Appendix E – 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)

- AppendixE_HydrologicModel.pdf (74 KB) – this file
- FutureScenarios_110712.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 CART analysis of the Potomac-Susquehanna dataset of gaged watersheds.
- 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 – Hydrologic Model

Modeling Five Future Scenarios

Introduction

The five future scenarios, described in Report Appendix B, were modeled in the Chesapeake Bay Program's Phase 5.2 HSPF model for 153 river segments in the Middle Potomac study area and the North Branch of the Potomac River. The scenarios are domestic and public supply 1 (DP1), domestic and public supply 2 (DP2), power, climate change, and hot and dry. Each scenario depicts a set of future watershed conditions (land use, meteorology, and water use) to evaluate the effects on hydrology utilizing alteration in flow metrics and biology utilizing alteration in biometrics (Appendix 1 of this document). The purpose of this technical report is to detail the methodology utilized to simulate the five future scenarios in the hydrologic model, resulting in the generation of 5 sets of daily flow time series – one for each future scenario.

Within each future model scenario, there are five components that may change including withdrawals, discharges, temperature, evapotranspiration, precipitation, and land use. In subsequent sections, the specific changes made within the modeling environment to each of these components are outlined. For a complete description of the CBP HSPF model and how it is utilized in other aspects of the Middle Potomac River Watershed Assessment, see Report Appendix E related to the development and implementation of the hydrologic models. For a complete description of the rationale behind each future scenario, see Report Appendix B.

In principle, all of the future scenarios except hot and dry utilize a snapshot of potential 2030 watershed conditions to model the hydrology over a 21 year meteorological time period. The hot and dry scenarios differs in that it estimates the hydrologic effect of a 2 year drought; therefore, 2030 watershed conditions are simulated over a 2 year period. The meteorology of the 2 year period was developed to mimic the 1930 drought in the Potomac Basin. Appendix 1 of this document displays the major components of each future scenario. All 16 impoundments were simulated with standard, current operating procedures for the year 2030. A description of the creation of withdrawal, discharge, meteorological, and land use inputs follows.

Withdrawals and Discharges

As a result of the consumptive use analysis (Report Appendix B), each withdrawal in the basin was projected to 2030 to include varying degrees of population change and per capita water use change. With an exception in one scenario, the number of withdrawals and discharges does not change between the current and future scenarios. The future projections were quantified based on existing withdrawal locations. The exception is the power scenario which included the addition of a new power plant in Frederick County, MD.

The future withdrawal and consumptive use database included monthly withdrawal and consumptive use totals for each year at a five year time interval. So, values were present for January 2005, January 2010, January 2015, and so on for every month through 2030. These monthly amounts were disaggregated into a daily time series by dividing the monthly value by the number of days that month. Years between the five year intervals were estimated using linear interpolation. The withdrawals for each modeled river segment were summed to obtain a daily withdrawal time series for the river segment. The daily time series was converted to a WDM[1], the HSPF time series input format.

A similar procedure was followed to develop the discharge time series. A consumptive use amount was assigned to each withdrawal by water use type as part of the consumptive use analysis. Because the HSPF model does not simulate consumptive use directly, but only as a function of the difference between withdrawals and discharges, the future discharge dataset was developed by subtracting the consumptive use from the total withdrawal for each location. The monthly discharge amounts were disaggregated into a daily time series (as described above for withdrawals) and converted to a WDM format for input into the HSPF model.

Maps showing the net withdrawals (consumptive use) by modeled river segment for each of the five future scenarios are provided in Figures 1-5. Overall, the major consumptive use in the basin was projected to occur on the main stem of the Potomac River (shown in darker yellow, orange, and red). Grey areas are river segments with a negative net withdrawal, meaning there are more discharges than withdrawals. This could indicate either 1) an import of water into the river segment or 2) the presence of groundwater withdrawals that are not modeled but are included in the discharge database.

Temperature

The climate change and the hot and dry scenario included changes to the modeled temperature inputs. The 1984-2005 temperature time series utilized in the HSPF model for the current and baseline scenarios was used as the starting point for these future scenarios. For the climate change scenario, a 0.4°C increase in temperature was estimated through 2030. To achieve a 0.4°C increase by 2030, a daily increase amount was assigned to each day based on a linear growth. The growth amount was then added to the existing temperature data set to obtain the climate change temperature projections. For the hot and dry scenario, a 10.8% increase in temperature was assumed based on the 1930 drought. Therefore, each of the daily temperature values in the current time series was increased by 10.8%

Precipitation

Only the hot and dry scenario included a change to the precipitation time series. Precipitation data from 1984-2005 was adjusted based on the 2030 drought to simulate drought-like conditions. The adjustment was conducted by comparing 2005, the most current model year, to the 2030 drought to develop seasonal adjustment factors (Table 1). These factors were then applied to the observed 1984-2005 precipitation time series, resulting in the 1984-2005 hot and dry precipitation time series.

Evapotranspiration

One impact of the temperature change included in the climate change and the hot and dry scenarios is an increase in the potential evapotranspiration (EVAP) used as an input in the HSPF model. The EVAP variable was recalculated using the Hamon method for estimating evapotranspiration and the increased daily temperature described above (Hamon 1961). The adjusted daily EVAP values were recorded in the meteorological WDM input data files for the HSPF model.

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[1] Watershed Data Management (WDM) is a binary input file used to store input time series for HSPF.

Land use

For all scenarios, the land use utilized for this effort was developed by the Chesapeake Bay Program at the HSPF model land-river segment scale for the year 2030. Figures 6-8 show the projected 2030 percent forest, urban, and agriculture, respectively, by river segment.

Results

Once all model inputs were prepared, the data were brought into the modeling environment. A new model scenario was developed, new control files were generated for each scenario that pointed to the new inputs, and the model was executed. The results of these efforts included five time series for each river segment in the simulation area, one for each of the future scenarios. A suite of flow metrics were then calculated based on the time series and alteration was calculated for each metric between the current and future scenarios as well as the baseline and future scenarios.

In general, the most extreme hydrologic alteration was found in the hot and dry scenario, followed by the climate change scenario. One example of this is found in median daily flow (Figure 9). Portions of the basin are expected to experience increases in median daily flow under the DP1, DP2, and power scenarios resulting from a decrease in forest associated with a decrease in evapotranspiration. 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. The climate change and hot and dry scenarios, on the other hand, show substantial decreases in median daily flow due to urbanization, population growth, and an increase in withdrawals in addition to the meteorological stressors associated with the two scenarios. A full suite of maps showing the alteration in various flow metrics between baseline and future scenarios and current and future scenarios were presented in the February webinar.

References

Hamon, W.R. 1961. Estimating potential evapotranspiration. Proceedings of the American Society of Civil Engineers 87:107-120.

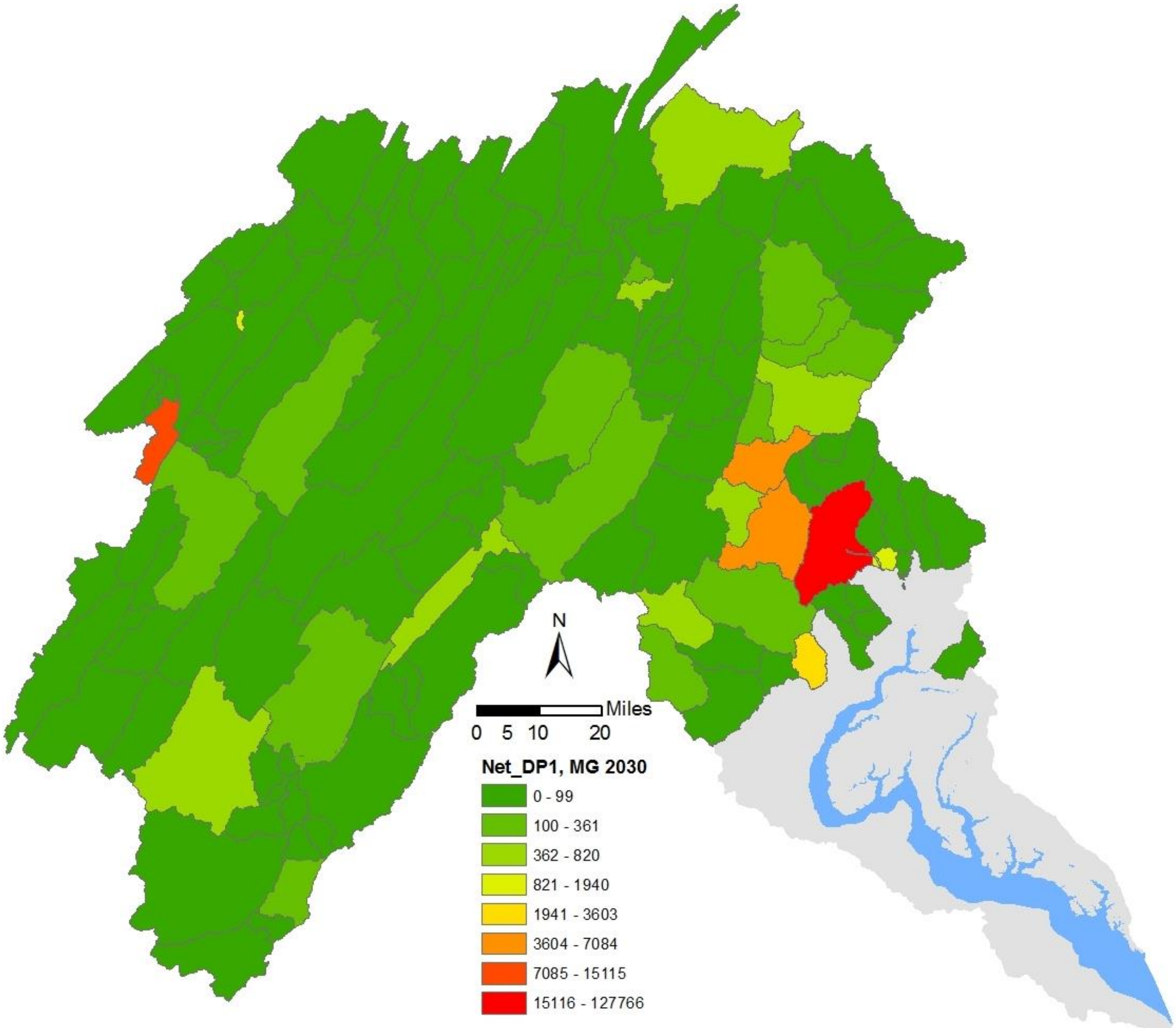

Figure 1. Total net withdrawals for the year 2030 in the DP1 scenario (MG).

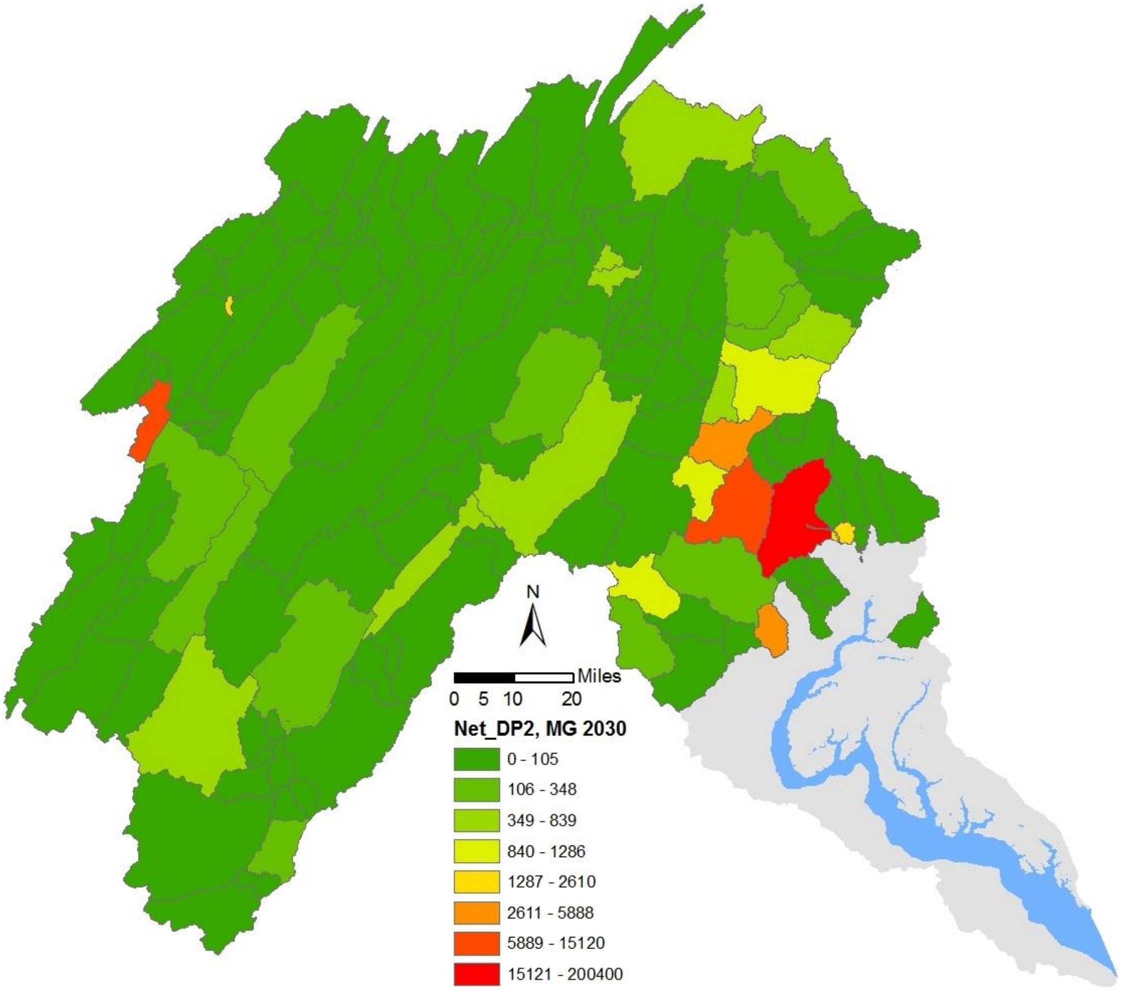

Figure 2. Total net withdrawals for the year 2030 in the DP2 scenario (MG).

