Middle Potomac River Watershed Assessment: Potomac River Sustainable Flow and Water Resources Analysis

April 2013

U.S Army Corps of Engineers
Baltimore District

The Nature Conservancy
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Interstate Commission on the Potomac River Basin

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Cover photograph: Great Falls on the Potomac River as seen from Virginia. Jim Palmer (ICPRB)

Abstract

The Middle Potomac River Watershed Assessment (MPRWA) was a collaborative effort to assess the relationship between streamflow alteration and ecological response in the Potomac River and its tributaries in a study area defined as the Middle Potomac. The assessment is comprised of five distinct components: (1) a large river environmental flow needs assessment, (2) a stream and small rivers environmental flow needs assessment, (3) a projection of future water uses, (4) a stakeholder engagement process, and (5) development of a concept or scope for a strategic comprehensive plan for watershed management. This information can be used to balance and mitigate water use conflicts and prevent ecological degradation.

To assess flow needs in the Potomac watershed, the Ecologically Sustainable Water Management (ESWM) approach was used for large rivers and the Ecological Limits of Hydrologic Alteration (ELOHA) framework was adapted for streams and small rivers.

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

In streams and small rivers, strong relationships were found between urbanization (impervious surface), hydrologic alteration, and ecological impacts. Land use was found to be a more significant cause of hydrologic alteration than water withdrawals and impoundments at the present time. Impervious surfaces move rainfall and snowmelt more rapidly into rivers and streams than surfaces with natural vegetation, causing increased flashiness (rate of change). Increased flashiness correlates with declines in the status of stream macroinvertebrate, the streamflow assessment's indicator taxa. These taxa were not found to be sensitive to changes in low magnitude flows. Analyses of other taxa more sensitive to low magnitude flows, such as fish and mussels, could provide a more complete picture of biological response to flow alteration for water use decisions. Basin-wide datasets of these groups are not collected at present.

The impact on flow of future changes in water use was assessed through six scenarios: a) three different forecasts of per capita domestic water use; b) climate change; c) hot and dry summer conditions; and d) conversion of power plants to closed cycle operation. There was no regional pattern of flow alteration that applied to all scenarios and, within scenarios, impacts on flow varied for each subwatershed's unique combination of land and water uses.

Stakeholder education and engagement are key elements in the process of transferring scientific findings to management and policy. Workshops, webinars, and technical meetings were convened in order to obtain advice on methods, interpret draft results, and share findings with government agencies at all levels and other parties with significant roles in water management. This dialogue and information sharing contributes to state water management decision making processes and to the ongoing dialogue among stakeholders about ensuring the sustainable use of stream flows for all purposes.

Water use and basin development in each of the Potomac watershed's jurisdictions affects the other jurisdictions. The final objective of this study was to scope a basin-wide comprehensive plan process. Because there is no single agency with regulatory authority for water planning across the Potomac watershed, the concept for a future comprehensive plan is based on a collaborative, stakeholder driven model.
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Table of Contents

Appendices

List of Tables

Supplemental Tables

List of Figures

Executive Summary

The Middle Potomac River Watershed Assessment (MPRWA) was a collaborative effort to assess streamflows in the Potomac River and its tributaries in a study area defined as the Middle Potomac (Figure ES-1). Beginning in May 2009, and working with Potomac River watershed experts, the U.S. Army Corps of Engineers (USACE), the Interstate Commission on the Potomac River Basin (ICPRB), and The Nature Conservancy (TNC) collaborated to identify key ecological needs related to streamflow, existing and future impacts of human activities on flow, and the potential effects of climate change on the watershed's hydrology. As technical partner, ICPRB coordinated and conducted the study's scientific analyses.

To assess flow needs in the Potomac watershed, ICPRB adapted the Ecologically Sustainable Water Management (ESWM) approach (Richter et al. 2003) for large rivers and the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al. 2010) for streams and small rivers. Expert workshop participants and a technical advisory group, representing watershed jurisdictions and interested Federal agencies, provided input and feedback to inform the analyses. In addition to analyses and findings, the report presents research, monitoring, and modeling needs to complement the assessment, and provides lessons learned to inform other environmental flows analyses.

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

In streams and small rivers, strong relationships were found between urbanization (impervious surface), hydrologic alteration, and ecological impacts. Land use was found to be a more significant cause of hydrologic alteration than water withdrawals and impoundments. Impervious surfaces, in contrast to natural soils and vegetation, move rainfall and snowmelt more rapidly into rivers and streams, causing increased flashiness (rate of change). Increased flashiness correlates with declines in stream macroinvertebrate status, the streamflow assessment's indicator taxa. These taxa, however, were not found to be sensitive to changes in low flows. Analyses of other taxa more sensitive to low flows, such as fish and mussels, could provide a more complete picture of biological response to flow alteration for water use decisions, but basin-wide datasets of these groups are not collected.

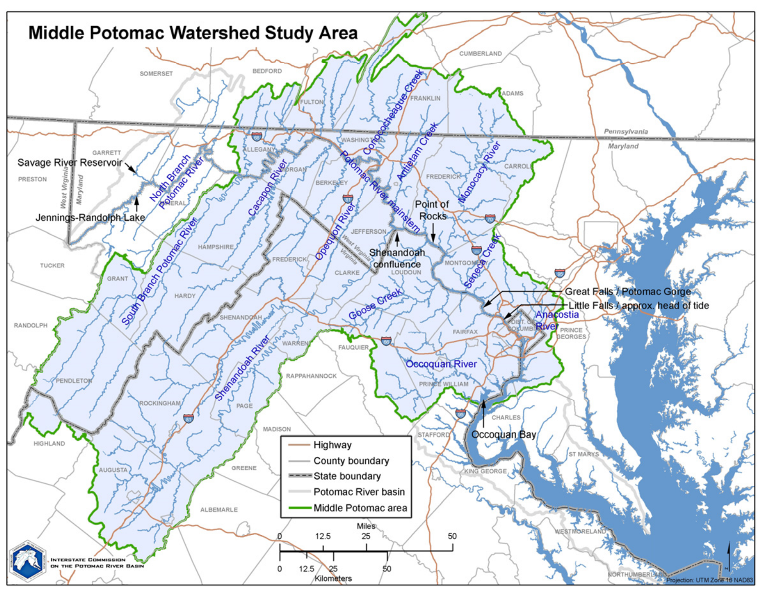

Figure ES-1. Middle Potomac watershed study area.

Project Background

The purpose of the MPRWA was to investigate the environmental flow[1] needs of rivers and streams in the Middle Potomac watershed, the area defined as the North Branch confluence to Occoquan Bay (Figure ES-1). Changes in natural flows are caused by water withdrawals, discharges, impoundments, land use change, and climate change. Environmental flows may differ from natural flows in order to accommodate human uses of water. Maintaining or restoring an environmental flow regime – including the magnitude, duration, timing, frequency, and rate of change of hydrologic events such as high and low flows – is important for stream health.

Many river ecologists consider flow to be a master variable for aquatic ecosystems because it influences water quality, biotic interactions, and the availability of food and habitat for fish and other species. However, flow is only one of multiple factors affecting biological community health, and flow itself is influenced by a wide range of natural and human-influenced watershed conditions. One challenge of this analysis was to distinguish biological changes caused by flow alteration from changes caused by other factors, such as poor water quality and instream habitat disturbance.

The Potomac River is the second largest tributary to the Chesapeake Bay. Its mainstem flows southeast, cutting through the Appalachian Mountains and Piedmont, becoming tidal as it enters the Atlantic Coastal Plain. Its watershed is shared by four states (Maryland, Pennsylvania, Virginia, and West Virginia) and the District of Columbia. Few dams regulate flow in the streams and large rivers of the Potomac River basin compared to other eastern U.S. river systems. Most of the 481 impoundments identified in the watershed are run-of-river facilities and only minimally alter flow patterns. For this reason, the Potomac River presents a rare opportunity to be proactive in defining the environmental flows required to sustain natural diversity and ecosystem functions while meeting the needs of a growing regional human population. Growth is expected to convert forest and farmland into hardened landscapes, increase levels of runoff and pollution to the river and the Bay, and increase electricity demands and consumptive uses of water. This study is timely considering the watershed jurisdictions' development of state water management plans and policies and the potential for more droughts and catastrophic floods due to global climate change.

Methods and Findings

The MPRWA was comprised of five distinct components: (1) a large river environmental flow needs assessment, (2) a projection of future water uses, (3) a stream and small rivers environmental flow needs assessment, (4) a stakeholder engagement process, and (5) development of a concept and process for a basin-wide comprehensive plan for watershed management. This assessment generated datasets and analyses that can help the Potomac River watershed jurisdictions protect environmental flows.

Large river environmental flow needs assessment

The large river assessment adapted the ESWM approach (Richter et al. 2003), which uses available hydrologic data, hydro-ecological literature, and expert judgment to determine environmental flows. A hydrologic risk assessment was conducted to identify large river segments and tributaries at greatest risk of hydrological alteration from several risk factors, including geology and current and projected future water and land use. The sub-basins deemed most at risk of hydrologic alteration

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[1] Environmental flows are defined as the seasonally variable flows of water that sustain healthy river ecosystems and the goods and services that people derive from them.

were the Occoquan, Monocacy, Aquia, Opequon, Mattawoman, Saint Mary's, Goose, Conococheague, Antietam, North Branch, Cameron Run, and Accotink. The mainstem river segments at greatest risk extended from the Potomac River above Paw Paw to the Potomac River above Little Falls.

The team chose to focus the large river flow needs assessment on four large river segments and two large tributaries: (1) Potomac River mainstem from the Shenandoah River confluence to Point of Rocks, (2) Potomac River mainstem from Point of Rocks to Great Falls, (3) Potomac River mainstem from Great Falls to Chain Bridge, (4) tidal freshwater Potomac River estuary from Chain Bridge to Occoquan Bay, (5) Monocacy River mainstem, and (6) Opequon Creek mainstem. These reaches are at highest risk for hydrologic alternation and were selected as regions of special interest for varying reasons including current development pressures, land use, physiography, and other criteria. Environmental flows for non-tidal, free-flowing rivers were based on fish, mussels, and instream and riparian plant needs; flows for the tidal freshwater estuary were based on fish, benthic macroinvertebrates, zooplankton, and phytoplankton needs.

Based on a review of available hydro-ecological literature, hydrologic data, and expert opinion, the project team found no current discernible adverse impact on key biotic taxa in large rivers due to human modification of flow. Potomac River flows, however, are naturally highly variable due to hydro-meteorological factors, so it is difficult to separate short-term, weather-related impacts from long-term, anthropogenic impacts on biota. As a precautionary measure, the team recommended that the current large river flow regime be maintained for the entire range of flows. The team also recommended maintaining the existing 100-mgd minimum flow requirement for Little Falls and 300-mgd minimum flow recommendation for Great Falls. Participants at a September 2010 workshop reviewed the draft assessment and recommended that a technical workgroup be convened to design a monitoring program to fill information gaps for these systems.

Projection of future water uses

The objective for the future water use component of this study was to better understand the magnitude of future increases in water withdrawals and especially consumptive uses, to identify the principal causes of those increases, and to estimate how those increases might affect the stream-flow regime through 2030. Water withdrawal is water diverted or removed from a source, a large percentage of which may be returned to the source, such as through wastewater treatment plant discharges. The portion of water withdrawal that is removed and is not available for downstream use by humans or the aquatic ecosystem is termed "consumptive use." Consumptive use is water withdrawn and permanently removed from surface or groundwater sources because it has been evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, transferred out of the watershed, or otherwise removed from the watershed (Kenney et al. 2009).

The rate of growth in withdrawals and consumptive use is strongly dependent on assumptions about individual behavior (per capita rates of consumption) and about future changes in the industry, power, and agriculture sectors. Currently, domestic and public supply (water withdrawn by public and private water suppliers and delivered to users) in the MPRWA study area (includes the Washington, D.C. metropolitan area) accounts for 27 percent of the 2,252-mgd total water withdrawals by all sectors, but 84 percent of the 394-mgd total consumptive water use by all sectors (Figure ES-2). For non-drought years and assuming no change in the per capita rate of domestic consumption, total consumptive use is predicted to increase to 488 mgd by 2030, a 24-percent

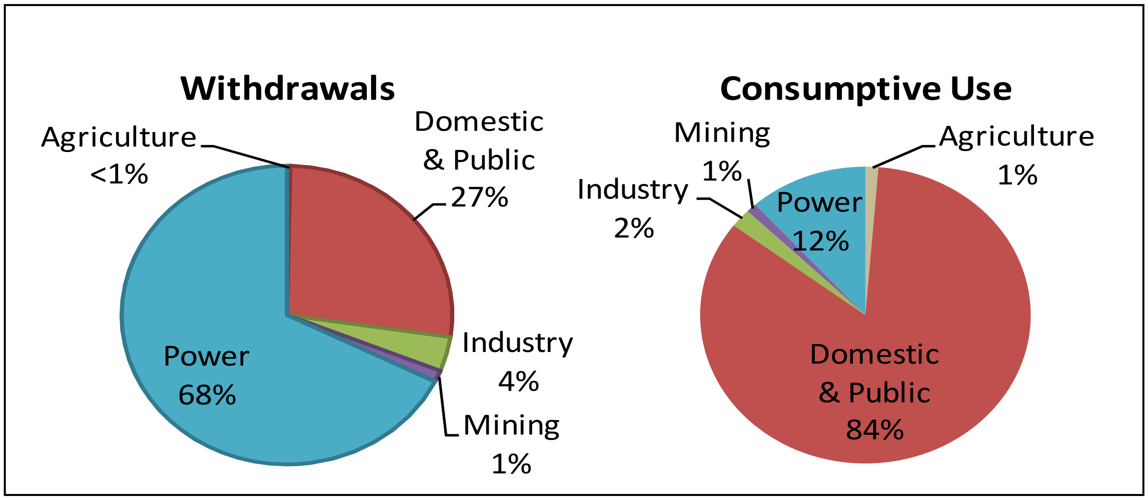

Figure ES-2. Percentage of surface withdrawals and consumptive use by sector in 2005 for the Middle Potomac River Watershed Assessment study area.

increase from 2005. Domestic and public supply would still account for 84 percent of the total consumptive use. Scenarios that assume an increase in the per capita domestic water use show higher increases in consumptive use. Water used for power plant cooling currently accounts for 68 percent of surface withdrawals by all sectors but most of that water is returned to streams, and so the power sector accounts for only 12 percent of total consumptive use. Conversion of power plants to closed-cycle cooling is predicted to result in an increase in consumptive use by this sector. Agriculture currently accounts for less than 1 percent of surface withdrawals and 1.3 percent of consumptive use. Consumptive use by agriculture during an extreme drought is predicted to increase by nearly three times, but still is only a few percent of the total basin-wide consumption. A comparison of consumptive use forecasts made by this project with those made by Steiner et al. (2000) is difficult due to differences in data and methods and inherent uncertainties in data sources, but the predicted rates of growth in consumptive use are similar – about one mgd each year.

The Chesapeake Bay Program's watershed model was adapted and linked with a river transport model to predict current and future daily water flows at ungaged outlets throughout the Potomac River watershed. Results provided a basis to estimate future flow alteration in subwatersheds (equivalent to watershed model river segments) and to make a spatial assessment of watersheds at greatest risk of future hydrologic alteration. Future flow alteration predicted by five modeled scenarios varied across the basin, depending on the assumptions of each scenario, on changes in individual watershed characteristics (land and water use), and on what aspect of the flow regime (as measured by a specific flow statistic) was being considered.

Stream and small rivers environmental flow needs assessment

For the streams and small rivers flow assessment, the ELOHA framework (Poff et al. 2010) was adapted and used to develop flow alteration-ecological response (FA-E) relationships from modeled flow data and a basin-wide biological dataset of benthic macroinvertebrates. This component of the MPRWA study is one of the first attempts to perform a large-scale quantitative analysis using the ELOHA approach. Stream macroinvertebrates were selected as biological response variables because of the larger size, better integration, and broader coverage of macroinvertebrate data across the basin jurisdictions and the lack of comparable fish data at the basin-wide scale. Macroinvertebrates are a major food source for fish and birds and are commonly used as indicators of stream health.

The team simulated streamflow and flow alteration at biological sampling sites because there are few gages recording flow data in streams where macroinvertebrates are sampled. The hydrologic modeling was done with the Chesapeake Bay Program's watershed model and the Virginia Department of Environmental Quality's Online Object Oriented Meta-Model (WOOOMM) routing module. Current and baseline flow time series were simulated for 747 macroinvertebrate sampling locations. The baseline flow time series is defined as modeled current conditions with the influence of water withdrawals, impoundments, and biologically significant hydrologic alterations due to land use removed via modeling. Flow metrics calculated from the simulated time series were tested against observed data. Through a series of analyses six flow metrics and seven biometrics were selected to generate FA-E relationships (Table ES-1). The selected flow metrics represent different aspects of the flow regime, show relationships with watershed and water use factors, and show relationships between flow alteration and biological status.

Watershed factors that alter flow in the Middle Potomac study area were related most often to urbanization, particularly impervious surface area. Flashiness increases sharply from baseline, or relatively unaltered conditions, when the area of impervious surface in a watershed exceeds a threshold of about one percent. Water withdrawals and discharges directly alter flows, but significant impacts on flow metrics were seen only in those watersheds where net withdrawals or net discharges are a large fraction of mean annual flow. Impacts of agriculture on streamflow were not readily apparent in the Middle Potomac study area, but they can confound some hydrologic impacts of impervious surface area.

The FA-E relationships developed through this analysis indicate that for a variety of flow metrics, hydrologic alteration is associated with a decrease in the likelihood of many macroinvertebrate metrics achieving comparatively healthy status ("fair" or better). Higher high flows, more frequent high and low flow events, shorter high and low flow periods, faster rise and fall rates, and more reversals had large and negative impacts on all metrics of macroinvertebrate health. None of the biological metrics responded to change in middle and low magnitude flow metrics (Table ES-2).

The Chessie BIBI, a basin-wide, multi-metric Benthic Index of Biological Integrity developed for stream macroinvertebrates in the Chesapeake Bay watershed, reflects biological condition. Figure ES-3 illustrates that as percent alteration of flashiness increases, biological condition decreases. The black line in the figure is a linear regression at the 90th percentile of the data. It is an approximate indication of the best possible biological status that can be achieved at different levels of flow alteration, given the existing mix of environmental factors affecting stream macroinvertebrates.

Table ES-1. Macroinvertebrate and flow metrics used to establish FA-E relationships for the Middle Potomac River Watershed Assessment study area.

Macroinvertebrate metrics	Flow metrics
Chessie BIBI (a multi-metric community index)	3-day maximum
%EPT (pollution-sensitive group)	High flow index MH21
FBI (Hilsenhoff family-level biotic index)	High flow duration DH17
%Chironomidae (pollution-tolerant group)	Low pulse duration
%Scraper (feeding group)	High pulse count
%Clinger (habit group)	Flashiness
SW (Shannon-Wiener diversity index)	

Table ES-2. Summary of flow alteration – macroinvertebrate relationships identified in the study.

Alteration in these aspects of the flow regime is associated with ⇨	Degradation in:	Possible mechanisms that could explain the association are:
• Higher maximum flows • Shorter duration of high flows • Shorter duration of low flows • More low flow pulses • More high flow pulses • Faster rates of change in flow (flashier)	All family-level macroinvertebrate metrics tested and the Chessie BIBI multi-metric index	• Scour of periphyton and organic matter (food) during high flows • Catastrophic accidental drift during floods • Displacement from habitat and stranding when waters recede • Physical alteration of stream bed habitat • Indirect effects of poor runoff water quality (sedimentation, pollutants) • Interruption of development or dispersal cues
• Lower middle and low magnitude flows, includes median flow, August median flow, summer Q85 flow, baseflow index, 3-day and 1-day annual minima, and 7Q10	None of the biometrics	• Swift recovery due to adaptations to low flow (drought resistant or diapausing life stages) • Multi-voltine (short) life cycles • High mobility, able to find refugia and later recolonize

As other environmental factors become more stressful (e.g., poor water quality, physical disruption of stream habitat), the "cloud" of data points in Figure ES-3 shifts lower on the plot. Figure ES-4 illustrates how reduced water quality or habitat condition reduces the limit of best possible biological status (represented by the regression line). The regression line in a severely degraded stream (dashed) is lower than the line in an otherwise excellent stream environment (solid). Point (A) indicates where increasing flow alteration lowers biological status below what could be deemed an "acceptable" threshold in an excellent quality stream. Point (B) indicates the threshold is crossed much sooner in an already degraded stream. To accurately forecast change in the biological community caused by a specific change in flow, projections must account for all the natural and anthropogenic factors in addition to flow that impact biological communities. Water quality and habitat improvements can potentially ameliorate the impacts of future flow alteration and the regression line would shift up. Conversely, future flow alteration will further degrade biological status even if water quality and habitat conditions are unchanged. This finding is why the study does not put forth any specific flow alteration limits to protect the environmental flow needs of streams and small rivers in the Middle Potomac River study area.

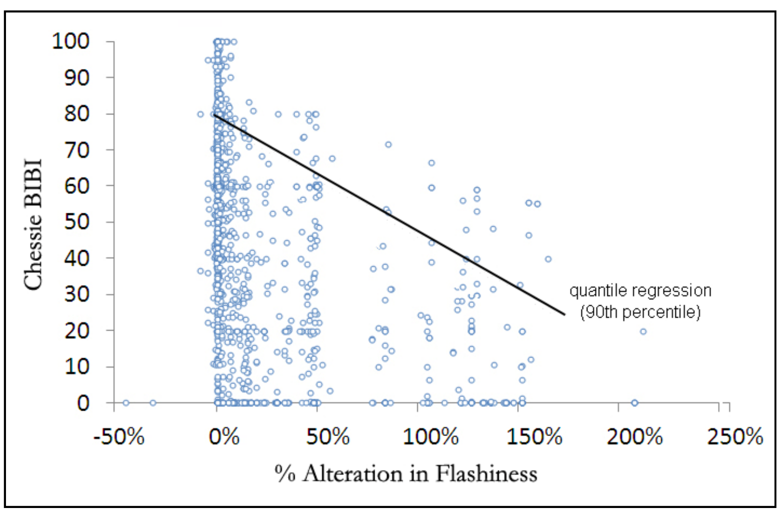

Figure ES-3. Relationship between percent alteration of flashiness with Chessie BIBI.
The black quantile regression line is significant at the 0.01 level.

This study's FA-E relationships can be used to evaluate the biological impact of alternative scenarios for watershed development or water use if the impacts of other factors are taken into account. Conditional probability plots that relate flow alteration to the probability that biological status will be fair or better can be used to estimate an increased risk to biological health due to flow alteration. Thresholds in the relationships between flow alteration and land use, developed for this project, can inform managers when changes in specific land uses are likely to begin altering stream flows. For example, proposed (future) increases—or decreases—in watershed impervious surface area can be evaluated for their potential impact on flashiness and stream macroinvertebrate condition (Figure ES-5). Differences in the curves indicate different levels of sensitivity to flow alteration in the macroinvertebrate metrics; however, the general pattern is a decline in biological condition with an increase in flashiness. Plots have been developed for the 42 FA-E relationships (7 macroinvertebrate metrics x 6 flow metrics) developed for the MPRWA.

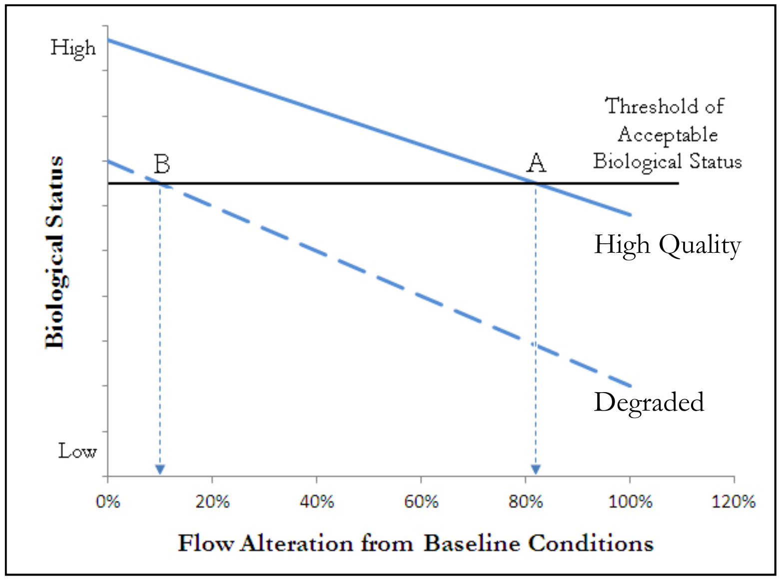

Figure ES-4. Generalized illustration of the influence of water quality and stream habitat conditions on macroinvertebrate responses to flow alteration.
The solid line represents a high quality stream and the dashed line represents a degraded stream.

Although the FA-E relationships developed in the study are generally applicable across the non-tidal Potomac watershed, consideration must be given for the confounding influences of other environmental factors and the innate differences in biometric response strength. In watersheds that hydrologic models can not represent well at this time, such as the small watersheds in the broad corridor of karst geology bisecting the project's study area, the study's FA-E relationships should not be applied. In these watersheds, resource managers could apply a presumptive flow protection standard (Richter et al. 2011).

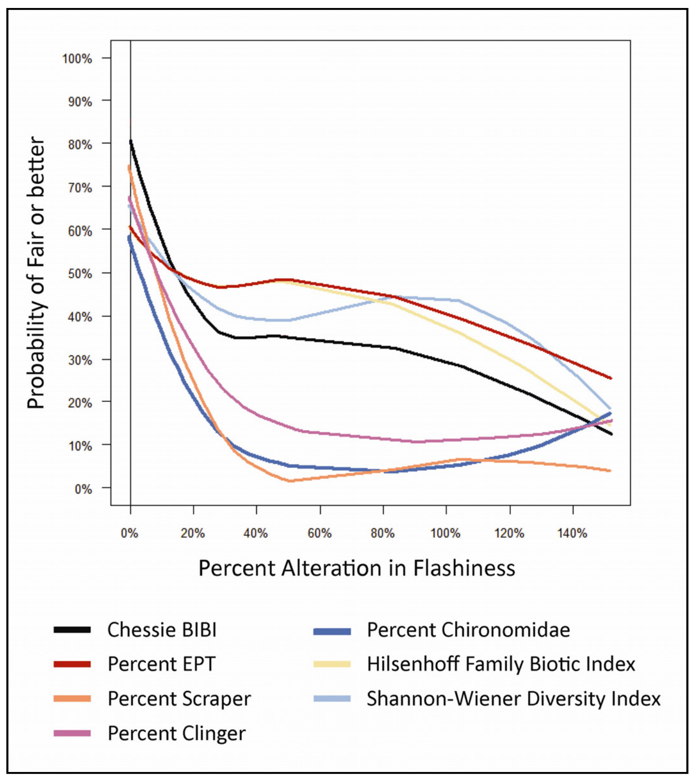

Figure ES-5. Conditional probability plots of FA-E relationships for positive alteration (increase) in flashiness.

Stakeholder engagement process

This study provided extensive stakeholder education and engagement to inform and review the analysis and to encourage the future transfer of scientific findings to management and policy. Workshops, webinars, and technical meetings were convened to obtain advice on methods, interpret draft results, and share interim findings with government agencies and other parties with significant roles in water management. The objective was to contribute to water management decision making and to the ongoing dialogue among stakeholders about ensuring sustainable water use for all purposes.

Development of basin-wide comprehensive plan concept

Water use and land development in each of the Potomac River watershed's jurisdictions affect the other jurisdictions. Basin-wide collaboration is needed to protect flow regimes, healthy watersheds, and river and stream health across the watershed. To put this environmental flow assessment in a broader watershed management context, and to promote the development of a basin-wide vision for Potomac River management, this project included the scoping of a basin-wide comprehensive plan process. The process is expected to include four phases: (1) Define roles of participating organizations, establish interdisciplinary oversight committee, and define goals of plan; (2) Assess water resources issues and identify problems; (3) Identify and evaluate alternatives, and recommend practical solutions; and (4) Develop the comprehensive water resources plan document. Because there is no single agency with regulatory authority for water or land use planning across the Potomac River basin, the concept for the comprehensive plan is based on a collaborative, stakeholder driven model, which ICPRB will be pursuing in the future with the watershed jurisdictions.

Potential applications of study products and findings

The MPRWA explored how biological communities respond to hydrologic alteration and other changes in watershed conditions. Its datasets, methods, and analysis results can be used by watershed jurisdictions to assist with water resources protection efforts. Maintaining healthy streams and watersheds, as reflected through the status of stream biological communities, is important to meet Potomac River and Chesapeake Bay restoration goals. Healthy stream communities are more resilient to natural, extreme events and to the multitude of anthropogenic stressors that accompany human activities. They are more capable of processing both natural leaf litter and human pollutants. They provide greater support to organisms higher in the food web, many of which are economically and recreationally important. Healthy stream systems are more capable of providing the many goods and services that humans depend upon, from drinking water supply to wastewater assimilation to flood mitigation to recreation.

Defining limits of acceptable hydrologic alteration towards management of ecological health, a final step in the ELOHA process, is a stakeholder driven decision-making process. Limits of acceptable alteration were not defined in this study. The process of defining societal values and needs, determining desired ecological conditions for specific streams and watersheds, and setting limits to flow alteration can best be pursued at a watershed jurisdictional scale, in accordance with state- and local-level priorities, needs, and regulatory mandates. This study's results can provide a scientific foundation to inform that process. Local water resource managers or planners could go through a series of steps to develop flow recommendations based on the FA-E response relationships identified in this analysis. At the local level, the results may be most applicable for land use planning and zoning. At the state level, the results could influence the development or refinement of state stormwater laws to advance Bay restoration goals, or support the development of new flow-related water quality standards.

Chapter 1. Introduction

This chapter describes the background and scope of the Middle Potomac River Watershed Assessment (MPRWA) project. The project consisted of five related components. One component—an application of the Ecological Limits of Hydrologic Alteration (ELOHA) process to streams and small rivers in the study area—is described at length in Chapter 5 and several appendices of this report. Three components are described in separate technical reports, included as appendices of this report. Their highlights and conclusions are summarized in chapters 3 (large river environmental flow needs), 4 (future water use projections), and 6 (stakeholder outreach and implementation options). Chapter 2 describes existing conditions in the study area. Chapter 7 presents the overall study conclusions, lessons learned, and next-steps.

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The Middle Potomac River watershed encompasses 11,550 mi^2, or 79 percent, of the Potomac River basin (Figure 1), from the North Branch confluence to Occoquan Bay. This area had a population in 2010 of 5.57 million people and includes much of the Washington DC metropolitan area in the east. The Middle Potomac River watershed has a diverse landscape of mountains, valleys, and coastal plains, with urban, rural, and natural areas. The river is the second largest tributary to the Chesapeake Bay and, with four states (Maryland, Pennsylvania, Virginia, West Virginia) plus the District of Columbia, it is the only tributary shared by a majority of the Bay watershed jurisdictions. Although the official geographic scope of this assessment is the Middle Potomac River watershed, the project team recognized the need, for both hydrologic and ecological considerations, to include the North Branch and the estuarine Potomac for some analytical purposes.

The Potomac River basin has experienced rapid population growth in recent years, growing 15.6 percent between 2000 and 2010. With this growth has come increased development, including new and larger water withdrawals (surface and groundwater) and more urbanization. Stream corridors are increasingly experiencing water resource, or flow, related problems including: degradation and loss of wetlands and fish and wildlife habitat; excessive stream bank erosion; exacerbated flooding; excessive nutrients and sediments; and water supply and management conflicts. Clear connections between land uses, water uses, and flow alteration, and between flow alteration and biological degradation, are quantitatively described in the literature, most recently in publications such as Carlisle and Meador 2007, Kennen et al. 2009, Falcone et al. 2009, Carlisle et al. 2010, Cruise et al. 2010, Cuffney et al. 2010, and Poff and Zimmerman 2010. Continued population growth in the watershed is expected to heighten demand for water and electricity, as well as convert forest and farmland into developed and hardened landscapes and increase levels of runoff and pollution to the river and the Chesapeake Bay. This growth will likely amplify the severity of flow alteration and flow-related impacts. The extent and cumulative impact of these problems is of concern to the region's natural resources agencies.

Compared to other large eastern U.S. river systems, the Potomac River is relatively intact with respect to stream flow, with only a few large dams that significantly change flow. For this reason, the Potomac presents a rare opportunity to evaluate increasing human impacts on flow originating from sources that are more diffuse, such as agricultural and urban land uses, surface and groundwater withdrawals, and discharges. The opportunity is timely considering the watershed jurisdictions' development of state water management plans and policies, the increasing demand for consumptive use of river water (amount of water withdrawn but not returned), and the potential for greater incidences of droughts or catastrophic floods with global climate change. Approaches exist for developing science-based environmental flows and implementing plans and policies to protect them (e.g., Richter et al. 2003, Poff et al. 2010, Richter et al. 2011) and are being tried in the United States (e.g., Kendy et al. 2012).

The Middle Potomac River Watershed Assessment (MPRWA) was conducted under the authority of Section 729 of the Water Resources Development Act (WRDA) of 1986, as amended. In addition to the Section 729 authority, several Congressional committee resolutions provide additional authority for the U.S. Army Corps of Engineers (USACE) to study the Potomac River watershed. After scoping the watershed assessment, The Nature Conservancy (TNC), the non-federal sponsor, and USACE, Baltimore District, entered into a partnership agreement in May 2009. The Interstate Commission for the Potomac River Basin (ICPRB) was contracted to provide technical expertise and conduct much of the analysis in the MPRWA.

Five separate but related components were executed as part of the MPRWA. The overall goal was to provide a foundation for implementing future protection and restoration of the basin's water resources over the next several decades. The assessment included data gathering, flow modeling,

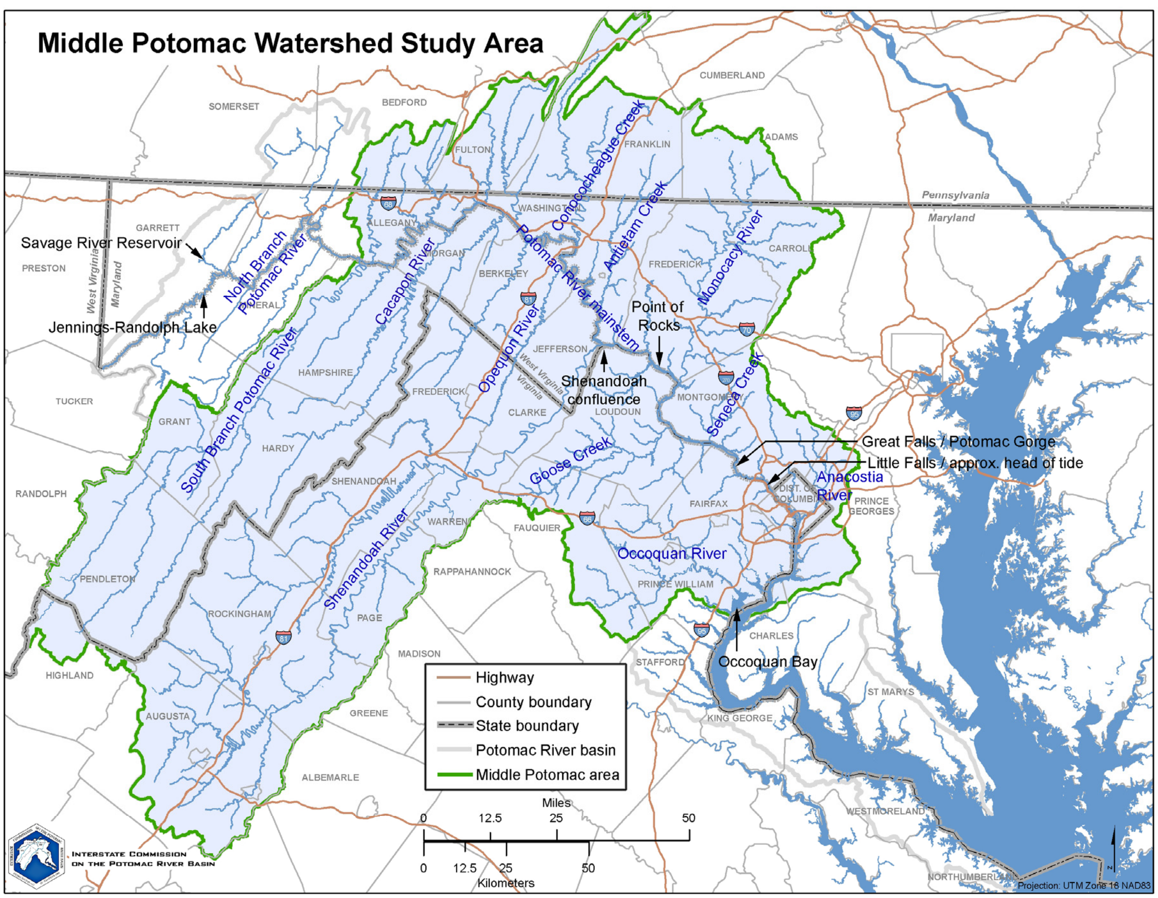

Figure 1. Middle Potomac watershed study area.

ecological investigations, and consultation with stakeholders. The project team considered water and land uses that affect the flow regime and investigated environmental flow[2] needs, landscape changes, and watershed resource management in the Middle Potomac River watershed in the District of Columbia, Maryland, Pennsylvania, Virginia, and West Virginia. Also considered was how future changes in human activities (especially withdrawals, impoundments, and land use development) and climate change might impact the flow regime. The five project components are:

1) A large river environmental flow needs assessment for the mainstem Potomac River (below Harpers Ferry to the confluence with the Occoquan River) and mainstem Monocacy River and Opequon Creek based on a literature review of environmental flow needs of key species compared to the current flow regime, plus an expert stakeholder review;
2) A forecast of future water use to 2030 based on state databases of water use for domestic and public supply, literature estimates of water use by industrial and agricultural sectors, and projections of population, land use, industry, and climate change;
3) A stream and wadeable rivers environmental flow needs assessment using the Ecological Limits of Hydrologic Alteration (ELOHA) approach and based on observed benthic macroinvertebrate data and simulated streamflow for 747 subwatersheds of varying size, land use characteristics, and location;
4) A stakeholder engagement process involving a series of webinars, two workshops, and a technical advisory workgroup; and
5) A conceptual plan for a basin-wide comprehensive water resource plan, which also includes a review of existing computer-based, decision-making tools.

Flowing waters in the study area were divided into small (wadeable) and large (non-wadeable) types because the biological data collected in these two types are not comparable and require different analytical approaches for determining flow needs. Streams and small rivers are defined as Strahler order[3] 4 or less and wadeable. In the Middle Potomac study area, these waters correspond to the 1a, 1b, 2, and smaller 3 size categories of the Northeast Aquatic Habitat Classification System[4] (NEAHCS; less than 1,000 sq. mi. in upstream drainage area). Large rivers are the major tributaries of the Potomac River mainstem in the study area, as well as the mainstem itself. They correspond to NEAHCS categories 4 and greater (equal or greater than 3,861 sq. mi. in upstream drainage area).

The large river assessment approximately followed the Ecologically Sustainable Water Management (ESWM) approach described by Richter et al. (2003) which relies largely on published literature and expert judgment to identify environmental flow needs. The paucity of biological data in the study area's large rivers necessitated an ESWM approach. The objectives of this study component included: (1) compiling a literature review of basin-wide flow ecology relationships for flow-dependent species and; (2) developing environmental flow recommendations for the mainstem Potomac River. The methods and results of the large river environmental flow needs assessment are discussed in Chapter 3.

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[2] Environmental flows are defined as the seasonally variable flows of water that sustain healthy river ecosystems and the goods and services that people derive from them.
[3] In the Strahler stream order classification system class 1 streams are headwater streams and each successively higher number indicates a larger stream (Strahler 1957).
[4] The Northeast Aquatic Habitat Classification System is a standard classification system which describes stream systems across thirteen northeastern states (Olivero and Anderson 2008).

The objective for the future water use component of the project was to better understand the sources and projected magnitude of water withdrawals, and especially consumptive withdrawals, in the Middle Potomac study area by 2030. These projections were used to complete a spatial assessment of watersheds at greatest risk of future hydrologic alteration. An additional element of this component was to compare estimates of future water use with those generated by a previous study (Steiner et al. 2000). Future water use projections are presented in Chapter 4.

The stream and small river assessment was more quantitative than the large river assessment, relying on a large macroinvertebrate database compiled from 23 local, state, and federal monitoring programs and a hydrologic model that simulated different flow conditions at locations to match the biological data. The study focused on macroinvertebrate communities because there is no fish data collected basin-wide with comparable methods. Analysis of biology, hydrology, and watershed characteristics was done using a variation of the ELOHA approach described in Poff et al. (2010). This component of the MPRWA study is one of the first attempts to perform a large scale quantitative analysis using the ELOHA approach. The objectives of this study component were to: (1) identify flow metrics that, when altered, associate with strong biological response, and; (2) develop flow-alteration ecological response relationships that describe how aquatic ecology responds to flow alteration in a semi-quantitative manner and can be used to aid in the future development of environmental flow recommendations for tributary streams. The methods, results, and implications of the small stream environmental flow needs assessment are discussed in Chapter 5 along with lessons learned about the ELOHA approach.

Stakeholder education and engagement was an important study component. The project team solicited advice on methods and draft result interpretation, and shared results with government agencies and other parties with significant roles in water management. The objective of stakeholder education and engagement is to contribute to state-level water management decision making processes and to the on-going dialogue among stakeholders about ensuring the sustainable use of stream flows for all purposes. Stakeholder engagement is discussed in Chapter 6.

Water resources planning in the Potomac basin historically has been done by the five individual jurisdictions: the District of Columbia, Maryland, Pennsylvania, Virginia, and West Virginia. Water use and basin development in each jurisdiction affects the other jurisdictions, however, and another objective of the fifth project component was to develop a concept for a basin-wide comprehensive plan process. The time and resources required to initiate and conduct the comprehensive plan process are beyond what is available within this project, so this component was to develop a "plan" for the basin-wide comprehensive plan. Because there is no single agency with regulatory authority for water planning across the Potomac watershed, the concept for the comprehensive plan is based on a collaborative, stakeholder driven, model. The basin-wide comprehensive plan is described in Chapter 6, along with a review of computer-based, decision-making tools that have been developed by states outside the Chesapeake Bay basin.

Chapter 2 sets the stage for the major components in the project by describing existing conditions in the watershed. Chapter 7 presents overall study conclusions, lessons learned, and next-steps. Supporting materials, including datasets, additional information on methods, stand-alone reports that address aspects of the study, and copies of stakeholder outreach products are provided in technical appendices, which are referenced at appropriate places in Chapters 2-6 and are available on disc. The overall organization of the report is depicted in Table 1.

Table 1. Organization of the MPRWA Report.

MPRWA Main Report	
Chapter	**Description of Contents**
1	Introduction
2	Existing Conditions
3	Component #1 – Large River Environmental Flow Needs
4	Component #2 – Future Water Use Projections
5	Component #3 – Stream Environmental Flow Needs
6	Components #4 and #5 – Stakeholder Outreach and Implementation Options (including Comprehensive Water Resources Plan)
7	Conclusions

MPRWA Technical Appendices (on Disc)	
Appendix	**Description of Contents**
A	Component #1 – Large River Environmental Flow Needs Report
B	Component #2 – Water Withdrawals and Consumptive Use in the Potomac River Basin Report
C	Component #3 – Compilation of Measured Stream Data
D	Component #3 – Development and Refinement of Hydrologic Model
E	Component #3 – Flow Metric Testing
F	Component #3 – Stream Classification
G	Component #3 – Basin-Wide Hydrologic Alteration Assessment
H	Component #3 – Development of Flow Alteration – Ecological Response Relationships
I	Component #4 – Stakeholder Engagement
J	Component #5 – Implementation Options

Chapter 2. Existing Conditions

This chapter summarizes existing conditions in the Potomac River basin, including physiography, climate, hydrology, land uses, water withdrawals and discharges, impoundments, and water quality. Emphasis is placed on factors important to aquatic communities in streams and wadeable rivers. Many statements in the chapter are based on data and information assembled from various sources and analyzed by ICPRB for previous studies. A more detailed description of the existing conditions can be found in the attached "Potomac Basin Large River Environmental Flow Needs" report (Appendix A).

