14 ppt. Four species are euryhaline and one–eelgrass—prefers high salinities (Bergstrom et al. 2006). Scouring and wave action during high flow events can dislodge SAV and suspended sediments can coat the leaves and cloud the water, impairing photosynthesis. Tropical Storm Agnes in June 21-27, 1972, which delivered 16.5x the normal flow over the course of a week, caused long-term damage to many Chesapeake SAV populations already weakened by eutrophication, invasive species, and/or disease (Kerwin et al. 1977) and brought about a regime shift in the Chesapeake Bay ecosystem according to some researchers. Potomac SAV populations began to recover in the early 1980s but large storm events, higher turbidity levels, and potentially other factors (Moore and Jarvis 2008) have slowed the improving trends (**Figure 34**).

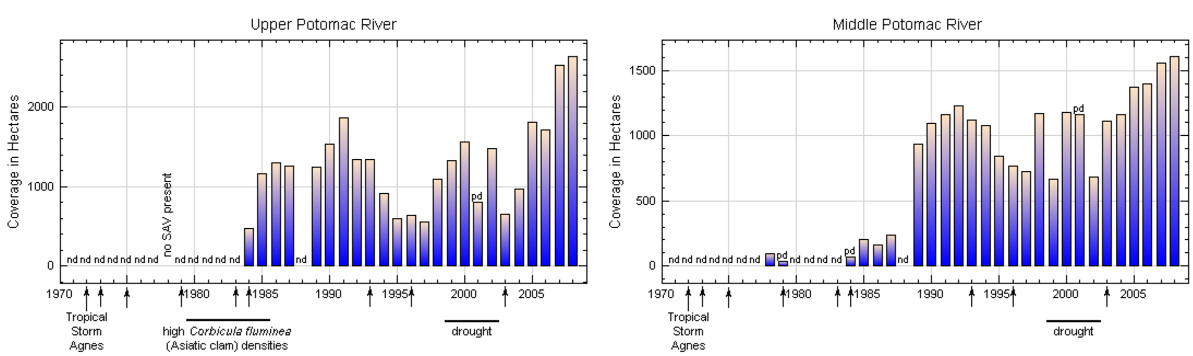


Figure 34. Time series of submerged aquatic vegetation (SAV) coverage in the upper and middle Potomac River estuary, 1978 – 2008.

Time series of submerged aquatic vegetation (SAV) coverage in the upper (fall-line to Indian Head) and middle (Indian Head to Morgantown) Potomac River estuary, 1978 – 2008, from http://web.vims.edu/bio/sav/?svr=www. Earlier observations and surveys indicate SAV was absent from the upper Potomac after the 1950s, well before Tropical Storm Agnes impacted other SAV beds in the Chesapeake. SAV began to return to the upper Potomac in 1982 (Carter and Rybicki 1986). Years with wet springs and summers are noted with arrows (1972, 1978, 1984, 1993, 1996, 2003); pd, partial data; nd, no data.

Light is the primary factor regulating Potomac estuary SAV and acts both directly and indirectly on the plants, with multiple feedback loops (Carter et al. 1998). River discharge is an important factor controlling Potomac tidal fresh and oligohaline SAV in that it affects light penetration in the water column via its effect on suspended sediments, nutrients concentrations, phytoplankton, and other variables (Carter and Rybicki 1990, Carter et al. 1994, Carter et al. 1998, Landwehr et al. 1999). The complexity of the relationships between SAV and twelve internal and external controlling factors is diagramed in **Figure 35** and discussed in Carter et al. (2000). These authors compared the explanatory power of these 12 factors with that of the five parameters used by the CBP to characterize desirable SAV habitat, namely light attenuation (Secchi depth), chlorophyll *a*, dissolved inorganic nitrogen, dissolved inorganic phosphorus, and TSS (Batiuk et al. 2000).

In the tidal fresh reach, Carter et al. (2000) found SAV increased during periods when the five parameters of the CBP habitat requirements for SAV were generally satisfied, and SAV declined during periods when three of them—TSS, Secchi depth, and/or chlorophyll *a*—failed the requirements. The CBP habitat requirements seem to adequately characterize the tidal freshwater SAV habitats. TSS, Secchi depth and chlorophyll *a* all co-varied strongly with flow and other external variables (e.g. chlorophyll *a* co-varies with available sunshine in high flow years). Relationships in the upper half of the tidal fresh reach, from the fall-line to Dogue Creek, and in the lower half, from Dogue Creek to Possum Pt, followed the same general pattern but had different regression coefficients. Thus, relationships between SAV and the dominant controlling factors vary depending on location in the Potomac estuary. The upper and lower tidal fresh river segments differ in their general morphology, with the upper half being narrower and swifter than the lower half.

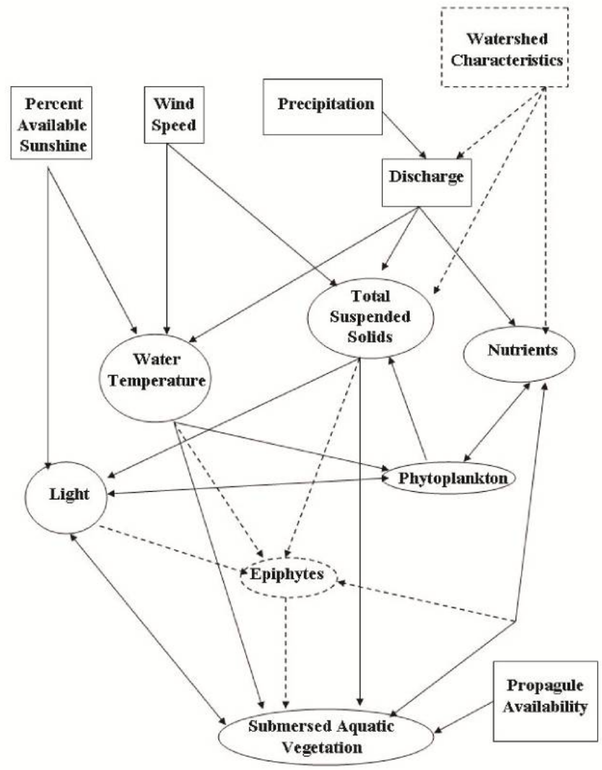


Figure 35. Model of interrelationships of SAV with selected chemical, physical, and biological factors.
Model of interrelationships of submersed aquatic vegetation (SAV) with selected chemical, physical, and biological factors. External and internal variables are shown in rectangles and ellipses, respectively. Relationships involving either watershed characteristics or epiphytes are shown with dashed lines. (adapted from Carter et al. 2000).

Xi et al. (2007) explored the effects on SAV of watershed and estuarine characteristics in 101 shallow sub-estuaries (embayments) of Chesapeake Bay from1984 - 2003. They were looking for watershed and estuarine drivers or correlates of nearshore water quality, expressed as SAV abundance. Using change point analysis, the researchers identified significant shifts in SAV abundance at values above a watershed area to subestuary area ratio of 3.7, 39 septic system per km^2, 17.6 kg km^{-2} day^{-1} total nitrogen load (watershed dominated by developed land), and 1.3 kg km^{-2} day^{-1} total phosphorus load (watershed dominated by developed land and mixed-land use). Using Category and Regression Tree (CART) analysis, they identified combinations of five factors that explained 49% - 60% of the variation in SAV abundance. Four were estuarine (subestuary shape complexity, mean tidal range, the ratio of watershed to subestuary area, and mean wave height) and only one was a watershed factor (land cover). Forested watersheds overall had higher SAV abundances. SAV abundance was higher in dry years than in wet years in subestuaries dominated by agriculture or developed land, but higher in wet years in subestuaries dominated by forests. This contrast likely reflects land cover differences in nutrient and sediment yields for wet, average and dry periods.

Again, flow alteration in the form of less river water entering the estuary could theoretically improve habitat conditions for SAV in the Potomac upper tidal fresh reach, assuming low flows create improved water quality conditions in shallow, nearshore waters. (Note: **Figure 30** reflects mid-channel conditions in the mainstem.) Low flows would constrict the tidal fresh reach by shifting the salinity gradient upstream. SAV species not tolerant of higher salinities would be forced to relocate upstream. A persistent loss of freshwater flow could reduce the importance of the more diverse tidal fresh SAV community relative to the brackish water community.

Zooplankton

Zooplankton constitute an important food web link between primary producers and the fish and other organisms at the upper end of the trophic pyramid. In addition to nurturing planktivorous fish, zooplankton are particularly valuable to larvae and smaller stages of valuable sport and commercial fish which will become piscivores when they mature. Zooplankton in a tidal system subject to appreciable freshwater input must deal with the downstream movement and mixing of incoming freshwater with the more saline marine system. Due to its elongate nature and relatively high freshwater inflows, the Potomac estuary has an extensive tidal freshwater segment that allows development of a robust freshwater zooplankton community including rotifers, cladocerans, and freshwater copepods. These populations have been extensively documented in numerous studies. A summary of Chesapeake Bay mesozooplankton monitoring data including stations in the tidal Potomac from the collections in the 1985-2000 indicated a diverse community with high abundances relative to other Chesapeake Bay tributaries (Versar and PBS&J 2001). Most abundant taxa were the cladocerans *Bosmina longirostris*, *Diaphnosoma leuchtenbergianum*, and *Moina micrura*; cyclopoid copepods *Cyclops bicuspidatus*, *Mesocyclops edax*, and *Cyclops vernalis*; and the calanoid copepod *Eurytemora affinis*.

In a long term study of Gunston Cove and the nearby Potomac mainstem, the small-bodied rotifers have attained the highest densities. Mean rotifer densities in the river mainstem over the period 1990-2008 were several hundred per liter with median values in the shallower cove approaching 1000/L. These densities indicate a very productive rotifer community. Likewise, large numbers of freshwater cladocerans and copepods are found (**Table 10**). *Bosmina*, a small cladoceran, has mean densities of 30 per liter in the cove and 57 per liter in the river over this period while the early larval stage of copepods know as nauplii have averaged 67 per liter in the cove and 100 per liter in the river over the period. Of the larger adult cladocera *Diaphanosoma* is most common averaging 3/L in the cove and 1.5 per liter in the river while adult and subadult (copepodid) calanoid copepods averaged 2.7 in the cove and 2.6 in the river. *Eurytemora affinis* was the dominant calanoid in this study.

Table 10. Average zooplankton densities (#/liter), 1990-2008. Gunston Cove Study.

Zooplankton	River	Cove
ROTIFERS		
Brachionus	136	541
Conochilus	60	65
Filinia	24	154
Keratella	182	193
Polyarthra	59	104
Synchaeta	27	66
Trichocerca	26	44
CLADOCERA		
Bosmina	57	30
Diaphanosoma	1.5	3
Daphnia	0.1	0.2
Leptodora	0.1	0.3
COPEPODS		
Nauplii	100	67
Cyclopoids	1.5	0.7
Calanoids	2.6	2.7

Being plankton, the horizontal distribution of these organisms is controlled mainly by current. The larger crustaceans do have a distinct ability to migrate vertically and many have been shown to effectively do this on a diel (24 hour) basis. Generally, there is a net movement to lower layers during the day and back to upper layers at night. This has been conceptualized in the limnological literature as a response to conflicting demands of feeding and predator avoidance. The food of herbivorous zooplankton is phytoplankton which will grow most successfully in the upper, lit layers of the water column. However, zooplankton residing in this portion of the water column will experience enhanced predation by visual predators like fish. The diel migration pattern discussed above would be an effective trade-off: food collection in the upper layer at night to minimize predation losses.

Working against this explanation in the tidal freshwater Potomac is the totally mixed nature of the water column, particularly in the river mainstem, due to tidal currents. Thus, the ability to effectively migrate vertically in the river mainstem is being continually disrupted by strong tidal mixing currents. Consistent with this assertion, Buchanan and Schloss (1983) were unable to demonstrate diel vertical migratory patterns in most tidal fresh taxa in the Potomac River. The exception was *Eurytemora affinis*.

As a freshwater parcel with its associated zooplankton reaches the salt water interface and mixing begins, those zooplankton intolerant of salinity will start to die off. Since most freshwater zooplankton are very intolerant of salinity, it is not surprising that their densities drop off rather dramatically at relatively low levels of salinity. Maps in Lippson et al. (1979) suggest that freshwater rotifers and cladocera start to decline at about 0.5-1.0 ppt and are virtually absent when salinity reaches 5 ppt. Since water containing these organisms is moving into the brackish waters and mixing with them and zooplankton have limited migratory ability, this implies extensive mortality of these organisms at the salt/fresh interface.

As the fresh water encounters the more saline brackish water, mixing is not immediate. Rather, the fresh water tends to override the heavier, more saline brackish water creating a stable vertical stratification. The freshwater layer tends to flow out toward the ocean, while the lower more saline layer has a net upriver flow along the bottom. Zooplankton that can withstand moderate levels of salinity like *Eurytemora* can use the stratification pattern to maintain their position in the estuary. By alternating between feeding in the surface freshwater layer where phytoplankton production is greatest and riding upstream in the lower layer, they can minimize population losses downstream and stay in a zone of optimal salinity.

The location of the relevant transitions in salinity then becomes very important for the distribution and ecology of zooplankton in the tidal freshwater and oligohaline portions of the tidal Potomac River. The principal boundary of interest is the 0.5 ppt, commonly identified as the boundary between tidal freshwater and oligohaline. Upstream of this boundary, the water column is well-mixed and freshwater zooplankton are free to develop independent of salinity constraints. Downstream of this boundary, salinities start to pick up in general and salinity stratification starts to become more important.

The location of the 0.5 ppt isohaline is depicted monthly on a series of maps by Lippson et al. (1979). The 0.5 ppt isohaline is pushed downriver in the late winter and early spring and reaches the mouth of Aquia Creek (Mile 60 from the mouth or 39 miles downstream of Chain Bridge) by May of a typical year. This is due to the effect of increasing freshwater discharge at the fall line which seasonally peaks in March. As average fall line discharge subsides during the summer and early fall, the location for the 0.5 ppt isohaline gradually moves back upstream and can reach just upstream of Indian Head (Mile 75 from the mouth or 24 miles downstream of Chain Bridge) by September. Thus, the habitat available to freshwater zooplankton shrinks in distance by about 1/3. However, given the much large volume of the lower part of this reach, the actual freshwater habitat volume in September turns out to be only about 1/3 of what it was in May. Lower summer discharges which might result from increasing diversion or consumptive use of the Potomac's freshwater flow would further exacerbate this shrinkage.

Benthic Macroinvertebrates

Benthic macroinvertebrates are a taxonomically diverse group of organisms larger than 0.5 mm that includes clams, oysters, crabs, worms, snails, sponges, hydroids, sea squirts, and shrimp-like crustaceans called amphipods. They are important as consumers of organic matter in the bottom layer, and as food sources for many fish and waterfowl. Benthic macroinvertebrates can live in bottom sediments (infauna) or on sediments and hard surfaces (epifauna). Most feed selectively on settled or buried food particles (deposit-feeders) or strain suspended food particles from the water (filter-feeders). Some have limited mobility their whole lives; some have planktonic life stages that can drift with currents over significant distances before settling to a permanent location on the bottom; and others are able to migrate into the water column at night, to search for food while avoiding predators. Benthic macroinvertebrates have evolved a wide variety of behavioral, morphological, and physiological adaptations to withstand the environmental stresses they are exposed to living in an estuary, especially low dissolved oxygen, and most can tolerate fairly wide ranges of salinity (Lippson et al. 1979, Day et al. 1989). Dauer et al. (1993), Weisburg et al. (1997), and other investigators have qualitative and quantitative described desirable benthic communities for the Chesapeake Bay system. From this, a Benthic Index of Biotic Integrity (BIBI) was developed and is now routinely used to evaluate Bay responses to restoration activities (e.g., CBP 2009a).

The critical life stage of many estuarine benthic macroinvertebrates is the larval stage. A diversity of parental and larval adaptations help larvae encounter suitable habitats where they are more likely to survive. Mechanisms include parental brooding, the ability to delay metamorphosis and settling until a suitable habitat is encountered, and sensitivity to light, temperature, current, and chemical cues in the environment. Salinity, substrate type, currents, dissolved oxygen concentrations and pollutant concentrations in the tidal Potomac initially affect the densities and distribution of benthic communities, which are then further shaped by competition for food, predation, and disease. Since many benthic macroinvertebrates do not move far after they settle to the bottom, any local change in the environment that exceeds tolerance limits can eliminate a population.

Salinity and substrate type are the primary factors governing the distribution and composition of estuarine benthic macroinvertebrates when other factors are not limiting. Communities in the tidal fresh reach of the Potomac are composed of taxa physiologically adapted to fresh water, or 0 ppt salinity, but most are able to withstand salinities ranging up to 5 ppt. and a few (*Rangia cuneata* (brackishwater clam), *Congeria leucopheata* (Conrad's false mussel)) can tolerate higher salinities (Appendix Table 5 in Lippson et al. 1979). Communities inhabiting mud sediments are dominated by deposit-feeding infauna that benefit from the mud's higher carbon content and bacterial abundances. Some tube-forming deposit feeders are also successful in sand substrates in the Potomac because the water is sufficiently enriched with organic particles. Filter-feeding infauna tend to dominate in sandy sediments where resuspended mud does not interfere with or obstruct their filtering appendages (Day et al. 1989, Appendix Table 5 in Lippson et al. 1979). Filter-feeding epifauna would normally be abundant on hard substrates such as oyster reefs or rock, but in the Potomac much of these substrates have either been harvested and/or buried by sedimentation. In each community, there are also a variety of mostly larger sized, predatory or omnivorous taxa such as the blue crab (*Callinectes sapidus*), sand shrimp (*Crangon septemspinosa*), and mantid shrimp (*Squilla empusa*), which are in turn prey to many fish species.

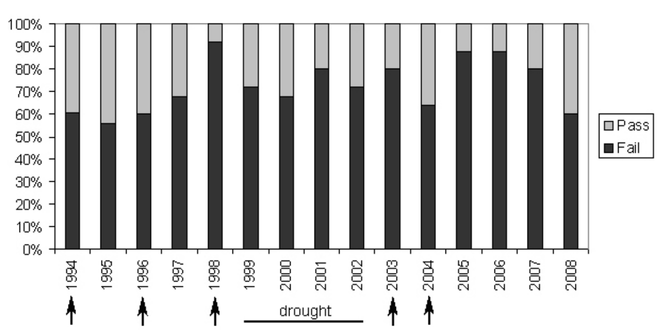


Figure 36. Time series of the Benthic Index of Biotic Integrity (BIBI), 1994-2008.
Time series of the Benthic Index of Biotic Integrity (BIBI), 1994 – 2008, expressed as percent of Potomac River estuary bottom community passing or failing an index score of 3 on a scale of 1-5. Arrows indicate wet years. drought occurred 1999 – 2002. Samples were collected using a random stratified sampling design.

Approximately 80% of the Potomac estuary bottom area failed the CBP restoration goal in 2007 (**Figure 36**), and severely degraded and depauperate benthic communities occur often in the lower estuary - the result of prolonged stress by summer hypoxia/anoxia in bottom waters (Llansó et al. 2008). In the tidal fresh and oligohaline Potomac estuary, excessive abundances and biomasses of benthic organisms indicate poor water quality caused by nutrient over-enrichment, or eutrophication (Llansó et al. 2008). These strong responses to low dissolved oxygen and eutrophication in the Potomac estuary make it difficult to detect organism responses to salinity changes related to flow. The earlier and stronger salinity stratification in the lower estuary that results from high flow events often leads to a larger "dead zone" of hypoxic/anoxic bottom waters. However, this salinity effect can not be separated from the impacts of the higher nutrient and sediment loads carried by the same high flow events.

Benthic macroinvertebrate communities inhabiting the tidal fresh Potomac have changed dramatically since the pre-Colonial period. Sandy bottom habitats in the tidal fresh and oligohaline were overcome by mud and silt loads from the watershed settling out of the river water. The huge populations of fish anecdotally recorded in the Colonial period likely depended on significant epibenthic populations of macroinvertebrates for food. Today's monitoring data indicate macroinvertebrate populations in the Potomac mainstem are typically infauna living in soft muds. The resurgence of SAV in Potomac shallow water environments is encouraging larger epibenthic populations.

Several introduced species have successfully colonized the Potomac River and are now integral members of the benthic community, including the brackishwater clam *Rangia cuneata* and the Asiatic clam *Corbicula fluminea*. *Corbicula* was initially detected in the tidal fresh Potomac River estuary in 1975 (Dresler and Cory 1980). The subsequent resurgence of SAV and disappearance of a bottom dissolved oxygen "sag" below Indian head have been attributed in part to very high *Corbicula* abundances in the 1980s and 1990s (**Figure 37**) (Cohen et al. 1984, Phelps et al. 1994).

As with phytoplankton, SAV, and zooplankton, the direct impacts of flow regime are hard to discern because the impacts of eutrophication are more immediate and detrimental. Estuarine benthic macroinvertebrates have evolved multiple, diverse adaptations to a wide range of salinity and substrates. Under improved water quality conditions, these taxa would acclimate easily to changes in flow regime. Low flows will constrict the tidal fresh reach by shifting the salinity gradient upstream, and a persistent loss of freshwater flow could reduce the relative importance of the tidal fresh benthic macroinvertebrate community.

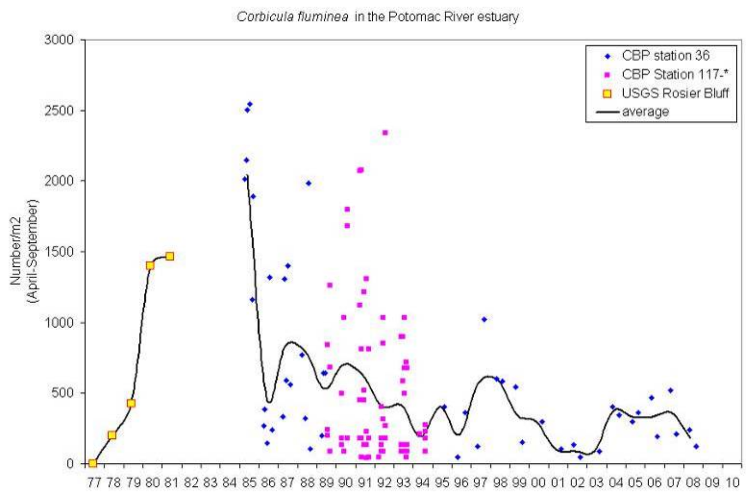


Figure 37. Time series of seasonal abundance of *Corbicula fluminea* (Asiatic clam).
Time series of seasonal (April-September) abundance of *Corbicula fluminea* (Asiatic clam), an introduced species initially detected in the tidal fresh Potomac River estuary in 1975 (Dresler and Cory 1980). Samples were collected at fixed stations downstream of Washington, D.C. in the tidal fresh zone. USGS Rosier Bluff data from R. Cohen.

Fishes

Over seasonal time scales, zoogeographic ranges vary in concert with changes in freshwater flow that limit the upstream movements of marine fishes or seaward expansion of freshwater fish. The volume and quality of available freshwater habitat can have strong effects on growth, mortality and reproduction, directly affecting population dynamics of valuable fisheries. Species that are perhaps the most sensitive to changes in flow are the anadromous fish that seasonally migrate from the ocean through the estuary to spawn in freshwater. Anadromous migrations in the Potomac occur during spring when freshets and rising temperatures generate favorable conditions for growth and survival of early life stages. Due to a natural barrier, Great Falls, the anadromous spawners are restricted to a short stretch of free-flowing river below Great Falls and to the tidal fresh mainstem (**Figure 1**). They also migrate up the smaller tidal freshwater tributaries of the Potomac until natural or artificial blockages stop them. While the upstream limits of migration are relatively fixed, the volume of tidal freshwater—and the available spawning habitat—is determined by the downstream position of the salt wedge.

Larval survival is often closely coupled with physical processes of estuarine circulation. Pelagic larvae of anadromous species maintain their spatial position in suitable habitats by migrating vertically between the surface layer which moves in a net downstream direction and the bottom layer which moves in a net upstream direction. The weak estuarine circulation patterns characteristic of low flow conditions are unfavorable for retention within larval nursery areas and decrease feeding opportunities. Seasonal changes in freshwater flow also have manifold effects on larval and juvenile habitats, such as oxygen concentration in benthic habitats and the growth of submerged vegetation. Effects of these changes on juvenile fishes vary by species according to their unique life history adaptations and physiological sensitivities to water quality. The potential effects of low freshwater flow on sturgeons (Atlantic and shortnose) and temperate sea basses (striped bass and white perch) were examined. These groups have contrasting life history characteristics (**Table 12**), exhibit widely varying current population sizes, and support either currently or historically significant fisheries.

Sturgeon are long-lived, slow growing, highly fecund, large, benthic fishes that supported significant and highly valuable caviar fisheries in the Chesapeake bay during the early 19th century. Around the turn of the 19th century, rangewide catches of Atlantic sturgeon exceeded 3200 metric tons, and numbers in Chesapeake Bay have been approximated at more than 20,000 spawning adults during this time (Secor 2002). Due to several factors including overfishing, and habitat degradation, Atlantic sturgeon are now either extirpated or persist in extremely low numbers in tributaries of Chesapeake Bay (Secor 2002). Atlantic sturgeon have been protected by a fishing moratorium since 1998, but still only small relict populations persist in a few tributaries of Chesapeake Bay (Grunwald et al. 2008). Shortnose sturgeon populations have undergone similar declines, and they are listed under the endangered species act to protect the remaining populations (Kynard 1997). Although a shortnose sturgeon was recently captured in the Potomac River, it was determined to be a stray individual from the Delaware population that probably migrated through the C&D canal (Grunwald et al. 2002). More recently, two adult shortnose sturgeon were captured and tracked in the Potomac River to understand seasonal movements, providing some hope that the species could recover within this system (Kynard et al. 2009)

Habitats for both sturgeon species overlap in oligohaline and tidal freshwater habitats (Wilson and McKinley 2004). Atlantic sturgeon utilize freshwater habitats for spawning, a wide range of estuarine habitats as small juveniles, and live in coastal marine habitats as large juveniles and adults. Shortnose sturgeon are limited to oligohaline and freshwater habitats throughout their lives. Both species require suitable coarse grained substrate and moderate to high water velocities to deposit eggs. Episodic high flows remove fine sediments and deposit new coarse grained sediments to the spawning grounds, which may contribute to hatching success of eggs. Hatchlings occupy deep channels and juveniles spread out into shallow habitats throughout the estuary, gradually occupying deeper and more saline regions as they grow. Juvenile growth is rapid, and requires access to a variety of benthic habitats as they forage for epifauna and benthic invertebrates.

Although it is clear that the most important factor in the decline of sturgeons in Chesapeake Bay was overfishing, stocks have not shown signs of recovery since fishing was curtailed. One of the key factors that may prevent a recovery of sturgeon populations is seasonal hypoxia in bottom waters. Sturgeon are more sensitive to low oxygen conditions than most other estuarine fishes, with acute and lethal effects that begin to occur at concentrations <3.3mg/L (Niklitschek and Secor 2009a). In addition, low oxygen interacts with high temperature by increasing routine metabolism. These effects can be modeled to predict bioenergetic growth potential across the entire Chesapeake Bay, and reveal that summer conditions restrict available habitat for sturgeon to oligohaline and shallow mesohaline areas (Niklitschek and Secor 2005; Niklitschek and Secor 2009b). In wet years, low salinity areas support positive growth potential based upon bioenergetic models, meaning that with sufficient forage the biomass of a cohort of juveniles would increase throughout the summer. During low flow conditions, these same areas have negative growth potential, meaning that cohort biomass could decline through summer leading to recruitment failure. As increasing temperature exacerbates the effects of low oxygen for sturgeon, predictions of climate change for Chesapeake Bay (Najjar et al. 2010) indicate that the extent of suitable summer time habitat for juvenile sturgeon in Chesapeake Bay would tend to decrease and the frequency of years with overall negative growth potential would also increase.

Temperate sea basses in the Potomac River are white perch (*Morone americana*) and striped bass (M. saxatilis). Currently, both species are at high population levels, and in particular, striped bass have recovered rapidly over that past 2 decades from being highly overfished during the 1990s (Secor 2000a). Similar to Atlantic and shortnose sturgeon, striped bass and white perch migrate to tidal freshwater areas for spawning, and a significant period of early life history takes place in oligohaline habitats. White perch are smaller, mature earlier and deposit demersal eggs closer to the head of tide than striped bass, which release pelagic eggs, but these species are similarly influenced by environmental factors and abundances at each life stage frequently exhibit strong correlations within and between sub-estuaries of Chesapeake Bay (Kraus and Secor 2005b; Wood and Austin 2009). Whereas adult white perch migrate to deeper brackish portions of the estuary during non-reproductive periods, adult striped bass typically undertake long coastal migrations. These stereotypical anadromous migration patterns are variably expressed among individuals, as both species have significant portions of adults that are resident in natal freshwater areas (Secor and Piccoli 2007; Kerr et al. 2009). Thus, freshwater flow impacts can have a disproportionate effect on the resident sub-populations. For both species, the timing and success of spawning is closely linked with physical processes that occur during spring.

The timing of upstream spawning runs and spatial distribution of eggs and larvae is frequently and widely mis-matched with optimal conditions for recruitment due to inter-annual variability in spring time freshwater flow events (Ulanowicz and Polgar 1980), but protracted spawning seasons and long iteroparous reproductive lifespans tend to ensure recruitment success through spatial and temporal bet-hedging strategies (Secor 2000b). A large amount of early larval mortality is due to spring storms that dramatically reduce water temperatures reducing larval growth and influencing size based mortality effects (Rutherford and Houde 1995). Warmer spring water temperatures that coincide with reduced freshwater flows and high levels of zooplankton food resources tend to produce the strongest year-classes of striped bass in the Potomac (Rutherford et al. 1997). Freshwater flows also directly influence the foraging success of *Morone* larvae through two-layer gravitational circulation in the estuary. Vertical distribution data support the concept that larvae can maintain their position at or above the salt front through vertical movement. One advantage to this behavior is that zooplankton prey are also concentrated in this region; therefore, larval feeding success can be enhanced in this zone (North and Houde 2001). In years with moderate to high freshwater flows gravitational circulation is intensified, and when the timing of high flows concentrates feeding-stage larvae and zooplankton prey, strong recruitment of juveniles occurs in both species (North and Houde 2003).

As juveniles, striped bass and white perch occupy a wide range of shallow habitats throughout the estuary. The divergence of individuals from natal freshwater habitats to brackish areas is positively correlated with high flows and provides significantly higher growth potential (Kerr and Secor 2009). By comparison, individuals that remain in tidal freshwater represent a minority of the population, but freshwater habitats may make a disproportionately greater contribution to the spawning population during years with low freshwater flow and corresponding poor recruitment (Kraus and Secor 2005a). Both tidal freshwater and brackish habitats function in unique and complementary ways that tend to stabilize the population dynamics of both species in Chesapeake Bay. In addition, more complex influences of freshwater flow may act indirectly on the population dynamics of these species by modifying seasonal hypoxia and the suitability of adult habitats in brackish portions of the estuary.

Table 11. Tidal fresh anadromous fish life history summaries.

	Life Stage	Timing		Habitat				Hydro- Ecology Relationships			
		Event	**Cue**	**Substrate**	**Temp**	**DO +**	**pH**	**Velocity**	**Depth**	**Habitat Unit**	**Comments**
Shortnose Sturgeon *Acipenser brevirostrum*	**Egg and Larval development**	Late March through June	temperature & recent flow history	demersal, adhesive eggs	incubation is 111hrs (18-20C) to 200hrs (12C)	>3mg/L		microtidal	deep channel habitats	head of tide or riverine	salinity <9ppt
	Juvenile Growth and migration	Juveniles remain in freshwater for >1year, diet is amphipods and dipteran larvae		demersal; mud substrate (not sand) at first; older individuals found on a variety of substrates (sand, mud, near vegetation)	temperatures in Chesapeake Bay range from 4 to 30C, and SS are year round residents	>3mg/L		microtidal	wide range of channel and shoal habitats	riverine and tidal	salinity <9ppt
	Adult Growth			primarily channel habitats	feeding occurs at >7C	>3mg/L		microtidal	wide range of channel and shoal habitats	riverine and tidal	salinity <9ppt
	Migration and Spawning	upstream migration limited by Great Falls, downstream migration not likely at salinities >3ppt	river discharge, temperature, distance to spawning location	demersal; gravel/rubble substrate for spawning	9-15C	>3mg/L		moderate river discharge after peak spring flows; <300cm/s	demersal, channel habitats	head of tide or riverine	may skip spawning for 1 to 3 years
Atlantic Sturgeon *Acipenser o. oxyrhynchus*	**Egg and Larval development**	February through July		demersal	incubation ranges from 94hrs (20C) to 168hrs (17.8C)	>3mg/L		microtidal			
	Juvenile Growth and migration	may remain in estuary for at least the first year of life		demersal; mud substrate (not sand) at first; older individuals found on a variety of substrates (sand, mud, near vegetation)	temperatures in Chesapeake Bay range from 4 to 30C, and SS are year round residents	>3mg/L		microtidal	wide range of channel and shoal habitats	estuarine and nearshore coastal areas	
	Adult Growth	year round; some individuals may skip spawning for 1 to >3 years			wide range, dependent upon location inshore or offshore	>3mg/L		microtidal	channel and coastal habitats, 10-40m	estuarine and coastal migrants	
	Migration and Spawning	Late Winter upstream; protracted post-spawn migration downstream through summer and possibly fall	various including temperature and river discharge	typically migrates in channels in upper estuary; rock, rubble, hard clay for spawning	13-18C			microtidal	11-13m	oligohaline to head of tide	
Striped Bass *Morone saxatilis*	**Egg and Larval development**	Late April through June		pelagic eggs, slightly buoyant; pelagic larvae concentrated in region of salt front	14-20C; I = -4.6T + 131.6 where I is incubation time in hours and T is temperature in Celsius	>5.0 mg/L	7.0-9.5	microtidal	found at all depths	oligohaline estuarine zone, <3ppt	turbidity at the salt front may provide concealment from potential predators
	Juvenile Growth and migration	juveniles may remain in freshwater for >1year	declining fall temperatures trigger movement into deeper more saline habitats	found in a wide range of habitats with coarse to fine substrate; vegetated and unvegetated; from freshwater to barrier islands in some years	18-21	>5.0 mg/L	7.0-8.5	microtidal	typically inhabit nearshore shoal areas during warmer months	full range of estuarine salinites, but <16 ppt most important	

	Life Stage	Timing		Habitat				Hydro- Ecology Relationships			
		Event	Cue	Substrate	Temp	DO +	pH	Velocity	Depth	Habitat Unit	Comments
	Adult Growth			pelagic, mainstem estuarine habitats	temperatures in Chesapeake Bay range from 4 to 30C, and many SB are year round residents	>3-4mg/L; >6mg/L optimal	7.0-9.5	microtidal	all depths, but typically deeper non-shoal areas	full range of esturaine habitats from freshwater to ocean	piscivorous, generalist predators
	Spawning and Migration	spawning mid-April through May, 2 to 3 peaks in activity are typical; partially migratory population - not all individuals migrate	triggered by rise in water temperature, ranging between 11 and 24C	spawning in pelagic tidal freshwater, mainstem river areas near the salt front	11-24C	>5.0mg/L	7.0-9.5	microtidal	all depths, but typically deeper non-shoal areas	full range of esturaine habitats from freshwater to ocean	
White Perch *Morone americana*	**Egg and Larval development**	Late April through June	incubation time inversely related to temp, ranging between 114hrs (11C) and 24 to 30hrs (20C)	demersal non-adhesive eggs, slightly negatively buoyant in still water and pelagic in flowing water; pelagic larvae concentrated in region of salt front	12-14C	>5.0 mg/L	6.5-8.5	microtidal	demersal eggs; pelagic larvae	oligohaline estuarine zone, <3ppt	turbidity at the salt front may provide concealment from potential predators
	Juvenile Growth and emigration	some individuals mature after one year of life in the Potomac	declining fall temps trigger movement into deeper more saline habitats	found in a wide range of habitats with coarse to fine substrate; vegetated and unvegetated; from freshwater to mesohaline salinities	10-30C	>5.0 mg/L	7-9	microtidal	typically inhabit nearshore shoal areas during warmer months	riverine and oligohaline estuarine habitats	
	Adult Growth			demersal and pelagic habitats of shoal and channel regions	temperatures in Chesapeake Bay range from 4 to 30C, and WP are year round residents	>4mg/L ; >6mg/L optimal	6.5-8.5	microtidal	<12m	riverine and oligohaline estuarine habitats	generalist predators of zooplankton, small fishes, epibenthic crustaceans and benthic inverts.
	Spawning and Migration	late March through early June, group synchronous batch spawners; ; partially migratory population - not all individuals migrate	spawning triggered by rising water temperatures	Spawn in pelagic, riverine, and tidal freshwater habitats; also to brackish salinities as high as 4.2ppt	12-14C	>5.0mg/L	6.5-8.5	microtidal	<12m; spawning usually 1-6m	riverine and oligohaline estuarine habitats	

References:

Funderburk SL, Mihursky JA, Jordan SJ, Riley D (1991) Habitat requirements for Cheaspeake Bay living resources; Chesapeake Research Consortium, Solomons, MD.
Gilber CR (1989) Species Profiles: Atlantic and Shortnose Sturgeon; FWS Biolofical Report 82(11.122).
Kynard B (1997) Life history, latitudinal patterns, and status of the shortnose sturgeon, Acipenser brevirostrum. Environmental Biology of Fishes 48: 1-4.
Kynard B, Breece M, Atcheson M, Kieffer M, Mangold M (2009) Life history and status of shortnose sturgeon (Acipenser brevirostrum) in the Potomac River. Journal of Applied Ichthyology 25: 34-38.
LeBreton GTO, Beamish FW, McKinley RS (2004) Sturgeons and paddlefish of North America; Kluwer Academic Publishers.

Flow-Ecology Hypotheses for Biological Communities in the Tidal Fresh Potomac Estuary

The salt wedge, or 0.5 ppt isocline, defines a tidal freshwater habitat volume that now ranges from 53 to 260 billion gallons (200 - 990 million m3). Inter-annual and seasonal variability in flow governs structure and function of biological communities in the estuary primarily through its effect on the longitudinal salinity gradient. Low flow reduces the volume of freshwater habitat upstream and, when not confounded by poor water quality and other factors, diminishes productivity of species dependent on freshwater and favors species that prefer the brackish waters downstream. High flows have the reverse effect, except when they are so high that they flush and scour the upper estuary. A wide variety of behavioral, morphological, and physiological adaptations allows most estuarine organisms to temporarily withstand or avoid the negative effects of high or low flow conditions. They can maintain their populations when conditions are unfavorable and flourish when conditions are favorable. Over time, a broad range of freshwater flows gives intermittent opportunity to many species and produces a biologically diverse ecosystem.

The flow "needs" of most freshwater species in the tidal fresh segment are a reflection of their salinity preferences and tolerances, although there are several instances where unregulated flows that are not confounded by poor water quality can be linked to important estuarine phenomena. Seasonal high flows, in conjunction with the daily light cycle and temperature, cue fish spawning migrations in spring and out-migrations of juveniles in autumn. Episodic high flows remove fine sediments and deposit new coarse grained sediments to the spawning grounds, which may contribute to hatching success of sturgeon eggs.

Eutrophication and sedimentation of the Potomac River have changed many estuarine flow relationships. Higher flows to estuaries in late winter and early spring typically fuel the quintessential spring plankton blooms that sustain each year's larval and juvenile fish. Lower summer flows are expected to have lower nutrient concentrations, support less phytoplankton, and improve light penetration to underwater grasses, or SAV. In the Potomac tidal fresh reach, low and moderate flows rather than high flows are presently linked to higher nutrient levels—a consequence of urban runoff and wastewater plants in the Washington, DC metropolitan area. High flows coming into the estuary at Little Falls dilute excessive nutrient concentrations in the tidal fresh reach and flush them downstream. Low flows rather than high flows are linked to poorer light penetration in the Potomac tidal fresh because fine sediments are stirred up by semidiurnal tides from the now shallower, siltier bottom and take longer to flush downstream. Peak phytoplankton production now occurs in summer rather than spring and its biomass is much greater than grazers can consume. Decomposition of the uneaten biomass eventually results in hypoxia/anoxia in the bottom layer of downstream waters, stressing and even blocking migrations of bottom-oriented fish and invertebrates.

No research or empirical data exist to define thresholds of acceptable hydrologic alteration for the Potomac tidal fresh estuary. Potomac River, the largest source of freshwater to the estuary, is unmanaged except during very low flow periods. Most river water removed immediately upstream of the Washington metropolitan area is returned to the tidal fresh estuary. While flow governs the structure and function of the Potomac estuarine communities through its effect salinity, flow alteration as a factor affecting these communities is presently far outweighed by poor water quality and the other stressors to the estuary.

A persistent loss of freshwater flow could in theory reduce the importance of tidal fresh communities relative to brackish water communities. For example, modeling and monitoring results indicate that mean and minimum flows are lower in "all forested" watersheds as compared to agricultural and urbanized watersheds. This is a reflection of a forest's enormous capacity to absorb and transpire ground water. Historical anecdotes suggest the Potomac estuary was originally saltier. Lower flows constrict the tidal fresh reach by shifting the salinity gradient upstream, and species not tolerant of higher salinities are forced to relocate upstream. The impact of such a shift on the present-day estuarine food web is not clear, and might not be important given the adaptability and salinity tolerances of many estuarine species. Much would depend on the water quality in both the upstream river and the tidal fresh estuary.

A persistent gain of freshwater resulting from climate change is more likely than not in the unregulated Mid-Atlantic rivers (e.g., Palmer et al. 2008, Lins 2005). Increasing trends have been observed in the flow records, especially in the low and moderate percentiles of stream flow and in autumn and winter. These trends should be related to increases in regional rainfall and changes in evapotranspiration rates in order to confirm the climate change link. Increasing river flow could theoretically increase the extent and importance of tidal fresh communities at the expense of brackish water communities. The impact of persistent higher flows on the present-day estuarine food web is also not clear, although brackish water species like oysters could be negatively impacted. Again, much would depend on the water quality in both the upstream river and the tidal fresh estuary.