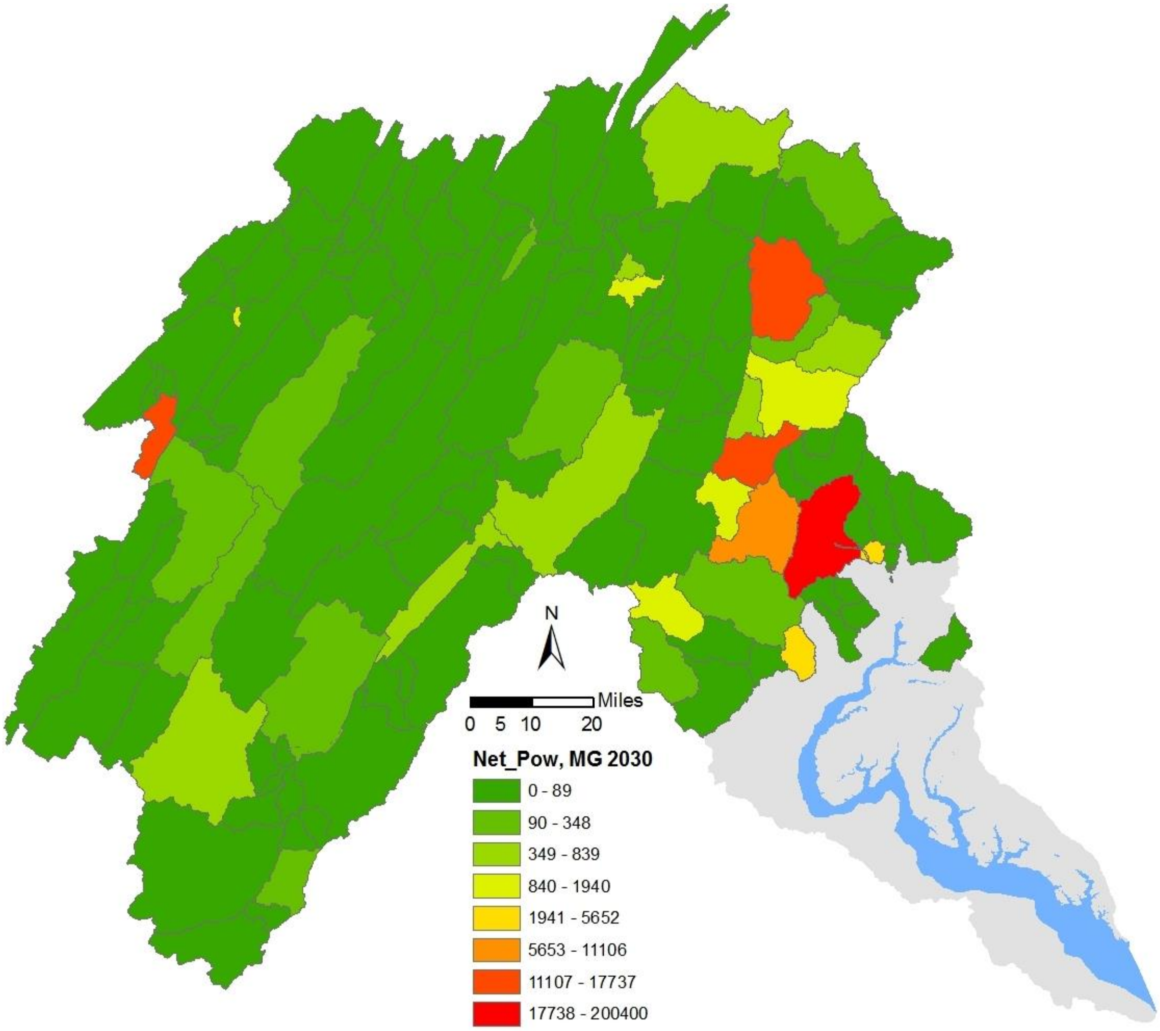

Figure 3. Total net withdrawals for the year 2030 in the power scenario (MG).

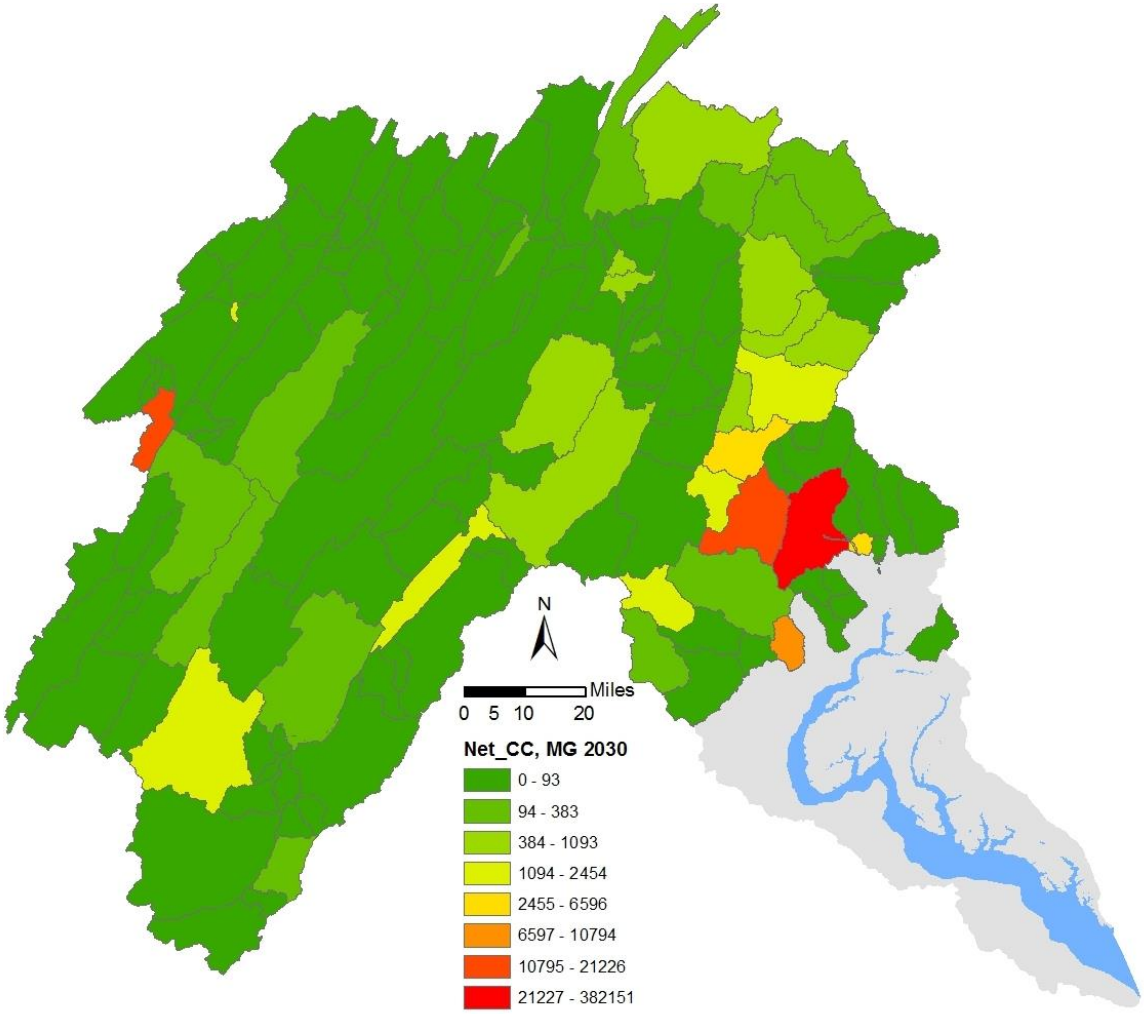

Figure 4. Total net withdrawals for the year 2030 in the climate change scenario (MG).

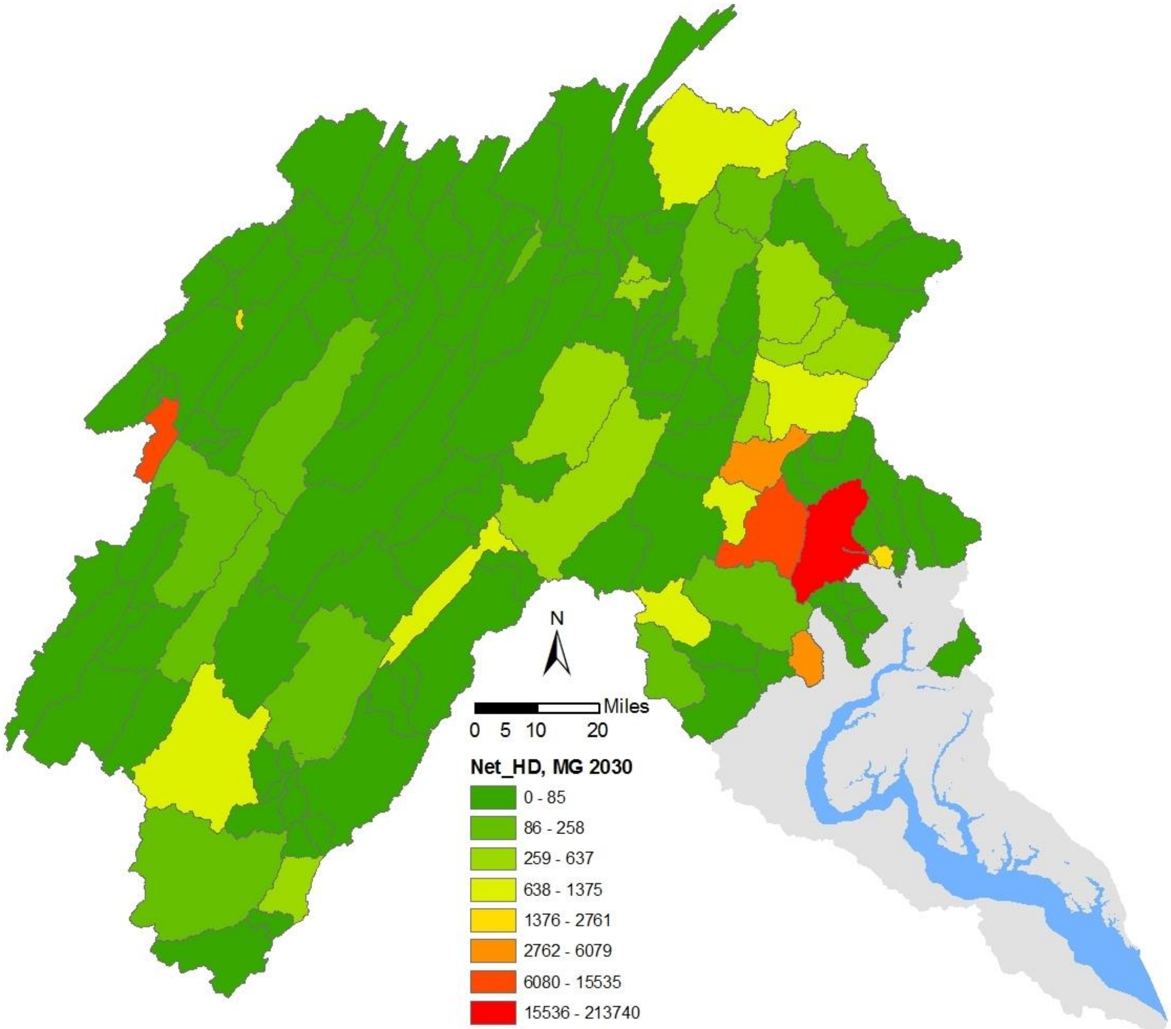

Figure 5. Total net withdrawals for the year 2030 in the hot and dry scenario (MG).

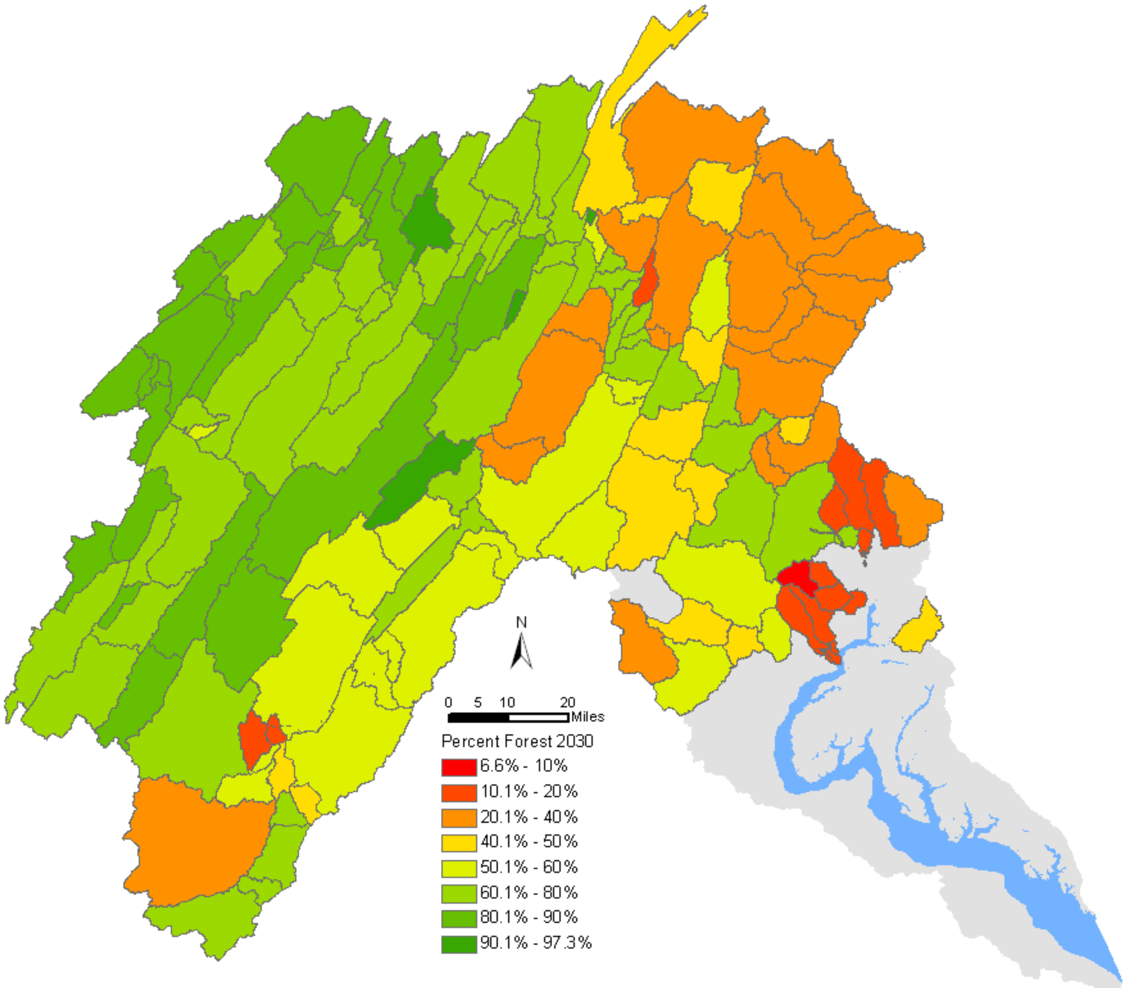

Figure 6. CBP projected 2030 percent forest by river segment.

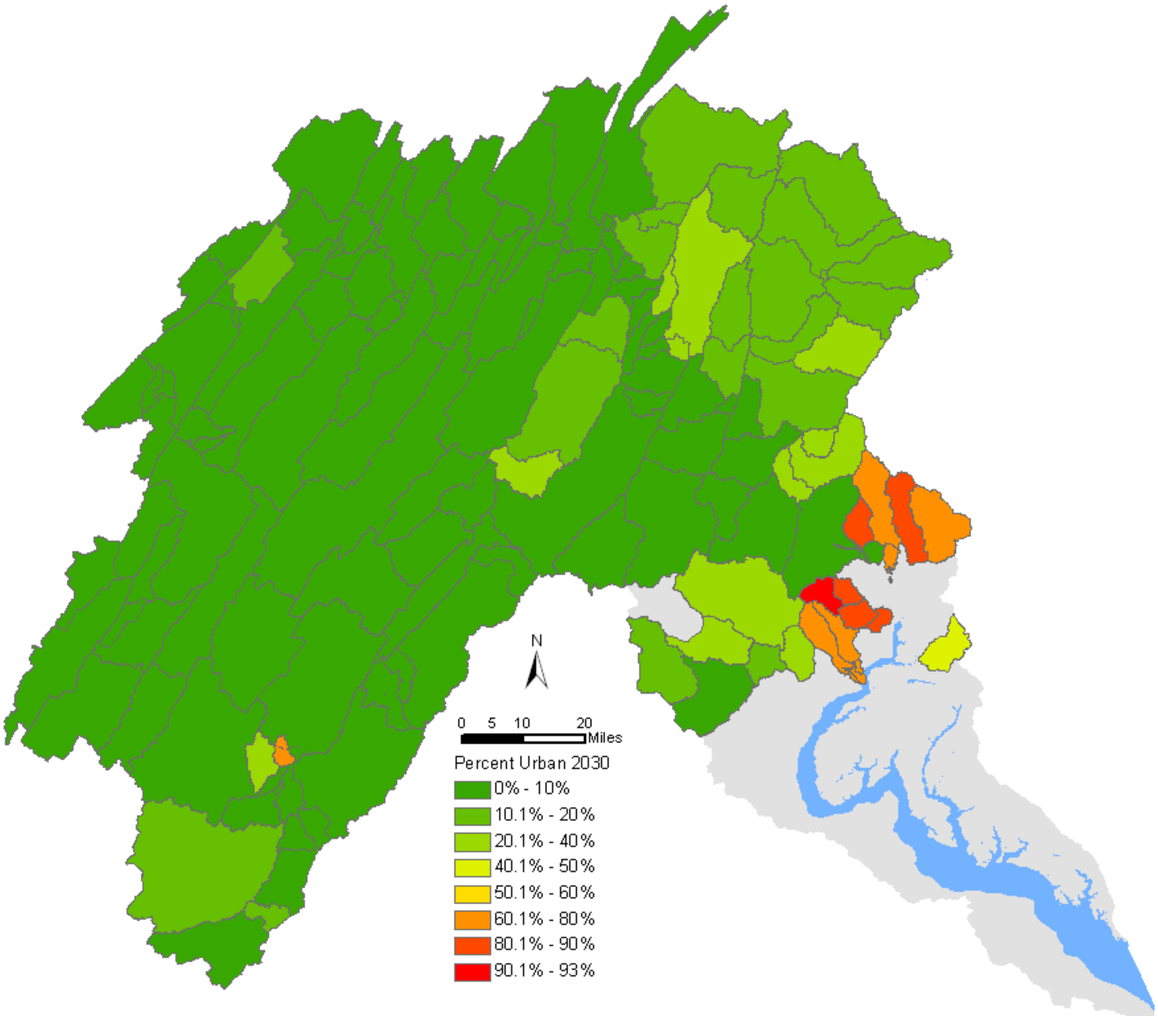

Figure 7. CBP projected 2030 percent urban areas by river segment.