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2.1. Physiography

The Potomac River basin is the second largest drainage basin to the Chesapeake Bay after the Susquehanna River basin. The basin covers 14,670 mi^2 and encompasses the District of Columbia and portions of Maryland, Pennsylvania, Virginia, and West Virginia (Figure 1). The river mainstem flows 283 miles in a generally southeastern direction from the confluence of its uppermost North Branch and South Branch tributaries to the Chesapeake Bay. Other major tributaries include the Shenandoah, Monocacy, Cacapon, Opequon, and Occoquan Rivers. The Potomac River is tidally

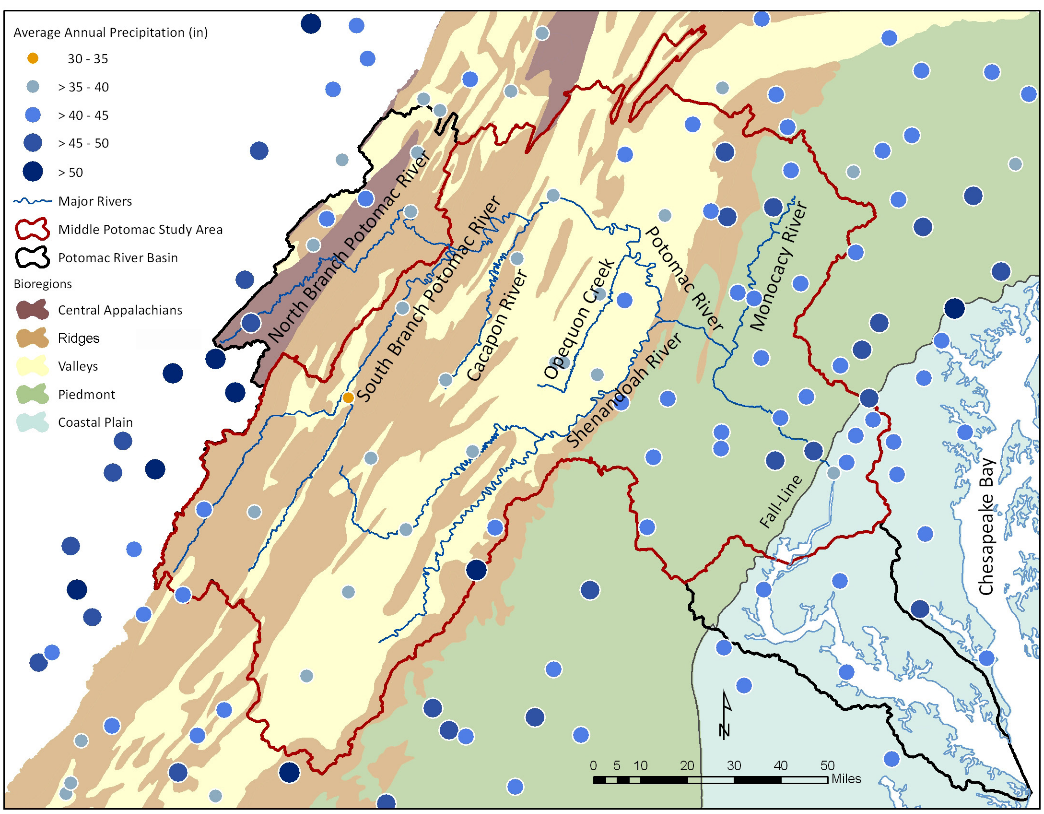

Figure 2. Potomac River basin boundaries.
Major tributaries, bioregions, and average annual precipitation are indicated.

influenced for its last 113 miles. Average discharge at the mouth is approximately 14,300 cubic feet per second (cfs).

The river crosses five major physiographic provinces which have been subdivided into Level 4 "ecoregions" by the U.S. Environmental Protection Agency (EPA)[5]. Ecoregions are physiographic regions "of relative homogeneity in ecological systems … soils, vegetation, climate, geology, and physiography" (Wood et al. 1999). Aggregation of these Level 4 ecoregions into "bioregions" has proven an effective method of classifying macroinvertebrate communities in the Potomac River basin and the larger Chesapeake Bay basin (Astin 2006, Buchanan et al. 2011). Four bioregions are found in the Middle Potomac study area (Figure 2). The mountainous Ridges[6] bioregion is characterized by high gradient, cool, trellised streams with many riffles and active down-cutting. The Valleys bioregion, interspersed between mountain ridges, has warmer, low gradient streams. Portions of this bioregion are underlain by karst geology and have a low density of streams. The Piedmont bioregion has low to moderate gradient streams with falls, islands, and rapids. The Coastal Plain bioregion—a little of which is located in the study area—has very low gradient streams on poorly drained, alluvial sediments and streams are often poorly incised and lack a defined channel. The Atlantic seaboard fall line separates the Piedmont and Coastal Plain bioregions.

2.2. Climate

Located in the north temperate zone of the United States, the river basin can still experience extreme temperatures ranging from -30°F in the western mountains to 105°F in the Piedmont and low-lying coastal plain. Seasons are well-defined although changeable in spring and summer due to rapid successions of cold and warm fronts. Climate change in the Middle Atlantic region is projected to increase the average yearly temperature. Average monthly precipitation is fairly even across the year (Figure 6 in Appendix A), and summer lows in stream flow are primarily due to watershed losses to evaporation and plant transpiration between March and September. Most plant transpiration is caused by forests, which cover about 63 percent of the basin west of the fall line. Agriculture also contributes. Dry periods characterized by low and infrequent precipitation can occur at any time during the year but they reduce flow levels the most when coupled with the natural summer water losses. High flows are driven by storm events, which can occur throughout the year; they are not dependent on snowmelt. Storms usually move on a northeast track parallel to the mountain ridges and coastal zone or on an easterly track parallel to the Great Lakes and Ohio River Valley. A sizable rain shadow (the dry area on the back side of a mountainous region) caused by the Appalachian mountain system exists over the Potomac basin's Valleys and western Ridges bioregions (Figure 2). As discussed elsewhere in this report, climate change is projected to increase the numbers of both storm events and dry periods (droughts) in the basin.

2.3. Hydrology

Average daily flows have been measured uninterrupted since February 1895 at the Point of Rocks gage (01638500) on the Potomac River mainstem. The gage has one of the longest time series, or

[5] http://www.epa.gov/wed/pages/ecoregions/reg3_eco.htm
[6] The Ridges bioregion combines the Blue Ridge province and the hilltops and mountain ridges of the Ridge and Valley province.

hydrographic records, in the United States. Approximately 96 other flow gages with hydrographic records of varying length and continuity are also located on streams and rivers in the Middle Potomac study area (Appendix C Figure 2). Flow metrics are used to evaluate the patterns of flow in streams and rivers. Flow metrics describe the magnitude, duration, frequency, and timing of different portions of the hydrograph including floods and droughts. Most are calculated from daily mean values of measured or estimated flow rate, or volume per unit time, published by the U.S. Geological Survey (USGS).[7]

Normal flow conditions in streams and wadeable rivers of the Middle Potomac study area are considered those found in heavily forested watersheds. The area was originally blanketed with mature stands of oaks, cedars, chestnuts, and other climax species prior to European settlement. Over the last three centuries, normal flow conditions have been altered directly with impoundments, withdrawals, and discharges and indirectly through many landscape changes in the watershed. Approximately 60 - 70 percent of the original forests were gone by the 1890s, the result of logging, mining, clear-cutting for agriculture, and catastrophic forest fires. Young forests began to reestablish in abandoned, marginal agricultural lands in the late 1800s, restoring some of the original forest's ecological and hydrological functions. The recovering trend reversed, however, when urbanization and population growth began to increase rapidly in the basin in the 1900s. Most of this growth was concentrated in the Washington DC area, leaving much of the basin rural. Future population growth is expected to spread outward from the Washington area and into the "Great Valley" between the Blue Ridge and Appalachian mountains.

There are numerous flow metrics—for example, there are 171 in the Hydrologic Index Tool (HIT) software program developed by Henriksen et al. (2006) for the USGS. Flow metrics representing all aspects of the hydrograph should be considered when investigating flow alteration-ecology (FA-E) relationships. Aquatic organisms in lotic environments exhibit many morphological adaptations and behavioral responses which allow them to cope with or avoid specific stresses associated with different flow conditions. The adaptive capabilities of an individual taxon determine to a large extent its population abundance, distribution, and resilience. The full and normal spectrum of flow conditions, from extreme low flows to large, powerful floods, helps to maintain the overall ecological integrity of streams and rivers (Poff et al. 2010). Some flow conditions may be essential to individual taxa in that they strongly affect survival or reproductive timing and potential; others may not. The large river component of this study (Chapter 3) focuses on the environmental flow needs of migratory and resident fish, freshwater mussels, and aquatic and riparian vegetation as well as tidal fresh communities in the Potomac River estuary. The stream component (Chapter 5) focuses on the environmental flow needs of benthic macroinvertebrates, the organisms most commonly and consistently monitored across Middle Potomac streams and wadeable rivers (waters in which biological samples can be collected without boats).

2.4. Impoundments

The Potomac is presently one of the least dam-regulated river basins 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 percent of median annual flow. A total of 481 impoundments are identified in the Potomac River basin by the National Inventory of Dams (2007). Many of the

[7] http://waterdata.usgs.gov/nwis

smaller impoundments are run-of-river and comparable in function to structures such as beaver dams. There are 153 "significant" impoundments, meaning the normal storage capacity is greater than 10 percent of mean annual flow volume and/or the dam is actively used or was once used for hydroelectric purposes (Appendix C Figure 1). In the Middle Potomac study area, the largest impoundments with respect to median annual flow volume are listed in Table 2. Included are two large impoundments that are technically upstream of this project's study area: Jennings Randolph Lake and Savage River Reservoir in the North Branch Potomac River drainage. They are important in modeling flows in the Middle Potomac watershed. Only four of the impoundments listed in Table 2 are operated for water supply purposes. Other purposes for the selected impoundments include hydroelectric operations, recreation, and flood management. Impoundments may have ecological impacts upstream of dams in addition to downstream impacts. These within-pool non-flow related ecological impacts are not addressed in this study.

USACE owns and operates Jennings Randolph Lake for flood risk management, water supply, and recreation. Savage River Reservoir is owned and operated by the Upper Potomac River Commission for flood risk management, and water supply. Its construction was completed in 1953 by USACE under Section 7 of the 1946 Flood Control Act. USACE provides operational direction for the Savage River Reservoir, primarily for flood control in concert with Jennings Randolph Lake. Because the water from one reservoir is alkaline and acidic from the other, USACE provides a system operation on the North Branch of the Potomac River that allows for improved water quality and adequate water supply.

Table 2. Impoundments in the Middle Potomac River study area and North Branch Potomac River holding more than 10 percent capacity of annual flow volume. Not included are impoundments upstream of the ones listed in the table that also have more than 10 percent capacity. Also not included are impoundments selected for inclusion in the study solely for hydroelectric purposes. Ratio: the normal storage of each impoundment, obtained from the National Inventory of Dams and converted to cubic feet, divided by model simulated median flow converted to cubic feet per year.[1]

Impoundment Name	Normal Storage (ac-ft)	Median Flow (cfs)	Ratio (Normal Storage to Annual Flow)
Jennings Randolph Lake[2]	130,900	102.27	1.77
Rocky Gap Dam	5,381	4.58	1.62
Little Seneca Lake[2]	13,050	13.39	1.35
Occoquan Reservoir[2]	25,567	53.95	0.65
Lake Barcroft	2,500	6.45	0.54
Sleepy Creek Dam	2,460	6.58	0.52
Patterson Creek No. 4 Dam	1,989	5.79	0.47
Blairs Valley Dam	486	2.12	0.32
Savage River Reservoir	20,000	90.78	0.30
Lake Gordon[2]	3,633	20.68	0.24
Patterson Creek No. 41 Dam	5,480	33.91	0.22

[1] Values for Occoquan Reservoir are observed values provided by Fairfax Water and the Occoquan Watershed Monitoring Lab. Normal storage capacity was determined from a 2010 bathymetric survey.
[2] Impoundments are used for water supply and their flows can be affected by dam operations.

2.5. Water Withdrawals and Discharges

Freshwater withdrawals in 2005 averaged 6,185 cfs for the entire Potomac River basin and represented nearly half of the estimated surface freshwater entering the estuary from all streams and rivers in the basin. Most of withdrawals (about 97.5 percent) are from surface waters. The available information suggests 78.5 percent of withdrawals are for power generation, 18.28 percent for drinking and domestic uses, 2.12 percent for industry, 0.92 percent for mining, and 0.18 percent for agriculture. Hydrologic impacts of withdrawals in the upper basin are balanced to a large degree at some point downstream by discharges which return most of the water to the river. The exception is the free-flowing Potomac River directly above the head-of-tide, where an average 574 cfs is taken from the river to supply the Washington, DC metropolitan area (WMA) and returned to the Potomac estuary at the Blue Plains wastewater treatment plant, rather than to the non-tidal river. During dry periods, these withdrawals have a large local impact on river flow but do not substantially alter the total volume of freshwater to the estuary. The Washington Aqueduct, a division of the Baltimore District, USACE, supplies drinking water for a substantial portion of the WMA, including the District of Columbia, Arlington County, Virginia, and the City of Falls Church, Virginia.

One large impact of withdrawals and discharges not related to flow alteration is their effect on water quality. As more and more people repeatedly withdraw, use, and discharge surface waters, water quality can deteriorate to the point of overwhelming the stream's assimilative capacity. Systems operated under state and federal requirements, including the Clean Water Act, can ameliorate potential water quality issues resulting from loss of assimilative capacity.

2.6. Land Uses

The western side of the Middle Potomac study area is mostly forested, the middle is heavily agricultural, and the eastern side intersects the heavily urban WMA (Figure 3). Deforestation and urbanization in a watershed, such as experienced in the Potomac River basin, increases the proportion of rainfall running off the landscape instead of seeping into the ground to replenish aquifers or to be taken up by plants. Increased runoff changes the magnitude, frequency, duration, and possibly the timing of stream flows. More impervious surface area makes streams flashier and gives them greater erosive power. Flow alteration impacts are not always apparent because they can be confounded by other factors normally associated with land use. Agricultural and urban land uses are often accompanied by physical disruption of stream banks and beds, either by grazing livestock or by channelization and burial under streets. Eroded top soils and sediments accumulate in stream beds. Removal of riparian buffers leads to higher temperatures and increased runoff of nutrients, herbicides, and pesticides. The presence and impacts of these other stressors on stream communities is aptly summarized in the US EPA Stressor Identification Guidance Document (2000), on the EPA Causal Analysis/Diagnosis Decision Information System (CADDIS) website (www.epa.gov/caddis/), and in numerous text books (e.g., Ward 1992, Wetzel 2001, Thorp and Covich 2001, Merritt et al. 2008). These impacts need to be untangled from impacts that are specifically and directly related to flow alteration.

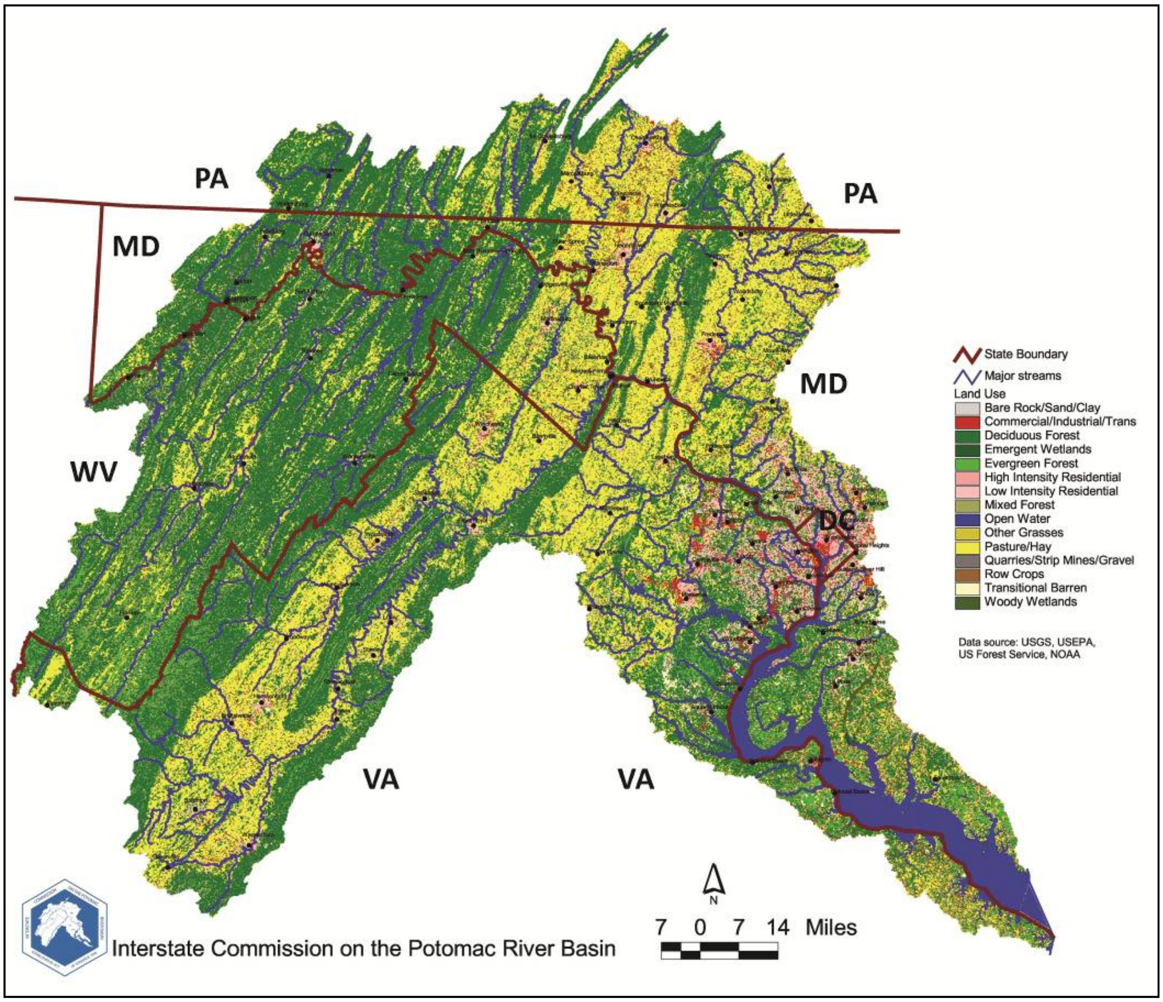

Figure 3. Land use in the Potomac River basin.

Chapter 3. Large River Environmental Flow Needs

The large river environmental flow needs assessment is the first component of the MPRWA. The complete report, including the workshop participants' comments, can be found in Appendix A. This chapter summarizes the assessment's key findings and recommendations. The assessment was made using the Ecologically Sustainable Water Management (ESWM) approach, which relies largely on published literature and expert judgment to identify environmental flow needs. The objectives of this study component included: (1) compiling a literature review of basin-wide flow ecology relationships for flow-dependent species and: (2) developing environmental flow recommendations for the mainstem Potomac River. The taxonomic groups investigated were fish, mussels, instream and riparian plants in the free-flowing large rivers and fish, macrobenthic invertebrates, zooplankton, and phytoplankton in the tidal fresh estuary. There was particular emphasis, driven by stakeholder interest, in low flows. The project team found no discernible adverse impact on key biotic taxa due to human modification of *flow* in the free-flowing large rivers. The team recommended that the current large river flow regimes be maintained, particularly at low flows. They concurred with the 100-mgd (million gallons per day) and 300-mgd minimum flow requirements for Little Falls and Great Falls, respectively. A diverse group of experts reviewed the study's findings and conclusions at a two-day workshop in September 2010.

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3.1. Introduction

The assessment of large river environmental flow needs for four mainstem Potomac River segments and two large tributaries was a stand-alone component of the MPRWA. There is insufficient comparable biological data for large river segments in the Potomac to develop quantitative flow-ecology relationships using the methodology employed for smaller streams. For this reason the hydrologic needs of flow-dependent species and communities in four mainstem Potomac segments and two selected large tributaries deemed to be at risk of hydrologic alteration were identified using a modification of the Ecologically Sustainable Water Management (ESWM) approach described in Richter et al. (2003). The methods and results of that assessment are summarized here and reported in full in a stand-alone report, "Potomac Basin Large River Environmental Flow Needs" (Cummins et al. 2011), which is included in Appendix A. The National Park Service (NPS) provided funding for this portion of the MPRWA.

The Potomac Basin Large River Environmental Flow Needs assessment was developed by a research team from the ICPRB, TNC, Leetown Science Center Aquatic Ecology Branch of USGS, and the Potomac Environmental Research and Education Center of George Mason University (GMU). It includes a comprehensive literature review, development of flow hypotheses, assessment of large river environmental flow needs, statistics proposed to track those flow needs, and recommendations for additional research, monitoring, and analysis to improve understanding of flow needs. As part of the literature review, more than 480 sources of information were collected, reviewed, and organized into a searchable on-line database (Appendix G in Cummins et al. (2011)).

The Potomac Basin Large River Environmental Flow Needs assessment included a workshop, held September 22-23, 2010, at the National Conservation Training Center in Shepherdstown, WV (hereinafter referred to as the September 2010 workshop), at which 60 hydrologists, biologists, engineers, water resource managers, and regional and national experts on flow and river ecology discussed draft findings from the project research team. A summary of that workshop and participants' comments is available as Appendix H in Cummins et al. (2011). At the September 2010 workshop, participants concluded that despite the detailed review and analysis of currently available literature, more research and monitoring is needed to fill information gaps to define ecologically protective flow alteration thresholds for Potomac large river systems. A new technical working group will be convened to plan for additional hydroecological research and monitoring that will support the development of quantitative large river flow recommendations.

3.2. Large River Flow Needs Assessment Approach

Based on the results of a hydrologic alteration risk assessment, four Potomac mainstem segments and two large tributary streams were selected for this flow needs assessment due to the high count and severity of risk factors that can lead to altered hydrology (Appendix B in Cummins et al. (2011)). These river segments (Figure 1) 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) the tidal fresh Potomac estuary from Chain Bridge to Occoquan Bay;
5) Monocacy River mainstem; and
6) Opequon Creek mainstem.

The Potomac Gorge is of special concern because of its relatively unique and rare riparian biological communities. One charge to the study's research team was to re-examine the 100 million gallons per day (mgd; 155 cfs) minimum flow-by requirement for the Potomac Gorge. This flow-by value was established by the Maryland Department of Natural Resources' (MDDNR) Potomac River Environmental Flow-by Study in 1981, as a follow-up to the 1978 Potomac River Low Flow Allocation Agreement which identifies the DC area water supply allocations during low flow periods.

The research team did not find sufficient research or empirical data to define thresholds of ecologically acceptable hydrologic change for the large rivers of the Middle Potomac River study area. Therefore, the ESWM approach was applied. Four plant communities, twelve fish species, and sixteen native mussel species were identified 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. The research team used the available literature and professional judgment to develop four general flow-ecology hypotheses that apply to a broad range of species/communities and 18 specific flow-ecology hypotheses tailored to selected indicator taxa in the non-tidal Potomac large river segments and selected large tributaries (Cummins et al. (2011), pp. 50-51).

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, freshwater inflow to the estuary delivers nutrients, sediment, and other constituents, and influences 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. Although of lesser importance than water quality impacts, seven general flow-ecology hypotheses for the tidal fresh estuary also were articulated (Cummins et al. (2011), p. 71).

3.3. Findings of the Large River Flow Needs Assessment

Drawing upon the literature review of aquatic species' flow needs and analysis of the historical record of flows for these rivers, the following key considerations were synthesized. These considerations shaped the project team's findings regarding large river flow needs:

1) The Potomac River has only minimal flow regulation and that occurs only at very low flows. There are no dams regulating flow on Opequon Creek or Monocacy River. Magnitude, frequency, and duration of high and mid-range flow events, therefore, are more influenced by land use management than operational management.
2) The observed river flow characteristics appear to be primarily the result of weather, climate, and land use factors, except for low flows from Great Falls to Little Falls, and potentially in the Monocacy.
3) Evidence suggests that there have been changes in flow distributions over the past 100 years, but additional analyses are 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 for these stream reaches.
5) For aquatic species, very few studies in the literature provided directly applicable quantitative measures of flow needs (beyond 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 research or monitoring evidence of species impairment due to current levels of 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. Minimum flow-by's of 300 mgd (464 cfs) at Great Falls and 100 mgd (155 cfs) at Little Falls were recommended by MDDNR (1981) which have been maintained by the Washington metro region water suppliers under the guidance of the ICPRB CO-OP section since the early 1980s. During that time flows have rarely approached these limits. In 2002, when flows were approaching these levels, field observations in surveyed areas 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 freshwater biota do not consider the very significant confounding influence of the tidal freshwater 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 greater precipitation and higher temperatures (which could increase demand for electricity and consumptive water use).

Considering these points, the team's approach was 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. The Large River Flow Needs assessment provides that characterization in both qualitative and quantitative terms.

3.4. Conclusions for Large River Flow Needs Assessment

Based on the considerations described in Cummins et al. (2011) and summarized above, the project team made the following conclusions to characterize the Potomac's large river flow needs:

1) For the entire range of flows, the current flow characteristics, as defined in Cummins et al. (2011)[8], should be maintained as a precautionary principle. If additional monitoring and analysis provides more definitive indications of biological degradation due to flow, then other more protective flow recommendations might be needed.
2) Extreme floods: High flows and floods in the river segments in this study are not controlled by dams or other structural measures and so there are no operational mechanisms for controlling high flows. The impact on extreme high flows of impervious surface area and extent of vegetative cover in the watershed upstream of these river segments is not known presently but is being evaluated as part of the Middle Potomac River Watershed Assessment.
3) Small Floods: No observed major problems, so current flow characteristics should be maintained.
4) Low Flows at Potomac Harpers Ferry to Point of Rocks: This section benefits from slightly augmented flows during low flows due to water quality and water supply releases from Jennings Randolph and Savage River reservoirs. There are no observed flow-related, ecological problems in this reach, therefore, recommend maintaining current flow characteristics.
5) Low Flows at Potomac 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 stream flow gage be installed to measure actual flow levels at the Great Falls weir.
6) Low Flows at Potomac Great Falls to Little Falls: (a) prior (1981) recommendation for a 300 mgd minimum flow should be continued, but (b) implement an ecological monitoring program to better understand if there are impacts and need to adapt our management, and (c) as a precautionary measure until this study is completed, develop

[8] Table 16 in Cummins et al. (2011) provides numerical values for 20 flow statistics for stream gages on Opequon Creek, the Monocacy River, and at Point of Rocks and Little Falls on the Potomac. For the Little Falls gage, statistics are provided for adjusted (water supply withdrawals added to observed flow) and unadjusted flows.

reservoir operating procedures which give consideration to maintaining variability at extreme low flows.

7) Low Flows at Potomac Little Falls to Chain Bridge (tidal river): (a) maintain the existing 100 mgd minimum flow-by, but (b) implement an ecological monitoring program to better understand if there are impacts and need to adapt our management, and (c) as a precautionary measure until this study is completed, develop reservoir operating procedures which give consideration to maintaining variability at extreme low flows.
8) Low Flows at Potomac Chain Bridge to Occoquan Bay: Water quality is the major determinant of biological health, not freshwater flow. Current flow characteristics should be maintained.
9) Low Flows at Monocacy River and Opequon Creek: As a conservative measure, until additional investigations of potential low flow impairment can be conducted, current low flow statistics should be maintained and withdrawal volumes not be allowed to push flows below those observed in 1999 and 2002.

3.5. Large River Information Gaps and Monitoring Needs

For most of the species discussed in the Potomac Basin Large River Environmental Flow Needs assessment, existing information is adequate only for qualitative estimates of how normal variability in population and distribution is affected by alterations in flow conditions. Therefore, additional monitoring, or analysis could help to define ecologically acceptable levels of hydrologic change, or acceptable thresholds of hydrologic alteration from current conditions for species in large rivers.

Although the September 2010 workshop aimed to define the full range of natural flow conditions for six river segments, the participants paid greatest attention to low flow conditions and ecological response in the Great Falls to Little Falls river segment. Some of the workshop participants' most significant suggestions include:

1) Address monitoring and data analysis gaps identified in the 2004 and 2005 Potomac low flow workshops, including studies to better understand "normal" variation of species populations and ranges, and studies to better understand the effects of extreme low flows on species and their habitat.
2) Monitor effects of high flows on floodplain plants and communities. The Potomac Gorge should be a priority site for monitoring the effects of high flows due to its great concentration of rare flood-dependent vegetation community types.
3) Monitor impacts of low flows on mussels. The species recommended are *Elliptio complanata, Pyganadon cataracta, Utterbackia imbecillis, Lampsilis sp,* and possibly *Strophitus undulatus and Alasmidonta undulata.*
4) Monitor fish to establish a better quantification of their flow needs, including fall young-of-year fish, alosid passage over the Little Falls weir, and in- and out-migration of fish. Also pursue research on fish species which live near drinking water intake pipes, focusing on short rather than long life span species.
5) Acknowledge opportunities and limitations for researching flow-ecology relationships in other species groups:
   a) Macroinvertebrates may be useful for flow-ecology research, but large river study protocols are not well developed. Crayfish may be an important group to study as

they are an important food source to other species, and to discern their life-cycle relationships to flow.
    b) Amphibians and reptiles are difficult to study because they are mobile, but could be of interest for tracking loss of habitat if flooding is reduced.
    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.
6) Track cumulative upstream consumptive use of water because of its potential role in reducing extreme low flows.
7) Investigate the use of remote-sensed imagery, such as Light Detection and Ranging (LIDAR) high-resolution topographic data, for determining the extent of loss of habitat at different flow levels.
8) Consider pursuing a modified Instream Flow Incremental Methodology (IFIM) study for evaluating the relationship between flow and habitat at flows below 1000 mgd in the stretch from Great Falls to Little Falls.

September 2010 workshop participants recognized that funding, staff time, and public attention or political will are constraining factors for developing a large river flow needs research and monitoring program. They concluded that a coordinated federal, interstate, and academic partnership would be needed to obtain resources and long-term commitment to: (a) developing a baseline during mid-range flow conditions, and (b) enabling monitoring and additional research during the more extreme high and low flow conditions.

Chapter 4. Future Water Use Projections

The objective of the second component of the MPRWA project was to better understand the magnitude of future increases in water withdrawals and consumptive losses, to identify the principal causes of those increases, and to estimate how those increases might affect the stream flow regime. These future projections could then be used to determine how future flow alterations might influence biological communities as an element of the stream flow needs assessment, and to complete a spatial assessment of watersheds at greatest risk of future hydrologic alteration. The future water use component of this study involved a comparison of estimates of future water use with those generated by a 2000 study of basin-wide (above Little Falls) consumptive use (Steiner et al. 2000). The methods and assumptions used to estimate increased water use, by use sector, and the comparison to the 2000 basin-wide consumptive use study are fully described in a report titled "Water Withdrawals and Consumptive Use in the Potomac River Basin." The report is a stand-alone component of the MPRWA; it is included in this report as Appendix B. The application of future water use scenarios to estimate impacts on the stream flow regime, as represented by alteration in selected flow statistics, is described in Appendix D.

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4.1. Methods for Future Water Use Projections

Current water withdrawal (surface and groundwater) estimates were based on USGS county-level withdrawal data attributed to specific withdrawal points obtained from each basin state with 2005 as the base year. Withdrawals were assigned to one of six use sector categories: (1) domestic and public supply, (2) mining, (3) thermo-electric power, (4) industry, (5) livestock, and (6) irrigation. Withdrawals in each water use sector were assigned a consumptive use factor based on historical values assigned by the USGS. The methods and data sources used to project future water use varied by use sector. Projections were made to 2030. The assumptions used to predict future consumption become less reliable as the projection time period increases. Therefore, the analysis is constrained to forecasted conditions for 2030.

Six scenarios were designed to provide insight into possible flow impacts across a range of possible future conditions (Appendix B, section 5). Rates of change in withdrawals for the mining, thermo-electric power, industry, livestock, and irrigation sectors were constant across the scenarios unless otherwise noted. The scenarios are:

1) DP1 – 0 percent per year increase in per capita withdrawal in domestic and public supply, so the increase in total withdrawals is due solely to population growth.
2) DP2 – 1.82 percent per year increase in per capita withdrawal in domestic and public supply, coupled with population growth.
3) DP3 – 4.38 percent per year increase in per capita withdrawal in domestic and public supply (referred to as "base" in Appendix B), coupled with population growth.
4) Power – New closed cycle, thermo-electric power plant on the Monocacy River in Frederick County, MD, and conversion from open cycle to closed cycle cooling at the other thermo-electric power plants. Closed cycle cooling increases consumptive use but dramatically reduced withdrawals. This scenario builds on the DP2 growth rate for domestic and public supply.

5) Climate Change – Applies Intergovernmental Panel on Climate Change (IPCC) projections for temperature increase and consequent changes in irrigation, power demand, and summer demand for domestic and public supply. This scenario builds on the DP2 growth rate for domestic and public supply.
6) Hot and Dry – Domestic and public supply sector withdrawals increased by 15.2 percent during April through August. Power sector withdrawals increased by 6.15 percent during May through September. Irrigation sector withdrawals increased by 284 percent during May through September. This scenario builds on the DP2 growth rate for domestic and public supply.

The six scenarios were developed as representative of future conditions of interest for basin stakeholders based on known development trends, projected population trends, or projected weather and climactic conditions. The DP3 scenario is characterized as the "base" scenario on which the other five scenarios are derived. The DP2 scenario corrects data inconsistencies in several of the withdrawal values reported by USGS for certain jurisdictions. The resulting changes led to a reduction in the annual change in the per person withdrawal rate. The DP1 scenario isolates the growth in withdrawals in the domestic and public supply sector that was due solely to projected population growth. This scenario assumed that there was no change in withdrawal per person over time, holding the withdrawal per person constant at the 2005 rate. The power sector scenario assesses the withdrawal and consumptive use impacts that could be expected if a new power plant becomes operational in the basin as well as assessing potential impacts of retrofits at existing power plants. This scenario is based on current expectations of power plant development in the basin. The climate change scenario assesses the impact of climate changes on the 2030 water demand projections in the DP2 scenario. The hot and dry scenario examines water withdrawals under weather conditions that are occasionally historically experienced in the basin, not factoring in changes to incidence of hot and dry weather that might be altered under future climate change conditions.

An overall increase in water withdrawals is forecasted for all future scenarios. The scenarios assume there will be no decrease in future water demand in the domestic and public supply sector. This is predicated on the assumption that past usage indicates future usage (per capita), and that conservation measures mandated by the Energy Policy Act of 1992 have largely been implemented and energy saving reductions realized. Changes in plant operations at thermo-electric power plants (conversion to close-cycle) are assumed to decrease withdrawals but increase consumptive use. The future scenarios were designed conservatively, to ensure that planning efforts do not result in overutilization of water resources. A detailed description of the methods and calculations used to project future water uses can be found in Appendix B.

These scenarios, excluding the DP3 scenario, were used to configure future hydrologic model scenarios with which flow time series were generated, flow statistics calculated, and flow alteration determined. Future flow time series were generated for 153 subwatersheds representing the Chesapeake Bay Program's Hydrologic Simulation Program-Fortran (HSPF) model segments in the study area. Future flow alteration is the relative difference between baseline and future scenario flow metrics. The methods for modeling the future scenarios and maps of predicted future hydrologic alteration for selected flow metrics are presented in Chapter 5 (Figures 20a-d) and in Appendix D (FutureScenarios_011912.pdf).

4.2. Findings for Future Water Use Projections

Table 3 shows cumulative withdrawals and consumptive use, by use sector, for the Middle Potomac River study area and North Branch watershed combined[9] (Figure 1). The North Branch is included in estimates for the MPRWA study area because it is upstream of the study area. See Appendix B for details on source information and methods for forecasting changes in each use sector. There are uncertainties in the estimates for each use sector.

The use sector with the largest water withdrawals was power generation, accounting for 68 percent of total withdrawals in the base year 2005 and 42 - 65 percent of total withdrawals in the six future scenarios. Domestic and public supply was the next largest sector, accounting for 27 percent of total water withdrawals in 2005 and 29 - 55 percent in the future scenarios. The combined agriculture, industry, and mining sectors accounted for 5 percent of total withdrawals in 2005 and 3 - 5 percent in the future scenarios.

Results for consumptive use are significantly different from withdrawals. The domestic and public supply sector accounts for 84 percent of total consumption in 2005 and 84 - 94 percent in the future scenarios. The power sector is a distant second (8 – 12 percent), and agriculture, industry, and mining each account for 2 percent or less of total consumption. One reason for the very high consumption rate in the domestic and public supply sector is the way consumption is calculated. If withdrawals eventually are returned to free-flowing waters, a consumption rate of 11 percent is applied. If, however, withdrawals from free-flowing waters eventually are discharged to an estuary, as they are in the parts of the Washington D.C. metropolitan area, they are considered 100 percent consumed. In the estuary, the discharged water is no longer considered available for domestic and public supply withdrawals and is therefore a computational "loss" included in the consumptive use total. In the study, all of the water withdrawn from the Potomac River mainstem by Washington Aqueduct, Washington Suburban Sanitary Commission, and the City of Rockville is assumed to be discharged to the estuary, primarily through the Blue Plains Wastewater Treatment Plant. Except for the reaches between withdrawal and discharge locations, discharged water is not truly lost from the river system; it represents a very large freshwater input to the estuary.

At the scale of the MPRWA study area, different assumptions or calculation methods for use sectors other than domestic and public supply are not likely to have much impact on estimate of total consumptive use. Agriculture does become a more significant water consumer during periods of drought. The hot and dry scenario, roughly equivalent to the 1930-31 drought of record, increased agricultural consumptive use from 5 mgd in 2005 to 13 mgd in 2030. Agriculture sector water use in other scenarios decreases from 2005 to 2030 due to a predicted decrease in the agricultural acreage (also present in the hot and dry scenario). Consumptive use is higher in the hot and dry scenario and climate change scenario compared to the DP2 scenario from which they were built. In the power sector, there is an overall increase in consumptive use in all future scenarios due to population growth. In the power sector of the power scenario, withdrawals and consumption reflect the change to closed cycle technology, which withdraws less water but has a much higher consumptive rate per kilowatt hour of electricity produced.

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[9] Tables with equivalent information for the entire Potomac basin (Potomac) and for the upper basin above the fall-line (AFL) are available in Appendix B supplemental tables. Also included are county breakouts for each scenario.

Table 3. Withdrawals (mgd) and consumptive use (mgd) in the Middle Potomac River Watershed Assessment study area (includes the North Branch Potomac River watershed), by sector, for six future scenarios.

See text for full descriptions of scenarios. The values presented are rounded to the nearest whole number. Comparable tables for the entire Potomac River basin (Potomac) and the upper basin above the fall-line (AFL) are provided as supplemental tables in Appendix B. In this table, the livestock and irrigation use sectors are combined into agriculture.

Scenario		Agri-culture	Domestic & Public	Industry	Mining	Power	Total	
2005								
Current	Withdrawals	7	609	84	28	1,524	2,252	
	Consumption	5	331	8	4	46	394	
2030								%Change from 2005
DP1	Withdrawals	5	856	119	30	1,895	2,904	29%
	Consumption	4	411	11	4	57	488	24%
DP2	Withdrawals	5	1,343	119	30	1,895	3,391	51%
	Consumption	4	645	11	4	57	722	83%
DP3	Withdrawals	5	2,494	119	30	1,895	4,543	102%
	Consumption	4	1,199	11	4	57	1,275	224%
Hot and Dry	Withdrawals	16	1,433	119	30	1,947	3,545	57%
	Consumption	13	688	11	4	58	775	97%
Climate Change	Withdrawals	8	2,563	119	30	1,946	4,665	107%
	Consumption	6	1,231	11	4	58	1,311	233%
Power	Withdrawals	5	1,343	119	30	1,657	3,154	40%
	Consumption	4	645	11	4	138	803	104%

Maps of future hydrologic alteration predicted in five of the six scenarios for selected flow metrics in 153 large subwatersheds are presented in Chapter 5 (Figures 20a-d). The direction of future hydrologic alteration in a flow metric often differed between watersheds due to differences in anticipated watershed changes. (The relationships of watershed drivers to alterations in the suite of selected flow metrics are described in detail in Appendix G.) Overall, the cumulative impacts of predicted land and water use changes coupled with the meteorological stressors in the climate change and hot and dry scenarios result in the most hydrologic alteration. The DP1, DP2, and power scenarios result in more moderate alteration because temperature, precipitation, and evapotranspiration regimes are assumed to remain constant. While the current (2005) and projected consumptive use in sectors other than domestic and public supply have a very small impact on the total when summed across the Middle Potomac watershed, consumptive use in subwatersheds may have substantial impacts. These subwatershed impacts are discussed in more detail in Chapter 5. Water conservation and demand reduction should be pursued as part of a wise use of water. The scenarios described here are not prescriptions for future action.

4.3. Comparison to Previous Studies

A previous study conducted by the ICPRB Section for Cooperative Water Supply Operations on the Potomac (CO-OP; Steiner et al. 2000) estimated current and future demands, consumptive use rates, and available resources through 2030. Comparison of the forecasts of withdrawals and consumptive use by the previous study and by this project are difficult because of differences in data and methods; therefore, several modifications were made to the assumptions in this study to perform a direct comparison of the results.

One approach used in Steiner et al. (2000) was to provide consumptive use forecasts by HUC 8 watershed. The study area was the area above Little Falls and it did not include the WMA water utilities. The results represented use in a typical stream flow year and the approach was able to reflect changes that could be expected under hot and dry conditions, similar to the hot and dry scenario developed for the MPRWA.

In a second approach used in Steiner et al. (2000), it was assumed that withdrawal or consumptive use rates for the commercial, industrial, thermoelectric, mining, or livestock sectors would remain constant, but that increases would be seen in the domestic and irrigation sectors. The domestic sector increases were based on the consumptive use rate in 1999, which was a drought year, so the assumption was made that increases in use would be representative of a future hot and dry condition. This rate was multiplied by the forecast number of single family households in the study area for future years. Irrigation sector increases were based on use rates in 1995, which was not a hot or dry year, and then increased by 35 percent across an entire year to simulate conditions in a drought. To forecast for future years, the estimate of consumptive use was applied to the expected future number of irrigated acres.

The results of the Steiner et al. (2000) study indicate a consumptive use rate of 169.1 mgd in June, July, and August for the drainage area above Little Falls, and an increase in consumptive use of approximately 30 mgd between 2000 and 2030. Those estimates, however, exclude the WMA utilities upstream of Little Falls which are included in the scenarios generated in this study. When the WMA utilities are excluded from water use totals in the MPRWA study's future scenarios, then the basin-wide water use totals are similar. At the HUC8 watershed scale there are significant differences between the studies in predicted water use which probably reflects different assumptions and data sources for each water use category (Appendix B, Table 23).