1. A range of freshwater flows gives intermittent opportunity to both freshwater and brackish water species and produces a biologically diverse estuarine ecosystem.

2. Salinity, and specifically the location of the "salt wedge," is a surrogate measure of freshwater flow in the upper, tidal fresh estuary

3. The flow "needs" of most freshwater species in the tidal fresh segment are typically a reflection of their salinity preferences and tolerances

4. High flows, in conjunction with the daily light cycle, temperature and/or turbidity, cue diadromous fish migrations into estuaries and rivers in spring and out-migrations in autumn

5. Eutrophication and sedimentation of the Potomac River have changed many estuarine flow-ecology relationships:

    a. The tidal fresh reach of the estuary is irreversibly longer and shallower than it once was
    b. Wastewater returns to the tidal fresh estuary result in increasing rather than decreasing nutrient concentrations when flows from the upper basin are low; high flows from the upper basin dilute tidal fresh nutrient concentrations
    c. Water clarity is poorer during low flow periods rather than high flow periods
    d. Phytoplankton and zooplankton blooms now occur predominantly in summer rather than spring and are not as closely linked to high flows in spring as they once were
    e. Uneaten phytoplankton sink and cause bottom layer hypoxia and anoxia in brackish waters that can both stress and block migratory life stages of bottom-oriented fish and benthic invertebrates to the tidal freshwater

6. Depending on water quality conditions, a persistent loss of freshwater flow (e.g., due to consumptive use or increased forest evapotranspiration) could reduce the extent of tidal fresh communities relative to brackish water communities

7. Depending on water quality conditions, a persistent increase of freshwater flow (e.g., due to climate change) could increase the extent of tidal fresh communities at the expense of brackish water communities such as oyster reefs

CHAPTER 4: FLOW NEEDS SYNTHESIS AND DRAFT RECOMMENDATIONS

Summary

This chapter provides a synthesis of information developed in previous chapters and the appendices, including: A discussion of what the history of flow on the Potomac River tells us about current flow conditions; a conceptual model of flow impacts on riverine systems; key points that shape the flow recommendations; and tables summarizing ecological flow needs, define flow statistics that address those flow needs, and show calculated values for those statistics. Eight flow recommendations are derived from this synthesis and a set of information gaps are identified.

An examination of 104 years of daily flows on the mainstem Potomac river shows that there have been changes in flow patterns on multi-decade time scales. Low flows have been lower, and high flows higher, in the past than they are now. These flow changes are the result of some combination of changes in climate, land use, consumptive uses, and low flow augmentation.

The conceptual model of flow impacts on riverine systems shows that the major impacts -- both positive and negative -- occur with the infrequent, extreme high flow and low flow events rather than with the more common mid range flows. Extreme events will simultaneously work to the disadvantage of some species and to the advantage of other species.

Flow in the Potomac River basin is to a large extent unregulated and analyses indicate that, at this large river scale, land use change is probably a greater source of hydrologic alteration than dams, impoundments or withdrawals. The literature review provided qualitative, rather than quantitative, flow needs for species. No documented evidence of species impairment due to flow management was found. For these reasons, and because of the other key points described in the chapter, the flow characteristics that are defined and calculated are presented as documenting current conditions rather than defining limits to what is ecologically sustainable.

One general, overarching, flow recommendation for the Opequon Creek, Monocacy River, and the four Potomac river sections, is to maintain approximately the current set of flow statistic values. It is pointed out that, since there are so few impoundments, there is no operational mechanism for controlling high or mid range flows. Withdrawals for water supply purposes can affect extreme low flows and recommendations are made that the existing Great Falls to Little Falls 300 mgd minimum flow "recommendation", and the Little Falls 100 mgd minimum flow-by requirement, be continued. In addition, however, it is recommended that the variability in flows near 100 mgd, observed during the 1999 and 2002 droughts, should be maintained. Similarly, consumptive withdrawals on Opequon Creek and the Monocacy River should not cause flows to fall below those observed in 1999 and 2002. Extreme low flow events such as occurred in 1999 and 2002 are lower in magnitude and frequency than any of the low flow statistics show in **Table 16**.

Suggestions for additional analytical work include analysis of the historical record of flows, precipitation, etc., to better understand what the "normal" variation in species' populations and ranges are and to quantify at what point changes in flow characteristics result in degraded biota. The Middle Potomac Watershed Assessment, currently underway, may provide some of those results. Recommendations are made for additional field work, or monitoring, to learn more about certain fish, mussel, and invertebrate species as particularly useful sentinel species. Additional recommendations for new monitoring activities are dependent on recommendations from the Potomac Environmental Flows Workshop.

Appendix A provides definitions of the indicators of hydrologic alteration (IHAs) and ecological flow component (EFC) parameters calculated by software developed for the Nature Conservancy.

Factors that control the hydrology of the Potomac River and its tributaries were introduced and discussed in Chapter 1. River flows in undisturbed (reference) watersheds are governed primarily by topography, geology, climate, and vegetation. Human land and water uses interrupt or break many of the natural connections between river flow and these factors. The companion Middle Potomac Watershed

Assessment project, of which this study is one component, will attempt to quantify the relative importance of land and water uses on flows in the basin's streams and rivers but results will not be fully available until 2012. Meanwhile, historic and contemporary information about the Potomac River basin suggest land uses have had, in most cases, more impact on river flow than direct human withdrawals and river flow management.

First, the Potomac River has relatively few large dams and is one of the least regulated large rivers in the eastern United States. The storage capacity of all impoundments in the basin upstream of Chain Bridge and the Little Falls gage (**Figure 1**) is collectively just 6.65% of the Potomac River median flow at Little Falls. Storage capacity of impoundments in the Monocacy watershed is 0.84% of median flow and in the Opequon watershed is 0.07% of median flow. Second, although ground and surface withdrawals in some of the sub-basins examined for this study reach as high as 50.6% of the median flow (Appendix B, **Table B-1**), most of the water is returned to the river system a short distance downstream. Compared to median annual flow, consumptive losses amount to 1.7% at Point of Rocks (129 cfs), 3.2% at Little Falls (332 cfs), 1.5% on the Monocacy and 2.3% on Opequon Creek. Third, much of the basin has reforested after the extensive clear-cutting for lumber and agriculture in the 1800s and early 1900s, and this change in land use appears to be reflected to some extent in the Point of Rocks flow records (**Figure 38**). The western half of the basin is upstream of Point of Rocks. It is now 69% forested and closer to its Pre-Colonial condition than at any other time in the last century. By comparing the historical trend in forest cover shown in **Figure 8** with the flow hydrographs for successive 26-year periods in **Figure 38**, one can see that: a) reforestation corresponds with fewer very large floods at Point of Rocks; b) summer low flows, which are driven primarily by evapotranspiration, have become lower and last longer; and c) daily mean flows across all seasons in the 1957-1982 and 1983-2008 periods are roughly 33% (1,761 cfs) lower than those in the 1905-1930 period, or more than can be accounted for by human consumptive losses. The changes have persisted despite significant dry and wet periods in the latter half of the gage records. Finally, preliminary results from the Middle Potomac Watershed Assessment

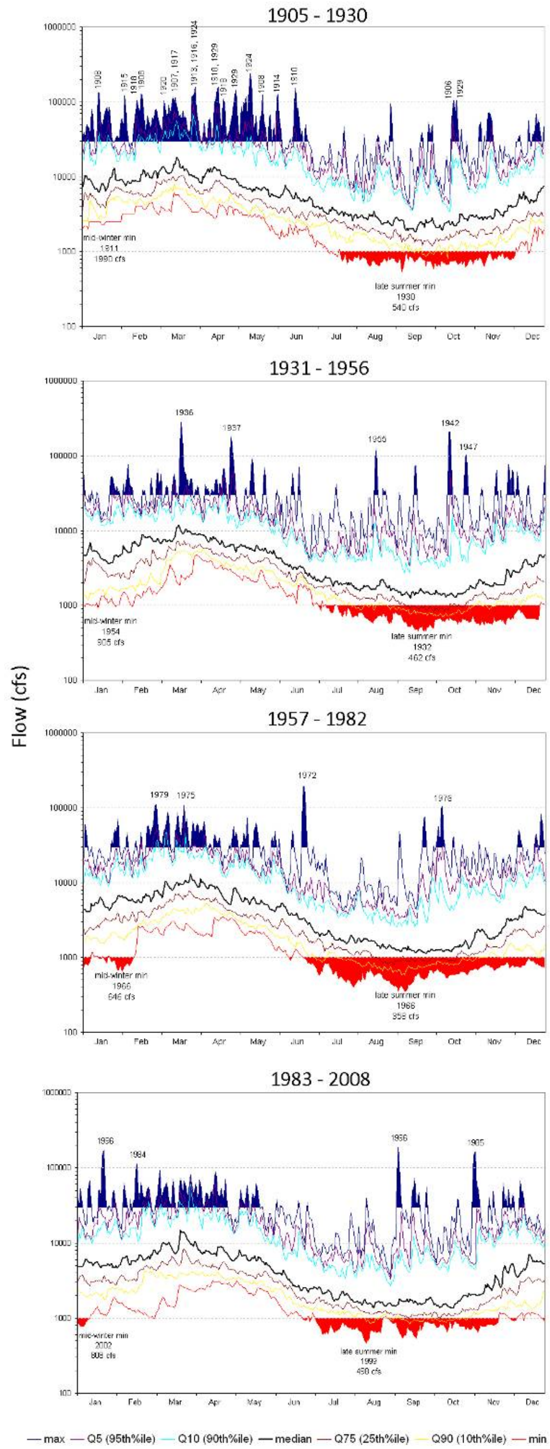


Figure 38. Extent of Point of Rocks daily mean flows in four 26-year periods beginning in 1905.
Percentiles are indicated for each day of the year within each period. Solid blue, daily mean flows above 30,000 cfs (years with flows above 100,000 cfs identified); solid red, daily mean flows below 1,000 cfs. The 30,000 cfs and 1,000 cfs thresholds are arbitrary and chosen to illustrate change in the frequency of large floods and the intensity and duration of seasonal low flow periods, respectively, over four time periods. Low flows in 1983 – 2008 were augmented by reservoir releases. The potential climate change effects on flow during these periods have not been established.

project indicate that elsewhere in the basin, increasing percent impervious surface (urbanization) corresponds to higher pulse counts, higher rise rates, more reversals and shorter high pulse durations.

To date, the impacts of impoundments and/or withdrawals on large river flows in the Middle Potomac Watershed Assessment study area are not clear, except possibly in the mainstem of the Potomac River where low flow augmentation by reservoir releases in recent decades probably increased low flows slightly. This is suggested in **Figure 38** where the minimum daily mean flows for the 1983 – 2008 period are slightly higher than those for the preceding two periods.

In Chapters 2 and 3, a set of flow-ecology hypotheses for riparian plant communities, fish, mussels, and tidal fresh biota were presented that are derived from a review of the literature and professional judgment of the project research team. The hypotheses coalesce around the several concepts summarized below and illustrated in **Figure 39** for free-flowing rivers. Mid-range flows occurring much of the time provide a stable, predictable environment for biological communities. Naturally occurring high and low flows intermittently disturb river ecosystems, simultaneously imparting negative or positive impacts on different ecosystem components. Over time, variability caused by natural high and low flow events creates diverse in-stream and riparian habitats, increases overall biological productivity, and protects the density and richness of biological communities. In dam-regulated rivers, maintaining just the mid-range flows or removing or introducing too many high or low flow events will weaken a river ecosystem's resilience and reduce its biodiversity. Heavily urbanized or agricultural landscapes can similarly alter natural flow regimes and break down the river ecosystems.

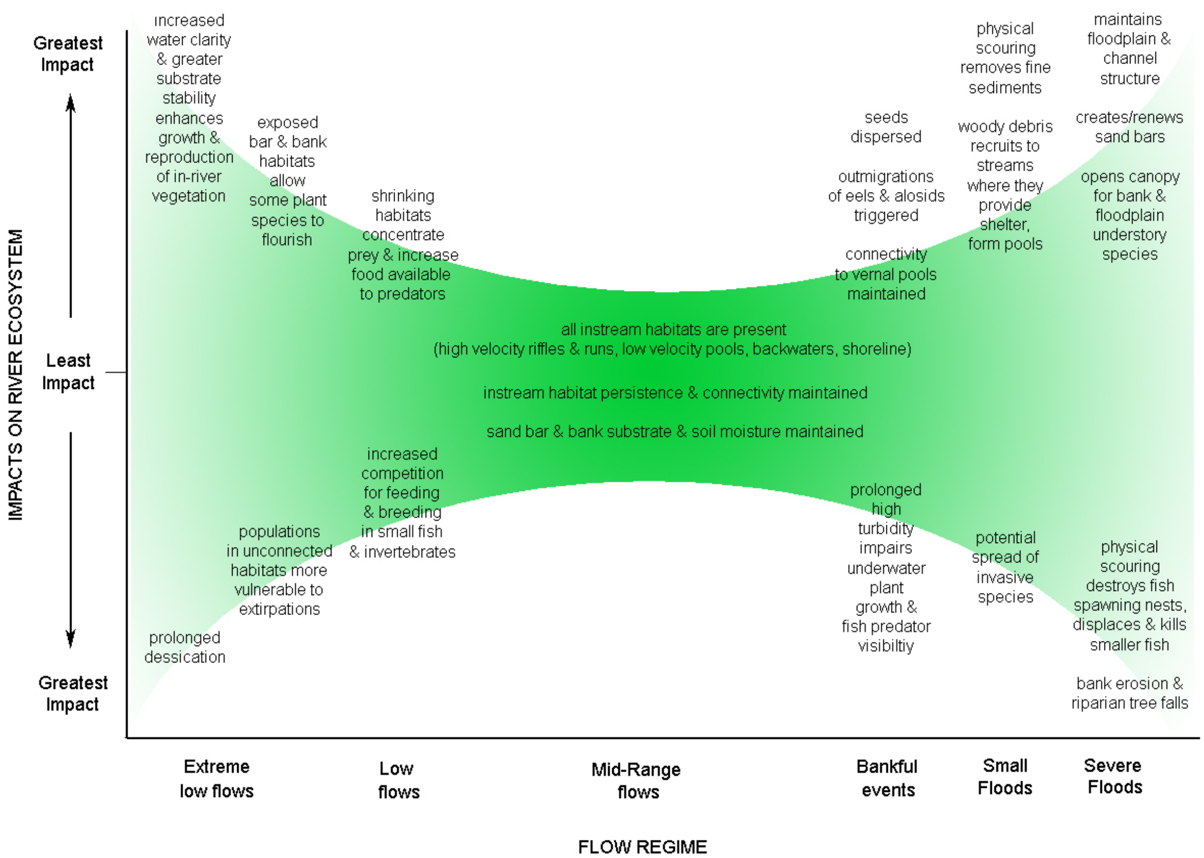


Figure 39. Conceptual diagram of flow impacts on riverine ecosystems in the Potomac River basin.

Key points that shaped the team's flow recommendations

1) The Potomac River has only minimal flow regulation, and that only at very low flows. There are no dams regulating flow on Opequon Creek or Monocacy River. Thus, high and mid range flow magnitude, and frequency and duration of events, are not subject to operational management.
2) Except for low flows from Great Falls to Little Falls, the observed distribution of flows appears to be the result of weather, climate, and land use factors.
3) Evidence suggests that there have been changes in flow distributions over the past 100 years but additional analysis is required to determine the roles of climate, land use, or other factors, in those changes.
4) Intra- and inter-annual variability in flows is high.
5) For aquatic species, no studies were found in the literature that provided directly applicable quantitative measures of flow needs. Instead, flow needs were expressed as velocity requirements at the individual organism scale, which cannot be converted to river flow values. These requirements could not be translated to stream discharge values. The literature and expert judgment did provide qualitative descriptions of flow needs.
6) No documented evidence of species impairment due to flow management was found in Potomac large rivers.
7) Low flows in the Great Falls to Little Falls reach are lower than they would otherwise be due to drinking water withdrawals at, and above, Great Falls. A 100 mgd (155 cfs) minimum flow-by at Little Falls and 300 mgd (464 cfs) from Great Falls to Little Falls recommendation has been observed since the early 1980s. During that time flows have rarely been that low. In 2002, when flows were approaching these levels, field observations did not identify any stressed communities and there did not seem to be a significant loss of habitat in these reaches.
8) The flow “needs” of most freshwater species in the tidal fresh river segment are typically a reflection of their salinity preferences and tolerances. High river flows can benefit taxa and life stages that prefer freshwater while low flows can benefit taxa and life stages that prefer salt water.
9) Eutrophication and sedimentation of the tidal Potomac River have significantly changed many estuarine flow-ecology relationships. The flow needs identified for tidal fresh biota do not consider the very significant confounding influence of the tidal fresh Potomac River’s poor water quality. Nor do they consider the flow needs of higher salinity taxa such as oysters, young-of-year menhaden, and older, resident striped bass.
10) Future impacts on flow from climate change are uncertain but studies have suggested that impacts in the middle Atlantic region of the U.S. will be lower in magnitude than elsewhere and may result in both higher precipitation and higher temperatures.

Considering these points, the team's approach has been less a question of determining what flows are required to restore these river sections, and more a matter of defining and characterizing how existing flows are functioning to maintain ecological values. **Tables 12-16** provide that characterization. **Tables 12** and **13** relate the flow hypotheses listed at the end of Chapters 2 and 3 to flow needs, grouped into high, mid-range, and low flow categories and, within categories, addressing magnitude, frequency and duration of events. In **Table 14**, a set of flow metrics, or statistics, are proposed to “capture” the ecological needs identified in **Tables 12-13**. **Table 15** provides a cross reference showing which flow statistics are relevant to the flow needs of each biotic community.

Table 16 shows values computed for each flow statistic for the five large river reaches (the Opequon Creek mainstem, the Monocacy River mainstem, and three Potomac River mainstem segments between the Shenandoah River confluence and Little Falls) selected for this study. The flow statistics for each reach were calculated from daily mean flows recorded at US Geologic Survey gages between 1984 and 2005. Freshwater inflow to the upper tidal estuary can be represented by either the Little Falls or Great

Falls flow statistics. Most of the drinking water withdrawn above Little Falls is returned to the tidal fresh estuary at Blue Plains as treated wastewater. Since Great Falls flow equals Little Falls flow plus drinking water withdrawals, the Great Falls flow is a better measure of total Potomac River contribution to the entire tidal fresh zone. Little Falls flow is the better measure of Potomac River contribution to the portion of the tidal river above the confluence with the Anacostia River. **Table 16** includes first and third quartile values, in addition to medians, in order to indicate variability in these measures.

Draft Flow Recommendations

1) **A general flow recommendation**: Maintain current flow characteristics. Because no overtly stressed (due to flow) biotic communities were identified and because the flow statistics shown in **Table 16** represent current conditions, it is reasonable to expect that maintaining these flows will continue to support these communities (other factors such as water quality aside). It should be emphasized that the values in **Table 16** are not limits but represent flow distributions. Observed flows in any given year will be higher or lower than these statistics. Evaluation of the impacts from possible new withdrawals, impoundments, or other flow management proposals should be done on the basis of what changes to the current distribution of flows is expected. Similarly, evaluation of impacts from land use change and climate change should be done on the basis of expected changes to the current distribution of flows.
2) **Extreme floods:** As noted above, there are no operational mechanisms for controlling floods. In the long term, land use changes such as increases in impervious surface and reduction in forest cover will increase peak flows. Where possible, impervious surface cover should be reduced and vegetative cover increased to reduce extreme floods.
3) **Small Floods**: There were no observed major problems in this flow component, therefore recommend maintaining current flow characteristics.
4) **Low Flows - Potomac Mainstem Harpers Ferry to Point of Rocks:** This section benefits from slightly augmented flows during low flow due to water quality and water supply releases from Jennings Randolph and Savage River reservoirs. There are no discernable problems in this reach, therefore recommend maintaining current flow characteristics.
5) **Low Flows - Point of Rocks to Great Falls:** There are large consumptive withdrawals in this section including the Dickerson power station and metropolitan Washington area water utilities. All currently provide augmentation during low flow conditions. There is no gage at the downstream end of this section to monitor flows. It is recommended that withdrawals be managed so that Potomac river flows do not fall below those experienced in the 1999 and 2002 droughts. It is recommended also that a gage be installed to measure low flow levels at the Great Falls weir.
6) **Low Flows - Great Falls to Little Falls:** The 1978 agreement establishing a 100 mgd minimum flow past Little Falls also included a recommendation (not requirement) that a minimum flow of 300 mgd (465 cfs) be maintained from Great Falls to Little Falls. Although not a requirement, water utilities have managed their operations to always exceed this target. During the 1999 and 2002 droughts, when flows approached this low level, there were no overt observed ecological stresses to the system. These events, however, represent extreme lows and it is recommended that this prior "recommendation" be continued.
7) **Low Flows - Little Falls to Chain Bridge (tidal river):** There is an existing 100 mgd (155 cfs) minimum flow requirement past Little Falls dam, which is well below the ${}_7Q_{10}$ statistic of 498 cfs. No overt ecological stresses were observed in this section during the 1999 and 2002 droughts, but there is a definite need to better understand impacts here. In past droughts, even at extreme low flows, there has been some variability in daily flows with flows generally several hundred mgd higher than the 100 mgd minimum and only occasionally and briefly dipping toward the 100 mgd minimum. There is concern that a continuous, multi-day, period of flows at, or very close to, 100

mgd (155 cfs) would be injurious to the biota. There also is concern that future increases in drinking water demand and development of new techniques enabling flow managers to release "just enough" water increase the risk that multi-day 100 mgd (155 cfs) events will occur. The recommendation, then, is to a) maintain the 100 mgd minimum flow-by, and also b) maintain also the variability in extreme low flows observed in 1999 and 2002. This could be done, for example, by allowing only single day dips in flow to 100 mgd, but maintain weekly average flows of 200 mgd and at least one peak of 300 mgd every two weeks. Note that all of these flow are below the ${}_{7}Q_{10}$ flow and thus will occur very infrequently.

8) **Low Flows - Chain Bridge to Occoquan Bay:** Water quality is the major determinant of biological health, not freshwater flow. No problems due specifically to flow regimes were identified, therefore recommend maintaining current flow characteristics.
9) **Low Flows - Monocacy River and Opequon Creek**: Extreme low flows in these watersheds are similar, on a flow per square mile drainage area basis, to that found in other watersheds with similar geology and healthy biological communities. Thus, it is unlikely that any observed biological stress is the result of human caused changes in flow conditions. Nevertheless, it is recommended that the current low flow statistics be maintained and withdrawal volumes not be allowed to push flows below those observed in 1999 and 2002.

Information Gaps and Research Recommendations

1) The low-flow workshops held in 2004 and 2005 identified two main monitoring and data analysis issues which still need to be addressed:
    a. What is the "normal" variation of species' populations and ranges for the river, and
    b. What are the effects of extreme low flows on species and their habitat.
2) Mussels: The group felt strongly that mussels are an excellent group to use for studying the impacts of low flows because they are relatively sessile, more likely to become stranded, and therefore easier to study than fish. Other comments on mussel research included: Adults may survive low-flows but have problems with reproduction; therefore recruitment issues should be examined. These elements are recommended for study:
    a. The distribution and composition of mussel beds
    b. Change in the assemblages and distribution of beds over time. Should look at population densities by doing mark/recapture studies each year.
    c. Signs of mortality or stress during low flows; respiratory, thermal, reproductive, growth, etc.
    d. The following species are suggested as being good candidates for study in the low flow area:

        Elliptio complanata
        Pyganadon cataracta
        Utterbackia imbecillis
        Lampsilis sp.
        and possibly, *Strophitus undulatus and Alasmidonta undulata.*
3) Fish:
    a. Research on fish which live near the drinking water intake pipes.
    b. May want to remove long-lived species from the list of species with critical flow needs because it will be more difficult to determine causality of population changes.
    c. Discussed the possibility of sampling at the new fishway during low-flows. Gear recovery might be difficult as the area is dangerous at all flows, especially flows above about 1,547 cfs which occur about 95% of the time August-November.

4) Other possible species or groups of species that may be useful to study include:

a. *Macroinvertebrates* – It may be useful to do density and abundance studies. Large river study protocols are not well developed for this kind of river environment. Crayfish may be a good group to study because they are an important prey for many fish such as catfish and smallmouth bass. Crayfish abundance estimates based on area density or trap catch-rates would offer good potential.
b. *Amphibians and reptiles* – Difficult to study because they are mobile and able to readily exchange with the canal, but could be of interest in regard to loss of habitat if flooding is reduced.
c. *Cormorants* – their impact on concentrated fish populations may be of concern. They tend to only use the area part of the time, fly in from downriver tidal sites. Would be hard to document flow impacts upon them or other birds, since changes in their population may be due to changes in other habitats or other outside factors.

5) Monitoring:
   a. This study did not find empirical evidence to indicate what acceptable levels of hydrologic change are, or what the acceptable thresholds of deviation from current conditions are, so additional monitoring is important.
   b. The companion Middle Potomac Watershed Assessment study is in the process of determining in a more quantitative way what acceptable thresholds of change might be and what key flow measures should be considered. After that study is complete, it will be appropriate to revisit this issue to propose new monitoring that is targeted at measuring change in a few key flow measures and for potential disruptions to key biotic communities.
   c. For most of the species discussed in this report, there simply is not enough information with which to define the normal variability in population and distribution. Additional studies on selected key species would be helpful.

Table 12. Flow component needs for nontidal large rivers (Monocacy R., Opequon R., Potomac R. mainstem).

Biota	**Flow Component**			**Reference**
	High Flow Events	**Mid-Range Flows**	**Low Flows**	
Group A fish (large-bodied, long-lived, late maturation, migratory, flow-velocity generalist) e.g., American eel	Sep-Feb – provides one of several cues for out-migration of adult eel (silver eels) (Flow Statistics 15-# events Winter, 16-# events Spring)	Dec-Apr - one of several cues for upriver migrations of juvenile eel (elvers) (Flow Statistic 9-# events Fall)	Sept-Feb - Out-migration delayed if prolonged. (Flow Statistics 7-duration events Fall, and 8-duration events Summer)	• High flows trigger adult eel out-migrations (Smogor et al. 1995). • Migrating eels may delay migration when velocities are too low or too high (Greene et al 2009).
Group B1 fish (Alosid, medium-sized, migratory, moderate flow-velocity specialization, e.g., blueback herring, alewife, American shad	Mar-Jun – provides one of several cues for upriver migrations of adults to nontidal spawning grounds Mar-Aug - high flow pulses not too numerous or too strong to cause loss of larvae and young-of-year class August-November- High flow are one emigration trigger. (Flow Statistics 13-2 yr R.I. event, 15- # events Winter, 16-# events Spring, and 18- # events Fall)	Mar-Jun – provide adults with access to natal spawning streams (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)		•High flows in summer limit recruitment success. (Jenkins and Burkholder 1994) • Cues for emigration include high flows (Greene et al 2009).
Group B2 fish (non-Alosid, small home range, medium-sized, moderate flow-velocity specialization), e.g., smallmouth bass, shorthead redhorse, redbreast sunfish	Dec - Mar – Extreme flows during dormancy period displace and cause energy consumption. (Flow Statistic 12- Annual Q_{10} flow)	May - Oct – stable flows best for developing young (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Jun-Oct – Competition, increase exposure of young to predators. (Flow Statistics 2-Annual Q_{90} flow, 3- ${}_7Q_{10}$ flow, 5-# events Summer, 6- # events Fall, 7- duration events Summer, 8-duration events Fall)	• Availability and persistence of shallow-slow water habitats were directly correlated with fish abundance, particularly percids, catostomids and cypriids (Bowen et al 1998) • Strongest smallmouth bass year class observed when June flows within 40% of long-term mean. Smith et al 2005 • Juveniles and adults directly compete for refuge (Rashleigh and Grossman 2005)

Biota	Flow Component			Reference
	High Flow Events	**Mid-Range Flows**	**Low Flows**	
Group C fish (small-sized, short-lived, early maturation, flow-velocity specialist fish), e.g., margined madtom, satinfin shiner, fantail darter	Apr-Jun - high flow pulses not too numerous or too strong to cause loss of larvae and young-of-year class May-Sep – magnitude of high pulses, pulse duration, and rate of change should not cause large losses of larvae and young-of-year (Flow Statistics 11- Monthly Q_{10} flow, 13- 2 yr R.I. flow, 16- # events Spring, 17- # events Summer, 19- duration events Spring, and 20- duration events Summer)	Dec-Feb - maintains sufficiently range of habitat types, sufficient deep water to minimize freezing May-Sep – provides flows needed to maintain diversity of spring and summer spawners; range of diverse habitat types (high velocity riffles, low velocity pools, backwaters, stream margins); habitat persistence and connectivity; sufficient shallow slow water habitat for young-of-year (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Jul-Sep – maintain habitable water quality, incl. temperature and DO in mainstem and backwaters; maintain assimilative capacity of stream; minimize downstream effects of AMD (Flow Statistics 2-Annual Q_{90} flow, and 3- $_7Q_{10}$ flow)	• Sheer stress and scouring during extreme high flow events causes adult and juvenile mortality (Schlosser 1985) • Extreme scouring flows in spring destroy spawning nests (Fausch et al. 2001) and other habitat (Jackson et al. 1989) • High flows recruit large woody debris into stream channels & promotes pool development (Naiman et al. 2000). • Visual predators may be less effective during high flows due to turbidity, could benefit prey. • Great Falls may be permeable to fishes when the Falls are submerged during high flows (Garrett and Garrett 1987). • Low flows increase competition for feeding and breeding
Benthic macroinvertebrates (includes aquatic insects)	Annual – high flows recruit organic matter (Flow Statistics 12- Annual Q_{10} flow and 13- 2 yr R.I. flow)	Nov-Feb - maintains sufficient habitat to protect density/richness of pre-emergent insects and benthic macro-invertebrate taxa May-Sep – maintains habitat diversity/ volume and biodiversity (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Jul-Oct – maintain adequate and persistent flow to ensure healthy, diverse community structure, density, and composition; for seasonal temperature regulation (Flow Statistics 2-Annual Q_{90} flow, and 3- $_7Q_{10}$ flow)	• Extreme flow events & increased frequency of extreme events impacts benthic macroinvertebrate communities High flows: Argerich 2004, Robinson 2004, Scrimgeour and Winterborn 1989, Sheldon 2006, Snyder 2006 Low flows: Bouton 2003, Acuna 2005, Griswold et al. 2008, Soren and Jowett 2006, Cattaneo 2004, Blinn et al. 1995, Canton 1984, Weisberg et al. 1990 • High flows recruit organic matter into stream (leaf litter) ultimately providing bacterial and fungal food sources for consumers (Webster and Meyer 1997)

Biota	**Flow Component** **High Flow Events**	**Mid-Range Flows**	**Low Flows**	**Reference**
Mussels	Oct-May – bankfull and higher flow events needed to flush fine sediments for taxa preferring sand & gravel (*Alasmidonta* spp., *Lampsilis* spp.) Jun-Sep – minimize high flow pulses to avoid negative impacts on recruitment of short-term brooders (e.g., *Elliptio* spp.) (Flow Statistics 11- Monthly Q_{10} flow, 12- Annual Q_{10} flow, 13- 2 yr R.I. flow, 15- # events Winter, 16- # events Spring, and 17- # events Summer)	Jun-Sep – maintains habitat conditions needed for peak spawning and larval survival (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Jun-Sep – maintain adequate flow to ensure mussel recruitment, presence of aerated surface water, minimal current, and surface flow connectivity (Flow Statistics 2-Annual Q_{90} flow, and 3- ${}_7Q_{10}$ flow)	• Mussel populations in isolated riffles are more vulnerable to flow-induced extirpations that “connected” riffles
Amphibians & reptiles	Jan - Apr – Some over-bankful events are necessary to fill vernal pools. Too many over-bank may introduce predators into seasonally important nurseries in floodplain intermittent pools (Flow Statistics 13- 2 yr R.I. event, 16- # events Spring)	Sep-Apr - maintains flowing water adjacent to hibernation sites in river banks (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow,)		
In-river vegetation (inundated or seasonally exposed) e.g., water stargrass, water willow	Nov-Feb – nutrients recruited to streams during high flow events can enhance primary production		Mar-Oct – enhanced growth and reproduction due to increased water clarity and greater substrate stability. Rapid	• Nutrients recruited to stream during high flows (Likens et al. 1970) • Prolonged high turbidity and erosive flows impair underwater plant photosynthesis

Biota	Flow Component High Flow Events	 Mid-Range Flows	 Low Flows	Reference
	Mar-Oct – poorer growth due to turbid, erosive flows (Flow Statistics #17, 18, 20, 23-26 12- Annual Q_{10} flow, 13- 2 yr R.I. flow, 15- # events Winter, 18- # events Fall, and 20- duration events Summer)		deterioration after 8 weeks dessication, (Flow Statistics 2-Annual Q_{90} flow, 3- $_7Q_{10}$ flow, 4- # events Spring, 5- # events Summer, 6- # events Fall, 7- duration events Summer, 8- duration events Fall)	
"Bar and bank" vegetation (mean water's edge to bankfull) e.g., big bluestem, switchgrass, willow, river birch, silver maple, green ash	Annual – Q50 to 2 year RI flow maintains moisture, plant communities and structure/composition of bank and bar (Flow Statistics 12- Annual Q_{10} flow, 13- 2 yr R.I. flow)	Annual – Q50 to 2 year RI flow maintains moisture, plant communities and structure/composition of bank and bar (Flow Statistics 10- Monthly Q_{50} flow , and 11- Monthly Q_{10} flow,)		•(Lea 2000)

Biota	Flow Component High Flow Events	Mid-Range Flows	Low Flows	Reference
Floodplain vegetation & trees e.g., Piedmont/Central Appalachian Riverside Outcrop Prairie – white ash, post oak, eastern red cedar	Annual - inundation by overbank flows (2-10 yr R.I.) maintains geomorphic disturbance patterns; delivers moisture, gravels, sand, silt; flood-downed trees open canopy for understory Annual – ensures seed dispersal and survival of riparian species; prevent riparian encroachment into former channels May-Oct –inundation frequency can deter establishment of non-native vegetation (Flow Statistics12- Annual Q_{10} flow, 14- 10 yr R.I. flow, 15- # events Winter, 16 - # events Spring, and 18- # events Fall,)	Jul-Sep - maintains riparian substrate and soil moisture (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Jul-Sep – plants exhibit some adaptation to seasonal drying (Flow Statistic 2-Annual Q_{90} flow)	• Floodplain plants depend on floods for seed dispersal, deposition of sediment to maintain floodplain surfaces & enrich soils, remove debris and potential competitors from germination sites, and provide moisture for germination and growth (Dixon 2003). • Flood duration and frequency important in determining riparian vegetation community structure (Hupp and Osterkamp 1985). • Species richness increases with topographic complexity of the floodplain (Everson & Boucher 1998). • up to 90% of material is moved by flows smaller than the 5 year recurrence interval flood event rather than by the extreme but rare flood events (Leopold et al. 1964)
Flood terrace vegetation & trees (inundated by extreme floods, >10 yr return frequency) e.g., box elder stands, sugar maple, white ash, basswood, bitternut hickory (alluvial), pignut hickory, northern red oak, tulip poplar, Virginia pine, red cedar, post oak	>10 yr flood events – deposited sediment and nutrients produce fertile soils (Flow Statistic 14- 10 yr R.I. flow)			• Periodic floods deposit sediments on flood plain (Leopold et al. 1964)

Biota	**Flow Component** **High Flow Events**	**Mid-Range Flows**	**Low Flows**	**Reference**
All biota	Annual – Overbank flows maintain geomorphic disturbance patterns, bedload transport, island formation/ erosion, floodplain inundation, in-channel and floodplain habitat structure, nutrients recruited to stream from watershed; > 10 year events maintain floodplain and channel structure Jun-Nov – flush fine sediments; transport downstream and breakdown organic matter (Flow Statistics 12- Annual Q_{10} flow, 13- 2 yr R.I. flow, and 14- 10 yr R.I. flow)		Jul-Sep – maintain habitable water quality, incl. temperature and DO in mainstem and backwaters; maintain assimilative capacity of stream (Flow Statistic Annual 1 day Min. flow)	• High flows reorganize substrates, flush fine sediments out (Galay 1983). • Temporal variation in flow magnitude is important for maintaining ecological complexity – floods and droughts have differential effects, each adversely affecting some communities while benefitting others. • “Intermediate disturbance hypothesis” – greatest production and diversity occurs with an “intermediate” level of disturbance that periodically reduces competitive pressures (Connell 1978). • Low flows can disconnect pool-riffle-run sequences, alter substrate deposition dynamics at confluences (Benda et al. 2004)

Table 13: Qualitative flow component needs for the tidal fresh Potomac estuary.

Biota	**Flow Component** **High Flow Events**	**Mid-Range Flows**	**Low Flows**	**References**
Tidal Fresh Phytoplankton Community	Annual – very high flows hydraulically push estuarine waters downstream, diluting cell concentrations, altering species composition and disrupting pelagic trophic relationships (Flow Statistics 12-Annual Q_{10} flow, 13- 2 yr R.I. flow, and 14- 10 yr R.I. flow)	Jan-May – Seasonal mid-range flows extend the tidal fresh reach downstream, allowing more generations of spring diatoms to accumulate before populations reach the salt wedge and die (Flow Statistics 9- Monthly Q_{90} flow, and 10- Monthly Q_{50} flow)	June-Sep – prolonged low flows presently can set up water quality conditions favorable to development of potentially toxic cyanobacteria (blue-green algae) blooms (Flow Statistics 2-Annual Q_{90} flow, 3- ${}_7Q_{10}$ flow, 4- # events Spring, 5- # events Summer, and 7- duration events Summer)	• Extreme high flows flush out chlorophyll a (Boyer et al. 1993, Borsuk et al. 2004) •Extreme high flows limit light penetration and flush nutrients downstream (Lin et al. 2008) •High flows decrease abundance of phytoplankton (Paerl et al. 2006) •During high flows water residence time can be less than cell doubling time (Sin et al. 1999) •High flows physically displace phytoplankton downstream (Valdes-Weaver et al. 2006) •Diatoms are a dominant phytoplankton class during winter and spring months and diatoms are a preferred food source for freshwater zooplankton (Valdes-Weaver et al. 2006) •Low summer flows lead to cyanobacteria blooms (Klug 2006, Paerl et al. 2006, Valdes-Weaver et al. 2006)
Tidal Fresh Zooplankton Community	Annual – very high flows hydraulically push estuarine waters downstream, diluting organism concentrations, altering species composition and disrupting pelagic trophic relationships (Flow Statistics 12-Annual Q_{10} flow, 13- 2 yr R.I. flow, and 14- 10 yr R.I. flow)	Jan-May – Seasonal mid-range flows extend the tidal fresh reach downstream, allowing more zooplankton generations to accumulate before populations reach debilitating salinity levels, these flows also increase diatoms, a favored food supply (Flow Statistics 9- Monthly Q_{90} flow, and 10- Monthly Q_{50} flow)	Annual - persistent loss of freshwater flow reduces importance of the more diverse tidal fresh zooplankton community relative to the brackish water community. Adaptable species like *Eurytemora* can survive and prosper at a range of salinities, but true freshwater species have their ranges truncated by persistent low flows. (Flow Statistics 3- ${}_7Q_{10}$ flow)	• In a mesocosm study, freshwater zooplankton were maintained at salinities below 0.1 ppt, but as salinity increased above that, they disappeared (Nielsen et al. 2008). •Density of the dominant copepod characteristic of the upstream areas of the Chikugo estuary (Japan) was negatively and significantly influenced by freshwater flow (Islam and Tanaka 2007). •*Eurytemora affinis* is an adaptable zooplankton species which can grow over a wide range of salinities (Mouny and Dauvin 2002, Lee et al. 2003). •During low flows *Eurytemora affinis* specialized on phytoplankton, but reverted to allochthonous organic matter at higher flows (Hoffman et al.2008)

Biota	Flow Component High Flow Events	Mid-Range Flows	Low Flows	References
Tidal Fresh Benthic Macroinvertebrate Community	Annual –high flow events may bring in suspended sediments which could layer over existing benthos. (Flow Statistics 12- Annual Q_{10} flow, and 13- 2 yr R.I. flow)		Annual - persistent loss of freshwater flow allows brackish water to penetrate into areas formerly colonized by freshwater macroinvertebrates which may be more diverse than the brackish fauna. (Flow Statistics 3- $_7Q_{10}$ flow)	• Decreasing salinity and increasing sediment mud content decrease species diversity (Hyland et al. 2004) •Gammaridean amphipods, insect larvae, *Corbicula fluminea* and oligochaeates are indicative of tidal freshwater systems and are replaced at salinities above a few ppt (Hyland et al. 2004) •Salinity is considered the most important factor determining the distribution of molluscan species (Sousa et al. 2007, Montagna et al. 2008) and can act as a proxy for freshwater inflow (Montagna et al. 2008).
Tidal Fresh Submerged Aquatic Vegetation Community	Apr-Oct – High flows may increase suspended sediment concentrations in the upper tidal fresh region resulting in lower light levels and growth inhibition (Flow Statistics 12- Annual Q_{10} flow, 13- 2 yr R.I. flow, and 14- 10 yr R.I. flow)	Mar-Oct – seed dispersal (Flow Statistics 9- Monthly Q_{90} flow, and 10- Monthly Q_{50} flow)	Annual - persistent loss of freshwater flow reduces the portion of the river capable of supporting the more diverse tidal fresh SAV community relative to the brackish water community (Flow Statistics 3- $_7Q_{10}$ flow)	•Increases in salinity induced by decreased freshwater flow into Lake Pontchartrain, LA resulted in the elimination of some freshwater SAV species and the significant reduction of others. Subsequent increases in freshwater flow lowered salinity, but not all freshwater SAV recovered. (Cho and Poirrier 2005) •Regrowth of SAV in the Choptank River required suspended sediment less than 20 mg/L (Stevenson et al. 1993). •While *Vallisneria* (a typical freshwater SAV species) can be found at salinities of 5 psu or greater, it's light requirements are much higher which would restrict its coverage (French and Moore 2003) •In three tidal freshwater rivers in Florida, SAV biomass was sharply lower at salinities above 3.5 psu (Hoyer et al. 2004)

Biota	Flow Component High Flow Events	 Mid-Range Flows	 Low Flows	References
Atlantic Sturgeon	Annual – episodic high flows needed to remove fine sediments and deposit new coarse grained sediments on spawning grounds (contributes to hatching success of eggs) Jun-Sep – formation of too strong a pycnocline can lead to oxygen depletion and bottom layer anoxia, impairing bottom habitat and blocking seasonal migrations of sturgeon to spawning grounds (Flow Statistics 12- Annual Q_{10} flow, 13- 2 yr R.I. flow, and 14- 10 yr R.I. flow)	Feb-Jul – moderate to high water velocities are one of several cues to deposit demersal eggs (Flow Statistic 11- Monthly Q_{10} flow)		
Shortnose Sturgeon	Annual – episodic high flows needed to remove fine sediments and deposit new coarse grained sediments on spawning grounds (contributes to hatching success of eggs) Jun-Sep – formation of too strong a pycnocline can lead to oxygen depletion and bottom layer anoxia, impairing bottom habitat and blocking seasonal migrations of sturgeon to spawning grounds (Flow Statistics 12- Annual Q_{10} flow, 13- 2 yr,	Mar-Jun – moderate to high water velocities are one of several cues to deposit demersal eggs (Flow Statistic 11- Monthly Q_{10} flow)		

Biota		**Flow Component**		**References**
	High Flow Events	**Mid-Range Flows**	**Low Flows**	
	R.I. flow, 14- 10 yr R.I. flow, 15- # events Winter, and 16- # events Spring)			
Striped Bass	Jun-Sep – cues juveniles to leave natal freshwater habitats for brackish areas, and results in higher growth potential (Flow Statistics 12- Annual Q_{10} flow, 16- # events Spring, 17- # events Summer, and 18- # events Fall)	Mar-May – intensified estuarine circulation concentrates feeding stage larvae and zooplankton prey, favoring strong recruitment of juveniles (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Mar-May – weak estuarine circulation patterns characteristic of low flow conditions are unfavorable for retention within larval nursery areas and decrease feeding opportunities (Flow Statistic 3- ${}_7Q_{10}$ flow)	
White Perch	Jun-Sep – cues juveniles to leave natal freshwater habitats for brackish areas, and results in higher growth potential (Flow Statistics 12- Annual Q_{10} flow, 16- # events Spring, 17- # events Summer, and 18- # events Fall)	Mar-May – intensified estuarine circulation concentrates feeding stage larvae and zooplankton prey, favoring strong recruitment of juveniles (Flow Statistics 9- Monthly Q_{90} flow, 10- Monthly Q_{50} flow, and 11- Monthly Q_{10} flow)	Mar-May – a weak estuarine circulation patterns characteristic of low flow conditions are unfavorable for retention within larval nursery areas and decrease feeding opportunities (Flow Statistic 3- ${}_7Q_{10}$ flow)	

Table 14. Flow statistics for flow components for nontidal large rivers.