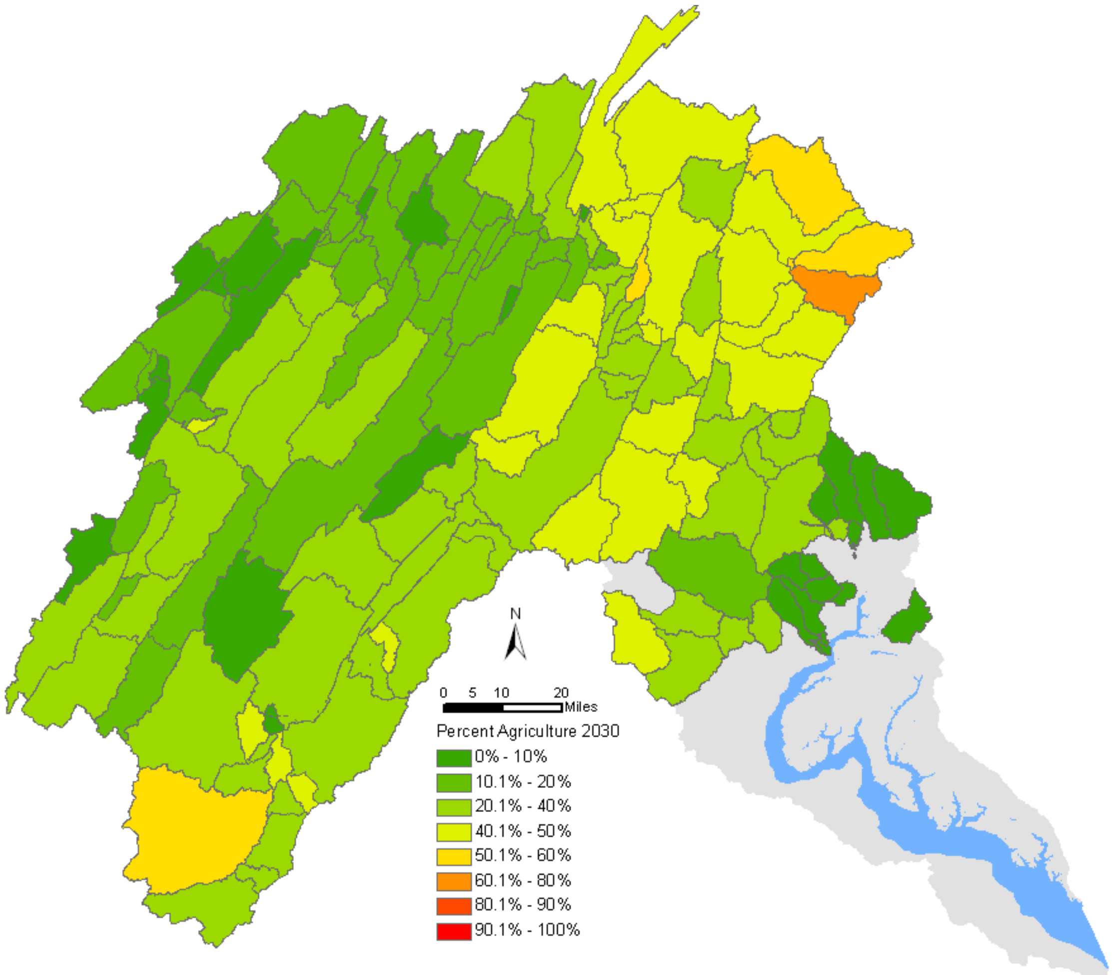

Figure 8. CBP projected 2030 percent agriculture by river segment.

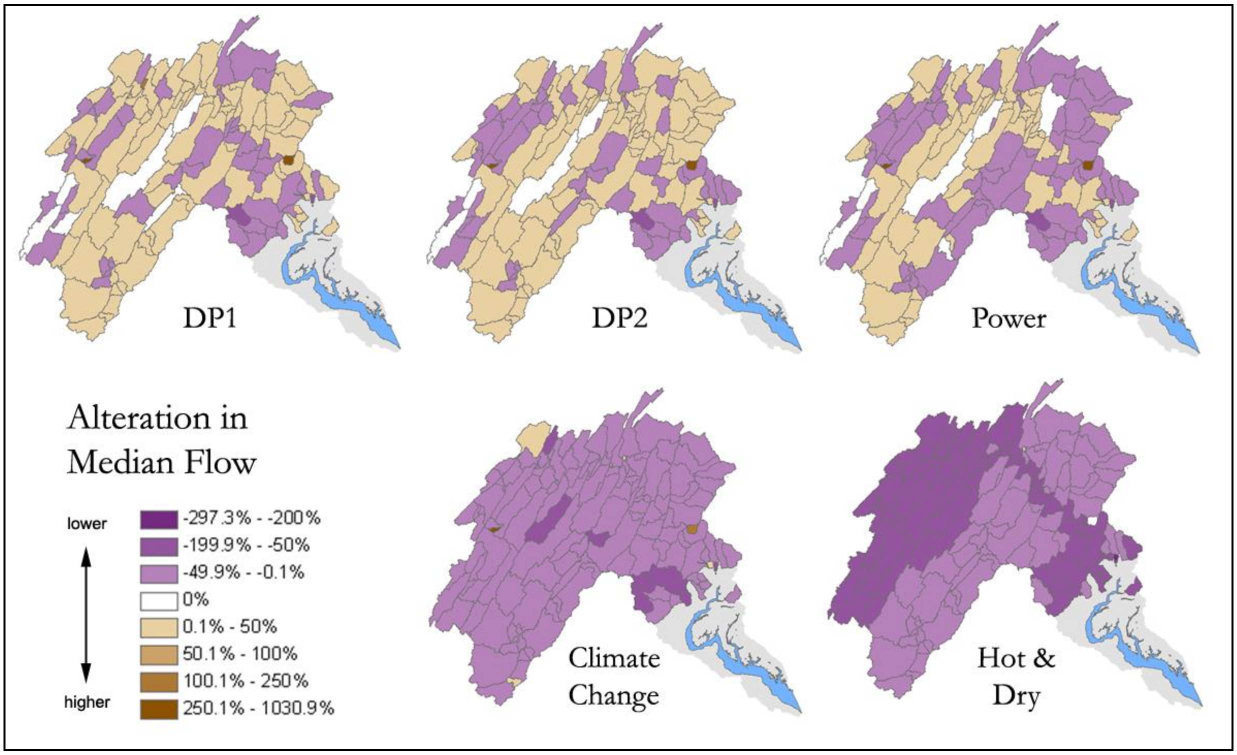

Figure 9. Future alteration in select flow metrics, displayed spatially by HSPF model river segment. Hydrologic alteration that is expected to occur in the future is calculated utilizing IHA results and the following equation: ((future-baseline)/baseline) - ((current-baseline)/baseline).

Table 1. Hot and dry scenario seasonal adjustment factors.

Season	Months	Factor
Winter	Dec, Jan, Feb	0.151
Spring	Mar, Apr, May	0.4545
Summer	Jun, Jul, Aug	0.6723
Fall	Sept, Oct, Nov	0.8365

Appendix 1. Baseline, current, and five future model scenarios and a summary of the watershed characteristics depicted in each one.

Scenario	Land Use	Withdrawal	Discharge	Impound	Temperature	Precipitation
Baseline	>78% forest, <0.35% impervious cover	0	0	0	CBP (84-05)	CBP (84-05)
Current	2000 RESAC converted to P5 land use categories	ICPRB 2005	CBP point source database, 2005	16	CBP (84-05)	CBP (84-05)
DP 1	CBP 5.1 future projections	per capita increase 0%	withdrawal - CU	16	CBP (84-05)	CBP (84-05)
DP 2	CBP 5.1 future projections	per capita increase 1.82%	withdrawal - CU	16	CBP (84-05)	CBP (84-05)
Power	CBP 5.1 future projections	projected and additional power plant and retrofits	withdrawal - CU	16	CBP (84-05)	CBP (84-05)
Hot and Dry	CBP 5.1 future projections	DP2 base with increases in DP, PO, and irrigation	withdrawal - CU	16	10.8% increase (1930 drought)	Decrease (1930 drought v "normal" year)
Climate Change	CBP 5.1 future projections	per capita increase 4.38%	withdrawal - CU	16	0.4C increase by 2030	CBP (84-05)

DP=domestic and public supply; CU=consumptive use; CBP=Chesapeake Bay Program

Appendix E – Hydrologic Model

Watershed Delineation

Watersheds were delineated above each of the biologic sampling sites. The objective of this effort was to select a minimum of 30 sites per stream class and ecoregion of interest. The stream classes were classified by contributing watershed area into four classifications utilizing the Northeast Aquatic Habitat Classification System (NEAHCS); < 5.18 km^2 (Class 1), 5.18 km^2 - <25.9 km^2 (Class 2), 25.9 km^2 – 259 km^2 (Class 3), and > 259 km^2 (Class 4). Ecoregions of interest included karst, Triassic Lowlands, highlands, and coastal plain.

The delineation was performed in a graphical information system (GIS) using geographic datasets of biological monitoring locations, stream networks, and watersheds associated with the stream network. The process involved selecting monitoring locations based on a previously determined ranking of biological condition, identifying the stream network associated with each monitoring location and the contributing watershed of the stream and any tributaries above each monitoring location.

The dataset of biological monitoring locations used was extracted from the 2009 Chesapeake Bay B-IBI database (see Appendix C), selecting those monitoring locations within the Potomac River basin. This dataset included the geographic coordinates of each location and a ranking of the biological condition (Rank) at that location. These were used to generate a unique identifier for each location point and in the selection of the points for delineation, respectively. A unique identifier was generated for each of these points based on the point's latitude and longitude in degrees, minutes, and seconds concatenated to a single 15 character string.

The stream network utilized was the NHDPlus (USEPA, 2005) dataset produced by Horizon Systems for the US Environmental Protection Agency and the US Geological Survey. This dataset contains a medium-resolution NHD stream network and elevation-derived catchments associated with the streams.

An initial selection was made of those monitoring locations that were within 200 ft of a stream feature in the NHDPlus stream network dataset. This was done to remove monitoring locations with coordinates that placed the point too far from a stream feature in the stream network to be certain of the sampled stream. The monitoring locations were then selected based on the value of their macroinvertebrate Chessie BIBI rank, from possible rankings of "Excellent", "Good", "Fair", "Poor", or "Very Poor". Monitoring locations with a rank of "Excellent", "Good", or "Fair" initially were given preference for watershed delineation on the premise that these would best reflect the effects of flow alteration and avoid the affects of other factors impacting stream macroinvertebrates such as poor water quality and degraded habitat conditions. This approach was expected to produce the least confounded flow alteration-ecology curves. The final data set of 747 watersheds includes sites with the full range of BIBI rankings to ensure that the full range of flow alteration impacts, confounded or otherwise, was represented in the analysis.

First, the monitoring points located in the headwaters of the stream network, with a contributing area of less than 5.18 square kilometers (km^2), or 2 square miles (mi^2) were selected. The NHDPlus catchment associated with each of these points was assigned the unique identifier of the monitoring point and a Size Classification of Class 1. Monitoring points with were individually selected from the remaining points in the monitoring location dataset and the stream network above each point was selected and the catchments associated with these streams combined into a single watershed. The area of the watershed was calculated in the GIS and a Size Classification was assigned according to this area. The unique identifier of the monitoring point was assigned to the resulting watershed. Exceptions to this procedure were taken for cases where the monitoring point was not located at or near the downstream end of a NHDPlus catchment. These points did not have their contributing watershed delineated with this method because the difference between the actual contributing area above the point and the area of the existing catchments would be large enough to introduce unacceptable errors in subsequent area-based flow estimations.

An alternative watershed delineation process was used to delineate these 'exceptions', watersheds where the monitoring location point was too far removed from the downstream end of the identified watershed. This process used the Multi-Watershed Delineation (MWD) Tool, a standalone program created by developers at Utah State University to derive watershed polygons, river networks, and watershed attributes for multiple sites across large geographic extents. The tool requires the pre-processing of Digital Elevation Model (DEM) and stream network datasets for an area including the watersheds to be delineated using GIS tools and creation of a database of points for which the contributing watersheds to be delineated. The tool was then run on the set of monitoring location points identified as being too far removed from the downstream end of the existing watershed.

A primary advantage of the MWD method of delineation is the increased accuracy of the calculated area of the watershed for each monitoring point. The watershed area used for analysis is the delineated contributing area above each point, not the area of existing, previously created catchments. This will reduce the errors in any subsequent area-based flow calculations. The cost involved in using this method is the up-front time required to prepare the datasets and post-processing time for each set of points to get the tool results into the desired format. The watersheds delineated as a result of these two approaches are presented in Figures 1-4.

The resulting watersheds were combined in GIS with a dataset of Level III and IV Ecoregions of EPA Region 3 to calculate the percent of karst, Triassic Lowlands, Highlands, and Coastal Plain Ecoregions within each of the delineated watersheds. This data was appended to the dataset for each of the Size Classes. The number of watersheds in each NEAHCS size class is presented by Ecoregion in Table 1. The number of watersheds was also counted utilizing the NEAHCS classification (Northeast Aquatic Habitat Classification System) (Table 2).

Subsequent revisions to this selection of watersheds occurred to 1) increase the sample size of biological monitoring points and 2) remove biological sampling locations on large rivers that utilized a different, non-comparable sampling methodology. A map of the final 747 watersheds is provided in Figure 5.

References

USEPA. 2005. National Hydrography Dataset Plus – NHDPlus. Produced by Horizon Systems.