Chapter 5. Stream Environmental Flow Needs

The third component of the MPRWA project used the Ecological Limits of Hydrologic Alteration (ELOHA) approach (Poff et al. 2010) to investigate biological responses of flow alteration in streams and small rivers in the Middle Potomac study area. The objectives of this study component were to: (1) identify flow metrics that, when altered, associate with strong biological response, and; (2) develop flow-alteration ecological response relationships that describe how aquatic ecology responds to flow alteration in a semi-quantitative manner and that can be used to aid in the future development of environmental flow recommendations for tributary streams. This chapter and six supporting appendices (C-H) describe in detail how the ELOHA framework was applied. Streams and small rivers are defined as Strahler order 4 or less and wadeable; in the study area these waters correspond to the 1a, 1b, 2, and smaller 3 size categories of the Northeast Aquatic Habitat Classification System (NEAHCS). A major part of this MPRWA component involved pairing biological sampling data with observed and/or simulated flow data at numerous, diverse stream locations across the study area. Biological data were extracted from a Chesapeake basin-wide macroinvertebrate database compiled from 23 federal, state and local sources. Observed flow data corresponding to each biological sampling site were limited because the majority of Potomac flow gages are located on rivers. Hydrologic modeling was required to simulate flow time series at ungaged locations. The Chesapeake Bay Program's Phase 5.2 HSPF model and the Virginia Department of Environmental Quality's Online Object Oriented Meta-Model (WOOOMM) routing module were used to estimate daily streamflows for 747 watersheds draining to biological monitoring locations. Time series were simulated for baseline and current conditions in each watershed (water years 1984-2005). The current scenarios were validated with observed (gage) data. Five future scenarios were also simulated at 153 of the larger HSPF watershed model segments. The difference between baseline and current scenarios measures the amount of hydrologic alteration already present in a given watershed; the difference between current and future scenarios estimates potential future alteration. A suite of flow metrics was calculated from each scenario time series. The responses of family-level metrics of stream macroinvertebrate to alteration in representative flow metrics were examined with three statistical methods: Pearson correlation, quantile regression and conditional probability. Conditional probability plots were used to create flow alteration-ecology (FA-E) curves. These curves provide a scientific basis for defining environmental flows that sustain healthy stream communities as well as the goods and services that humans derive from well-functioning stream ecosystems. All the data used in this component of the study can be found in Appendix C. Appendix D contains technical memoranda describing details of the hydrologic model. Appendix E provides an in-depth comparison of flow metrics calculated from observed (gaged) and modeled time series. Appendix F contains an analysis of nine possible stream classifications (the classification system eventually selected is presented in 5.2.4). Appendix G provides a detailed look at hydrologic alteration in the Middle Potomac study area today and explores possible links to different land uses. Appendix H provides additional details about the FA-E relationships.

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5.1. Ecological Limits of Hydrologic Alteration (ELOHA)

The ELOHA framework was adapted for the stream and small river environmental flow needs assessment (Figure 4). The four major scientific steps in the ELOHA approach are: (1) build a hydrologic foundation with models that can produce hydrographs for different watershed conditions, including an undisturbed (baseline) watershed, (2) classify rivers according to flow regimes and geomorphic features to reduce biological variability, (3) compute flow alteration using undisturbed hydrological conditions as the baseline, and (4) formulate FA-E response relationships for environmental flows. These four steps were followed in the MPRWA with a little modification.

Several important characteristics of the Middle Potomac study area and available data shaped the project and/or required modifications to the prescribed ELOHA process. These included:

- Biological monitoring programs and methods. The Middle Potomac is an interstate watershed, with most of the significant biological monitoring conducted by loosely coordinated but independent state and local agencies using their own methods. A review of the data showed that benthic macroinvertebrates were the only taxonomic group for which comparable metrics could be calculated across jurisdictional boundaries and for which there was a sufficiently large number of samples to allow application of the ELOHA method. Benthic macroinvertebrates are

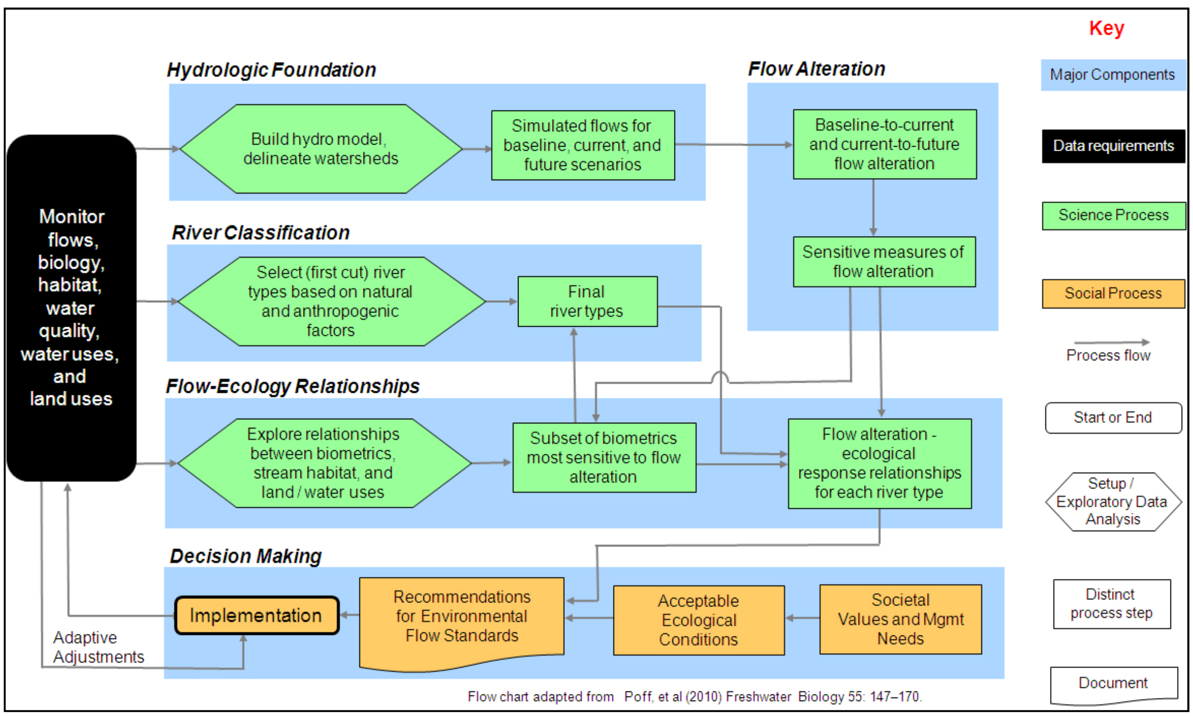

Figure 4. Conceptual diagram of the major steps in developing flow alteration-ecology (FA-E) relationships for the Middle Potomac study area.
This diagram is a framework and the stream/small river component of the MPRWA is one piece of the framework. The black box indicates ongoing monitoring programs that provide the information needed to track changes in flow and stream biota; the green boxes indicate analysis steps taken in the stream/small river component of the MPRWA for the purpose of determining FA-E relationships; the orange boxes indicate both ongoing and future steps in the states' planning efforts, which are supported by this project's outreach and consensus-building efforts. Adapted from Poff et al. (2010).

commonly used indicators of ecosystem health, but this project's reliance on macroinvertebrates, though necessary, has implications for interpretation of the FA-E relationships that result. Fish, for example, may react to certain flow characteristics that macroinvertebrates do not.

- Stream classification. Poff et al. (2010) recommend classifying streams by type to reduce natural variability in biological communities. The step is intended to remove variability from, and strengthen confidence in, the FA-E relationships. An established stream classification approach (Olivero and Anderson 2008) was explored in this project; it proved only somewhat successfully because it did not account for the confounding influences of other anthropogenic stressors, which can be significant in the Middle Potomac study area. When stream classification was attempted with a subset of the data comprised of the highest quality (reference) sites, with good water quality and habitat conditions, a strong classification system based on the USEPA Level IV ecoregions was found. Ecoregions have distinct regional differences in topography, soils, geography, and vegetation – all of which are factors that affect the structure and function of stream macroinvertebrate communities (e.g., Feminella 2000, Hawkins et al. 2000, Kennan 1999). In these high quality streams, anthropogenic influences are minimized, macroinvertebrate communities are primarily governed by natural features of the ecoregion, and ecoregion differences in the communities are significant ($p<0.01$). Stream size (Strahler 1^{st} – 4^{th} order), season (spring, summer, autumn/winter), and karst geology proved less important as classification factors explaining natural variability. A scoring protocol based on each ecoregion's reference communities can be used to evaluate macroinvertebrates anywhere in the basin on a comparable scale of 0% to 100%, thus obviating the need to analyze the data separately by ecoregion classes.

- Flow metrics. Although similar studies in other areas have identified FA-E relationships for particular flow characteristics there was no *a priori* reason to believe that the available data in the Potomac watershed would identify those relationships. Therefore, the data were used to define, rather than to test, FA-E relationships. Computer programs for calculating many flow metrics were available and so a large suite of flow metrics and biometrics were calculated. Then, through a series of analytical steps, the list of metrics was winnowed to a very small set that represent different aspects of the flow regime, show a relationship with watershed and water use factors, and show a relationship between flow alteration and biological status.

- Confounding factors. It is universally recognized that stream biological status is affected by many natural and anthropogenic factors interacting in complex ways that cannot be easily disaggregated. Figure 5 is a conceptual diagram showing biological community health as the result of multiple processes, of which flow is just one. A challenge of the MPRWA was to distinguish macroinvertebrate changes caused by altered flow from macroinvertebrate changes caused by other environmental factors such as poor water quality and in-stream habitat disturbance. Then, statements could be made about anthropogenic activities that alter flow and the effect of flow alteration on biological community health. As with any data analysis, it is imperative to remember that each dataset has its own particular distribution of natural watershed characteristics and anthropogenic impacts. These features will influence the flow alteration – ecology relationships, either by limiting avenues of investigation or more heavily weighting some results.

Several general premises underlie the ELOHA approach used in this study, namely:

(1) humans can alter the stream flow regime of a watershed through direct (impoundments, withdrawals, discharges) and indirect (land uses) actions;
(2) status of the macroinvertebrate community is a function of, among other factors, stream flow regime;
(3) macroinvertebrate status can be represented by a diverse set of family-level metrics which quantify community composition and function;
(4) key features of the flow regime (magnitude, duration, frequency, and rate of change) are important to macroinvertebrate communities;
(5) increasing alteration in these features, expressed as flow metrics, away from a baseline condition corresponds to changes in macroinvertebrate status, generally for the worse; and
(6) the flow alteration signal can be separated from other, natural and anthropogenic factors affecting macroinvertebrates (e.g., bioregion, pollution).

These premises are derived from the large body of literature on flow effects, which has been discussed and summarized by multiple authors going back to Hynes (1970). The term "premise" is used rather than the recently coined "flow hypothesis" because the project's analyses do not follow the scientific method and do not test the statements above in controlled experiments. Rather the study's results and their interpretations lend support to—or counter—the statements by revealing consistent associations between biological communities and conditions with altered flow.

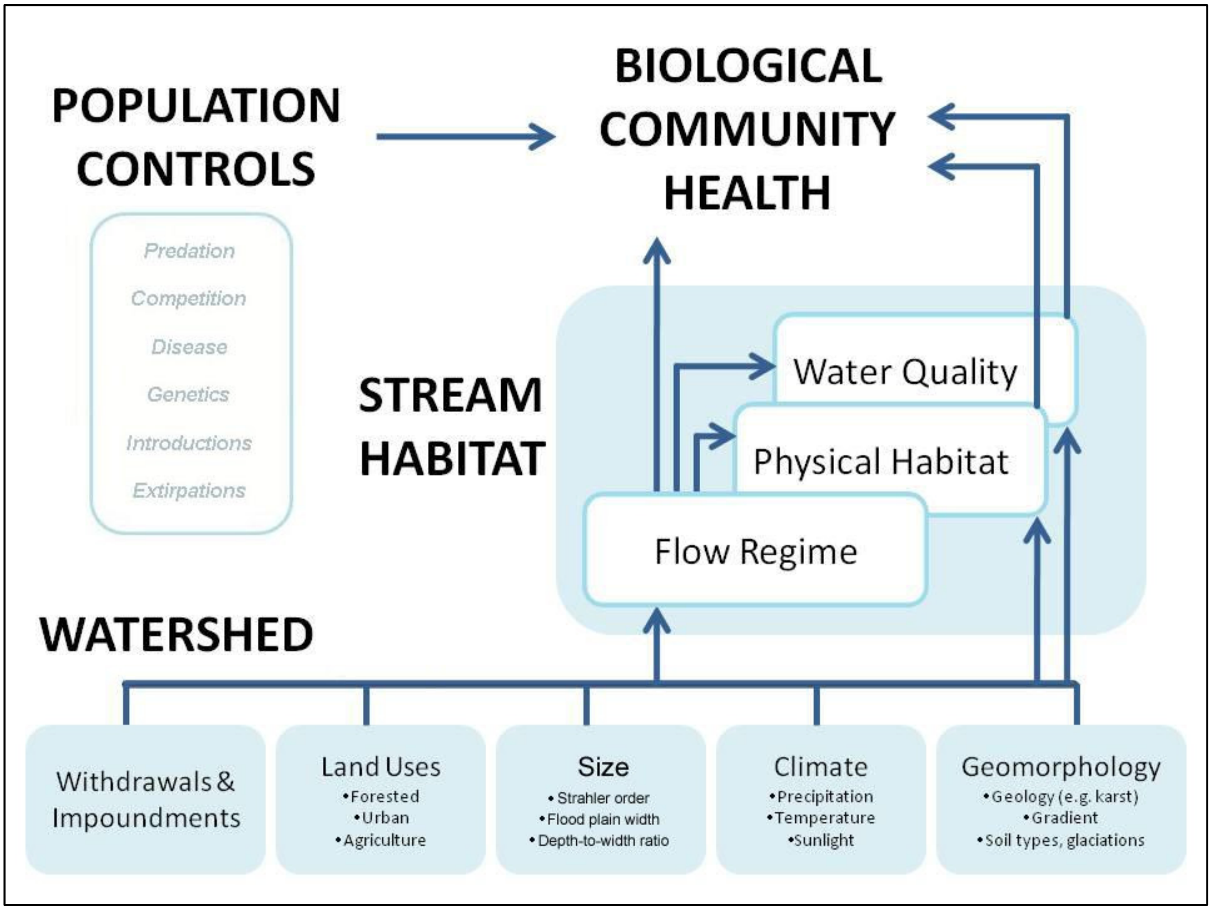

Figure 5. Conceptual diagram of biological community health.
Flow is only one of multiple factors affecting biological community health.

5.2 Application of ELOHA

5.2.1. Compilation of Stream Data

The compilation and analysis of several types of stream monitoring data was a large and important project effort. These observed data consist of daily flow time series measured at USGS gages and biological, habitat, and water quality data collected at stream monitoring stations. The daily flows were used to validate baseline and current scenario model results and relate watershed land and water uses to flow conditions. Metrics calculated from the biological data were used as ecological response variables in developing FA-E relationships. Habitat and water quality data were used to investigate environmental factors potentially masking or confounding the FA-E relationships. Appendix C describes in detail the various stream monitoring datasets compiled for the project. The data are available on the disc accompanying this report.

USGS flow gages

One hundred and seventeen USGS gages are listed for the entire Potomac River basin (http://waterdata.usgs.gov/nwis). All but approximately 20 are located in the Middle Potomac study area. A careful review of the data identified 65 gages with nearly continuous data records for 1984 – 2005, the time period on which current and baseline model scenarios are executed. This time period was selected to correspond to the hydrologic modeling time period and is limited based on the availability of observed input time series required by the hydrologic model (e.g. meteorology). Fifty-four are calibration points for the Chesapeake Bay Watershed Model P5. Flow data for the 65 gages were downloaded from the USGS website. Watersheds upstream of the selected gages were delineated and their natural features and land and water uses quantified from graphical information system (GIS) layers for stream networks, elevation, ecoregion, geology, precipitation, land cover, withdrawals, impoundments, and discharges (data sources are available in Appendix C). Fifteen flow metrics capturing different portions of the hydrograph were calculated from the observed flow time series using Indicators of Hydrologic Alteration (IHA) version 7.0 software (TNC 2007) and the USGS Hydrologic Index Tool (HIT) program (Henriksen et al. 2006). Information about the hydrologic and biologic importance of these flow metrics can be found in both TNC (2007) and Apse et al. (2008). To increase sample size and statistical rigor of the analyses, the same fifteen flow metrics for 40 stream gages in the neighboring Susquehanna River basin were added to the Potomac dataset. The associated natural features and land/water uses for the Susquehanna watersheds and most of the flow metrics were provided by Michele DePhilip and Tara Moberg of the Pennsylvania chapter of TNC and Jennifer Hoffman of the Susquehanna River Basin Commission (SRBC). Watersheds in the combined Potomac-Susquehanna dataset varied in size from 2.7 mi^2 to 27,100 mi^2 and covered a broad range of land and water uses. This dataset was used to check flow metrics calculated from model output and corroborate the relationships found between flow metrics and watershed characteristics in the modeled data (5.2.3).

Biological data

The technical team reviewed the available macroinvertebrate and fish data for their usefulness as the biological element in FA-E relationships. At the time, both types of data were being acquired from federal, state, and local sources and assembled into relational database structures by ICPRB as part of an effort supported by the Chesapeake Bay Program (CBP). The macroinvertebrate database was significantly larger and more complete than the fish database due to the fact that all of the state agencies in the region collect macroinvertebrate samples as part of their routine monitoring programs. The compiled database consisted of 5,410 sampling events collected with roughly comparable field methods at 3,310 stations throughout the Chesapeake region between 1986 and 2009. Comparable family-level metrics could be generated from all of the contributed datasets and evaluations of macroinvertebrate status could be done in a consistent manner across the entire Middle Potomac region. Furthermore, family-level metrics responsive to anthropogenic disturbance had been combined in a Chesapeake basin-wide index of biotic integrity ("Chessie BIBI") for the purpose of evaluating stream health (Foreman et al. 2008; Buchanan et al. 2011). Finally, CBP had implemented an annual data call to acquire and incorporate new data and data sources. In contrast, the database of available fish data was smaller with approximately 2,600 sampling events collected at 1,667 stations. Only records from the state of Pennsylvania, Montgomery County in Maryland, and Fairfax County in Virginia were included at the time the database was reviewed. Programmatic differences in gear type and protocols made it difficult to find comparable fish data across the Middle Potomac region and little work had been done to develop a multi-metric index of fish community status. The decision was made to use macroinvertebrates as biological response variables because of the larger size, better integration, and broader coverage of the macroinvertebrate database and the comparability and utility of the family-level metrics.

Stream macroinvertebrates are a diverse group of organisms with many morphological, behavioral, and feeding adaptations for life in flowing waters. They consume detritus, algae, bacteria, and microscopic animals, and are food for fish and birds. They have a broad range of tolerances and sensitivities to different stressors and anthropogenic pollutants, and fill many ecological niches. This makes them ideal as indicators of the health of most streams and rivers.

Certain constraints come with using macroinvertebrates as the ecological variable in FA-E relationships. Aquatic macroinvertebrates are a diverse group representing numerous phylogenic taxa, but most communities in free-flowing waters are dominated by insects. Insect life cycles are relatively short—on the order of weeks to a few years—and their responses to extreme but infrequent events (extreme droughts, extreme floods) occur in the year of the event and then fade as successive generations recover. An appropriate suite of flow metrics for macroinvertebrates may be those that reflect flow alteration occurring on a regular basis. Macroinvertebrates also are sensitive to environmental stressors that do not alter flow *per se* but that can be associated with flow and can confound the effects of flow alteration, such as water chemistry (pH, conductivity, dissolved oxygen, nutrients) and habitat condition (loss of riparian zone vegetation, sedimentation, channelization). Removing the influence of these factors, many of which are anthropogenic in origin, is an important step in isolating and quantifying the true impacts of flow alteration.

Habitat and water quality data

Another feature of the macroinvertebrate database influenced the decision to use this biological group. Several habitat and water quality parameters are measured concurrently with the macroinvertebrate samples and are included in the database. Habitat and water quality data are crucial for independently identifying high quality, or "reference" sites. Some physical habitat parameters are directly impacted by flows (e.g., bank stability). Connections between flow, habitat, and macroinvertebrate status could be explored in the future with this dataset, and would facilitate development of environmental flow standards where habitat and water quality data are available but biological data are scarce.

5.2.2. Hydrologic Modeling

The ELOHA framework is predicated on the ability to couple flow and biological data. In the Potomac River basin, biological monitoring data is most often available for headwaters, streams, and small and medium sized rivers. Conversely, flow data is most often collected at USGS gages on medium and large sized rivers. To this end, hydrologic modeling efforts were undertaken to estimate flows at ungaged locations corresponding to select biological monitoring points. The hydrologic modeling efforts included the Middle Potomac study area as well as the North Branch of the Potomac River, an upstream tributary that is required for efficient modeling of the study area (Figure 6). Detailed descriptions of key steps in the modeling approach are provided in Appendix D.

Biological monitoring locations in the Middle Potomac study area were selected from the CBP macroinvertebrate database. Of the 3,310 biological sampling locations in the database, 869 sites were selected for the MPRWA that (1) represented a range of hydrologic alteration, (2) represented a range of watershed sizes, (3) included broad spatial distribution across the study area, (4) were located within 200 feet of a National Hydrography Dataset (NHD) stream (deviation from the stream is indicative of erroneous monitoring point location information, or less commonly, spatial accuracy problems in the NHD dataset), and (5) were sampled between 2000 and 2008 to correspond to the current hydrologic model scenario (the current scenario is defined later in this document). Watersheds that drain to the 869 biological monitoring points were delineated with two methods: selection of the NHDPlus catchments associated with biological monitoring points in ArcGIS and implementation of the Utah State University Multi Watershed Delineation Tool.

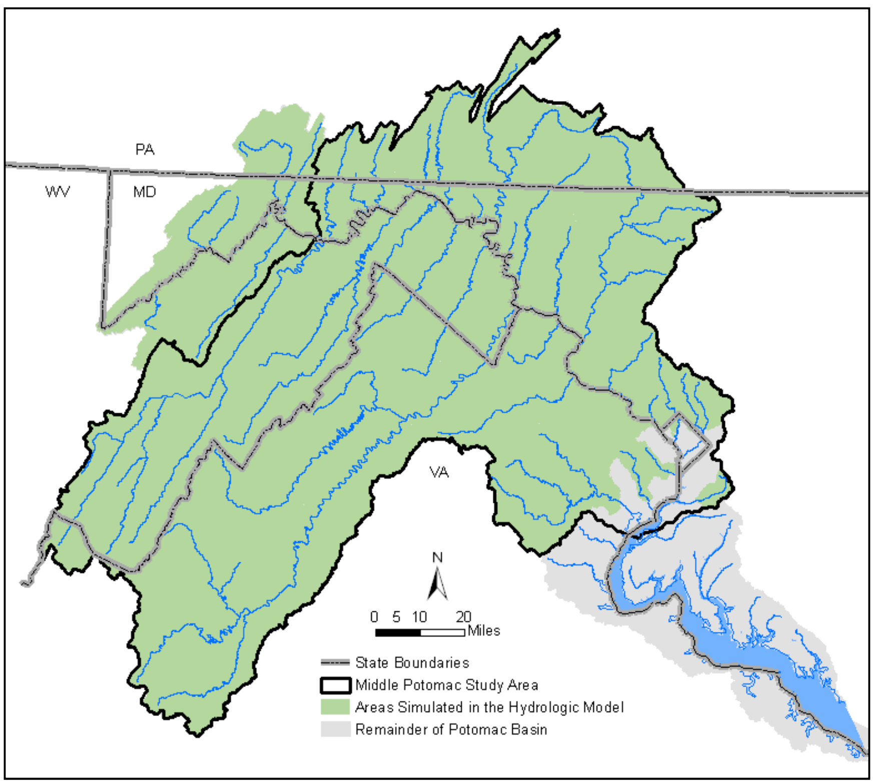

Figure 6. Geographic areas simulated in the hydrologic model in relation to the Middle Potomac study area.

Three hydrologic modeling tools were evaluated for potential use in the MPRWA including the US Geological Survey (USGS) Sustainable Yield Estimator (SYE), the Chesapeake Bay Program's HSPF model, and the Virginia Department of Environmental Quality's (VADEQ) Online Object Oriented Meta Model (WOOOMM) (Appendix D, Application of Modeling Tools). SYE was evaluated as it has been used in similar projects (Waldron and Archfield 2006; Archfield et al. 2010). SYE is capable of simulating baseline but not future scenarios, a desired capability for the Potomac project. The Potomac River Basin, being a part of the Chesapeake Bay Watershed, is fortunate to have a fully developed HSPF model through the Chesapeake Bay Program (Linker et al. 1999). The HSPF model has undergone collaboration, development, peer review, research, revision, and implementation over the past 30 years. It was designed to understand freshwater inflows to the Chesapeake Bay as well as the nutrients and sediments transported by the flows. Phase 5.2 of the HSPF model was utilized because it was the most recent, complete version available at the time of analysis. The HSPF model is capable of simulating current, baseline, and future scenario flows. The model is divided into more than 2,000 simulated segments across the 64,000 square mile Chesapeake Bay Watershed (Chesapeake Bay Program 2010). The spatial resolution of the modeled segments averages 89 square miles in the study area. This is a much coarser spatial resolution than needed to simulate the range of watershed sizes in this study – from small creeks to large rivers.

WOOOMM complements the capabilities of the HSPF model by using the latter's land simulation coupled with a USGS channel morphology module and a WOOOMM channel routing routine to estimate flows at locations of interest (Kudlas 2009). In combination, the HSPF model and the WOOOMM enable simulation of streamflows at locations in the study area corresponding to biological monitoring points. The result was the selection of the HSPF model,[10] in combination with the WOOOMM routing module.[11] The channel routing routine utilizes Manning's equation to simulate flow through a trapezoidal channel utilizing input parameters such as channel length, side-slope ratio, Manning's roughness coefficient, base width, and slope. The channel morphology module estimates the channel properties for input into the channel routing routine such as the side-slope ratio, base width, and Manning's roughness coefficient using regression equations developed by the USGS. These equations describe the relationship of the channel properties to drainage area and physiographic province.[12] The strength of combining HSPF with WOOOMM is the ability to effectively simulate flows at any selected stream location, enabling estimation of flows at selected biological monitoring points in the study area. Further details about the WOOOMM module are available in Appendix D (WOOOMM Inputs).

Two enhancements were made to the HSPF model prior to use in this study. The first enhancement was re-segmentation at "significant" impoundments (Appendix D, Resegmentation at Impoundments). Significant, in this case, indicated that: (1) the normal storage capacity of the impoundment was greater than 10 percent of the mean annual flow volume OR the impoundment was used for hydroelectric purposes, AND (2) biological monitoring points were located upstream and downstream of the impoundment. This effort was conducted to eliminate the influence of major sources of hydrologic alteration within a model component. Of the 481 impoundments

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[10] The HSPF model is freely available from the Chesapeake Community Modeling Program http://ches.communitymodeling.org/models/CBPhase5/index.php). Model documentation is also provided through the program.
[11] The WOOOMM is an online tool accessible at http://deq1.bse.vt.edu/wooomm/login.php. A Wiki describing the tool and its capabilities are online at http://sifn.bse.vt.edu/sifnwiki/index.php/Creating_Flow-Ecology_Relationships.
[12] Personal communication, R. Burgholzer (VADEQ) in memo "modeling an unaltered flow regime" (2010).

found in the National Inventory of Dams in the Potomac River basin, 12 impoundments were selected for inclusion in the model. The HSPF model was re-segmented so that these 12 impoundments were located at river segment outlets. The dam operations such as pass-by requirements and whitewater releases were also included in the model where information could be obtained. The result was a revised HSPF model with a total of 16 simulated impoundments, 4 of which were previously included. The second enhancement was implementation of a nonlinear groundwater recession algorithm (Schultz et al. In review). The HSPF model is typically utilized to understand nutrient and sediment transport during high flows. As a result, low flows are often under-simulated. To improve the simulation of low flows, the traditional linear groundwater recession algorithm was replaced with a nonlinear algorithm. The nonlinear algorithm was included in the subsequent CBP Phase 5.3 version of the HSPF model.

Hydrologic model calibration

The HSPF model was calibrated using the CBP auto-calibration routine (USEPA 2010). The HSPF model was then evaluated for simulation efficiency using the Nash Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970) and the coefficient of determination, or R^2. The NSE compares simulated and observed flows to quantify the variation from the 1:1 line. Values range from negative infinity to one, with one indicating that simulating values are identical to observed values. Decreasing NSE values are an indication of poorer model efficiency, with negative values indicating that it is more reliable to use the observed mean value than the model results. The NSE is considered by some to be the most commonly used metric to evaluate model efficiency (Gassman et al. 2007). R^2 values ranged from 0.39 to 0.82 at the 43 model calibration locations. Daily NSE values at the same locations ranged from 0.33 to 0.82 (Figure 7). The calibration locations are shown in Figure 8. Consistent with a "weight of evidence" model evaluation approach (Lumb et al. 1994; Donigian 2002), the results of the calibration represent an acceptable range of model error and show an overall modest improvement in the HSPF model performance.

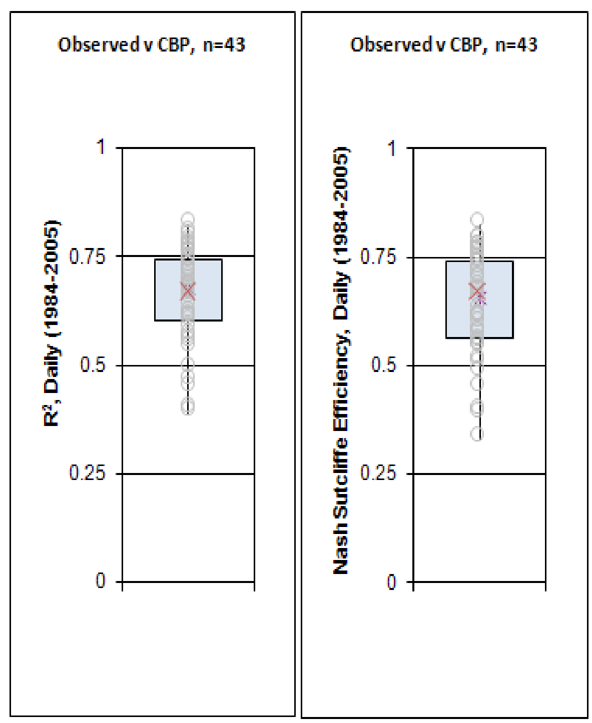

Figure 7. Distribution of daily Nash Sutcliffe Efficiency (NSE) coefficient and coefficient of determination (R^2) values for 43 model calibration locations.

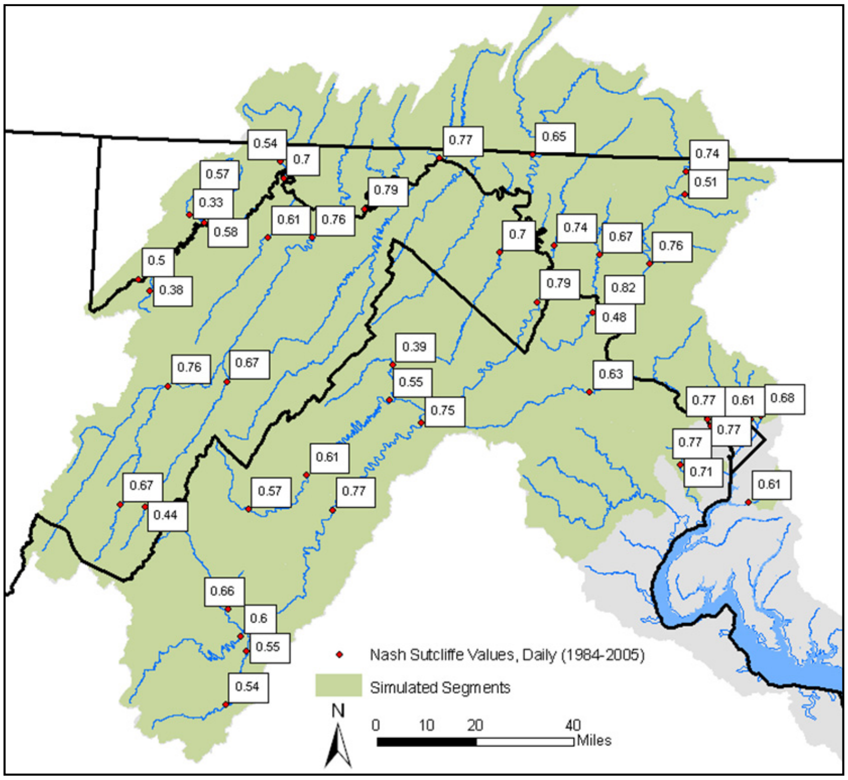

Figure 8. Daily NSE values at model calibration locations.

Hydrologic model implementation

Once the HSPF model was calibrated utilizing the approach described in the model calibration methodology (Chesapeake Bay Program 2010), the watersheds draining to biological monitoring points that are the subject of this study's stream flow needs analysis were established in the WOOOMM routing module (Appendix D, Watershed Delineation). The watersheds represent a sub-set of the originally delineated 869 watersheds. Specifically, a total of 28 duplicate watersheds were identified (Appendix D) and removed. Duplicates occurred when biological sample locations were so close their delineated watersheds were effectively the same for modeling purposes. An additional 94 delineated watersheds needed for simulating flows in nested or adjacent watersheds were also removed because there were no biological data available to couple with them. (Simulated baseline and current flows for these 94 "assisting" watersheds are included in the Master spreadsheet in Appendix C). The remaining 747 watersheds constitute the "ELOHA" analysis dataset. Each is associated with one or more biological samples.

Two scenarios were developed and executed within the WOOOMM routing module. The baseline scenario simulated the hydrologic conditions given nominal anthropogenic influence. All withdrawals, discharges, and impoundments were turned off for the baseline scenario. Land uses were returned to mostly forested conditions (greater than 78 percent forest) and impervious surface area was minimized (less than 0.35 percent). These two land use thresholds were initially identified in the large river environmental flow needs report (Appendix A). The thresholds were a result of a recursive partitioning analysis, called "Category and Regression Tree Analysis" (CART), performed on the Potomac-Susquehanna dataset. CART is similar to cluster analysis and indicates breakpoints where the clusters divide (Appendix D, Potomac-Susquehanna CART analysis). A complete description of how these thresholds for baseline land use conditions were applied in modeling baseline flows is available in Appendix D (Baseline Landuse and Baseline Scenario). The second scenario executed in the WOOOMM was a current conditions scenario. The current scenario was a snapshot of current watershed conditions, including withdrawals, discharges, land uses, and impoundments, run over a 21-year period (1984-2005) of meteorological conditions (the common time period of necessary observed model input time series). A comparison of baseline and current scenario streamflows provided an indication of how much hydrologic alteration is currently found in watersheds draining to the biological monitoring points.

Five future scenarios were also developed and run in the HSPF model at the river segment scale. The purpose was to understand the hydrologic effects of various possible future (2030) conditions. Future scenarios included DP1, DP2, power, climate change, and hot and dry, and are briefly described in 4.1. The scenarios included combinations of changes to land use, population in terms of increases in withdrawals and discharges, per capita water use, temperature, evapotranspiration, and precipitation. A detailed description of the modeling efforts for the future scenarios is available in Appendix D (Future Scenario).

Each of the seven model runs (current, baseline, DP1, DP2, power, climate change, and hot and dry) resulted in a 21-year daily flow time series. The time series were utilized to calculate a suite of 256 hydrologic metrics representing various portions of the hydrograph and including all flow levels (high, medium, and low flows). Metrics were calculated utilizing IHA (TNC 2007), EPA's DFLOW (Rossman 1990), and HIT (Henriksen 2006) as well as several metric calculations developed by ICPRB. The number of flow metrics was reduced through a process of identifying those that are responsive to alteration, not correlated, most efficiently modeled, easily understood, and correlated with biological health (Figure 9). Metrics were also selected to ensure that all parts of the hydrograph were represented. Flow metrics that best meet the screening criteria up to this point are listed in Table 4. Subsequent testing and analysis refined and expanded this list to finalize the list of flow metrics for which FA-E relationships were developed and spatial analyses were conducted.

Hydrologic model uncertainty

"How well does the model simulate stream flow?" This question lies at the heart of decisions about when and how to use simulated stream flows in watershed management. Simulated flows are credible when they accurately represent observed flows across a range of environmental conditions. The Potomac and its neighbor river basin the Susquehanna are fortunate to have roughly 100 USGS flow gages in continuous operation between 1984 and 2005. Their watersheds range from comparatively undisturbed to heavily urban and/or agricultural. Responses of flow metrics to different land and water uses in these observed watersheds provide a standard against which to test flow metrics calculated from simulated flows.

There are numerous sources of uncertainty in the model results including, but not limited to, mathematical errors, errors in observed data utilized during the modeling process, and limited knowledge of the system being modeled (Rode and Suhr 2006). Evidence of this uncertainty was present in the MPRWA in several areas. When comparing flow metrics calculated from observed and simulated datasets, the differences provided an indication of the magnitude of model uncertainty (Figure 10). Some differences were expected between simulated and observed values as the model was a simplified representation of a complex reality. Overall, the model results were shown to adequately represent reality in response to changes in watershed characteristics such as land and water uses for the purposes of this project (Appendix E).

During an investigation of the behavior of simulated flow metrics, a sub-set of watersheds were identified as having conspicuously different flow metric values. The sub-set of watersheds were identified as either being located in the karst regions of the basin or in modeled land segments containing karst (Figure 11). This was an indication that the hydrology of karst watersheds was different than non-karst regions, the watershed model had difficulties simulating the effects of karst geology, or a combination of the two. Unfortunately, sufficient observed flow data from karst

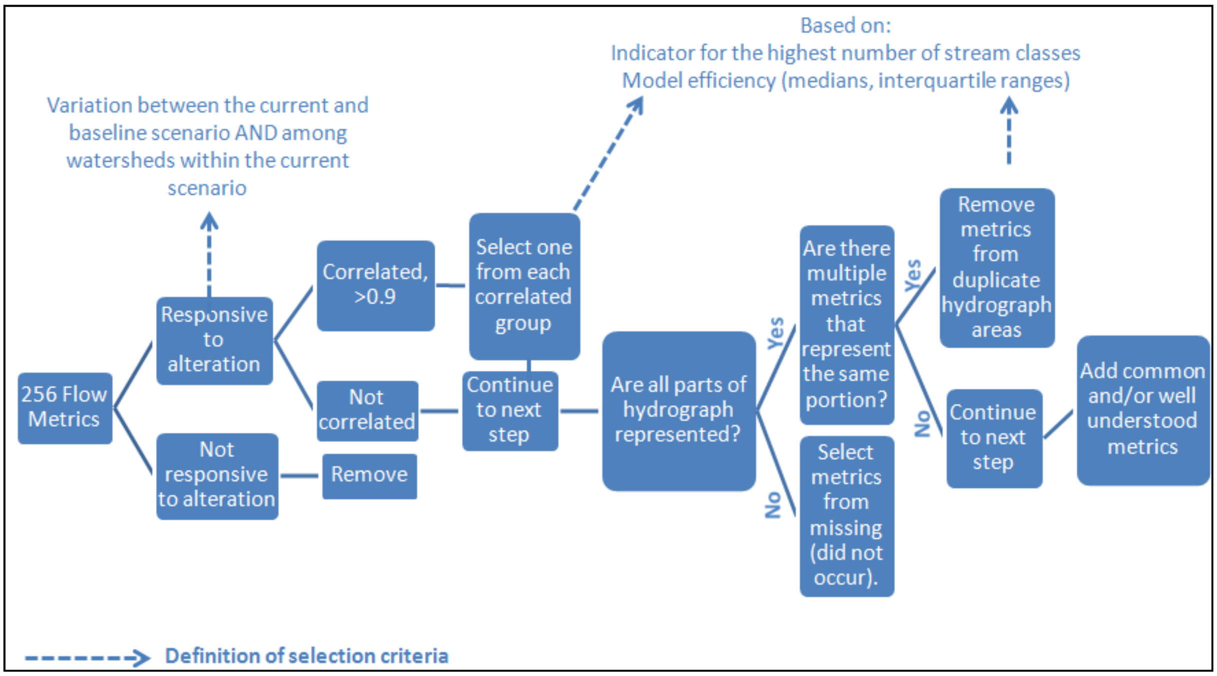

Figure 9. Decision-tree for selection of flow metrics.

Table 4. Flow metrics that best meet the criteria used in the Middle Potomac study to evaluate model simulations of flow time series.

Statistic (units)	Source	Flow Range	Characteristic
3 day maximum (cfs/mi^2)	IHA	High	Magnitude
High flow duration (days)	HIT	High	Duration
High pulse count (#/year)	IHA	High	Frequency
Flashiness (unitless)	ICPRB	All	Rate-of-Change
August median (cfs/mi^2)	IHA	Mid	Magnitude
7Q10 (cfs)	DFLOW	Low	Magnitude
Seasonal Q85 (Maryland Method) (cfs/mi^2)	ICPRB	Low	Magnitude
Low pulse duration (days/year)	IHA	Low	Duration
Low pulse count (#/year)	IHA	Low	Frequency

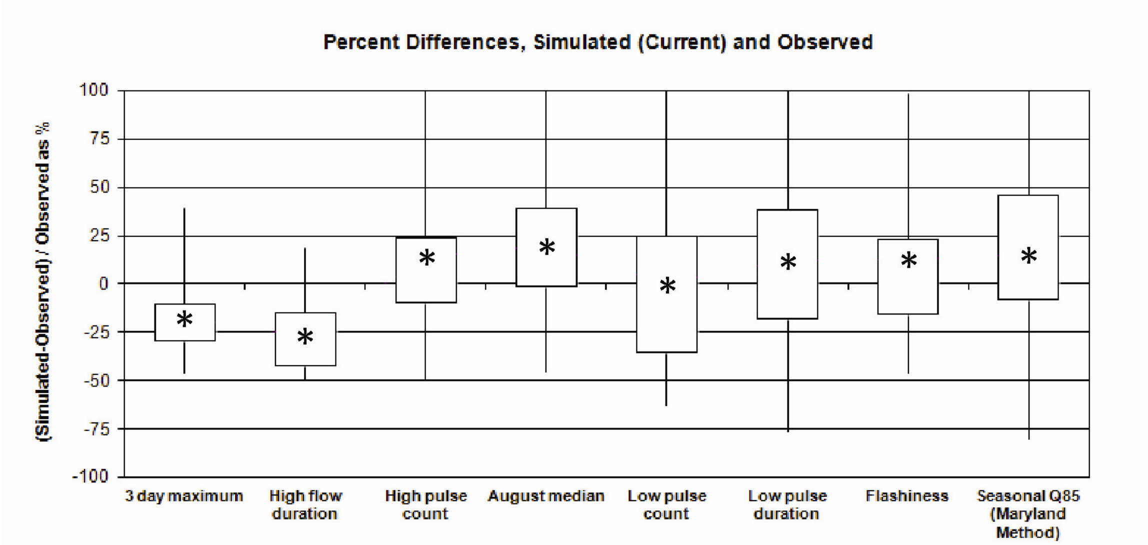

Figure 10. Comparison of observed flow metrics.
Calculated at 31 model calibration locations and HSPF simulated, current scenario flow metrics at the same locations.

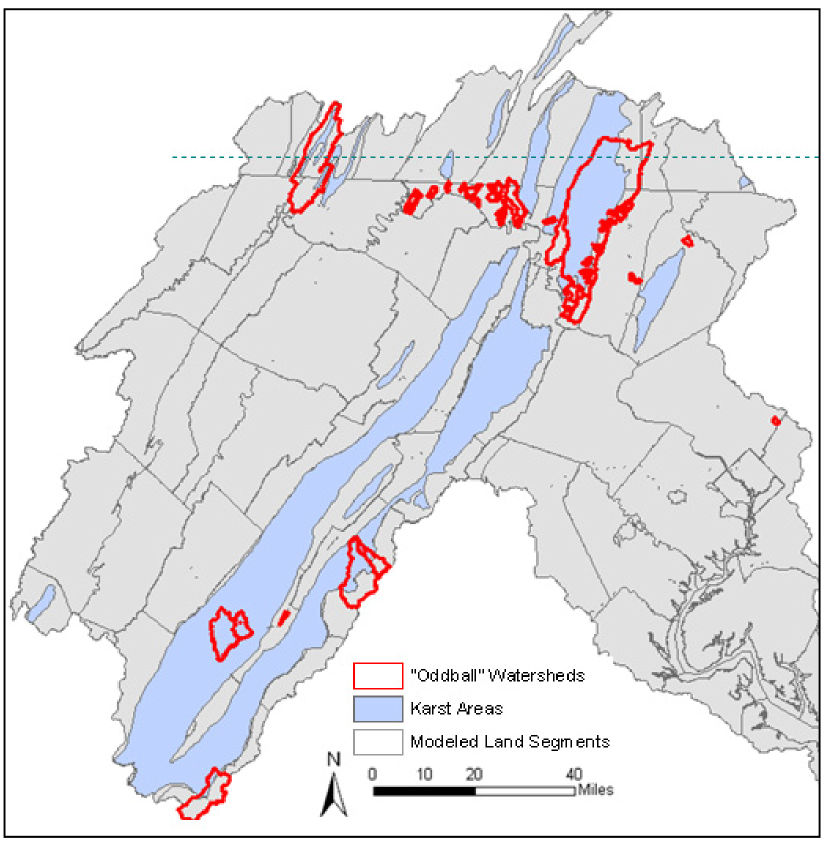

Figure 11. Location of watersheds with one or more flow metrics that behave differently than those in the observed dataset.
These watersheds are primarily located in regions of karst geology or in modeled land segments that contain karst geology.

watersheds was not available for comparison to determine the extent to which these conspicuous flow metrics were a result of model uncertainty or physical differences in the behavior of karst systems. Similarly, the availability of observed data to test model efficiency in small watersheds was limited. Most USGS gages were located in watersheds greater than 10 mi^2; however, roughly two thirds of the ELOHA watersheds were smaller than this threshold, with a median watershed size of just over 3.5 mi^2. Additional observed hydrologic data on smaller watersheds would enhance understanding of the extent to which these smaller watersheds were being adequately simulated.