Flow category	Flow Statistics		
	Magnitude (cfs)	Frequency (#)	Duration (days)
Low flows (flow < Q_{90})	1. Annual 1 day min. flow 2. Annual Q_{90} flow 3. $_7Q_{10}$ (7 day, 10 year) flow	Median # of low flow events 4. Spring (Apr - Jun) 5. Summer (Jul - Sep) 6. Fall (Oct - Dec)	Median duration of low flow events 7. Summer (Jul - Sep) 8. Fall (Oct - Dec)
Mid-range flows (Q_{90} < flow < Q_{10})	9. Monthly Q_{90} flow 10. Monthly Q_{50} flow 11. Monthly Q_{10} flow		
High flows (> annual Q_{10}), Small Floods (>= 2 yr R.I. and < 10 yr R.I. event), and Large Floods (>= 10 yr R.I. event)	12. Annual Q_{10} flow 13. 2 yr Recurrence Interval (R.I.) event (approx. bank full) 14. 10 yr R.I. event (Large flood)	Median # of high flow events 15. Winter (Jan-Mar) 16. Spring (Apr - Jun) 17. Summer (Jul - Sep) 18. Fall (Oct - Dec)	Median duration of high flow events 19. Spring (Apr - Jun) 20. Summer (Jul - Sep)

Notes

a) Mid-range flows provide stability and predictability for ecosystems
b) High and low flow events define the frequency and magnitude of flow excursions (disturbances).
c) All references to "flow" are mean daily flows.
d) $_7Q_{10}$ is the 7 day mean low flow with a 10 year recurrence interval and is the traditional low flow management benchmark. Computed using the DFLOW 3.1b program (U.S. EPA 2006).
e) All statistics, except $_7Q_{10}$, computed using the Indicators of Hydrologic Alteration Version 7.1.0.10 program (The Nature Conservancy (2007)).
f) Q_{90}, Q_{50}, and Q_{10} are the flows equaled or exceeded 90%, 50%, and 10% of the time. Values were calculated for each calendar year, 1984 - 2005, and the median of the resulting 22 values used as the flow statistic.
g) High flows are those that exceed 75% of daily flows for the period. A high flow event is a sequence of days during which the peak flow exceeds the high flow threshold. The event begins when daily flow increases by more than 25% and continues until flows decrease by less than 10% per day.
h) Low flows are those that are below 10% of daily flows for the period. A low flow event is a sequence of days with flows below this level.

Table 15. Statistics used for each biotic community.

		Statistic	Group A fish	Group B1 fish	Group B2 fish	Group C fish	Benthic macroinv.	Mussels	Amphibians & reptiles	In-river vegetation	"Bar and bank" vegetation	Floodplain vegetation	Flood terrace vegetation	All biota	Tidal Fresh Phytoplankton	Tidal Fresh Zooplankton	Tidal Fresh Benthic Macroinv.	Tidal Fresh SAV	Atlantic Sturgeon	Shortnose Sturgeon	Striped Bass	White Perch	Count
Low Flows	1	Annual 1 day min. flow												X									1
	2	Annual Q90 flow			X	X	X	X		X				X	X								7
	3	7Q10 (7 day, 10 year) flow			X	X	X	X		X					X								6
	4	# events Spring (Apr - Jun)								X					X								2
	5	# events Summer (Jul - Sep)			X					X					X								3
	6	# events Fall (Oct - Dec)			X					X													2
	7	duration events Summer (Jul - Sep)	X		X					X					X	X	X	X					7
	8	duration events Fall (Oct - Dec)	X		X					X						X	X	X					6
Mid Flows	9	Monthly Q10 flow	X	X	X	X	X	X	X		X	X									X	X	11
	10	Monthly Q50 flow		X	X	X	X	X	X		X	X			X	X		X			X	X	13
	11	Monthly Q90 flow		X	X	X	X	X	X			X		X	X	X		X			X	X	13
High Flows	12	Annual Q10 flow			X		X	X		X	X	X		X	X	X	X	X	X	X	X	X	15
	13	2 yr Recurrence Interval (R.I.)		X		X	X	X	X	X	X	X		X	X	X	X	X	X	X			15
	14	10 yr R.I. event (Large flood)										X	X	X	X	X		X	X	X			8
	15	# events Winter (Jan-Mar)	X	X				X		X		X							X	X	X	X	9
	16	# events Spring (Apr - Jun)		X		X		X	X			X								X	X	X	8
	17	# events Summer (Jul - Sep)						X							X				X	X	X	X	6
	18	# events Fall (Oct - Dec)	X	X						X		X											4
	19	duration events Spring (Apr - Jun)				X				X													2
	20	duration events Summer (Jul - Sep)				X				X													2

Table 16. Current values for ecological flow statistics, by river.

		Opequon - 1616500		Monocacy - 1643000		Potomac Point of Rocks - 1638500		Great Falls - 1646502		Little Falls - 1646500	
Ref.	Flow Statistic	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)
1	Annual 1 day min. flow (cfs)	58	(43 - 72)	96	(67 - 153)	1,500	(1,215 - 1,895)	1,755	(1,445 - 2,380)	990	(753 - 1,753)
2	Annual Q_{90} flow (cfs)	66	(57 - 84)	152	(99 - 207)	1,977	(1,686 - 2,653)	2,541	(1,941 - 3,084)	1,826	(1,278 - 2,441)
3	${}_7Q_{10}$ (7 day, 10 year, low flow) (cfs)	40		47		1,060		1,220		498	
4	# events, Spring	1	(0 - 2)	1	(0 - 2)	1	(1 - 2)	1	(1 - 2)	1	(0 - 2)
5	# events, Summer	0	(0 - 3)	0	(0 - 3)	1	(0 - 2)	1	(0 - 2)	1	(0 - 3)
6	# events, Fall	0	(0 - 2)	0	(0 - 1)	0	(0 - 2)	0	(0 - 2)	0	(0 - 2)
7	Duration (days) of events, Summer	4.8	(3.5 - 7.0)	4.5	(1.5 - 9.3)	4.0	(2.0 - 7.0)	4.5	(3.0 - 6.0)	2.8	(1.6 - 6.5)
8	Duration (days) of events, Fall	3.0	(2.0 - 6.3)	7.5	(3.0 - 13.3)	4.5	(1.0 - 8.5)	2.0	(1.0 - 7.5)	1.8	(1.0 - 5.1)
9	Monthly Q_{90} flow (cfs)										
	Jan	137	(95 - 207)	427	(305 - 672)	5,015	(3,350 - 6,903)	6,555	(4,235 - 9,103)	5,980	(3,610 - 8,538)
	Feb	158	(111 - 227)	587	(379 - 734)	6,230	(3,883 - 8,308)	8,146	(5,276 - 11,235)	7,554	(4,698 - 10,713)
	Mar	177	(141 - 368)	702	(516 - 1,135)	8,065	(6,103 - 13,550)	9,880	(7,698 - 17,950)	9,345	(7,143 - 17,375)
	Apr	190	(123 - 311)	666	(442 - 863)	7,539	(5,094 - 12,070)	10,444	(6,890 - 15,138)	9,886	(6,311 - 14,515)
	May	133	(113 - 228)	465	(305 - 629)	5,820	(4,505 - 8,145)	7,630	(5,925 - 10,340)	7,000	(5,323 - 9,728)
	Jun	112	(90 - 153)	258	(173 - 374)	3,350	(2,699 - 4,861)	4,044	(3,575 - 5,881)	3,352	(2,838 - 5,171)
	Jul	89	(68 - 113)	193	(104 - 258)	2,510	(1,930 - 3,280)	3,050	(2,180 - 4,018)	2,340	(1,390 - 3,250)
	Aug	76	(57 - 91)	139	(88 - 179)	2,025	(1,625 - 2,590)	2,550	(1,900 - 3,198)	1,855	(1,133 - 2,470)
	Sep	67	(50 - 85)	102	(93 - 171)	1,660	(1,418 - 2,561)	1,919	(1,735 - 2,913)	1,292	(1,023 - 2,297)
	Oct	67	(58 - 80)	151	(97 - 203)	1,825	(1,573 - 2,280)	2,275	(1,890 - 2,895)	1,655	(1,278 - 2,328)
	Nov	77	(62 - 162)	277	(191 - 424)	2,665	(1,955 - 5,149)	3,453	(2,441 - 6,519)	2,869	(1,840 - 5,950)
	Dec	120	(64 - 171)	462	(269 - 615)	4,605	(2,665 - 6,340)	6,100	(3,565 - 7,750)	5,540	(3,003 - 7,188)
10	Monthly Q_{50} flow (cfs)										
	Jan	196	(115 - 263)	722	(459 - 1,093)	8,500	(5,085 - 10,850)	10,700	(5,990 - 13,675)	10,200	(5,418 - 13,150)
	Feb	222	(176 - 362)	990	(711 - 1,301)	8,610	(6,259 - 15,888)	11,325	(7,883 - 21,175)	10,825	(7,341 - 20,638)
	Mar	287	(192 - 478)	1,185	(878 - 1,518)	13,750	(9,750 - 19,725)	16,350	(12,400 - 25,675)	15,800	(11,825 - 25,175)
	Apr	251	(169 - 458)	1,053	(636 - 1,335)	10,850	(7,883 - 17,163)	14,275	(9,635 - 22,338)	13,700	(9,063 - 21,750)
	May	203	(142 - 386)	634	(430 - 1,268)	9,025	(5,818 - 14,150)	11,600	(7,338 - 17,425)	11,000	(6,720 - 16,875)

		Opequon - 1616500		Monocacy - 1643000		Potomac Point of Rocks - 1638500		Great Falls - 1646502		Little Falls - 1646500	
Ref.	Flow Statistic	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)
	Jun	134	(114 - 185)	343	(279 - 523)	4,783	(4,261 - 6,581)	6,095	(5,104 - 7,794)	5,425	(4,466 - 7,134)
	Jul	114	(85 - 133)	285	(142 - 389)	3,300	(2,545 - 4,068)	4,165	(2,963 - 5,803)	3,505	(2,185 - 5,215)
	Aug	89	(73 - 107)	191	(104 - 281)	2,705	(1,940 - 3,718)	3,470	(2,278 - 5,088)	2,730	(1,565 - 4,375)
	Sep	85	(65 - 118)	183	(109 - 304)	2,585	(1,758 - 4,504)	3,015	(2,148 - 5,218)	2,390	(1,440 - 4,620)
	Oct	82	(65 - 117)	228	(144 - 380)	2,675	(1,765 - 4,800)	3,155	(2,380 - 6,190)	2,515	(1,745 - 5,573)
	Nov	91	(76 - 231)	397	(299 - 627)	3,533	(2,701 - 8,325)	4,490	(3,470 - 10,545)	3,938	(2,914 - 10,028)
	Dec	167	(96 - 293)	834	(472 - 1,150)	7,680	(4,238 - 11,975)	10,030	(5,265 - 14,825)	9,465	(4,715 - 14,300)
11	Monthly Q_{10} flow (cfs)										
	Jan	342	(238 - 612)	1,805	(1,220 - 2,755)	15,550	(10,950 - 32,850)	18,600	(12,825 - 39,825)	18,100	(12,325 - 39,225)
	Feb	356	(254 - 770)	1,890	(1,329 - 3,258)	17,560	(9,403 - 29,578)	22,265	(12,035 - 40,480)	21,715	(11,510 - 39,905)
	Mar	705	(439 - 1,168)	2,620	(1,993 - 4,113)	28,400	(21,825 - 45,425)	35,850	(26,200 - 52,200)	35,300	(25,625 - 51,625)
	Apr	437	(276 - 834)	1,982	(1,270 - 3,061)	27,455	(17,730 - 37,820)	30,720	(22,618 - 53,570)	30,170	(22,018 - 52,993)
	May	349	(178 - 664)	1,120	(617 - 2,675)	17,000	(12,100 - 26,125)	19,800	(15,225 - 32,400)	19,200	(14,625 - 31,825)
	Jun	224	(169 - 327)	807	(423 - 1,093)	10,470	(5,253 - 14,613)	12,045	(7,386 - 19,213)	11,445	(6,813 - 18,605)
	Jul	170	(123 - 229)	617	(270 - 1,037)	5,515	(3,805 - 9,315)	7,070	(4,233 - 12,250)	6,340	(3,610 - 11,625)
	Aug	126	(89 - 225)	328	(196 - 611)	4,700	(2,588 - 8,820)	5,655	(3,188 - 10,650)	5,040	(2,428 - 10,045)
	Sep	118	(85 - 289)	330	(213 - 1,054)	3,672	(2,233 - 8,775)	4,385	(3,068 - 10,182)	3,779	(2,421 - 9,640)
	Oct	155	(79 - 306)	439	(284 - 1,358)	4,620	(2,593 - 9,928)	5,520	(3,268 - 13,425)	4,915	(2,675 - 12,825)
	Nov	209	(106 - 467)	1,090	(536 - 1,875)	6,202	(4,646 - 17,028)	8,221	(5,915 - 20,605)	7,671	(5,343 - 20,035)
	Dec	317	(235 - 564)	1,955	(1,358 - 2,813)	15,700	(8,003 - 25,550)	19,050	(10,760 - 31,250)	18,450	(10,213 - 30,675)
12	Annual Q_{10} flow (cfs)	374	(324 - 779)	1,766	(1,393 - 2,830)	17,490	(15,120 - 28,100)	22,730	(19,085 - 35,425)	22,230	(18,485 - 34,938)
13	2 yr Recurrence Interval (R.I.) event (cfs)	4,050		15,600		89,500		116,000		115,000	
14	10 yr R.I. event (Large flood) (cfs)	8,730		23,970		229,300		268,500		267,800	
15	# events, Winter	2	(2 - 4)	3	(2 - 4)	2	(1 - 3)	2	(1 - 3)	2	(1 - 3)

		Opequon - 1616500		Monocacy - 1643000		Potomac Point of Rocks - 1638500		Great Falls - 1646502		Little Falls - 1646500	
Ref.	Flow Statistic	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)	Median	(q1 - q3)
16	# events, Spring	3	(0 - 4)	2	(1 - 4)	2	(1 - 3)	2	(1 - 3)	2	(1 - 3)
17	# events, Summer	2	(0 - 4)	3	(2 - 6)	2	(0 - 3)	2	(0 - 3)	2	(0 - 3)
18	# events, Fall	2	(1 - 5)	4	(2 - 5)	2	(0 - 3)	2	(1 - 3)	2	(1 - 3)
19	Duration (days) of events, Spring	2.0	(1.0 - 3.8)	2.0	(1.8 - 3.8)	4.0	(2.8 - 4.0)	3.0	(2.0 - 4.5)	3.0	(2.0 - 4.5)
20	Duration (days) of events, Summer	2.0	(1.3 - 2.9)	2.0	(1.0 - 2.0)	3.0	(2.0 - 6.5)	3.0	(2.4 - 4.8)	3.0	(2.4 - 4.8)

Notes:

a) See Table 14 for definition of statistics.
b) Statistics computed on observed flows for the period 1/1/1984 through 12/31/2005. This period was chosen for two reasons. First, a longer time series would have included flows representative of different land use patterns, climate, low flow augmentation, and consumptive use compared to current conditions. Second, the 1984-2005 time period matches the time period being simulated in flow models developed for the Middle Potomac Watershed Assessment project. Using the same time period facilitates comparison with results from that project.
c) For each river reach, the number following the reach name is the USGS gage ID.
d) q1 and q3 are the 1st and 3rd quartile values which provide an indicate of inter-annual variability.

LITERATURE CITED

Also see **Appendix F** for instructions to access an on-line bibliographic database with these plus additional references.

Acuña, V., I. Muñoz, A. Giorgi, M. Omella, F. Sabater, and S. Sabater. 2005. Drought and postdrought recovery cycles in an intermittent Mediterranean stream: structural and functional aspects. Journal of the North American Benthological Society 24:919-933.

Allan, J.D. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284.

Annapolis, MD: U.S. Department of the Interior, National Park Service.Grunwald, C, J. Stabile, J. R. Waldman, R. Gross, and I. Wirgin. 2002. Population genetics of shortnose sturgeon Acipenser brevirostrum based on mitochondrial DNA control region sequences. Molecular Ecology 11:1885-1898.

Apse, C., M. DePhilip, J. Zimmerman, and M.P. Smith. 2008. Case Study 5: Development of flow alteration-ecological response curves for Pennsylvania Streams. In Developing instream flow criteria to support ecologically sustainable water resource planning and management. The Nature Conservancy:195.

Argerich, A., M. A. Puig, and E. Pupilli. 2004. Effect of floods of different magnitude on the macroinvertebrate communities of Matarranya Stream (Ebro River Basin, NE Spain). Limnetica. 23:283-294.

Arthington, A. H., S. E. Bunn, N. L. Poff, and R. J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16: 1311-1318.

Batiuk, R., R. Orth, K. Moore, J. C. Stevenson, W. Dennison, L. Staver, V. Carter, N. Rybicki, R. Hickman, S. Kollar, S. Bieber, and P. Heasly. 1992. Submerged Aquatic Vegetation Habitat Requirements and Restoration Targets: A Technical Synthesis. Chesapeake Bay Program, Annapolis, MD.

Benda, L. E., N. L. Poff, D. D. Miller, T. Dunne, G. H. Reeves, G. R. Pess, and M. M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54: 413-427.

Bennett, J. P., J. W. Woodward, and J. Shultz. 1986. Effect of discharge on the chlorophyll a distribution in the tidally-influenced Potomac River. Estuaries 9:250–260.

Bergstrom, P. W., R. F. Murphy, M. D. Naylor, R. C. Davis, and J. T. Reel. Underwater Grasses in Chesapeake Bay and Mid-Atlantic Coastal Waters: Guide to Identifying Submerged Aquatic Vegetation. Maryland Sea Grant College. 77 p.

Blinn, D. W., J. P. Shannon, L. E. Stevens, and J. P. Carder. 1995. Consequences of fluctuating discharge for lotic communities. Journal of the North American Benthological Society. 14:233-248.

Booth, D.B. and C.R. Jackson. 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. Journal of the American Water Resources Association 33(5):1077-1090.

Borisova, T. et al. 2006 “Benefits from Improved Water Quality- The Opequon Watershed in West Virginia And Virginia.” Delivered at the 2006 USDA-CSREES National Water Quality Conference "Research, Extension and Education for Water Quality and Quantity" February 5-9, 2006. San Antonio, TX http://www.soil.ncsu.edu/swetc/waterconf/2006 (Accessed December 2009)

Borsuk, M. E., C. A. Stow, and K. H. Reckhow. 2004. Confounding Effect of Flow on Estuarine Response to Nitrogen Loading. Journal of Environmental Engineering. 130:605-614.

Bowen, Z.H., M.C. Freeman, K.D. Bovee. 1998. Evaluation of Generalized Habitat Criteria for Assessing Impacts of Altered Flow Regimes on Warmwater Fishes. Transactions of the American Fisheries Society. 127.455-468.

Boyer, J. N., R. R. Christian, and D. W. Stanley. 1993. Patterns of phytoplankton primary productivity in the Neuse River estuary, North Carolina, USA. Marine ecology progress series. 97:287-297.

Boynton, W. R., J. H. Garber, R. Summers, and W. M. Kemp. 1995. Inputs, transformations and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. Estuaries 18:285–314.

Bray, J. R., and J. T. Curtis. 1957. An ordination of the upland forest communities of Wisconsin. Ecological Monographs 27: 325-349.

Brush, G. S., and R. S. DeFries. 1981. Spatial distributions of pollen in surface sediments of the Potomac estuary. Limnol. Oceanogr. 26(2):295-309.

Buchanan, C. 2008. From a Drowned River Valley to a Drowned River. Paper prepared for the Metropolitan Washington Council of Governments Potomac River Monitoring Forum, March 10-11, 2008. Available online at www.mwcog.org/environment/PotomacForum/presentations.asp.

Buchanan, C. 2009. An analysis of continuous monitoring data collected in tidal Potomac embayments and river flanks. ICPRB Report 09-3. Available online at www.potomacriver.org.

Buchanan, C. and J. A. Schloss. 1983. Spatial distributions and hypothetical grazing pressures of zooplankton in the tidal, freshwater Potomac River. J. Freshwater Ecol. 2(2):117-128.

Buchanan, C., R. V. Lacouture, H. G. Marshall, M. Olson, and J. Johnson. 2005. Phytoplankton reference communities for Chesapeake Bay and its tidal tributaries. Estuaries 28:138–159.

Bunn, S. E., and A. H. Arthington. 2003. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30: 492-507.

Canton, S. P., L. D. Cline, R. A. Short, and J. V. Ward. 1984. The macroinvertebrates and fish of a Colorado stream during a period of fluctuation discharge. Freshwater biology. Oxford. 14:311-316.

Carter, V., and N. B. Rybicki. 1990. Light attenuation and submersed macrophyte distribution in the tidal Potomac River and Estuary. Estuaries 13:441-442.

Carter, V., and N. Rybicki. 1992. "Upper Potomac River." In Batiuk et al. 1992. Submerged Aquatic Vegetation Habitat Requirements and Restoration Targets: A Technical Synthesis. Chesapeake Bay Program, Annapolis, MD.

Carter, V., J. M. Landwehr, N. B. Rybicki, J. T. Reel, and H. A. Ruhl. 2000. Linkages among submersed aquatic vegetation, nutrients, river discharge, and weather in the tidal Potomac River and Estuary. Available in the Potomac Integrative Analysis Online Collection at http://www.potomacriver.org/cms/wildlifedocs/PIA_AppE_2000_Carter_etal.pdf.

Carter, V., N. B. Rybicki, J. M. Landwehr, and M. Turtora. 1994. Role of weather and water quality in population dynamics of submersed macrophytes in the tidal Potomac River. Estuaries 17:417-426.

Carter, V., N. B. Rybicki, J. M. Landwehr, J. T. Reel, and H. A. Ruhl. 1998. Summary of correlations among seasonal water quality, discharge, weather, and coverage by submersed aquatic vegetation in the tidal Potomac River and Potomac estuary, 1983-1996. USGS Open-File Report 98-657. Available online at http://water.usgs.gov/nrp/proj.bib/sav/ofr98/.

Carter, V., N. B. Rybicki, R. T. Anderson, T. J.Trombley, and G. L. Zynjuk. 1985. Data on distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and transition zone of the Potomac River, Maryland, Virginia and the District of Columbia, 1983 and 1984. Open-File Report 85-82. United States Geological Survey, Reston, Virginia.

Cattaneo, A., L. Cloutier, and G. Methot. 2004. The response of invertebrates in moss and in gravel to water level fluctuations in a Quebec stream. Archiv fuer Hydrobiologie. 161 161:21-43.

Chesapeake Bay Program. 2009a. Bay Barometer: A Health and Restoration Assessment of the Chesapeake Bay and Watershed in 2008. CBP/TRS 293-09, EPA-903-R-09-001. Available online at: www.chesapeakebay.net/content/publications/cbp_34915.pdf

Chesapeake Bay Program. 2009b. Chesapeake Bay Hydrologic Simulation Program-Fortran model phase 5.186. Website: http://ches.communitymodeling.org/models.php.

Cincotta, D. A., K. L. Dull, S. L. Markham, and R. D. Williams. 1986. Ichthyofaunal checklist and comparison of two North Branch Potomac River tributaries where alleged Ohio-Potomac River stream captures occurred. Proceedings of the Pennsylvania Academy of Science PPASAK 60(2):129-134.

Clarkson, Roy B. 1964. "Tumult on the Mountains - Lumbering in West Virginia -1770-1920." McClain Printing Company, Parsons, WV.

Clarkson, Roy B. 1964. "Tumult on the Mountains - Lumbering in West Virginia -1770-1920." McClain Printing Company, Parsons, WV.

Cohen, R. R. H., P. V. Dresler, E. J. P. Philips, and R. L. Cory. l984. The effect of the Asiatic clam, Corbicula fluminea, on phytoplankton of the Potomac River, Maryland. Limnol. Oceanogr. 29(l):l70-l80.

Connell, J. H. 1978. Diversity in tropical rain forests and coral reefs. Science 199: 1302-1310.

Cronin, W. B., and A. W. Pritchard. 1975. Additional statistics on the dimensions of the Chesapeake Bay and its tributaries: Cross-section widths and segment volumes per meter depth. Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, MD. Special Report 42, Ref. 75-3.

Cronin, W. B. 1971. Volumetric, aereal, and tidal statistics of the Chesapeake Bay estuary and its tributaries. Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, MD. Special Report 20, Ref. 71-2.

Cushman, R. M. 1985. Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. North American Journal of Fisheries Management 5: 330-339.

Day, J. W., Jr., C. A. S. Hall, W. M. Kemp, and A. Yanez-Arancibia. 1989. Estuarine Ecology. John Wiley & Sons, New York. 558p.

DeFries, R. S. 1986. Effects of land-use history on sedimentation in the Potomac estuary, Maryland: A Water-Quality Study of the Tidal Potomac River and Estuary. U. S. Geological Survey water supply paper 2234-K.

Diaz, R. J. 2001. Overview of Hypoxia Around the World. J Environ Qual 30:275-281.

Dresler, P. V., and R. L. Cory. 1980. The Asiatic clam, Corbicula fluminea (Muller), in the tidal Potomac River. Estuaries 3(2):l50-l5l.

Dunne, T. and L.B. Leopold. 1943. Water in Environmental Planning. W.H. Freeman and Company, New York: 818p.

Everson, D. A., and D. H. Boucher. 1998. Tree species-richness and topographic complexity along the riparian edge of the Potomac River. Forest Ecology and Management 109:305-314.

Fausch, K. D., Y. Taniguchi, S. Nakano, G. D. Grossman, and C. R. Townsend. 2001. Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. Ecological Applications 11: 1438-1455.

Fleming, G. P. 2006. Vegetation Ecology of the Potomac Gorge. Presented at the October 14, 2006 annual meeting of the Maryland Native Plant Society in Shady Grove, Maryland. From the Virginia Department of Conservation and Recreation, Division of Natural Heritage. (http://www.dcr.virginia.gov/natural_heritage/documents/pogotext3.pdf).

Frimpong, E. A., and P. L. Angermeier. 2009. FishTraits: a database of ecological and life-history traits of freshwater fishes of the United States. Fisheries 34: 487-495.

Galay, V. J. 1983. Causes of river bed degradation. Water Resources Research 19: 1057-1090.

Garrett, W. E. and K. Garrett. 1987. George Washington's Patowmack Canal. National Geographic 171: 716-753.

Graves, John. 1966. "A River and a Piece of Country", a Potomac Essay from The Potomac Interim Report to the President, Federal Interdepartmental Task Force on the Potomac, Potomac River Basin Advisory Committee.

Greene, K.E., J.L. Zimmerman, R.W. Laney and J.C. Thomas-Blate. 2009. Atlantic coast diadromous fish habitat: A review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission. 484 pp.

Griswold, M. W., R. W. Berzinis, T. L. Crisman, and S. W. Golladay. 2008. Impacts of climatic stability on the structural and functional aspects of macroinvertebrate communities after severe drought. Freshwater Biology. 53:2465-2483.

Grumet, R. S. 2000. Bay, Plain, and Piedmont: A Landscape History of the Chesapeake Heartland from 1.3 Billion Years Ago to 2000. (The Chesapeake Bay Heritage Context Project, 183 p.)

Grunwald, C, L. Maceda, J. Waldman, J. Stabile, and I. Wirgin. 2008. Conservation of Atlantic sturgeon Acipenser oxyrinchus oxyrinchus : delineation of stock structure and distinct population segments. Conservation Genetics 9:1111-1124.

Harding, J. R., L. W., D. DeGobbis, and R. Precali. 1999. Production and fate of phytoplankton: Annual cycles and inter-annual variability, p. 131–172. In T. C. Malone, A. Malej, L. W. Harding, Jr., N. Smodlaka, and R. E. Turner (eds.), Ecosystems at the Land-Sea Margin: Drainage Basin to Coastal Sea. Coastal and Estuarine Studies 55, American Geophysical Union, Washington, D.C.

Hitt, N. P., and P. L. Angermeier. 2008. Evidence for fish dispersal from spatial analysis of stream network topology. Journal of the North American Benthological Society 27: 304-320.

Hocutt, C. H. 1979. Drainage evolution and fish dispersal in the central Appalachians: summary. Geological Society of America Bulletin 90:129.

Hoffman, J. C., D. A. Bronk, and J. E. Olney. 2008. Organic Matter Sources Supporting Lower Food Web Production in the Tidal Freshwater Portion of the York River Estuary, Virginia. Estuaries and Coasts. 31:898-911.

Hupp, C. R., and W. R. Osterkamp. 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. Ecology 66(3):670-681.

Hurley, L. M. 1991. Submerged Aquatic Vegetation, p. 2-1—2-19. In S. L. Funderburk, S. J. Jordan, J.A.. Mihursky, and D. Riley (eds.), Habitat Requirements for Chesapeake Bay Living Resources. Maryland Department of Natural Resources.

Hyland, J. L., W. Balthis, M. Posey, C. T. Hackney, and T. Alphin. 2004. The Soft-bottom Macrobenthos of North Carolina Estuaries. Estuaries. 27:501-514.

ICPRB (Interstate Commission on the Potomac River Basin). 2010. 2010 Washington metropolitan area water supply reliability study. Part 1: Demand and resource availability forecast for the year 2040. ICPRB Report No. 10-01.

Jackson, L.E. Jr., Hungr, O., Gardner, J.S., and C. Mackay. 1989. Cathedral Mountain debris flows, Canada. Bulletin of the International Association of Engineering Geology. 40: 35-54.

Jaworski, Norbert A., William Romano, Claire Buchanan, and Carole Jaworski. 2007. The Potomac River Basin and its Estuary: Landscape Loadings and Water Quality Trends, 1895-2005. Available from the Potomac Integrative Analysis Online Collection at www.potomacriver.org

Jenkins, R. E., and N. M. Burkhead. 1994. Freshwater Fishes of Virginia. American Fisheries Society, Bethesda, Maryland.

Jones, R. C., and C. Buchanan. 2009. Analysis of continuous water quality monitoring data from the tidal freshwater Potomac River. Proceedings of the 2009 Virginia Water Research Conference, October 15-16, 2009. Available online at www.vwrrc.vt.edu/2009conference_program.html.

Kame'enui, Ani and E. R.Hagen, 2005. Climate change and water resources in the Washington metropolitan area: research motivations and opportunities. Interstate Commission on the Potomac River Basin, Rockville, Maryland. Report No. ICPRB-05-05

Kame'enui, Ani, Erik R. Hagen, Julie E. Kiang. 2005. Water Supply Reliability Forecast for the Washington Metropolitan Area Year 2025. Interstate Commission on the Potomac River Basin, Rockville, Maryland. Report No. ICPRB-05-06. 176 p.

Kemp, W. M., W. R. Boynton, J. E. Adolf, D. F. Boesch, W. C. Boicourt, G. Brush, J. C. Cornwell, T. R. Fisher, P. M. Glibert, J. D. Hagy, L. W. Harding, E. D. Houde, D. G. Kimmel, W. D. Miller, R. I. E. Newell, M. R. Roman, E. M. Smith, and J. C. Stevenson. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. Marine Ecology-Progress Series 303:1-29.

Kerr, L. A., and D. H. Secor. 2009. Bioenergetic trajectories underlying partial migration in Patuxent River (Chesapeake Bay) white perch (Morone americana). Canadian Journal of Fisheries and Aquatic Sciences 66:602-612.

Kerr, L. A., D. H. Secor, and P. M. Piccoli. 2009. Partial Migration of Fishes as Exemplified by the Estuarine-Dependent White Perch. Fisheries 34:114-123.

Kerwin, J. A., R. E. Munro and W. W. A. Peterson. 1977. Distribution and abundance of aquatic vegetation in the upper Chesapeake Bay, 1971-1974. In: The effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System. J. Davis, Ed. Chesapeake Research Consortium, Inc. Publication No. 54.The Johns Hopkins University Press, Baltimore. pp. 393-400.

Klohe, C. A., and R. T. Kay. 2007. Hydrogeology of the Piney Point-Nanjemoy, Aquia, and Upper Patapsco aquifers, Naval Air Station Patuxent River and Webster Outlying Field, St. Mary's County, Maaaaryland, 2000-2006. U. S. Geological Survey Scientific Investigations Report 2006-5266, 26p.

Klug, J. L. 2006. Nutrient limitation in the lower Housatonic River estuary. Estuaries and Coasts. 29:831-840.

Kneeland, S. C. and J. M. Rhymer. 2008. Determination of fish host use by wild populations of rare freshwater mussels using a molecular identification key to identify glochidia. Journal of the North American Benthological Society 27:150-160.

Kozar, M.D., and Weary, D.J., 2009, Hydrogeology and ground-water flow in the Opequon Creek watershed area, Virginia and West Virginia: U.S. Geological Survey Scientific Investigations Report 2009-5153, 61 p.

Kraus, R. T, and D. H. Secor. 2005a. Application of the nursery-role hypothesis to an estuarine fish. Marine Ecology-Progress Series 291:301-305.

Kraus, R. T, and D. H. Secor. 2005b. Connectivity in estuarine white perch populations of Chesapeake Bay: evidence from historical fisheries data. Estuarine Coastal and Shelf Science 64:108-118.

Kynard, B. 1997. Life history, latitudinal patterns, and status of the shortnose sturgeon, Acipenser brevirostrum. Environmental Biology of Fishes 48:1-4.

Kynard, B., M. Breece, M. Atcheson, M. Kieffer, and M. Mangold. 2009. Life history and status of shortnose sturgeon (Acipenser brevirostrum) in the Potomac River. Journal of Applied Ichthyology Zeitschrift für angewandte Ichthyology 25:34-38.

Landwehr, J. M., J. T. Reel, N. B. Rybicki, H. A. Ruhl, and V. Carter. 1999. Chesapeake habitat criteria scores and the distribution of submersed aquatic vegetation in the tidal Potomac River and Potomac estuary, 1983 - 1997. USGS Open-File Report 99-219. Available online at http://pubs.usgs.gov/of/1999/of99-219/.

Lawrence, R.L. and A. Wright. 2001. Rule-based classification systems using Classification and Regression Tree (CART) Analysis. Photogrammetric Engineering and Remote Sensing 67:1137-1142.

Lea, C. 2000. Plant communities of the Potomac Gorge and their relationship to fluvial factors. Unpublished M.S. Thesis, George Mason University, p. 219

Legrand, H.E and V.T. Stringfield. 1973. Karst hydrology - A review. Journal of Hydrology 20:97-120.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman and Company, p.522

Lettenmaier DP, Wood AW, Palmer RN, et al. 1999. Water resources implications of global warming: a US regional perspective. Climate Change 43: 537–79.

Li, X., D. E. Weller, C. L. Gallegos, T. E. Jordan, and H. C. Kim. 2007. Effects of watershed and estuarine on the abundance of submerged aquatic vegetation in Chesapeake Bay Subestuaries. Estuaries and Coasts 30(5):840-854.

Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher, and R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecological Monographs 40: 23-47.

LimnoTech. 2007. PCB TMDL Model for the Potomac River Estuary: Final Report on Hydrodynamic/Salinity and PCB Transport and Fate Models. EPA Contract No. 68-C-03-041. Work Assignment No. 4-34. Prepared for Battelle by LimnoTech, September 28, 2007.

Lin, J., L. Xie, L. J. Pietrafesa, H. Xu, W. Woods, M. A. Mallin, and M. J. Durako. 2008. Water quality responses to simulated flow and nutrient reductions in the Cape Fear River Estuary and adjacent coastal region, North Carolina. Ecological Modelling. 212:200-217.

Lins, H.F. 2005. Stream flow Trends in the United States, U.S. Department of the Interior, United States Geological Survey. Fact Sheet 2005-3017. March, 2005.

Lippson, A. J. and R. L. Lippson. 1997. Life in the Chesapeake Bay, Second Edition. The Johns Hopkins University Press, Baltimore, MD.

Lippson, A. J., M. S. Haire, A. F. Holland, F. Jacobs, J. Jensen, R. L. Moran-Johnson, T. T. Polgar and W. A. Richkus. 1979. Environmental Atlas of the Potomac Estuary. Johns Hopkins University Press, Baltimore & London. 280p+9 Folio Maps.

Llansó, R. J., J. Dew-Baxter, and L. C. Scott. 2008. Chesapeake Bay Water Quality Monitoring Program, Long-Term Benthic Monitoring and Assessment Component, Level 1 Comprehensive Report. July 1984 – December 2007 (vols. 1&2). Prepared for Maryland Department of Natural Resources, Annapolis MD by Versar, Inc., Columbia, MD.

Lorie, M. and E. Hagen. 2007. Placing Potomac River droughts in context using synthetic and paleoclimatic data. Proceedings of World Environmental and Water Resources Congress 2007 "Restoring Our Natural Habitat," Environmental & Water Resources Institute of the American Society of Civil Engineers. Publication number 40927.

Malone, T. C., L. H. Cocker, S. E. Pike, and B. W. Wendler. 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. Marine Ecology Progress Series 48:235–249.

Mann, K.H., and J. R. N. Lazier. 2006. Dynamics of marine ecosystems : biological-physical interactions in the oceans. Blackwell Pub., Malden, MA.

Marchetti, M. P., T. Light, P. B. Moyle, and J. H. Viers. 2004. Fish invasions in California watersheds: testing hypotheses using landscape patterns. Ecological Applications 14: 1507-1525.

Maryland Department of the Environment (MDE). 2008. Integrated Report of Surface Water Quality (formerly known as the 303(d) List and 305(b) Report). Available online at http://www.mde.state.md.us/programs/waterprograms/tmdl/maryland%20303%20dlist/index.asp

MDE (Maryland Department of the Environment) 2007. Total Maximum Daily Loads of Fecal Bacteria for the Lower Monocacy River Basin in Carroll, Frederick, and Montgomery Counties, Maryland. Baltimore, MD: Maryland Department of the Environment.

McCoy, J.L., and R.M. Summers. 1992. Water quality trends in Big Pipe Creek during the Double Pipe Creek Rural Clean Water Program. Proceedings: National Rural Clean Water Symposium, U.S.EPA, EPA/625/R-92/006.

McCune, B., and J. B. Grace. 2002. Analysis of Ecological Communities. MjM Software Design, Gleneden Beach, OR.

MGS (Maryland Geological Survey). 2007. A Brief Description of the Geology of Maryland. http://www.mgs.md.gov/esic/brochures/mdgeology.html (Accessed December, 2009).

Moltz, H. 2009. DRAFT Middle Potomac River Watershed Assessment, Ecologically Sustainable Water Management (ESWM), Risk Assessment Methodology (October 16, 2009). Draft ICPRB report.

Montagna, P. A., E. D. Estevez, T. A. Palmer, and M. S. Flannery. 2008. Meta-analysis of the relationship between salinity and molluscs in tidal river estuaries of southwest Florida, U.S.A. American Malacological Bulletin. 24:101-115.