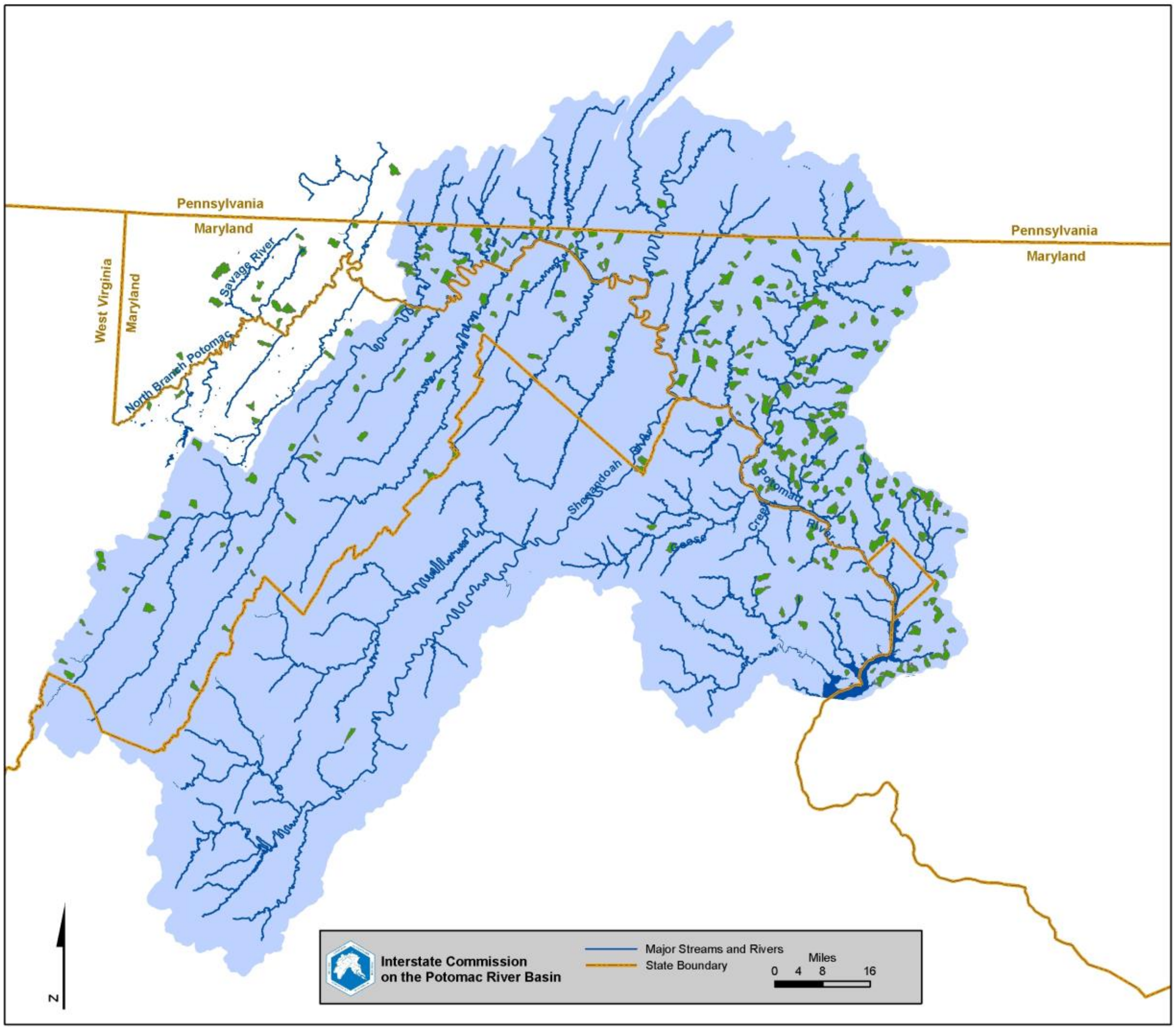

Figure 1. Size class 1 watersheds above selected biological monitoring locations.

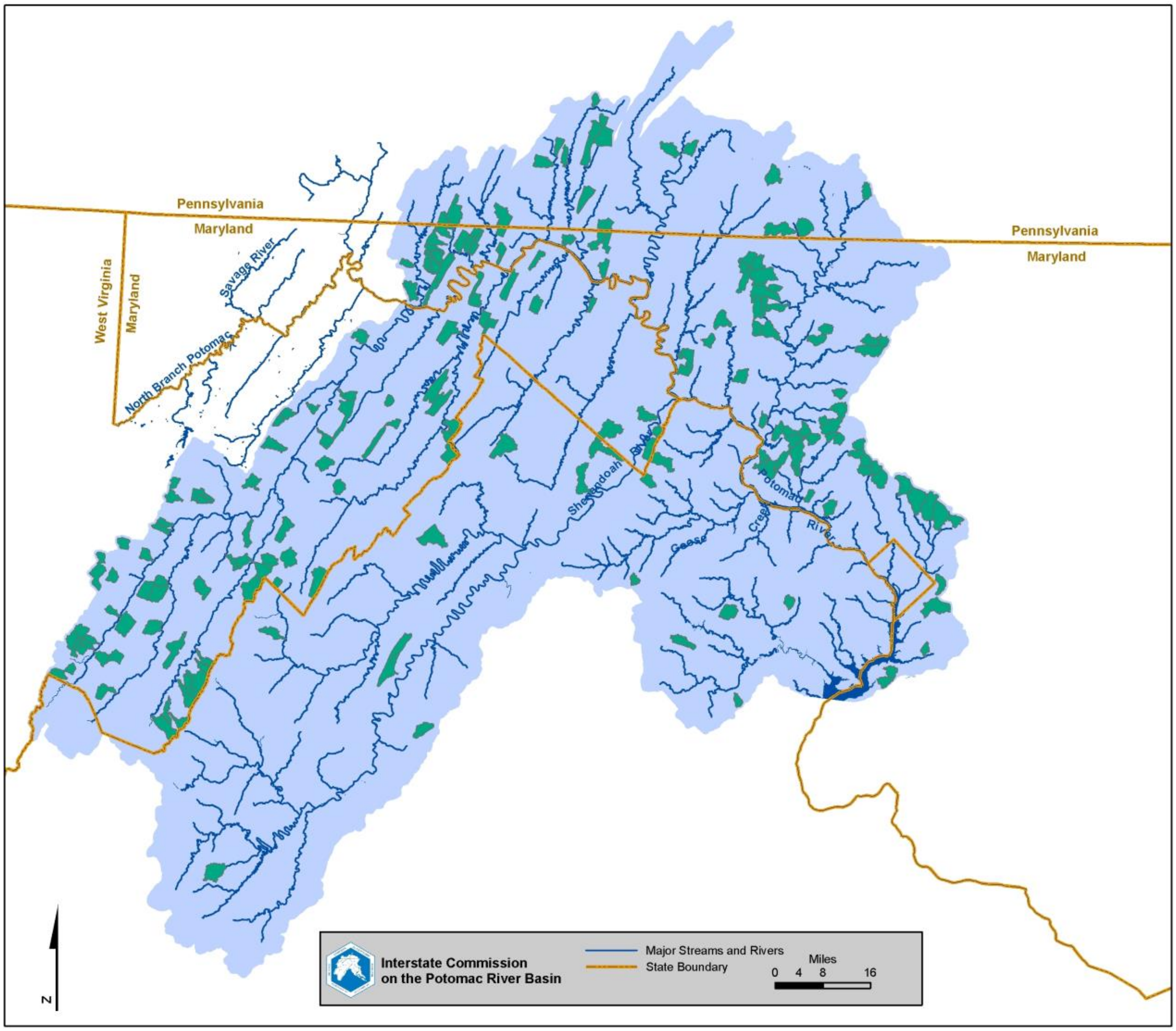

Figure 2. Size class 2 watersheds above selected biological monitoring locations.

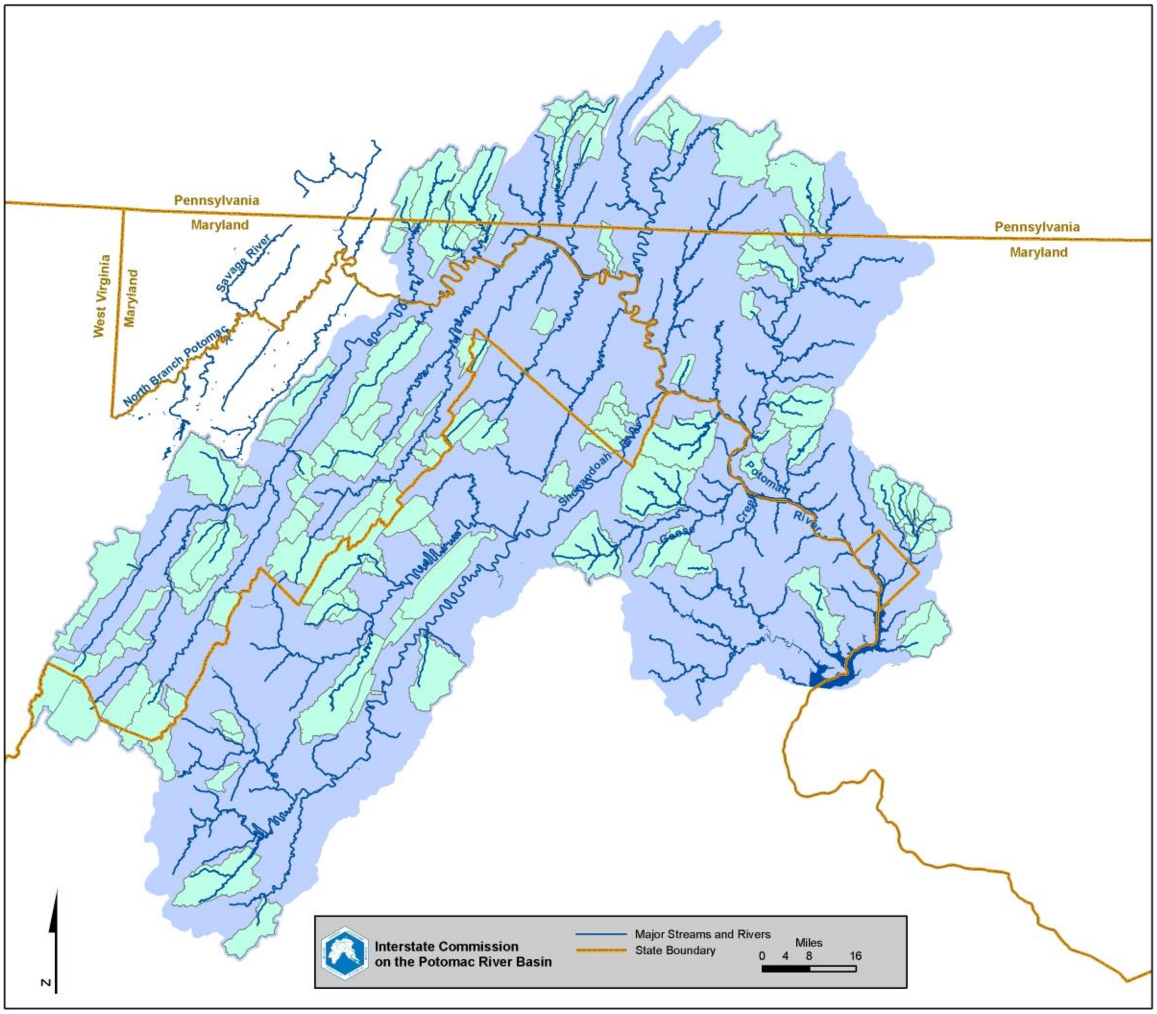

Figure 3. Size class 3 watersheds above selected biological monitoring locations.

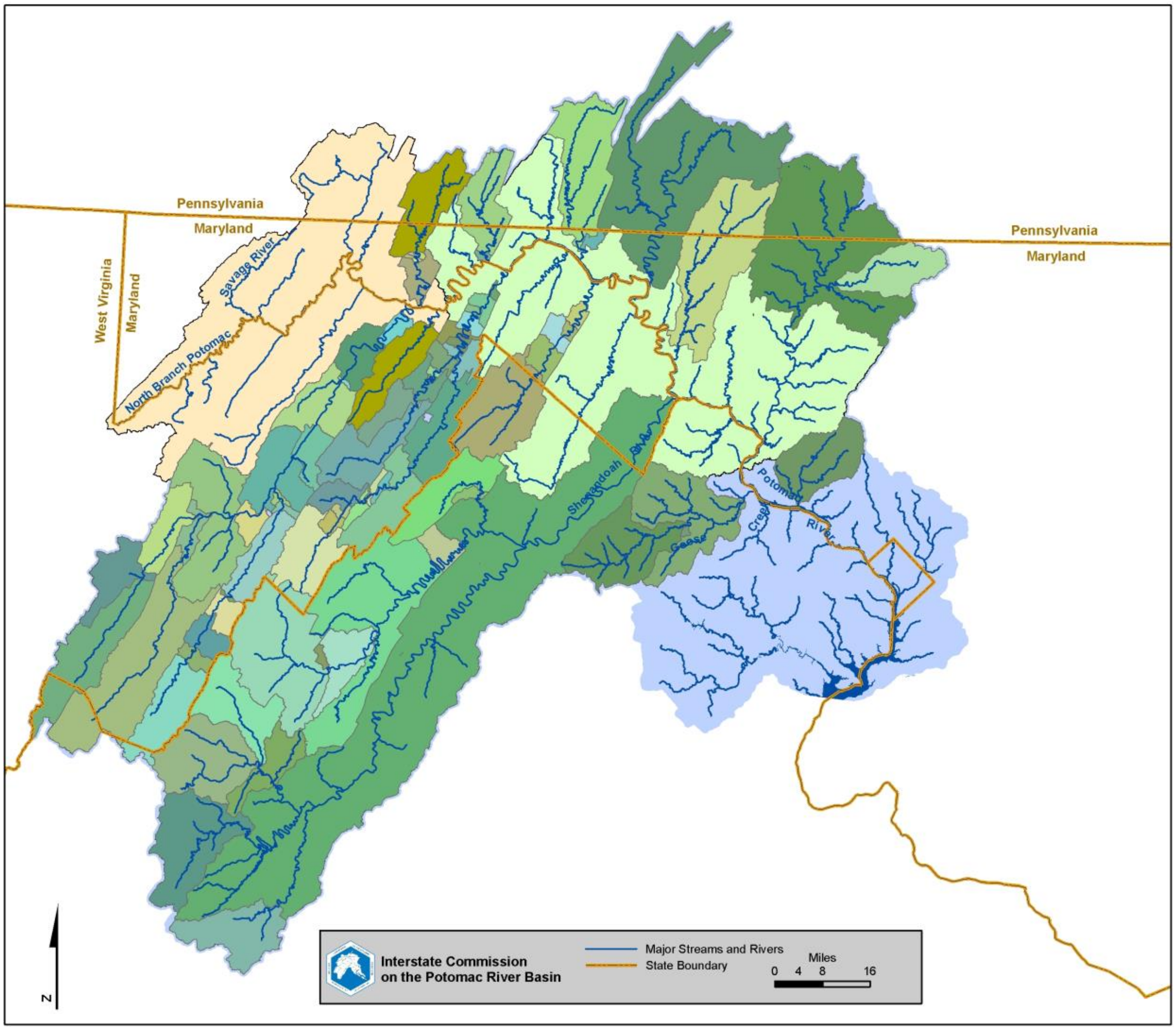

Figure 4. Size class 4 watersheds above selected biological monitoring locations.