Spatial distribution and the scale of the model inputs, particularly meteorological inputs, compared to the scale of modeled watersheds is also a potential source of model uncertainty. Meteorological inputs to the HSPF model were developed by the CBP from regional observation stations (USEPA 2010). Hourly meteorological input time series for each land segment in the Potomac basin study area were developed using 52 stations with daily data and 8 stations with hourly data (Figure 12). These meteorological data drive the hydrology of the HSPF modeled watersheds, and subsequently the WOOOMM routing module for the ELOHA watersheds. The meteorology in many of the

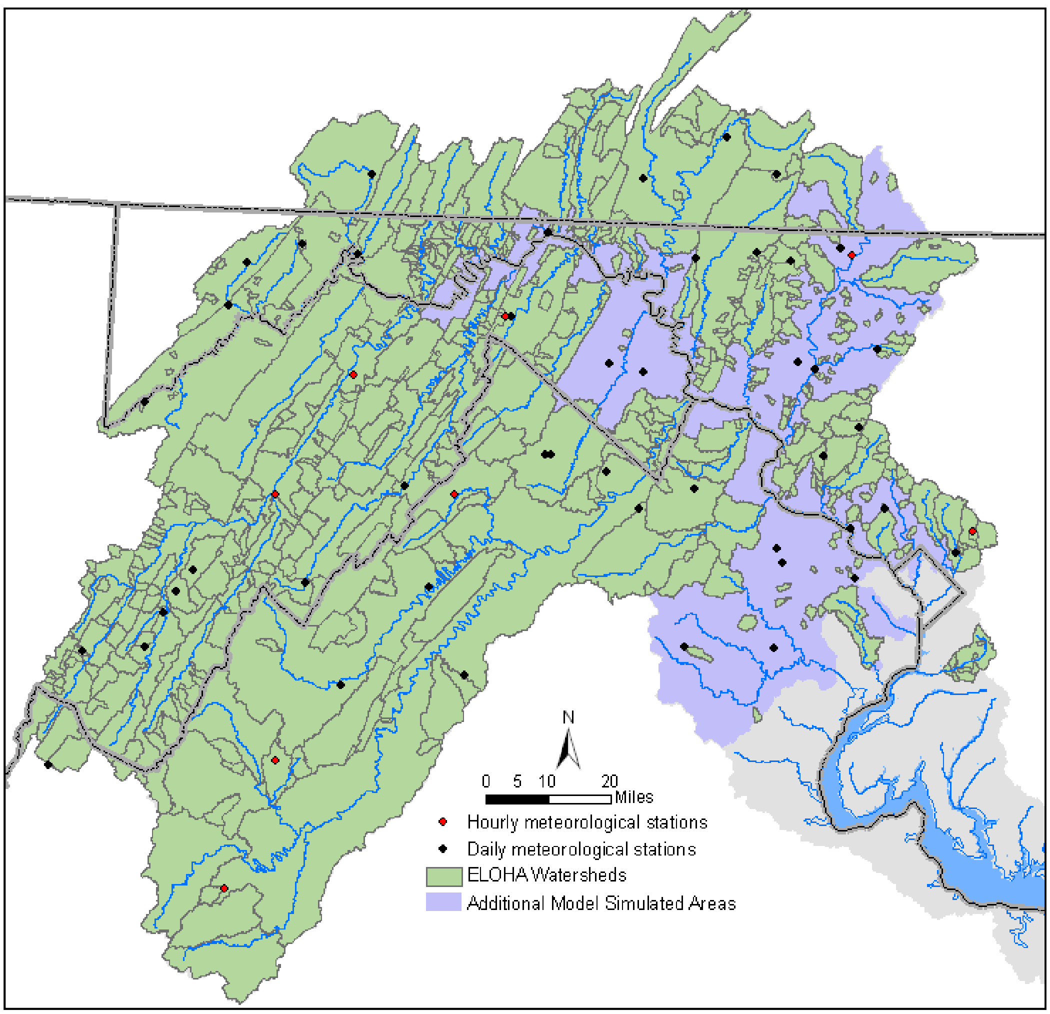

Figure 12. HSPF meteorological stations, major rivers, and the ELOHA watersheds. The additional model simulated areas indicated in the map are areas that were simulated in the HSPF model that were not coupled with biological data in the ELOHA analysis.

ELOHA watersheds, however, may be quite different from the regionally assigned meteorological station due to spatial differences. Conceptually, it is quite likely that the actual precipitation in a small headwaters watershed is not well represented by regional meteorological data. The regional generalization of meteorological data is, therefore, likely a source of model uncertainty.

Future population growth, changes in meteorological conditions, per capita water use, and land use change at differing rates than are represented in the future scenarios was an additional source of uncertainty (Semmens et al. 2006). For example, if climate change affects precipitation amounts by 2030, the predictions of this climate change scenario will differ from actual 2030 conditions as precipitation changes were not simulated in this scenario.

5.2.3. Flow Metric Testing and Model Validation

The model's ability to represent actual flows can be further validated through quantitative comparisons of flow metrics which correspond to different parts of the hydrograph. Flow metrics calculated from simulated flow time series are compared to their counterparts calculated from observed flow time series in the Potomac-Susquehanna gage dataset (described above and in Appendix C). Before these comparisons were made, the ELOHA dataset of simulated flows was further winnowed to remove certain types of watersheds.

Of the 747 ELOHA watersheds, 59 had "oddball" flow metric values in the baseline scenario. (Twelve of the 94 assisting watersheds also had oddball baseline values.) Baseline flow metric values should show consistent, tight relationships to natural landscape features because their watershed environments are very similar—heavily forested, little or no imperviousness, and no impoundments, withdrawals, or discharges. Oddball watersheds have baseline values of one or more flow metrics that are significantly different in their relationships to watershed size and gradient. The discrepancies put into question the accuracy of the percent flow alteration calculations derived from those values. Most of the affected watersheds are small, less than 20 mi^2, or located in specific, western regions of the Middle Potomac study area. Oddballs are described in detail in Appendix C. Close examination of the individual oddball watersheds could uncover acceptable reasons for their differences but at this stage it was deemed prudent to remove them from the analyses.

Coastal Plain watersheds in the Middle Potomac study area were also excluded from the final analysis in consideration of that bioregion's unique hydrologic properties. Coastal Plain watersheds comprise relatively small portions of both the simulated flow data (n=32 or 4.3 percent) and the observed Potomac-Susquehanna data (n=7 or 6.7 percent). Model performance in these few watersheds could not be adequately tested.

Removal of the oddball and Coastal Plain watersheds left a total of 656 ELOHA watersheds in the analysis dataset. Simulated flows for these watersheds formed the basis for the FA-E relationships. To equitably compare simulated and observed flow metrics, however, a final selection step was applied which compensated for differences in the watershed size distributions. All but two of the 98 Potomac-Susquehanna watersheds with observed (gaged) flows are greater than 10 mi^2 whereas just 239 of the 656 selected ELOHA watersheds (36.4 percent) with simulated flows are greater than 10 mi^2. This is a consequence of many biological sampling locations being located in headwater streams. For the purpose of comparing flow metric performance, only the 239 ELOHA watersheds with sizes greater than 10 mi^2 were compared to the 98 non-Coastal Plain watersheds in the Potomac-Susquehanna dataset.

Simulated versus observed flow metrics

Good agreement in simulated and observed flow metric values in least-disturbed watershed conditions indicates the model is accurately representing the influence of natural landscape factors governing flow. As stated previously, least-disturbed watersheds are defined for the Middle Potomac study area as heavily forested (greater than 78 percent) with little or no impervious surface (less than 0.35 percent) and no surface withdrawals, discharges, or. Flow in least-disturbed watersheds is governed primarily by natural factors such as watershed size, gradient, and geology. The baseline scenario for the ELOHA watersheds was simulated using these criteria. Eleven watersheds in the Potomac-Susquehanna dataset fully meet or almost meet these criteria. They are identified as “reference” to distinguish them from simulated baseline watersheds.

Good agreement in simulated and observed flow metric values with respect to different anthropogenic factors indicates the model is accurately representing the influence of these factors on flow. Current scenario and observed flow metrics represent the net effect of present-day land and water uses on the flow regime in their respective datasets. The intensities and proportions of land and water uses in current scenarios are not necessarily the same as those in the Potomac-Susquehanna watersheds. Therefore, flow metric responses in the current scenario cannot be expected to exactly match those found in the Potomac-Susquehanna gaged watersheds. Strong similarities and minimal differences between the two, however, should occur if the model is accurately representing anthropogenic impacts. Simulated and observed flow metric responses tested in the same watersheds should behave nearly identically.

Table 5 summarizes the comparison results of fifteen simulated and observed flow metrics (Appendix E). Five of the fifteen flow metrics tested rated “excellent” and three rated “good.” They are high pulse count, high flow duration DH17, high flow index MH21, median, flashiness, low pulse duration, 3-day minimum, and the frequency of extreme low flows (Supplemental Table A has a description of all metrics referenced in this report). Simulated and observed values of these eight metrics are not significantly different from one another and the metrics respond similarly to watershed area, gradient, and percent impervious surface, a major anthropogenic cause of flow alteration. When tested together in the same watersheds, the metrics identify the same primary anthropogenic factors altering flow and in many cases, the identical thresholds of impact for each factors. They collectively represent all aspects of the hydrograph except the highest annual flows. These eight flow metrics are therefore good candidates to use in developing FA-E relationships.

High pulse duration and 3-day maximum, the two flow metrics representing highest annual flows, did poorest in the comparison tests between the modeled flow data and the Potomac-Susquehanna gaged watersheds. Simulated values of these two metrics were significantly lower than their observed counterparts and their responses to impervious surface did not parallel those of the observed values.

Despite their drawbacks, these two poor performing metrics reveal interesting relationships to land and water uses in the watershed. Baseline and current scenario values of the two metrics are internally consistent even if the accuracy of their calculated percent flow alteration in ELOHA watersheds, or the percent difference between the two scenarios, is uncertain. As such, the metrics are useful for understanding relationships between land and water uses and stream flow alteration. The same argument can be made for the five flow metrics rated “fair” - annual mean, August median, rise rate, fall rate, and number of reversals. These metrics each fail one of the comparison tests but their responses to percent impervious surface area successfully parallel those found in the corresponding observed values.

Gage data were not available to test how well the simulated flow metrics represent flows in karst areas or flows in headwater streams. None of the Potomac-Susquehanna gaged watersheds with substantive amounts of karst meet the Reference criteria, and very few USGS stream gages are located in watersheds less than 10 mi^2. The watershed model appears to alter flow time series to reflect the effects of karst geology since 10 of the 15 tested flow metrics responded significantly and in a logical manner to karst in the baseline scenario ($p<0.05$). Due to the sampling designs of state macroinvertebrate monitoring programs, more than half of the final ELOHA watershed dataset (56 percent) are less than or equal to 10 mi^2. There was no real justification for taking small or highly karsted watersheds out of the final ELOHA dataset used to develop FA-E relationships, however. After some consideration, the decision was made to keep the untested simulated flow metrics from these watersheds in the ELOHA dataset. This maintained a larger sample size, which increases statistical confidence in the conditional probability curves predicting flow alteration impacts.

In summary, the modeling tools used in this study successfully account for the influences of several important natural factors on flow regimes and respond similarly to the dominant anthropogenic factors disturbing flow regimes in the ELOHA study area. The model provides a solid hydrologic foundation upon which to explore flow interactions with both water and land uses in the watershed.

Table 5. Results of simulated and observed flow metric comparisons.

See Supplemental Table A at the end of the main report for flow metric definitions and Appendix E for details about the comparison tests.

Flow Metric	Metric Type	Comparison of Simulated and Observed
3-day maximum (cfs/mi^2)	magnitude	poor
annual mean (cfs/mi^2)	magnitude	fair
median (cfs/mi^2)	magnitude	excellent
August median (cfs/mi^2)	magnitude	fair
3-day minimum (cfs/mi^2)	magnitude	good
flashiness (ratio)	rate of change	excellent
rise rate (cfs/mi^2)	rate of change	fair
fall rate (cfs/mi^2)	rate of change	fair
number of reversals (#/year)	frequency	fair
high pulse count (#/year)	frequency	excellent
ext. low flow frequency (#/year)	frequency	good
high flow index MH21 (days)	duration	good
high pulse duration (days)	duration	poor
high flow duration DH17 (days)	duration	excellent
low pulse duration (days)	duration	excellent

5.2.4. Stream Classification and Biometric Scoring

Poff et al. (2010) and Konrad (2011) suggest classifying streams and rivers in ELOHA studies if ecological responses to flow alteration are expected to vary by type. Classification serves two purposes in the ELOHA framework: (1) it allows extrapolation of FA-E relationships in gaged streams to ungaged streams of the same type, and (2) it informs the selection of future biological monitoring sites in regions with sparse pre-existing biological data or limited monitoring and research resources (Poff et al. 2010). It also increases the statistical significance of FA-E relationships by reducing natural variability in the biological variables.

Stream classification organizes water bodies into types, or classes, with similar attributes. It is a "subjective procedure, dependent upon its purpose and the type of data available" and numerous stream classification systems have been developed (Gordon et al. 1992). Poff et al. (2010) recommend classification to stratify "natural variation in measured characteristics among a population of streams and rivers to delineate river types that are similar in terms of [baseline] hydrologic and other environmental features." Baseline hydrologies represent undisturbed flow regimes for the streams under consideration. They are normally created with watershed models. Another approach developed by Olivero and Anderson (2008) uses attributes of existing conditions in the stream and landscape, such as gradient, temperature, stream size, geology, and baseflow, to create distinct stream classes. Both approaches use classification of the environment to reduce natural variability in biological communities, thus increasing confidence in the FA-E relationships. Both approaches assume each stream class has biological communities that (1) are similar to each other and distinctly different from communities in other classes, and (2) respond similarly to hydrologic alteration. A corollary to the baseline hydrology approach is: biological communities that are not otherwise influenced by anthropogenic, non-flow stressors and are very similar can be assumed to belong to the same stream class and will respond similarly to hydrologic alteration.

Several features in the Middle Potomac study area are well recognized as important natural factors governing aquatic communities. The River Continuum Concept (Vannote et al. 1980) describes the longitudinal gradient of physical and biological changes in free-flowing waters as headwater streams merge into small rivers and eventually large rivers. Watershed area and the closely related Strahler stream order are the physical framework on which the concept is based. Karst geology dominates portions of the Middle Potomac study area and, with its many springs and close connections to groundwater, is an important factor affecting stream density and flow volume. The elevated and highly variable topography of the Potomac River basin west of the Piedmont fall-line contrasts sharply with the flat, low-lying Coastal Plain in the east, suggesting fundamental differences in the stream hydrology and biological community structure and function by region.

Preliminary analyses of stream classification

Stream classification was initially tested using an existing Susquehanna River basin dataset with the purpose of finding a classification system that could potentially be applied to Middle Potomac streams and rivers (Appendix F). Applying the "attribute-based" approach of Olivero and Anderson (2008), statistical relationships between hydrologic alteration and biological responses were developed for the Susquehanna River, which was without a stream classification system (Apse et al. 2008, Case study 5). A single measure of anthropogenic impacts on flow—an index of cumulative water use relative to the 7Q10—was paired with macroinvertebrate and water quality data collected at the same locations and their relationships tested in stream classes defined by various attribute combinations. Attributes included watershed size, gradient, geology, temperature, baseflow, and the

CBP bioregions. Nine stream classification systems were examined. The impacts of watershed land uses, impoundments, and discharges were not considered. Systems representing flow volume (watershed size) and groundwater input (baseflow index, karst) had relatively strong relationships, but only in medium sized Susquehanna rivers with low to moderate baseflow contribution or karst presence. Relationships in other stream classes were for the most part insignificant or weak. A full description of the analysis is provided in Appendix F.

A similar watershed area-karst geology classification system was tested using the Middle Potomac ELOHA dataset of delineated watersheds draining to biological sampling sites. Again, the only cause of flow alteration considered was withdrawals and biological data from all watersheds, disturbed and undisturbed, were used in the analysis. Watersheds were grouped according to the NEAHCS size categories (Table 6) and, in smaller watersheds, by whether or not they had relatively high karst geology (greater than 44 percent). The classification resulted in a preponderance of smaller NEAHCS streams because most macroinvertebrate monitoring programs in the study area focus on streams and small rivers. In NEAHCS classes 1a, 1b, and 2, relationships between surface withdrawals expressed as a percent of median stream flow and a suite of 20 biological metrics were weak at best (Table 7). Of the 120 size-karst-biometric regressions, only 10 (8 percent) were significant at $p<0.05$, suggesting most relationships are a result of Type I or II error. None of the significant relationships explained more than 11.2 percent ($r^2=0.112$) of biological variability.

In both the Susquehanna and Middle Potomac dataset with varying degrees of anthropogenic, non-flow disturbances, classification based solely on watershed size and karst did not remove much of the variability in the biological response to surface water withdrawals. Surface withdrawals are only one of several anthropogenic factors altering flow in these watersheds, and flow alteration is only one of several anthropogenic factors impacting macroinvertebrate communities. The attribute-based approach to stream classification was not very successful in the Susquehanna and Middle Potomac watersheds, at least as it relates to surface water withdrawals.

Reference streams

An alternative to the Poff et al. (2010) recommendation to classify streams based on modeled baseline hydrologies is to classify streams based on the biota found in actual high quality, or "reference," stream sites. This approach requires sufficient numbers of these reference sites in the

Table 6. Watershed size categories of the Northeast Aquatic Habitat Classification System (NEAHCS). From Olivero and Anderson (2008).
#, number of sampling events per watershed size category in the Middle Potomac study.

Category	Class 1a	Class 1b	Class 2	Class 3a	Class 3b	Class 4	Class 5
Name	Head-water	Creek	Small River	Medium Tributary River	Medium Mainstem River	Large River	Great River
Area (mi^2)	<3.86	3.86 - <38.6	38.6 - <200	200 - <1,000	1,000 - <3,861	3,861 - <9,653	≥ 9,653
Area (km^2)	<10	10 - <100	100 - <518	581 – <2,590	2,590 - <10,000	10,000 - <25,000	≥ 25,000
#	607	407	215	74	10	0	0

study area. When stream classification analysis is based on the highest quality stream sites, the confounding influences of anthropogenic activities on the biota are minimized and the watershed's natural features govern its macroinvertebrate communities. Highest quality sites are defined here as having excellent habitat conditions (habitat metric scores 16 – 20) and non-stressful levels of pH (6 – 9), conductivity (<500 μS/cm), and dissolved oxygen (>5 mg/liter). It is assumed that these sites have relatively undisturbed flow regimes since scores for habitat features such as bank stability, bank vegetation, embeddedness, channel alteration, epifaunal substrate, and riffle/run/pool ratios are all excellent. An examination of the simulated current hydrologies at the 78 reference sites found in the ELOHA dataset supports this assumption. Twenty-three of the sites (29 percent) were in watersheds that fully met the criteria for baseline. Fifty-five of the sites (71 percent) were in watersheds with more than 52 percent forest cover, a threshold identified in the Category and Regression Tree (CART) analysis of the Middle Potomac large river flow needs assessment as low risk of flow alteration (Appendix A). Average impervious surface cover was 0.34 percent; none of the watersheds were associated with more than 1.3 percent imperviousness. Most flow metrics at the reference sites showed less than +/-20 percent alteration from modeled baseline values. The exceptions typically occur in the low magnitude flow metrics, with alteration greater than 20 percent, and are associated with karst geology, discharges, and/or land use dominated by agriculture.

Table 7. Linear regression coefficients (r^2) for biometrics versus surface withdrawals (expressed as a percent of annual median stream flow) in six size-karst classes, Middle Potomac study area.

Significance: * = 0.01<p≤0.05; ** = p≤0.01; ns = not significant. See Supplemental Tables for explanation of biometrics.

	NEAHCS	Class 1a				Class 1b				Class 2			
	Karst is:	Low		High		Low		High		Low		High	
Biometric	n is:	(593)		(14)		(325)		(82)		(180)		(35)	
Chessie BIBI		0.001	ns	0.024	ns	0.005	ns	0.032	ns	0.031	*	0.024	ns
ASPT modified index		0.000	ns	0.006	ns	0.013	*	0.028	ns	0.010	ns	0.003	ns
Beck's Index		0.000	ns	0.007	ns	0.008	ns	0.112	**	0.017	ns	0.014	ns
Number of Ephemeroptera		0.000	ns	0.072	ns	0.000	ns	0.086	**	0.003	ns	0.047	ns
%EPT		0.001	ns	0.042	ns	0.001	ns	0.020	ns	0.000	ns	0.024	ns
%Ephemeroptera		0.000	ns	0.014	ns	0.004	ns	0.024	ns	0.012	ns	0.042	ns
Hilsenhoff Family-Level Biotic Index		0.001	ns	0.024	ns	0.000	ns	0.055	*	0.001	ns	0.060	ns
GOLD Index		0.002	ns	0.056	ns	0.001	ns	0.021	ns	0.001	ns	0.019	ns
%Gatherers		0.000	ns	0.043	ns	0.003	ns	0.018	ns	0.005	ns	0.006	ns
%Scrapers		0.001	ns	0.007	ns	0.005	ns	0.052	*	0.001	ns	0.019	ns
%Dominant3		0.000	ns	0.028	ns	0.001	ns	0.015	ns	0.012	ns	0.019	ns
%Filterers		0.001	ns	0.020	ns	0.000	ns	0.006	ns	0.009	ns	0.001	ns
%Swimmers		0.000	ns	0.011	ns	0.002	ns	0.005	ns	0.018	ns	0.000	ns
%Tolerants		0.001	ns	0.010	ns	0.000	ns	0.017	ns	0.000	ns	0.013	ns
%Chironomids		0.001	ns	0.065	ns	0.001	ns	0.024	ns	0.000	ns	0.008	ns
%Clingers		0.002	ns	0.013	ns	0.001	ns	0.023	ns	0.004	ns	0.026	ns
Number of Sensitive Families		0.000	ns	0.005	ns	0.007	ns	0.116	**	0.018	ns	0.000	ns
Shannon-Weiner Index		0.000	ns	0.056	ns	0.000	ns	0.022	ns	0.016	ns	0.014	ns
Family-level Taxa Richness		0.000	ns	0.169	ns	0.000	ns	0.100	**	0.008	ns	0.016	ns
%Collectors		0.001	ns	0.044	ns	0.008	ns	0.065	*	0.056	**	0.004	ns

The "reference site" approach successfully identified distinct macroinvertebrate communities in the Potomac River basin (Astin 2006) and across the Chesapeake Bay watershed (Buchanan et al. 2011). A CART analysis of the Chesapeake data showed the strongest classification factor for a range of family-level biometrics was most often Level 4 ecoregion followed by elevation, latitude, and hydrogeomorphic region. The latter three factors are elements used to define ecoregions. Aggregation of the Level 4 ecoregions into "bioregion" classes maintained the ecoregion classification efficiency while increasing the number of reference samples in each class. Four bioregions underlay the Middle Potomac study area: Ridges, Valleys, Piedmont, and Coastal Plain (Figure 2). More than 80 percent of streams in the ELOHA dataset flow across two bioregions by the time they drain out of NEAHCS Class 2 watersheds. Nevertheless, a Kruskal-Wallis one-way analysis of variance found significant differences between the Ridges, Valleys, and Piedmont bioregions in 38 of the 42 biometrics tested ($p<0.05$).[13] Reference macroinvertebrate communities are similar within bioregion and show significant differences with communities outside their bioregion. Recall that this is a desired outcome of the stream classification step recommended by Poff et al. (2010).

Three other classification factors were investigated by Buchanan et al. (2011) because of their known or suspected influence on macroinvertebrate communities. Under the River Continuum Concept, stream size imposes a longitudinal gradient on community composition and trophic relationships (Vannote 1980). Season governs macroinvertebrate growth rates, life cycles, and behaviors through its control of temperature and sunlight. Karst geology could potentially influence macroinvertebrate communities through its distinct influence on stream water flow, physical habitat, and chemistry, particularly conductivity.

Within bioregion, the number of macroinvertebrate metrics responding to stream size expressed as Strahler order is directly related to sample size for Strahler orders 1-4 (Figure 13, left panel). In Chesapeake bioregions with the fewest reference samples (North Central Appalachian, n=26; Northern Appalachian Plateau and Uplands, n=28) only 6 or 7 of the 42 biometrics examined showed significant differences across Strahler order; in the bioregion with the most reference sites (Piedmont, n=222) 35 of the 42 metrics showed significant differences across Strahler order. Just one metric (%Shredders) showed a consistent change across Strahler order in all bioregions. Inherent variability in the biometrics, even under reference conditions, appears to confound macroinvertebrate relationships with stream order until sample sizes are large enough to overcome this variability and show statistically significant differences. The sample size effect indicates macroinvertebrate relationships to Strahler stream order are weak relative to other natural controls in first to fourth order streams, at least in the Chesapeake Bay drainage bioregions.

Evidence of seasonal controls on macroinvertebrate populations within bioregion is more pronounced and not as dependent on reference sample size (Figure 13, right panel). Of the three Middle Potomac bioregions, Ridges with its higher elevations and shorter growing season exhibited significant differences across season in 21 of 42 biometrics, whereas Valleys and Piedmont exhibited seasonal differences in only 14 and 16 of the 42 biometrics, respectively. Seven biometrics representing highly seasonal taxa (e.g., Diptera, Trichoptera) or taxa dependent on seasonal food sources (e.g., filterers, gatherers, net caddisfly) responded to season in all three bioregions. Twelve biometrics representing the range of macroinvertebrate community features show no season effect

[13] Habitat and water chemistry data needed to precisely identify reference stream sites in the Coastal Plain were not available at the time of this analysis, so the Kruskal-Wallis test could not be applied to the Coastal Plain data.

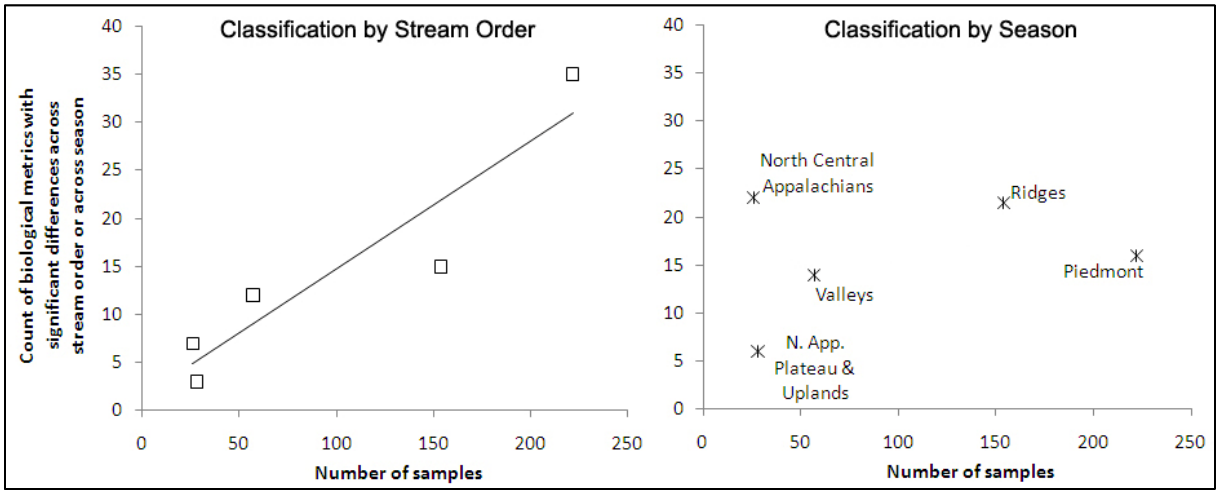

Figure 13. Number of biological metrics in each bioregion that show significant differences across first to fourth Strahler stream order (left panel) and across season (right panel), versus total number of samples from reference-quality sites.
Total number of family-level macroinvertebrate metrics tested is 42. (Figure 4 in Buchanan et al. 2011)

in any bioregion, including five taxa richness and diversity metrics, four pollution sensitivity metrics, two composition metrics, and one habit metric (%Clinger).

Karst geology is found in a broad swath through the Valleys bioregion in the Middle Potomac study area, and in a few areas of the Piedmont (Figure 4 in Appendix C). Comparisons of reference sample sites with and without karst geology in the Valleys bioregion indicated only two biometrics respond significantly to karst ($p<0.01$). Proportions of clingers and Ephemeroptera are significantly higher in karst areas; the remaining 40 biometrics are not significantly different.

In summary, for the Chesapeake Bay watershed which includes the Middle Potomac study area, stream size, season, and karst are less important than bioregion as classification factors explaining natural variability in macroinvertebrate communities of streams and small rivers. Stream size and season have some influence, however, it is impractical to minimize natural variability in macroinvertebrate communities by splitting the ELOHA dataset into 64 stream classes (4 bioregions x 4 Strahler stream orders x 4 seasons), or even more classes if karst is also considered. Macroinvertebrate metrics that are not responsive to one or more of the natural environmental factors would be needlessly split and the number of all samples in many stream classes would be very low. Even if similar classes are merged, only a few would have sample sizes adequate for developing FA-E relationships. Only bioregion was used to classify streams in the ELOHA dataset.

Biometric scoring

To avoid stream classification altogether, one can employ a scoring technique that takes into consideration each sample location's bioregion, stream order, season, and karst geology and converts the sample's biometric values to a common scale of low to high status. Such a scoring approach was developed in Buchanan et al. (2011) for the Chesapeake Bay bioregions. Percentiles of the distribution of each macroinvertebrate metric's values at reference sites were used to create bioregion-specific scoring thresholds for each metric. Within each bioregion, careful selection of the scoring thresholds avoided or minimized the effects, if any, of stream order, season, and karst. Metric scores could then be directly compared across the entire Chesapeake region.

The gradient of possible values for each biometric ranges widely in the study area, from least-like reference (degraded) to most-like reference. The narrower distributions of biometric values at independently identified reference and degraded sites typically overlap, creating a middle range of indeterminate values. A percentile in the tail of the reference distribution of biometric values (T percentile)—often the 25th percentile for biometrics that decrease with disturbance and the 75th percentile for biometrics that increase— is a threshold that most effectively separates the indeterminate values into "more like reference" and "more like degraded" groups. Values in the latter group, as well as those with clearly degraded values, receive the lowest score on the scoring scale. The remaining biometric values are further divided with the 50th percentile of the biometric's reference distribution (M percentile). Values above the 50th percentile for biometrics that decrease with disturbance (and below the 50th percentile for biometrics that increase with disturbance) are most different from biometric values found at degraded sites and receive the highest score on the scoring scale, along with a status of "good." (To increase resolution, this highest scoring range can be further divided to create a "good" and an "excellent" status.) Values between the T and M percentiles receive an intermediate score and a status equivalent to "fair." The T and M scoring thresholds for the biometrics included in this study are presented in Table 8.

In summary, the use of biometric scores rather than values in the MPRWA obviates the need to split the biological data into stream classes. All the biological data associated with the ELOHA watersheds spread across the study area can be merged into a single data pool once the metrics have been scored. The large size of this pool strengthens confidence in the resulting FA-E relationships.

5.2.5. Flow Alteration Assessment

The purposes of the basin-wide hydrologic alteration assessment were to identify where flow alteration has occurred in the basin and the physical stressors associated with the alteration. The drivers of hydrologic alteration evaluated as part of the MPRWA include land uses, impounded waters, withdrawals, and discharges.

Flow alteration is the percent difference in a particular flow metric between baseline and current conditions in a given watershed, as simulated by the hydrologic model for the ELOHA watersheds. This report section describes the spatial distribution of alteration found in the Potomac basin flow metrics and correlates them with the watershed characteristics driving the changes. A discussion on limitations is also presented.

Watershed characteristics

Watershed characteristics that are adjusted between the baseline and current scenarios to simulate hydrologic alteration include withdrawals, discharges, impoundments, and land uses. A brief description of each is provided below; however, a complete description of the ELOHA watershed characteristics, including maps of their spatial distribution, is provided in Appendix G. Details on the associated data sources are available in Appendix C.

The current model scenario includes withdrawals and discharges from the year 2005. Withdrawals and discharges are not simulated in the baseline scenario. Simulated withdrawals include only those taken from surface waters due to limitations in the groundwater withdrawal dataset and in the

Table 8. Bioregion-specific thresholds used to score macroinvertebrate family-level metrics. M%ile is the 50th percentile of the biometric distribution at independently identified reference quality stream sites; T%ile is a percentile in the tail of the reference distribution closest to values associated with degraded quality stream sites. For biometrics that respond to degradation by increasing (pos), values greater than T%ile score 1, between T%ile and M%ile score 3, and less than M%ile score 5. For biometrics that respond to degradation by decreasing (neg), values less than T%ile score 1, between T%ile and M%ile score 3, and greater than M%ile score 5. See text for more detail.

		Piedmont		Ridges		Valleys	
Biological Metric Name	**Resp.**	**M%ile**	**T%ile**	**M%ile**	**T%ile**	**M%ile**	**T%ile**
ASPT modified index	pos	4.2	4.6	3.5	3.7	4.1	4.4
Beck's Index	neg	9.0	7.0	13.0	10.0	9.0	6.9
Number of Ephemeroptera Families	neg	3.0	3.0	4.0	3.0	4.0	3.0
Hilsenhoff Family-Level Biotic Index	pos	3.63	4.54	3.64	4.05	4.10	4.70
GOLD Index	neg	0.919	0.804	0.827	0.793	0.827	0.675
%Chironomids	pos	3.25	6.31	9.29	11.80	7.53	10.78
%Clingers	neg	85.64	83.83	70.82	62.21	67.8	60.08
%Collectors	pos	52.71	71.02	54.93	54.93	66.67	74.18
%Dominant3	pos	63.14	69.89	60.47	69.13	65.45	70.50
%Ephemeroptera	neg	35.10	21.94	26.83	13.51	29.33	18.97
%EPT	neg	72.24	48.12	71.94	68.42	64.94	50.94
%Filterers	neg	30.14	18.62	17.25	17.25	23.20	20.00
%Gatherers	pos	16.92	39.20	34.44	34.44	37.72	45.52
%Scrapers	neg	19.16	10.62	11.06	3.37	14.41	7.02
%Swimmers	neg	10.45	4.36	10.73	4.59	10.74	6.19
%Tolerants	pos	3.23	12.30	10.77	12.48	9.14	17.60
Number of Sensitive Families	neg	7.0	6.0	9.0	7.0	6.0	5.4
Shannon-Weiner Index	neg	2.170	1.920	2.261	1.990	2.086	1.878
Family-level Taxa Richness	neg	15.0	14.0	16.0	13.25	15.0	13.0

hydrologic model. There are 253 simulated surface withdrawals in the study area (Figure 14). The withdrawals are spatially distributed such that only 115 of the 747 ELOHA watersheds have any amount of modeled withdrawal. Further, a total of 143 point source discharges are simulated in the current scenario (Figure 15). These discharges are located in 82 of the ELOHA watersheds.

There are 16 modeled impoundments in the current scenario (five in Virginia, four in West Virginia, four in Maryland, one in Pennsylvania, and two that are located along the Maryland-West Virginia border). Only 15 of the ELOHA watersheds contain some amount of simulated impounded waters. Impoundments are not simulated in the baseline scenario.

Current scenario land uses are those represented in the model from the year 2000. Baseline land uses adjust the percent forest to be a minimum of 78 percent. If, under current conditions, a watershed has higher than 78 percent forest then the percent forest is not adjusted for baseline conditions. Percent impervious cover is also adjusted to a maximum of 0.35 percent.[14] All other land use categories were maintained in their original, current scenario proportions, but were adjusted to maintain the total watershed area. A complete description of the land use adjustment utilized to model baseline conditions is available in Appendix D. The land use changes resulted in a small increase in urban areas across much of the study area from baseline to current conditions, with larger increases in the WMA. Agriculture increased from the baseline to current scenario across most of the basin, with the largest increases occurring in the Monocacy, Antietam, Conococheague, and Shenandoah watersheds. Corresponding to this increase in urban and agricultural areas, much of the basin had a decrease in the amount of forest cover between baseline and current conditions.

Spatial distribution of flow alteration

The spatial distribution of alteration in selected flow metrics between the baseline and current scenarios can be found in Figures 16 – 19. The figures are grouped by the flow range of the metrics. A complete definition of each flow metric is available in the supplemental tables. A discussion of the spatial distribution of hydrologic alteration found in these metrics follows.

High flow metrics include high flow index MH21, high flow duration DH17, high pulse count, and 3-day maximum (Figure 16). High flow index MH21 decreases over much of the basin, with focused areas of increasing values. The most extreme decreases in the high flow index MH21 are located in the WMA. A similar spatial pattern is found in the high flow duration DH17 metric. Both of these metrics measure duration of high flow events. High pulse count, driven to a large extent by the number of rainfall events, was somewhat less sensitive to landscape changes. Much of the basin exhibits zero percent alteration in this metric and only those watersheds with greater than approximately 1-2 percent impervious surface area, large withdrawals, and large discharges deviated from baseline levels. The 3-day maximum, representing the highest annual magnitude of flow, decreases relative to baseline levels through most of the South Fork of the Shenandoah watershed, the Conococheague, and through most of the central portion of the basin – regions which tend to be agricultural and/or underlain by karst geology but which also have increasing development. The metric increases moderately in the North Fork of the Shenandoah watershed, the Monocacy, and the North and South branches of the Potomac River, and increases steeply in the urbanized WMA and other urban areas. Multiple land and water uses appear to alter these high range flow metrics, sometimes in opposing directions, making it hard to generalize about net anthropogenic impacts across the Middle Potomac region.

The two mid-range flow metrics (median annual flow and August median flow) are similar in their overall distribution of alteration (Figure 17); however, there are some distinctions. For example, August median flow decreases, sometimes as much as 100 percent, in many of the WMA watersheds while a few of these same watersheds show slight increases in their overall median flows. August median flow decreases in a large section of the North Branch of the Potomac River while the overall median flow shows a slight increase. The competing influences of various land uses and withdrawals and discharges again make it difficult to generalize across the Middle Potomac region.

[14] The thresholds for baseline forests and impervious cover were determined utilizing a CART analysis, documented in Appendix D.

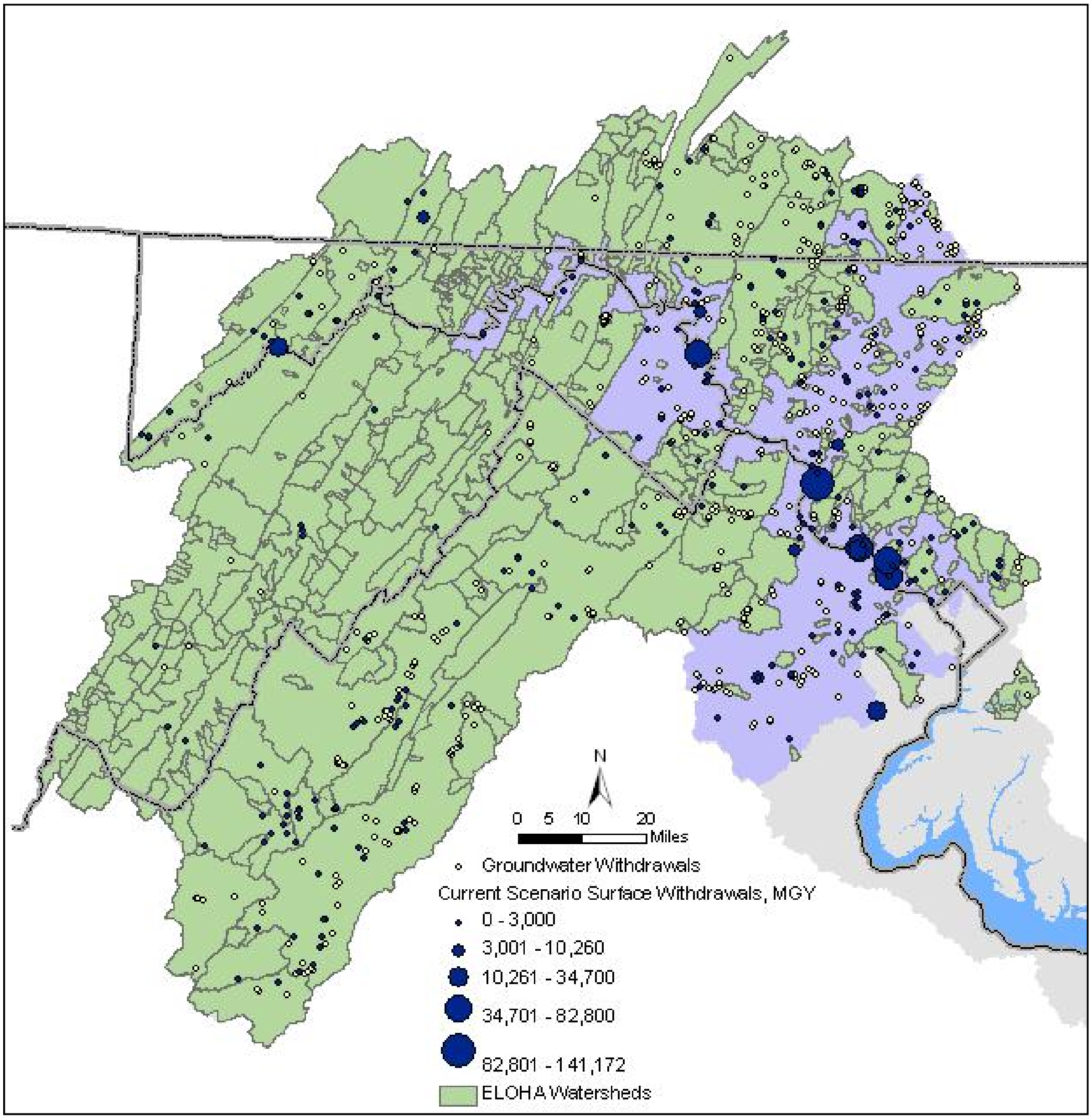

Figure 14. Withdrawal locations in the model simulated area.