Moore, K. A., and J. C. Jarvis. 2008. Environmental factors affecting recent summertime eelgrass diebacks in the Lower Chesapeake Bay: implications for long-term persistence. Journal of Coastal Research. 55: 135-147.

Naiman, R. J., R. Bilby, E., and P. A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50: 996-1011.

Najjar, R. G., C. R. Pyke, M. B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M. R. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science 86:1-20.

Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R. Bord, J. Gibson, V.S. Kennedy, C.G. Knight, P. Megonigal, R. O'Connor, C.D. Polsky, N.P. Psuty, B. Richards, L.G. Sorenson, E. Steele, and R.S. Swanson, 2000. The potential impacts of climate change on the Mid-Atlantic Coastal Region. Climate Research, 14: 219-233.

Neff R., H. Chang, C.G. Knight, R.G. Najjar, B. Yarnal and H.A. Walker, 2000. Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources. Climate Research,14: 207-218.

Niklitschek, E. J., and D. H. Secor. 2005. Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay. Estuarine, Coastal and Shelf Science 64:135-148.

Niklitschek, E. J., and D. H. Secor. 2009a. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: I. Laboratory results. Journal of Experimental Marine Biology and Ecology 381:S150-S160.

Niklitschek, E. J., and D. H. Secor. 2009b. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: II. Model development and testing. Journal of Experimental Marine Biology and Ecology 381:S161-S172.

North, E. W., and E. D. Houde. 2001. Retention of white perch and striped bass larvae: Biological-physical interactions in Chesapeake Bay estuarine turbidity maximum. Estuaries 24:756-769.

North, E. W., and E. D. Houde. 2003. Linking ETM physics, zooplankton prey, and fish early-life histories to stiped bass Morone saxatilis and white perch M. americana recruitment. Marine Ecology Progress Series 260: 219-236.

Novotny, V. and O. Harvey. 1993. Water Quality: Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand Reinhold, New York: 1054p.

O'Dee, S. H. and G. T. Watters. 2000. New or confirmed host identifications for ten freshwater mussels. Proceedings of the Conservation, Captive Care, and Propagation of Freshwater Mussels Symposium, 1998, pg. 77-82.

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

Olson, M. 1999. January 7, 1999 memo to Data Analysis Work Group entitled ''Summary of Flow Characterization for 1985–1996.'' Chesapeake Bay Program, Annapolis, Maryland.

OPCIPSC (Opequon Creek IP Steering Committee). 2006. "Opequon Creek Watershed TMDL Implementation Plan. Available online at: http://www.tmdl.bse.vt.edu/index.php/publication_db/show_all/opequon_creek_watershed_tmdl_implementation_plan/ (Accessed December, 2009)

Ortmann, A. E. 1913. The Alleghenian divide, and its influence upon the freshwater fauna. Proceedings of the American Philosophical Society 52: 287-381

Paerl, H. W., L. M. Valdes, B. L. Peierls, J. E. Adolf, and L. W. Harding. 2006. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. Limnology and Oceanography. 51:448-462.

Palmer et al, 2008. "Climate change and the world's river basins: anticipating management options." By Margaret A Palmer, Catherine A Reidy Liermann, Christer Nilsson, Martina Flörke, Joseph Alcamo, P. Sam Lake, and Nick Bond. Front Ecol Environ 2008; 6(2): 81–89, doi:10.1890/060148

Palmer, M.A., D. Lettenmeier, S. Postel, et al. 2007. Adaptation options for climate-sensitive ecosystems and resources: wild and scenic rivers. Washington, DC: US Climate Change Science Program. Synthesis and assessment product 4.4.

Phelps, H. L. 1994. The Asiatic clam (Corbicula fluminea) invasion and system-level ecological change in the Potomac River estuary near Washington, D.C. Estuaries 17(3):614-621.

Poff, N.L., M.M. Brinson, and J.W. Day. 2002. Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems. Arlington, VA: US Pew Center for Global Change.

Poff, N. L. and 18 co-authors. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55: 147–170.

Poff, N. L., D. J. Allan, M. A. Palmer, D. D. Hart, B. D. Richter, A. H. Arthington, K. H. Rogers, J. L. Meyer, and J. A. Stanford. 2003. River flows and water waters: emerging science for environmental decision making. Frontiers in Ecology and the Environment 1: 298-306.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47: 769-784.

Poff, N.L., B.P. Bledsoe, C.O. Cuhaciyan. 2006. Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. Geomorphology 79:264-285.

Postel, S. and B. Richter, 2003. Rivers for Life: Managing Water for People and Nature. Island Press, Washington, D.C.

Rashleigh, B. and G.D. Grossman. 2005. An individual based simulation model for mottled sculpin (Cottus bairdi) in a southern Appalachian stream. Ecological Modeling. 187(2-3): 247-258l.

Reed, J. C., Jr. 1981. Disequilibrium profile of the Potomac River near Washington, D.C. – A result of lowered base level or Quaternary tectonics along the Fall Line? Geology 9(10): 445-450.

Richter, B.D., A.T. Warner, J.L. Meyer, and K. Lutz. 2006. A collaborative and adaptive process for developing environmental flow recommendations. River Res. Applic. 22:297-318.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter, B.D., R. Mathews, D.L. Harrison, and R. Wigington, 2003. Ecologically Sustainable Water Management: Managing River Flows for Ecological Integrity. Ecological Applications 13:206-224.

Robinson, C. T., S. Aebischer, and U. Uehlinger. 2004. Immediate and habitat-specific responses of macroinvertebrates to sequential, experimental floods. Journal of the North American Benthological Society 23:853-867.

Rutherford, E. S., and E. D. Houde. 1995. The Influence of Temperature on Cohort-Specific Growth, Survival, and Recruitment of Striped Bass, Morone saxatilis, Larvae in Chesapeake Bay. Fishery Bulletin 93: 315-332.

Rutherford, E.S., E. D. Houde, and R. M. Nyman. 1997. Relationship of larval-stage growth and mortality to recruitment of striped bass, Morone saxatilis, in Chesapeake Bay Estuaries 20:174-198.

Schlosser, I. J. 1985. Flow regime, juvenile abundance, and the assemblage structure of stream fishes. Ecology 66: 1484-1490.

Schultz, C., D. Tipton, and J. Palmer. 2004. Annual and seasonal water budgets for the Monocacy/Catoctin drainage area. Interstate Commission on the Potomac River Basin. ICRPB Report No. 04-04.

Schwartz, F. J. 1956. The distribution and probable postglacial dispersal of the percid fish, Etheostoma b. blennioides, in the Potomac River. Copeia 1965(3): 285-290.

Scrimgeour, G. J., and M. J. Winterbourn. 1989. Effects of Floods on Epilithon and Benthic Macroinvertebrate Populations in an Unstable New Zealand River. Hydrobiologia. 171.

Secor, D. H. 2000a. Longevity and resilience of Chesapeake Bay striped bass. ICES Journal of Marine Science 57:808-815.

Secor, D. H. 2000b. Spawning in the nick of time? Effect of adult demographics on spawning behaviour and recruitment in Chesapeake Bay striped bass. ICES J. Mar. Sci. 57:403-411.

Secor, D. H. 2002. Atlantic Sturgeon Fisheries and Stock Abundances During the Late Nineteenth Century. Biology, Management, and Protection of North American Sturgeon. 28 p.

Secor, D. H., and P. M. Piccoli. 2007. Oceanic migration rates of Upper Chesapeake Bay striped bass (Morone saxatilis), determined by otolith microchemical analysis. Fishery Bulletin 105:62-73.

Sellner,K.G. and Fonda-Umani. 1999. Dinoflagellate blooms and mucilage production, p. 173–206. In T. C. Malone, A. Malej, L. W. Harding, Jr., N. Smodlaka, and R. E. Turner (eds.), Ecosystems at the Land-Sea Margin: Drainage Basin to Coastal Sea. Coastal and Estuarine Studies 55, American Geophysical Union, Washington, D.C.

Sepkoski, J. J. and M. A. Rex. 1974. Distribution of Freshwater Mussels: Coastal Rivers as Biogeographic Islands. Systematic Zoology 23: 165-188.

Sheldon, A. L. 1988. Conservation of stream fishes: patterns of diversity, rarity, and risk. Conservation Biology 2: 149-156.

Sheldon, F., and M. C. Thoms. 2006. Relationships between flow variability and macroinvertebrate assemblage composition: data from four Australian dryland rivers. River Research and Applications. 22:219-238.

Sin, Y., R. L. Wetzel, and I. C. Anderson. 1999. Spatial and Temporal Characteristics of Nutrient and Phytoplankton Dynamics in the York River Estuary, Virginia: Analyses of Long-term Data. Estuaries. 22:260-275.

Smith, S.M., J.S. Odenkirk and S. J. Reeser. 2005. Smallmouth Bass Recruitment Variability and its Relation to Stream Discharge in Three Virginia Rivers. North American Journal of Fisheries Management. 25:1112-1121.

Smogor, R. A., P. L. Angermeier, and C. K. Gaylord. 1995. Distribution and abundance of American eels in Virginia streams: tests of null models across spatial scales. Transactions of the American Fisheries Society 124: 789-803.

Snyder, C. D. et al. 2003. Influences of upland and riparian land use patterns on stream biotic integrity. Landscape Ecology 18: 647–664, 2003. Young J. A. ; Villella R. Lemarie D. P. Biological Resources Division, Leetown Science Center, United States Geological Survey, Kearneysville, West Virginia 25430, ETATS-UNIS

Snyder, C. D., and Z. B. Johnson. 2006. Macroinvertebrate assemblage recovery following a catastrophic flood and debris flows in an Appalachian mountain stream. Journal of the North American Benthological Society 25:825-840.

Sousa, R., C. Antunes, and L. Guilhermino. 2007. Species composition and monthly variation of the Molluscan fauna in the freshwater subtidal area of the River Minho estuary. Estuarine, Coastal and Shelf Science. 90-100.

Sprague, E., D. Burke, S. Claggett, and A. Todd. 2006. The state of the Chesapeake forests. The Conservation Fund, pp. 144.

Sprague, L. A., M. J. Langland, S. E. Yochum, R. E. Edwards, J. D. Blomquist, S. W. Phillips, G.W.Shenk, and S. D. Preston. 2000. Factors Affecting Nutrient Trends in Major Rivers of the Chesapeake Bay Watershed. Water Resources Investigations Report 00-4218, Richmond, Virginia.

Starnes, W. C. 2002. Current diversity, historical analysis, and biotic integrity of fishes in the lower Potomac basin in the vicinity of Plummers Island, Maryland - Contribution to the natural history of Plummers Island, Maryland XXVII. Proceedings of the Biological Society of Washington 115: 273-320.

Steiner, R. C., E. R. Hagen, and J. Ducnuigeen. 2000. Water supply demands and resource analysis in the Potomac River basin. ICPRB Report 00-5.

Stoddard, A., J. Harcum, J. Simpson, J.R. Pagenkopf, and R.K. Bastian. 2002. "Municipal Wastewater Treatment - Evaluating Improvements in National Water Quality " John Wiley and Sons, New York.

Suren, A. M., and I. G. Jowett. 2006. Effects of floods versus low flows on invertebrates in a New Zealand gravel-bed river. Freshwater Biology. 51:2207-2227.

Taylor, R. W. 1985. Comments on the distribution of freshwater mussels (Unionacea) of the Potomac River headwaters in West Virginia. Nautilus 99(2-3): 84-87

The Nature Conservancy. 2007. Indicators of Hydrologic Alteration, Version 7 User's Manual. Available online at: http://www.nature.org/initiatives/freshwater/conservationtools/

Thompson, E. 1996. Natural Communities of Vermont Uplands and Wetlands. Vermont Non-game and Natural Heritage Program, Waterbury, VT.

Thompson, H. D. 1939. Drainage evolution in the southern Appalachians. Bulletin of the Geological Society of America 50(8): 1323-1356.

Thomson, D, et al., 1999. Floodplain Forests of Maryland's Potomac Watershed -- Vegetation Classification / Description and Recommended Reference Sites. By Diane Thomson, MA Berdine, J Meininger, and A Gould. Wildlife and Heritage Division, Maryland Department of Natural Resources,

Thomson, D, et al., 1999. Floodplain Forests of Maryland's Potomac Watershed -- Vegetation Classification / Description and Recommended Reference Sites. By Diane Thomson, MA Berdine, J Meininger, and A Gould. Wildlife and Heritage Division, Maryland Department of Natural Resources, U.S. EPA Reference: Wetland Natural Communities of the Potomac Drainage Floodplain Forests Grant # CD993275, June, 1999.

Thorp, J. H., and A. P. Covich. 2001. Ecology and Classification of North American Freshwater Invertebrates, Second Edition. Academic Press, 1056p.

Tisdale, E.S. 1931. The 1930-1931 Drought and Its Effect Upon Public Water Supply. Am J Public Health Nations Health. 1931 Nov;21(11):1203-15.

Tiner, R. W. 1987. Mid Atlantic Wetlands - A Disappearing Natural Treasure. Copies through U.S. Fish and Wildlife Service, Ecological Services, Northeast Region, Hadley, MA

Ulanowicz, R.E., and T. T. Polgar. 1980. Influences of anadromous spawning behavior and optimal environmental conditions upon striped bass (Morone saxatilis) year-class success. Canadian Journal of Fisheries and Aquatic Sciences 37:143-154.

U. S. Environmental Protection Agency (USEPA). 1999. Reference: Wetland Natural Communities of the Potomac Drainage Floodplain Forests Grant # CD993275, June, 1999.

U. S. Environmental Protection Agency (USEPA). 2006. DFLOW 3.1 computer program. Available at: http://www.epa.gov/waterscience/models/dflow/. See also U.S. EPA. 1986. Technical Guidance Manual for Performing Wasteload Allocations Book VI - Design Conditions, Chapter 1 - Stream Design Flow for Steady-State Modeling. PB92-231178.

U. S. Environmental Protection Agency (USEPA). 2003. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity, and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries. EPA 903-R-03-002. Available online at: www.chesapeakebay.net/publication.aspx?publicationid=13142.

U. S. Geological Survey (USGS). 1998. Estimated Use of Water in the United States in 1995. W.P. Solley, R.R. Pierce, H.A. Perlman. U.S. Geological Survey Circular 1200, U.S. Department of the Interior. U.S. Government Printing Office.

Valdes-Weaver, L. M., M. F. Piehler, J. L. Pinckney, K. E. Howe, K. Rossignol, and H. W. Paerl. 2006. Long-term temporal and spatial trends in phytoplankton biomass and class- level taxonomic composition in the hydrologically variable Neuse-Pamlico estuarine continuum, North Carolina, U.S.A. Limnology and Oceanography. 51:1410-1420.

Versar, Inc., and PBS&J. 2001. Chesapeake Bay Water Quality Monitoring Program, 2000 Mesozooplankton Component. Prepared for Maryland Department of Natural Resources, Annapolis, MD.

Versar. 2003. Habitat Assessment of the Potomac River from Little Falls to Seneca Pool. Prepared for the Maryland Department of Natural Resources Power Plant Assessment Division, Annapolis, MD. Publication Number PPAD-03-1. Also at http://esm.versar.com/pprp/potomac/Habitat_Report_2002/Potomac_Low_Flow_Report_Final.pdf

Virginia Department of Environmental Quality (VADEQ). 2008. Virginia 305(b)/303(d) Water Quality Integrated Report to Congress and the EPA Administrator for the Period January 1, 2001 to December 31, 2006. Available online at http://www.deq.state.va.us/wqa/ir2008.html.

Vroblesky, D. A., and W. B. Fleck. 1991. Hydrogeologic framework of the Coastal Plain of Maryland, Delaware, and the District of Columbia. U.S. Geological Survey Professional Paper 1404-E.

Waele, J.D., L. Plan, and P. Audra. 2009. Recent developments in surface and subsurface karst geomorphology: An introduction. Geomorphology 106:1-8.

Watters, G. T. and S. H. O'dee. 1998. Metamorphosis of Freshwater Mussel Glochidia (Bivalvia: Unionidae) on Amphibians and Exotic Fishes. American Midland Naturalist 139: 49-57.

Webster, J. R., and J. L. Meyer. 1997. Stream organic matter budgets - introduction. Journal of the North American Benthological Society 16: 5-13.

Weisberg, S. B., A. J. Janicki, J. Gerritsen, and H. T. Wilson. 1990. Enhancement of benthic macroinvertebrates by minimum flow from a hydroelectric dam. Regulated Rivers: Research & Management. 5:265-277.

Weisberg, S.B., J.A. Ranasinghe, D.M. Dauer, L.C. Schaffner, R.J. Diaz, and J.B. Frithsen. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20:149-158.

Wilson JA, McKinley RS (2004) Distribution, habitat, and movements. In: LeBreton GTO, Beamish FW, McKinley RS (eds) Sturgeons and paddlefish of North America. Kluwer Academeic Publishers, Boston, pp 40-72.

Winemiller, K. O., and K. A. Rose. 1992. Patterns of life-history diversification in North American fishes: implications for population regulation. Canadian Journal of Fisheries and Aquatic Sciences 49: 2196-2218.

Witmer, P.L., P.M. Stewart, and C.K. Metcalf. 2009. Development and use of a sedimentation risk index for unpaved road-stream crossings in the Choctawhatchee watershed. Journal of the American Water Resources Association 45:734-747.

Wood, R.J., Austin HM (2009) Synchronous multidecadal fish recruitment patterns in Chesapeake Bay, USA. Canadian Journal of Fisheries and Aquatic Sciences 66:496-508.

Woods, A. J., J. M. Olmernik, and D. D. Brown. 1999. Level III and IV ecoregions of Delaware, Maryland, Pennsylvania, Virginia, and West Virginia. Available online at: http://www.epa.gov/wed/pages/ecoregions/reg3_eco.htm.

Zipper, C. E., J. J. Ney, L. A. Smock, E. P. Smith, J. C. Little, K. Stephenson, P. A. Bukaveckas, G. Yagow, J. Walker, and T. Younos. 2005. Issues related to freshwater nutrient criteria for lakes and reservoirs in Virginia. 98 pg. Virginia Water Resources Research Center, Blacksburg, VA.

APPENDIX A

FLOW METRICS CALCULATED BY THE INDICATORS OF HYDROLOGIC ALTERATION SOFTWARE

Table A-1. Summary of IHA metrics and their associated ecosystem influences (TNC 2007).

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal 12 parameters*	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for furbearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year *Subtotal 12 parameters*	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum *Subtotal 2 parameters*	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) *Subtotal 4 parameters*	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals *Subtotal 3 parameters*	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

Table A-2. Summary of Environmental Flow Component (EFC) parameters and their ecosystem influences (TNC 2007).

EFC Type	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows	Mean or median values of low flows during each calendar month *Subtotal 12 parameters*	• Provide adequate habitat for aquatic organisms • Maintain suitable water temperatures, dissolved oxygen, and water chemistry • Maintain water table levels in floodplain, soil moisture for plants • Provide drinking water for terrestrial animals • Keep fish and amphibian eggs suspended • Enable fish to move to feeding and spawning areas • Support hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event: • Duration (days) • Peak flow (minimum flow during event) • Timing (Julian date of peak flow) *Subtotal 4 parameters*	• Enable recruitment of certain floodplain plant species • Purge invasive, introduced species from aquatic and riparian communities • Concentrate prey into limited areas to benefit predators
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters*	• Shape physical character of river channel, including pools, riffles • Determine size of streambed substrates (sand, gravel, cobble) • Prevent riparian vegetation from encroaching into channel • Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants • Aerate eggs in spawning gravels, prevent siltation • Maintain suitable salinity conditions in estuaries
4. Small Floods	Frequency of small floods during each water year or season Mean or median values of small flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters*	Applies to small and large floods: • Provide migration and spawning cues for fish • Trigger new phase in life cycle (i.e insects) • Fish can spawn in floodplain, provide nursery area for juveniles • Provide new feeding opportunities for fish, waterfowl • Recharge floodplain water table • Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances) • Control distribution and abundance of plants on floodplain • Deposit nutrients on floodplain
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters*	Applies to small and large floods: • Maintain balance of species in aquatic and riparian communities • Create sites for recruitment of colonizing plants • Shape physical habitats of floodplain • Deposit gravel and cobbles in spawning areas • Flush organic materials (food) and woody debris (habitat structures) into channel • Purge invasive, introduced species • Disburse seeds and fruits of riparian plants • Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes) • Provide plant seedlings with prolonged access to soil moisture

APPENDIX B

CART ANALYSIS TO IDENTIFY AT-RISK RIVER SEGMENTS AND TRIBUTARIES IN THE POTOMAC RIVER BASIN

A preliminary risk assessment of sub-basins in the Potomac River Basin was conducted to identify watersheds with the highest risk of hydrologic alteration from multiple factors. To this end, 35 sub-basins and 5 Potomac River mainstem segments were assessed. Small tributaries and lands draining directly to the Potomac River were not considered in this phase of analysis. Coastal Plain sub-basins were selected based on location of impoundments, proximity to urban areas/threat of urban expansion, size, and distribution throughout coastal area. The mainstem segments were selected based on the location of USGS flow gages along the Potomac River. Risk factors calculated for the mainstem Potomac are cumulative (i.e. risks were calculated for the entire watershed upstream of the gage).

The risk assessment methodology consisted of four phases: (1) identifying possible risk factors in the Potomac Basin related to hydrologic alteration, (2) identifying correlation of risk factors with other risk factors and with Indicators of Hydrologic Alteration (IHA) metrics (Richter et al. 1996), (3) establishing risk thresholds utilizing hydrologic metrics, and (4) calculating a cumulative risk index for each sub-basin and mainstem segment based on selected risk factors.

Risk Factors Calculations

Risk factors that may influence instream flows were identified. Factors included urban, forest, and agricultural land uses; predicted future land use change in urban, forest, and agricultural areas; withdrawals; surface withdrawals; impoundments; consumptive use; impervious cover; karst geology; and Triassic Lowland geology. Urban land use and percent impervious cover were considered because increases in impervious cover increase overall system flashiness, the volume of surface run-off, and storm peaks while decreasing the time to hydrograph peak among other hydrologic impacts (Dunne and Leopold 1943, Novontny and Harvey 1993). Future land use change represents the potential risk of hydrologic alteration from urbanization, deforestation, and changes in agricultural land uses over time. Karst geology can also uniquely influence surface and groundwater hydrology (Waele, et al. 2009, Legrand and Stringfield 1973). Triassic lowlands were considered a risk factor for hydrologic alteration in the Potomac Basin due to documented decreased water yield to aquifers and high groundwater recession rates, i.e., water reaching the aquifer is only available for use for a short period of time (Schultz et al. 2004). Procedures utilized to calculate risk factor values are described below.

Land Uses

The 30m resolution RESAC land use raster data set (2000) developed by the University of Maryland was utilized to calculate percent urban, percent forest, and percent agricultural areas within each sub-basin. Forested land uses were a combination of deciduous forests, evergreen forests, and mixed forests for the purposes of this analysis. Agricultural land uses included pasture, hay, and croplands. Urban areas included low, medium, high intensity developed, transportation, and urban treed and grassed. The ArcToolbox 'tabulate area' tool was utilized to calculate land use areas for each sub-basin, which were subsequently converted to a percentage of the total area in Excel. The resulting land use percentages are shown in **Table B-1**. Percent urban cover ranged from 0.75% in the Little Cacapon sub-basin to 84.98% in the Cameron Run sub-basin. The median percent urban cover among all sub-basins was 7%. Areas at "severe" risk of hydrologic alteration from urban areas were primarily in the District of Columbia metropolitan area. Agricultural lands ranged from 0.35% in Cameron Run to 53.48% in the Catoctin Creek, VA sub-basin. The median agricultural land use was 16.18%. Sub-basins at "severe" risk of hydrologic alteration from agricultural land uses were primarily located in karst regions. Overall, the Potomac Basin is heavily forested with a median cover of 61.43%. The minimum percent forest is 3.38% in the Cameron Run sub-basin while the maximum is 87.53% in the Town Creek sub-basin. Low percent forest was considered a high risk of hydrologic alteration for this analysis. Therefore, Cameron Run was found to be at the highest risk followed by Rock and Anacostia, all of which are in the District of Columbia metropolitan area.

Impervious Cover

The 30m resolution RESAC impervious cover raster was used to calculate average percent impervious cover for each sub-basin. The raster was clipped to each sub-basin boundary, creating a unique raster for each sub-basin. Each raster cell has an associated percent impervious cover value. The values of all cells across a sub-basin were averaged using the 'calculate statistics' tool in ArcGIS 9.2. The resulting impervious cover percentages are shown in **Table B-1**. The median impervious cover was 1.22%. The maximum impervious cover was 30.59% in Cameron Run followed by Anacostia and Rock. Sub-basins with the highest percent impervious cover were located in the District of Columbia metropolitan area. The minimum impervious cover (0.12%) was found in the Sleepy Creek sub-basin.

Future Land Uses

Predicted future land use data were obtained from the Chesapeake Bay Program (CBP) for the years 2010, 2020, and 2030. The tabular land use data were spatially 'joined' in ArcGIS 9.2 to CBP HSPF land-river segments.[1] Land uses for each land-river segment were summed for each watershed under consideration. The percent change from 2010-2030 was calculated for forest, urban, agricultural areas (**Table B-1**). According to the CBP data, urban areas will increase in all sub-basins over the next 20 years. The sub-basin with the largest urban growth was Occoquan with an estimated 9.05% increase, followed by Potomac Creek and Mattawoman. Sub-basins at highest risk are located primarily in the coastal plain and the larger DC metropolitan area. The median increase in urban areas was 2.1%. Town Creek of northern Maryland/southern Pennsylvania was predicted to have the smallest increase in urban areas, 0.23%.

Surface and Total Withdrawals

Withdrawal data for the year 2005 were obtained from Pennsylvania, West Virginia, Virginia, and Maryland. The data were formatted and combined into a single comprehensive database and imported into a GIS point shapefile using reported latitude and longitude values. Data quality control procedures were employed by comparing withdrawal attributes to Google Earth imagery. The resulting shapefile was utilized to calculate: (1) percent surface water withdrawals (total withdrawals [100%] – percent groundwater withdrawals), (2) percent ground water withdrawals (total withdrawals [100%] – percent surface water withdrawals), (3) total withdrawals, (4) withdrawals as a percent of 50th percentile flows (total withdrawals/[flow + total withdrawals]), and (5) surface withdrawals as a percent of 10th percentile flows (surface withdrawals/[flow + total withdrawals]).

To calculate the 10th and 50th percentile flow statistics, flow values were obtained at the sub-basin outlets from the CBP HSPF model simulated flows for 20 of the 35 sub-basins. The outlet segments of the remaining 15 sub-basins drain directly into the tidal Potomac and do not contain simulated rivers from which to obtain flow values in the CBP HSPF model. For these sub-basins, flow values were obtained using area weighted USGS gage data. All five of the mainstem segment flows were obtained from USGS

[1] For more information on land-river segmentation, see section 3 of the Phase 5 model documentation at http://www.chesapeakebay.net/model_phase5.aspx?menuitem=26169.

Table B-1. Potomac sub-basins and river mainstem segments and their calculated risk factor values.

Sub-basin	% Urban	% Agri-culture	% Forest	% Future Urban (2010-2030)	Avg % Imper-vious	% Impnd of 50th %tile Flow	% Karst	% With-drawals of 50th %tile Flow	% Surf. With-drawals of 10th %tile Flow	% Cons. Use of 50th %tile Flow
Coastal Plain										
Occoquan	13.72	28.89	50.06	9.05	4.50	42.26	0.00	37.41	65.69	8.10
Aquia	11.22	6.77	70.50	4.44	2.92	55.18	0.00	21.42	63.08	4.74
Mattawoman	24.80	7.70	56.41	6.93	4.16	0.34	0.00	16.75	29.80	4.78
Saint Marys	14.91	14.11	42.39	6.22	2.31	10.35	0.00	10.35	4.51	2.56
Accotink	57.12	2.63	28.25	1.62	19.15	15.37	0.00	0.68	1.09	0.25
Cameron Run	84.98	0.35	3.38	1.49	30.59	16.61	0.00	0.52	0.54	0.13
Anacostia	70.27	2.64	16.92	1.39	27.34	0.83	0.00	0.66	0.50	0.39
Rock	69.85	5.13	16.00	1.36	23.25	5.15	0.00	0.36	0.53	0.26
Piscataway	38.26	8.63	45.19	3.03	8.77	0.31	0.00	2.57	0.00	0.64
Potomac Creek	3.22	15.73	70.75	8.27	0.82	5.92	0.00	4.83	14.19	1.03
Wicomico	14.59	20.85	50.17	5.34	1.52	1.11	0.00	4.32	0.94	0.99
Quantico	11.21	1.87	77.04	2.29	3.50	47.42	0.00	0.12	0.82	0.03
Saint Clements	9.41	27.44	42.50	3.51	1.06	0.18	0.00	0.26	0.00	0.06
Machodoc	4.53	16.62	68.67	3.87	1.19	0.00	0.00	0.57	0.00	0.12
Upper Basin										
Monocacy	14.95	47.11	31.97	5.54	3.40	0.84	7.35	5.51	14.69	1.54
Opequon	10.99	37.05	47.99	5.17	3.13	0.07	61.32	8.44	6.46	2.29
Antietam	17.00	40.71	37.99	4.23	4.42	0.72	71.05	4.48	2.44	1.15
Conococheague	9.02	43.13	43.63	2.80	3.16	1.24	35.74	2.86	5.32	0.94
Goose	4.47	48.45	43.65	5.10	1.35	6.99	0.00	9.19	36.02	1.98
Potomac above Little Falls*	9.04	26.13	63.01	2.15	1.67	6.65	21.83	37.51	59.13	3.22
Potomac above Point of Rocks*	6.60	23.16	68.76	1.75	1.07	7.08	25.36	31.03	46.92	1.66
Potomac above Shepherdstown*	5.72	17.42	75.29	1.41	0.89	10.83	11.21	41.70	62.46	1.82
Potomac above Paw Paw*	4.50	12.79	80.99	0.61	0.54	16.51	1.83	50.62	72.60	1.94
Potomac above Hancock*	4.13	11.82	82.42	0.70	0.46	13.73	1.59	45.74	68.49	1.77
North Branch	5.68	12.44	79.15	0.66	0.76	14.43	1.30	49.75	81.45	1.81
Seneca	29.26	28.71	31.36	3.87	7.39	15.15	0.00	0.72	0.41	0.25
South Fork Shen.	7.39	31.52	59.86	2.06	1.25	2.02	52.67	6.29	4.15	1.56
North Fork Shen.	4.70	28.37	65.54	1.57	0.69	0.90	45.40	3.26	2.52	0.77
Catoctin, MD	12.32	41.83	41.90	3.85	1.39	0.09	0.00	0.65	1.82	0.38
Catoctin, VA	3.17	53.48	40.06	4.47	0.77	0.63	0.00	1.15	2.96	0.15
Back	2.70	12.86	82.01	2.19	0.22	6.51	7.20	0.41	0.00	0.10
Licking	2.23	18.62	76.69	0.71	0.36	1.78	7.68	0.26	0.00	0.06
Sleepy	2.34	8.88	86.84	1.43	0.12	2.44	0.00	0.69	7.40	0.17
South Branch	1.55	13.40	81.78	0.62	0.42	1.92	0.97	1.08	6.78	0.26
Tonoloway	2.63	21.11	72.96	1.08	0.47	0.04	8.31	0.02	0.00	0.00
Yeocomico	2.81	34.58	44.33	0.48	0.95	0.54	0.00	0.10	0.00	0.02
Town	1.92	8.86	87.53	0.23	0.17	0.10	16.21	0.00	0.00	0.00
Cacapon	1.00	9.33	87.50	0.83	0.16	0.52	0.00	0.03	0.11	0.01
Little Cacapon	0.75	15.60	82.23	0.60	0.19	0.14	0.00	0.00	0.00	0.00
Sideling Hill	2.50	12.44	81.45	1.24	0.20	0.13	0.00	0.00	0.00	0.00

Coastal, Coastal Plain physiographic province; Upper, the upper Potomac River basin, including the Piedmont, Blue Ridge, Ridge & Valley, and Central Appalachian physiographic provinces. *, risk factor values are based on the entire upstream contributing area.

gage data. Withdrawals and surface withdrawals expressed as a percent of the 10^{th} or 50^{th} (median) flow statistic are shown in **Table B-1**.

Both surface and groundwater withdrawal effects were considered in relation to median flow conditions. Three sub-basins had no documented withdrawals (Sideling Hill, Little Cacapon, and Town). Total withdrawals are generally greatest in the eastern half of the basin (**Figure B-1**) In the west, the North Branch sub-basin had high withdrawals from mining, industrial, water supply, and power generation (49.75%) as well as the immediately downstream mainstem segments, Potomac above Paw Paw (50.62%) and Hancock. The median withdrawal of the 50^{th} percentile flow among all sub-basins was 1.86%.

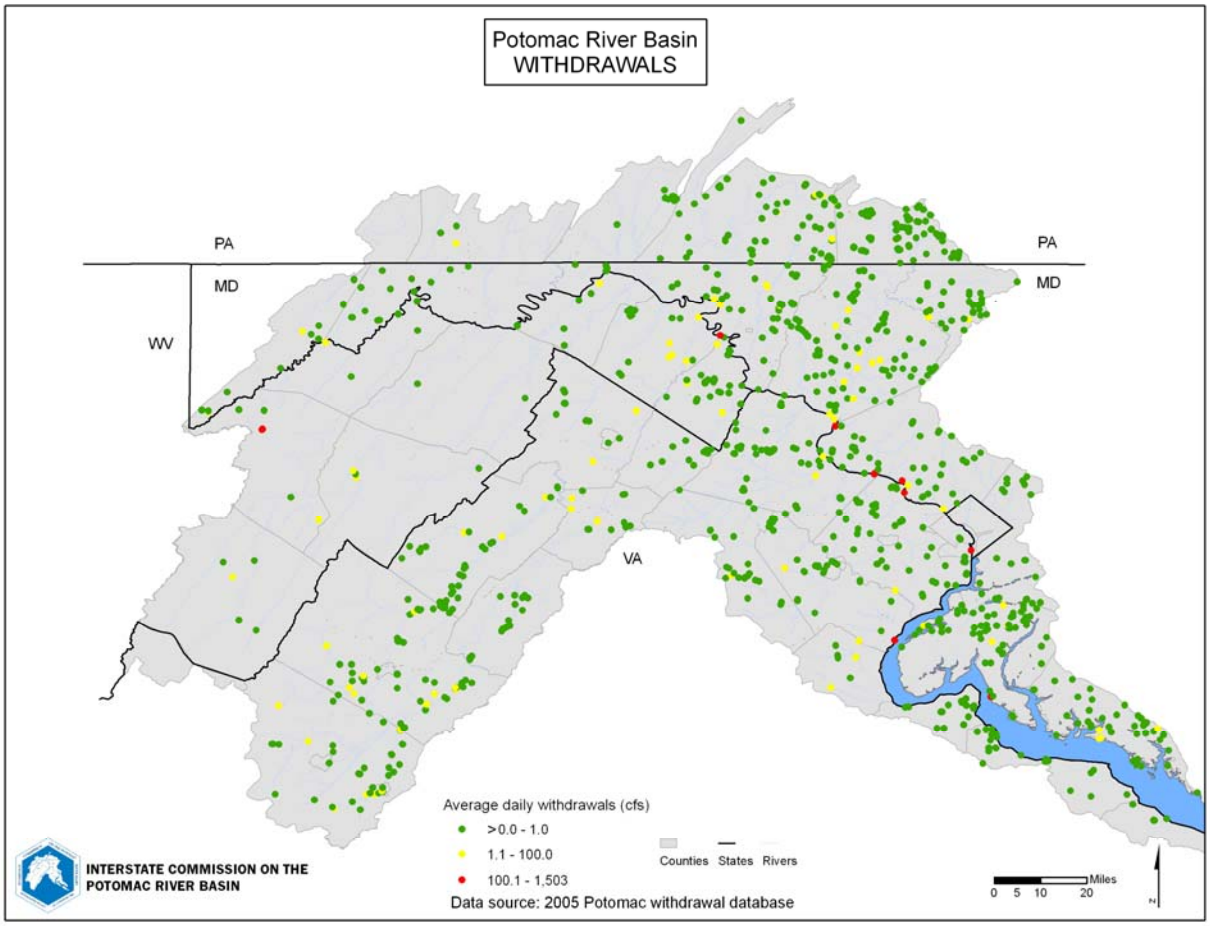


Figure B-1. Significant total withdrawals in the Potomac River Basin.

The surface withdrawal statistic represents the effects of surface withdrawals on low flow conditions. The maximum percent surface withdrawal of 10th percentile flow (81.45%) was found in the North Branch followed by the Potomac River above Paw Paw and Hancock. The median value was 2.48%. Again, the minimum value was 0% due to several watersheds with no documented withdrawals.

Consumptive Uses

USGS Aggregate Water Use Data System (AWUDS)[2] county data from 1995 were obtained for all counties in the Potomac Basin. A consumptive use coefficient for each reported water use was estimated by dividing consumptive use by withdrawals. The average consumptive use coefficients by water use in the Potomac Basin are shown in **Table B-2**. Consumptive use coefficients calculated for the Potomac Basin are comparable to literature values for the Great Lakes Region and similar hydrologic areas (http://pubs.usgs.gov/sir/2007/5197/). The consumptive use coefficients were multiplied by the 2005 total withdrawals (MG/year) for that water use type to estimate total consumptive use (MG/year) for each sub-basin.

[2] AWUDS data available at http://water.usgs.gov/watuse/wuawuds.html.

Consumptive uses for each sub-basin are shown in **Table B-1**. The maximum consumptive use is 8.1% for the Occoquan sub-basin. The median value is 0.51% while the minimum consumptive use is 0 due to lack of reported withdrawals in three sub-basins.

Table B-2. Average consumptive use coefficients.

Water Use	Consumptive Use Coefficient
Domestic	21.4%
Industrial	24.8%
Thermoelectric	2.5%
Mining	17.4%
Livestock	75.2%
Irrigation	84.2%
Average	15.2%

Impoundments

A total of 437 impoundments were identified by county in the National Inventory of Dams (NID)[3] (**Figure B-2**). The total storage capacity of impoundments within each sub-basin was calculated by summing the NID reported normal storage capacities. The total storage capacity was then compared to the annual flow volume for 50th percentile flows in the sub-basin. As with the withdrawal calculations above, the 50th percentile flows were calculated at sub-basin outlets using CBP HSPF model simulated flows for 20 of the 35 sub-basins. The outlet segments of the remaining 15 sub-basins drain directly into the tidal Potomac and do not contain simulated rivers from which to obtain flow values in the CBP HSPF model. For these sub-basins, flow values were obtained

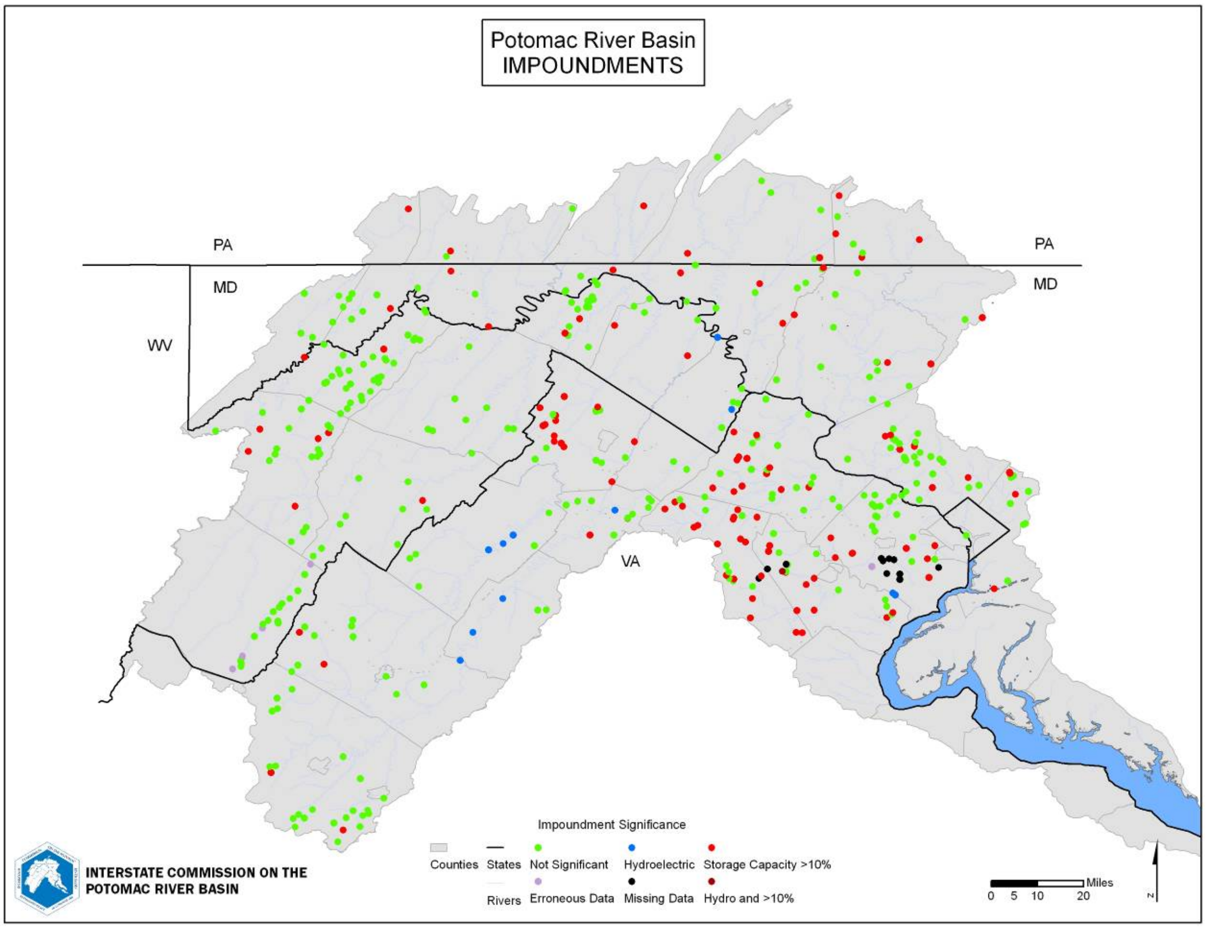


Figure B-2. Impoundments in the Potomac River basin.