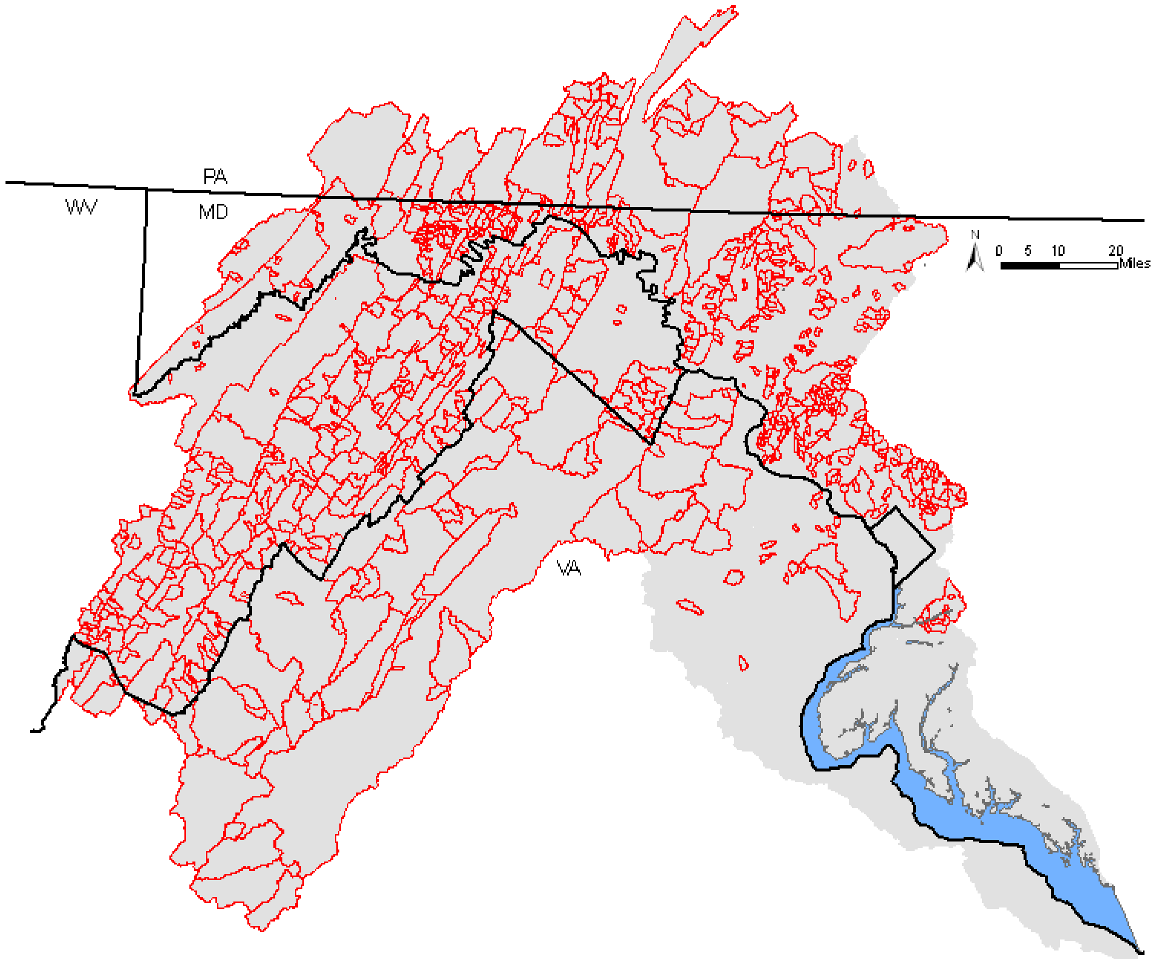

Figure 5. Map of the final 747 watersheds.

Table 1. Number of watersheds with biological monitoring locations in selected ecoregions based on NEAFWA size class.

	size(km²)			
Region	<5.18	5.18-25.9	25.9-259	<259
ValleyRidge				
non-karst	122	151	107	80
karst	13	12	26	16
Piedmont				
non-karst	114	42	13	4
karst	5	1	0	1
Lowland Triassic	28	15	14	3
Non-Triassic, non-karst				
Coastal Plain	37	11	17	0
Highlands	87	102	61	47
Valleys	48	61	72	49

Table 2. Number of watersheds with biological monitoring locations in selected ecoregions by NEAHCS size class.

size(km^2)

Region	<10	10 - <100	100 - <518	518 - <2,590	2,590 - <10,000	10,000 - <25,000	>=25,000
ValleyRidge							
non-karst	202	137	82	31	8	0	0
karst	14	30	12	11	0	0	0
Piedmont							
non-karst	143	19	10	1	0	0	0
karst	5	1	0	1	0	0	0
Lowland Triassic	33	20	6	0	0	0	1
Non-Triassic, non-karst							
Coastal Plain	43	18	4	0	0	0	0
Highlands	141	81	57	10	8	0	0
Valleys	75	86	37	32	0	0	0

Appendix E – Hydrologic Model

Resegmentation at Impoundments

Introduction

Re-segmentation of the Chesapeake Bay Program (CBP) hydrologic model was conducted to improve spatial representation of watershed characteristics and to aid in the development of model scenarios. In anticipation of estimating flows at biological monitoring locations, factors significantly altering hydrology between current model outlets and selected upstream biological monitoring points needed to be explicitly included in the model. Withdrawals and land uses may potentially affect hydrology but adjustment of these factors to simulate baseline conditions does not require re-segmentation. The ICPRB re-segmentation of the CBP model, therefore, was conducted at impoundments with potential significant hydrologic alteration. Prior to this effort, only a handful of impoundments were explicitly simulated in the Potomac portion of the CBP model including the Upper Occoquan, Stony River, Savage River, Jennings Randolph, and T. Nelson Elliot. Re-segmentation occurred in several stages including (1) identification of significant impoundments, (2) generating necessary model inputs, (3) implementing the new segmentation in the modeling environment, and (4) auto-calibration.

Identification of significant impoundments

Impoundments were identified for inclusion in the model if they were "significant" and had biological monitoring sites upstream and downstream of them within the existing CBP Phase 5 river segment. 481 impoundments were identified by county in the National Inventory of Dams for the Potomac River basin (Figure 1). Impoundments were identified as "significant" using the following criteria: (1) water was impounded to generate hydroelectricity; (2) reservoir normal storage capacity was greater than 10% of the mean flow; or (3) both 1 and 2. Of the 153 significant impoundments, 15 had biological monitoring sites upstream and downstream within a CBP Phase 5 river segment and, therefore, met the requirements for inclusion in the HSPF model.

Three dams met all criteria for re-segmentation but were not included. These impoundments were Edinburg and Burnshire Dams in Virginia and Thomas W. Koon Dam in Pennsylvania. Edinburg and Burnshire were identified based on their use for hydroelectric power generation (NID). During ICPRB data collection, it was confirmed that these impoundments are no longer utilized for hydroelectric purposes and, therefore, no longer meet the criteria for re-segmentation (personal communication by J. Palmer, Friends of the North Fork of the Shenandoah, December 2009). Thomas W. Koon Dam is utilized to maintain flows to nearby, downstream Lake Gordon, a drinking water supply reservoir. Drinking water withdrawals are taken from Lake Gordon and downstream flows are dependent on the releases from Gordon (personal communication by J. Palmer, Evitts Creek Water Company, December 2009). For this reason, Gordon (the downstream reservoir) was selected for re-segmentation.

The remaining 12 significant impoundments were considered candidates for model re-segmentation at the dam outlet; namely, Little Seneca Dam, Blairs Valley Dam, Rocky Gap Dam, Lake Gordon

Dam, Barcroft Dam, Newport Dam, Luray Dam, Chapman Dam, Sleepy Creek Dam, Patterson Creek Dam Nos. 4 and 41, and Dam No 4 Hydro Station. Appendix 1 of this document provides summary characteristics of each impoundment.

Developing Model Inputs

Generating necessary inputs for the modeling environment included (1) delineating the new river segment boundaries and quantifying new segment characteristics, (2) calculating the land uses, (3) developing input and output time series necessary to run the model, and (4) generating reservoir hydraulic function tables (FTABLEs). A description of these efforts is presented below.

Delineating River Segments

Twenty-four new river segments were delineated (Figure 2). The National Hydrography Dataset Plus (NHDPlus) layer was used to refine watershed boundaries within the larger Phase 5 river segment boundaries. The appropriate polygons from these layers were selected and merged in ArcGIS 9.2 to form the new boundaries. An attribute was added to the polygon shapefile containing the new river segment ID (Table 1). The segment IDs are consistent with the CBP naming convention documented in Section 3 (EPA 2009).

River length and watershed area were calculated for each of the new river segments and are required input for the hydrologic model. When the new segment contained a Phase 5 simulated river, the river length was calculated in ArcGIS 9.2 by intersecting the new river segment boundary and the river polylines. For new river segments not previously containing a simulated river, the higher resolution NHDPlus stream classification was used to create a simulated river. The ArcGIS ruler tool was used to measure the length of the mainstem within the new model segment.

Land Uses

Land use inputs for the CBP Phase 5 model are comprised of a series of Excel spreadsheets as described in Section 4 (EPA 2009). Within a spreadsheet, land uses are given for each land-river segment. Note, however, that land uses are not spatially explicit within the land-river segments. A different spreadsheet is utilized for 1982, 1987, 1992, 1995, 1997, and 2002 land use inputs. The CBP model interpolates between years resulting in changing land uses over the 21 year simulation. To divide non-spatially explicit Phase 5 land uses into 24 new segments for the year 2002, the spatially explicit University of Maryland RESAC raster grid was obtained for the Potomac River basin.[1] For each new land-river segment, the RESAC land uses were calculated using the Tabulate Area tool in ArcGIS 9.2. Due to discrepancies in areas and land use categories between the RESAC (21 land use categories) and Phase 5 land uses (29 land use categories), an optimization was performed. The ICPRB developed an automated macro-based spreadsheet capable of converting RESAC to Phase 5 land uses (personal communication, J. Palmer, ICPRB). The optimization routine utilized a five-phase process: (1) combine RESAC land uses for each land-river segment into 5 broad categories (developed, extractive, barren, crop/pasture, and forest); (2) obtain Phase 5 land uses for the original land river segment and combine them into the same 5 categories; (3) optimize these categories such that the areas for each land use category are the same for the Phase 5 and

[1] 2000 RESAC data was utilized to estimate the 2002 land use time series step in the Phase 5 model.

RESAC land uses; (4) calculate the percentage of each Phase 5 category contained in the broad 5 categories; (5) use these percentages to expand the optimized RESAC categories into the Phase 5 categorization system (personal communication, Ross Mandel, ICPRB).

After calculating 2002 re-segmented land uses, the % change in 2002 land use to each previous time step was calculated for the Phase 5 land-river segments. The percent change for each Phase 5 land use were applied to the new land-river segment's 2002 land uses to obtain the new areas for each time period. The results were quality controlled to ensure the total area of each river segment was maintained throughout the 21 year simulation period.

Input Time Series

Input time series including point sources, septics, and withdrawals are summed for each river or land-river segment and input as daily load.

Point sources

Point source locations within the Potomac River basin were obtained from the CBP point source database by searching for facility information in MD, PA, DC, WV, and VA.[2] The facility locations were imported by latitude and longitude into GIS, clipped to re-segmented areas, and linked to the CBP Phase 5 point source database by facility number.

For new segments with no point sources, a blank WDM,[3] provided in the CBP HSPF modeling environment, was used. For new segments that include all of the point sources from the Phase 5 segment, a copy of the Phase 5 segment's input time series was used. For segments where the WDMs are divided between new segments, the CBP database was used to divide the allocation of flow between the two new segments. WDMUtil, a program developed by AQUA TERRA to create and edit WDMs, was used to create the new point source time series based on an existing WDM's format.

Diversions

The ICPRB withdrawal database (based on 2005 Potomac River basin withdrawal data obtained from the basin jurisdictions) was utilized to assess the locations of diversions within new model segments. For new model segments with no withdrawals, a blank WDM (available within Phase 5) was utilized. For new model segments that contain all withdrawals from the original model segment, a copy of the original WDM was utilized. For new segments that contain only part of the withdrawals from the original river segment, a percentage of the total withdrawals were calculated based on the ICPRB withdrawal database since the withdrawal information used by the CBP to develop the Phase 5 model is not available in a spatially explicit format necessary for re-segmentation. The CBP only has combined diversion WDMs for existing river segments, not spatially explicit time series data for individual withdrawals (personal communication, Gary Shenk, CBP, December 11, 2009).

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[2] http://www.chesapeakebay.net/data_pointsource.aspx

[3] Watershed Data Management (WDM) is a binary input file used to store input time series for HSPF.

Septics

Either the original segments septic WDM or a blank WDM were utilized for the new segments. These files were included in the model, however, they were not used in the model runs as they only affect nitrogen simulation.

Water supply releases

Little Seneca reservoir releases water during low flow conditions to meet the minimum flow-by requirement at Little Falls. Historic releases were included in the re-segmented model as a point source of water to the river segment downstream of Seneca reservoir. Data were obtained for this time series in ICPRB COOP reports (Kiang and Hagen 2003; Steiner 1999).

FTABLE Development

"The HSPF model uses a hydraulic function table, called an FTABLE, to represent the geometric and hydraulic properties of both stream reaches and fully mixed reservoirs. The FTABLE describes the hydrology of a river reach or reservoir segment by defining the functional relationship between water depth, surface area, water volume, and outflow in the segment (Table 2) (EPA 2007)." Each new segment required development of an FTABLE. FTABLE development procedure differed for river and reservoir segments.

Reservoir Segments

Physical and operational characteristics of each impoundment were obtained from NID, VADEQ, State Dam Safety Offices, and other dam owners, operators, and designers. For Patterson No. 4, Patterson No. 41, and Little Seneca, information detailing the relationships of depth, area, volume, and discharge was readily available. Detailed information was not available for other reservoirs, however, FTABLES were developed using hydraulic and hydrologic principles. For example, FTABLEs were created for Chapman, Newport, Luray, Sleepy Creek, and the Dam No. 4 Hydro station using the USGS seamless topographic maps, USGS NED 1/3 ArcSecond DEM, and NID data. After converting the DEM to contours in ArcGIS, contours lines were turned into polygons to calculate reservoir surface areas at various depths. Depths were calculated by normal storage elevation, dam elevation, or reservoir bottom elevation from NID or topographic maps. Volumes were calculated by multiplying depths and surface areas. Discharge was calculated for each depth using the formula: Q=CwLh(3/2) where C=coefficient between 3 and 4 (this study used 3.5), L=length of spillway, h=height of water above spillway (Chapra 1997).

River Segments

FTABLEs for river reaches downstream of the newly modeled reservoirs were developed using the USGS XSECT program (Moyer and Benentt 2007). XSECT is "a computer program that requires nine input variables used to represent channel morphology. These input variables are reach length, upstream and downstream elevation, channel bottom width, channel bankfull width, channel bankfull stage, slope of the floodplain, and Manning's roughness coefficient for the channel and floodplain." Inputs for the USGS XSECT program were developed utilizing 30m DEMs, CBP river reaches, and empirically developed values for simulated river segments.

Implementation of New Segmentation

After FTABLES, land uses, and input time series were complete, the new segments were implemented in the HSPF modeling environment. Files and folders within the CBP modeling structure that were updated in the re-segmentation process are provided in Table 3.

Auto-calibration

The CBP developed "an automated calibration procedure that distilled the experience of the hand calibration into a set of rules that could be implemented in a program. The automated calibration procedure iteratively adjusted parameter values based on the values of output statistics at calibration stations (EPA 2009)." Table 4 lists the key parameters that were calibrated and their range of values.

Auto-calibration of the non-tidal Potomac River basin, including the new segmentation, was conducted using ten iterations of the automatic calibration routine. Flows downstream of each impoundment are presented to illustrate the effects of re-segmentation on flow simulation (Figures 3 through 12). Observed flows are also provided for the segment if available. The downstream effects of Lake Gordon and Rocky Gap dams are shown in the Rocky Gap figure. Similarly, the Patterson figure includes the effects of both Patterson Creek No. 4 and No. 41 on the simulated downstream flows. Calibration statistics for the Phase 5 model and the re-segmented model are provided in Appendix 2 of this document.

References

Chapra, S.C. 1997. Surface water-quality modeling. WCB McGraw-Hill, New York.