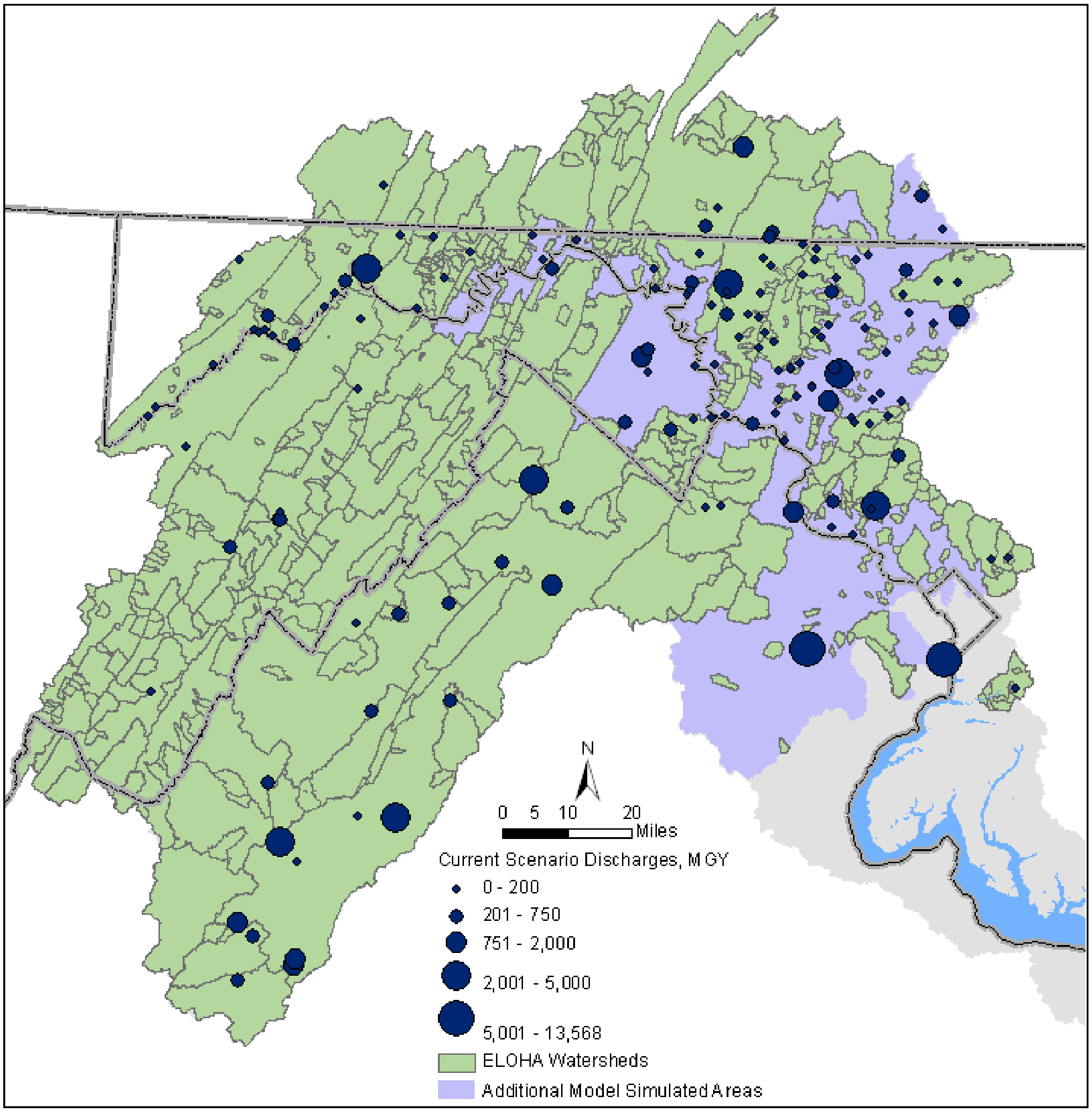

Figure 15. Location of current scenario discharges.

Flow metrics representing low flow conditions include low pulse duration, 3-day minimum, 7Q10, seasonal Q85, and low pulse count (Figure 18). Seasonal Q85, 3-day minimum, and 7Q10 represent low magnitude and for the most part show similar spatial patterns of decreasing levels over much of the basin. A large number of watersheds in the upper portion of the basin show no alteration in the duration of low pulses, while the majority of the basin experiences shorter periods of low flows. Some exceptions include (but are not limited to) the Conococheague, portions of the North Fork of the Shenandoah River, and Goose Creek – all showing increases in the duration of low pulses between the current and baseline scenarios. Similarly, the count of low pulses shows zero alteration in many watersheds in the upper portions of the basin, but in the swath of the basin from the Shenandoah through the Conococheague, an area underlain by karst geology, extreme amounts of negative alteration in the count of low pulses are noted. The WMA and scattered upstream watersheds, on the other hand, show increases up to 1900 percent in the count of low pulses.

Rate of change metrics include flashiness, number of reversals, rise rate, and fall rate (Figure 19). Overall, flashiness and the number of reversals increase with development over much of the basin. Flashiness is the frequency and rapidity of short-term changes in flow. Alteration in rise rate and fall rates show more spatial variation, with portions of the basin increasing while others decrease. It is evident in the comparisons that multiple anthropogenic factors are at play in altering the stream flow of each watershed in the Middle Potomac study area, sometimes in opposing directions. The net result of these factors leads to some sharp discrepancies between watersheds in how stream flow changes from baseline, and prevents making many generalizations for the entire study area. Watersheds need to be examined on an individual basis, to account for the combined impacts of different land and water uses.

Flow alteration associations with watershed characteristics

Understanding which anthropogenic factors drive the largest changes in stream flow can facilitate management efforts. An analysis was undertaken to evaluate how changes in watershed characteristics are correlated with the alteration in various flow metrics. A complete description of the results of this analysis is provided in Appendix G. Figure 10 in the appendix illustrates the relationships in the ELOHA watersheds between seventeen flow metrics and percent forest, percent agriculture, and percent urban land uses. Figure 11 in the appendix illustrates the relationships between the seventeen flow metrics and percent impervious surface cover. The findings are summarized below and in Table 4 of Appendix G.

Several watershed features are associated with the high range flow metrics. (1) Decreases in the duration of high flow events as measured by the high flow index MH21 and the high flow duration DH17 occur in many places in the Potomac basin and are correlated with urban areas. These changes were experienced across much of the basin as the region was converted from predominantly forested and agricultural to urbanized areas. (2) High pulse count shows relatively little alteration across the basin, however, increases are associated highly urban areas. This explains why the most extreme increases in high pulse count occur in the WMA. Decreases in high pulse count are associated with increasing withdrawals. (3) Increases in the 3-day maximum are associated with increasing urban area, again explaining why the most extreme positive alteration values are found in the WMA. Increasing agriculture is associated with decreases in the 3-day maximum, found in the Shenandoah watershed and other agricultural watersheds throughout the basin. Increasing withdrawals is another cause for decreases in the 3-day maximum. Keep in mind that multiple

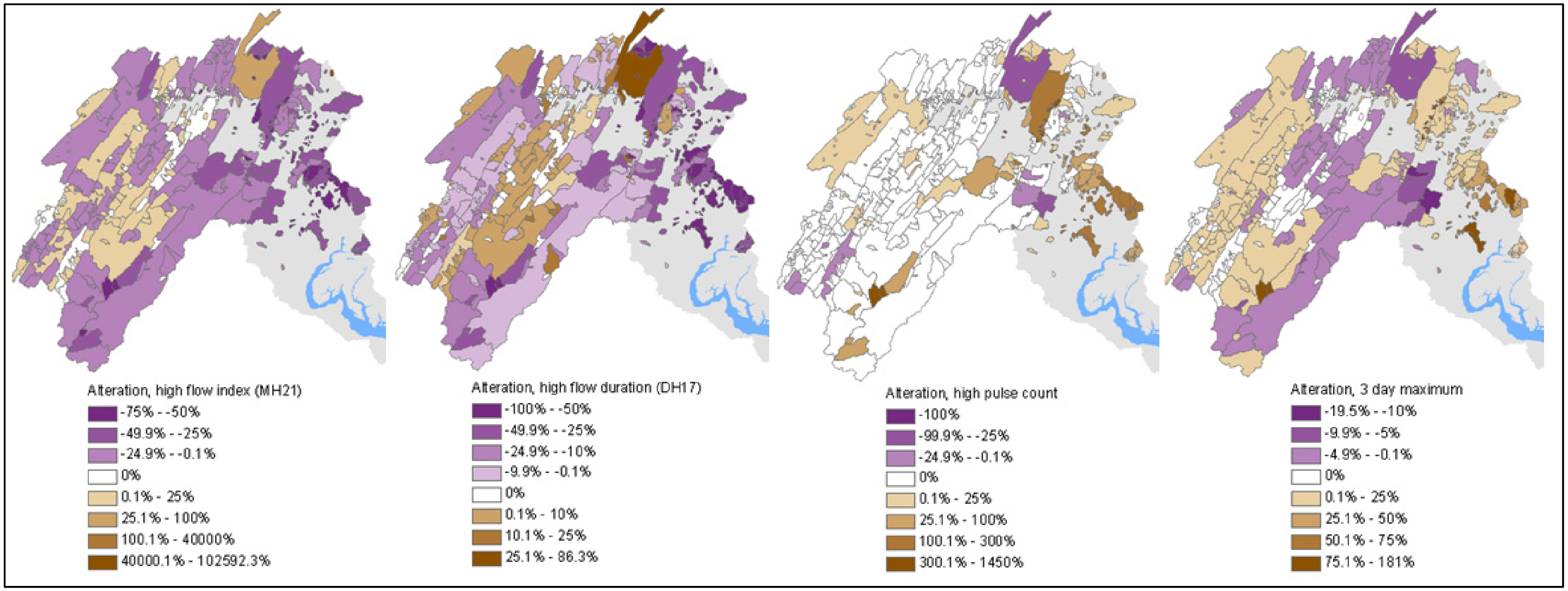

Figure 16. Alteration in select high-range flow metrics between the baseline and current scenarios. Alteration in each metric is calculated as (current-baseline)/baseline and is expressed as a percent. Negative alteration is shown in purple and positive alteration is shown in brown. Negative and positive are not indicative of “good” and “bad”, but rather indicate the direction of change from baseline conditions. More extreme alteration is shown in darker shades of either purple or brown. See Supplemental Table A at the end of the main report for flow metric definitions.

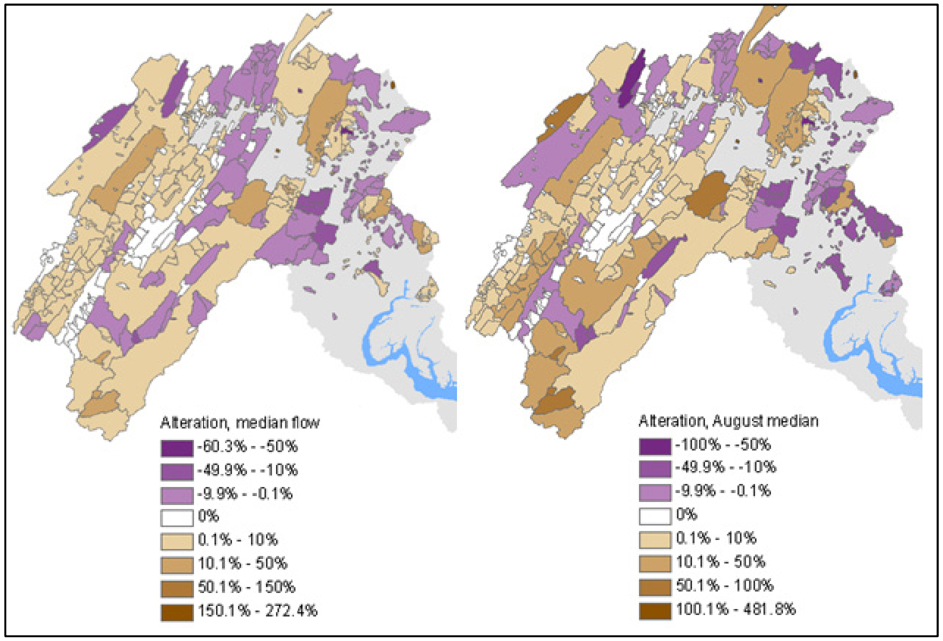

Figure 17. Alteration in select mid-range flow metrics between the baseline and current scenarios.
Alteration in each metric is calculated as (current-baseline)/baseline and is expressed as a percent. Negative alteration is shown in purple and positive alteration is shown in brown. Negative and positive are not indicative of "good" and "bad", but rather indicate the direction of change from baseline conditions. More extreme alteration is shown in darker shades of either purple or brown. See Supplemental Table A at the end of the main report for flow metric definitions.

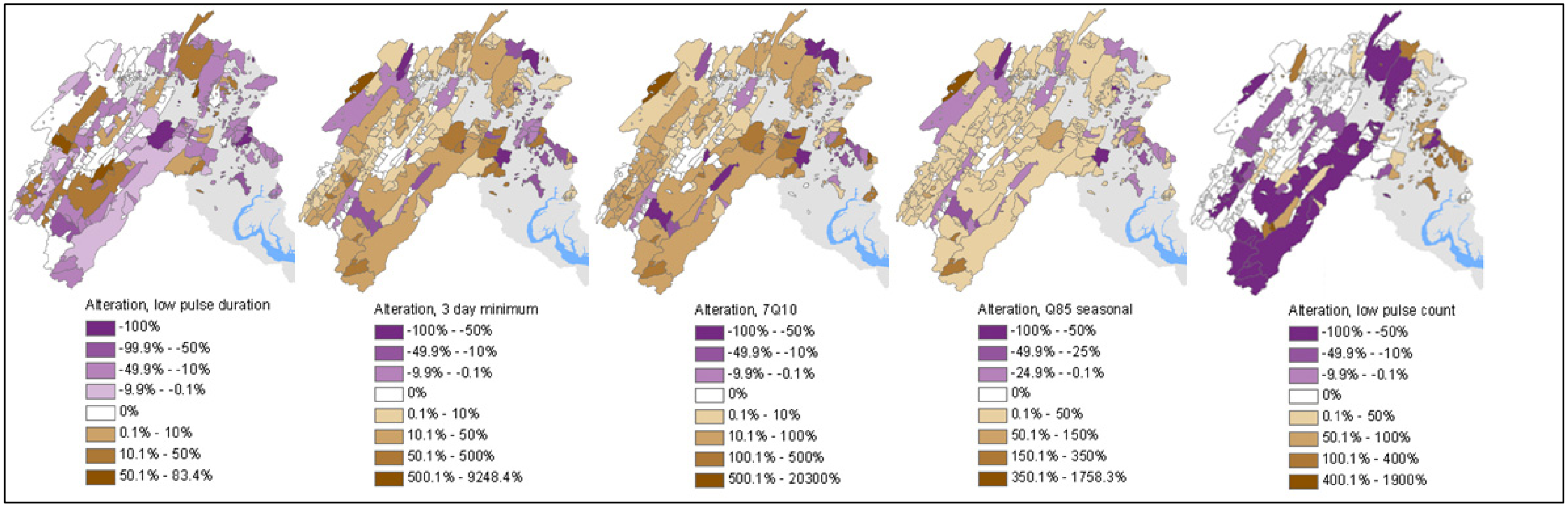

Figure 18. **Alteration between the baseline and current scenarios in select low-range flow metrics.** Alteration in each metric is calculated as (current-baseline)/baseline and is expressed as a percent. Negative alteration is shown in purple and positive alteration is shown in brown. Negative and positive are not indicative of "good" and "bad", but rather indicate the direction of change from baseline conditions. More extreme alteration is shown in darker shades of either purple or brown. See Supplemental Table A at the end of the main report for flow metric definitions.

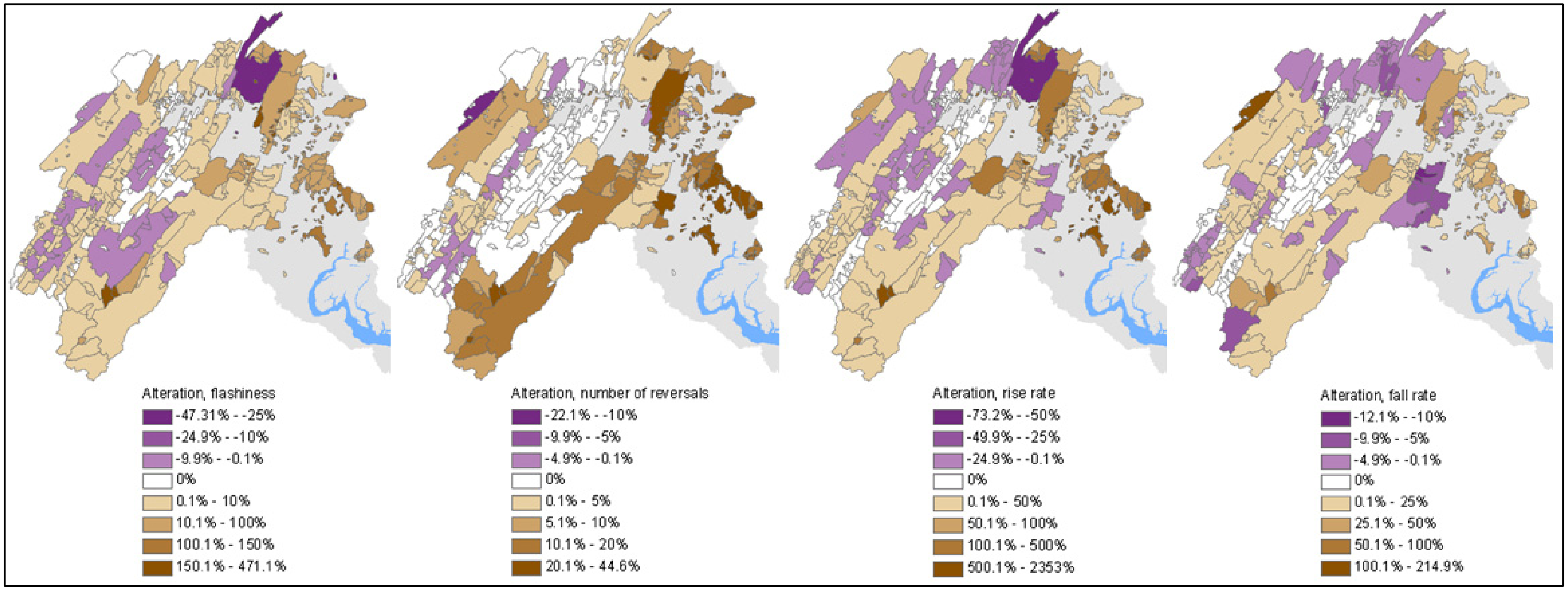

Figure 19. Alteration in select rate of change flow metrics between the baseline and current scenarios. Alteration in each metric is calculated as (current-baseline)/baseline and is expressed as a percent. Negative alteration is shown in purple and positive alteration is shown in brown. Negative and positive are not indicative of "good" and "bad", but rather indicate the direction of change from baseline conditions. More extreme alteration is shown in darker shades of either purple or brown. See Supplemental Table A at the end of the main report for flow metric definitions.

watershed characteristics are changing simultaneously. A moderate change in one direction from a particular watershed characteristic may be overcome by an extreme influence of another watershed characteristic in the opposite direction.

Changes in watershed characteristics also correlate with changes in mid-range flow metrics—median flow and August median flow. Lower levels of these two flow metrics occur in highly urban areas with greater than 10 percent impervious surface however the strongest deviations from baseline are related to discharges and withdrawals. The largest increases are associated with proportionally large discharges in the watershed; the largest decreases are associated with proportionally large withdrawals. Impoundments may also change median levels, sometime increasing and other times decreasing the levels. August median also appears influenced by the percent agriculture in the watershed. A possible explanation is the drop in usual evapotranspiration when forest is converted to agriculture. Reducing forest cover decreases the amount of water lost to evapotranspiration, and makes more rainwater available for streamflow.

The low magnitude flow metrics 3-day minimum and 7Q10 show responses similar to the August median (above). Large withdrawals decrease levels because less water is available in-stream; large discharges increase levels by adding water, albeit with different water quality. Levels of both flow metrics are lower in areas with greater than roughly 25-30 percent urban cover although this threshold is often confounded by withdrawals and discharges. On the other hand, increasing agricultural area increases low flows, particularly 3-day minimum because of lower evapotranspiration rates under crop cover (current scenario) when compared to forest (baseline scenario). Decreasing evapotranspiration makes more water available for streamflow. Simulated low flows below the major impoundments in the Middle Potomac study area suggest that flow management may serve to increase minimum flows.

The number of low pulses is zero in watersheds with very high discharges, but low pulses become more frequent in watersheds with large withdrawals and in highly urban areas. They appear unaffected by agricultural land cover. The duration of low pulses is shorter in highly urban areas but longer in watersheds with large withdrawals. Increasing the duration of low pulses can be moderately associated with increasing withdrawals and impoundments. The number of low pulses is reduced significantly in areas with the greatest increases in agriculture, the Shenandoah and Conococheague watersheds, for reasons provided above. The number of low pulses is most dramatically increased in the WMA, where the largest urbanization occurred between baseline and current conditions.

Metrics representing the rate of hydrologic change, including flashiness, number of reversals, rise rate, and fall rate, all increase sharply in highly urban watersheds. This explains why the most populated watersheds in the basin show extreme positive alteration in rate of change flow metrics. Increases in withdrawals also increase overall flashiness and fall rate; however, they slightly decrease the number of reversals. Discharges tend to reduce flashiness.

Limitations

The spatial assessments of hydrologic alteration show where hydrologic alteration has occurred across the basin, and the associations between alteration in individual flow metrics and anthropogenic activities suggest which factors are driving those changes. There are several limitations to this analysis, however. First, this alteration assessment was conducted utilizing simulated flows and available observed data in the study area and is, therefore, subject to the limitations of the model as described in the discussion model uncertainty as well as the limitations in observed data described in the conclusions of this chapter. One limitation stems from the locations and sizes of the ELOHA watersheds which were originally selected based on the locations of biological monitoring stations. The specific characteristics of these ELOHA watersheds bound the degree of alteration that can be described through this work. For example, a large number of ELOHA watersheds have experienced urbanization and/or agriculture, so relationships between land uses and flow alteration are more readily discernible. A limited number of watersheds show the influence of large impoundments, withdrawals, and discharges, making it difficult to discern the associated flow impacts of these anthropogenic activities. Results of some statistical analysis on the impacts of withdrawals and discharges on select flow metrics are presented in Appendix G and indicate the tenuousness of their flow metric associations. Finally, a large number of the ELOHA watersheds are less than 10 mi^2 and their simulated flows are difficult to confirm since most gaged watersheds are larger than 10 mi^2.

Another limitation to this assessment of hydrologic alteration is that groundwater withdrawals were not included in the hydrologic model due to the limited availability of groundwater data and current limitations in the hydrologic model. Over 70 percent of the permitted withdrawal locations in the study area are from groundwater sources. (The volume of the groundwater withdrawals, and therefore its percent of total withdrawals, is not well documented.) Although many of them are relatively small, the cumulative impacts of these groundwater withdrawals may be considerable and are worth evaluating in future efforts.

Utilizing the withdrawal and discharge data in combination, consumptive use estimates can be obtained for the ELOHA watersheds; however, the consumptive use values are potentially problematic for a number of reasons. As mentioned before, there are no groundwater withdrawals in the hydrologic model. Discharge amounts, however, include waters originating from ground and surface water sources. Due to limitations in the data, it is not possible to model only discharges associated with surface water withdrawals. In addition, the withdrawal and discharge datasets are not linked. That is, the dataset does not explicitly note which withdrawals are released to which discharge locations. A simple comparison of withdrawals and discharges for a particular watershed to estimate consumptive use could be erroneous without taking into account these linkages because withdrawals and associated discharges can be located in different watersheds.

Although there are numerous small impoundments in the study area, only 16 are included in the hydrologic model (Appendix D has a description of this methodology). This relatively small sample size limits the statistical ability to evaluate the hydrologic impacts of impoundments. Additional efforts to understand the impacts of impoundments could include incorporating additional dams in to the hydrologic model and/or selecting additional watersheds that are influenced by the 16 that are already included to increase the sample size.

Future flow assessment

The assessment of hydrologic alteration from baseline to current conditions demonstrated significant relationships between flow alteration and increases in agriculture and especially urban areas, which correspond to decreases in forest cover. The assessment made some limited conclusions about the influence of impoundments, withdrawals and discharges on flow statistics. The Middle Potomac watershed is projected to experience significant increases in human population between now and 2030, accompanied by land cover changes and increasing demands for water. Details are described in Chapter 4 and Appendix B.

Flow alterations projected for five different future scenarios were evaluated to identify areas of potential concern. In Appendix D, the details of developing the five future scenarios in the CBP HSPF modeling environment are described and the resulting hydrologic alteration in seven selected flow metrics are presented. The maps in Figure 20 illustrate the effects on four of the seven metrics of the projected changes from current conditions to the five future scenarios. Simulated flows for these future scenarios suggest that subwatersheds within the Potomac basin will be variously affected depending on the intensities of each natural or anthropogenic factor. The magnitude and direction of change of hydrology (future compared to current conditions) depends on the assumptions of each scenario, on changes in individual watershed characteristics (land and water use), and on what aspect of the flow regime (as measured by a specific flow statistic) is being considered. There was no regional pattern of flow alteration that applied to all scenarios and all flow metrics, and the impact on flow of each future scenario on different subwatersheds is subject to its own unique interpretation. The climate change scenario, for example, shows changes (from current conditions) in low pulse duration in both the positive and negative direction, but typically decreased high pulse count and median flow across the entire area, and decreased flashiness in most places except for areas projected to experience development. Portions of the basin are expected to experience increases in median flow under the DP1, DP2, and power scenarios resulting from a decrease in forest. Forest removal decreases the amount of water lost to evapotranspiration, making more water available for streamflow. Other portions of the basin under those same scenarios are expected to have a decrease in median daily flows due to urbanization, population growth, and an increase in net withdrawals. In general, the most extreme hydrologic alteration was found in the hot and dry scenario, followed by the climate change scenario.

The major conclusion of this analysis is that flow alteration projections for different future scenarios need to account for all the natural and anthropogenic factors at work in each watershed that significantly and often simultaneously alter flow, sometimes in competing directions. Figure 5 lists many of these factors. Despite similar intensities or spatial distributions in one factor, differences in other factors in otherwise comparable watersheds can change streamflow in divergent ways, eventually leading to differences in flow regimes. Drafts of the maps presented in Figure 20 were presented in the February 2012 webinar and are discussed in more detail in the notes associated with the presentation slides (Appendix I).

5.2.6. Development of Flow Alteration-Ecology Relationships

From the initial set of 256 flow metrics and 51 family-level macroinvertebrate metrics, 24 flow metrics and 20 macroinvertebrate metrics were selected as candidates for development of FA-E relationships. They are listed in two supplemental tables at the end of this report. An important criterion was representation of major components of both the flow regime and macroinvertebrate community without much redundancy. Other considerations included: (a) the model's accuracy in reproducing observed flow metric responses to natural and environmental factors, (b) flow metrics that show strong relationships to land/water uses, (c) professional judgment based on literature pertaining to flow alteration effects on biological metrics, some of which is cited in the upcoming section on possible mechanisms underlying FA-E relationships, and (d) flow and macroinvertebrate metrics commonly used by state agencies in the Potomac River watershed.

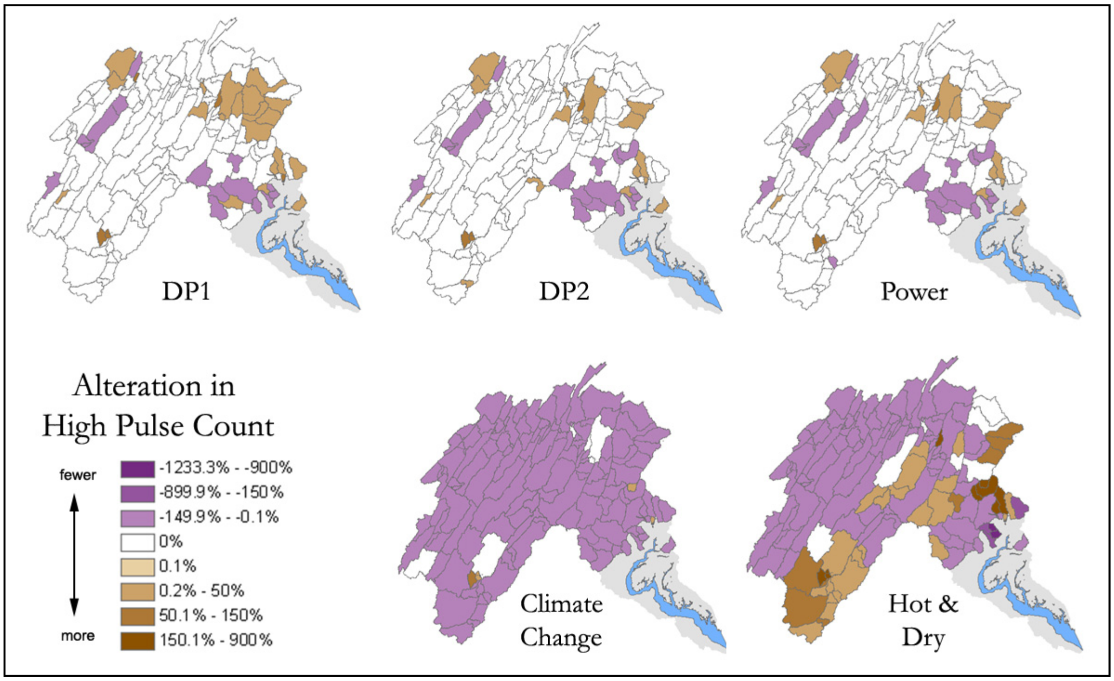

Figure 20a. Future alteration from current conditions in high pulse count under the five future scenarios, displayed spatially by HSPF model river segment.

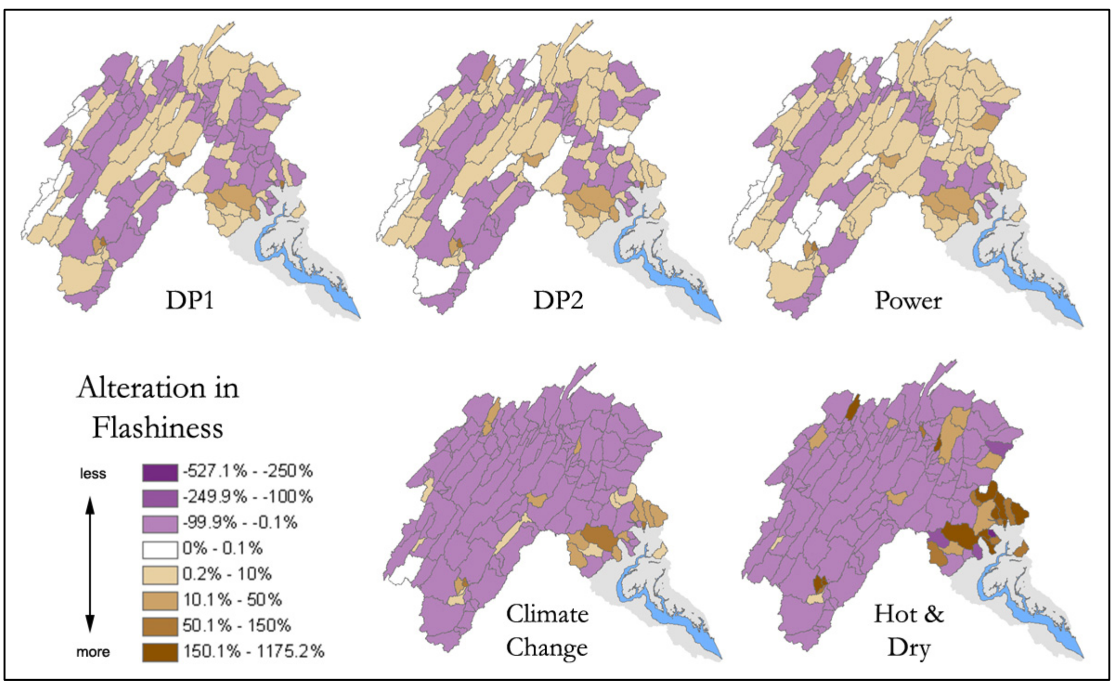

Figure 20b. Future alteration from current conditions in flashiness under the five future scenarios, displayed spatially by HSPF model river segment.

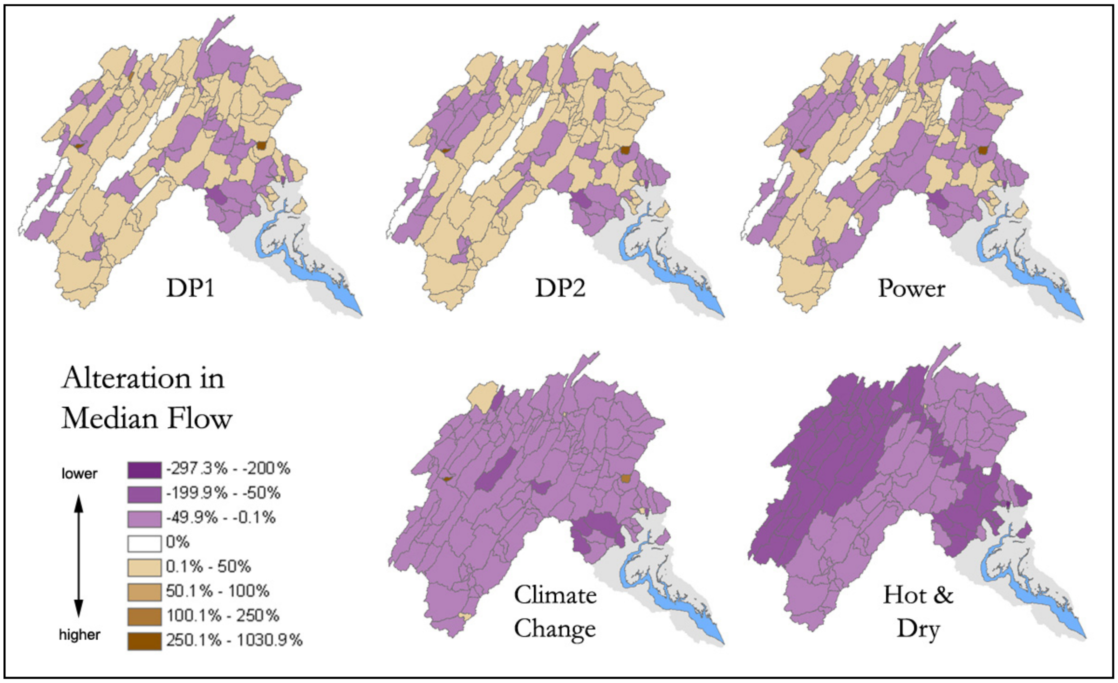

Figure 20c. Future alteration from current conditions in median flow under the five future scenarios, displayed spatially by HSPF model river segment.

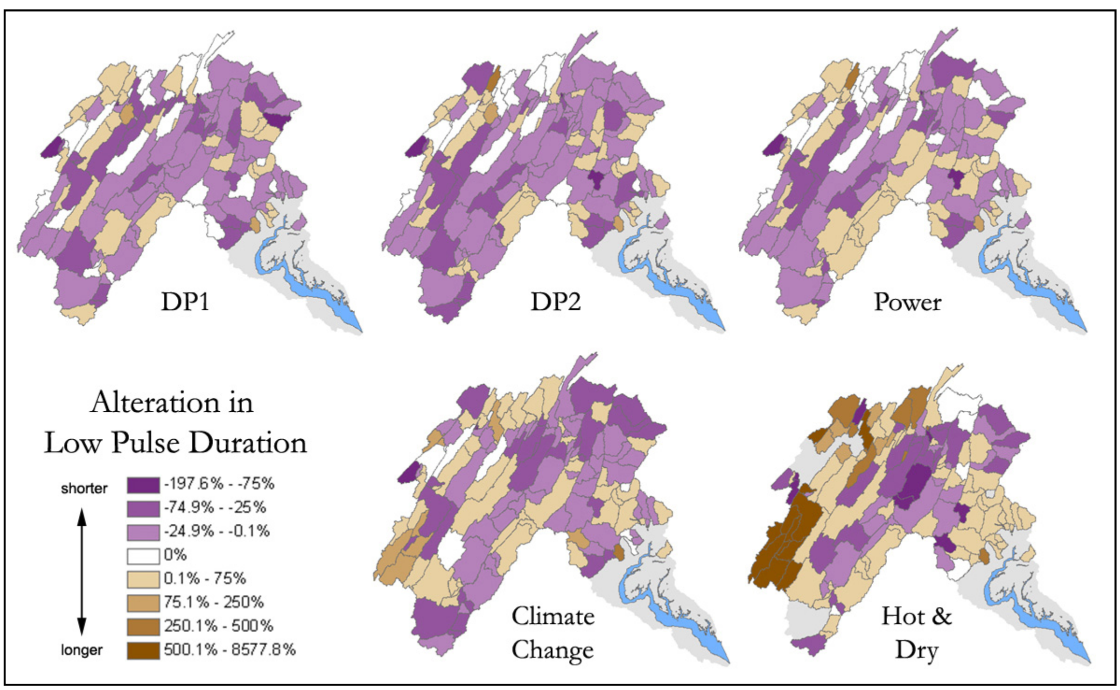

Figure 20d. Future alteration from current conditions in low pulse duration under the five future scenarios, displayed spatially by HSPF model river segment.

Three methods were used to examine macroinvertebrate responses to flow alteration: Pearson correlations, quantile regression plots, and conditional probability plots. Each has its strengths and weaknesses (Table 9). This process continued to narrow the selection of biological and flow metrics.

Pearson correlations

The Pearson correlation method measures strength of the linear relationship between macroinvertebrate metrics and percent alteration in each flow metric. The objective was to identify flow metrics that, when altered, associate with strong biological responses. The Pearson method returns a correlation coefficient (r) value between +1 and −1; 0 indicates no relationship and ± 1 indicates a perfect relationship. A positive sign signifies both variables increase together and a negative sign signifies one variable decreases as the other increases. In this analysis, biometric values and not scores were used, so the results do not account for biological differences relating to bioregion and other natural factors ("Stream Classification and Biometric Scoring", above).

Table 10 presents color-coded results of the Pearson correlations. For biological metrics that decrease with increasing stress ("neg"), flow alteration that tends to shift away from baseline values in either the positive (brown) or negative (purple) direction relates to a decrease in the biological metric. For biological metrics that increase with increasing stress ("pos"), flow alteration away from the baseline in either the positive (purple) or negative (brown) direction relates to an increase in the biological metric. The darkest colors indicate the strongest correlation coefficients ($r > 0.45$) and represent good possibilities for developing FA-E relationships. The lightest colors indicate weaker relationships.

Almost all macroinvertebrate metrics correlated strongly with alteration in high magnitude flows, many of the duration and frequency metrics for high and low flow events, and flashiness and rise rate. The exceptions are %Collectors, %Filterers, %Clingers, and taxa richness, each of which correlated weakly with alteration in all of the flow metrics. None of the 20 biometrics correlated strongly with alteration in the median or metrics representing low magnitude flows, frequency of extreme low flow events, or fall rates.

If metric values from the current flow scenario are used rather than flow alteration percentages, the overall strength of the correlation coefficients diminishes and some of the relationships even disappear. Figure 21 illustrates for one flow metric, flashiness, why this happens. This flow metric is significantly affected by both watershed size and %karst (Figure 1 in Appendix E). Current scenario values of the flow metric reflect the influences of these two natural factors and the anthropogenic factors in the watersheds (Figure 21 top panel). Baseline scenario values reflect only the natural factor influences. In some watersheds, values of the flow metric are strongly influenced by the natural factors while in others they are not. The calculation of percent alteration in the flow metric, when each watershed's baseline value is subtracted from its current value and the difference is expressed as a percent of baseline, effectively removes natural variation from the flow metric value and leaves the variation due to anthropogenic factors (Figure 21 bottom panel).

Quantile regressions

Scatter plots that relate biological metrics to alteration in flow metrics, such as the bottom panel in Figure 21, show a lot of biological variability, even in watersheds where current flow conditions are essentially the same as baseline conditions (i.e., percent alteration equals zero). This is because flow alteration is only one of several factors affecting macroinvertebrate communities. The broad

Table 9. Methods used to investigate flow alteration-ecology relationships. Some of their strengths and weaknesses are also listed.

	What the method does	Strength	Weakness
Pearson Correlations†	Quantifies strength of flow alteration impacts on biometrics in the context of all other environmental factors affecting biometrics	• Does not require large dataset	• No control of natural variability in biometrics (i.e., data not classified by bioregion) • Linear regression crosses both negative and positive flow alteration • Relationship affected by other anthropogenic factors impacting biometrics
Quantile Regressions†	Quantifies best possible biological status that can be achieved as flow alteration increases or decreases away from baseline condition	• Other anthropogenic impacts on biometrics do not affect quantile regression much, if at all • Responses to negative and positive flow alteration are separated	• No control of natural variability in biometrics (i.e., data not classified by bioregion) • Quantile regression line may shift if water or habitat quality changes significantly • Linear regression • Requires large dataset
Conditional Probability Plots‡	Quantifies probability of biometric attaining a specific condition (e.g., a status of "fair" or better) at a given level of flow alteration in the context of all other environmental factors affecting biometrics	• Natural variability in biometrics minimized by bioregion classification and biometric scoring • Non-linear relationship (LOESS regression) • Responses to negative and positive flow alteration are separated	• Probability at a given flow alteration level may change if water or habitat quality changes significantly • Requires large dataset

†Uses biometric values
‡Uses scoring

Table 10. Pearson correlations between percent alteration in flow metrics and macroinvertebrate metrics.
See Supplemental Tables A and B for metric descriptions. Correlation coefficient values (r) are color coded. For biometric values that are *lower* in degraded conditions ("neg"): brown = as [flow metric] increases from baseline, [biometric value] decreases; purple = as [flow metric] decreases from baseline, [biometric value] decreases. For biometric values that are *higher* in degraded conditions ("pos"): brown = as [flow metric] decreases from baseline, [biometric value] increases; purple = as [flow metric] increases from baseline, [biometric value] increases.

Pearson correlation Dark purple: r > 0.45 White: r = -0.1 to 0.1 Dark brown: r < -0.45	Response to Degradation	1Day Maximum	3Day Maximum	Annual Mean	Median	Q85Seas	August median	Base Flow Index	1Day Minimum	3Day Minimum	7Q10	High Pulse Duration	High Flow Index MH21	High Flow Duration DH17	Flood Free Season	Low Pulse Duration	Extreme Low Flow Dur.	High Pulse Count	High Flow Frequency	Number Reversals	Low Pulse Count	Extreme Low Flow Freq.	Flashiness	Rise Rate	Fall Rate
BIBI	Neg																								
%EPT	Neg																								
%Ephemeroptera	Neg																								
# Ephemeroptera Families	Neg																								
#Sensitive Taxa	Neg																								
Family Hilsenhoff Index	Pos																								
ASPT Modified Index	Pos																								
%Tolerant	Pos																								
%Dominant3	Pos																								
%Chironomidae	Pos																								
Beck's Index	Neg																								
Gold Index	Neg																								
%Gatherer	Pos																								
%Collector	Pos																								
%Scraper	Neg																								
%Filterer	Neg																								
%Swimmer	Neg																								
%Clinger	Neg																								
Shannon Wiener Index	Neg																								
Taxa Richness	Neg																								

distribution of biometric values at a given level of flow alteration shows the combined impact of flow alteration and multiple other stressors. The quantile method applies a linear regression to the upper or lower boundary of a cloud of data points. The envelope created by the regression line represents the best possible biological status that can be achieved as flow alteration increases or decreases away from baseline condition.

Alteration in some flow metrics usually occurs in one direction in the ELOHA watersheds (section 5.2.5). For example, flashiness usually changes in a positive direction and high flow duration DH17 in a negative direction, meaning the watershed factors in the study area that alter flow tend to make streams flashier with shorter high flow periods. In the few instances where flashiness and low pulse duration changed in opposite directions, becoming less flashy with longer periods of high flow, some of the sites are associated with sizeable discharges. Alteration in the middle and low magnitude flow metrics occurs about equally in the negative and positive directions. These include the annual mean, median, Q85Seas, August median, baseflow index, and the 1-day and 3-day minimum. The occurrence and extent of flow alteration in positive and negative directions in the other flow metrics is discussed below and depends largely on the combination of flow-altering factors that are present in the ELOHA watersheds.