[3] NID database: http://geo.usace.army.mil/pgis/f?p=397:12:1043044450946708

using area weighted USGS gage data. All 5 of the mainstem segment flows were obtained from USGS gage data. The impoundment risk factor values are shown in **Table B-1**. The Aquia sub-basin in the Coastal Plain province had the highest percent impoundment, 55.18%. The median percent impoundment in the Potomac is 1.85%. Machadoc, also in the Coastal Plain province, had the lowest score with no impoundments.

For two sub-basins found to be “severe” for both withdrawals and impoundments, Occoquan and North Branch, an additional analysis was conducted to determine the hydrologic effects of withdrawals and impoundments. North Branch was at high risk primarily due to large water supply and flood control impoundments and withdrawals from mining, industry, water supply, and power generation. Occoquan was at high risk primarily due to water supply and hydroelectric impoundments and withdrawals. A Watershed Online Object Oriented Meta-Model (WOOOMM) developed by Virginia Department of the Environment as a companion model for the Chesapeake Bay Program HSPF model was utilized to simulate current flows and unaltered flows (i.e. flows without the effects of impoundments or withdrawals). The percent hydrologic alteration caused by withdrawals and impoundments was calculated as the difference of these two data sets. **Figures B-3** and **B-4** show the percent difference in 12 Indicators of Hydrologic Alteration (IHA) metrics from current to unaltered conditions (Richter et al. 1996). In the Occoquan sub-basin, minimum flows were shown to increase if withdrawals and impoundments are removed while low flows decrease under these conditions in the North Branch. The mean annual flow and hydrograph risk rates and fall rates increased for both the Occoquan and the North Branch.

Karst Geology

Karst, or carbonate rock, is slowly dissolved by groundwater, forming subterranean fractures and caverns that allow rainwater to seep more rapidly into the ground. A broad band of karst geology cuts through the Potomac River basin, forming a broad valley (**Figure B-5**). The percentage of karst geology in each sub-basin was calculated using the US EPA’s Region 3 ecoregion polygon shapefile in ArcGIS 9.2. Two Level 4 ecoregions were identified; namely, Northern Limestone/Dolomite Valleys and Piedmont Limestone/Dolomite Lowlands. The ‘tabulate area’ tool was utilized to calculate the karst area of each sub-basin. The calculated karst areas were divided by the total area of each respective sub-basin. No karst geology was found in 23 of the 35 sub-basins. The maximum percent karst geology was 71.05% in the Antietam sub-basin followed by the Opequon and the South Fork of the Shenandoah. Percentages of karst geology for each sub-basin are shown in **Table B-1**.

Triassic Lowland Geology

The Triassic lowlands in the Piedmont physiographic province (**Figure B-6**) are composed of unmetamorphosed red shale, siltstone, and sandstone and are thus more permeable than the hard, crystalline igneous and metamorphic rocks elsewhere in the Piedmont. The percent Triassic Lowland geology for each sub-basin was calculated with the US EPA’s Region 3 ecoregion polygon shapefile in ArcGIS 9.2 utilizing the ‘tabulate area’ tool. The resulting areas were compared to the total area of each respective sub-basin. The areas of the sub-basins were calculated using the ‘calculate area’ tool. 30 of the 35 sub-basins had no Triassic Lowlands.

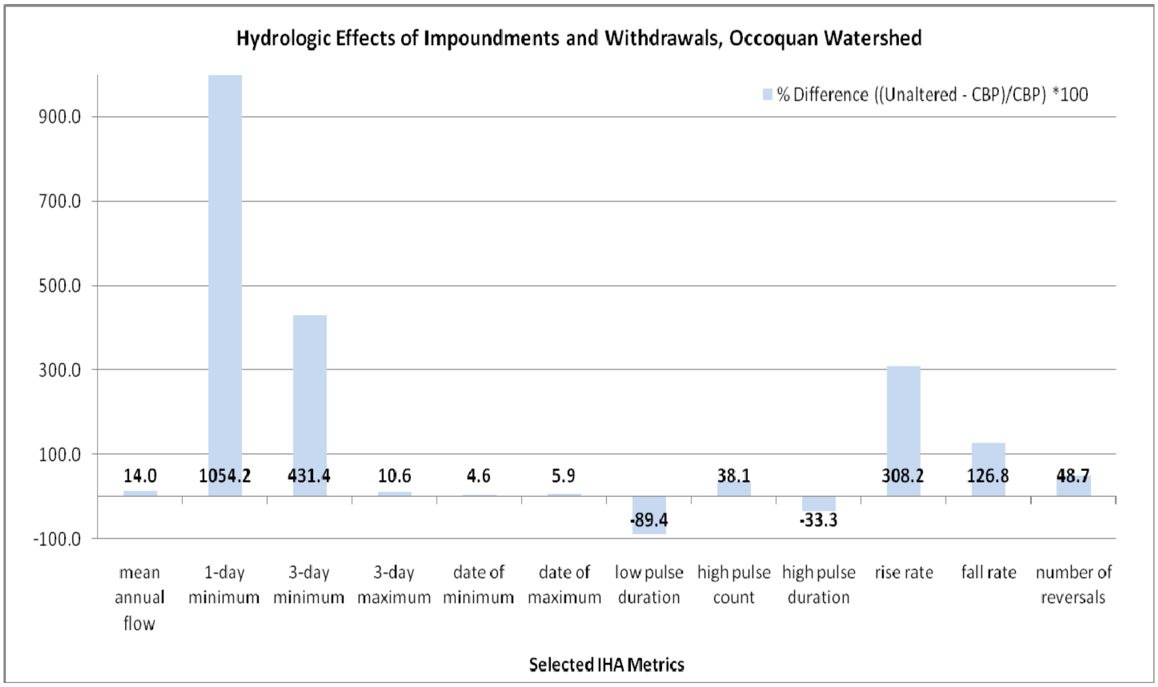


Figure B-3. Percent difference in 12 IHA metrics under unaltered conditions for the Occoquan.

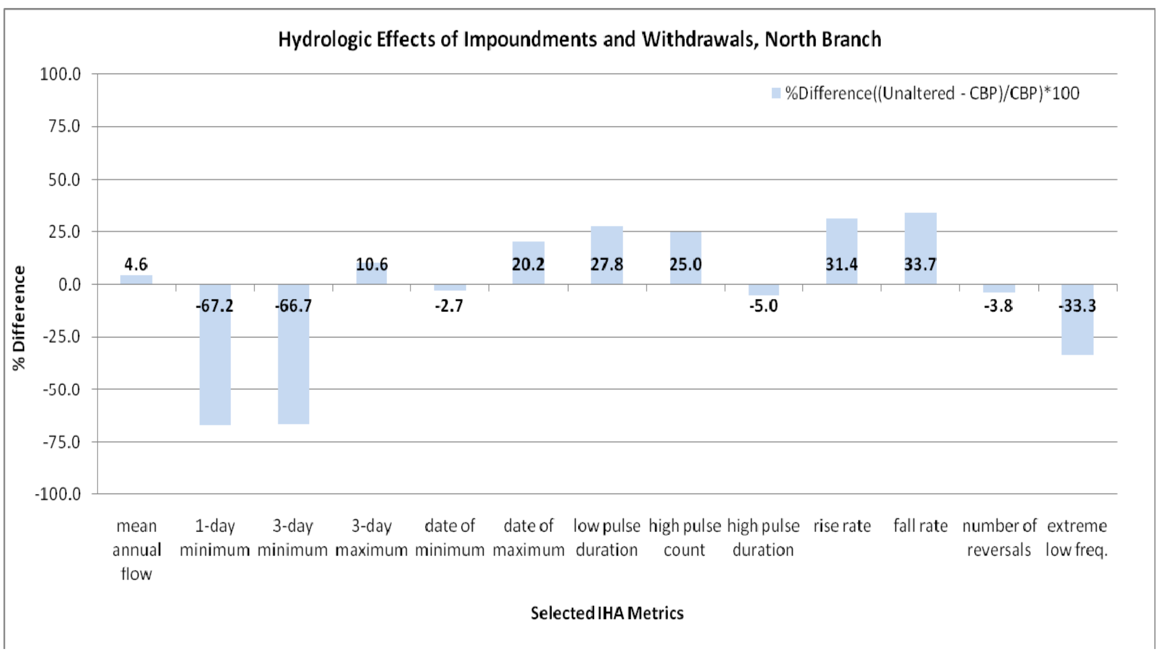


Figure B-4. Percent difference in 12 IHA metrics under unaltered conditions for the North Branch.

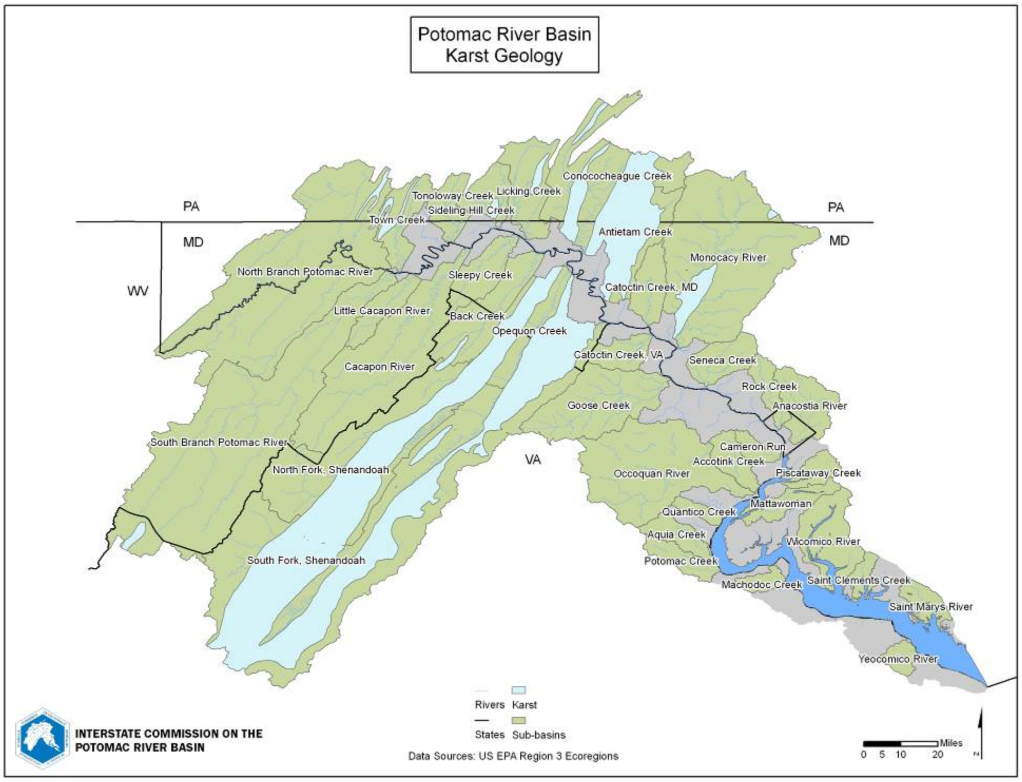


Figure B-5. Karst geology areas in the Potomac River basin.

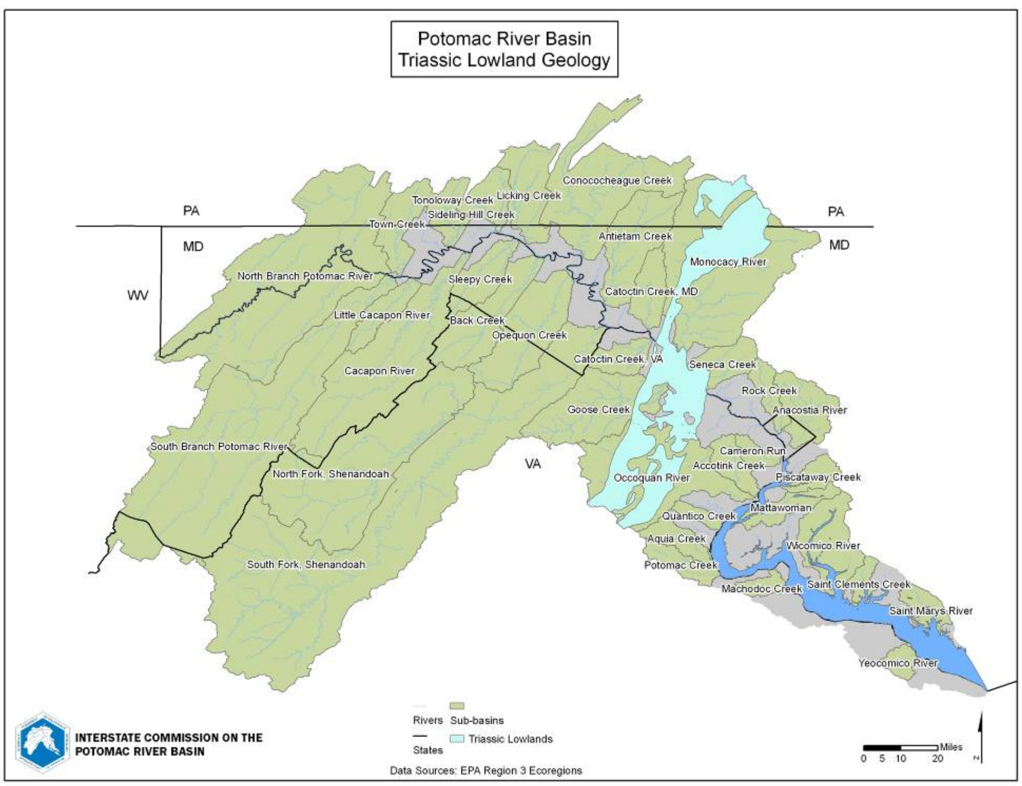


Figure B-6. Triassic Lowland areas in the Potomac River basin.

Correlation of Risk Factors with Other Risk Factors and with IHA Metrics

Correlation coefficients were calculated for the 17 potential risk factors to identify and eliminate redundancy in risk factors. If several factors were found to be significantly correlated ($R > 0.5$ or < -0.5), those factors were candidates for elimination. Correlated risk factors, however, were utilized to develop the risk index if they explained different portions of the hydrograph, as explained below. Correlation coefficients of risk factors utilized in cumulative index development are given in **Table B-3**.

Efforts were also made to select risk factors that influence different portions of the hydrograph. Eleven IHA metrics were selected to capture different portions of the hydrograph. Selected metrics include mean flow, 3 day maximum, 1 day minimum, 3 day minimum, high pulse count, high pulse duration, low pulse duration, extreme low frequency, number of reversals, rise rate, and fall rate as suggested in Apse et al. (2008).[4] IHA metrics were calculated for the 26 sub-basins with USGS gage data at the outlet (**Table B-4**). To identify the portion of the hydrograph affected by each risk factor, correlations were calculated between risk factors and IHA statistics.

Due to correlation with other risk factors and lack of correlation with IHA metrics, several risk factors were removed from further analysis including predicted future agricultural land use change, predicted future forest land use change, percent Triassic Lowlands, total withdrawals (MG/year), total consumptive use (MG/year), percent groundwater withdrawal (total withdrawals [100%] – percent surface water withdrawals), and percent surface withdrawal (total withdrawals [100%] – percent groundwater withdrawals). The remaining risk factors included percent urban, percent agriculture, percent forest, percent predicted urban change (2010-2030), percent impervious, percent impoundment, percent karst, percent withdrawals of the 50th percentile flow, percent surface withdrawals of the 10th percentile flow, and percent consumptive use of the 50th percentile flow.

Risk Factor Thresholds

The ten risk factors were categorized by severe, high, medium, and low risk utilizing Classification and Regression Tree (CART) analysis, literature values, and the distribution of risk factor values. CART analysis was performed using S-PLUS software on IHA metrics for the 26 sub-basins with USGS gage data at the outlet. IHA metrics were utilized as dependent variables to develop thresholds for the risk factor values (independent variables). CART analysis divides the data into consecutively smaller groups until the minimum sample size for each group is reached. The breaking points between groups are threshold values of the independent variables (risk factors) that minimize deviance within each group. The first threshold of the CART analysis, or primary break, is identified in the risk factor that can minimize deviance in the IHA statistic values. After the primary break is identified, the process continues until a terminal node is reached, where the minimum number of observations per group is reached or the deviance in the group is minimized.

For this study, CART analysis was conducted for each IHA statistic using several iterations of user-specified criteria: minimum number of observations before split equaled 5 and minimum node size equaled 10; minimum number of observations before split equaled 4 and minimum node size equaled 8; minimum number of observations before split equaled 3 and minimum node size equaled 6; and minimum number of observations before split equaled 2 and minimum node size equaled 4. The strength in creating multiple trees for each independent variable is that consistent thresholds can be identified.

[4] The IHA user's manual provides definitions to each of these metrics and discusses their hydrologic and biologic importance (http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html).

Table B-3. Correlation of risk factors utilized in cumulative index development.

	% Urban	% Agri-culture	% Forest	% Change Urban	Avg % Imper-vious	% Impound -ment	% Karst	% Total With-drawal	% Consump-tive Use	% Surface With-drawal
% Urban	1.00	-0.40	-0.77	-0.07	0.98	0.11	-0.15	-0.10	-0.04	-0.15
% Agriculture		1.00	-0.22	0.34	-0.40	-0.28	0.41	0.00	0.09	-0.04
% Forest			1.00	-0.25	-0.74	0.02	-0.04	0.09	-0.06	0.18
% Change Urban				1.00	-0.13	0.25	0.00	0.36	0.69	0.40
Avg % Impervious					1.00	0.12	-0.14	-0.12	-0.08	-0.13
% Impndment						1.00	-0.22	0.46	0.53	0.43
% Karst							1.00	-0.03	0.04	-0.13
% Total Withdrawal								1.00	0.75	0.83
% Consumptive Use									1.00	0.56
% Surface Withdrawal										1.00

Table B-4. Metrics calculated with the Indicator of Hydrologic Alteration software (TNC 2007). IHA metrics were only calculated for the 26 sub-basins with USGS gage data at the outlet.

Name	1 Day Min	3 Day Min	3 Day Max	Low Pulse Duration	High Pulse Count	High Pulse Dur	# Reversals	Extreme Low Freq	Avg Annual Flow	Rise Rate	Fall Rate
Piscataway	0.00	0.00	7.28	4.5	21	2	119	2	43.89	9.475	-3
Saint Clements	0.01	0.02	8.98	5	19.5	2	116.5	2	18.79	2.9	-1.5
Sideling Hill	0.00	0.00	13.74	10.5	12	5	87	1	107.10	7	-3
Cacapon	0.10	0.10	9.51	10.75	9	5	85.5	2	598.60	22	-24.5
Seneca	0.20	0.22	8.20	4	20	2	122	1.5	132.80	14	-7
Anacostia	0.11	0.12	8.98	5	30.5	2	123	4	93.01	24.5	-7
Rock	0.10	0.10	7.00	4.25	29	2	124	2	68.56	22	-5
Cameron	0.08	0.09	8.69	3.5	38	2	135	0.5	37.39	10.5	-3.325
Quantico	0.01	0.01	12.02	5.5	17.5	2	114.5	1	7.50	0.74	-0.4
Wicomico	0.00	0.00	8.47	5.75	18	3	95.5	1	91.02	15.25	-6.5
Accotink	0.03	0.03	12.09	3.5	39	2	137	3.5	30.37	10.13	-2
Catoctin, MD	0.02	0.02	9.02	6.25	11	2	102	1.5	81.79	7	-4
Antietam	0.29	0.30	5.50	5.75	7	3	107	1	321.50	17.5	-9
North Fork Shenandoah	0.11	0.11	5.50	7.5	9	4.25	104.5	1	671.3	27	-25
Catoctin, VA	0.03	0.03	11.95	6.75	13	2	104	1	98.92	7.25	-4.75
South Fork Shenandoah	0.18	0.19	6.93	10.5	8.5	6.25	102	0	3047.00	92.5	-109
Saint Marys	0.07	0.08	11.58	6	17.5	3	115	0.5	27.79	3	-2
Conococheague	0.14	0.15	8.59	7	10	4	101	1.5	643.20	42.5	-23.25
Opequon	0.21	0.21	8.74	6	10.5	3	109.5	0	278.20	15	-8.75
South Branch	0.08	0.08	8.69	8.25	9	5.5	87	2	1513.00	70	-51.25
Monocacy	0.09	0.10	8.96	7.75	14	3	106	1.5	1022.00	94.5	-49.5
Mattawoman	0.00	0.00	11.34	5.5	19	3	88	2	68.52	14	-5
Goose	0.02	0.02	8.60	6.25	12	2.75	106	1	357.70	27.38	-17.5
Aquia	0.02	0.02	9.44	6	19	2.5	113	1	32.85	4.5	-2
Occoquan	0.01	0.01	10.46	4.75	14	3	116	1	88.91	8	-5
North Branch	0.20	0.21	6.31	5.75	9.5	5.5	113	0.5	1416.00	70.25	-48.5

According to Lawrence and Wright (2001), "CART will usually over-fit the model, creating a tree that explains substantially all of the deviance in the original data, but in a manner specific to the particular data used to fit the tree. The tree must be pruned back, therefore, to a level where it can reasonably be expected to be robust." For this reason, mostly primary and secondary breaks were utilized in this analysis. The tree and statistical results for the 1 day minimum IHA metric with 5 observations before split and a minimum node size of 10 is provided in **Figure B-7** for example.

The identified thresholds and rationale for each risk factor are given below. For thresholds identified using CART analysis, the residual mean deviance and the IHA statistics for which the threshold was identified are given. **Figures B-8** to **B-17** show the distribution of values for each risk factor.

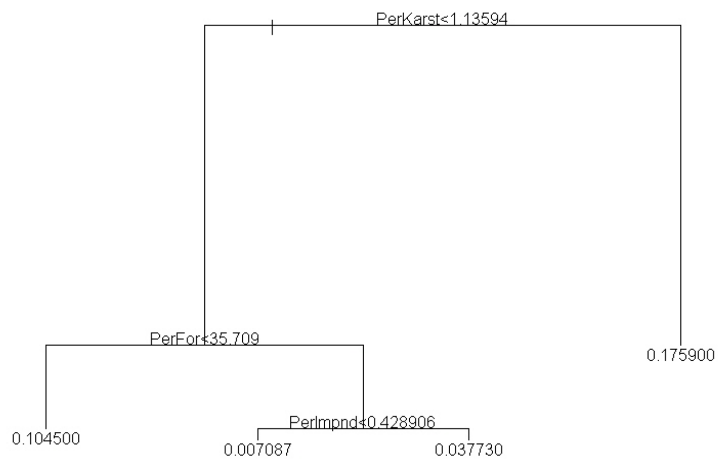
```
*** Tree Model ***

Regression tree:
tree(formula = X1DMin ~ PerUrb.F + PercUrb + PerImp + PerImpnd +
PerKarst +
PerWithdr + PerSurWithdr + PerConsumUse + PerFor + PerAg + Type, data
= RiskFactor.ForSPLUS.100909, na.action = na.exclude, mincut = 5,
minsize = 10, mindev = 0.01)
Variables actually used in tree construction:
[1] "PerKarst" "PerFor"   "PerImpnd"
Number of terminal nodes:  4
Residual mean deviance:  0.002482 = 0.0546 / 22
Distribution of residuals:
Min.     1st Qu.    Median      Mean    3rd Qu.      Max.
-0.082470 -0.023920 -0.006414  0.000000  0.025400  0.116500
```

Independent Variable = 1 Day Minimum

Seires of Dependent Variables, Risk Factors

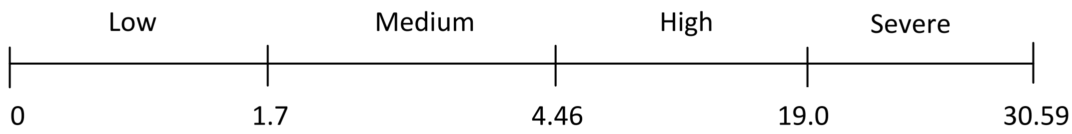
User Specified Criteria



Interpretation: Based on the data set of 26 gaged sub-basins, the CART program selected the independent variables %karst, %forest, and %impoundment as the most useful variables to construct the tree for the dependent variable 1-day minimum. %Karst was the variable used to create the "primary break" indicating it had the most influence on the dependent variable. Watersheds with %karst > 1.13594% formed a homogeneous group with a mean 1-day minimum of 0.1759 cfs/mi2. Watersheds with little or no levels of karst geology (<1.13594%) had lower 1-day minimum flows. Watersheds with little or no %karst were further split by %forest ("secondary break"). Those with relatively little forest cover (<35.709%) had moderate 1-day minimum values (0.1045 cfs/mi2) while those with more forest cover (>35.709%) had low 1-day minimum values. The low karst-more forest group was further split by %impoundment (tertiary break). Watersheds in this low karst-more forest group having few or no impoundments (<0.428906%) had the lowest mean 1-day minima of all the 26 sub-basins.

Figure B-7. Example of CART output.

Percent Impervious Cover



Low < 1.7 (n=11)

Threshold is explained by distribution of risk values.

Medium 1.7 – 4.46 (n=8)

CART residual mean deviance = 0.321.

CART threshold is explained by number of reversals (primary break) and low pulse duration (secondary break).

High 4.46 – 19.0 (n=3)

Threshold is explained by distribution of risk values. Corresponds to hydrologic impacts documented in the literature at 20% (Poff et al. 2006, Booth et al. 1997).

Severe >19 (n=4)

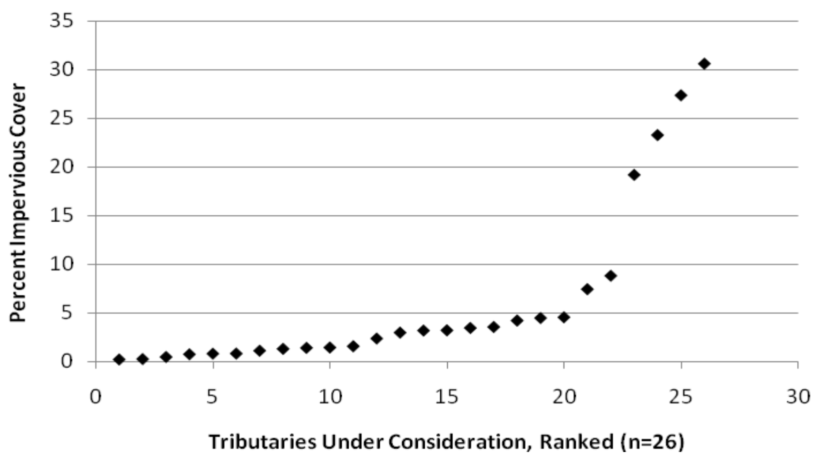


Figure B-8a. Distribution of percent impervious cover values for 26 sub-basins in the Potomac River basin.

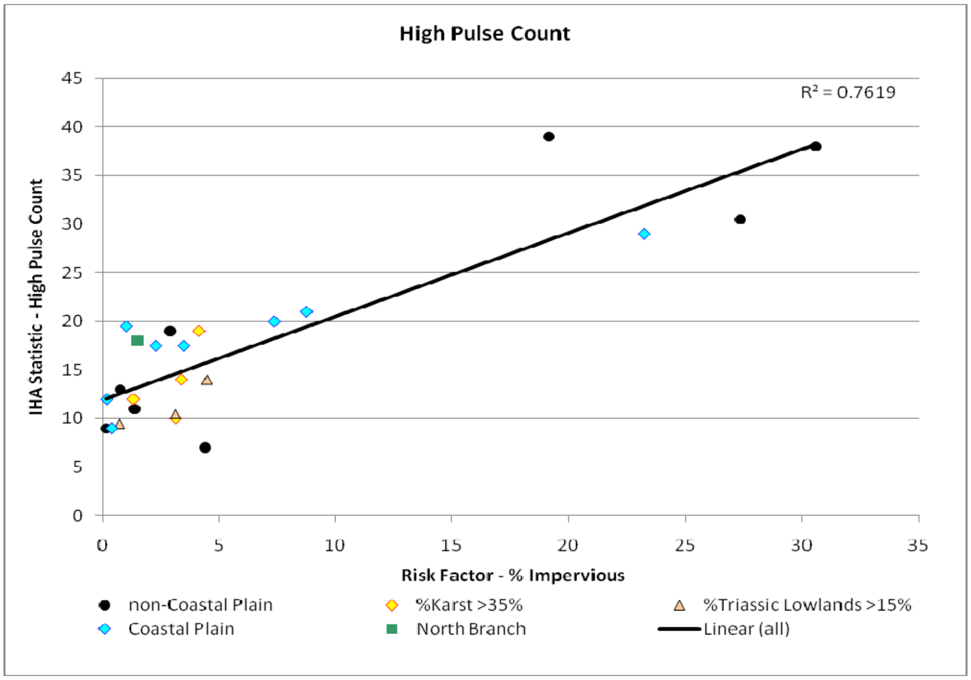


Figure B-8b. Regression between %impervious surface and high pulse count.

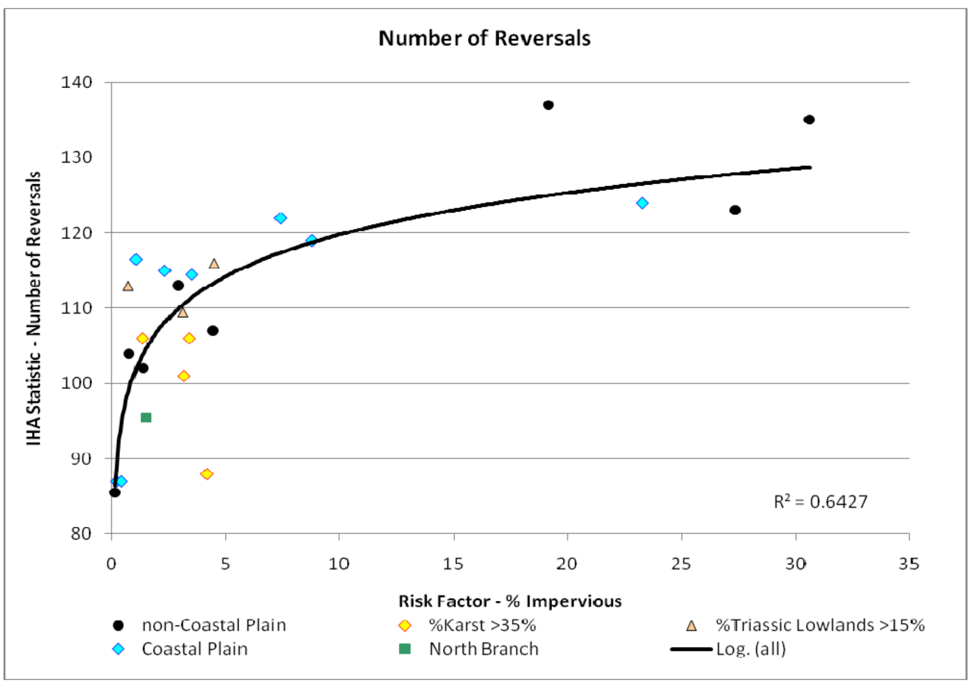
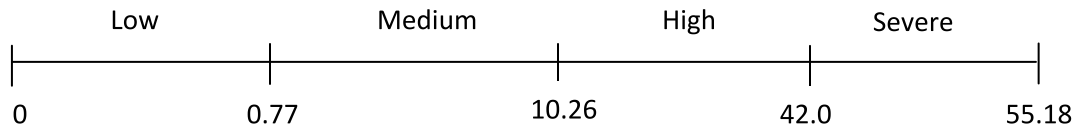


Figure B-8c. Regression between %impervious surface and number of flow reversals.

Percent Impoundment Normal Storage Capacity of 50th Percentile Flow



Low <0.77 (n=9)

CART residual mean deviance = 0.0008.

CART threshold is explained by 1 day minimum (secondary break).

Medium 0.77 – 10.26 (n=9)

CART residual mean deviance = 2.439.

CART threshold is explained by high pulse count (secondary break).

High 10.26 – 42.0 (n=5)

Threshold is explained by distribution of risk values.

Severe >42.0 (n=3)

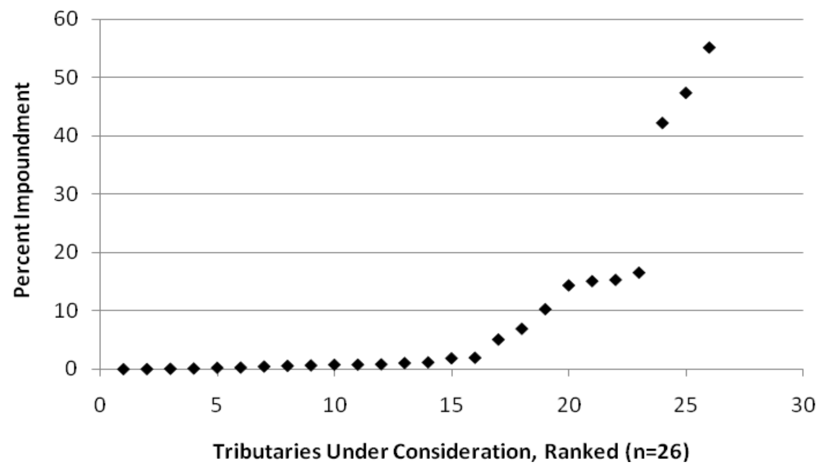
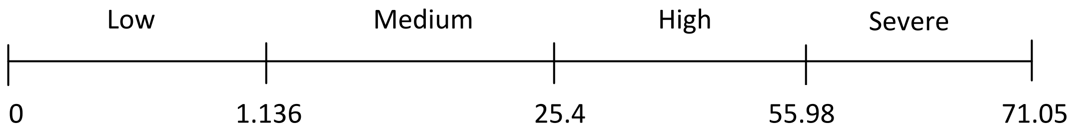


Figure B-9. Distribution of percent impoundment values for 26 sub-basins in the Potomac River basin.

Percent Karst Geology



Low <1.136 (n=19)

CART residual mean deviance = 0.008.

CART threshold is explained by 3 day min (primary break), 3 day max (primary break), and 1 day min (primary break).

Medium 1.136 – 25.4 (n=2)

Threshold is explained by distribution of risk values.

High 1.136 – 55.98 (n=3)

CART residual mean deviance = 0.0009.

CART threshold is explained by 3 day minimum (secondary break).

Severe >55.98 (n=2)

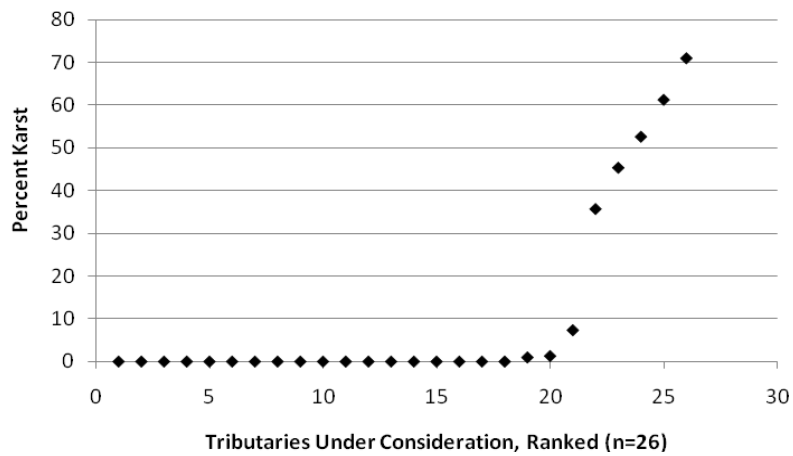


Figure B-10. Distribution of percent karst values for 26 sub-basins in the Potomac River basin.

Percent Withdrawals of 50th Percentile Flows

Low <2.39 (n=11)
Threshold is explained by distribution of risk values.
Medium 2.39 – 8.2 (n=8)

> CART residual mean deviance = 0.1029
> CART threshold is explained by extreme low frequency (secondary break).

High 8.2 – 21.5 (n=5)

> Threshold is explained by distribution of risk values.

Severe >21.5 (n=2)

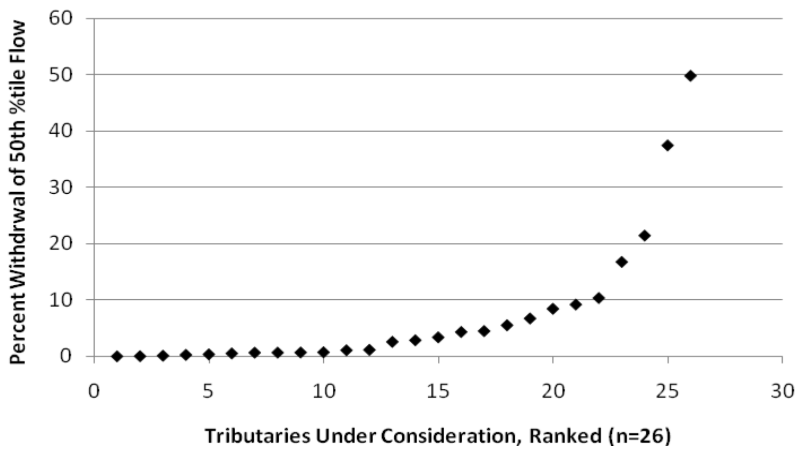
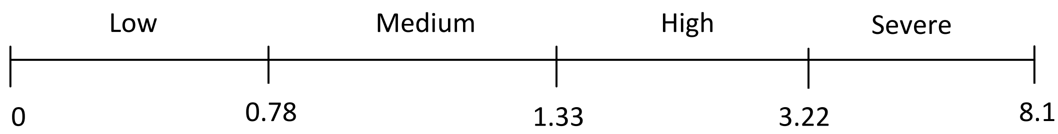


Figure B-11. Distribution of percent withdrawal values for 26 sub-basins in the Potomac River basin.

Percent Consumptive Use of 50th Percentile Flows



Low < 0.78 (n=14)

CART residual mean deviance = 1.393.

CART threshold is explained by 3 day max (secondary break).

Medium 0.78 – 1.33 (n=3)

CART residual mean deviance = 0.437.

CART threshold is explained by 3 day max (secondary break).

High 1.33 – 3.22 (n=6)

Threshold is explained by distribution of risk values.

Severe >3.22 (n=3)

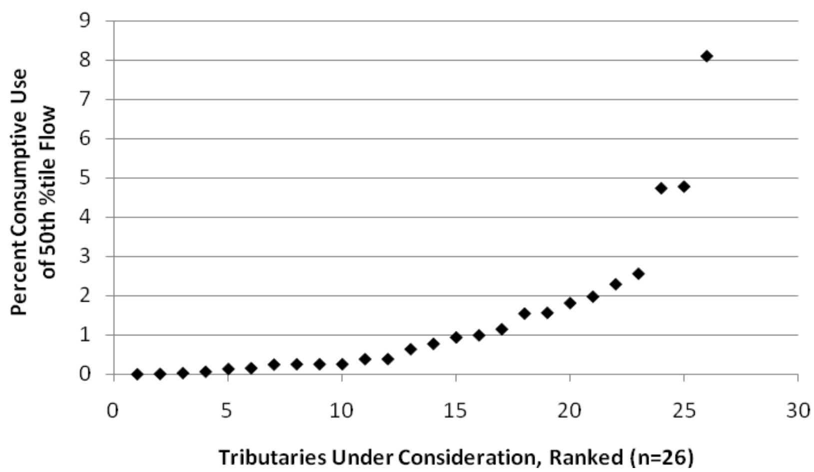
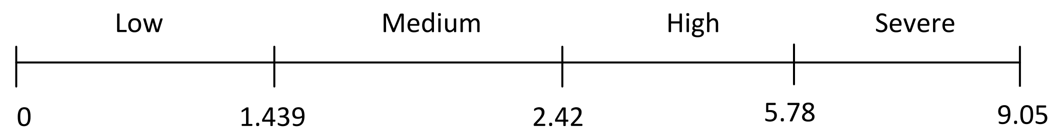


Figure B-12. Distribution of percent consumptive use values for 26 sub-basins in the Potomac River basin.

Percent Predicted Future Urban Change (2010-2030)



Low <1.439 (n=6)

CART residual mean deviance = 43.43.

CART threshold is explained by rise rate (secondary break).

Medium 1.439 – 2.42 (n=5)

CART residual mean deviance = 241.1.

CART threshold is explained by fall rate (secondary break).

High 2.42 – 5.78 (n=12)

CART residual mean deviance = 0.47.

CART threshold is explained by 3 day max (secondary break).

Severe >5.78 (n=3)

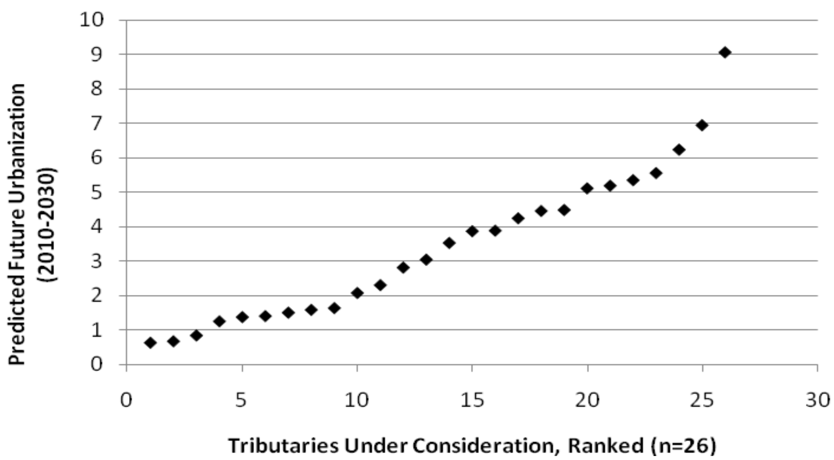
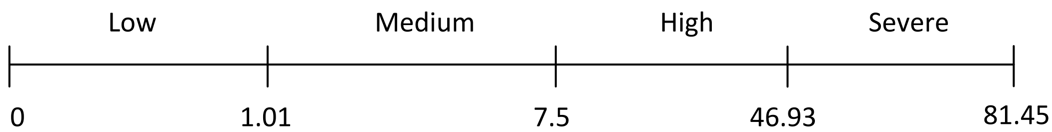


Figure B-13. Distribution of predicted future urbanization values for 26 sub-basins in the Potomac River basin.