EPA. 2007. BASINS Technical Note 1: Creating Hydraulic Function Tables (FTABLES) for Reservoirs in BASINS. U.S. Environmental Protection Agency. Retrieved from http://www.epa.gov/waterscience/basins/docs/tecnote1.pdf.

EPA. 2009. Chesapeake Bay Phase 5 Community Watershed Model. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD.

Kiang, J., and E. Hagen. 2003. 2002 drought operations and lessons learned: Washington metropolitan area. Interstate Commission on the Potomac River Basin.

Moyer, D., and M. Benentt. 2007. Development of relations of stream stage to channel geometry and discharge for stream segments simulated with Hydrologic Simulation Program - Fortran (HSPF), Chesapeake Bay Watershed and Adjacent Parts of Virginia, Maryland, and Delaware. USGS Scientific INvestigations Report, USGS. Retrieved from http://pubs.usgs.gov/sir/2007/5135/pdf/SIR2007-5135.pdf.

Steiner, R.C. 1999. Cooperative management of Washington area 1999 drought operations. Interstate Commission on the Potomac River Basin.

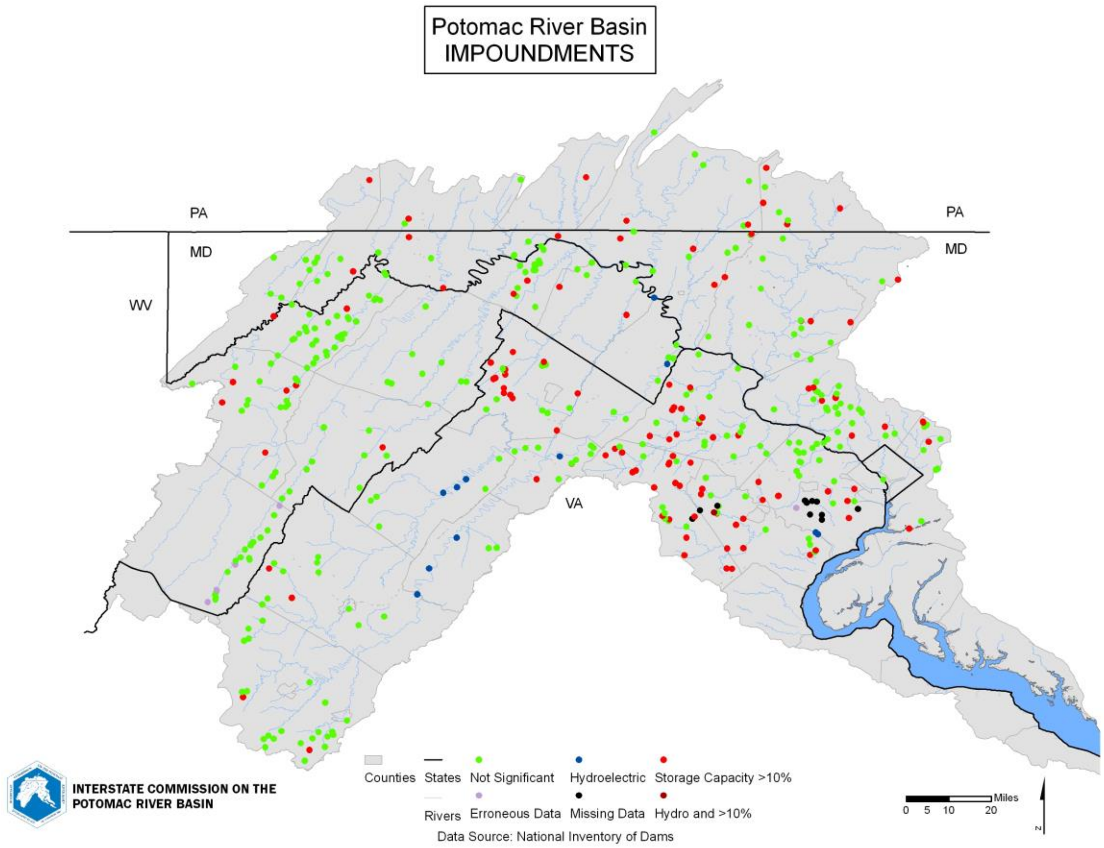

Figure 1. Impoundments of the Potomac River Basin.

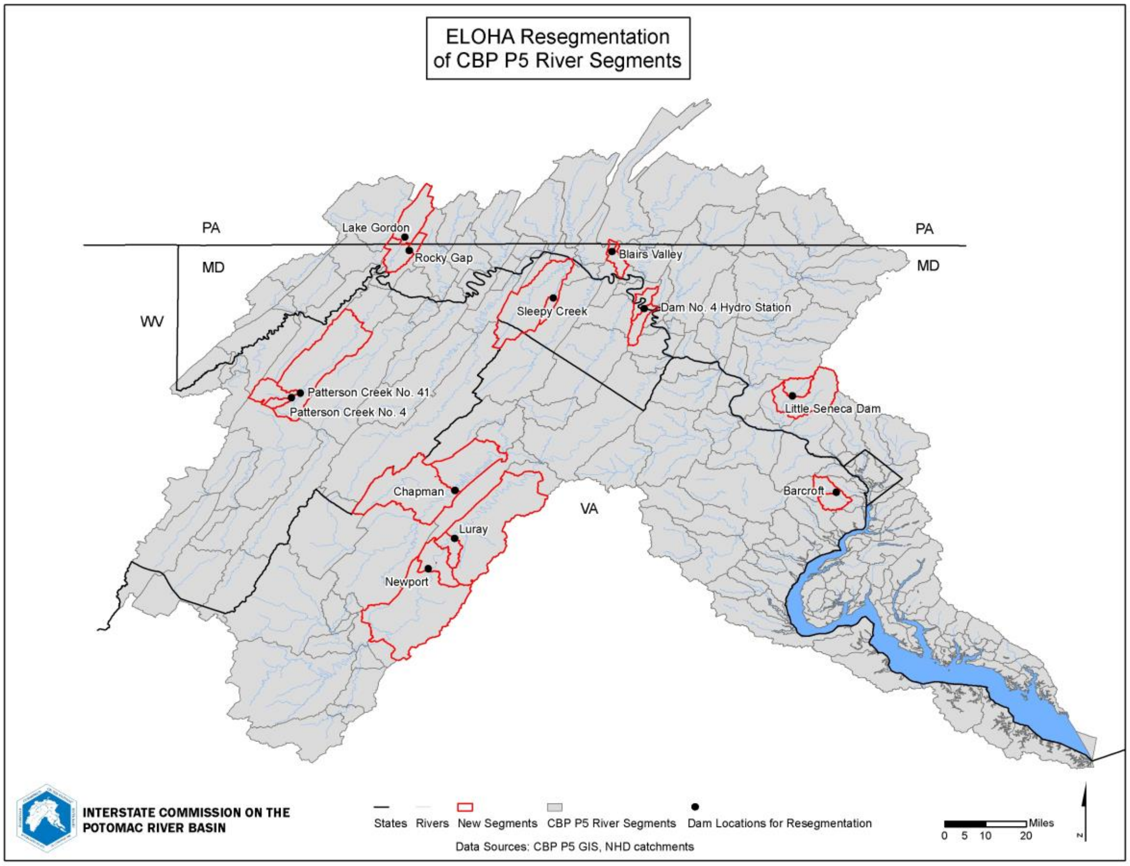

Figure 2. Revised model segmentation at selected impoundments.

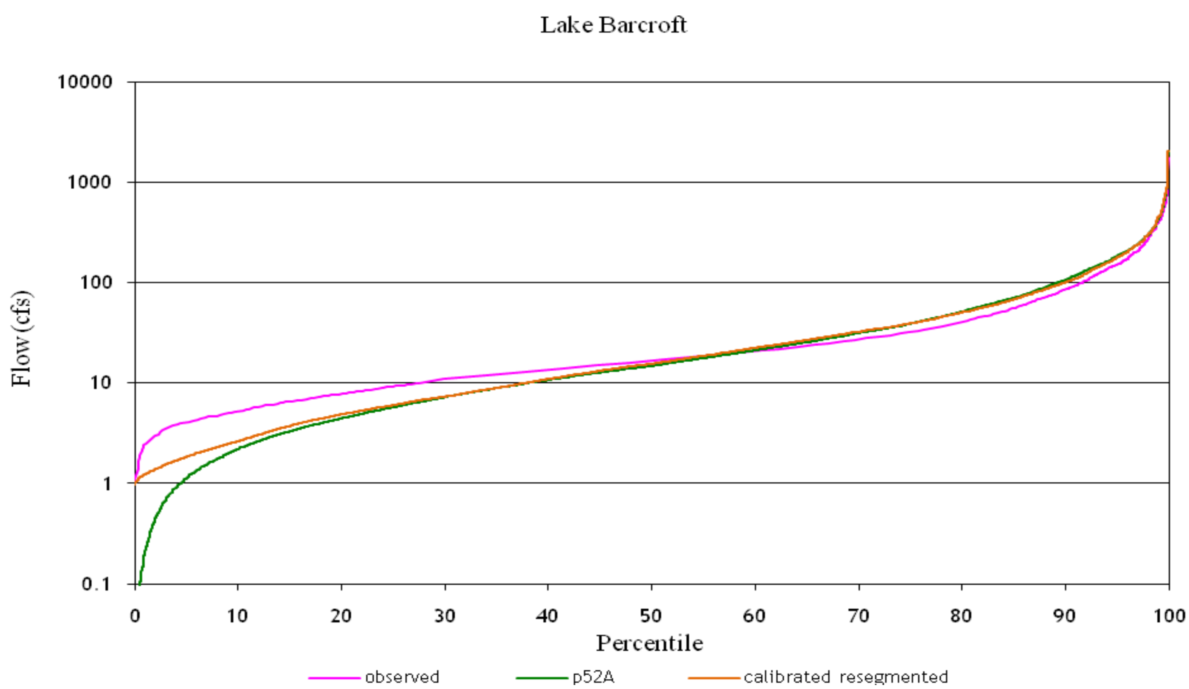

Figure 3. Original, re-segmented, and observed flows downstream of Lake Barcroft.

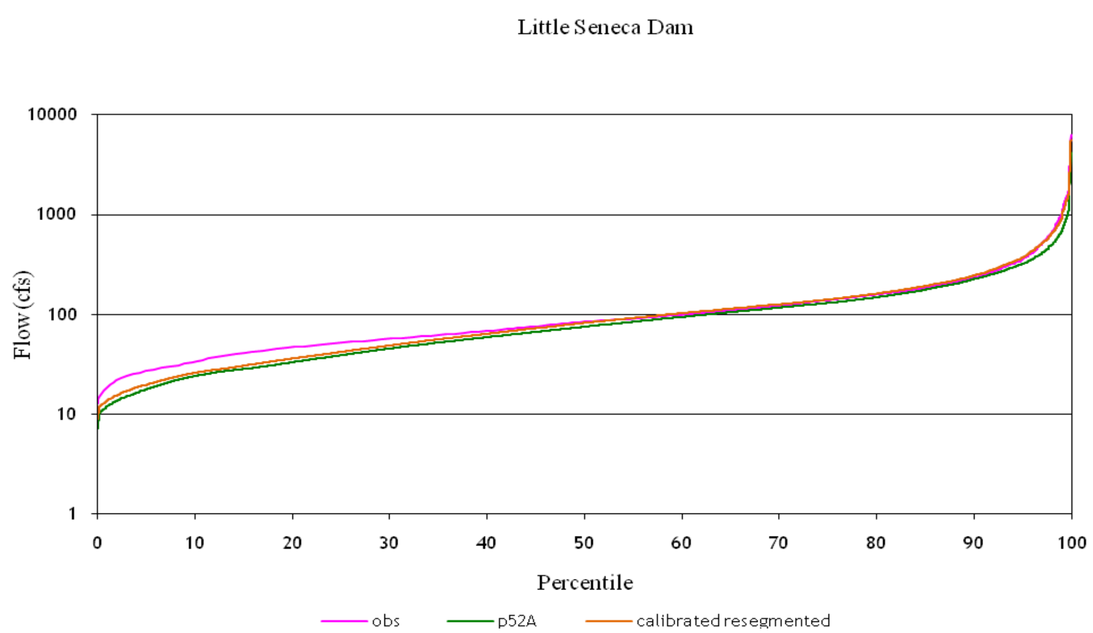

Figure 4. Original, re-segmented, and observed flows downstream of Little Seneca Dam.

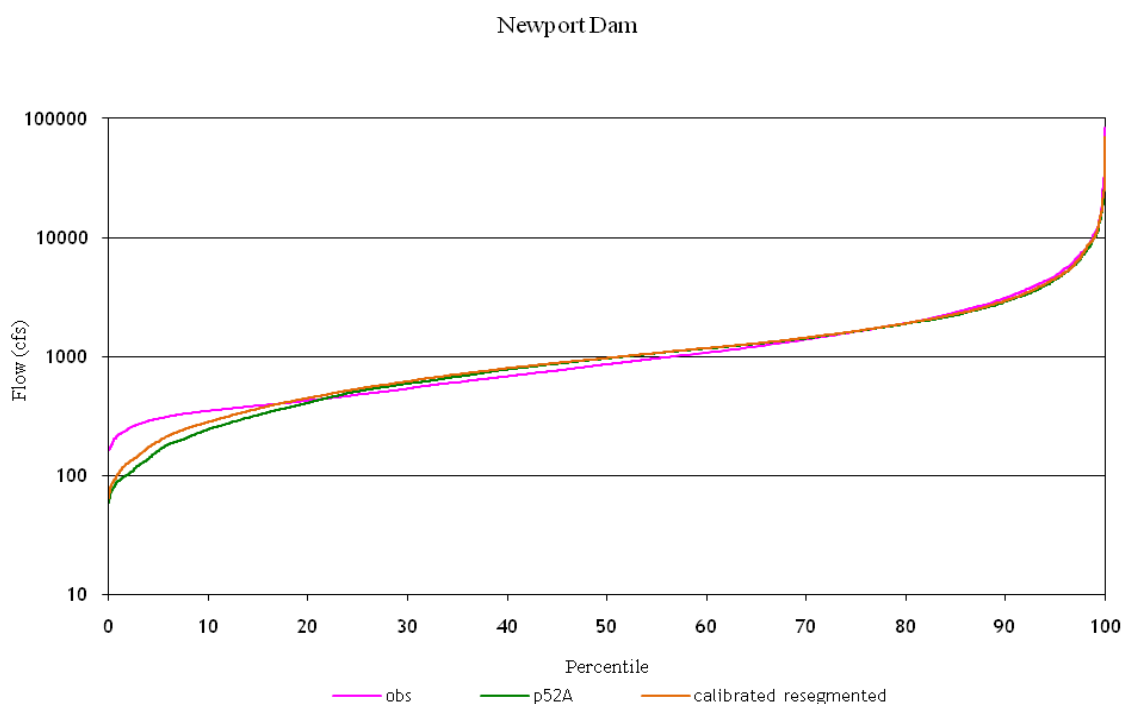

Figure 5. Original, re-segmented, and observed flows downstream of Newport Dam.