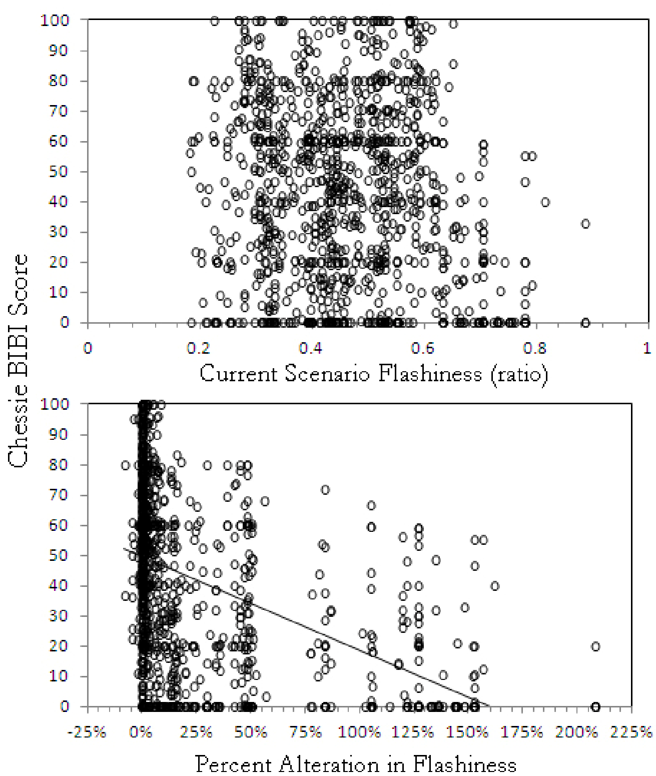

Figure 21. Chessie BIBI plotted against current scenario values of flashiness (upper panel) and against percent alteration in flashiness from baseline (lower panel). A significant relationship (solid line) is found only in the latter.

Quantile regression was used to determine if alteration in the positive or negative direction was statistically significant for combinations of representative flow metrics and macroinvertebrate metrics ($p<0.01$). Those with significant relationships were among the likely candidates for developing FA-E relationships. Again in these analyses, biometric values and not scores were used, so the results do not account for biological differences relating to bioregion and other natural factors. Details of how the quantile method was applied are described in Appendix H.

Macroinvertebrate metrics did not show strong, significant quantile regressions in either the positive or negative direction with the low magnitude flow metric (3-day minimum), frequency of extreme low flow, or median flow. Of the remaining flow metrics, significant quantile regressions occurred most often on the positive side for high pulse count and flashiness and on the negative side for the high flow index MH21, high flow duration DH17, and low pulse duration. The quantile regression results corroborate the Pearson correlation results above for the same metrics. They also indicate if there is an adequate and sufficient amount of data to discern a response to negative and positive alteration and justify development of FA-E relationships.

Conditional probability

The biological scoring approach (5.2.4) configures each metric so that values most like those in each bioregion's reference population receive high (fair or better than fair) scores and those most like those in the degraded populations receive low ("poor") scores. Scores are thus directly comparable across bioregion. The probability of a biological metric receiving a fair or better than fair score is then calculated for increments of flow alteration moving either in the positive or negative direction. Details of how conditional probabilities were calculated are described in Appendix H.

Conditional probability curves were developed from the proportion of samples scoring fair or better than fair in each flow alteration increment. An example illustrating positive flow alteration away from baseline is shown in Figure 22. The considerable scatter in the conditional probability points reiterates that environmental factors other than flow alteration impact biological communities, including recent weather events. Recall that biological values are single observations while flow alteration is calculated from baseline and current model scenarios covering a 21 year period (water years 1984-2005). The regression line and its confidence interval nevertheless show a strong tendency to decrease as the amount of flow alteration increases.

Some biometric – flow metric combinations show stronger relationships than others but there is a consistent pattern of decreasing probability of fair or better biological status as the amount of flow alteration increases. For many biometric – flow metric combinations, the decrease in the probability of fair or better status is quite steep at low levels of flow alteration. In the next section, the FA-E plots are individually examined and interpreted.

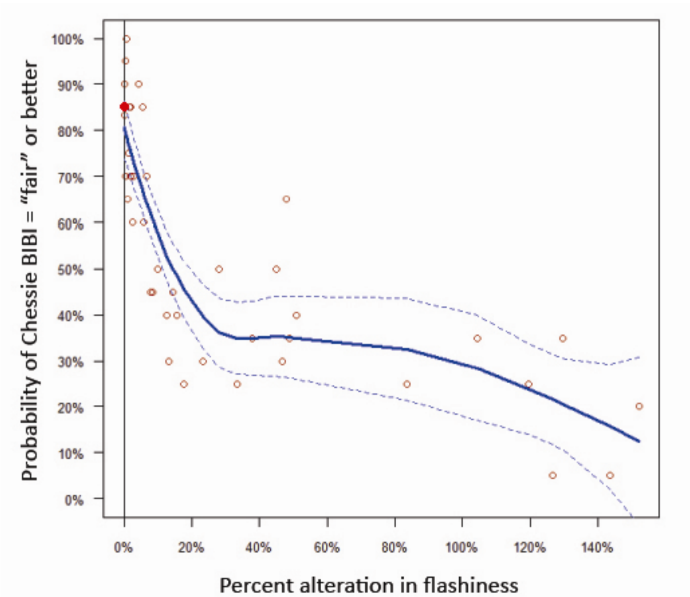

Figure 22. Illustration of a flow alteration-ecology (FA-E) plot.
Open red circles, conditional probabilities that biological status (Chessie BIBI) is "fair" or better for increments of alteration in Flashiness; solid blue line, Loess smoothed regression through the probabilities; dashed blue lines, 0.05 confidence interval around the regression line (the confidence interval around the data points is not shown); solid dark red circle on vertical line at 0 percent alteration, probability of "fair" or better status for just the watersheds meeting reference habitat and water quality criteria.

5.3. Findings for Stream Environmental Flow Needs: Interpretation and Use of Flow Alteration-Ecology Relationships

Each of the three methods described in the preceding section—Pearson correlations, quantile regression plots, and conditional probability plots—has limitations (Table 9) but could be used in specific circumstances to examine macroinvertebrate responses to flow alteration. The Pearson correlations and quantile relationships demonstrate that alteration in multiple flow metrics has a negative impact on biological health, but also have drawbacks that complicate their interpretation. First, the calculated correlations and regressions were linear. Examination of scatter plots suggests the relationships may not be linear. Second, most macroinvertebrate metric values vary naturally by bioregion and to a lesser extent by season and stream size. Some biometric values can qualify as reference in one bioregion but not in another, which can lead to ambiguous results when the data are pooled without consideration of these natural factors. These limitations could be overcome with (1) a larger dataset collected from a greater diversity of sampling locations within each bioregion, and (2) for each bioregion, an adequately broad range of watersheds experiencing flow alteration. Bioregion-specific FA-E curves could then be developed and used.

The conditional probability method requires a large dataset to produce meaningful results, but it removes much of the underlying natural variability through the use of biometric scores instead of values. Including scores of fair in the calculation reduced additional variability relating to season and stream size in this study (section 5.2.4). The use of LOESS regressions to establish the probability curves also removed the linearity imposed on the relationships in the two other methods. As discussed below (section 5.3.6), the conditional probability curves can in theory be shifted by non-flow changes to water quality and in-stream habitat conditions. At this juncture, however, the curves are most suited for developing FA-E relationship curves.

The final suite of macroinvertebrate and flow metrics used to establish FA-E relationships for the Middle Potomac study area are listed here:

Macroinvertebrate metrics	Flow metrics
Chessie BIBI (a multi-metric community index)	3-day maximum
%EPT (pollution-sensitive group)	High flow index MH21
FBI (Hilsenhoff family-level biotic index)	High flow duration DH17
%Chironomidae (pollution-tolerant group)	Low pulse duration
%Scraper (feeding group)	High pulse count
%Clinger (habit group)	Flashiness
SW (Shannon-Wiener diversity index)	

Each of the seven biometrics represents an important but different component or function of the macroinvertebrate community; each of the six flow metrics represents a particular section of the hydrograph and has a relationship to land or water uses in the watershed. The metrics are not necessarily the "best" ones for all uses but they serve the purpose of illustrating the array of FA-E relationships in the Middle Potomac study area. The 42 FA-E plots (7 x 6) are presented in Appendix H. All plots of flow metric percent alteration versus land use can be found in Figure 10 of Appendix G.

Factors that are typically responsible for flow alteration such as dams, withdrawals, and discharges are significant in some ELOHA watersheds but the amount of biological data available to associate with these factors is limited. Urbanization—and impervious surface area in particular—was found in this analysis to be the major factor altering flow regimes in most of the ELOHA watersheds and in the Middle Potomac study area in general. The final FA-E plots display the direction of flow alteration (positive or negative) that has adequate data and exhibits strong flow-macroinvertebrate relationships. Summarized below are the study's major FA-E findings.

5.3.1. Magnitude

All seven macroinvertebrate metrics related strongly to alteration in high magnitude flow metrics but none related significantly to alteration in median flow or any of the low magnitude flow metrics. As a result, FA-E relationships were only developed for high magnitude flows, represented by the IHA 3-day maximum metric. Simulated baseline values of the 3-day maximum are consistently lower than observed reference values, indicating the model underestimates high magnitude flows. However, the metric's baseline responses to natural factors (watershed size, gradient, karst) and current responses to anthropogenic factors paralleled those in the observed data (Appendix E). Simulated metric values appear to be internally consistent despite their displacement from observed values and were used to develop FA-E relationships.

Results from this study indicate that the 3-day maximum flow metric has increased in more than half of the ELOHA watersheds (i.e., current values higher than baseline values). Positive alteration and percent impervious surface area are very closely related after percent impervious area exceeds a threshold of about one to two percent. Positive alteration in 3-day maximum is also linked to percent urban area, but not as strongly. About a quarter of the ELOHA watersheds showed no alteration (zero percent); the remaining watersheds showed slight negative alteration (current values lower than baseline values) and are often heavily agricultural.

All seven macroinvertebrate metrics exhibit a much lower probability of fair or better status as 3-day maximum increases from baseline (Figure 23). The biometrics %Scrapers, Shannon-Wiener diversity index, and Chessie BIBI show the largest, steepest declines from baseline percentages of fair or better than fair status; %EPT and %Chironomidae show the smallest declines. The biometrics %Clinger, %Scraper, and %Chironomidae drop most quickly as alteration increases from baseline.

5.3.2. Duration

All seven macroinvertebrate metrics declined in relation to changes in the duration of both high magnitude and low magnitude flows. Three metrics were used to represent duration: the HIT high flow index MH21 metric, the HIT high flow duration DH17 metric, and the IHA low pulse duration metric. MH21 and DH17 are calculated differently. MH21 is the volume of the high flows (cubic feet) divided by median daily flow (cubic feet per day), where high flows are all those above the study period's overall median. DH17 is the average duration of events (consecutive days) above the study period's overall median. Low pulse duration is the median of the annual average number of days per year that flow persists below the study period's overall 10th percentile. All three metrics are well characterized by the project model.

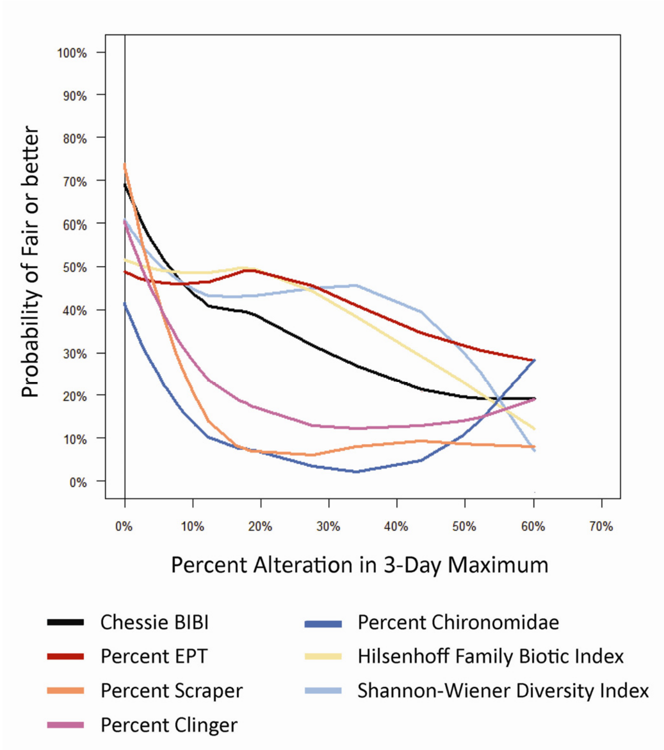

Figure 23. FA-E relationships for positive alteration (increase) in annual 3-day maximum flow.
The Loess smoothed regression lines of the conditional probability plots are shown. "Fair" status of each biological metric is defined by the bioregion-specific thresholds (T%ile) listed in Table 8.

Negative alteration from baseline indicates flow events have shorter durations. A little over half of ELOHA watersheds exhibit negative alteration in low pulse duration and approximately two-thirds exhibit negative alteration in the two high flow duration metrics. Negative alteration and percent impervious surface area are very closely related after percent impervious area exceeds a threshold of about 0.3 - 0.4 percent. Watersheds with substantially shorter low pulses but relatively unchanged duration of high flow metrics tend to be agricultural. A number of ELOHA watersheds with particularly large discharges no longer have low pulses, meaning their current flows never drop to the lowest levels experienced in the baseline. Many of these same watersheds show a corresponding increase in their high pulse counts. The Eagle Run watershed near Martinsburg, WV no longer experiences any low pulses and its entire simulated current flow time series is above the baseline threshold for high pulses. The watershed is estimated to have discharges equaling 101.5 percent of median flow.[15]

All seven macroinvertebrate metrics exhibit a lower probability of fair or better status as the duration of both high or low flow events decreases from baseline (Figure 24 and 25). The biometrics %Scrapers, %Clingers, and Chessie BIBI show the largest declines from baseline percentages of fair or better than fair status; %EPT again shows the smallest declines.

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[15] This watershed was not included in the Pearson correlations because it throws the result off so much.

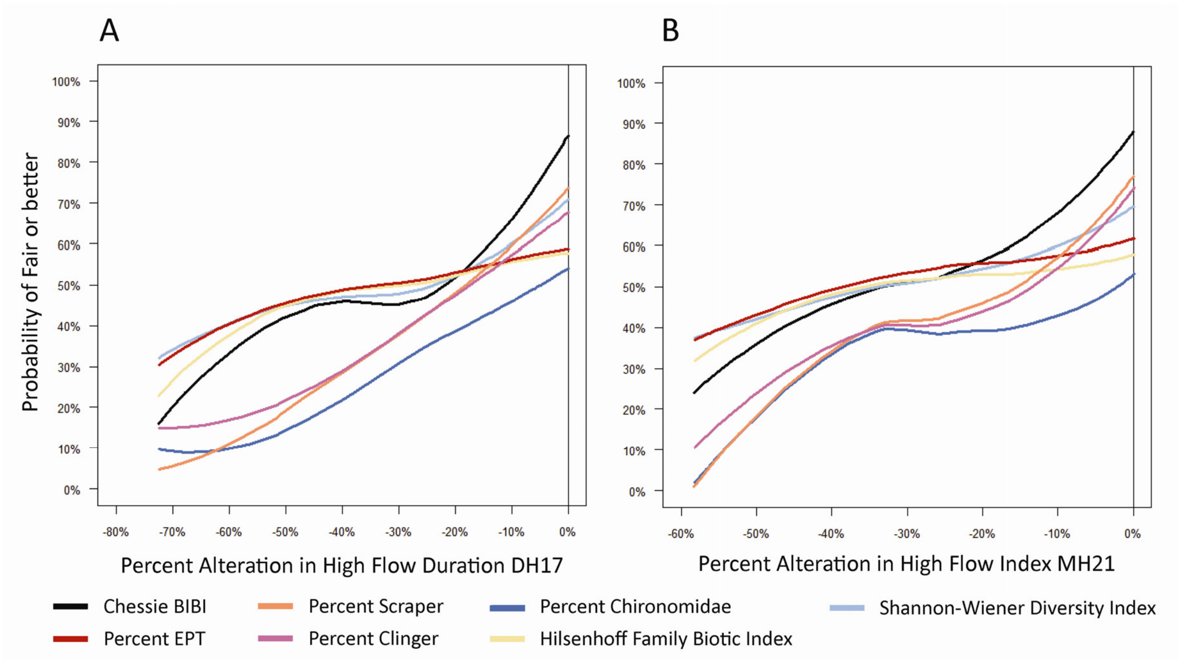

Figure 24a-b. FA-E relationships for negative alteration (decrease) in the high flow duration metrics DH17 (A) and MH21 (B).
See Figure 23 heading for details.

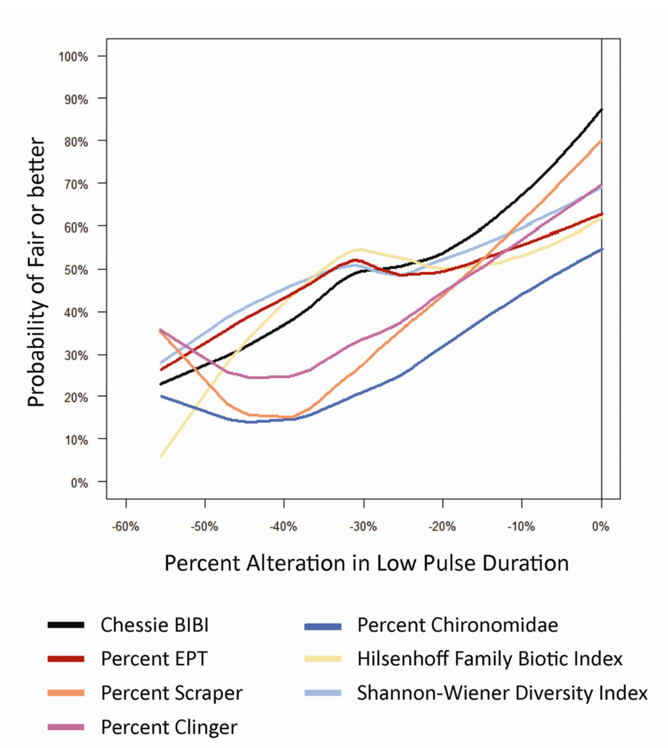

Figure 25. FA-E relationships for negative alteration (decrease) in low pulse duration.
See Figure 23 for details.

5.3.3. Frequency

In the ELOHA watersheds, all seven macroinvertebrate metrics were strongly related to alteration in the frequency of high pulses and to a change in the number of reversals in flow; it is difficult to discern any responses to altered frequencies of low pulses or extreme low flows. The final selection of FA-E plots was for the high pulse count metric. The model appears to have difficulty representing the effect of gradient on number of reversals, which is the reason this flow metric is excluded at this time. High pulse count is the median of the 21 annual averages of high pulse events (consecutive days) in the study period. Flows exceeding the study period's overall 90th percentile are classified as high pulses. Flow metric testing shows the model does an excellent job of representing high pulse count.

Roughly 60 percent of ELOHA watersheds show no alteration in high pulse count. Alteration, when it occurs, is most often in the positive direction, meaning an increase occurs in the number of high pulses. Positive alteration corresponds significantly with percent impervious surface area in the ELOHA dataset when impervious surface exceeds a threshold of about one percent. As percent impervious surface area increases the frequency of high pulses increases. The uncommon instances of negative alteration (fewer pulses) tend to occur in watersheds with large water manipulations such as discharges, withdrawals, and regulated impoundments.

All seven macroinvertebrate metrics exhibit a lower probability of fair or better status when the number of high pulse counts increases from baseline (Figure 26). The biometrics %Scrapers and Chessie BIBI show the largest declines from baseline percentages of fair or better than fair status, followed by FBI and the Shannon-Wiener diversity index. %EPT, %Chironomidae, and %Clinger show the smallest declines in response to more high pulses.

5.3.4. Rate of Change

In the ELOHA watersheds, all seven macroinvertebrate metrics were related to alteration in the amount of day-to-day change in daily mean flow. Flashiness, and specifically the Richards-Baker Index (Baker et al. 2004), is the flow metric representing rate of change. The absolute values of all day-to-day changes in daily mean flows are summed for the entire study period and divided by the sum of all the daily mean flows. The higher the index value the flashier the stream. Flashiness is well characterized by the project model.

Roughly three-quarters of ELOHA watersheds exhibit positive alteration from baseline in the flashiness metric. Positive alteration indicates an increase in the metric's value. The metric is most closely related to impervious surface in the ELOHA watersheds. Flashiness increases sharply from baseline when impervious surface exceeds a threshold of about one percent. Agriculture typically has no impact on the metric. Significant withdrawals can enhance positive alteration in flashiness; discharges in some circumstances reduce flashiness (negative alteration).

All seven macroinvertebrate metrics exhibit a much lower probability of fair or better status as flashiness increases from baseline (Figure 27). The biometrics %Scrapers and Chessie BIBI show the largest declines from baseline percentages of fair or better than fair status, followed by %Clinger, %Chironomidae, FBI, and the Shannon-Wiener Index. The %EPT metric showed the weakest response to flashiness.

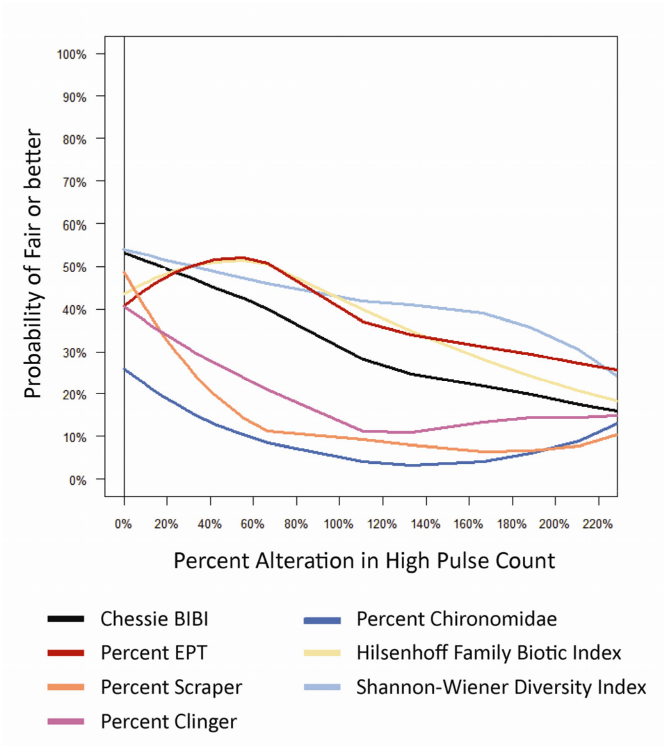

Figure 26. FA-E relationships for positive alteration (increase) in high pulse count. See Figure 23 heading for details.

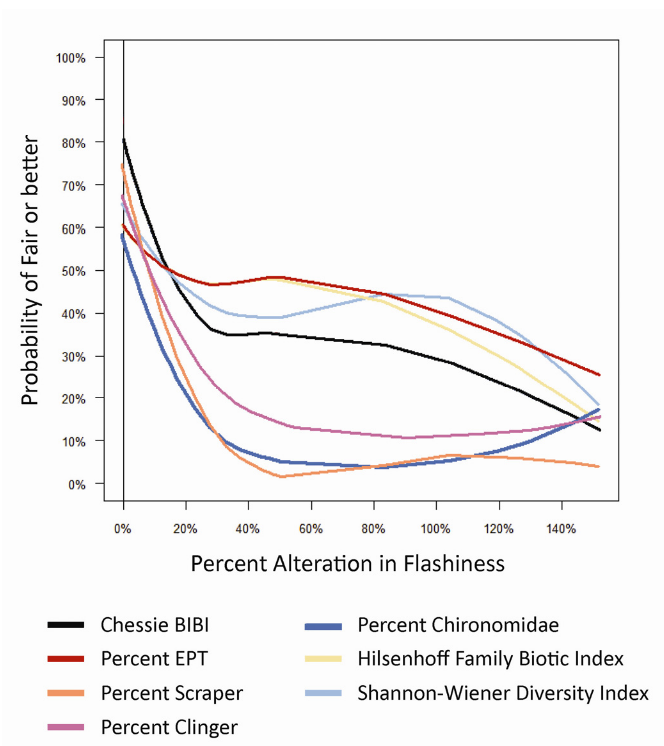

Figure 27. FA-E relationships for positive alteration (increase) in flashiness. See Figure 23 heading for details.

5.3.5. Possible Mechanisms Underlying FA-E Relationships

Annual low magnitude flows were represented in the study by five metrics. They are, in descending order:

August median > Q85Seas ≈ Baseflow Index > 3-day minimum > 1-day minimum

The absence of biological responses to negative alteration (lower magnitude) in the five annual low magnitude flow metrics above, as well as median flow and the inter-annual 7Q10 metric, appears to be real. Of the 1,155 records in the ELOHA dataset, negative alteration occurred in median flow in 43.6 percent of records, in August median in 45.8 percent of records, in the Maryland Q85Seas metric in 31.7 percent of records, in the Baseflow Index in 32.8 percent of records, in the 3-day and 1-day minima in about 38 percent of records, and in the 7Q10 in 14.7 percent of records. Thus, sample sizes were large enough to avoid spurious relationships. Negative alteration in the August median and Baseflow Index flow metrics was significantly related ($p<0.01$) to the Chessie BIBI, one of the more flow sensitive biological metrics, but the relationships explained little of the biological variation ($r^2<0.05$). No significant relationship between negative alteration and the Chessie BIBI was found for median flow or the other low magnitude flow metrics. Similar results were found in the quantile regression analysis. Negative alteration in the median and 3-day minimum metrics did not correlate significantly ($p<0.01$) with the Chessie BIBI, Shannon-Wiener Index, FBI, %EPT, %Chironomidae, %Scrapers, or %Clingers (Appendix H).

The lack of response by macroinvertebrate metrics to alteration in low magnitude flow metrics suggests their communities, as presently sampled by monitoring programs in the Potomac watershed, are not negatively impacted by existing levels of flow alteration in the magnitudes of normal or seasonal low flows. This result apparently is not an artifact of springtime sampling protocols. Greater than half of the macroinvertebrate data used in the study were sampled in spring and not in the annual low flow period. Spring sampling of macroinvertebrate communities will not necessarily reflect a single low flow event from the previous year; however, flow alteration that results in consistently higher or lower low flows could potentially interfere with summer reproductive timing and success in ways that could affect communities the following spring. This was not observed with the available data.

Recovery from extreme annual low flows may be swift among certain macroinvertebrate taxa that have acquired adaptations to periodic drought events (Humphries and Baldwin 2003). Multivoltine taxa may be able to recover from a seasonal low flow event through successive generations by the time a spring sampling occurs. Highly mobile taxa are also more likely to recover through rapid recolonization from refugia locations (Lake 2003). Additionally, taxa active in the spring may employ strategies that maximize reproductive success by avoiding summer drought impacts such as terrestrial eggs or drought-resistant egg or pupae life stages (Boulton 2003, Lytle and Poff 2004). Taxa that do not display adaptations for rapid dispersal or employ strategies to avoid seasonal drying events may show a lag in recovery. The diverse adaptations of stream macroinvertebrates to periodic dryness make them poor indicators of negative alteration in low magnitude flows.

The 7Q10, or lowest stream flow for seven consecutive days that is expected to occur once in ten years, was used in the study to represent inter-annual low flow magnitudes. Two low flow events typically meet the 7Q10 threshold in a 21-year study period such as this one. Since the study period overlapped the region's drought of 1999-2002, the low levels experienced during this drought would be reflected in the 7Q10 threshold. Macroinvertebrate metrics did not respond to alteration in the 7Q10. This result was anticipated. First, current and baseline 7Q10 flow levels as depicted by the project's model are approximately the same despite the fact that percent alteration ranges from -100 percent to upwards of 1,000 percent. In baseline scenarios of the ELOHA watersheds, the 7Q10 thresholds were on average 6.2 percent of median flows and ranged from zero percent (no flow) to as high as 26 percent. In current scenarios for the same watersheds, 7Q10 thresholds averaged 6.7 percent of median flows and again ranged from 0 percent to 26 percent with the exception of a few extremely high values associated with high discharges or large impoundments. Anthropogenic impacts for the most part do not appear to alter inter-annual low magnitude flows in the ELOHA dataset. Second, anecdotal evidence from the 1999-2002 drought suggests macroinvertebrates in the Potomac mainstem and larger tributaries were not negatively impacted by the extreme low flow levels (Appendix A). Finally, cross-year comparisons of BIBI scores did not reveal significant decreases in the drought period of 1999-2002 in summer or fall samples.

The combinations of anthropogenic factors present in the ELOHA watersheds tend to raise annual high magnitude flows above baseline levels, sometimes more than doubling peak daily flows. Alterations in annual high flows, represented in the study by the average annual 3-day maximum, inflicted consistent deleterious impacts on all seven of the macroinvertebrate metrics. The literature points to several possible mechanisms for these effects, including scour of periphyton and organic material, catastrophic accidental drift, stranding, alteration of stream-bed habitat, and the indirect effects of poorer water quality (Bunn and Arthington 2002, Poff and Zimmerman 2010, Richardson et al. 2004, Robinson et al. 2004). The particular sensitivity of Scrapers to high magnitude flow supports the concept of periphyton scour as a driver of stress. The strong response of the multi-metric Chessie BIBI coupled with those in the pollution-sensitive metrics, pollution-tolerant metrics, and Shannon-Wiener Index of diversity indicates that overall community structure is compromised by larger annual high magnitude flows. The modest response of the %EPT metric may be due to a lack of sensitivity within the metric. Many taxonomic families and genera comprised the EPT metric. The loss of flow-specialist taxa may result in replacement by more tolerant and flow-generalist taxa, the net effect being little change in a %EPT metric. One such example could be illustrated among caddisflies; *Macrostemum*, a net-spinning caddis fly that constructs firm refugia cemented to benthic substrate would likely be tolerant of peak flows, while other free-living taxa that cling to epibenthic surfaces may be susceptible to dislodgement (Holomuzki and Biggs 2000).

The impacts on macroinvertebrate community status of high and low flow events that are shorter and more frequent, with faster rates of change in daily flow between events, are likely related and share underlying mechanisms. Flow metrics that express duration, frequency, and rate of change in the hydrograph are different in focus but linked by the events that shape them. In urbanized watersheds, the frequency of high flow events and their rates of change increase as hardened surfaces deliver more water more quickly to stream channels, while the duration of flow events decrease. In this study, all seven biometrics showed signs of stress in response to changing frequency, duration, and rate of change in flow. Several underlying mechanisms can be implicated to explain how macroinvertebrate communities, over time, become impacted by the combined features of more frequent and flashier flow events of shorter duration, including: catastrophic drift, displacement from habitat and stranding, and interruption of development or dispersal cues (Lytle and Poff 2004, Poff and Zimmerman 2010, Richardson et al. 2004, Robinson et al. 2004).

The %Scrapers and Chessie BIBI metrics demonstrate the most abrupt declines with alteration in duration, frequency and rate of change flow metrics; %EPT was overall the least sensitive. The sensitivity of the %Scraper metric can be explained by that group's reliance on periphyton food, which is washed downstream by scouring high flows. Scrapers have been found to demonstrate greater sensitivity to changes in both flow duration and magnitude in other studies (Kennan at el. 2009). In addition to bottom scouring, several other ecological mechanisms can be implicated to explain the flow sensitivity of macroinvertebrate metrics. Rapid changes in flow (flashiness) when combined with unstable bed loads can cause more frequent occurrences of "catastrophic drift" and overwhelm an invertebrate's ability to find refugia resulting in decreases in abundance and richness (Richardson et al. 2004). More frequent high flow events increasingly interfere with longitudinal dispersion triggers, cues for reproduction and development, and the likelihood of coinciding with a flow-susceptible life stage (Poff and Zimmerman 2010). More frequent disturbances do not allow flow-sensitive taxa time to recover and leads to changes in lotic community structure (Poff and Ward 1989).

5.3.6. Other Environmental Stressors

Although flow is sometimes considered the master variable (e.g. Poff et al. 2010) and even the primary predictor (Carlisle et al. 2010) of stream biological integrity, it is not the only factor stressing macroinvertebrate populations in the Middle Potomac watershed. As shown in all the quantile regression plots (Appendix H), poor biometric values can and do occur in streams with little or no flow alteration. Further investigation of these poor-performing streams usually uncovers the presence of other stressors such as low pH, high conductivity, low dissolved oxygen, nutrient enrichment, an altered stream channel, poor substrate, or an embedded stream bottom. When streams in the ELOHA dataset with documented high quality are analyzed separately from those with documented degraded quality, the effects of non-flow factors become readily apparent. An example involving the Chessie BIBI and flashiness is shown in Figure 28. Panel A consists of the subset of stream sites with documented high quality habitat and water conditions; panel B has all the ELOHA stream sites; and panel C consists of the subset of stream sites with known habitat and/or water quality problems. The 90th percentile regression line (red) trends downward in all groups as flow alteration diverges from baseline, indicating the limits on biological condition set by flow alteration. The 90th percentile regression line in the degraded group (C) is positioned lower than in the high quality group (A), reflecting the overall lower macroinvertebrate scores in the degraded group. The line also has a steeper slope. The 90th percentile regression line in the middle panel with all the ELOHA data (B) is intermediate to those in the high quality and degraded groups. One can infer from these graphs that if water quality and physical habitat conditions are significantly improved, biological scores will increase regardless of the level of flow alteration at the site. One can also assume that if water quality and habitat conditions remain the same at a site, increasing flow alteration will degrade the biological community.

Conditional probability curves similarly respond to significant water and habitat quality changes. The curves are displaced downward (e.g., there is a lower probability of "fair" or better status) when actions in the watershed increase the overall impact of the non-flow stressors such as pollutants or temperature but do not alter the flow regime. Ameliorating the impacts of non-flow stressors through water quality improvements and stream habitat restoration raises the conditional probability curves.

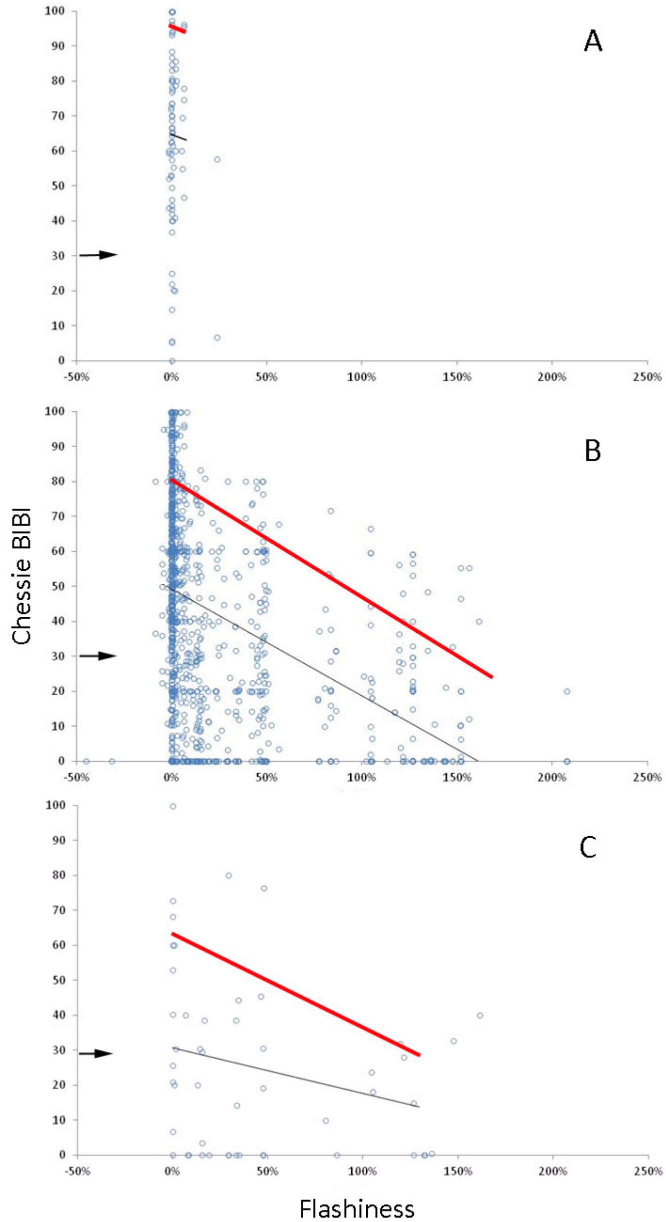

Figure 28. Chessie BIBI vs percent alteration in flashiness in high quality streams (A), all streams (B), and degraded streams (C) in the ELOHA dataset.

Red line: 90th percentile regression line. Black line: linear regression line. High quality streams (A): habitat scores ≥16 of 20 and pH ≥6 and DO≥5 mg/L and conductivity ≤300 μS/cm and turbidity ≤50 NTU. Degraded streams (C): water quality is poor (pH<6, DO<5 mg/L, conductivity >300 μS/cm, or turbidity >50 NTU) and/or physical habitat score ≤12 of 20. There are 78 data records in A; 1,155 in B; 51 in C. No evaluation was made of nutrients, toxic pollutants, or other factors that also impact macroinvertebrates. Chessie BIBI scores above 30% (arrow) are "fair" or better.

5.3.7. Using the FA-E Curves

If water quality and stream habitat conditions are not expected to change significantly, then the conditional probability relationships established in the preceding sections can be developed into tools for relating a proposed watershed change to a change in flow characteristics and ultimately a likely change in stream health. Figure 29 provides one illustration of how a proposed (future) increase in watershed impervious surface area can be evaluated for its potential impact on stream macroinvertebrate condition. The flow metric in this example is flashiness. The blue arrows in Figure 29A indicate a hypothetical watershed with a current condition of approximately one percent impervious surface area and minimal discharges, withdrawals, and impoundments. The proposed change in the watershed is projected to increase impervious cover to two percent (red arrows). Since the current condition is above the threshold for unaltered flashiness (yellow arrows), there is a strong likelihood that the increase will further alter flow. The red arrows indicate an increase from 10 percent to 20 percent alteration in flashiness can be expected.

If the current and future levels of flashiness are indicated on the corresponding FA-E plots, this information can be translated into an impact on the biological metrics. In Figure 29B, the horizontal axis is percent alteration in flashiness and the vertical axis is the conditional probability of one of the biological metrics, Chessie BIBI, having a fair or better rating. Because many factors affect biological condition, the amount of change in biology cannot be precisely estimated. However, based on the hundreds of samples in the ELOHA dataset, it is apparent that the probability of a Chessie BIBI status of fair or better declines as alteration diverges from baseline. Figure 29C-E demonstrate the relationship between flashiness and %EPT (Figure 29C), %Scrapers (Figure 29D), and %Clingers (Figure 29E).

In some states, numeric limits of flow alteration have been established and applied to FA-E plots relating fish community status to flow alteration (e.g., Michigan, Massachusetts). The identical approach can be applied to this study's macroinvertebrate FA-E plots if agreements on an acceptable level of macroinvertebrate community status—specifically, the probability of a fair or better score—are reached. The choice of measure or measures of macroinvertebrate status used to develop benchmarks can be flexible. However, a suite of macroinvertebrate metrics is recommended in order to outweigh uncertainty caused by the natural and normal variability found in biological communities and to remain sensitive to varying responses to stress among the community constituents. The diverse array of family-level macroinvertebrate metrics tested in this study showed consistent and predictable responses to flow alteration. Further analysis with more specific genus-level metrics should corroborate and perhaps refine these results but probably will not change them.

FA-E curves based on region-specific quantile regressions plots could prove useful to individual states in their 303(d) assessments. Each state in the Middle Potomac study area relies on a suite of macroinvertebrate metrics to decide if stream designated uses are impaired. Some of the family-level macroinvertebrate metrics analyzed in this study are included in these state assessments (e.g., percent EPT, Hilsenhoff FBI). If a sampling site's biometric values indicate impairment according to state thresholds and those values are positioned close to or above the 90^{th} percentile regression line when plotted at the stream's current level of flow alteration, chances are good that flow alteration is an important factor impacting the site's macroinvertebrate community.

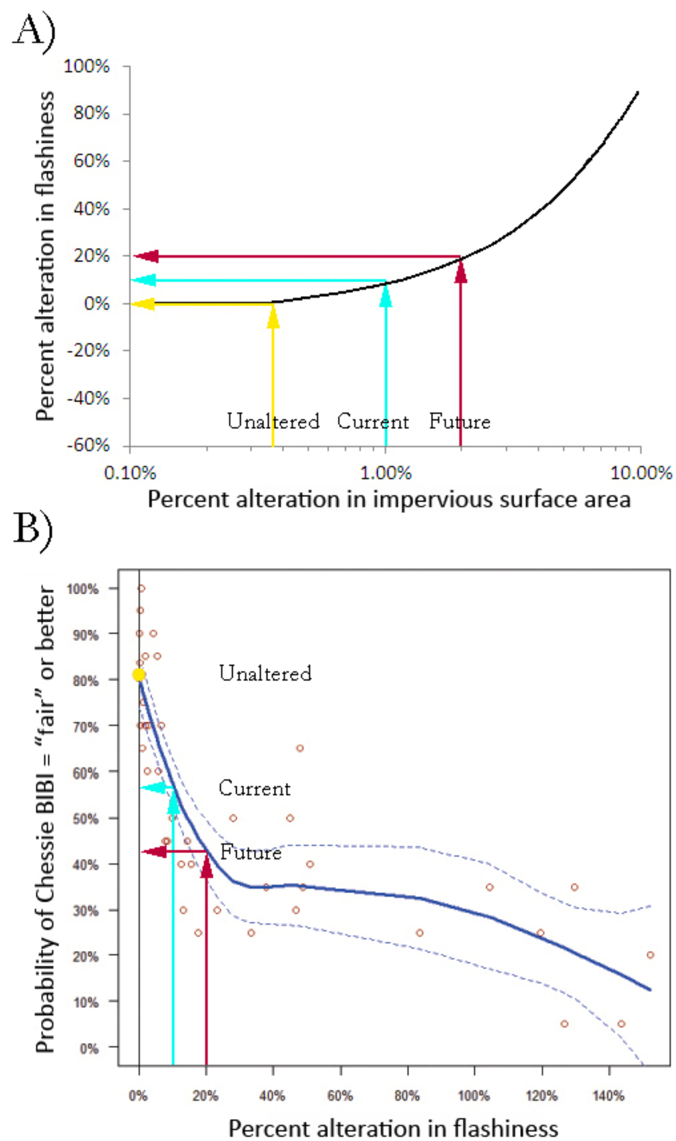

Figure 29a-b. An illustration of how watershed characteristics can be linked to flow alteration (A) and flow alteration linked to the Chessie BIBI, a biological response metric (B) in three scenarios: unaltered, current, and future.

Arrows indicate how values on horizontal (x) axis are associated with values on vertical (y) axis for each scenario. Solid black line (A), log regression relationship between percent alteration in flashiness and percent impervious surface; solid blue line (B), Loess smoothed regression through the conditional probabilities for increments of alteration in flashiness that biological status (Chessie BIBI) is "fair" or better; open red circles, the conditional probabilities; dashed blue lines, 0.05 confidence interval around regression line; solid yellow circle, Chessie BIBI probability of "fair" or better in high quality (reference) streams with no flow alteration.