Percent Surface Withdrawals of 10th Percentile Flows



Low <1.01 (n=10)

CART residual mean deviance = 1.113.

CART threshold is explained by 3 day maximum (tertiary break).

Medium 1.01 – 7.5 (n=10)

Threshold explained by the distribution of risk values.

High 7.5 – 46.93 (n=3)

Threshold explained by the distribution of risk values.

Severe >46.93 (n=3)

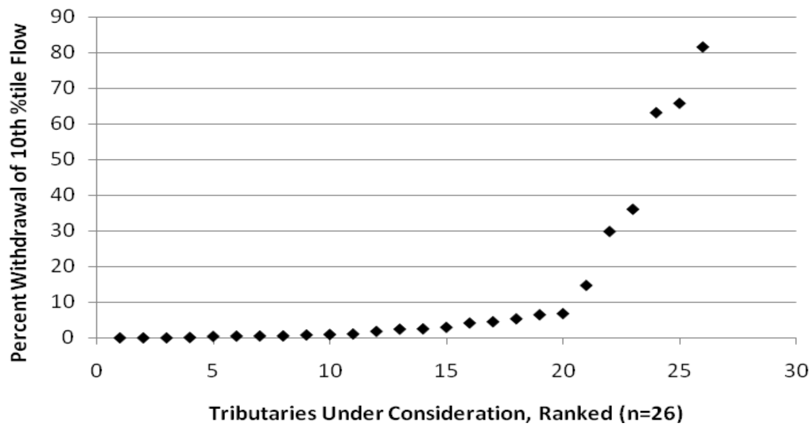


Figure B-14. Distribution of percent surface withdrawal values for 26 sub-basins in the Potomac River basin.

Percent Urban (2000)

Low <9.21(n=9)

CART residual mean deviance = 1.671.

CART threshold is explained by high pulse duration (primary break) and low pulse duration (primary break).

Medium 9.21-20.9 (n=10)

CART residual mean deviance = 0.103.

CART threshold is explained by extreme low frequency (primary break).

High 20.9 – 57.1 (n=3)

Threshold explained by the distribution of risk values.

High >57.1 (n=4)

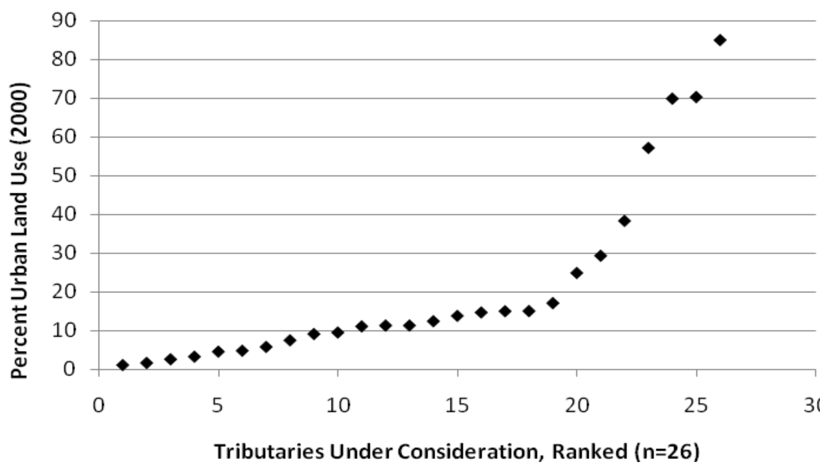


Figure B-15. Distribution of percent urban land use values for 26 sub-basins in the Potomac River basin.

Percent Forest

Severe <20.0 (n=3)

Threshold explained by the distribution of risk values.

High 20.0 – 35.7 (n=3)

CART residual mean deviance = 0.0009.

CART threshold is explained by 3 and 1 day minimums (secondary breaks).

Medium 35.7 – 51.75 (n=11)

CART residual mean deviance = 0.143.

CART threshold is explained by high pulse duration (secondary break).

Low >51.75 (n=9)

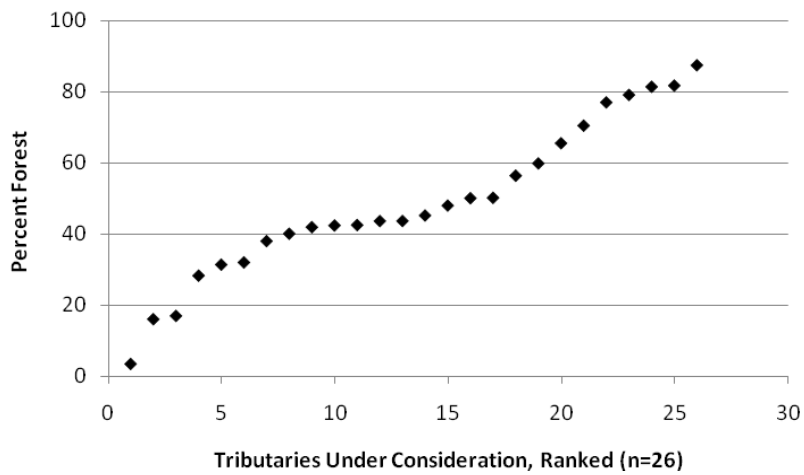


Figure B-16. Distribution of percent forest values for 26 sub-basins in the Potomac River basin.

Percent Agriculture

Low <2.634 (n=3)

CART residual mean deviance = 7.34.

CART threshold is explained by number of reversals (secondary break).

Medium 2.634 – 21.0 (n=11)

High 21.0 – 41.9 (n=8)[5,6]

CART residual mean deviance = 0.0009.

CART threshold is explained by 3 day minimum (secondary break) and 1 day minimum (secondary break).

Severe >41.9 (n=4)

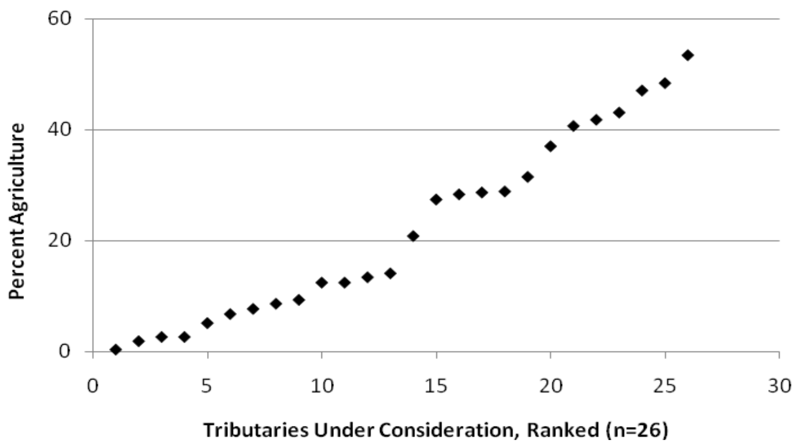


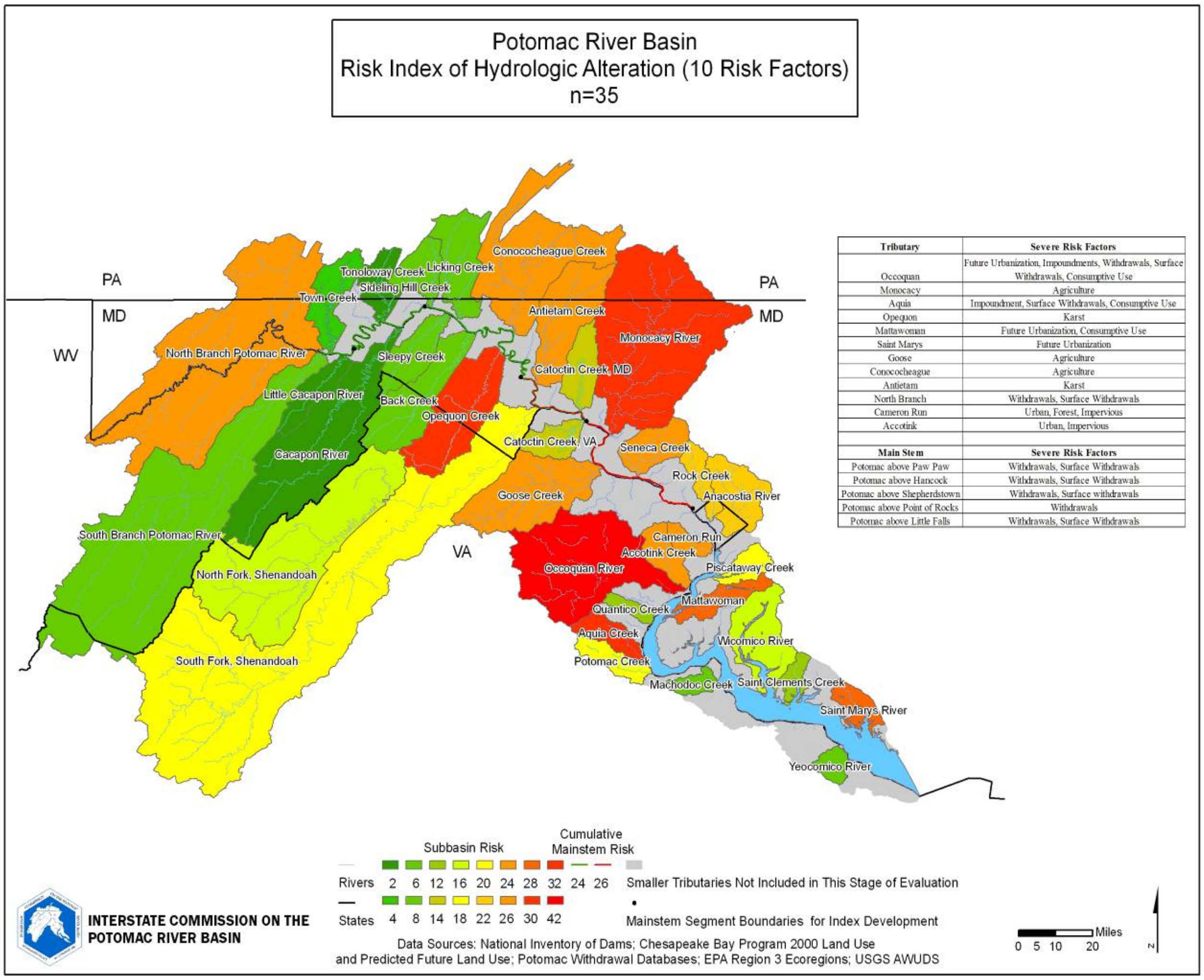
Figure B-17. Distribution of percent agriculture values for 26 sub-basins in the Potomac River basin.

[5] Poff et al. (2006) suggest another potential break at 25%.

[6] Allan (2004) suggests high percentage agriculture at 30-50% with indications of decline in BIBI at 30%.

Cumulative Risk Index

Utilizing the thresholds identified in the CART analysis, the risk factor categories were assigned unique values (low risk=0, medium risk=2, high risk =4, severe risk=6). For each sub-basin and mainstem segment, the assigned values for all ten risk factors were summed to calculate a cumulative risk index in the manner of Witmer et al. (2009). Cumulative risk index values for each sub-basin and mainstem segment are shown in **Table B-1**. Higher index values correspond to higher numbers of high or severe risk of hydrologic alteration. **Figure B-18** shows the spatial distribution of cumulative risk index values in the Potomac Basin.



Tributary	Severe Risk Factors
Occoquan	Future Urbanization, Impoundments, Withdrawals, Surface Withdrawals, Consumptive Use
Monocacy	Agriculture
Aquia	Impoundment, Surface Withdrawals, Consumptive Use
Opequon	Karst
Mattawoman	Future Urbanization, Consumptive Use
Saint Marys	Future Urbanization
Goose	Agriculture
Conococheague	Agriculture
Antietam	Karst
North Branch	Withdrawals, Surface Withdrawals
Cameron Run	Urban, Forest, Impervious
Accotink	Urban, Impervious
Main Stem	**Severe Risk Factors**
Potomac above Paw Paw	Withdrawals, Surface Withdrawals
Potomac above Hancock	Withdrawals, Surface Withdrawals
Potomac above Shepherdstown	Withdrawals, Surface withdrawals
Potomac above Point of Rocks	Withdrawals
Potomac above Little Falls	Withdrawals, Surface Withdrawals

Figure B-18. Cumulative risk index values for selected tributaries and mainstem segments in the Potomac River basin.

Discussion

The cumulative risk index is useful for focusing future analysis towards high risk areas at a broad scale in the Potomac River basin. Several aspects about the development and use of the cumulative risk index should be kept in mind when applying the index. First and foremost, the Potomac River basin has multiple risk factors that alter hydrology, and the cumulative risk index weights each of the risk factors equally. However, three of the risk factors may be relatively more influential than the others in the Potomac River basin because they are repeatedly used to create the "primary break" in the CART tree.

They are percent impervious cover, percent urban area, and percent karst geology. The index does not reflect the cumulative impact of all risk factors as much as it does a weighted *count* of the risk factors impacting each sub-basin and their relative severity.

Second, this analysis was performed on a large range of sub-basin sizes. It is possible, if not likely, that watershed size affects behavior of one or more of the IHA statistics used as the independent response variables.

Third, the percents of the different land uses each tend to converge as sub-basin size increases, so the widest range of environmental conditions is not found in the larger watersheds. For example, percent impervious cover in this data set ranges from 0.75% - 84.98% in the small (n=24, <200 mi^2) watersheds and only from 1.0% - 17.0% in the large watersheds (n=16, ≥ 200 mi^2). Similarly, percent forest cover ranges from 3.38% - 87.53% in small watersheds and only from 31.97% - 87.5% in large watersheds.

APPENDIX C

REGIONS OF SPECIAL INTEREST

Two sub-basins and four river segments in the Middle Potomac River study area were identified as regions of special interest: Opequon Creek, Monocacy River, the Potomac mainstem from the Shenandoah River confluence to Point of Rocks, from Point of Rocks to Great Falls, from Great Falls to Chain Bridge, and the tidal fresh estuary of the river below Chain Bridge (**Report Figure 1**). The reasons for selecting these regions for special consideration are outlined in the report's "Assessment of Risk Factors" section. This appendix provides additional descriptions of the river hydrologies measured at four USGS flow gages in these regions, as well as more detail about watershed geology and land uses.

Opequon Creek

Opequon Creek (**Figure C-1**) is free-flowing and drains approximately 345 mi² of the Shenandoah Valley in Virginia and West Virginia. Its source is northwest of the community of Opequon at the foot of Great North Mountain in Frederick County, Virginia. The mainstem flows south to north about 35 miles before meeting the Potomac northeast of Martinsburg, West Virginia. The Opequon forms part of the boundary between Frederick and Clarke counties in Virginia and also partially forms the boundary between Berkeley and Jefferson Counties in West Virginia's Eastern Panhandle.

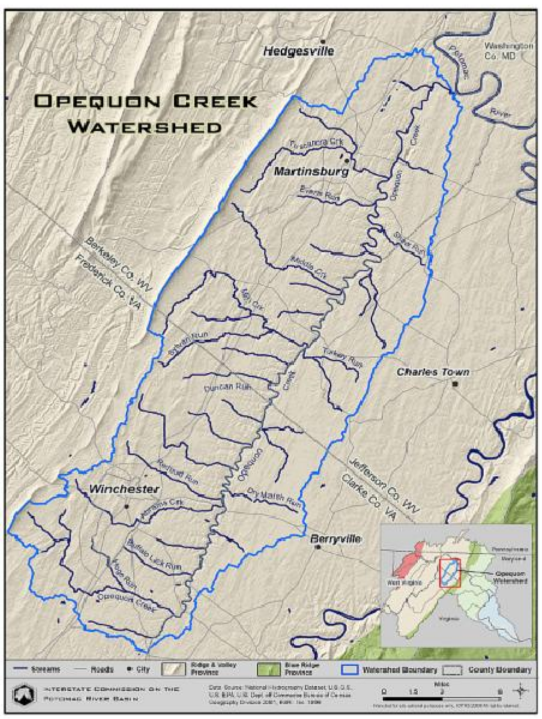


Figure C-1. Opequon Creek watershed.

The basin is located within the Ridge and Valley physiographic province and is largely underlain by limestone and shale geology. The average precipitation is approximately 40"/yr. Agriculture is the predominant land use in the basin, most of which is pasture, although some rowcrops and orchards also occur. There are two urban areas in the basin: Winchester, Virginia in the southern portion of the basin, and Martinsburg, West Virginia in the northern portion. In addition, many smaller municipalities and residential developments are scattered throughout the watershed and urban land use represents about 5% of the total watershed. The basin has experienced substantial suburban growth, the human population has increased 53% since 1970. Residential development in West Virginia is intense in the eastern panhandle. In 2004, Berkeley and Jefferson Counties had the largest percentages, 34% and 10% respectively, of building permits issued in West Virginia. Forest covers about 37% of the basin and the remaining area is mainly water (primarily farm ponds), barren (mostly limestone and shale mines), and a small amount of forested wetlands (Snyder, 2003).

The Opequon watershed is of special concern in the Chesapeake Bay cleanup effort due to its high nitrogen and phosphorus levels (http://www.opequoncreek.org/). Impairment indices developed in 2004 by the Potomac Tributary Stakeholder Team showed that the Opequon Creek had the highest value for both nitrogen and phosphorus, more than any other West Virginia Potomac sub-watershed. The Opequon is also on both Virginia and West Virginia 303d lists for bacterial and aquatic life impairments. Impairments originate from both point and non-point source pollution contributors including sewage treatment plants (the creek and its tributaries receive effluent from several wastewater treatment plants), livestock, development, and agricultural and urban runoff (Borisova, 2006). As part of a bi-state TMDL study, sediment was determined to be the most probable cause of the benthic impairments in Abrams and Lower Opequon Creeks (OPCIPSC 2006).

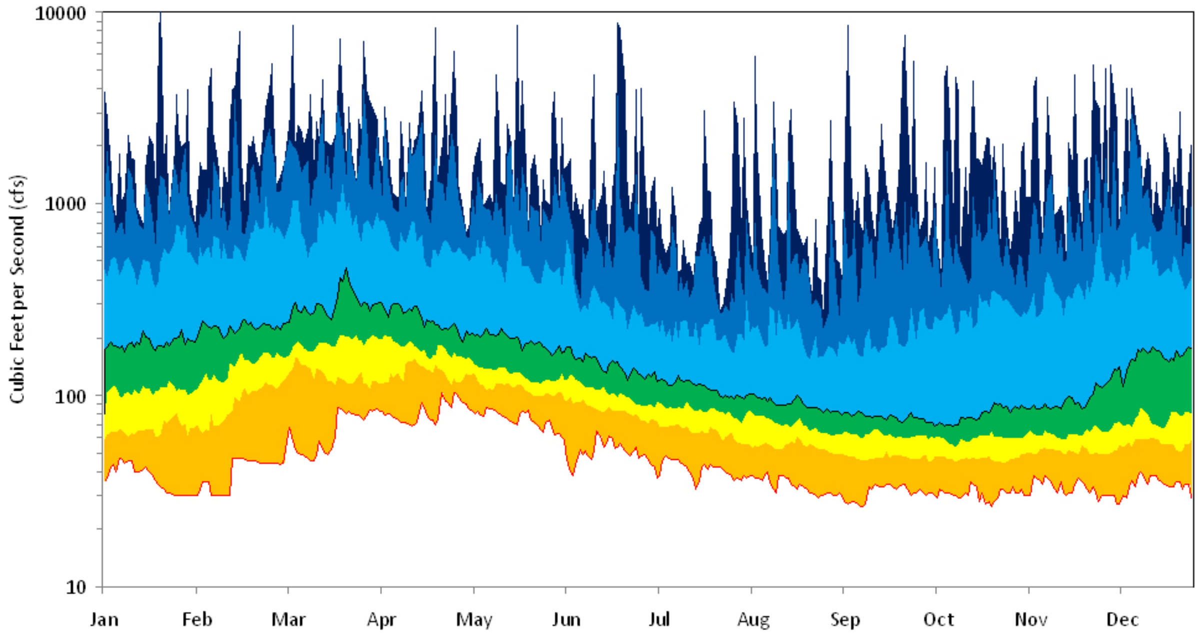
The USGS (Snyder, 2003) explored land use, fish assemblage structure, and stream habitat associations in 20 catchments in West Virginia to determine the relative importance of urban and agriculture land use on stream biotic integrity, and to evaluate the spatial scale (i.e., whole-catchment vs riparian buffer) at which land use effects were most pronounced. They found that index of biological integrity (IBI) scores were strongly associated with extent of urban land use in individual catchments. Sites that received ratings of poor or very poor based on IBI scores had > 7% of urban land use in their respective catchments. Habitat correlations suggested that urban land use disrupted flow regime, reduced water quality, and altered stream channels. The study also reported that variation in gradient (channel slope) influenced responses of fish assemblages to land use, i.e., urban land use was more disruptive to biological integrity in catchments with steeper channel slopes. The authors hypothesized that the potential for riparian forests to mitigate deleterious land uses effects in upland portions of the watershed is inversely related to gradient.

In 2009 a ground-water flow model was developed for the Opequon Creek by the USGS (Kozar 2009). A primary objective of the model's simulation was to develop water budgets for average and drought hydrologic conditions. Precipitation is the major input of water into the study area, but there is an interbasin transfer of water into the watershed as a result of a water intake on the Shenandoah River and subsequent wastewater-treatment return flow from Winchester, Virginia. The study reported that surface and ground water over a very broad area of the watershed are funneled along faults, especially where the faults are in close proximity to low-permeability bedrock such as the Conococheague Limestone and Martinsburg Formation. These structural and lithologic controls are responsible for many of the large springs in the Opequon Creek watershed area, especially in the limestone dominated eastern portions, one of which, at Priest Field, produced over 9 million gallons per day (mgd). The study also found indications of a substantial component of direct ground-water discharge to the Potomac River. During average conditions, approximately 148 mgd of surface water discharges to the Potomac River. An additional 32.8 mgd of ground water was also estimated to discharge directly to the Potomac River, representing approximately 18 percent of the Opequon Creek's total discharge to the Potomac River. Mean and median measured streamflow for the Opequon Creek near Martinsburg streamflow-gaging station during the 16-month drought were 90 mgd and 57 mgd, respectively. The US Weather Service's Middle Atlantic River Forecast Center reports that the Opequon has a 100% chance of exceeding flood stage each year (http://www.erh.noaa.gov/marfc/potomac.htm). What is not clear is whether these flood are ecologically damaging or more a matter of floods which are damaging to man-made structures located in the floodplain.

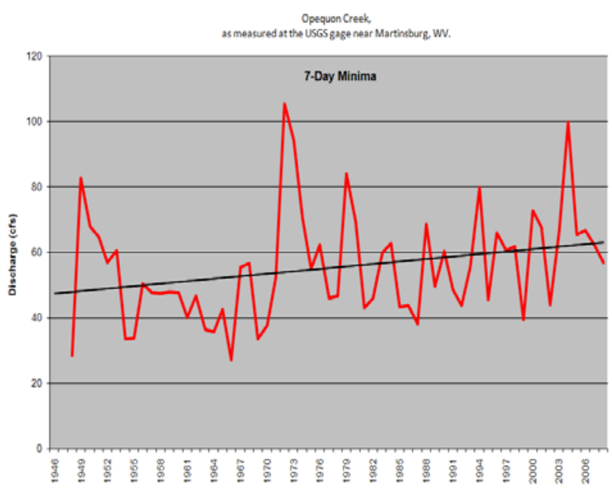
The Opequon Creek basin was found to have the fourth highest risk of hydrologic alteration (**Report Table 2**). The "severe" risk factor in the Opequon was percent karst. Karst geology was found in 61% of the sub-basin. Opequon also had "high" risk for agriculture, predicted threat of future urbanization, total withdrawals, and consumptive use. With high percent agriculture, Opequon Creek may see high run-off, erosion, and nutrient transport to waterways. Groundwater and surface water withdrawals make up a relatively large part of the median flows and high consumptive use means a sub-set of these withdrawals will not return to the system.

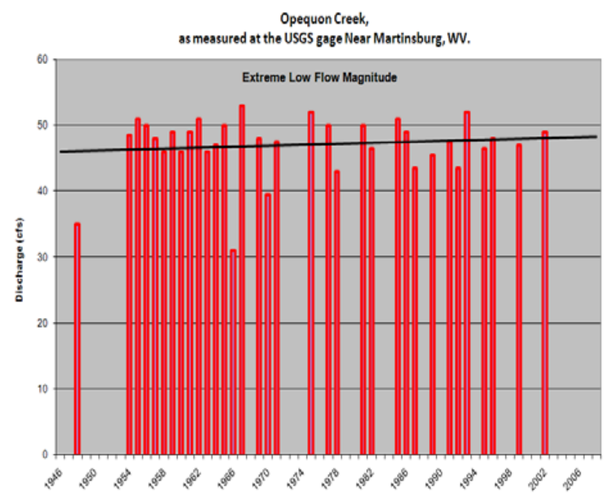
The first panel in **Figure C-2** shows the range of daily mean flows experienced each day of the year in the 1930-2008 period of record. The following panels illustrate the long-term trends in several low flow and high flow indicators of the Opequon's hydrology. High flow pulses correspond roughly to bankfull events and small floods to over-bank events.

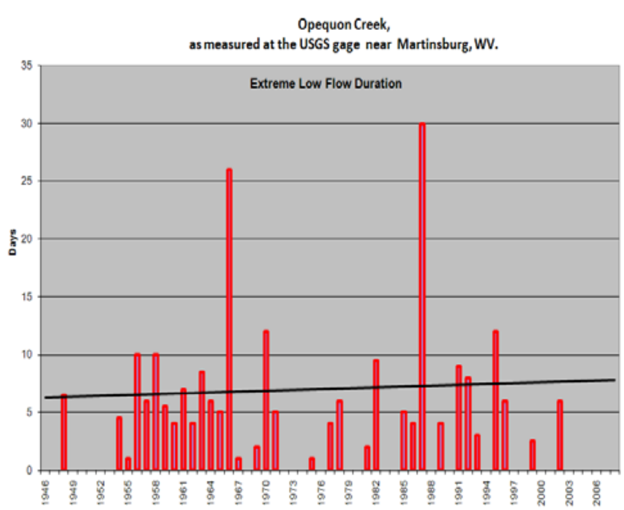
Figure C-2. Extent of flows and IHAs for Opequon Creek at the USGS gage near Martinsburg, WV., 1947-2009.

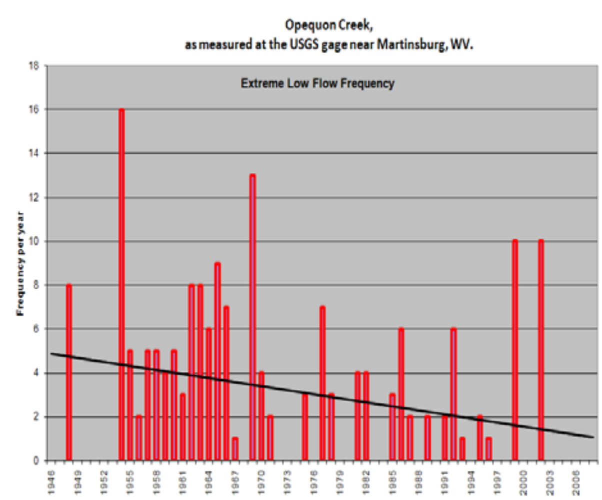


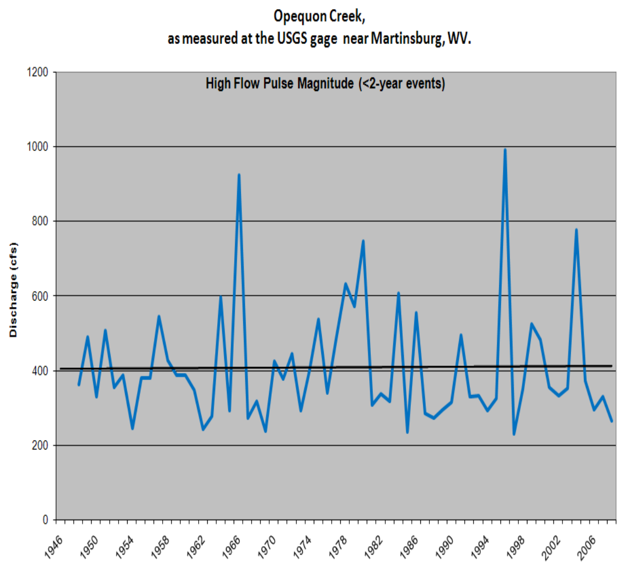
The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows are shown above.

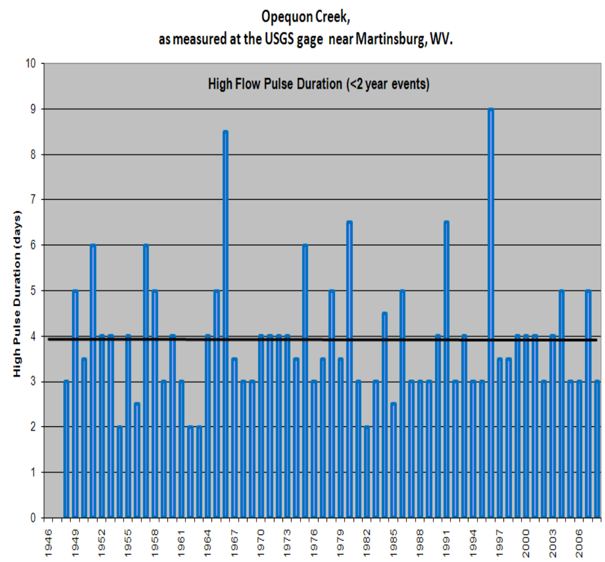


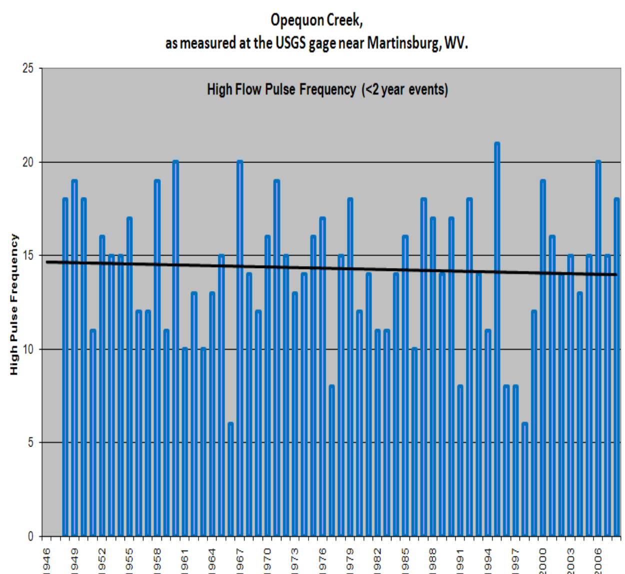


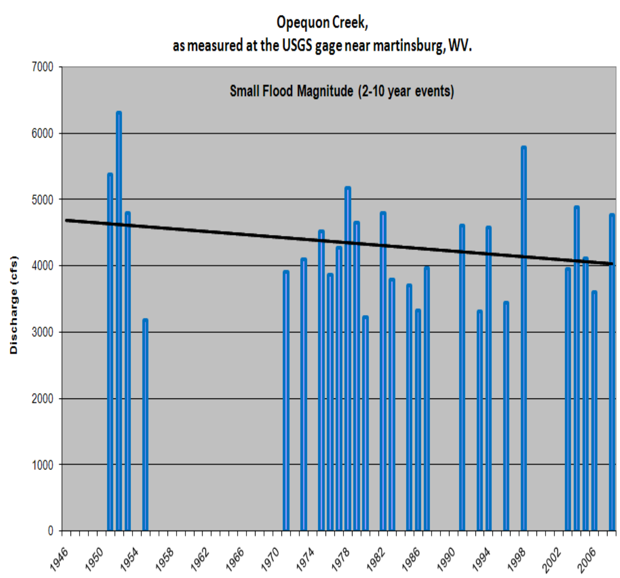


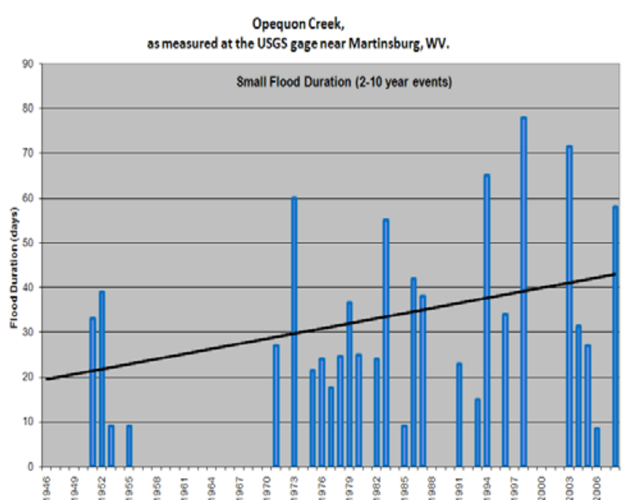


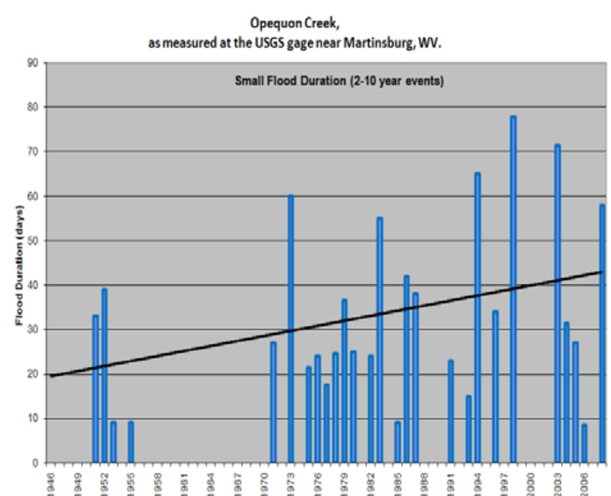

Opequon Creek,
as measured at the USGS gage near Martinsburg, WV.
High Flow Pulse Magnitude (<2-year events)
Discharge (cfs)

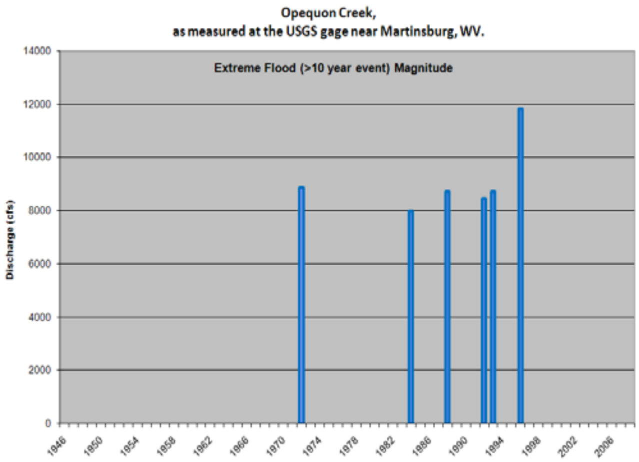

Opequon Creek,
as measured at the USGS gage near Martinsburg, WV.
High Flow Pulse Duration (<2 year events)
High Pulse Duration (days)

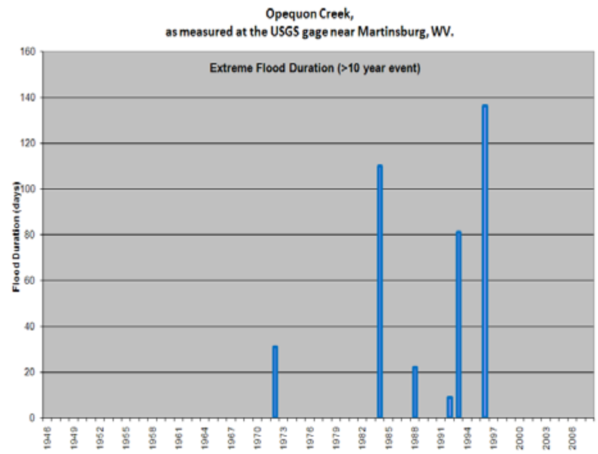

Opequon Creek,
as measured at the USGS gage near Martinsburg, WV.
High Flow Pulse Frequency (<2 year events)
High Pulse Frequency


Opequon Creek,
as measured at the USGS gage near martinsburg, WV.
Small Flood Magnitude (2-10 year events)
Discharge (cfs)


Opequon Creek,
as measured at the USGS gage near Martinsburg, WV.
Small Flood Duration (2-10 year events)
Flood Duration (days)


Opequon Creek,
as measured at the USGS gage near Martinsburg, WV.
Small Flood Duration (2-10 year events)
Flood Duration (days)





Monocacy River

The Monocacy River (**Figure C-3**) is a free-flowing tributary to the Potomac River which originates near Gettysburg, Pennsylvania, and flows approximately 58 miles in a meandering, southerly course to its confluence with the Potomac River near Dickerson, Maryland. Its mean flow is roughly 600 mgd. It watershed is approximately 966 square miles, of that roughly 224 square miles are located in Pennsylvania and 742 square miles in Maryland.

The watershed lies within two physiographic provinces, the Piedmont and Blue Ridge. The Piedmont is composed of hard, crystalline igneous and metamorphic rocks and extends from the inner edge of the Coastal Plain westward to Catoctin Mountain. The predominant soils are moderately erodible. Ground water occurs primarily in fractures and bedding-plane partings of rocks. In the broad, flat Frederick Valley which is underlain by limestone as well as dolomite, groundwater also occurs in solutional cavities in limestone and marble (McCoy and Summers 1992). A prominent topographic feature of the Piedmont is an erosion resistant monadnock, known as Sugarloaf Mountain, which is composed of highly weather resistant quartz (MGS 2007).

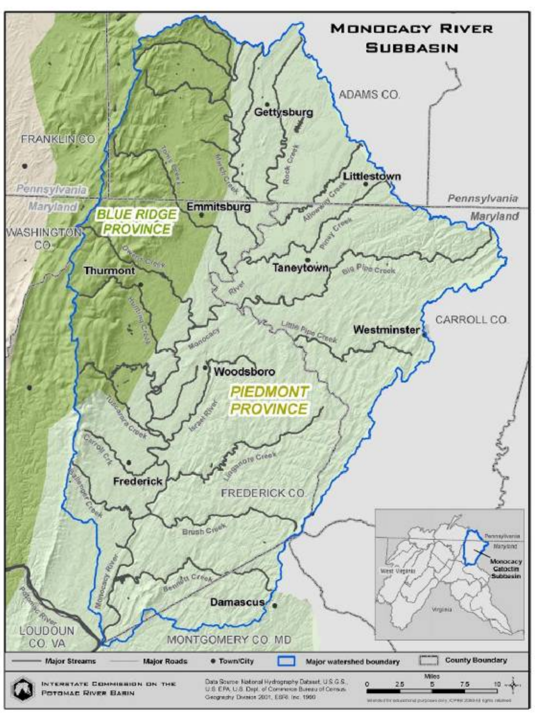


Figure C-3. Monocacy River watershed.

The Blue Ridge Province is underlain primarily by folded and faulted sedimentary rocks. The rocks of the Blue Ridge Province are exposed in a large anticlinal fold whose limbs are represented by Catoctin Mountain and South Mountain. (MGS 2007).

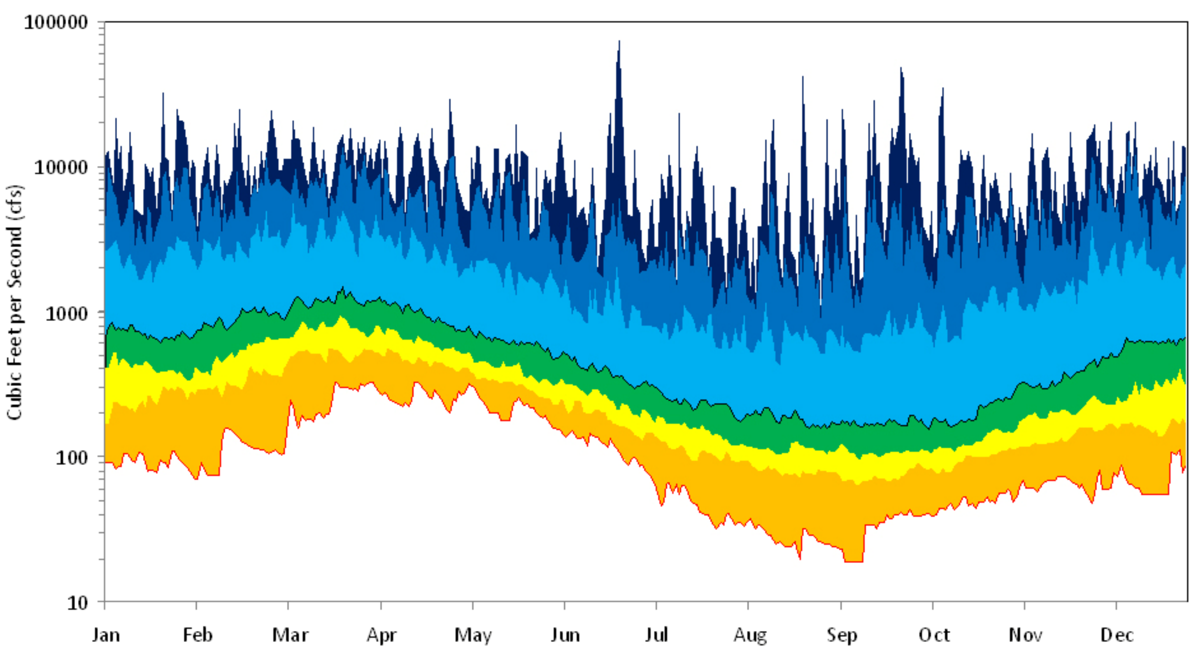
The Monocacy River has long been the focus of strong restoration efforts. Illustrative highlights start in 1949 with the creation of the Interstate Monocacy Watershed Council, designation in 1974 as a Maryland Scenic River, decades of agricultural water quality management priorities, and current extensive efforts to reduce sediment, nutrient and bacterial loads to the river as part of the two state's Total Maximum Daily Load processes.