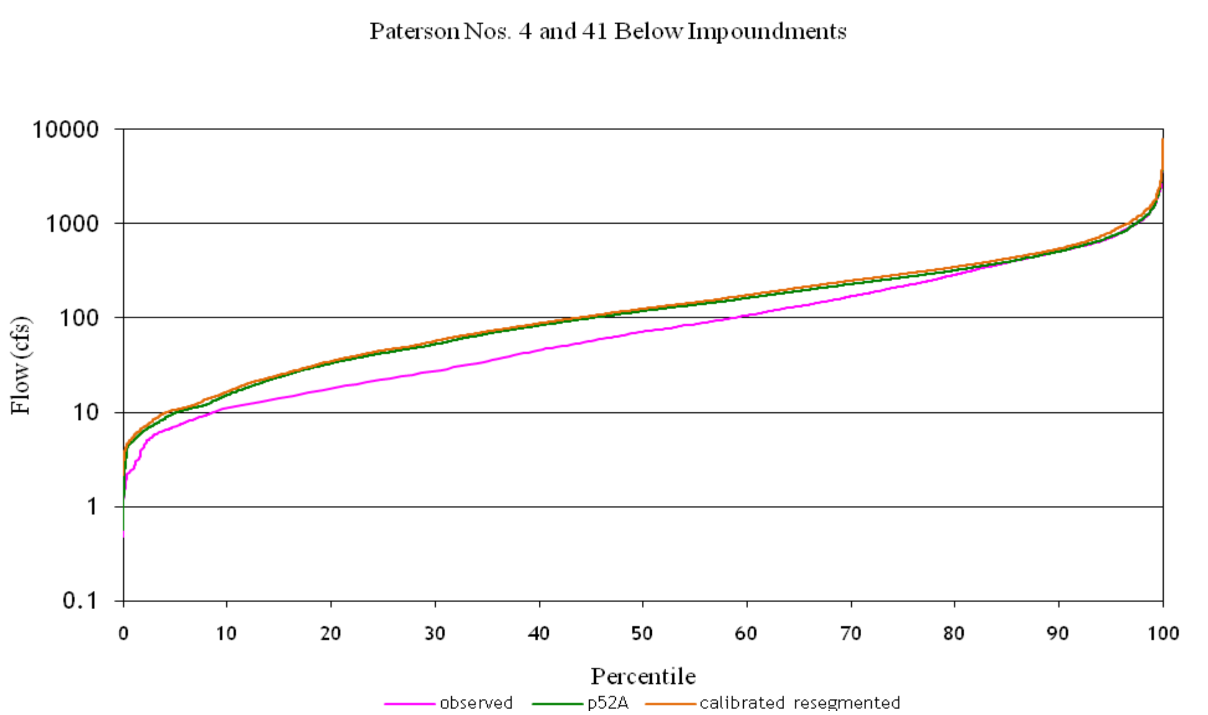

Figure 6. Original, re-segmented, and observed flows downstream of Patterson Nos. 4 and 41.

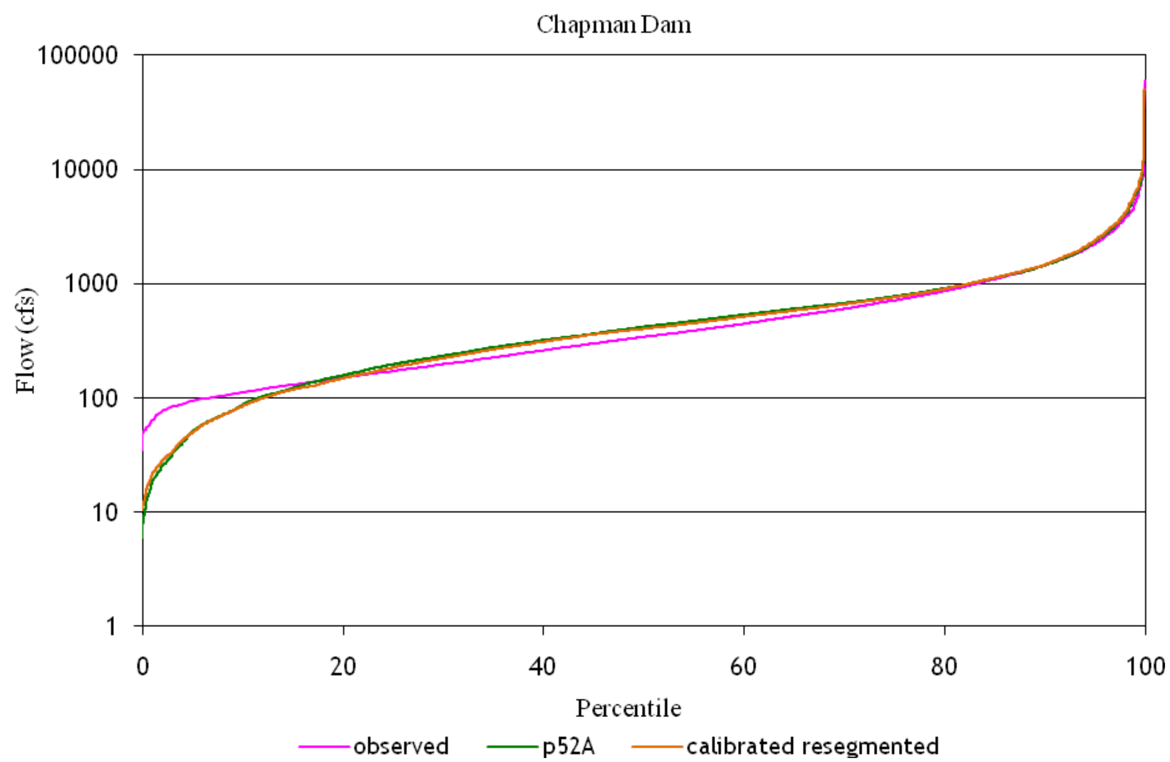

Figure 7. Original, re-segmented, and observed flows downstream of Chapman Dam.

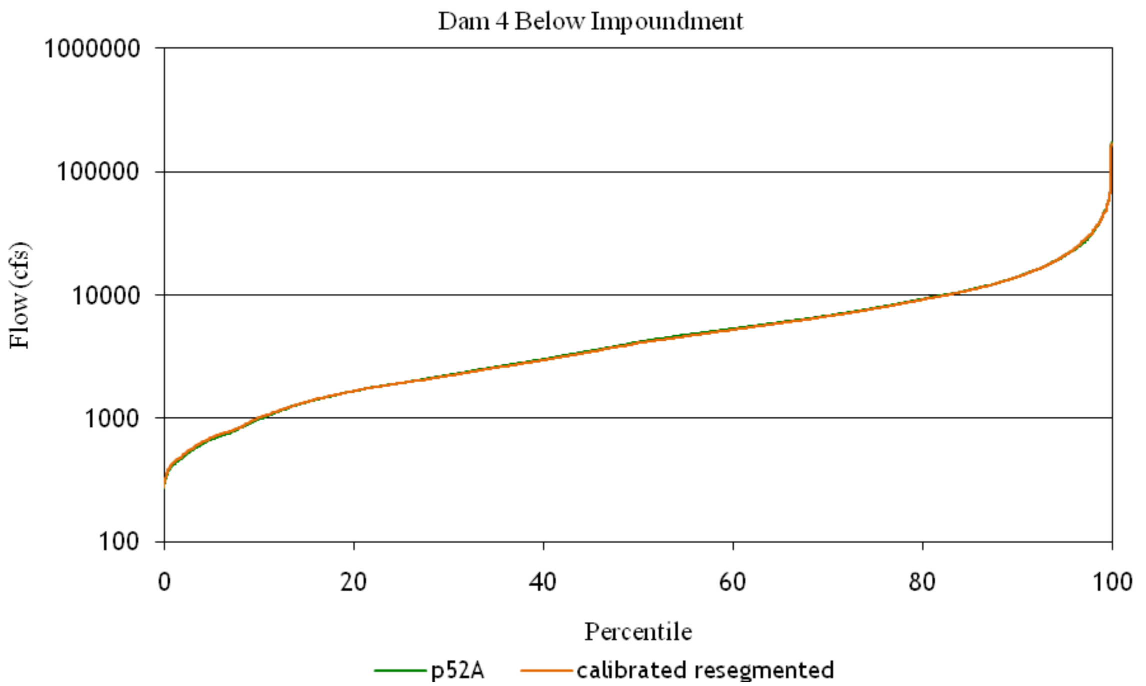

Figure 8. Original and re-segmented flows downstream of Dam No 4 on the Potomac River.

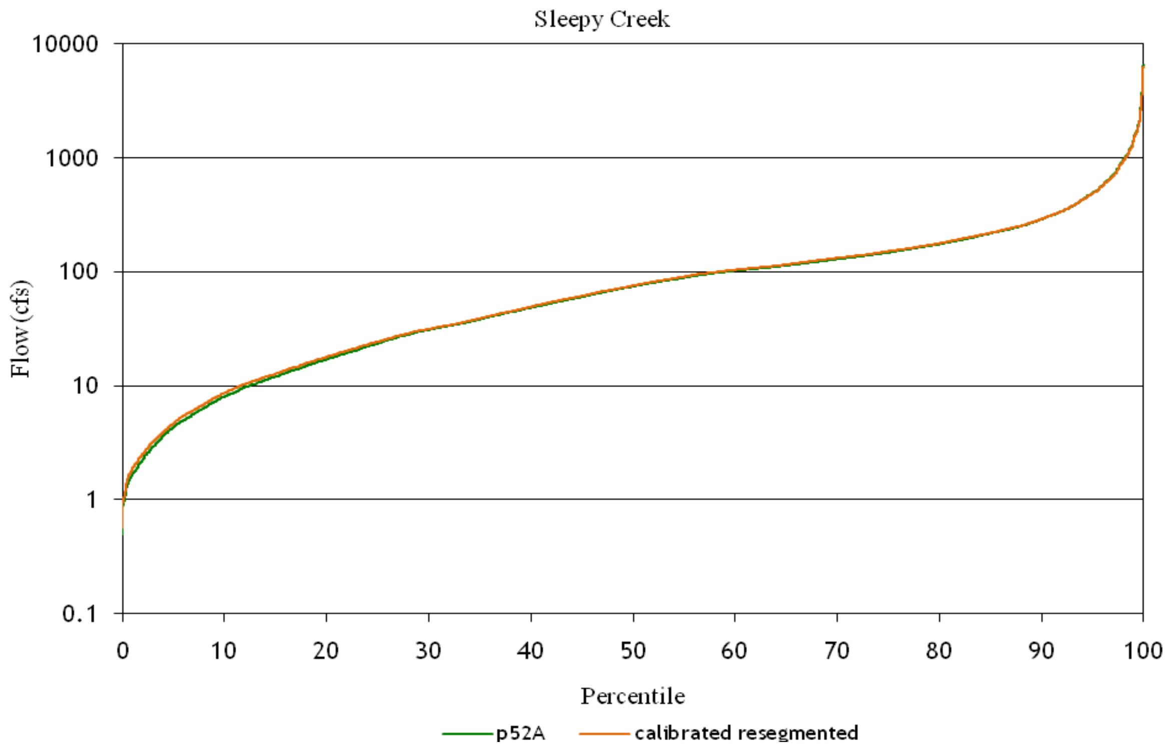

Figure 9. Original and re-segmented flows downstream of Sleepy Creek impoundment.

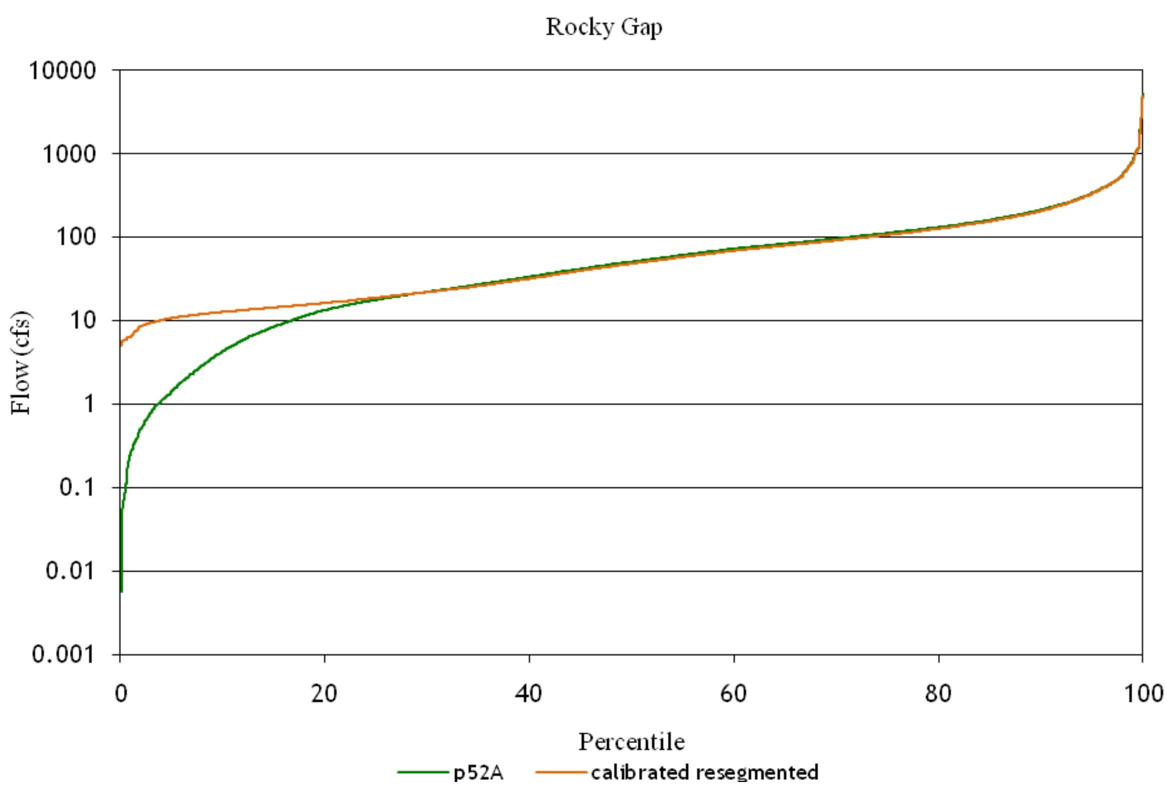

Figure 10. Original and re-segmented flows downstream of Rocky Gap Dam.

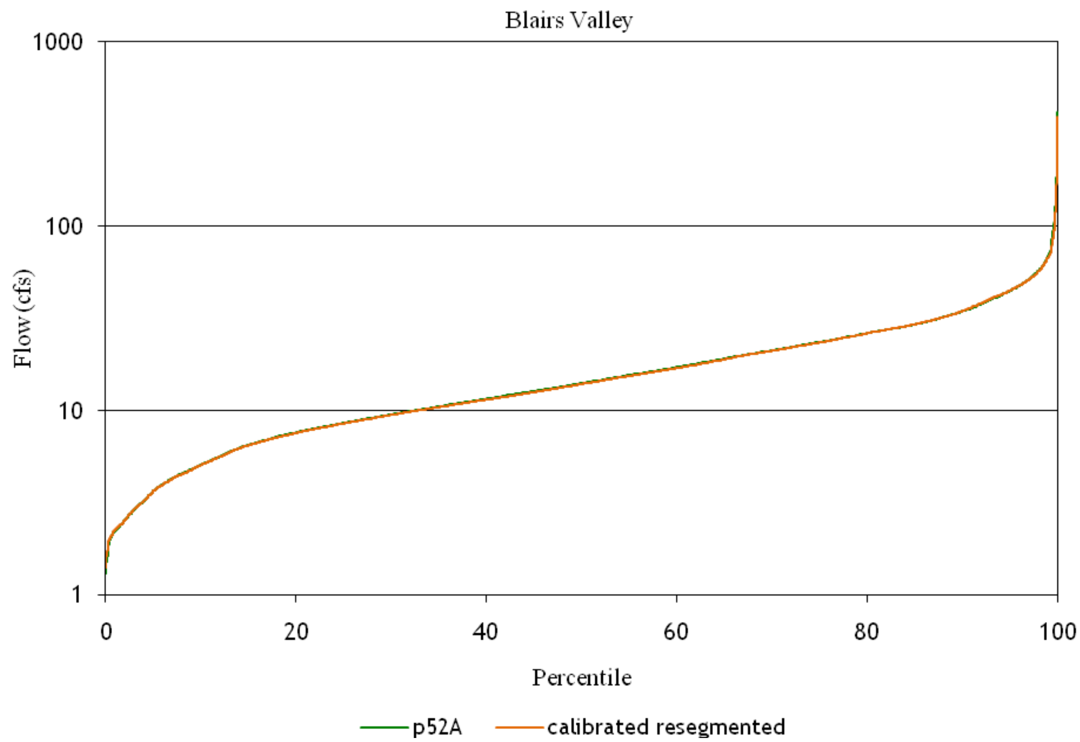

Figure 11. Original and re-segmented flows downstream of Blairs Valley Dam.