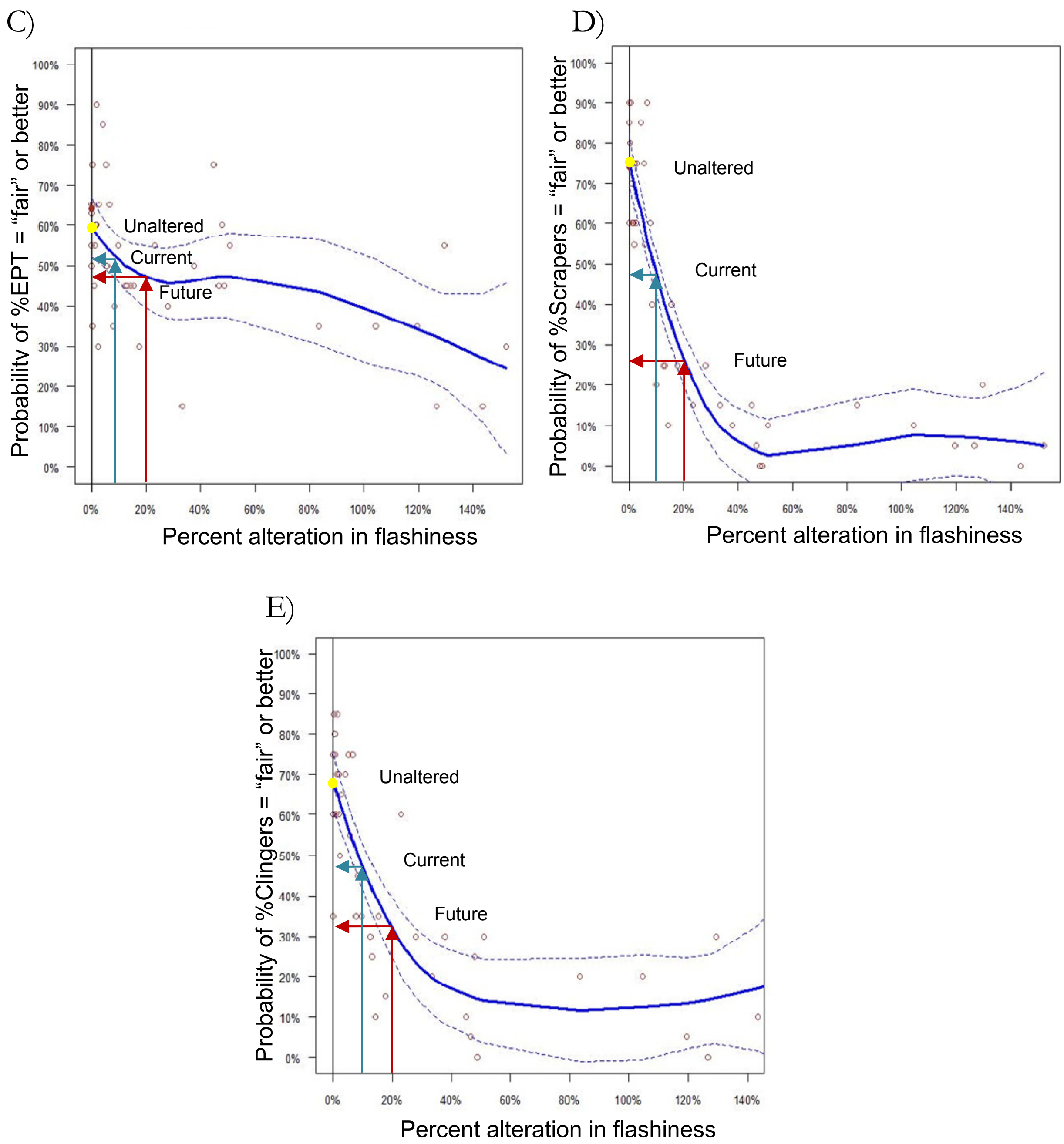

Figure 29c-d. **Additional illustrations of how flow alteration can be linked to biological response for C) %EPT, D) %Scrapers, and E) %Clingers.**

5.4. Discussion and Conclusions for Stream Environmental Flow Needs

The previous sections describe how the ELOHA framework was applied to streams and small rivers in the Middle Potomac study area for the purpose of building a scientific basis for defining flows that sustain healthy macroinvertebrate communities and the goods and services that humans derive from healthy stream ecosystems. In summary, recursive partitioning analysis of observed (gage) flow data suggested thresholds in various land and water uses that correspond to unaltered or baseline hydrographs. These thresholds were used to model baseline scenarios. Baseline and current scenario hydrographs were simulated for the watersheds of 747 biological sampling locations in the Middle Potomac. This hydrologic foundation yielded a diversity of flow metrics for each watershed and an estimate of alteration from baseline for each flow metric. Comparisons with flow metrics calculated from a Potomac-Susquehanna dataset of gaged flows identified the simulated metrics that most accurately simulated their counterparts in the observed data. Simulated metrics that poorly represented observed metrics and watersheds that did not appear to be accurately modeled were excluded. Anthropogenic causes of flow alteration were examined in the remaining 656 watersheds and FA-E relationships were generated from those watersheds' 1,155 macroinvertebrate samples. A simplified flow chart of the steps used to select the final sample locations, flow metrics, and macroinvertebrate metrics is shown in Figure 30.

Rigorous testing indicates the HSPF watershed model and WOOOMM routing module adequately represent baseline and current scenario flow time series and most of the flow metrics used in this study. Thus, one can reasonably estimate future alteration with flow time series generated with changes in land and water uses representing future conditions. One can also infer the impact of future flow alteration on stream macroinvertebrate status. The impacts of future flow alteration should be an important consideration, given that macroinvertebrate condition is a biocriterion for deciding stream impairment in all Potomac River basin states.

5.4.1. Land Use Change Thresholds of Potential Concern

With the exception of areas underlain by karst geology, the additive impacts of multiple land and water uses on flow appear to be accurately represented by the project's modeling approach (sections 5.2.2 and 5.2.3). Simulated flows plotted against increasing land use type closely parallel the corresponding graphs of observed flows (e.g., Figure 2 in Appendix E). Flow alteration due to projected changes in land and water uses can be estimated for individual watersheds, and the expected impacts of these changes on stream communities can assist in local and state planning and management activities. Specifically, planners and managers can minimize flow alteration impacts by limiting the amount of impervious surface area, requiring sustainable stormwater management practices, and prioritizing wetland and floodplain restoration and protection.

The plots of both observed and simulated flows suggest that significant alteration in flow metrics from a baseline condition is most often linked to increases in impervious surface and urbanization, and the concomitant loss of forest, in the Middle Potomac study area. In some watersheds, large differences in the quantity of withdrawals relative to discharges, and vice versa, also alter flows. A few large impoundments are located in the study area; however, their operations and subsequent impacts on flow are variable. The impacts of agricultural practices on flow as a whole appear to be comparatively benign. This finding contrast with the well-recognized impacts of agricultural sediment and nutrient runoff on water quality and livestock destruction of unfenced stream habitat.

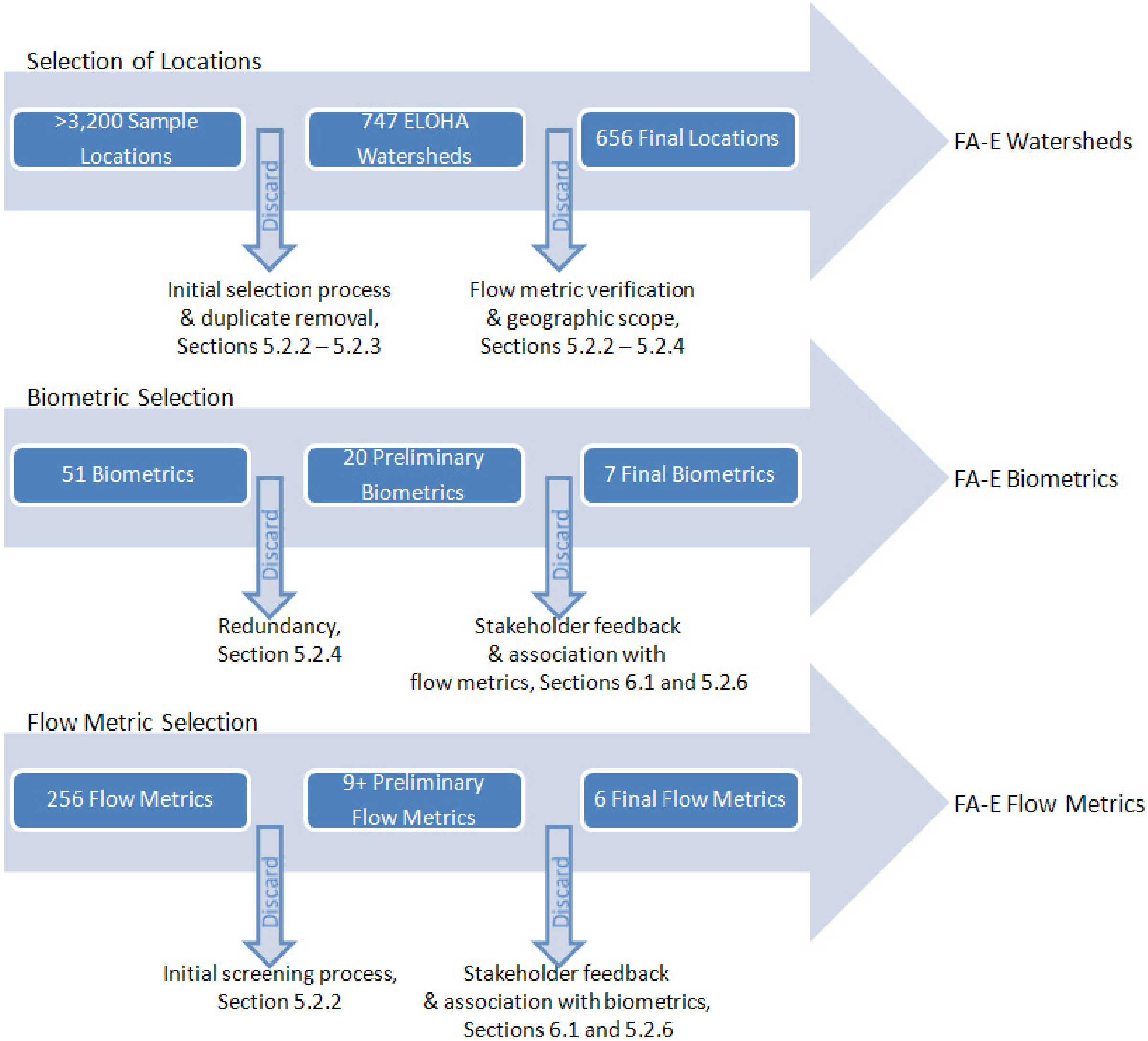

Figure 30. Simplified flow chart of the steps used to select the final sample locations, flow metrics, and macroinvertebrate metrics.

Careful examination of the watershed-to-flow alteration plots for the ELOHA dataset (Figures 10 and 11 in Appendix G) suggests thresholds exist specific to each flow metric and land use. Percent alteration in many flow metrics begins to diverge sharply from zero when land use exceeds 0.4 to 2.1 percent impervious surface or 5 to 15 percent urban land cover or when percent forest falls below 46 to 75 percent (Table 11, all watersheds). Thresholds may also occur in high flow duration metrics (DH17, MH21) when agricultural land cover exceeds 27 percent but other metric responses are weak, variable, and highly confounded by urban land use. Some variability may be due to (a) the fact that the "agriculture" category includes 16 sub-categories ranging from feedlot operations to pasture (Appendix D), and (b) the poor representation of groundwater withdrawals in the model (groundwater withdrawals are incompletely documented). Flow metrics with the lowest (most sensitive) thresholds in each land use type are the durations of high and low flow events and flashiness, which incorporates rise rate, fall rate, and number of reversals. Flow metrics with weak or no obvious thresholds are low magnitude flow metrics such as 3-day minimum, August median, 7Q10, and Q85Seas. These same low magnitude metrics, however, are strongly influenced by direct manipulations of flow volume such as withdrawals, discharges and impoundments. These results agree to some extent with Brandes et al. (2005) who found that increases in impervious area may not result in measureable reductions in base flow at the watershed scale.

Thresholds apparent in the watershed-to-flow alteration plots in Appendix G are strongly influenced by the mix of land and water uses in each ELOHA watershed. An analysis of selected types of watersheds avoids the additive effects of multiple land/water uses and refines the thresholds (Table 11, only forested and urban watersheds). In watersheds dominated by urban and forest cover and having little or no agriculture or surface water uses (impoundments, withdrawals, discharges), thresholds appear in all of the flow metrics except 7Q10. Increasing impervious cover with the concomitant loss of forest results in flashier streams, with shorter durations of both high and low flows, more reversals, faster rise rates and fall rates, and ultimately more high and low flow events. Thresholds for percent urban cover in these same metrics are approximately an order of magnitude greater than those for percent impervious surface, and flow metric responses to urban land cover are very similar which is not surprising considering imperviousness correlates closely with urban land cover in this group (r^2=0.94). For both imperviousness and urban cover, thresholds for flow metrics expressing middle and low annual magnitude flows are relatively high (6.8 – 16.6 percent and 33 – 68 percent, respectively), which suggests urbanization does not strongly affect middle and low flow magnitudes.

If watersheds are jointly dominated by agriculture and forest, and have little or no urban area or surface water uses, clear agriculture thresholds are only found for low magnitude flow and high flow duration metrics (Table 11, only forested and agricultural watersheds). Current levels of the low magnitude flow metrics were higher and durations of the high flow events were longer than baseline levels. This result suggests some water from rain or groundwater is being redirected to surface flows in agricultural landscapes. Differences between baseline (forested) and agricultural watersheds also may reflect lower evapotranspiration rates in pastures and croplands compared to forests. Metrics expressing frequency, rate of change, low flow duration, and inter-annual low flows (7Q10) in agricultural watersheds only intermittently exceed 5 percent alteration from baseline, suggesting other environmental factors are affecting flows. Metrics expressing high and middle magnitude flows in these watersheds show no thresholds. The comparatively benign effects of agricultural land cover on flow found this study indicates that a loss of forest to agriculture does not currently alter most flow metrics in the Middle Potomac study area.

5.4.2. Biological Thresholds of Potential Concern

Macroinvertebrate family-level metrics representing important aspects of community structure and function respond almost immediately when flow changes from the baseline condition. In some biological metrics, change is gradual; in others, change appears to be abrupt. Macroinvertebrate responses were examined with Pearson correlation, quantile regression, and conditional probability. Each method has strengths and weaknesses but all three demonstrate a degrading trend in the macroinvertebrate community metrics when flow changes sufficiently from the baseline condition. Degradation occurs regardless of whether alteration is in the increasing direction (baseline is higher than current) or decreasing direction (baseline is lower than current). Degraded stream communities are less resilient to natural, extreme events and to the multitude of anthropogenic stressors that accompany human activities. They are less capable of processing both natural leaf litter and human

Table 11. Apparent thresholds of potential concern for different combinations of land uses in the Middle Potomac simulated results.

Threshold identified when the 20-point moving average of a flow metric's percent alteration diverges ±5 percent from baseline and subsequently continues to diverge. Watersheds with impoundments, withdrawals, or discharges greater than one percent of median annual flow volume are not included in the analysis. Thresholds are rounded to whole numbers, except for percent impervious which is rounded to one decimal place. Key: ? = intermittent change occurs (change may be due to other factors in the watershed) and/or no consistent threshold is found. See text for details, and Appendix G Figure 10 for graphs. *Possible threshold at ~25-30 percent.

		Magnitude				Duration		Frequency		Rate	
		3-Day Maximum	Annual Median	3-Day Minimum, Q85Seas, Baseflow Index	7Q10	High Flow Duration (DH17), High Flow Index (MH21)	Low Pulse Duration, Extreme Low Flow Duration	High Pulse Count, High Flow Frequency	Low Pulse Count	Rise Rate, Number of Reversals	Flashiness
All watersheds in the ELOHA dataset (n=656)											
%Forest	<	46%	?	?	?	68% - 69%	67% - 75%	46% - 63%	56%	61% - 68%	57%
%Agriculture	>	?	?	?	?	27%	?	?	?	?	?
%Impervious	>	2.1%	?	?	?	0.4%	0.4%	0.5% - 1%	0.7%	0.4% - 0.7%	0.7%
%Urban	>	14%	?	?*	?*	5%	5% - 15%	7% - 12%	10%	7% -	10%
Only forested and agricultural watersheds (<0.35% imperviousness, <1% surface water uses, n=235)											
%Forest	<	?	?	77%	?	65% - 66%	?	?	?	?	?
%Agriculture	>	?	?	20% - 21%	?	30% - 32%	?	?	?	?	?
Only forested and urban watersheds (<5% agriculture, <1% surface water uses, n=152)											
%Forest	<	74%	20%	40% - 45%	?	81% - 82%	81%	77% - 82%	81%	81% - 83%	77%
%Impervious	>	2.0%	16.6%	6.8% - 10.7%	?	0.7% - 0.8%	0.8%	0.7% - 1.6%	0.9%	0.5% - 0.9%	1.6%
%Urban	>	16%	68%	33% - 55%	?	9% -10%	8% - 10%	9% - 14%	10%	6% - 10%	15%

pollutants. They provide less support to organisms higher in the food web, many of which are economically and recreationally important. In short, they are less capable of providing the goods and services that humans ultimately derive from healthy stream ecosystems.

It is important to ask whether flow alteration or a change in water quality or physical habitat is actually causing the observed biological degradation. As discussed above, many factors influence stream biological communities (Figure 5). Streams with little or no flow alteration can have sampling stations with poor macroinvertebrate status. The quantile regression and conditional probability plots in Appendix H reflect the 2000 – 2009 status quo in Middle Potomac streams with respect to existing levels of nutrients, toxic pollutants, physical habitat damage and alteration, disease, biological manipulation (e.g., fish stocking), and other non-flow impacts. Removing a few of the samples with water quality or habitat issues does not overtly change the quantile regressions, which seems to confirm that a flow alteration impact is present. However, the linear and quantile regressions can shift when stream quality differs considerably (Figure 28). Significant improvements in water quality and physical habitat conditions may counter flow alteration impacts to some extent, and conversely, significant water and habitat degradation may accentuate flow alteration impacts.

One weakness of the quantile regression method is it does not account for bioregion differences in what values of the biological metrics constitute a healthy, or reference, macroinvertebrate community. This weakness is avoided if quantile plots are done separately for each bioregion. Bioregion-specific FA-E curves based on the 90th percentile could then be developed. This approach is difficult to accomplish in the Middle Potomac region because human activities, and hence their flow impacts, differ by bioregion. For example, people prefer to build and farm on flatter land, which in the Middle Potomac is found primarily in the Valleys and Piedmont bioregions. The greatest amount of flow alteration in the Middle Potomac region presently occurs in the Piedmont. At this juncture, only the Piedmont has an adequate breadth of flow alteration and density of data points to begin development of bioregion-specific FA-E curves based on quantile regression plots.

Bioregional differences in the biometric values can also be avoided by scoring macroinvertebrate metrics against bioregion-specific scales such that communities in reference quality stream conditions receive equally high scores. This facilitates direct cross-comparisons of biological status and removes bioregion as an environmental factor causing variability. As shown in Figure 22, the effect of flow alteration on macroinvertebrate metrics under current conditions can be described by conditional probability curves, with confidence intervals around the curves. The confidence interval reflects spatial and temporal variability in the regression line and is caused by environmental factors unrelated to bioregion. This inherent variability is not static and, like the quantile regression lines, the conditional probability curves respond to significant recovery, remediation, and restoration activities, and conversely, rapid human population growth and urban development. If changes in water quality and physical habitat conditions in the near future are modest, the existing conditional probability curves should hold within their confidence intervals. Analysis of an expanded ELOHA dataset could begin to address the issue of the relative importance of water quality, physical habitat, and flow alteration.

Results of this study suggest it is reasonable to assume that (1) flow alteration will lower any stream's potential to achieve its best possible macroinvertebrate status, and (2) significant changes in other, non-flow stressors will make it difficult to predict exactly how flow alteration will impact biology. On this basis, simulated future scenarios that show flow altering from the baseline scenario or moving beyond existing or current scenario levels can be expected to degrade the macroinvertebrate community to some extent. The land use thresholds of potential concern in Table 11 can be used directly to determine if flow alteration is occurring or will occur in cases where the watershed meets certain criteria, i.e., forest and urban with little or no agriculture or water uses, forest and agriculture with little or no urbanization or water uses. Models such as the one used in this project or the proposed Computer-Based Evaluation Tool (6.2) may be more appropriate tools for determining the extent of future alteration in stream flow when watersheds have multiple land and water uses.

5.5. Technical Information Gaps, Research, and Analysis Needs

Data limitations and technical difficulties encountered while researching stream environmental flow needs for the Middle Potomac region identified information gaps and analysis needs. They are introduced at length elsewhere and summarized here.

1. Fish monitoring data collected with consistent, comparable methods

   Stream macroinvertebrates, which are typically dominated by relatively short-lived insect life stages, are most responsive to flow metrics that reflect alteration occurring on a regular basis. Their responses to extreme but infrequent events (extreme droughts, extreme floods) occur in the year of the event and then fade as successive generations recover. Fish are longer-lived and may be better indicators of alteration in these extreme flow events and perhaps alteration in summer low flows.

2. Groundwater withdrawals

   Additional information about groundwater is needed to improve the groundwater component of the HSPF model. Specifically, what aquifer is groundwater removed from and what the impact is of groundwater withdrawals on stream flow.

3. Flow metric analysis of a larger dataset of gaged reference watersheds

   Comparisons of flow metrics from gaged reference watersheds and simulated baseline conditions build confidence that the hydrologic simulations are accurately representing the natural effects on flow of watershed size, gradient, geology, etc. Presently, there are only 11 reference watersheds in the Potomac-Susquehanna gage dataset. The analysis should be expanded to include other Pennsylvania, West Virginia, and Virginia river basins adjacent to the Middle Potomac.

4. Flow metric analysis of more pairs of simulated and gaged watersheds

   Direct comparisons of gaged and simulated flow metrics build confidence that the HSPF model coupled with the WOOOMM routing module is accurately representing the multiple anthropogenic impacts on flow in diverse watersheds. Presently, flow metrics for only 53 watersheds have been directly compared. More gaged watersheds should be simulated for the purpose of direct pair-wise comparisons.

5. Flow metric analysis of small (<10 mi^2) watersheds

   Small watersheds are under-represented in the gage data, and are of most interest to local jurisdictions. The search for small gaged watersheds should be expanded to river basins adjacent to the Potomac. Comparisons of flow metrics from gaged and simulated small watersheds build confidence that the HSPF model coupled with the WOOOMM routing module is accurately representing the smallest watersheds.

6. Coastal Plain watersheds

The Coastal Plain physiographic region has experienced, and will continue to experience, significant impacts from agriculture and urbanization. It is also under threat of sea level rise. The Potomac River basin has a few Coastal Plain watersheds adjacent to its estuary. Determining flow alteration impacts on these watersheds would be best accomplished in the context of the larger, Mid-Atlantic region.

7. Karst watersheds

Karst geology underlies a broad swath of the Middle Potomac region which is expected to see some of the largest increases in urban development in the next 20 years. The simulated flows indicate that these watersheds behave differently than the rest in the Middle Potomac; hence, they show up as "oddballs." It is not known whether this is a good representation of reality or the consequence of a lack of observed data in karst watersheds for comparison. More observed data is needed to determine model efficiency in these karst regions.

8. Relative importance of water quality, habitat condition, and flow alteration in each bioregion

Analysis of an expanded ELOHA dataset could begin to address the issue of the relative importance of water quality, physical habitat, and flow alteration. The addition of watersheds with known flow alteration but documented good water quality would facilitate the analysis, especially in the Ridges and Valleys bioregions.

9. Enhanced groundwater model component

The HSPF model needs to be enhanced to allow it to simulate impacts of groundwater withdrawals on surface stream flow.

10. Impoundments

The Potomac basin is a relatively unregulated system, meaning there are relatively few impoundments in the basin. Sixteen impoundments were simulated as part of this study, including twelve that were not previously simulated in the Chesapeake Bay Program's HSPF model. This small sample size is problematic, however, in determining the impacts of impoundments on the flow regime. Additional efforts to enhance this understanding could include incorporating additional, smaller dams in to the hydrologic model and/or selecting additional watersheds that are influenced by the simulated impoundments to increase the sample size.

Chapter 6. Stakeholder Outreach and Implementation Options

The fourth and fifth components of the MPRWA project were, respectively, stakeholder participation and outreach, and development of implementation options. Stakeholder participation and outreach included construction of a website, a series of webinars, two in-person workshops, and Technical Advisory Group (TAG) meetings. Copies in PDF format of the webinar presentations, the streams and small rivers workshop materials, presentations, notes, and summary, and the TAG meeting materials and presentations are available in Appendix I. The large river workshop summary is included in Appendix A. Development of implementation options consisted of a literature review of Decision Support Tools from across the United States and a concept paper that scopes out a basin-wide comprehensive plan for the Potomac River basin. These documents can be found in Appendix J.

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6.1. Moving the Science into Management

The MPRWA scientific process yielded a quantitative understanding of the biological effects of hydrologic alteration, and associated these effects to watershed drivers such as land and water uses. Water resources decision-makers can utilize this information to manage watershed conditions to achieve desired hydrologic or biologic results. Case studies for utilizing ELOHA results for management purposes in Michigan and Massachusetts (Reeves et al. in review, Weiskel et al. 2010) were presented in the October 2011 webinar (Science to Management Applications, Appendix I). A list of case studies also is maintained by TNC.[16]

Management efforts, however, are dependent on governance drivers such as institutions, regulations, and policies, which often differ between political jurisdictions, making homogeneous basin-wide implementation difficult. To this end, a participatory process has been ongoing throughout the project to encourage communication with stakeholders across the basin. A description of these efforts is included below. Two products have been identified that may be useful in the implementation of the project findings -- a computer-based evaluation tool and a basin-wide comprehensive plan. The quantitative FA-E response curves can be implemented in a computer-based evaluation tool to assist managers in understanding the implications of various land and water management decisions. The results can also be utilized, along with other existing information, for planning purposes in a Potomac Basin Comprehensive Water Resources Plan. Development of these two products is outside the scope of the Middle Potomac River Watershed Assessment; however, preliminary evaluation and scoping were conducted.

[16] http://conserveonline.org/workspaces/eloha/documents/template-kyle

6.2. Stakeholder Participation

To encourage implementation of the MPRWA findings, managers and stakeholders have been included throughout the project. These efforts (documented in detail in Appendix I) include a website, a series of webinars, two in-person workshops, Technical Advisory Group (TAG) meetings, and correspondence with state and federal agencies. The outreach efforts were designed to inform stakeholders of the complex technical work as it was conducted. The benefits of stakeholder participation include enhanced understanding of the results and implications of the study, opportunities for feedback on the technical work, and modification of the study design to ensure development of the most appropriate tools and outcomes for implementation.

The project website[17] was designed to convey information to stakeholders and the general public regarding the MPRWA. Up-to-date information such as the webinar slides, draft reports, and workshop announcements were posted to the website to communicate project activities and outcomes.

The webinars allowed the technical team the opportunity to present methodologies and preliminary findings as well as incorporate stakeholder suggestions on the scientific analyses. The first webinar was held in September 2009 to introduce stakeholders to the project. Subsequently, a multi-part webinar series was conducted to describe the technical approach and associated results. The webinar topics for this series were: (1) overview of Potomac environmental flows project goals, outcomes, benefits, and audiences, (2) human uses of water: current and future demands and impacts on flows, (3) modeling stream flows: explanation of models and scenarios, and descriptive statistics for simulated flow scenarios, (4) developing FA-E response relationships part 1: data, variables, and methodology, (5) developing flow alteration-ecological response relationships part 2: what the relationships look like, dealing with data ambiguities, and interpretation, (6) from science to management implications, and (7) future scenarios. A final project wrap-up webinar was held in June 2012. The presentation portion of each webinar was approximately one hour followed by up to half an hour of discussion. The webinars were an integral part in building an understanding of the project so that the project team could obtain informed feedback. Copies of the webinars (PDF format) are available in Appendix I.

Two workshops were hosted in association with the MPRWA. The first workshop, held in September 2010, was the Potomac Basin Large River Environmental Flow Needs workshop. The second workshop, held in November 2011, was the Potomac Watershed Small Stream Environmental Flow Needs workshop. Both of these events convened a group of experts to review and provide feedback on the small and large river studies, utilizing the ESWM and ELOHA frameworks, respectively. These workshops provided an excellent forum for dialogue on the project methodologies, results, and conclusions. At the streams and small rivers workshop, for example, the technical team received and incorporated feedback on the types of flow metrics that are the most useful for management purposes and methods for conveying the findings in a meaningful way for managers. Participants at the large rivers workshop reviewed draft recommendations and their input is reflected in the final recommendations for Large River Environmental Flow Needs (Chapter 3). Complete compilations of feedback received from participants at the September 2010 large river and

[17] www.potomacriver.org/2012/projects/middle-pot-assess

November 2011 small stream flow needs workshops are provided as summary reports in Appendix A and I, respectively.

The TAG was established to provide critical feedback on the development of the flow alteration ecological response relationships. It was composed of experts in steam ecology, environmental flows, and watershed modeling. An effort was made to have state-level representation from all basin jurisdictions. The TAG met twice at ICPRB in Rockville, MD, in September and October 2011, leading up to the November workshop. The meeting materials are provided in Appendix I. All TAG members were invited to attend the November 2011 project workshop, where their expertise and knowledge of the project proved valuable in communicating with other stakeholders and providing thoughtful comments on the project.

Early in the study letters were sent to multiple federal and state agencies to convey initiation of the study and request their participation. All basin states and several federal agencies participated in the study, to varying degrees of involvement. Responses to the initial study correspondence were received from the Maryland Department of the Environment (MDE), MDDNR, Pennsylvania Department of Environmental Protection (PADEP), VADEQ, Natural Resources Conservation Service (NRCS), and USGS. Copies of correspondence are included in Appendix I.

6.3. Computer-Based Evaluation Tool

A computer-based evaluation tool could assist water resources managers in assessing potential impacts from development by providing the predicted hydrologic and biologic impacts of a particular management decision. The optimum configuration of a Potomac computer-based evaluation tool is still to be determined; however, the general concept is as follows. The FA-E responses developed as a result of this study provide managers with an understanding of the degree of biological alteration associated with a particular amount of hydrologic alteration. Computer-based evaluation tools can be utilized to look at different "what-if" scenarios to anticipate the degree of biological degradation or improvement associated with a particular activity. Then an informed management decision can be made about proceeding with the activity. Useful applications of this type of tool may include, but are not limited to, local land use planning and water withdrawal/discharge permitting.

Some tools, for different parts of the United States and Canada, have been developed already for similar purposes. A literature review was conducted to obtain additional information about existing tools and to assess the technologies available and costs associated with creating a user-friendly tool useful in basin-wide water resources management (Appendix J). Available tools varied widely in cost and scope. Some tools included web-based spatially explicit mapping capabilities while others were comprised of downloadable software applications. Depending on the application, tools were developed with a focus on the management of groundwater, surface water, or both. The cost of these tools, for organizations reporting costs, ranged from approximately $100,000 to almost $2,000,000. The more sophisticated tools often include online interactive capabilities, integration with existing hydrologic models, and various spatial resolutions for analysis.

6.4. Potomac Basin Comprehensive Water Resources Plan

The MPRWA included development of a concept for a Potomac Basin Comprehensive Water Resources Plan. Water resources planning efforts have been underway within the jurisdictions of the Potomac basin for some time. Maryland requires that local governments develop Water Resources Elements within their respective comprehensive plans under Maryland House Bill 1141 of 2006. As part of Virginia's Local and Regional Water Supply Planning Regulation of 2005, development of local or regional water plans is required. Pennsylvania has a State Water Plan process that includes the designation of Critical Water Planning Areas under Act 220 of 2002. West Virginia is working towards the development of a State Water Plan as part of the Water Resources Protection and Management Act, scheduled for completion in 2013. The purpose of a Potomac comprehensive plan is to build on these and other efforts to identify and address water resources issues of interstate or basin-wide concern.

The objective is the collaborative development of an adaptive basin-wide comprehensive water resources plan to serve as a roadmap for the sustainable use of this interstate resource now and into the future. A comprehensive plan would facilitate proactive, integrated management of the water resources in the Potomac basin. Development of the plan itself was outside of the scope of the MPRWA and will proceed as funding sources are identified and become available. It is anticipated that this effort would be led by ICPRB. However, the strategy for developing a basin-wide plan was prepared under the MPRWA (Appendix J).

In general, the planning process should be collaborative, adaptive, integrated, and participatory. Collaboration will be essential to developing a basin-wide comprehensive plan. Working together, a shared vision can be developed and common goals can be met. The plan should also be adaptive. That is, recommendations can be developed based on existing knowledge, re-evaluated after implementation, and revised as necessary to ensure goals are met. The planning effort should include an integrated perspective of water resources management, taking into account not only water quality, but water quantity, not only hydrologic, but biological concerns. And the planning process should be participatory to engage stakeholders from across the basin, ensuring all voices are heard and incorporated.

Because the specifics of the plan would be determined with significant stakeholder feedback, the planning framework is designed in four phases with the intent of being flexible, in anticipation of future adjustments. The four phases of the plan's development are scoping, identification of water resources issues, identification of solutions, and development of the plan. The scoping process was initiated as part of the MPRWA and includes defining roles of the participating organizations, establishing an interdisciplinary oversight committee, and defining the goals of the plan. Identification of water resources issues has been performed at various scales in numerous previous studies in the Potomac basin. The plan would build on the results of the MPRWA and other studies to identify water resources issues of interstate or basin-wide significance. Issues may include, but are not limited to, water availability, water quality, water use, potential climate change, stormwater and impervious cover, source water protections, and flood and drought management. Management alternatives will then be developed and evaluated to address the identified issues, leading to the recommendation of practical solutions. After compiling the results of the planning process, a Potomac Basin Comprehensive Water Resources Plan document will be prepared.

Benefits of the comprehensive plan would be numerous and include, but are not limited to (1) integration of existing data and research for analysis at the basin-wide scale, (2) enhancing interstate collaboration, (3) management the interstate resource of the Potomac basin at the interstate scale, and (4) increasing cost efficiency through collaboration.

Initial stakeholder outreach for the comprehensive plan was conducted as part of the Middle Potomac River Watershed Assessment at an ICPRB Commission meeting in December 2010, a webinar for key stakeholders and Commissioners in March 2011, personal conversations with representatives from each basin jurisdiction, and distribution of the concept document (Appendix J) to key basin stakeholders for review and comment. The comprehensive plan concept was also presented and published in the proceedings of the American Water Resources Association (AWRA) 2011 summer specialty conference on Integrated Water Resources Management: The Emperor's New Clothes or Indispensable Process (held June 27-29 in Snowbird, Utah). Participation in this conference provided the opportunity to receive feedback on the plan from practitioners. A challenge for successful completion of the basin-wide plan noted at the conference will be the difficulty in getting commitment of resources from organizations whose purview only covers a portion of the basin, because these organizations may feel limited responsibility for the entire watershed. Suggestions received from the group included utilizing Memoranda of Understanding to encourage implementation from basin jurisdictions as ICPRB is a non-regulatory entity.

6.5. Discussion

Ultimately, any land or water management decision-making that can be influenced by the findings of the MPRWA and the Potomac Basin Comprehensive Water Resources Plan will be conducted by local, regional, state, and federal managers throughout the basin. The participatory process of this project was intended to inform basin water managers and other stakeholders of the concepts and methods used to evaluate the impact of land use change and water use on stream flows and the consequent impacts on aquatic biology, and to obtain feedback from those experts that helped with interpretation of analytical results. Implementation of the Comprehensive Water Resources Plan is a logical next step. It can incorporate the technical findings of this project in a stakeholder led process to develop regionally appropriate, sustainable, water management. Development of a computer-based evaluation tool, by a project partner, could facilitate understanding of the implications of various land and water use management decisions. USACE could undertake development of a tool through the Interagency and International Support Technical Assistance Program.

Chapter 7. Conclusions

This chapter lists all the products of the MPRWA study. It summarizes the overarching findings of the study, lessons learned, information needs with respect to research, monitoring and modeling, some potential applications by the jurisdictions, and next steps in establishing environmental flows for the Middle Potomac River region.

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7.1. Introduction

The Middle Potomac study area presented both special opportunities and special challenges in this assessment. The assessment was an opportunity to evaluate the effects of flow alteration on stream and river ecology in a watershed with essentially unregulated flow. In this watershed, the causes of flow alteration are dominated not by dams but by land use changes, withdrawals, and discharges. There are opportunities to establish ecological benchmarks of flow alteration because the area has a rich and long history of monitoring both flow and biology in and near flowing waters. Potential impacts of future flow alteration were also investigated since water supply and population growth are of interest to, and studied by, several state and regional agencies. As an interstate watershed overlapping the District of Columbia and parts of Maryland, Pennsylvania, Virginia, and West Virginia, there were special challenges in acquiring comparable datasets. In scoping an approach to develop a comprehensive basin-wide water resources plan, the lack of a single basin-wide regulatory authority was a key driver in shaping the proposed participatory and multi-jurisdictional planning framework.

The Middle Potomac is exceptional in that relatively few large dams regulate water flow in the watershed. The combined storage capacity of all major impoundments in the basin upstream of Washington, DC presently makes up less than seven percent of median annual flow, and most impoundments are run-of-river. Extensive farming and timber harvesting historically impacted streams and rivers, but a majority of subwatersheds have since reforested. Many streams and rivers, particularly in the relatively undeveloped western portion of the watershed, are now considered relatively natural with respect to flow. Population growth and urbanization are larger causes of hydrologic alteration than impoundments. The eastern side of the watershed near Washington, DC has experienced significant urban growth since the 1930s. Population is expected to continue to grow and expand westward in the next decades, increasing water use and consumption and converting more forest and agricultural lands to suburban and urban land.

7.2. Study Products

The assessment generated datasets and analyses that may be useful in future studies and management actions in the Potomac watershed and elsewhere. Products of the study's five distinct components are listed in Table 12.

Table 12. Summary of major products.

Component	Product	Reference
Large River Environmental Flow Needs Assessment	Review of stream flow requirements of fishes, mussels, and plant species in the non-tidal and tidal river. Flow needs synthesis including conclusions about Potomac large river flow needs, identifying specific flow regime component needs for key species. Review by workshop participants with expertise in large river ecosystems. Recommendations to address environmental flow needs information gaps. On-line bibliographic database of literature relevant to environmental flow requirements of the Potomac River.	Chapter 2 and 3 Appendix A
Future Water Use Projections	Estimates of 2005 water withdrawals and consumptive use by economic sector. Estimates of 2030 water withdrawals and consumptive use by economic sector for five different future scenarios.	Chapter 4 Appendix B Appendix C
Stream Environmental Flow Needs Assessment	Datasets for impoundments, withdrawals, discharges, land cover, gaged streamflow, benthic macroinvertebrates, simulated streamflow time series, calculated flow metrics for observed and simulated flow time series, and GIS shapefiles for modeled watersheds.	Chapter 5 Appendix C
	Hydrologic model (HSPF) of Middle Potomac ELOHA watersheds and calculation of simulated and observed flow metrics.	Appendices D-E
	Statistical analysis of correspondence between watershed characteristics and flow metrics.	Appendices E-F
	Flow alteration correspondence with human water use and land use change.	Appendix G
	Flow alteration – ecology (FA-E) relationships.	Appendix H

Table 12. Continued.

Component	Product	Reference
Stakeholder Engagement Process	Workshop participant suggestions and comments for Large River Environmental Flow Needs. Webinars Workshop participant suggestions and comments for environmental flows. Correspondence with agencies	Chapter 6.1 Appendix A Appendix I Appendix I Appendix I
Implementation Options	Conceptual plan for a basin-wide comprehensive water resource plan. Review of computer based tools for determining impacts of flow alteration.	Chapter 6.3 Appendix J Appendix J

7.3. Study Findings

The MPRWA resulted in a number of findings about the study area, some of which have implications for other studies. These findings include the effects of a naturally highly variable flow regime, drivers of flow alteration in the Middle Potomac, recommendations from project stakeholders, and insights on using the ELOHA framework.

7.3.1. The Potomac Large River Environmental Flow Needs Assessment

The Potomac Large River Environmental Flow Needs Assessment found no current identifiable adverse impact on key biotic taxa due to human modification of flow, but the assessment also identified significant data gaps. Biological data collected in comparable ways in the largest river segments of the Potomac are presently insufficient for flow needs assessments. Independent development of FA-E relationships, such as those for macroinvertebrates in streams and small rivers, is not possible at this time. Furthermore, the FA-E relationships identified in streams cannot be extrapolated to the large rivers due to natural changes found in macroinvertebrate communities as rivers broaden and deepen (e.g., Vannote et al. 1980). Relationships between land use change and change in flow characteristics in small watersheds may be applicable to the larger watersheds. These relationships were consistent across a wide range of drainage areas.

The project team, with expert workshop participants' input, arrived at nine conclusions—the main one being that current large river flow characteristics should be maintained (Section 3.4). In particular, the existing minimum flow recommendations for Little Falls and Great Falls should be maintained until (and if) future ecological monitoring identifies impacts that suggest a need to modify flow management policies. The lack of observed adverse impact may be due to the fact that the Potomac watershed has naturally highly variable flows and the taxa present in the river ecosystems are adapted to the flow regime as it exists today.

7.3.2. Future Water Use Projections

Total consumptive use above Little Falls across all days in the base year 2005 was estimated to be 385 mgd. Domestic and public supply accounted for 84 percent of this amount. Agriculture, power production, and industry accounted for the remaining 16 percent of consumptive water use. These water use sectors, while accounting for a small fraction of the total water lost through natural and anthropogenic causes on a basin-wide and annualized basis, can be more significant within specific subwatersheds and during extreme low flow events. Scenarios projecting water use to 2030 suggest that domestic and public supply will continue to account for most of the basin-wide consumptive water use. The rate of increase in total consumptive use, if there is no change in the per capita use of water for domestic and public supply, is estimated to be about one mgd per year, which is roughly consistent with estimates from previous studies. Flow simulations that incorporated future water uses as well as future land uses show these changes will alter multiple flow statistics from their current levels and, given the FA-E relationships identified, these future changes are likely to increase the risk of degraded ecological health.

7.3.3. Stream and Small Rivers Environmental Flow Needs Assessment

The streams and small rivers environmental flow needs assessment evaluated the impact of watershed characteristics, change in land use/land cover, and human uses of water on ecosystem response. A total of 256 flow metrics and 51 macroinvertebrate metrics were initially considered. Fifteen flow metrics were used to evaluate flow responses to natural watershed characteristics and to human uses of land and water. Ultimately, six flow metrics and seven macroinvertebrate metrics were selected to develop FA-E response relationships. The six flow metrics (and their ranges of alteration in the ELOHA dataset) are: high flow index MH21 (-75 to +10 percent), high flow duration DH17 (-100 to +51 percent), low pulse duration (-100 to +78 percent), 3-day maximum (-20 to +94 percent), high pulse count (-100 to +534 percent), and flashiness (-45 to +208 percent). Flow alteration in the ELOHA dataset was predominantly negative (current scenario is less than baseline scenario) for the first three flow metrics; it was predominantly positive (current scenario is greater than baseline scenario) for the last three flow metrics.

Adding the WOOOMM module to the HSPF model improved flow simulations in watersheds smaller than CBP river segments, which average 89 mi^2. Rigorous testing confirmed that, for the most part, flow metrics calculated from simulated time series closely agreed with flow metrics calculated from measured (gaged) time series for watersheds between 10 and 1000 mi^2, for different land covers and water uses. Exceptions were the magnitude of the highest daily flows per year and the duration of high flow pulses (as calculated by the IHA program). The amount of impervious surface appears to be the largest driver of flow alteration in the Middle Potomac. The second largest driver of flow alteration is disproportionate amounts of withdrawals and discharges (i.e. watersheds with large withdrawals but no associated discharge or vice versa). Agricultural impacts on the flow regime are variable but generally weak, and are often confounded by water uses in other sectors and urban land use.

In addition to estimating hydrologic alteration from baseline to current conditions, alteration was estimated in the Middle Potomac watershed under five future scenarios. Future scenarios that incorporate meteorological changes, including the hot and dry and climate change scenarios, display the most extreme hydrologic alteration throughout the study area because decreases in precipitation and increases in temperature reduce the amount of water available for both human and ecosystem use. In future scenarios that include only changes in land and water uses (DP1, DP2, and power), alteration is primarily associated with decreases in forest and increases in impervious cover (driven by increases in population); although total alteration is a combination of various factors that may work to either temper or exaggerate the overall alteration in a particular location. The most extreme urban growth is expected in the Monocacy, Conococheague, Shenandoah, Occoquan, and smaller watersheds in the WMA. Loss of forest is expected to continue as urban areas expand into previously forested areas. The largest current and future withdrawals with respect to volume are located in the North Branch and on the mainstem Potomac River, altering the hydrology in the mainstem system. These withdrawals are typically associated with decreases in median flows and flashiness. Spatial analyses of hydrologic alteration and associated ecological alteration can be used to develop and implement management efforts, whether they are associated with land use planning, withdrawal/discharge permitting, or other types of water resource management activities.