The land in the Monocacy River basin is 25% forested, 64% agricultural and 8% urban development, with a total population estimated to be approximately 96,000 (MDE 2007). The watershed has two main urban centers, Frederick Maryland and Gettysburg, Pennsylvania, along with a number of smaller towns. Most of these communities, due to the watershed's proximity with Washington, DC and Baltimore, Maryland, have experienced population growth pressures. For illustration, in order to meet drinking water supply needs to accommodate expected growth, the Gettysburg area has requested an interbasin transfer of water from the Susquehanna watershed and Frederick, now too large to rely solely on Monocacy water resources, is tapping into the Potomac mainstem for water. Agriculture still remains the principal land-use within the watershed, which consists mostly of row crops, but also includes dairy production. Crop-land soil erosion in the Monocacy watershed ranges from two to 35 tons per acre, while the amount of soil which could be lost and still maintain productivity is only three tons per acre.

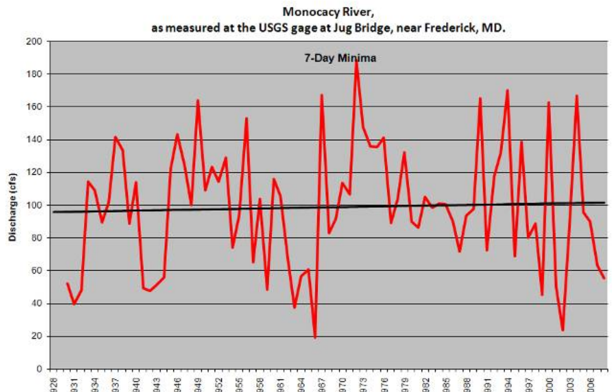
The Monocacy River sub-basin had the second highest Cumulative Risk Index score. The Monocacy was found to be at "severe" risk of hydrologic alteration from agriculture, "high" risk of forest loss, urbanization, surface withdrawals, and consumptive use (**Report Table 1**). Note that Monocacy's IHA are calculated from flow time series at the Jug Bridge, MD stream gage. This gage is located in the middle of the Monocacy watershed and thus is representative of only the upper half of the watershed. A flow time series for the entire watershed can be *estimated* with models.

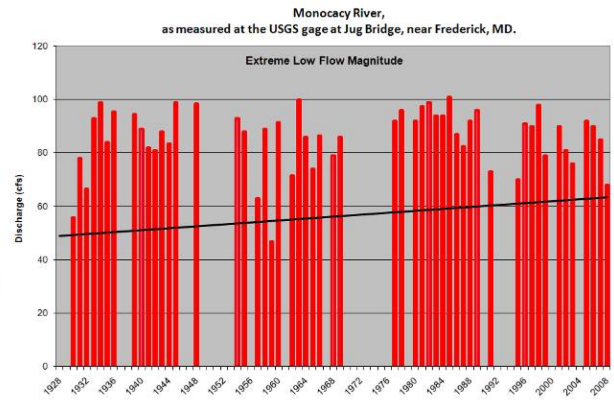
The first panel in **Figure C-4** shows the range of daily mean flows experienced each day of the year in the 1930-2008 period of record. The following panels illustrate the long-term trends in several low flow and high flow indicators of the Monocacy's hydrology. High flow pulses correspond roughly to bankfull events and small floods to over-bank events. The USGS gage on the Monocacy River represents only the upper 84.6% of the sub-basin area because it is located at Jug Bridge, 16.9 miles upstream from the confluence with the Potomac River mainstem. The gage is upstream of the Frederick, Maryland urban center which is growing rapidly, so these graphs may not represent the full hydrologic impact of land and water uses on Monocacy River.

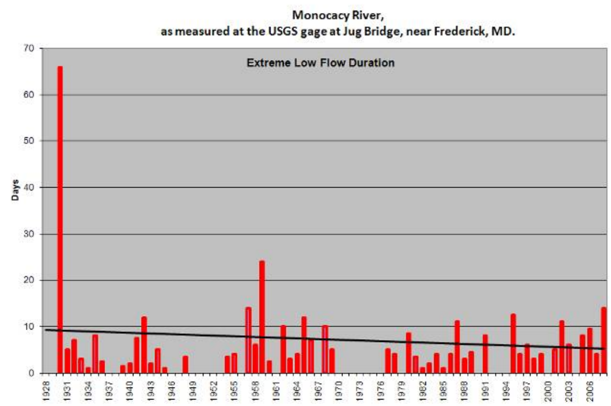
Figure C-4. Extent of flows and IHAs for Monocacy River at the USGS gage at Jug Bridge, MD, 1930-2009.

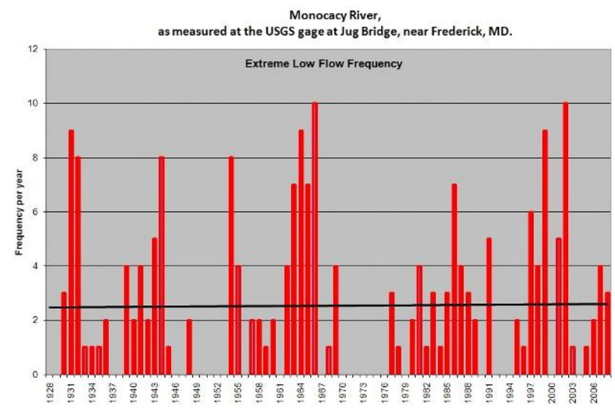


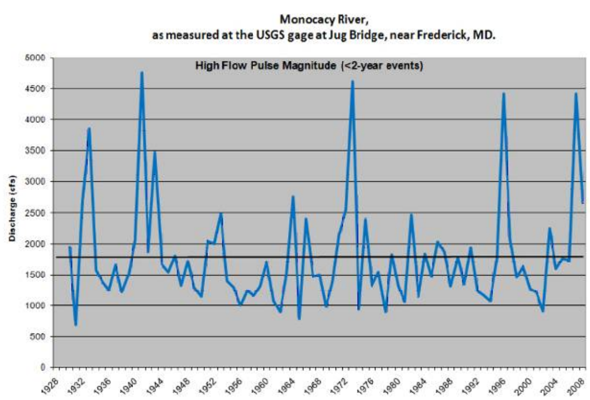
The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows are shown above.

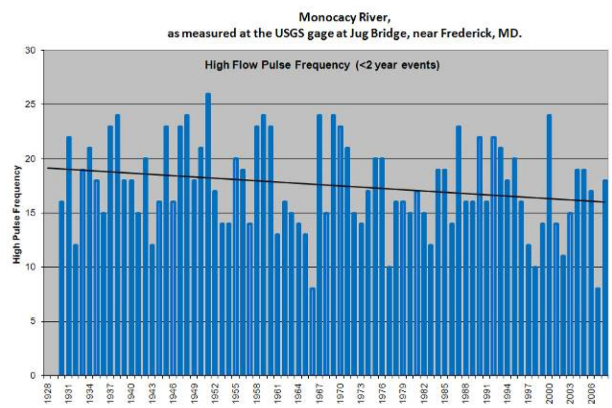

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
7-Day Minima
Discharge (cfs)

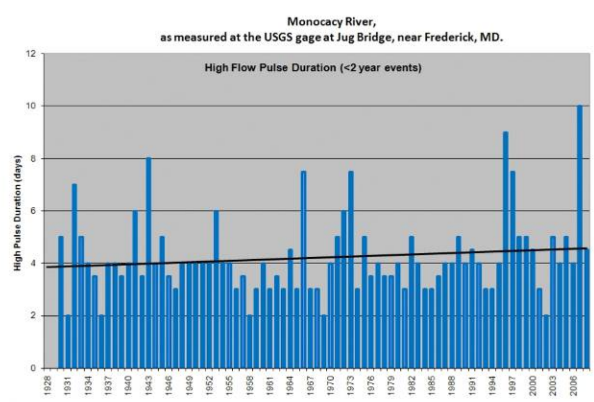

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
Extreme Low Flow Magnitude
Discharge (cfs)

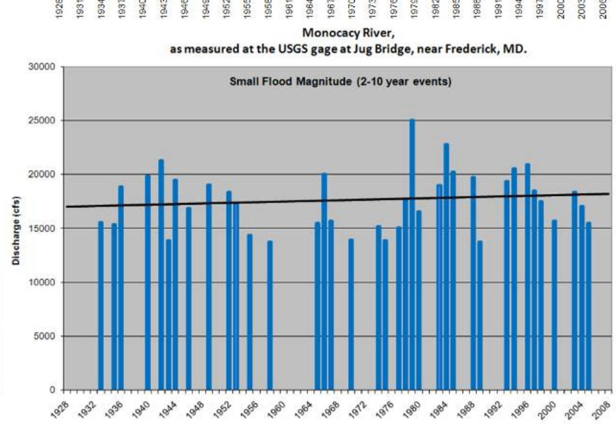

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
Extreme Low Flow Duration
Days

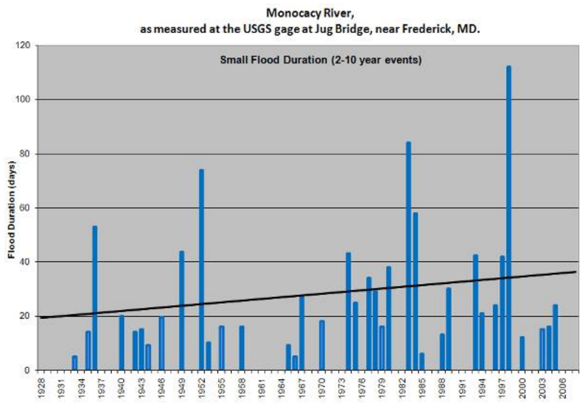

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
Extreme Low Flow Frequency
Frequency per year

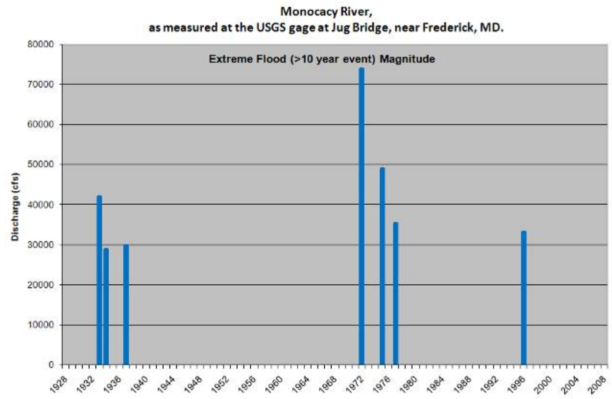

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
High Flow Pulse Magnitude (<2-year events)
Discharge (cfs)

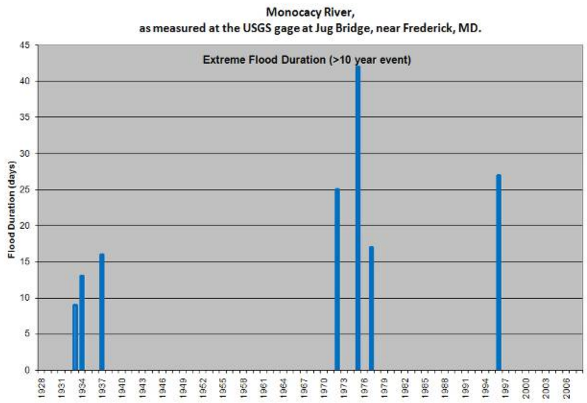

Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
High Flow Pulse Frequency (<2 year events)
High Pulse Frequency


Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
High Flow Pulse Duration (<2 year events)
High Pulse Duration (days)


Monocacy River,
as measured at the USGS gage at Jug Bridge, near Frederick, MD.
Small Flood Magnitude (2-10 year events)
Discharge (cfs)







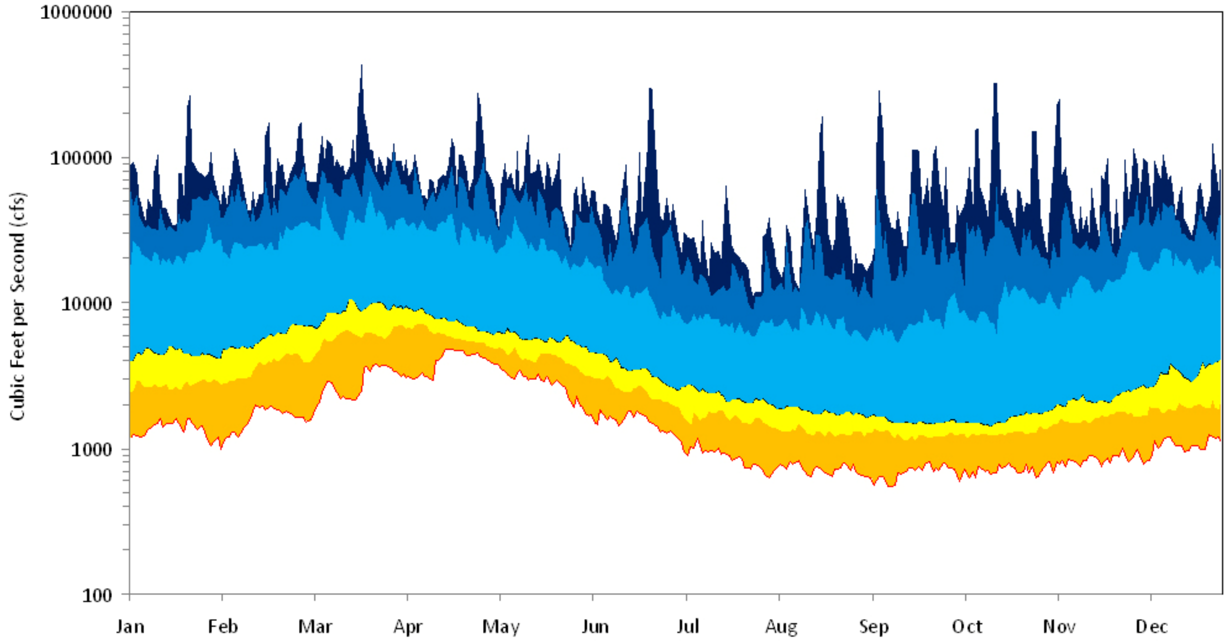
Point of Rocks

A USGS gage marks the downstream end of the Potomac River mainstem segment from the Shenandoah River confluence to Point of Rocks, and it marks the upstream end of the segment from Point of Rocks to Great Falls. The area of the Potomac River basin upstream of Point of Rocks is 9,651 square miles. Total water withdrawals in upstream basin amount to about 31% of the median (50^{th} percentile) flow at the gage (**Appendix B Table B-1**). Upstream surface withdrawals represent about 47% of the flow when flow is relatively low, or around the 10^{th} percentile of all flows in the 22 year study period. A significant portion of the withdrawals is returned to the river because consumptive use above Point of Rocks is estimated to be about 1.66% of the median flow (higher when flows are low). Approximately 25% of the basin above Point of Rocks is underlain by karst geology, a percentage that is significant enough to modify river hydrology by enhancing low flows with groundwater and minimizing high flows with quicker seepage of rainfall into the ground. Forest covers almost 69% of the basin above Point of Rocks, and most of it is located along the western side of the Potomac basin. Agriculture, located primarily in the Great Valley, covers 23% and urban areas cover 6.6% of the upstream basin (**Appendix B Table B-1**).

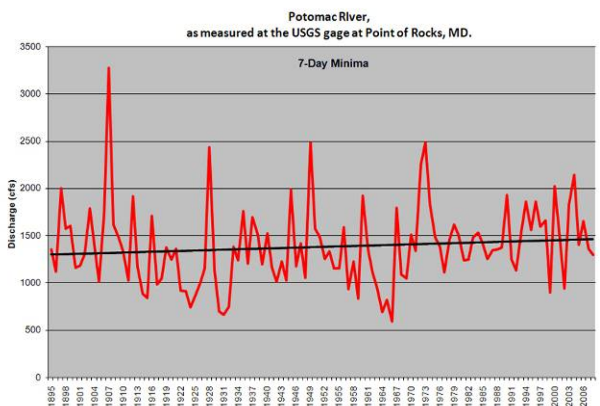
The USGS gage at Point of Rocks extends 115 years from February 1895 to the present day. It was one of the first river gages installed in the United States and is one of the oldest records of daily flow in the world. To allow direct comparisons with other river segments which were gaged later, only the period of record from 01/01/1930 to 09/30/2008 was used to determine trends in several IHA statistics.

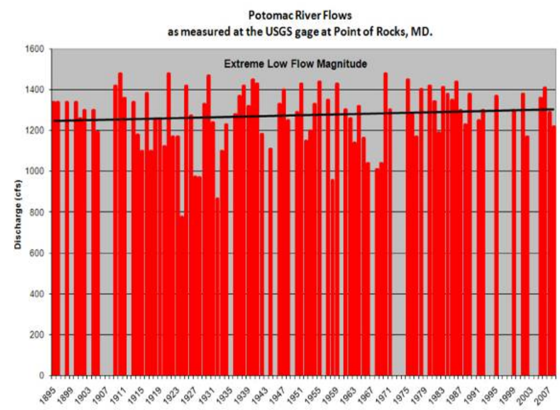
The first panel in **Figure C-5** shows the range of daily mean flows experienced each day of the year in the 1930-2008 period of record. The following panels illustrate the long-term trends in several low flow and high flow indicators of the Potomac River's hydrology at Point of Rocks. High flow pulses correspond roughly to bankfull events and small floods to over-bank events.

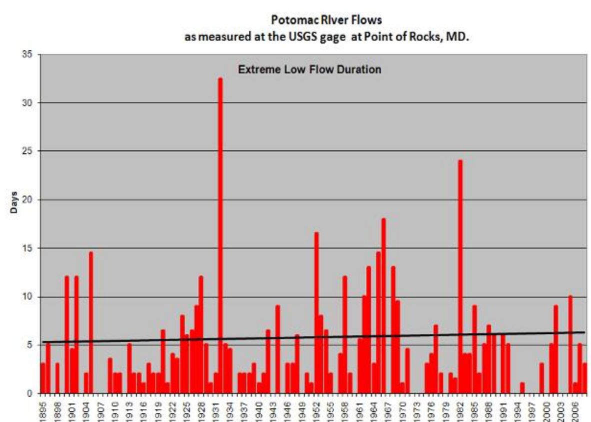
Figure C-5. Extent of flows and IHAs for Potomac River at the USGS gage at Point of Rocks, MD., 1895-2009.

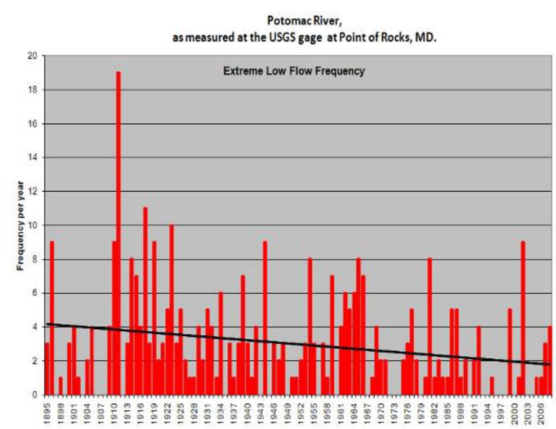


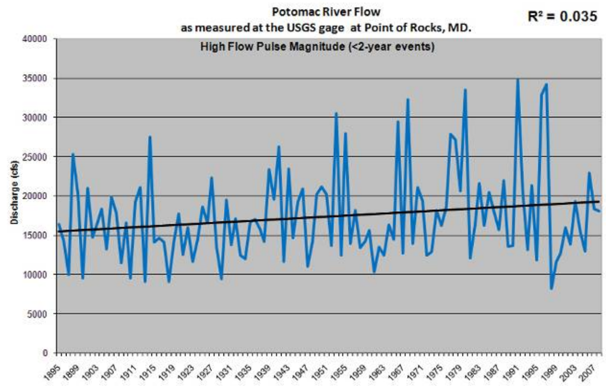
The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows are shown above.

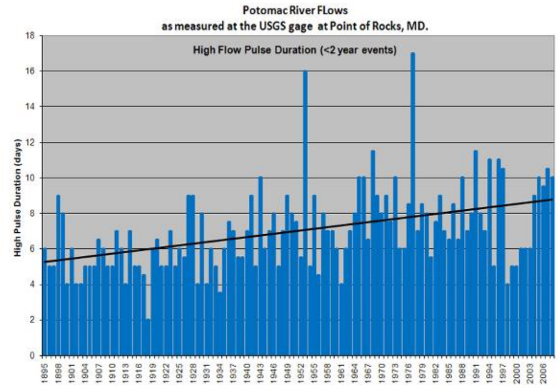


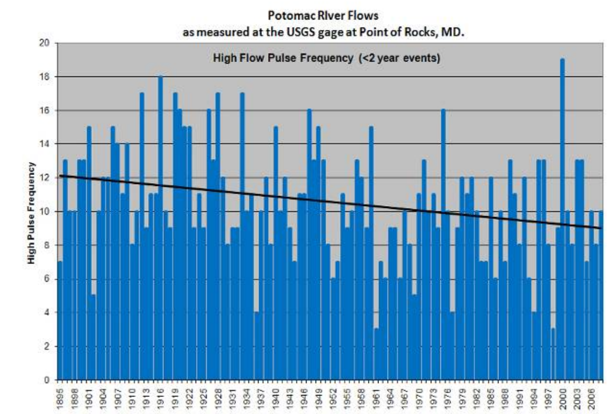


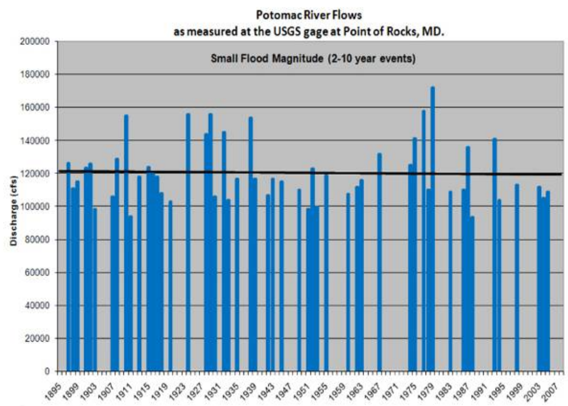


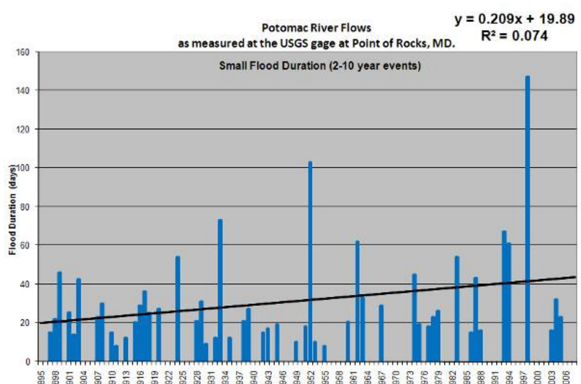


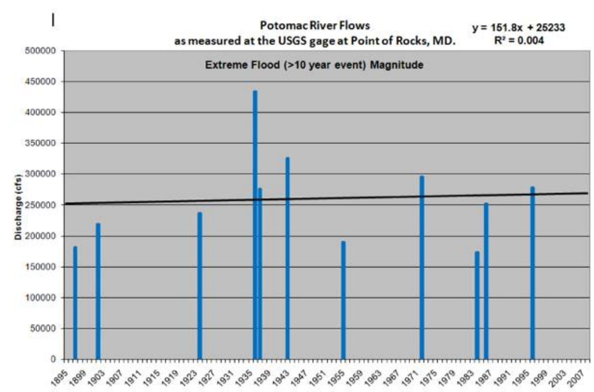

Potomac River Flow
as measured at the USGS gage at Point of Rocks, MD.
R² = 0.035
High Flow Pulse Magnitude (<2-year events)
Discharge (cfs)

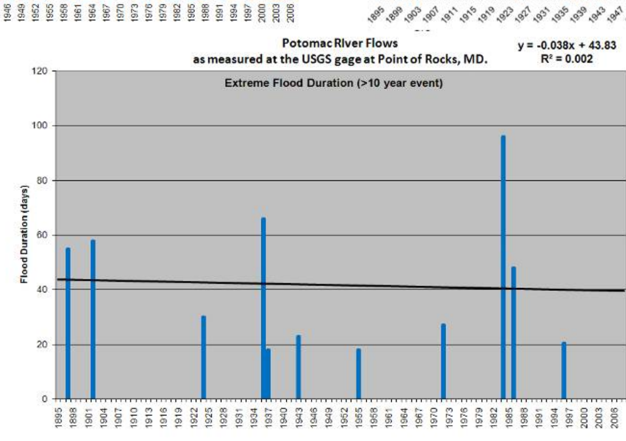

Potomac River FLows
as measured at the USGS gage at Point of Rocks, MD.
High Flow Pulse Duration (<2 year events)
High Pulse Duration (days)


Potomac River Flows
as measured at the USGS gage at Point of Rocks, MD.
High Flow Pulse Frequency (<2 year events)
High Pulse Frequency


Potomac River Flows
as measured at the USGS gage at Point of Rocks, MD.
Small Flood Magnitude (2-10 year events)
Discharge (cfs)


Potomac River Flows
as measured at the USGS gage at Point of Rocks, MD.
y = 0.209x + 19.89
R² = 0.074
Small Flood Duration (2-10 year events)
Flood Duration (days)


Potomac River Flows
as measured at the USGS gage at Point of Rocks, MD.
y = 151.8x + 25233
R² = 0.004
Extreme Flood (>10 year event) Magnitude
Discharge (cfs)


Potomac River Flows
as measured at the USGS gage at Point of Rocks, MD.
y = -0.038x + 43.83
R² = 0.002
Extreme Flood Duration (>10 year event)
Flood Duration (days)

Little Falls

The USGS gage at Little Falls (01646500) is less than a mile upstream of Chain Bridge and the two locations are considered to be equivalent for the purposes of this study. Chain Bridge (Little Falls) is the downstream end of the Potomac River segment from Great Falls to Chain Bridge, and the upstream end of the tidal fresh segment extending to Occoquan Bay. The Great Falls to Chain Bridge segment had the fifth highest risk index score. "Severe" risk values were found for total withdrawals and surface withdrawals and "high" risk values were found for agriculture and consumptive use (**Report Table 1**). This segment experiences significant withdrawals by several water supply operations totaling 136,636 million gallons per year and a major withdrawal for power of 141,171 million gallons per year (most of the withdrawal for power is returned immediately downstream). There are 308 points of withdrawal in the ICPRB database for this river segment and its bordering watersheds, totaling 340,544 million gallons per year.

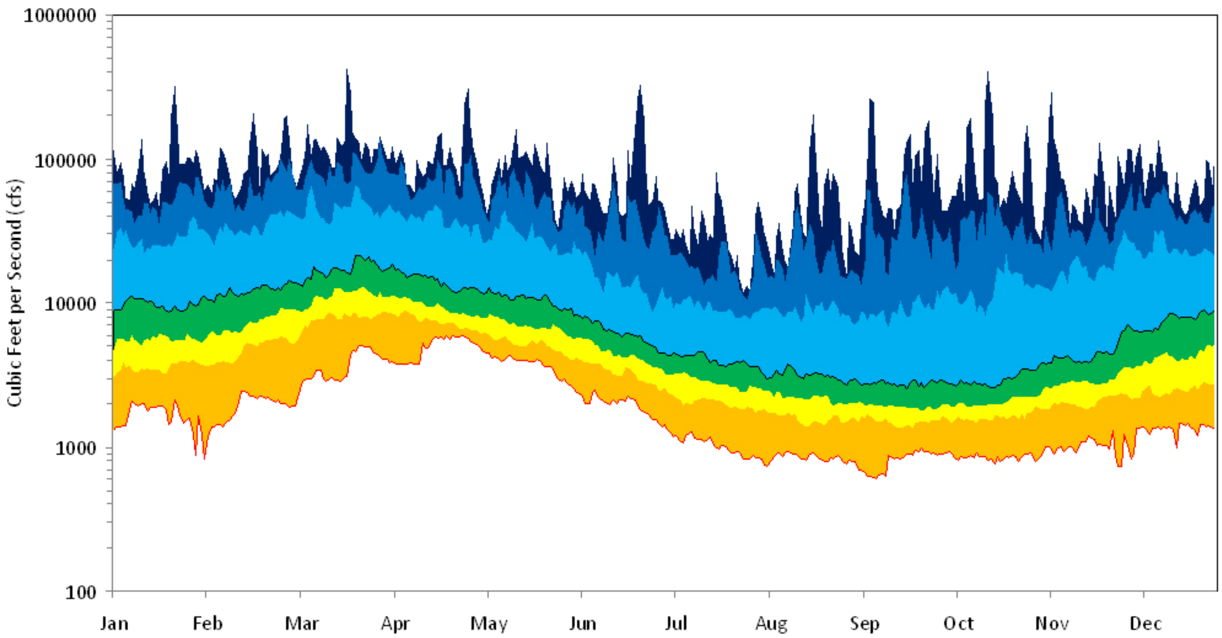
The distribution of the adjusted mean daily flows over the 1930-2008 time period is shown in **Figure C-6.** Adjusted flows have the upstream withdrawals for the metropolitan area added back**.** These adjustments vary depending on demand and can reach as high as ~400 mgd. The adjustment shows what “natural flows” would look like at Little Falls, and approximate flows at Great Falls. The adjustment is computed by using flow measurements at Little Falls gage, and then adding back the following:

1) withdrawals from the three major Metropolitan Washington Area (WMA) water supply utilities;
   a) Fairfax County Water Authority, intake near Seneca, supplies Fairfax, Prince William, portions of Loudoun County and the City of Alexandria, Virginia.
   b) Washington Suburban Sanitary Commission, intake near Muddy Run, supplies Montgomery and Prince Georges Counties, Maryland.
   c) Washington Aqueduct Division of the Corps of Engineers, intakes at Great Falls and Little Falls, supplies the District of Columbia, Arlington County and the City of Falls Church, Virginia.
2) large withdrawals from major municipalities within the WMA
   a) the City of Rockville's Potomac River intake
   b) the City of Fairfax's Goose Creek intake
3) flows diverted to the C&O Canal at Violet's Lock

Five floods with magnitudes of >386,750 cfs (250,000 mgd), often described as “100 year floods,” have occurred in the last 8 decades. The worst flood of record occurred in March of 1936 when the landscape was in the early stage of recovering from highly deforested conditions, and both floods and droughts were amplified by poor runoff conditions. It is uncertain whether that storm reflects a natural flood event. The January 1996 flood occurred when during a significant rain event falling on highly unusual amounts of snow covering frozen ground, and the runoff was essentially meeting a 100% impervious surface cover. This event could represent a natural 100-year event. Floods exceeding approximately 70,000 cfs (45,242 mgd) at Little Falls are considered a risk to human safety and health as well as damaging to human structures in the floodplain near and below Little Falls, especially the Potomac shores around Washington, DC. However, at this gage and others, such risks are largely due to human decisions to build in flood-prone areas.

The panels in **Figure C-7** and **C-8** illustrate the long-term trends in several low flow and high flow indicators of the Potomac River’s hydrology at Little Falls. Panels illustrating low flows present both adjusted (blue) and unadjusted (red) flows.

Figure C-6. Extent of adjusted daily mean flows for Potomac River at the USGS gage at Little Falls, 1930-2009.



The maximum, 98th percentile, 90th percentile, 50th percentile (green line), 25th percentile, 10th percentile, and minimum (red line) daily mean flows are shown above.

Figure C-7. Low flow IHAs of adjusted (blue) and unadjusted (red) mean daily flows at Little Falls.

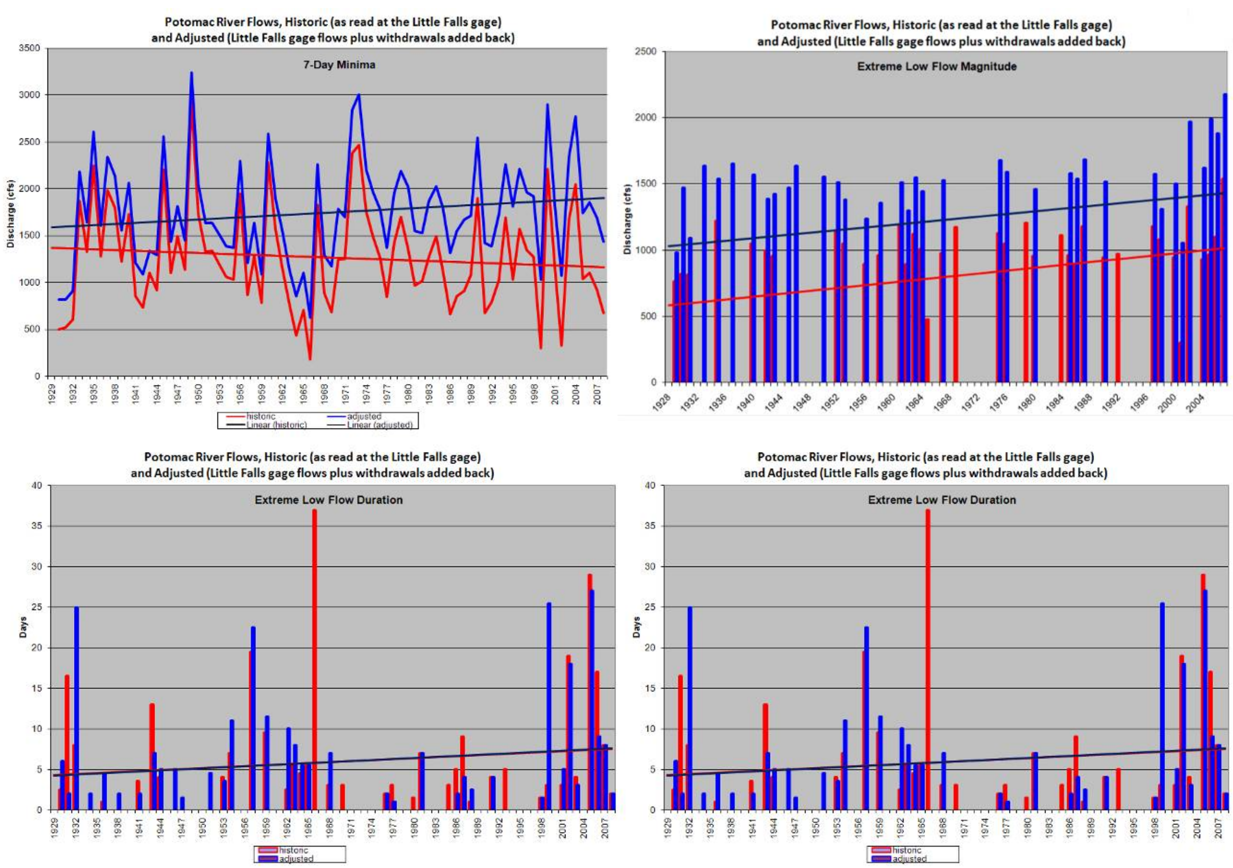
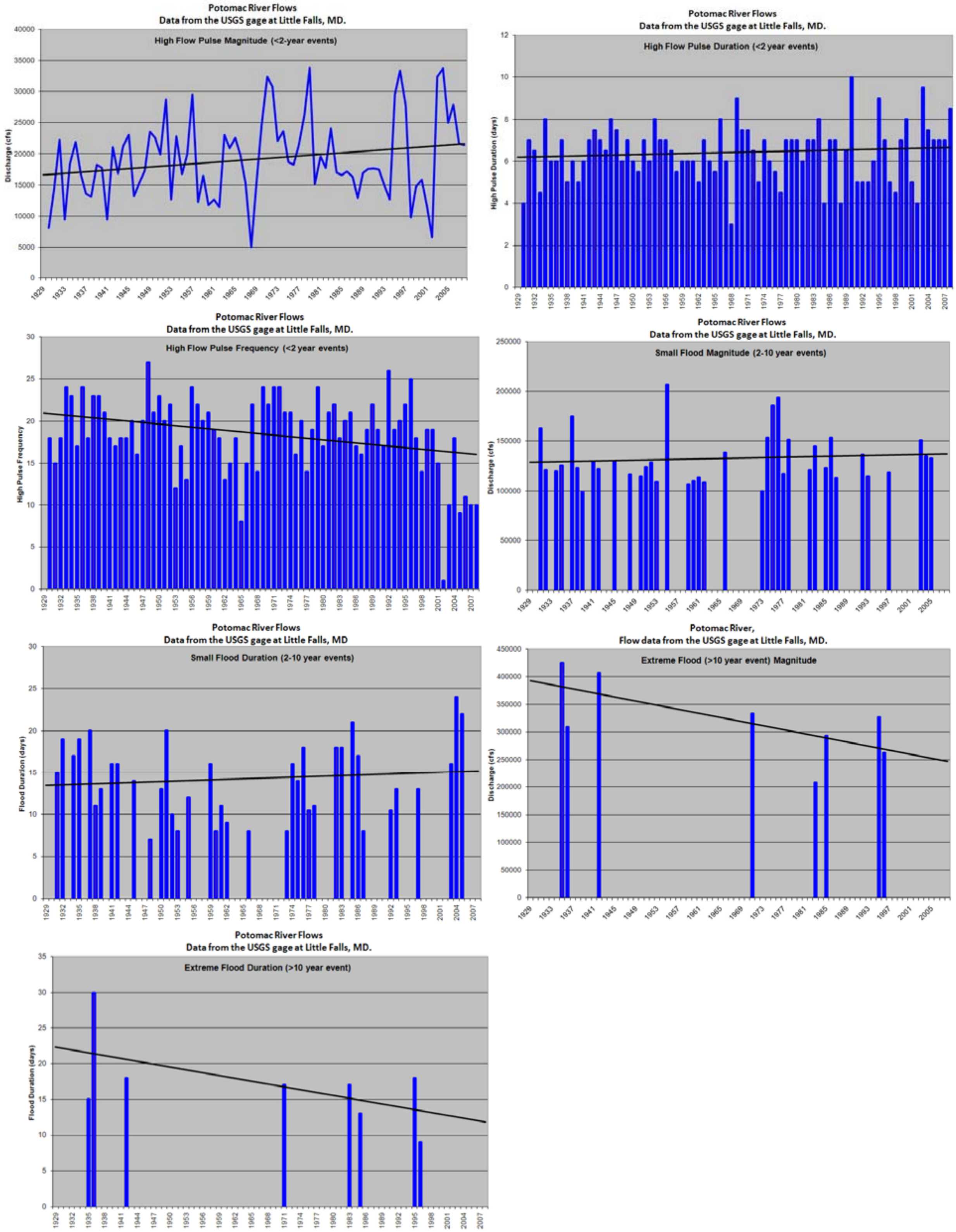


Figure C-8. High flow IHAs of unadjusted mean daily flows at Little Falls.



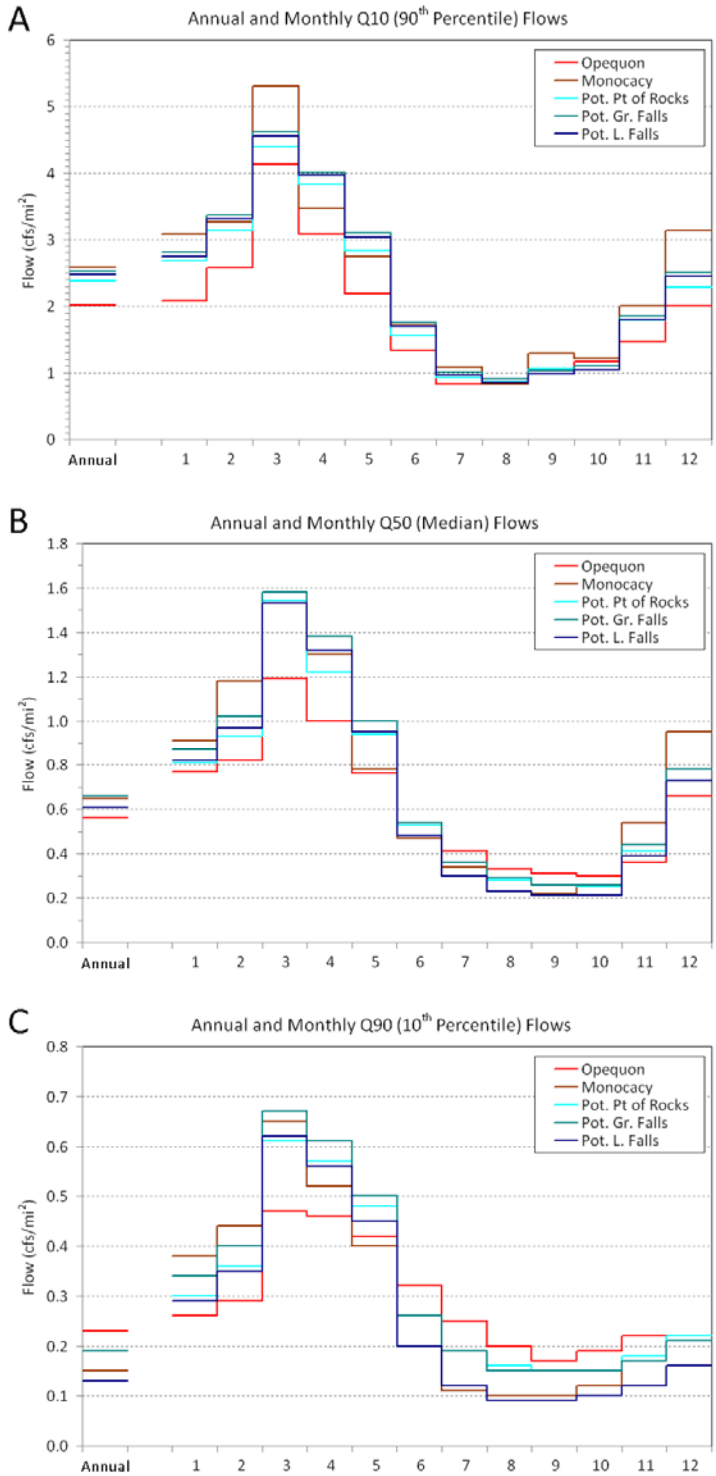


Figure C-9. Annual and monthly flows normalized to watershed area.
A) high flows, B) median flows, and C) low flows. Note: the Great Falls flow statistics are derived from Little Falls gage data that have been adjusted upward to account for upstream water supply withdrawals. The Little Falls flow statistics are unadjusted (actual).