Three statistical methods were used to evaluate biological responses to flow alteration. Each contributed to an understanding of the causes of flow alteration in the Middle Potomac study area. All demonstrate that change in the flow regime away from a baseline state is associated with increasing degradation in stream biological communities. Pearson correlations determined the strength of the correspondences between flow alteration and biological condition. Quantile regressions (90th percentile or 10th percentile) of biometric values versus percent flow alteration showed that: (a) biological condition is the result of many factors in addition to flow alteration, and (b) for those watersheds least impacted by these other factors there is a significant decrease in biological condition as flow alteration increases. Conditional probability plots of the probability of a fair or better biological score versus percent flow alteration showed that the likelihood of a macroinvertebrate community having an acceptable status decreases as alteration increases in most flow metrics. Biological metrics were strongly correlated with flow metrics representing high magnitude flows, the duration of high and low flow events, the frequency of high and low flow events, and the rate of change in flow. They were not correlated with alteration in the magnitudes of mid-range and low flows. Table 13 summarizes this study's results and lists the possible underlying mechanisms identified in other studies and discussed in Chapter 5.

An initial goal of the report was to define general, transferable FA-E relationships that represent the "environmental flow needs" of streams and small rivers in the Middle Potomac study area, but the report stops short of achieving this. The quantile regression plots illustrate that macroinvertebrate communities in the study area are locally impacted by factors other than flow alteration, such as poor water quality and disturbed stream habitat (e.g., Figures 21 and 28). The shapes and positions of the FA-E relationships depend heavily on the proportional impacts of *all* anthropogenic factors in the study area. For example, the response trajectory of biological change in a low quality site stream will roughly parallel that in a high quality stream, but biometric values will be displaced downward because of the additional impacts of poorer water quality and habitat conditions. As Poff and Zimmerman (2009) have concluded, it is not possible to develop "general, transferable quantitative relationships between flow alteration and ecological response" even though flow alteration increasing away from a baseline state is consistently and strongly associated with declining ecological condition.

Thresholds in the watershed-to-flow alteration relationships developed for this project can still inform managers as to when increases in specific land uses are likely to begin altering stream flows. Similarly, relationships between flow alteration and biological metrics can generally indicate how much flow alteration will impact biological communities. To accurately forecast change in the

Table 13. Summary of flow alteration – macroinvertebrate relationships identified in this study.
Possible underlying mechanisms that have been suggested in the literature are also listed.

Alteration in these aspects of the flow regime is associated with:	Degradation in these macroinvertebrate metrics:	Possible mechanisms that could explain the association are:
• Higher maximum flows • Shorter duration of high flows • Shorter duration of low flows • More low flow pulses • More high flow pulses • Faster rates of change in flow (flashier)	All 19 family-level macroinvertebrate metrics and the Chessie BIBI multi-metric index	• Scour of periphyton and organic matter (food) during high flows • Catastrophic accidental drift during floods • Displacement from habitat and stranding when waters recede • Physical alteration of stream bed habitat • Indirect effects of poor runoff water quality (sedimentation, pollutants) • Interruption of development or dispersal cues
• Lower middle and low magnitude flows, includes median flow, August median flow, summer Q85 flow, baseflow index, 3-day and 1-day annual minima, and 7Q10	None of the biometrics	• Swift recovery due to adaptations to low flow (drought resistant or diapausing life stages) • Multi-voltine (short) life cycles • High mobility, able to find refugia and later recolonize

biological community caused by a specific change in flow, however, projections must account for all the natural and anthropogenic factors in addition to flow alteration that impact biological communities. Degrading water quality and damaged in-stream physical habitat—or conversely water quality improvements and stream rehabilitation—can significantly influence the local biological community.

7.3.4. Stakeholder Engagement Process

The stakeholder process utilized during the MPRWA yielded valuable feedback/insights regarding the project findings. These lessons include a list of flow and biometrics that are of greatest interest for management purposes, methods for presentation of results to inform management efforts, and interpretation of results from the stakeholders' perspectives. A complete compilation of stakeholder feedback is available in Appendix I.

Defining limits of acceptable hydrologic alteration towards management of ecological health, a final step in the ELOHA process, is a stakeholder driven social or political decision-making process. Limits of acceptable alteration were not defined in this study. Ecological health is a function of many variables, of which flow is only one. Ecological health can be improved by reducing water pollution, improving in-stream habitat, etc. in the absence of restored, naturally variable flow regimes. Acid mine drainage remediation, point source pollution reductions, and agricultural and stormwater best management practices provide examples of this. And, as is often the case in urban areas, flow alteration is sometimes linked too closely with pollutant loads to easily distinguish it as the predominant stressor of the aquatic community. Defining a limit of hydrologic alteration alone to manage ecological health, therefore, is a difficult proposition due to the other confounding factors. This would be an appropriate next step based on the results of this study.

Land and water uses are in many cases subject to local government control. Therefore, actions such as stormwater management that maintain or restore environmentally sustainable flows may need to be implemented at that level of government. Urban stormwater management is capable of reducing peak stormwater flows and slowing the delivery of rainwater to streams and rivers. Actions that address stormwater runoff will reduce the tendency of impervious surfaces in urban areas to increase the magnitudes and shorten the durations of high flows in streams after storm events. Hydrologic alteration associated with disproportionate amounts of withdrawals and discharges may illustrate the hydrologic impacts of transfers between subwatersheds and, in some cases, may be due to limitations in the withdrawal and discharge datasets available for this study.

7.4. Lessons Learned

The MPRWA resulted in a number of lessons learned about the methods and approaches employed in the study. Insights arose from both the large river and stream/small river components and concern the steps involved in building the hydrologic foundation, model adequacy, projections of future conditions, and the stakeholder participation process. The Middle Potomac large river component applied the ESWM approach that has been used in several other watersheds including the Susquehanna River. It is driven by literature results and expert judgment primarily because of a lack of biological and/or hydrological data specific to the study area. The stream and small river component is one of the first-ever attempts to perform a large-scale quantitative analysis using the ELOHA methodology. This approach is more data driven.

A substantial effort is required to construct a hydrologic foundation that, despite inherent limitations and uncertainties, performs adequately in terms of both simulated daily flow time series and calculated flow metrics.

Model verification and flow metric testing are essential steps in building confidence in the simulated flow time series. Detailed comparison of simulated to observed results enhances confidence that the modeled time series and flow metrics are an acceptable representation of reality. In particular, flow metrics should behave as expected and relate to biota in an understandable way. Flow metrics should preferably represent portions of the hydrograph that can be influenced by management.

It is impossible to predict accurately what future conditions will look like. Evaluation of multiple future scenarios is useful for bounding the range of possible flow impacts. The range of conditions can then be utilized for planning and management purposes and adapted over time as additional information becomes available.

A modification of the stream classification approach described by Poff et al. (2010) proved best at delineating regionally distinct macroinvertebrate communities. The ELOHA framework recommends using similarities in baseline, or undisturbed, hydrologic regimes[18] to classify streams into types such as groundwater-fed streams, seasonally predictable snowmelt rivers, etc. These classes are expected to show distinct differences in their ecological characteristics and biological responses to flow alteration. In this study, stream classes were established based on similarities in the macroinvertebrate communities of reference stream sites, not in their hydrologies. Reference stream sites have good water quality, excellent habitat conditions, and are minimally disturbed by most anthropogenic factors. Their communities closely resemble the best possible natural state, and the streams—with few exceptions—have relatively undisturbed hydrologic regimes. The advantage of using reference sites rather than baseline hydrologies to classify streams is the impacts of multiple anthropogenic factors are minimized, and the composition and species abundances of macroinvertebrate communities at the sites are primarily governed by natural factors. In a recursive partitioning analysis (a form of cluster analysis), reference communities separated most strongly on combinations of USEPA Level IV ecoregions. Therefore, stream classes in this study were established on aggregates of the ecoregions called bioregions.

The MPRWA study process engaged stakeholders at several points in the project. Stakeholder engagement was essential to conveying large quantities of technical information and receiving feedback.

7.5. Information Needs

The Middle Potomac River Watershed Assessment identified a number of information needs that could improve this assessment and/or benefit future work. These information needs fall into three categories: research and analysis, monitoring, and modeling.

7.5.1. Research and Analysis

Recommendations made at the large river flow needs workshop (September 2010) focused primarily on monitoring needs. A few studies and analyses were suggested for mussel and fish populations, and ice scour impacts during low flows. A modified Instream Flow Incremental Method (IFIM) study was suggested to evaluate the relationship between flow and velocity, depth, and habitat below 1,000 MGD. The full set of suggestions can be found in Appendix A.

The large river flow needs study also identified a weakness in the existing literature. Specifically, there is a limited availability of information on flow requirements for aquatic species compared to velocity requirements. Flow is the total volume of water passing a fixed point over a given time period, and is commonly expressed as cubic feet per second (cfs) or million gallons per day (MGD). Flow is usually unaffected by stream morphology—speeding up when the stream narrows and slowing down when the stream widens. Velocity is the speed of the water, or the distance traveled

[18] A second classification approach attempted in this study and described in 5.2.4 (preliminary analysis) and Appendix F was the "attribute-based" approach. Stream classes are developed based on similarities in their current conditions (e.g., temperature, stream gradient, geology, and stream size) instead of similarities in their baseline hydrologic regimes. This approach does not require a modeling effort and assumes biological communities within a stream class will respond similarly when exposed to a hydrologic alteration (surface withdrawals were the hydrologic alteration tested in this study). The approach was not successful in the Middle Potomac study area (Table 7). The authors suspect this was because other, non-flow factors impact stream macroinvertebrates more than hydrologic alteration at many sampling sites.

by the water over time. It is strongly influenced by stream morphology. Translating flows into velocities for application at an ungaged location is difficult because detailed information about the depth, width, and slope at the new location are required.

Areas for further evaluation and analysis that were identified based on stakeholder feedback at the small river and stream flow needs workshop (November 2011) include evaluating (1) additional flow and macroinvertebrate metrics, (2) other taxa beyond benthic macroinvertebrates to develop flow-ecology relationships, (3) the results of the analyses using family versus genus level biological data, (4) flow-ecology relationships with additional stream classification factors, (5) the steep decline in stream health with less than 10 percent change in streamflow and the relationship of this to the model's margin of error (or, as was latter suspected, to a greater frequency of development-related, degraded water and habitat quality in the Piedmont), (6) the reliability of data at extreme ends of the FA-E curves, given the scarcity of data at the extremes, and (7) specific flow-ecology hypotheses. The full set of November 2011 stream and small river workshop participants' comments is available in Appendix I. Research needs identified by the project team during development of the stream flow ecology relationships include the need to enhance the understanding of (1) flow alteration in Coastal Plain watersheds and karst watersheds, (2) the confounding influences of non-flow factors impacting ecosystems and biological communities, and (3) methods used to ameliorate the negative impacts of both low and high flow conditions (e.g. efficacy of best management practices). An overarching research need for both rivers and streams in the Middle Potomac watershed is a better understanding of aquatic and riparian community responses to naturally prolonged low flows associated with regional droughts.

7.5.2. Monitoring

Observed flow and biological data are essential to understanding and defining environmentally sustainable flows. Funding for sustained river monitoring is a critical priority. Specific data needs identified in both the small and large river studies are documented below.

The large river flow needs assessment identified a number of monitoring suggestions. Recommendations included (but were not limited to) long-term floodplain vegetation monitoring, continued/enhanced mussel and fish studies, and additional surveys related to cormorants, macroinvertebrates, and amphibians and reptiles. The complete, detailed list of recommendations is available in Appendix A.

Creating the hydrologic and biologic foundations upon which the FA-E relationships were built in the small streams assessment requires copious amounts of observed data. In using the existing data, a number of data needs were identified. Continued long-term operation of the Potomac basin stream gage network is the cornerstone of effective hydrologic model calibration and verification as well as flow metric verification efforts. Without these data, modeled flows cannot be tested. The locations of existing gages, however, are most often on medium and large sized waterways in non-karst regions. To fully understand hydrologic alteration and the associated ecological response throughout the Middle Potomac, additional observed streamflow data is needed on smaller streams, in karst watersheds, and in relatively undisturbed, or reference, watersheds.

Enhancements to existing biological datasets would enable a more diverse assessment of biological health. The Potomac is fortunate to have a basin-wide macroinvertebrate database; however, environmental flow analyses would also benefit from basin-wide datasets of other organisms such as fish, mussels, and vegetation because macroinvertebrates can only represent some elements of aquatic ecosystem health. For example, low magnitude flows do not appear to significantly impact macroinvertebrates whereas the flow-ecology literature suggests they might impact fish communities. Additional basin-wide, comparable datasets for fish could provide a more complete picture of the ecological impacts of flow alteration.

That said, two major hurdles impede the use of fish survey data for flow analyses. First, state and local monitoring programs typically use different methodologies to collect fish. Sampling protocols vary depending on management objectives. Constraints on time, personnel, and objectives can make it impractical to obtain standardized fish population estimates at all survey sites within a state (J. Mulligan, MDDNR, personal communication). Careful consideration of each program's methods is required to ensure the dataset assembled for flow analysis contains comparable data. Second, biological factors unrelated to flow or the stream environment significantly stress and alter fish populations in the Middle Potomac study area, including fish stocking programs, introductions of non-native species, and disease. A major analytical challenge will be determining the extent to which these biological factors, in addition to the known water quality and habitat problems, confound the impacts of flow alteration on fish populations.

7.5.3. Modeling

The hydrologic model utilized in this study has undergone substantial calibration and verification. These efforts are limited by the availability and nature of observed datasets, as previously noted. Due to limited observed data in small watersheds, karst watersheds, and reference watersheds, the ability to evaluate model behavior in these locations is somewhat compromised. As mentioned above, additional daily flow data in these areas could inform further model evaluation and enhancements.

Another information gap in the modeling effort relates to groundwater withdrawals. Although the largest withdrawals in the Potomac basin are taken from the surface water resources, there is a much larger number of groundwater withdrawals. The cumulative impacts of these groundwater withdrawals is likely significant in some areas. To this end, the hydrologic model either needs to be enhanced to be capable of effectively simulating these groundwater withdrawals or information needs to be obtained on the interaction of each groundwater withdrawal with surface water supplies for input into the existing hydrologic model.

Meteorological data drive the hydrologic cycle in the model. The broad spatial resolution of these meteorological data is a limitation to the simulation of smaller watersheds. Obtaining and importing high resolution meteorological data would likely improve estimation of flows, particularly in smaller watersheds where biological monitoring often occurs.

Implementation of management practices as a result of this study may be informed by more detailed modeling of the impacts of spatially explicit land use practices. For example, the HSPF model utilized in this study is not capable of spatially discriminating land uses within a land-river segment. However, the efficacy of management practices depends on their implementation location, among other factors. A modeling tool that can evaluate how site-specific management practices will affect stream ecology and stream health would be a useful addition to this analysis.

7.6. Applicability to Jurisdictions

The case studies and decision support tools described in Appendix K (DST_CaseStudies.pdf) and in Kendy et al. (2012) demonstrate that states and river basins in the United States are successfully developing FA-E relationships and applying them to water resources planning and streamflow management. In lieu of the large hydrologic and biological datasets needed to develop FA-E curves, Richter et al. (2011) suggest implementing a presumptive flow standard based on the Sustainability Boundary Approach (Richter 2009). The presumptive standard restricts hydrologic alterations to within a percentage-based range of flows around natural or historic flow variability and protects vulnerable rivers from unlimited exploitation.

For the Middle Potomac study area, presumptive standards may best serve those watersheds that models cannot represent well at this time (5.2.2). Otherwise, FA-E relationships developed in the study (5.3, Appendix H) are generally applicable, with consideration for the confounding influences of other environmental factors and the innate differences in biometric response strength. All FA-E relationships show that macroinvertebrate family-level metrics respond as flow deviates from a baseline condition. Given the existing water quality and stream habitat conditions in the Middle Potomac region, a doubling in flashiness (100 percent alteration) can be expected to result in roughly a 40 percent drop in acceptable biometric status and more than two thirds of stream communities—as measured by the multi-metric Chessie BIBI—in a degraded state (Figure 27). The precise change in the percent of degraded communities depends on whether concomitant changes in water quality and habitat conditions occur as flashiness increases. A 50 percent increase in the highest annual flow magnitudes could be expected to drop acceptable levels of biometrics by about 40 percent (Figure 23). Shortening high and low flow events to half (-50 percent) of their baseline durations can reduce acceptable biometric levels by about 35 percent (Figure 24a-b, 25). High flow events that occur twice as often (100 percent) can reduce acceptable biometric levels by roughly 20 percent (Figure 26). The successful development of FA-E relationships in the Middle Potomac study demonstrates that existing and planned changes in a watershed's baseline flow regime can be related to alteration in streamflow and ultimately to responses in biometrics (Figure 29a-e).

There are potential applications of the study results for local and state jurisdictions. For example, a local water resources manager or planner might go through the following series of steps using FA-E relationships. At the local level, the results may be most applicable for land use planning and zoning.

- Identify the causes of ecological degradation in a watershed or jurisdiction of interest (e.g. flow alteration, water quality, stream habitat, etc.), and opportunities to mitigate those causes of degradation. If flow alteration is the primary cause of ecological degradation, proceed with the following steps. Otherwise, the flow alteration – ecological response relationships from this study would need to be modified before use.
- Determine how much ecological degradation is socially/politically acceptable within the area of interest. From a county perspective, a state perspective, and the Potomac River and Chesapeake Bay perspectives, how many degraded streams are allowable in the area of interest?
- Determine the watershed driver(s) of flow alteration in the area of interest (e.g. withdrawals, discharges, impoundments, land uses).

- For the watershed driver(s) of concern, determine how much of that driver will produce the maximum acceptable amount of degradation utilizing the modeled flow alteration – ecological response plots.
- Utilize regulatory, voluntary, or policy mechanisms to manage the watershed driver and prevent degradation past the acceptable threshold.

Similarly, state planning and regulatory entities may find the resulting FA-E relationships useful for state purposes, where withdrawal and discharge permitting typically occurs.

7.7. Next Steps

The Middle Potomac River Watershed Assessment establishes a scientific foundation for the larger process of identifying, managing and protecting environmental flows. Although information gaps and monitoring needs remain and should be addressed, social and political discussion and decision-making are important "next steps." They might include:

- Continue work begun in February 2012, when a technical workgroup was formed, under the auspices of the Maryland Department of Natural Resources. Develop a hydroecological monitoring plan and list of priority research needs for the mainstem Potomac River. Other recommendations from the September 2010 Workshop for this workgroup, including developing more quantitative flow recommendations and re-evaluating the 300/100 mgd flow-by recommendation, have been deferred until such time as additional data have been gathered indicating adverse impacts on aquatic species due to flow alteration.
- Consider how resource management agencies at local and state level in each jurisdiction can use the relationships developed in this assessment between land and water uses, flow alteration, and ecological status to inform watershed management decisions. This might include development of computer-based tools that use flow alteration-ecology relationships to predict the impact of proposed land and water use decisions.
- Use the study results to inform further development of the Potomac Basin Comprehensive Water Resources Plan and individual state plans.
- Use the quantitative flow alteration-ecology relationships to foster discussion and build consensus on acceptable levels of biological degradation resulting from changes in the flow regime.
- Perform additional research, monitoring, or analysis to fill information gaps and refine the findings from this study in an adaptive management context.
- Use project data products to support other planning and management needs of basin jurisdictions.

It is anticipated that these actions will be led by ICPRB, TNC, or basin jurisdictions. USACE may be a participating stakeholder in further activities, provide technical assistance, and will continue to advance the Chesapeake Bay restoration goals of Executive Order 13508 (The Chesapeake Bay Protection and Restoration Executive Order). No actions were identified for immediate USACE implementation.

Supplemental Tables

Supplemental Table A. Flow metrics.

Calculations were performed using the TNC Indicators of Hydrologic Alteration software program (IHA), the USGS Hydrologic Index Tool software program (HIT), the EPA DFLOW program, and with Excel 2007.

Metric Name	Description	Units
1-Day Maximum	The average of each year's highest daily mean flow (cfs) during the study period (1984-2005) divided by watershed area (mi^2). IHA.	cfs/mi^2
3-Day Maximum	The average of each year's highest 3-day moving average of daily mean flow (cfs) during the study period (1984-2005) divided by watershed area (mi^2). IHA.	cfs/mi^2
Annual Mean	The average of all the annual means of daily mean flows (cfs) during the study period (1984-2005) divided by watershed area (mi^2). The average of each year's mean daily flows is calculated, and then the means of each year are averaged. IHA.	cfs/mi^2
Median	The median of all the daily mean flows (cfs) during the study period (1984-2005) divided by watershed area (mi^2). Excel.	cfs/mi^2
Q85Seas	Calculate the 15th percentile flow (cfs) for each month (July – October) during the study period (1984-2005), and then average all the monthly values and divide by watershed area (mi^2). Adaptation of the Maryland method. Excel macro.	cfs/mi^2
August Median	The median of the August median flow for each year in the study period (1984-2005) divided by watershed area (mi^2). IHA.	cfs/mi^2
Base Flow Index	The median of each year's 7-day minimum flow (cfs) divided by the mean annual flow (cfs). IHA.	ratio (unitless)
1-Day Minimum	The average of each year's minimum daily mean flow (cfs) during the study period (1984-2005) divided by watershed area (mi^2). IHA.	cfs/mi^2
3-Day Minimum	The average of each year's lowest 3-day moving average of daily flow (cfs) during the study period (1984-2005) divided by watershed area (mi^2). IHA.	cfs/mi^2
7Q10	The lowest stream flow for seven consecutive days that would be expected to occur once in ten years. The 7-day moving average is calculated for the study period; the flow volume of the event that recurs every 10 years is the 7Q10 value. DFLOW.	cfs
High Pulse Duration	The median of the annual average number of consecutive days per year that daily flow is above the 90th percentile of the 1984-2005 period of record. IHA.	days/year

Supplemental Table A. Continued.

Metric Name	Description	Units
High Flow Index MH21	The average volume of high flow events (above a threshold equal to the median flow of the entire record) divided by the median daily flow for the entire record. HIT.	days
High Flow Duration DH17	The average duration of flow events with flows above the median flow for the entire period of record. HIT.	days
Flood Free Season	The length of the longest period common to all water years in the study period (1984-2005) where flows are at or below the high pulse threshold (usually less than the 90th percentile) in every year. IHA.	days
Low Pulse Duration	The median of the annual average number of consecutive days per year that daily flow is below the 10th percentile of the 1984-2005 period of record. IHA.	days/year
Extreme Low Flow Duration	Mean of extreme low flow event duration. An extreme low flow event is the occurrence of flow in the lowest 10th percentile of the low flows which are the lowest 10th percentile of all flows over the study period. IHA.	days/event
High Pulse Count	The median of the annual average of each year's number of times the daily mean flow is above the 90th percentile of all flows for the study period. IHA.	#/year
High Flow Frequency	Average of the number of events per year when the daily mean flow exceeds the 90th percentile of all flows in the study period. IHA.	#/year
Number of Reversals	The average number of times in a year that daily mean flow switches from rising to falling and vice versa. IHA.	#/year
Low Pulse Count	The median of the annual average of each year's number of times the daily mean flow is below the 10th percentile of all flows for the study period. IHA.	#/year
Extreme Low Flow Frequency	The frequency of extreme low flow events in a year, where daily flow is in the lowest 10th percentile of all the low flows (or below the 2.5th percentile of all flows in the 1984-2005 period of record). IHA.	#/year
Flashiness	(Richards-Baker Index) Sum of the absolute values of day-to-day changes in the daily mean flow divided by the sum of the daily mean flows. Excel.	ratio (unitless)
Rise Rate	The average of all positive differences in daily mean flow during "rising periods," or consecutive days for which change in daily flow is positive, in a year. IHA.	$cfs/mi^2/day$
Fall Rate	The average of all negative differences in daily mean flow during "falling periods," or consecutive days for which change in daily flow is negative, in a year. IHA.	$cfs/mi^2/day$

Supplemental Table B. Macroinvertebrate family-level metrics.

Calculations were performed using the Chesapeake Bay Program software program (Appendix 3). Metric type: C = composition; T = tolerance; R = richness; FG = feeding group; H = habit; index = multi-metric index. A metric can be more than one type. Family-level pollution tolerance values were originally developed by Hilsenhoff (1988) and refined by CBP. Values range from 0 to 10, with 0 being the most sensitive to pollution and 10 being the least (Appendix C).

Metric Name	Type	Description
ASPT Modified Index	T	Average of the family-level tolerance score of each family present in sample
Beck's Index	T	Index is ((3 x #families with tolerance value of 0) + (2 x #families with tolerance value of 1) + (1 x #families with tolerance value of 2))
BIBI	index	Chesapeake Bay basin-wide Benthic Index of Biological Integrity; also called “Chessie BIBI;” average of scores of five bioregion-specific, family-level metrics
Gold Index	C	Index is 1 minus the proportional abundances (percents) of gastropods (snails), oligochaetes (segmented worms), and Diptera (true flies) individuals
Hilsenhoff Family Biotic Index	T	Also called FBI; average of the family-level tolerance score of each individual
# Ephemeroptera Families	R	Number of Ephemeroptera (mayflies) families present
# Sensitive Taxa	T	Number of families with family-level tolerance values less than or equal to 3
%Chironomidae	C	Percent of individuals that are Chironomids (non-biting midges)
%Clinger	H	Percent of individuals present that are adapted for clinging to hard surfaces
%Collector	FG	Percent of individuals that are collectors (filterers + gatherers) and not predatory
%Dominant3	T	Percent of individuals in the three most common families
%Ephemeroptera	C	Percent of individuals that are Ephemeroptera (mayflies)
%EPT	C	Percent of individuals that are Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies)
%Filterer	FG	Percent of individuals that are adapted for filtering fine particles from the water column
%Gatherer	FG	Percent of individuals that are adapted for gathering a range of food particle sizes

Supplemental Table B. Continued.

Metric Name	Type	Description
%Scraper	FG	Percent of individuals that are adapted for scraping periphyton (algae, bacteria) from hard surfaces
%Swimmer	H	Percent of individuals that are adapted for swimming
%Tolerant	T	Percent of individuals with family-level tolerance values greater than or equal to 7
Shannon Wiener Index	R	Index is a measure of taxonomic diversity; it is the proportion of each family times the log of its proportion, summed for all families
Taxa Richness	R	The number of family-level taxa in the sample

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Glossary

Baseline Scenario – The set of model conditions applied to catchments that defined landscape, withdrawal, and discharge conditions that would result in an unaltered hydrologic regime.

Bioregion/ecoregion/physiographic province – Classification systems that defines geographic regions with similar attributes such as geology, soils, elevation, slope, and climate, and is useful for classifying ecological data for study.

Classification and Regression Tree (CART) and **Recursive Partitioning (RPART)** – Statistical methods that delineate groups and identify numerical breakpoints among independent variables and partition variance in the response variable.

Hydrologic Simulation Program-FORTRAN (HSPF) – Chesapeake Bay Program's version of the HSPF modeling system adapted by the Chesapeake Bay Program and utilized in this project in combination with the WOOOMM to simulate streamflows at ungaged locations.

Consumptive use – The amount of water withdrawn that is not subsequently returned to the source.

Current scenario – The set of model conditions applied to catchments that defined landscape, withdrawal, and discharge conditions that result in the existing hydrologic regime.

DFLOW – Software developed by the EPA to estimate low flow metrics from daily input time series.

Ecological Limits of Hydrologic Alteration (ELOHA) – Methodology developed by The Nature Conservancy, ELOHA is a "scientifically robust and flexible framework for assessing and managing environmental flows across large regions, when lack of time and resources preclude evaluating individual rivers."

Environmental flows – "Flows that sustain healthy river ecosystems and the goods and services that humans derive from them."

Flow Alteration-Ecology Response (FA-E) – Measureable shifts of biological indicator communities in response to the stresses caused by altered flow regimes.

Flow metric – A statistical measure of a system's hydrologic characteristic, based on an input flow time series.

Geographic Information Systems (GIS) – A GIS "integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information." (ESRI)

Hydrologic Index Tool (HIT) – Software developed by USGS to calculate 171 ecologically relevant flow metrics from input daily flow time series.

Hydrologic alteration – The amount of change in a flow metric between two conditions.

Indicators of Hydrologic Alteration (IHA) – Software developed by The Nature Conservancy to "understand hydrologic changes in ecologically-relevant terms." The software computes 67 flow metrics from input daily flow time series.

Karst – landscape formed by the dissolution of soluble carbonate bedrock such as limestone, dolomite, and gypsum. It has naturally elevated conductivity and is characterized by many springs, caves, sinkholes, and a network of aquifers and underground channels.

Macroinvertebrates – Animals without spines that are visible to the naked eye. Commonly includes insects, arthropods, and crustaceans.

Model scenarios – A run of a hydrologic model with a specific set of user-defined input data. In the Middle Potomac River Watershed Assessment, there are seven model scenarios (baseline, current, domestic and public supply 1 and 2, power, climate change, and hot and dry).

Nash-Sutcliffe Efficiency – A test capable of measuring the predictive power of a hydrologic model.

Reference – A series of biological sampling events that met an *a-priori* defined set of high-quality physical habitat and water quality conditions, which are expected to support high-quality biological communities.

River Continuum Concept – A general classification system for flowing waters and their communities from headwaters to large rivers. The concept is based on the idea that biological communities reach predictable dynamic equilibriums in response to physical river attributes of depth, width, velocity, and longitudinal shifts in productivity and respiration.

River segment – A uniquely modeled watershed area in the CBP HSPF model.

Watershed Data Management (WMD) – A binary input file used to store input time series for the HSPF model.

Online Object Oriented Meta-Model (WOOOMM) – a hydrologic routing module developed by Virginia Department of Environmental Quality and utilized in this project to route the CBP HSPF model to simulate streamflows at ungaged locations.

Abbreviations and Acronyms

AG	agricultural sector
AWUD	Aggregate Water Use Data system
CART	Category and Regression Tree Analysis
CBP	Chesapeake Bay Program
cfs	cubic feet per second
cfs/mi^2	cubic feet per second per square mile of watershed (water yield)
Chessie BIBI	Chesapeake Bay basin-wide Benthic Index of Biological Integrity
CO-OP	ICPRB section for cooperative water supply operations on the Potomac
CU	consumptive use
CUMP	consumptive use mitigation plan
DC	District of Columbia
DEM	digital elevation model
DP	domestic and public supply sector
DP1	domestic and public supply model scenario 1
DP2	domestic and public supply model scenario 2
DP3	domestic and public supply model scenario 3
ELOHA	Ecological Limits of Hydrologic Alteration
EPRI	Electric Power Research Institute
ESWM	Ecologically Sustainable Water Management
EVAP	evapotranspiration
FA-E	flow alteration-ecology relationship
FIPS	Federal Information Processing Standards
FRIS	Farm and Ranchland Information Survey
FTABLE	hydraulic function table
GIS	geographic information system
GMU	George Mason University
GW	groundwater
HD	hot and dry model scenario
HIT	hydrologic index tool
HSPF	Hydrological Simulation Program-FORTRAN
HUC	hydrologic unit code
ICPRB	Interstate Commission on the Potomac River Basin
IHA	indicators of hydrologic alteration
IN	industrial sector
IPCC	Intergovernmental Panel on Climate Change
IR	irrigation sector
IWRM	integrated water resources management
LV	livestock sector
MD	Maryland
MDDNR	Maryland Department of Natural Resources
MDE	Maryland Department of the Environment
MGD	million gallons per day
MG/year	million gallons per year
MI	mining sector

MPRWA	Middle Potomac River Watershed Assessment
MWD	multi-watershed delineation
NASS	National Agricultural Statistics Service
NEAFWA	Northeast Association of Fish and Wildlife Agencies
NEAHCS	Northeast Aquatic Habitat Classification System
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
PA	Pennsylvania
PADEP	Pennsylvania Department of Environmental Protection
PMP	Project Management Plan
PO	power sector
RESAC	Remote Sensing Application Center
RPART	Recursive Partitioning and Regression Tree
SRBC	Susquehanna River Basin Commission
SRES	IPCC special report on emission scenarios
SW	surface water
TAG	Technical Advisory Group
TMDL	total maximum daily load
TNC	The Nature Conservancy
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEIA	United States Energy Information Administration
USEPA	United States Environmental Protection Agency (also EPA)
USGS	United States Geological Society
VA	Virginia
VADEQ	Virginia Department of Environmental Quality
WAD	Washington Aqueduct
WD	withdrawal
WDM	Watershed Data Management format
WMA	Washington metropolitan area
WOOOMM	Online Object Oriented Meta-Model
WRE	water resources element
WSM	watershed model
WSSC	Washington Suburban Sanitary Commission
WV	West Virginia
WVDEP	West Virginia Department of Environmental Protection

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This project benefited from the discussion of ideas, of early versions of products, and of draft conclusions, with participants at the two workshops and with members of the Technical Advisory Group. Those individuals are identified in the workshop summaries and in the Stakeholder involvement summary (Appendices A and I). Special thanks are extended to Eloise Kendy, Colin Apse, Doug Sampson, Julie Zimmerman, John Mullican, Matthew Ashton, Steve Schreiner, and Fairfax Water for their reviews of the draft report and valuable suggestions.

The basic tool used for flow modeling was the Chesapeake Bay Watershed Model. Gary Shenk, US EPA, answered many questions about running that model.

The United State Geological Survey and its partners collected the surface flow data at gaging stations in the Potomac and Susquehanna watersheds and disseminated the data to the public, state and local governments, public and private utilities, and other federal agencies involved with managing water resources.

Monitoring programs of federal, state, interstate, and local agencies and academic institutions in Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia collected and processed the stream data made available to this project, and the Chesapeake Bay Program (CBP) incorporated the data into a uniform database and calculated the suite of biometrics used in the project.

Appendix A – Potomac Large River Environmental Flow Needs Report

Contents

This appendix contains the *Potomac Large River Environmental Flow Needs* report, which identifies the hydrologic needs of flow-dependent species and communities in four segments of the mainstem Potomac River and two selected large tributaries. The report was developed by a research team from the Interstate Commission on the Potomac River Basin (ICPRB), the Nature Conservancy (TNC), Leetown Science Center Aquatic Ecology Branch of the U.S. Geological Survey (USGS), and the Potomac Environmental Research and Education Center of George Mason University (GMU). It includes a comprehensive literature review, development of flow hypotheses, assessment of large river environmental flow needs, statistics proposed to track those flow needs, and recommendations for additional research, monitoring, and analysis to improve understanding of flow needs. The report is part of the broader effort to identify, protect, and, where necessary, restore the Potomac River watershed's environmental flows.

Several typographical errors (pages 4, 5, 6, 53, 72, and 77) that appeared in the report published in May 2011 have been corrected in this version.

Disc Contents
Document (PDF files)

- AppendixA_LargeRiverEnvironFlowNeedsRpt.pdf (100 KB)
- Potomac Lg River Env Flows Final Combined_March-2012.pdf (10,487 KB)

Appendix B – Water Withdrawals and Consumptive Use in the Potomac River Basin Report

Contents

This appendix contains the *Water Withdrawals and Consumptive Use in the Potomac River Basin* report. This stand-alone report describes how future water withdrawal and consumptive use for the year 2030 was estimated for six scenarios:

- high domestic and public water use (base scenario),
- medium domestic and public water use (DP2 scenario),
- low domestic and public water use (DP1 scenario),
- advanced technologies in the power sector and a new power generation facility (power scenario),
- conditions expected with climate change (climate change scenario), and
- drought conditions (hot and dry scenario).

The results were used to develop model inputs for future hydrologic alteration scenarios for other tasks in the Middle Potomac River Watershed Assessment project. Methodology for assembling datasets for those future flow scenarios is described in Appendix C, and methodology for how the future scenarios were modeled to produce flow time series is described in Appendix D. The study described here also serves as an update to a similar study done previously by ICPRB (Steiner et al. 2000). The two studies had different purposes and somewhat different datasets but some useful comparisons are made.

Disc Contents
Document (PDF files)

- AppendixB_FutureProjections.pdf (99 KB)
- FutureFlows_FINAL.pdf (2,011 KB)

Appendix C – Compilation of Measured Stream Data

Contents

This appendix discusses in more detail sources of the data and GIS layers used in the project, and the analyses done with them. It also lists the data files provided in separate directories on the attached disc. Section names in the AppendixC_Data.pdf document are identical to the directory names on the disc.

Disc Contents
Document (PDF file)

- AppendixC_Data.pdf (574 KB)

Eleven directories with data files and additional documentation (1.77 GB)

- 1_Impoundments
- 2_Withdrawals
- 3_Discharges
- 4_Land Cover
- 5_Potomac-Susquehanna Flow Gages
- 6_Stream Macroinvertebrates
- 7_Model Input-Output
- 8_Flow Metrics
- 9_Future Scenarios
- 10_GIS_Files
- 11_Master Data Set

Appendix D – Development and Refinement of Hydrologic Model

Contents

Hydrologic modeling efforts for the MPRWA project had multiple components. Detailed descriptions about the hydrologic modeling methodology are provided in the files on the attached disc. The file names listed below are identical to the file names on the disc.

Disc Contents
Documents (PDF files)

- AppendixD_HydrologicModel.pdf (74 KB)
- FutureScenarios_011912.pdf (1,891 KB)
  Describes the development of the five future scenarios in the CBP HSPF modeling environment. It also spatially presents the resulting hydrologic alteration in seven selected flow metrics.
- Watershed_delineation_011712.pdf (537 KB)
  Describes how biological monitoring points were selected from the Chessie BIBI database and, once selected, how the watersheds draining to those locations were delineated.
- Resegmentation_at_Impoundments_011712.pdf (376 KB)
  Describes the methodology utilized to re-segment the CBP HSPF model at "significant" impoundments in the study area.
- Pot-Susq_CART_analysis_011712.pdf (486 KB)
  Describes how thresholds of flow alteration risk were identified by a Category and Regression Tree (CART) Analysis of the Potomac-Susquehanna dataset.
- Baseline_Landuse_011212.pdf (143 KB)
  Describes the calculation of land uses in the baseline model scenario.
- Baseline_Scenario_011212.pdf (580 KB)
  Describes the development of the baseline scenario in the CBP HSPF modeling environment including the removal of impoundments, withdrawals, and discharges, and conversion of current to baseline land uses. Select results of the baseline scenario are also presented.
- WOOOMM_Inputs_011012.pdf (525 KB)
  Describes the inputs needed to establish the ELOHA watersheds in the VADEQ WOOOMM environment and documents how those inputs were developed.
- Application_of_ModelingTools_011312.pdf (619 KB)
  Describes the evaluation of the CBP Phase 5 model and VADEQ WOOOMM module for use in the Middle Potomac River Watershed Assessment.

Appendix E – Flow Metric Testing

Contents

This appendix provides a more detailed description of the analyses performed to verify the ability of the flow metrics generated from simulated time series to accurately represent those generated from observed time series.

Disc Contents
Document (PDF file)

- AppendixE_FlowMetricTesting.pdf (1,819 KB)

Appendix F – Stream Classification

Contents

This appendix contains a report written by Julie Zimmerman (previous of The Nature Conservancy) in 2010 and titled *Susquehanna River stream classification analysis: determining a stream classification system to apply to the Potomac River and Chesapeake Bay*. The analysis described in the report was intended to help determine the need for stream classifications in the ELOHA analysis of the MPRWA project.

Disc Contents
Document (PDF file)

- AppendixF_StreamClassification.pdf (189 KB)

Appendix G – Basin-Wide Hydrologic Alteration Assessment

Contents

The Middle Potomac River Watershed Assessment included a basin-wide assessment of hydrologic alteration. The purpose of this assessment was to understand the watershed drivers of hydrologic alteration (land uses, water uses, and meteorological conditions). The appendix describes in detail the methodology, sources, magnitude, and spatial extent of hydrologic alteration under current and future conditions in the study area, and the assessment results. It also provides an Excel file of the data and graphs used in the comparison of observed and simulated flow metrics plotted against different land uses.

Disc Contents
Document (PDF file)

- Appendix G_FlowAlterationAssessment.pdf (3,507 KB)

Data file (Excel 2007 spreadsheet)

- FlowAlt-vs-LandWater.xlsx (2,651 KB)

Appendix H - Development of Stream Flow Alteration–Ecology Relationships

Contents

This appendix provides detailed documentation on how the flow alteration – ecology (FA-E) relationships between the flow metrics and macroinvertebrate metrics were developed, and lists the files provided in separate directories on the attached disc.

Disc Contents
Document (PDF file)
- AppendixH_FA-E.pdf (234 KB)
- FA-E_ CondProb_plots.pdf (398 KB)
- FA-E_QuantileRegr_plots.pdf (433 KB)

Data file (Excel 2007 spreadsheet)
- QuantileRegr_Data_R-scripts.xlsx (27 KB)
- CondProb_Data_R-scripts.xlsx (1,412 KB)
- PearsonCorrelations.xlsx (1,628 KB)

Appendix I - Stakeholder Engagement

Contents

One objective of this project was a transfer of knowledge gained to “stakeholders, other interested parties, and USACE Districts and Divisions”. In addition, other tasks included elements specifying consultation and/or review of interim products by stakeholders or experts. The project team addressed these requirements by building a website for sharing information about the project, presenting webinars, holding two workshops, and establishing a Technical Advisory Committee and having two meetings with that group.

Disc Contents

Document (PDF file)

- AppendixI_StakeholderEngagement.pdf (146 KB)
- Potomac PMP signed.pdf (815 KB)
- MPRWA_fact_sheet_2011.pdf (591 KB)
- MPRWA_Intro_09_29_09.pdf (4,470 KB)
- LgRivWorkshopIntro_090910.pdf (3,841 KB)
- WebinarSeriesIntro_030811.pdf (5,667 KB)
- TechOverview_No1_041211_V3.pdf (1,110 KB)
- HumanUsesOfWater_No2_051011.pdf (2,073 KB)
- ModelingStreamflow_No3_061611.pdf (2,484 KB)
- FlowEcology1_No4_071411.pdf (3,166 KB)
- FlowEcology2_No5_090811.pdf (3,874 KB)
- Science_to_Mgmt_No6_102711.pdf (3,175 KB)
- FutureScenarios_No7_022312.pdf (2,341 KB)
- FinalWebinar_No8_06-21-12.pdf (2,066 KB)
- MPRWA_ATR.pdf (163 KB)
- MPRWA_constituent_comments_10_12_2012.pdf (175 KB)

Three directories (28.7 MB)

- TAG - contains materials presented at 28 September and 26 October, 2011 meetings of the Technical Advisory Group
- Workshop – contains materials presented at the 29-30 November, 2011 workshop
- Correspondence – contains copies of correspondence to federal and state agencies regarding the Middle Potomac River Watershed Assessment

Appendix J – Implementation Options

Contents

This appendix documents implementation efforts that have been investigated as part of the Middle Potomac River Watershed Assessment, including a literature review of Decision Support Tools (DST_CaseStudies.pdf) and a concept paper that scopes out a basin-wide comprehensive plan for the Potomac Basin (CompPlan_ConceptPaper_042911.pdf).

Disc Contents
Document (PDF file)

- AppendixJ_Implementation.pdf (69 KB)
- DST_CaseStudies.pdf (6,190 KB)
  One implementation consideration that underwent evaluation was the development of a computer-based decision making tool. To this end, case studies of Decision Support Tools from across the country were compiled and are contained in this document.
- CompPlan_ConceptPaper_042911.pdf (121 KB)
  The scoping phase of a Potomac Basin Comprehensive Water Resource Plan was completed as a part of the Middle Potomac River Watershed Assessment. This document outlines the planning process, as currently scoped. A version of this document was published in the AWRA 2011 summer specialty conference proceedings, held in Snowbird, Utah on June 27-29, 2011.