River Comparisons

When river flows are normalized to watershed area, a direct comparison of flow statistics can illustrate key differences between the rivers. **Figure C-9** illustrates the area-normalized Q10, Q50, and Q90: three flow statistics representing high, median, and low flow conditions, respectively. For each month in the 22 year study period (1984-2005), the 90th percentile, median, and 10th percentile of all normalized daily flows are calculated. The monthly Q10 is the median value of all 90th percentiles in a given month; the monthly Q50 is the median value of all 50th percentiles in that month; and the Q90 is the median value of all 10th percentiles in that month.

Opequon flows appear to be mostly affected by the watershed's predominantly karst geology. Karst allows for quicker exchanges of water between surface and ground. Rainwater permeates the ground faster and ground water flowing to the surface through springs and seeps strengthens baseflow. Karst underlies 61% of the Opequon sub-basin compared to 25% of Potomac basin above Point of Rocks and 7% of the Monocacy sub-basin (**Table B-1**). The Opequon monthly high (**Figure C-9A**), median (**Figure C-9B**) and low (**Figure C-9C**) Q values are roughly 4/5th of those for the Potomac River mainstem in winter and spring. In summer and fall, Q50s are slightly higher and the Q90s are about 30% higher. Generally speaking, the Opequon has lower high flows and higher low flows.

Flow statistics in the highly agricultural (47%) and urbanized (15%) Monocacy watershed reflect the effects of the land uses. The Richards-Baker Flashiness Index (Baker et al. 2004), a correlate of percent impervious surface, is relatively high (0.442). The duration of high pulses is shorter. The average 1-day and 3-day annual minima are relatively low. Except for the Potomac at Little Falls, the Monocacy has the lowest monthly Q90s of the five special interest segments in summer and autumn (**Figure C-9C**).

There is a drop of roughly 0.0525 cfs/mi^2 (~600 cfs) in all monthly Q values between Great Falls and Little Falls due the the metropolitan Washington, DC water supply withdrawals. The monthly and annual Q90s for the Potomac at Little Falls clearly show the influence of the withdrawals in summer and autumn, when flows are typically lowest (**Figure C-9C**). Summer and autumn monthly Q90s converted back to cfs at Little Falls range between 1,272 to 3,352 cfs. Therefore, months with the lowest flows are generally well above the Potomac River minimum flow-by requirement of 464 cfs, or 300 mgd. During the 22 year period between 1984 and 2005, flows only approached the minimum requirement in two drought years: 1999 and 2002.

APPENDIX D

OVERVIEW OF ESTUARINE HEALTH INDICATORS FOR THE CHESAPEAKE BAY PROGRAM

The multi-agency Chesapeake Bay Program (CBP) has identified thirteen indicators of Chesapeake Bay estuarine health and uses them to report annual progress to the U. S. Congress, resource managers, and the public (CBP 2009a). The recent status of each indicator is compared to restoration goals or desirable "reference" levels for the Bay and its tidal tributaries that the Program is trying to achieve. The indicators are based on three water quality parameters, a chemical contaminant index, four biological communities, and five fisheries species. Low flows either improve or degrade estuarine water quality, depending on whether upstream concentrations are higher or lower. The effect of freshwater flow on the biological indicators is usually indirect and expressed through flow's influence on the estuarine salinity gradient and water quality.

CBP recognizes that "levels of pollution entering the Bay each year generally correspond with the volume of water that flows from its tributaries." Dry and wet years thus affect Bay water quality (www.chesapeakebay.net/status_naturalfactors.aspx?menuitem=19786), which in turn affect the health of Bay biota. CBP does not relate annual measures of river flow to nutrient and sediment reduction goals at this time because freshwater flow is considered to be a natural factor influenced primarily by annual precipitation. The goals are instead based on averaged flows (www.chesapeakebay.net/status_riverflow.aspx?menuitem=19788).

The thirteen Bay Health indicators are briefly described below. More information can be found at http://www.chesapeakebay.net/status_bayhealth.aspx?menuitem=15045.

Dissolved oxygen – Natural year-to-year differences in flow affect the intensity and duration of salinity stratification in the lower Potomac estuary. High flows encourage formation of strong stratification in the lower Potomac, especially in summer. This blocks wind from mixing oxygenated surface waters to the bottom and facilitates the build-up of anoxic conditions in the bottom layer in summer. Low flows tend to weaken salinity stratification, allowing strong winds to mix surface waters to the bottom. The Bay states have dissolved oxygen criteria in their estuarine water quality standards (CBP 2003). As of 2008, about 16% of Bay waters met the criteria bay-wide.

Mid-channel water clarity – River concentration of suspended sediments is one of the major factors governing the status of this indicator in the Potomac estuary. Also important are bottom sediment types and their susceptibility to be re-suspended in the water column by tidal currents and wind storms. Mud, silt, and clay - a legacy of three centuries of upland soils being washed off the basin changing landscape - are the dominate sediment types in the upper and middle Potomac estuary and in much of the lower estuary (Lippson et al. 1979). The Bay states have water clarity criteria in their estuarine water quality standards (CBP 2003). As of 2008, about 14% of the criteria were attained bay-wide.

Chlorophyll *a* – Chlorophyll *a* is a photopigment found in all plants. Chlorophyll *a* extracted from water samples is used to approximate phytoplankton biomass. As of now, only the James River and the Potomac River in Washington DC have water quality criteria for maximum chlorophyll a concentrations. The CBP goal is for 100% of Chesapeake Bay tidal waters to be below certain threshold concentrations of chlorophyll *a* that reflect healthy, balanced phytoplankton communities and are acceptable levels for underwater bay grasses. As of 2008, 27% of Bay waters had met the goal.

Chemical contaminants – An ultimate goal of the CBP is a bay free of toxic impacts from chemical contaminants such as metals, PCBs, and tributyltin. The goal will be achieved by "reducing or eliminating the input of chemical contaminants [in the watershed] to levels that result in no toxic or bioaccumulation impact on living resources that inhabit the Bay or on human health" (www.chesapeakebay.net/status_chemicalcontaminantloads.aspx?menuitem=19816). As of 2008, 28% of the monitored segments in the Bay and its tributaries were unimpaired by chemicals.

Submerged Aquatic Vegetation - Flow impacts on SAV are predominantly expressed through its effects on salinity, nutrient concentrations, and turbidity. In high flow periods, the Potomac tidal fresh water quality tends to resemble the river water quality upstream of the fall-line. In low flow conditions, nutrient and sediment inputs from below the fall-line gain more influence on estuarine habitat conditions for SAV. The CBP goal of 185,000 acres of SAV in Chesapeake Bay is based on historical distributions. As of 2008, 42% of the goal was attained bay-wide.

Phytoplankton - Flow effects on phytoplankton are predominantly expressed through its effects on salinity, nutrient concentrations, and turbidity, although high flow events can hydraulically push phytoplankton downstream. In high flow periods, the Potomac tidal fresh water quality tends to resemble the river water quality upstream of the fall-line. In low flow conditions, nutrient and sediment inputs from below the fall-line gain more influence on estuarine habitat conditions for phytoplankton. Phytoplankton communities are rated with the CBP Phytoplankton Index of Biotic Integrity (PIBI). The index is calculated for each season and salinity zone from 5 – 9 phytoplankton community metrics that are sensitive to water quality condition (e.g., chlorophyll a, Chl:C ratio, pheophytin, biomasses of important taxonomic groups). Each metric is scored depending on how similar it is to a reference (least-impaired) community, and the index is the average of the individual scores. The CBP goal is for all PIBI index scores to rate 3 or better on a scale of 1-5. In 2008, approximately 53% of the goal was attained bay-wide.

Bottom Habitat - Flow effects on benthic macroinvertebrates are predominantly through flow effects on salinity and dissolved oxygen. Bottom habitat quality is measured with the CBP Benthic Index of Biotic Integrity (BIBI). The index is calculated for distinct bottom sediment types and salinity zones from 6 - 17 benthic community metrics that are sensitive to water quality conditions, especially dissolved oxygen. Each metric is scored depending on how similar it is to a reference (least-impaired) community, and the index is the average of the individual scores. The CBP goal is for all BIBI scores to rate 3 or better on a scale of 1-5. In 2008, approximately 42% of the goal was attained bay-wide.

Tidal Wetlands - Tidal wetland plant species are very adapted to survive tidal changes in water level and stochastic changes in salinity. Freshwater flow affects tidal wetlands only to the degree that it affects salinity. Sea level rise is more of an issue to these plants. CBP presently does not have a goal for tidal wetland acreage.

Blue Crab – Blue crab are primarily estuarine, and although juvenile crabs are occasionally found in tidal freshwaters, their life cycle is mostly governed by flows out of and back into the Bay at key life stages, and water quality, habitat quality, and food conditions in higher salinity waters. The CBP goal is to have 200 million blue crabs that are at least one year old in the Bay. This goal was 60% attained in 2008.

Oyster – A factor impacting the historic oyster bars near Morgantown was the long-term downstream movement of the salinity gradient in the Potomac estuary as river morphology changed. Presently, disease and overharvesting are the factors most damaging to Bay populations. High flow years can result in increased death rates along the low salinity boundaries of the populations. CBP has a goal of 31.6 billion grams of oyster biomass, and had attained 9% of this goal bay-wide as of 2008.

Striped Bass – Tidal freshwater reaches in the Chesapeake system are the nursery and spawning areas for striped bass. This species migrates from the ocean in early spring to spawn in tidal fresh reaches. Naturally high spring flow creates a larger tidal fresh nursery area which can benefit newly hatched larvae. Young-of-year begin to move downstream to higher salinities in their first year. The CBP goal for striped bass is 82.7 million pounds of females, or spawning stock. The goal has been repeatedly met in recent years due to adaptive fisheries management, however scientists are concerned about the high levels of mycobacteriosis disease in juvenile and adult fish.

American Shad - Tidal freshwater reaches in the Chesapeake system are the nursery and spawning areas for shad. This species migrates from the ocean in early spring to spawn in tidal fresh reaches. Naturally high spring flow creates a larger tidal fresh nursery area which can benefit newly hatched larvae. Shad young-of-year spend their first summer in tidal fresh waters before moving downstream in the fall to the ocean. CBP has established a composite goal for shad based on rough population estimates from four tributaries: Potomac, James, York, and Susquehanna. It is achieving this goal by removing fish passage blockages and improving upstream water quality.

Juvenile Atlantic Menhaden - Juvenile menhaden are primarily estuarine, and although juveniles are occasionally found in tidal freshwaters, their life cycle is mostly governed by ocean-to-estuary flows and habitat conditions in higher salinity waters. CBP does not presently have a juvenile menhaden goal.

APPENDIX E

DIMENSIONS OF THE POTOMAC ESTUARY MAINSTEM AND TIDAL TRIBUTARIES

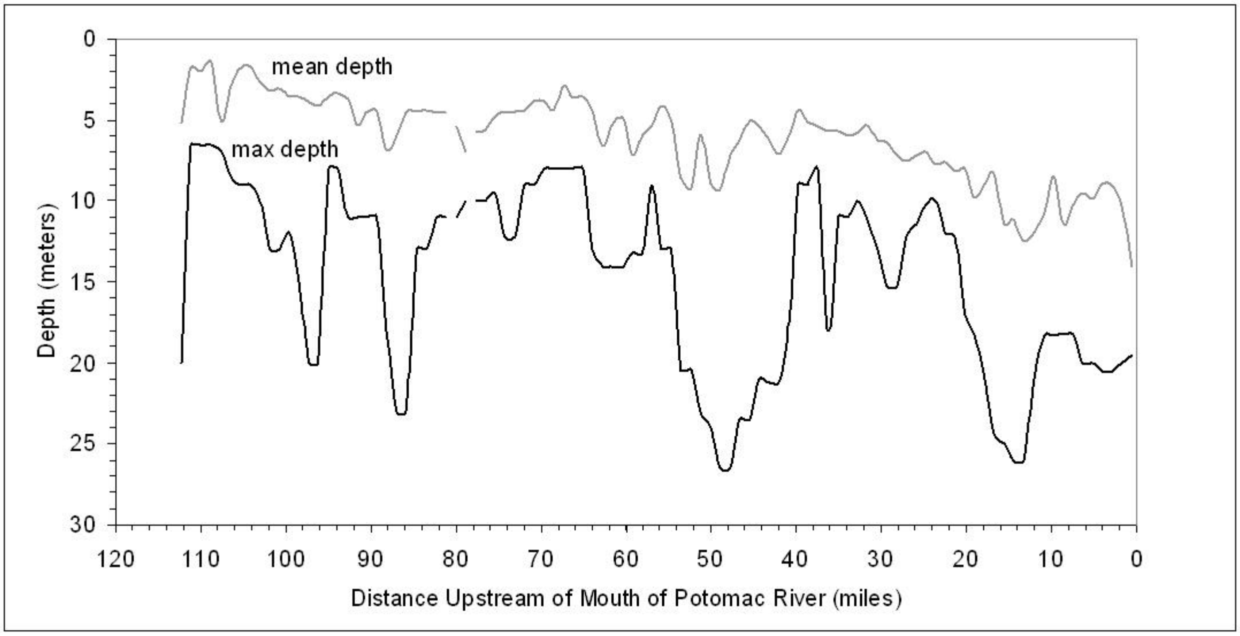
Average and maximum depths, surface areas, and water volumes for nautical river mile segments of the Potomac estuary mainstem and adjacent tidal tributary embayments (from Lippson et al. 1979). Average and maximum depths were originally in Cronin and Pritchard (1975). Surface areas were calculated mean low water (MLW) values in Cronin (1971). Volumes were calculated MLW values in Cronin and Pritchard (1975).

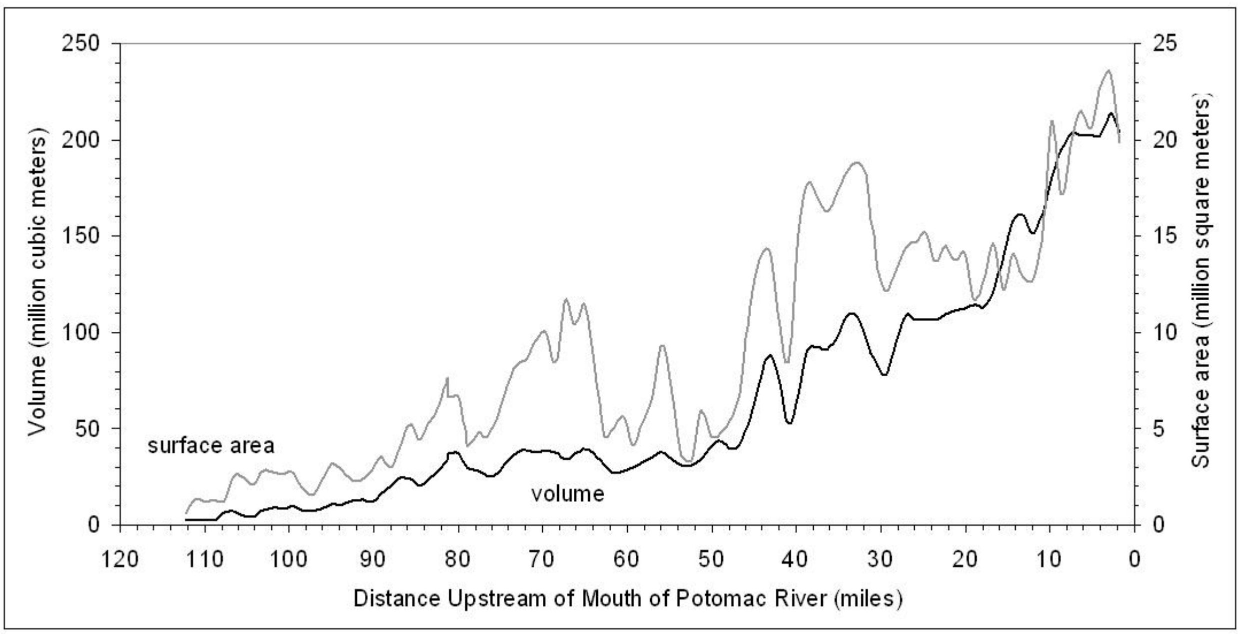
Potomac Mainstem Dimensions								**Landmark/Tributary**	**Tributary Dimensions**		
Nautical River Mile (midpoint of segment)	Nautical River Mile Interval	Kilometer	Statue Mile	Avg Depth m	Max Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3		Avg Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3
0.5	0 - 1	0.926	0.5755	14	19.5	60.92	852.88	River mouth			
1.5	1 - 2	2.778	1.7265	10.3	20	19.87	203.86				
2.5	2 - 3	4.63	2.8775	9.1	20.5	23.43	213.31				
3.5	3 - 4	6.482	4.0285	8.9	20.5	22.71	201.66				
4.5	4 - 5	8.334	5.1795	9.9	20	20.57	202.01				
5.5	5 - 6	10.186	6.3305	9.5	20	21.47	202.01	Coan R and the Glebe VA	2.3	11.99	27.23
6.5	6 - 7	12.038	7.4815	10.2	18.2	19.91	203.12				
7.5	7 - 8	13.89	8.6325	11.4	18.2	17.13	194.9	Yeocomico R VA	2.6	14.04	36.36
8.5	8 - 9	15.742	9.7835	8.5	18.3	21.04	180.3	Smith Cr MD	2.8	5.31	14.76
9.5	9 - 10	17.594	10.9345	10.7	18.3	14.92	161.17				
10.5	10 - 11	19.446	12.0855	11.9	21	12.65	150.99	St. Marys R MD	3.75	68.06	255.43
11.5	11 - 12	21.298	13.2365	12.5	26	12.85	161.06				
12.5	12 - 13	23.15	14.3875	11.2	26	14.08	157.73				
13.5	13 - 14	25.002	15.5385	11.4	25	12.24	140	Piney Pt MD			
14.5	14 - 15	26.854	16.6895	8.3	24.4	14.63	121.78				
15.5	15 - 16	28.706	17.8405	8.9	21	12.78	113.19	Herring Cr MD	1.4	2.09	2.97
16.5	16 - 17	30.558	18.9915	9.8	18.2	11.69	114.05	Ragged Pt VA			
17.5	17 - 18	32.41	20.1425	8	17	14.1	112.67				
18.5	18 - 19	34.262	21.2935	8.2	12.2	13.75	111.51	Lower Machodoc Cr VA	2.9	10.32	30.13
19.5	19 - 20	36.114	22.4445	7.6	12	14.5	109.34	Lower Machodoc Cr VA			
20.5	20 - 21	37.966	23.5955	7.7	10	13.65	106.34				
21.5	21 - 22	39.818	24.7465	7	10.2	15.22	106.92				

Potomac Mainstem Dimensions								**Landmark/Tributary**	**Tributary Dimensions**		
Nautical River Mile (midpoint of segment)	Nautical River Mile Interval	Kilometer	Statue Mile	Avg Depth m	Max Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3		Avg Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3
22.5	22 - 23	41.67	25.8975	7.2	11.4	14.71	106.56	Breton Bay MD	2.96	24.9	73.76
23.5	23 - 24	43.522	27.0485	7.5	12.2	14.4	108.67	Nomini Bay, Currioman Bay, Nomini Cr VA	7.1	21.77	54.76
24.5	24 - 25	45.374	28.1995	7.2	15.2	13.38	96.47	St. Clements Bay MD	3.40	22.01	74.81
25.5	25 - 26	47.226	29.3505	6.4	15.2	12.16	78.53				
26.5	26 - 27	49.078	30.5015	6.2	13	13.26	82.23				
27.5	27 - 28	50.93	31.6525	5.3	11.2	18.22	97.01				
28.5	28 - 29	52.782	32.8035	5.8	10	18.84	108.54	Wicomico R MD	2.36	89.31	210.55
29.5	29 - 30	54.634	33.9545	6	11	18.29	107.98	Wicomico R MD			
30.5	30 - 31	56.486	35.1055	5.7	11	17.27	97.55	Cobb Island MD			
31.5	31 - 32	58.338	36.2565	5.7	18	16.26	91	Popes Cr VA	0.6	1.72	1.05
32.5	32 - 33	60.19	37.4075	5.4	8	16.98	91.95				
33.5	33 - 34	62.042	38.5585	5.1	9	17.75	90.9	Mattox Cr VA	1.5	2.82	4.15
34.5	34 - 35	63.894	39.7095	4.4	9	15.14	67.95	Monroe Cr, Colonial Beach VA	0.9	1.72	1.62
35.5	35 - 36	65.746	40.8605	6.1	18.2	8.55	52.39				
36.5	36 - 37	67.598	42.0115	7.1	21.2	10.7	75.65	Rosier Cr VA	1.2	1.92	2.36
37.5	37 - 38	69.45	43.1625	6.2	21.2	14.23	87.95				
38.5	38 - 39	71.302	44.3135	5.4	21	13.73	73.23				
39.5	39 - 40	73.154	45.4645	5	23.5	11.3	55.03	Upper Machodoc Cr VA	2.3	1.55	3.55
40.5	40 - 41	75.006	46.6155	6.2	23.5	6.86	41.78	Morgantown MD			
41.5	41 - 42	76.858	47.7665	7.2	26.5	5.52	39.25	**Very large flows have extended 0.5 ppt isocline downstream of here**			
42.5	42 - 43	78.71	48.9175	9.3	26.5	4.75	43.5				
43.5	43 - 44	80.562	50.0685	8.9	24	4.59	40.62				
44.5	44 - 45	82.414	51.2195	5.9	23	5.89	34.47				
45.5	45 - 46	84.266	52.3705	9.2	20.4	3.34	30.85	Mathias Pt VA			
46.5	46 - 47	86.118	53.5215	8.6	20.4	3.6	30.85	Pt Tobacco R MD	2	22.23	44.46
47.5	47 - 48	87.97	54.6725	5.1	13	6.86	34.4				
48.5	48 - 49	89.822	55.8235	4.1	13	9.28	37.53				

Potomac Mainstem Dimensions								Landmark/Tributary	Tributary Dimensions		
Nautical River Mile (midpoint of segment)	Nautical River Mile Interval	Kilometer	Statue Mile	Avg Depth m	Max Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3		Avg Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3
49.5	49 - 50	91.674	56.9745	5.3	9	6.73	35.61	Nanjemoy Cr MD	1.5	10.39	15.48
50.5	50 - 51	93.526	58.1255	5.9	13.2	5.4	32.64				
51.5	51 - 52	95.378	59.2765	7.2	13.2	4.12	29.84				
52.5	52 - 53	97.23	60.4275	4.9	14	5.66	27.54	**Typical downstream limit of 0.5 ppt isocline**			
53.5	53 - 54	99.082	61.5785	5.3	14	5.03	26.75				
54.5	54 - 55	100.934	62.7295	6.6	14	4.64	30.77	Maryland Pt MD			
55.5	55 - 56	102.786	63.8805	4.4	13	8.43	36.87				
56.5	56 - 57	104.638	65.0315	3.5	8	11.41	39.06				
57.5	57 - 58	106.49	66.1825	3.6	8	10.38	36.56	Potomac Cr VA	0.6	5.84	3.56
58.5	58 - 59	108.342	67.3335	2.9	8	11.66	33.96				
59.5	59 - 60	110.194	68.4845	4.4	8	8.41	37.12	Aquia Cr VA	1.5	5.56	8.34
60.5	60 - 61	112.046	69.6355	3.8	8	9.98	38.48	**Average location of 0.5 ppt isocline**			
61.5	61 - 62	113.898	70.7865	3.8	9	9.6	37.38	Douglas Pt MD			
62.5	62 - 63	115.75	71.9375	4.4	9	8.59	38.43				
63.5	63 - 64	117.602	73.0885	4.5	12.2	8.26	37.41				
64.5	64 - 65	119.454	74.2395	4.6	12.2	7.18	33.2				
65.5	65 - 66	121.306	75.3905	4.7	9.6	5.62	26.33	Chopawamsic Cr VA			
66.5	66 - 67	123.158	76.5415	5.6	10	4.54	25.48				
67.5	67 - 68	125.01	77.6925	5.8	10	4.75	27.84	Possum Pt, Quantico Cr VA	1	3.25	3.28
68.5	68 - 69	126.862	78.8435					Chicamuxen Cr MD	1.4	2.27	3.13
68.5	68 - 69	126.862	78.8435	7	10	4.06	28.93				
69.5	69 - 70	128.714	79.9945	5.4	11	6.67	36.51	**Typical upstream limit of 0.5 ppt isocline**			
70.5	70 - 71	130.566	81.1455					Powell's Cr VA	0.8	1.55	1.18
70.5	70 - 71	130.566	81.1455	4.6	11	7.63	35.1	Mattawoman Cr MD	1.2	22.25	25.85
71.5	71 - 72	132.418	82.2965	4.6	11	6.22	28.6	Occoquan Bay VA	1.6	22.25	35.38
72.5	72 - 73	134.27	83.4475	4.4	13	5.32	23.92	Occoquan Bay VA			
73.5	73 - 74	136.122	84.5985	4.5	13	4.41	20.23				
74.5	74 - 75	137.974	85.7495	4.6	23	5.19	24.19	Indian Head MD			

Potomac Mainstem Dimensions								**Landmark/Tributary**	**Tributary Dimensions**		
Nautical River Mile (midpoint of segment)	Nautical River Mile Interval	Kilometer	Statue Mile	Avg Depth m	Max Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3		Avg Depth m	Surface Area 10^6 m^2	Volume 10^6 m^3
75.5	75 - 76	139.826	86.9005	6	23	4.02	24.46				
76.5	76 - 77	141.678	88.0515	6.8	18	2.99	20.36	Pomonkey Cr MD	1.3	1.19	1.57
77.5	77 - 78	143.53	89.2025	4.5	11	3.57	15.61				
78.5	78 - 79	145.382	90.3535	4.5	11	2.77	12.31	Gunston Cove VA			
79.5	79 - 80	147.234	91.5045	5.3	11	2.37	13.23				
80.5	80 - 81	149.086	92.6555	3.7	11	2.36	12.4	Dogue Cr VA	1.1	1.75	1.99
81.5	81 - 82	150.938	93.8065	3.4	8	2.94	10.42	**Uppermost limit of 0.5 ppt isocline, 1984 - 2008**			
82.5	82 - 83	152.79	94.9575	3.5	8	3.17	10.45	Little Hunting Cr VA	0.9	0.56	0.51
83.5	83 - 84	154.642	96.1085	4.1	20	2.21	8.13	Piscataway Cr MD	1	3.65	3.72
84.5	84 - 85	156.494	97.2595	3.9	20	1.55	6.81				
85.5	85 - 86	158.346	98.4105	3.5	15	1.95	7.55	Broad Cr MD	1.1	1.5	1.62
86.5	86 - 87	160.198	99.5615	3.5	12	2.75	9.53				
87.5	87 - 88	162.05	100.7125	3.1	13	2.58	8.16	Hunting Cr VA	1	2.26	2.1
88.5	88 - 89	163.902	101.8635	3.2	13	2.71	8.87				
89.5	89 - 90	165.754	103.0145	2.6	10	2.77	7.67	Oxon Cr DC	1.9	0.69	1.3
90.5	90 - 91	167.606	104.1655	1.7	9	2.09	3.97				
91.5	91 - 92	169.458	105.3165	1.8	9	2.44	4.18				
92.5	92 - 93	171.31	106.4675	2.9	8.5	2.54	6.75	Anacostia R DC	4.3	3.25	14.11
93.5	93 - 94	173.162	107.6185	5.1	7	1.24	6.17				
94.5	94 - 95	175.014	108.7695	1.4	6.5	1.31	2.39				
95.5	95 - 96	176.866	109.9205	2	6.6	1.18	2.36	Rock Cr DC			
96.5	96 - 97	178.718	111.0715	1.8	6.6	1.36	2.34				
97.5	97 - 98	180.57	112.2225	5.2	20	0.55	2.87				
				AVG		TOTAL	TOTAL		AVG	TOTAL	TOTAL
Calculated from entered values				7.41		953.28	7,059.38		2.46	389.97	961.07





Depth, surface area, and volume profiles of the Potomac River estuary.

APPENDIX F

USE OF ZOTERO BIBLIOGRAPHIC DATABASE

Constructing the Literature Database for this Project

Due to the extensive amount of scientific literature available, and the need to share resources amongst each of the collaborating organizations, a web-based research tool, Zotero©, was employed to manage resources for this project. Developed at George Mason University, Zotero© facilitated the construction, organization, and management, of a large literature database for the ESWM and ELOHA analyses of the Potomac Environmental Flows projects. This online database provides easy access to bibliographic information for researchers at any location with access to the internet, allows for continual refinement of the literature, and facilitates collaboration and the annotation of resources.

The online literature search was conducted by using keywords relevant to environmental flow requirements for the Potomac River and its ecological components. This search was not limited to large river environments, the focus of this first phase of the Middle Potomac River Study, because the information is also being used for parallel work on the Potomac's smaller tributaries. At the present time, over 480 sources of information were collected, of which a substantial subset has been cited in this report.

What is Zotero?

Zotero is an open-source research tool that helps to gather, organize, and analyze sources of information and allows collaboration on research and annotation. Zotero is a plugin to the Mozilla Firefox web browser. In order to use Zotero, you must be using Mozilla.

Features:

- Capture citations within Mozilla
- Remote access, backups, and syncing
- Store PDFs, images, and web pages
- Cite from within Word and OpenOffice
- Take rich-text notes
- Organize with collections and tags
- Automatically grab metadata for PDFs
- Use thousands of bibliographic styles
- Advanced search and data mining tools

Instructions:

As of July 2010, the Potomac River Flows database within Zotero was not open to the public. Interested individuals should contact Adam Griggs at agriggs@icprb.org and request that their e-mail address be given access to this database. Once that is done, proceed with the instructions provided below. It is the intent of this project that this on-line database will be converted to public access and maintained and expanded into the future. Administrative steps to accomplish that are underway.

Getting started

1. Open Mozilla Firefox and go to www.zotero.org. Create an account if you do not currently have one.
2. From the Zotero homepage, download the Zotero plugin. Be sure to select the beta version. Follow the instructions for installation.

3. Close and re-open Firefox. When the browser opens, click on the Z or Zotero button that now appears at the lower-right-hand corner of the window.
4. The Zotero program should now be running at the bottom of the browser window. It will appear as a three-paned window open at the bottom of the Mozilla browser window. See **Figure F-1** below for a screen capture of the open window.

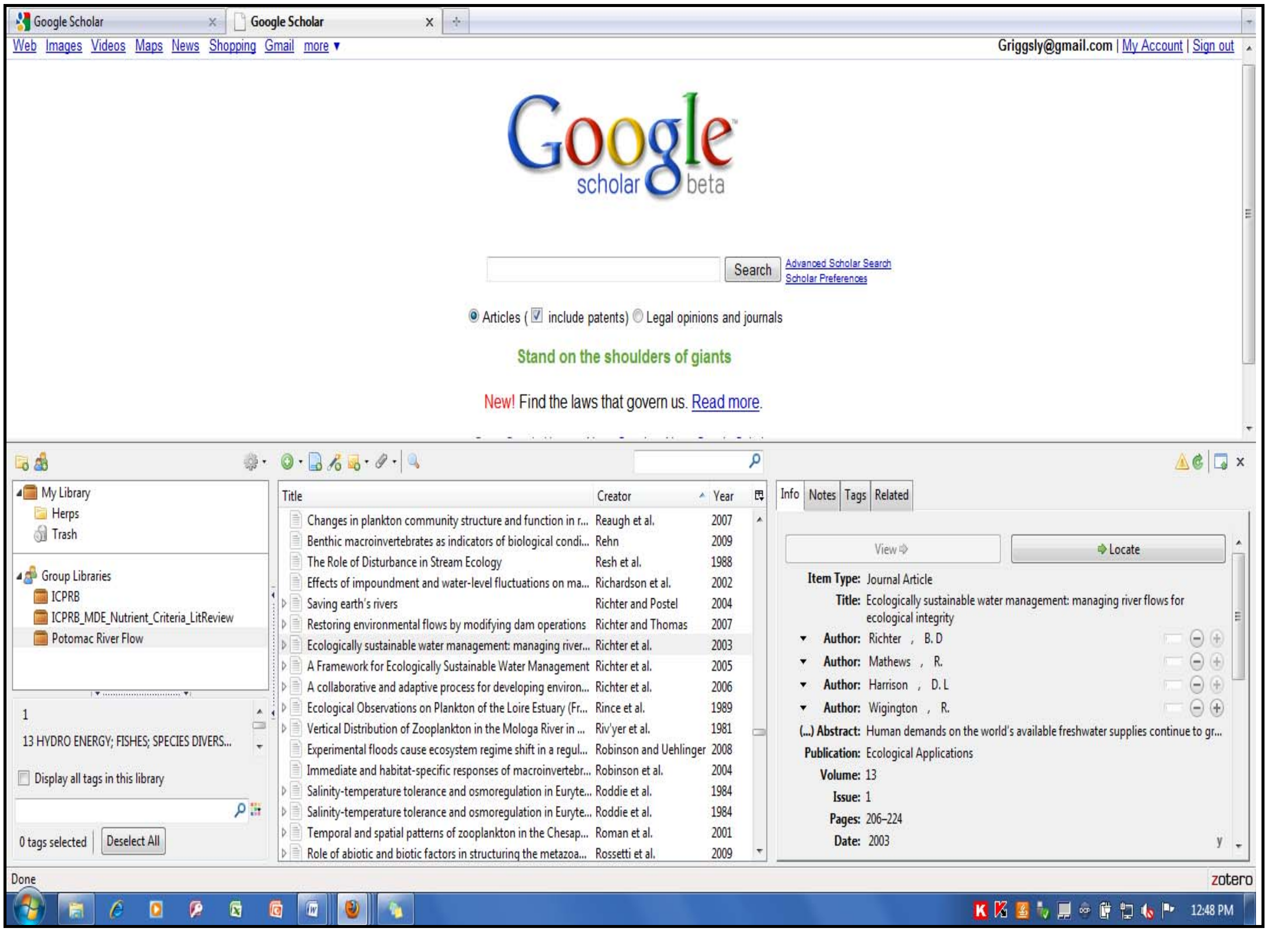


Figure F-1. A screenshot of the Zotero plug-in operating within the Firefox browser window.

Syncing with the Potomac River Flows group

1. Click on the cogwheel (action tab) located at the top left hand side of the Zotero window.
2. Scroll down to select “Preferences”. This will open the Preferences window.
3. Select the “Sync” tab.
4. Enter the Username and Password of your Zotero account.
5. Select “sync automatically” as an option.
6. Select OK and close the preferences window.
7. On the right-hand upper side of the Zotero window, click the green rotating arrow to start your first sync. It may take some time to sync the first time.
8. Upon syncing, the “Potomac River Flows” group should appear in the left-hand pane, provided that you have and received accepted the group invitation.

Using Zotero to capture resources from the web

Zotero can quickly capture most resources with a single click, extracting the desired bibliographical information, abstract, and keywords (if available). For some resources, this one-click retrieval is not yet compatible and the resource will have to be retrieved manually. Resources may be captured in several forms. Full-text PDFs may be captured, but these files quickly take up the free space on the Zotero servers. Retaining the full-text locally and only cataloguing the webpage article reference is adequate. How you search for articles is up to you, but Google Scholar© is one recommended tool.

1. Open your Mozilla browser and open Google Scholar© (http://scholar.google.com).
2. Start Zotero by clicking the "Z" or "Zotero" button in the bottom right-hand corner.
3. Search for a topic of interest using Google Scholar.
4. Once you have found a journal reference of interest, you may be able to one-click capture the resource using Zotero.
5. Find the symbol at the end of the URL address bar. Clicking this will add the reference and all bibliographical information to the Zotero library.
6. If this was not possible, the resource may be added manually by clicking the icon in the center pane of the Zotero Window.
7. Manually enter the bibliographical information in the right-hand pane.

Annotation and organization of captured resources

Zotero allows limited within-text annotation and high-lighting of text. Additionally, notes and tags may be added to any resource for sharing, organizing, and annotation. These notes can be exported with the library and may be useful as a starting point for creating reports. Once a resource has been catalogued, tags and notes may be added under those designated tabs in the right-hand pane. One may want to tag an article of interest with their name or other identifier for fast future-retrieval or separation from the larger database. You may also search within text and abstracts by using the search bar at the top of the center pane. The resource list will reflect any articles that match your search query.

Exporting bibliographic references

1. Highlight an article or articles in the center pane of which you would like to create a bibliography.
2. Right-click to bring up options and select "Create Bibliography from Selected Item…"
3. Select a standard journal format for the citation. Additional journal formats can be added through the preferences options.
4. Select "Copy to Clipboard" and hit OK.
5. You are now ready to paste the citation(s) into your document.

Using in-text citation with MS Word© or Open Office

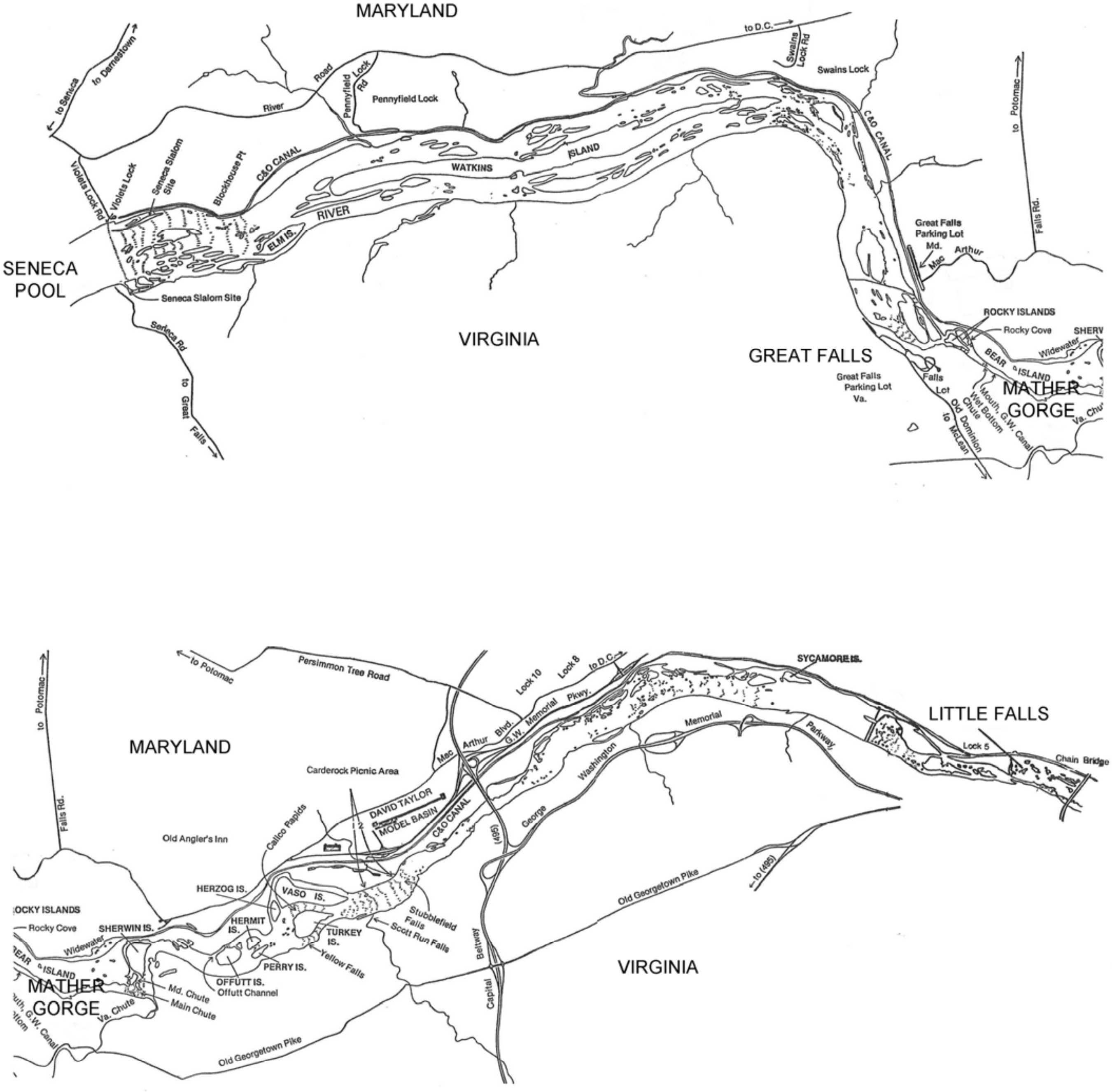
Zotero is compatible for use with Microsoft Word and Open Office and allows for easy entry of in-text citations. Also, each in-text citation will add the full bibliography to the Literature Cited section of your document. A plug-in is available for download that will operate within MS Word.

1. Direct your browser to http://www.zotero.org/support/word_processor_integration

2. Download the plug-in for your OS from the “Installation” link.
3. Re-start Word. The in-text and bibliography buttons will now appear in your “Add-ins”.
4. Simply hit the in-text citation button to add a citation from the library to your document.

Contact

Adam N. Griggs
agriggs@icprb.org
Aquatic Ecologist
Interstate Commission on the Potomac River Basin
51 Monroe St., Suite PE-8
Rockville, MD 20850
www.potomacriver.org
301.274.8103



POTOMAC RIVER

Seneca to Little Falls

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Adapted from “Potomac River Environmental Flow-By Study” (1981)
Maryland Department of Natural Resources, Water Resources Administration