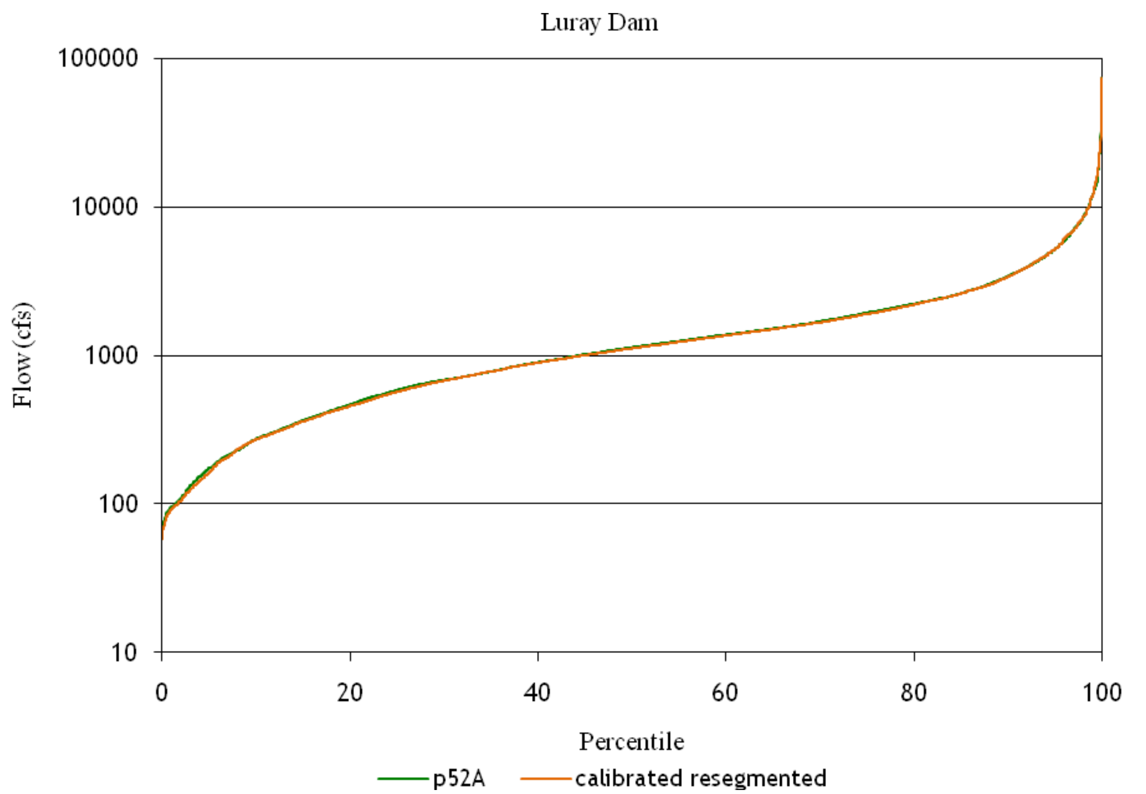

Figure 12. Original and re-segmented flows downstream of Luray Dam.

Table 1. River segment IDs for each of the new segments.

New Segment Names	New ID
Lake Barcroft Above Impoundment	PL0_9918_9919
Lake Barcroft Below Impoundment	PL0_9919_0001
Little Seneca Above Impoundment	PM1_9916_9917
Little Seneca Below Impoundment	PM1_9917_4500
Newport Dam Above Impoundment	PS4_5840_9901
Newport Dam Below Impoundment	PS4_9901_9902
Luray Dam Above Impoundment	PS4_9902_9903
Luray Dam Below Impoundment	PS4_9903_5200
Blairs Valley Dam Above Impoundment	PU0_9913_9914
Blairs Valley Dam Below Impoundment	PU0_9914_3602
Rocky Gap Dam Above Impoundment	PU1_9909_9910
Rocky Gap Dam Below Impoundment	PU1_9910_3780
Sleepy Creek Dam Above Impoundment	PU2_9911_9912
Sleepy Creek Dam Below Impoundment	PU2_9912_3590
Patterson Dam No 4 Above Impoundment	PU2_9905_9907
Patterson Dam No 4 Below Impoundment	PU2_9907_4160
Patterson Dam No 41 Above Impoundment	PU2_9906_9907
Potomac Dam No 4 Above Impoundment	PU6_3750_9915
Potomac Dam No 4 Below Impoundment	PU6_9915_3752
Chapman Dam Above Impoundment	PS2_5100_9904
Chapman Dam Below Impoundment	PS2_9904_5080
Lake Gordon Dam Above Impoundment	PU1_9908_9910

Table 2. Example of a river segment FTABLE.

```
FTABLE     2790
 ROWS COLS ***
   19    4
     DEPTH      AREA    VOLUME     DISCH  FLO-THRU ***
      (FT)   (ACRES)   (AC-FT)     (CFS)     (MIN) ***
      .000      .000     .0000      .000       0.0
     0.585   664.339    378.61     71.17    3862.1
     1.170   698.639    777.28    223.65    2523.2
     1.755   732.939   1196.01    471.78    1840.5
     2.340   767.240   1634.81    786.42    1509.2
     2.925   801.540   2093.68   1231.72    1234.1
     3.510   835.840   2572.62   1811.23    1031.2
     4.680   904.441   3590.68   3146.76     828.4
     5.850   973.042   4689.01   4444.93     765.9
     7.020  1041.642   5867.60   6835.53     623.2
     9.360  1767.893   9154.75  12210.99     544.3
    11.700  2494.144  14141.34  18814.67     545.7
    14.040  3220.395  20827.35  26583.41     568.8
    16.380  3946.646  29212.79  35474.31     597.9
    18.720  4672.896  39297.65  45457.25     627.6
    21.060  5399.147  51081.94  56510.60     656.3
    23.400  6125.398  64565.66  68618.72     683.1
    25.740  6851.649  79748.81  81770.23     708.1
    28.080  7577.900  96631.38  95957.16     731.1
  END FTABLE
```

Table 3. Required Phase 5 inputs modifications during the re-segmentation process.

Land Control File Group	**Directory**	**Modified during re-segmentation?**
CROP COVER	../input/scenario/land/crop_cover	No
FERTILIZER	../input/scenario/land/fertilizer	No
MANURE	../input/scenario/land/manure	No
LEGUME	../input/scenario/land/legume	No
TOTAL UPTAKE	../input/scenario/land/annual_uptake	No
MONTHLY UPTAKE	../input/scenario/land/monthly_fraction_uptake	No
DEFAULT CROPDATA		
SPECIAL ACTION	../input/scenario/land/spec_flags	No
PRAD	../input/scenario/climate/prad/…	No
METEOROLOGY	../input/scenario/climate/met/…	No
PARAMETERS	../input/param/<lu>/<scenario>	No
IOVARS	../config/catalog/iovars/<scenario>	No
GEOMETRY	../config/catalog/geo/<scenario>	Yes
River Control File Group	**Directory**	**Modified during re-segmentation?**
LAND USE	../input/scenario/river/land_use	Yes
BMPACRES	../input/scenario/river/bmpacres	No
TYPEBMP	../input/scenario/river/bmptype/lrseg_HGMRs.csv	Yes
TRANSPORT	../input/param/transport/	Yes
DIVERSIONS	../input/scenario/river/div	Yes
SEPTIC	../input/scenario/river/septic	Yes
POINT SOURCE	../input/scenario/river/ps	Yes
PRAD	../config/catalog/geo/river_prad_wdm.csv	Yes
METEOROLOGY	.../config/catalog/geo/river_met_wdm.csv	Yes
PARAMETERS	../input/param/river/<scenario>	Yes
IOVARS	../config/catalog/iovars/<scenario>	No
GEOMETRY	../config/catalog/geo/<scenario>	Yes

Table 4. Key Hydrology Calibration Parameters (reproduced from EPA 2009).

Parameter	Description	Permitted Range
LAND_EVAP	PET adjustment (similar to pan evaporation coefficient)	
INFILT	Base infiltration rate	0.0125 – 0.25
LZSN	Lower zone soil moisture storage index	1.0 – 12.0
AGWR	Baseflow recession coefficient	0.92 – 0.99
INTFW	Ratio of interflow to surface runoff	1.0 - 4.0
IRC	Interflow recession coefficient	0.35 – 0.85
AGWTP	Evapotranspiration from groundwater storage	0.0005 – 0.05

Appendix 1. Summary of 12 impoundments. Data source: National Inventory of Dams.

Dam Name	Owner Type	Owner Name	Primary Purpose	Dam Type	River	County	State	Dam Length (Ft.)	Drainage Area (sq mi)	Dam Designer	Dam Height (ft)	Hydraulic Height (ft)	Surface Area (acres)	Normal Storage (acre-feet)
Little Seneca	Local Gov.	WSSC	Recreation	-	Little Seneca	Montgomery	MD	600	21	Black and Veatch	99	0	505	13050
Blairs Valley	State	MD DNR	Recreation	Earth	Little Conococheague	Washington	MD	670	3	MD Dept.of Genl Services	34	0	32	486
Rocky Gap	State	MD DNR	Recreation	Earth	Rocky Gap Run	Allegany	MD	800	9	Whitman, Requardt & Assoc.	98	0	209	5381
Barcroft	State	Watershed Improv. Dist.	Recreation	Gravity	Holmes Run	Fairfax	VA	500	15	Unknown	69	66	154	2500
Newport	Public Utility	Potomac Edison Co	Hydro	Buttress	S Fk Shenan	Page	VA	518	1296	-	28	24	103	1090
Luray	Public Utility	Potomac Edison Co	Hydro	Buttress	S Fk Shenan	Page	VA	669	1383	-	21.89	18	126	880
Sleepy Creek	State	WVDNR	Recreation	Earth	Meadow Branch	Berkeley	WV	1100	9	-	38	33	225	2460
Patterson Creek No. 4	Local Gov.	Potomac Valley Scd	Flood & Storm Water Mgmt	Earth	Middle Fork	Grant	WV	795	8	USDA NRCS	69	68	8	1989
Patterson Creek No. 41	Local Gov.	Potomac Valley Scd	Flood & Storm Water Mgmt	Earth	North Fork	Grant	WV	1120	30	USDA NRCS	88	75	26	5480
Dam No. 4 Hydro Station	Federal	US NPS	Hydro	Gravity	Potomac	Berkeley	WV	110	5700	Chesapeake & Ohio Canal Co	20	0	675	6460
Chapman	Private	Shenandoah Hydro Co	Hydro	Buttress	N Fk Shenan	Shenandoah	VA	250	700	-	17	0	0	300
Lake Gordon	Private	City of Cumberland	Water Supply	Gravity	Evitts Creek	Bedford	PA	435	52	-	84	0	141	3633

Appendix 2. Accuracy statistics for resegmented model run at selected gages in the Potomac River basin and corresponding statistics for calibration CBP Phase 5 model.

Reseg Summary Statistics	**Tbias**	**Wstat**	**Sstat**	**Qstat**	**Bstat**	**Total_E**	**Total_LE**	**Mon_eff**	**QaveRI**	**BaveRI**	**Pbias**	**VPbias**	**WBaveRI**	**SBaveRI**	**lo10bias**
Goose Cr nr Middleburg	0.00	1.05	1.01	1.02	0.99	0.48	0.58	0.81	1.01	1.00	-0.11	0.06	1.01	1.00	15.06
Monocacy R at Jug Br	0.00	1.05	0.87	1.00	1.00	0.79	0.86	0.93	1.13	1.00	-0.21	0.01	1.02	0.99	0.27
Potomac R at POR	0.05	1.00	1.03	0.91	1.06	0.85	0.88	0.92	1.00	1.00	-0.02	0.03	1.01	0.99	-0.04
Shenandoah R at Millville	0.11	0.98	1.02	1.15	0.93	0.78	0.79	0.88	0.99	1.00	0.10	0.17	1.00	0.99	0.01
Sideling Hill Cr	0.00	1.12	0.98	0.71	1.31	0.68	0.62	0.82	0.99	1.03	0.14	-0.07	1.03	1.05	17.86
Antietam Cr nr Sharpsburg	0.00	1.03	0.95	1.28	0.95	0.82	0.82	0.94	1.00	1.00	0.07	0.12	1.00	0.99	-0.18
Opequon Cr nr Martinsburg	0.00	0.99	1.01	1.05	0.98	0.70	0.87	0.93	1.08	1.00	-0.08	0.19	1.01	0.99	0.04
Opequon Cr nr Berryville	0.06	0.99	0.93	0.94	1.05	0.39	0.71	0.88	1.14	1.01	0.00	0.22	1.03	0.99	0.11
Conococheague Cr nr Fairview	0.00	1.03	0.88	0.95	1.02	0.73	0.84	0.92	1.06	1.00	0.10	0.00	1.01	0.99	-0.01
Wills Cr	0.02	0.97	1.04	1.01	0.99	0.58	0.44	0.87	1.00	1.00	0.09	-0.11	1.04	0.95	-0.42
Cacapon R	0.00	1.00	1.00	1.02	0.99	0.58	0.58	0.81	1.13	1.00	0.00	0.17	1.02	0.98	-0.39
Potomac R at Hancock	0.01	1.03	1.00	0.92	1.05	0.82	0.84	0.90	1.04	1.00	-0.01	0.05	1.01	0.99	-0.23
p52An Summary Statistics	**Tbias**	**Wstat**	**Sstat**	**Qstat**	**Bstat**	**Total_E**	**Total_LE**	**Mon_eff**	**QaveRI**	**BaveRI**	**Pbias**	**VPbias**	**WBaveRI**	**SBaveRI**	**lo10bias**
Goose Cr nr Middleburg	0.00	1.05	0.99	1.00	1.00	0.46	0.62	0.81	0.98	1.00	-0.01	0.11	1.01	0.99	12.07
Monocacy R at Jug Br	-0.01	1.05	0.88	1.00	1.00	0.79	0.87	0.93	1.13	1.00	-0.23	0.00	1.02	0.99	0.26
Potomac R at POR	0.03	1.00	1.02	0.86	1.10	0.85	0.87	0.92	1.01	1.00	-0.04	-0.02	1.01	0.99	-0.07
Shenandoah R at Millville	0.01	0.98	1.00	0.98	1.01	0.82	0.80	0.91	1.06	1.00	0.00	0.09	1.01	0.99	-0.18
Sideling Hill Cr	0.00	1.12	0.98	0.76	1.26	0.69	0.62	0.82	0.98	1.04	0.15	-0.02	1.03	1.05	17.71

Antietam Cr nr Sharpsburg	0.00	1.03	0.95	1.24	0.96	0.82	0.82	0.94	0.99	1.00	0.11	0.14	1.00	0.99	-0.18
Opequon Cr nr Martinsburg	0.00	0.99	1.00	1.06	0.97	0.70	0.87	0.93	1.08	1.00	0.00	0.21	1.01	0.99	0.13
Opequon Cr nr Berryville	0.05	0.98	0.95	0.92	1.07	0.40	0.72	0.88	1.17	1.02	0.01	0.18	1.03	0.99	0.15
Conococheague Cr nr Fairview	0.00	1.02	0.89	0.91	1.04	0.73	0.84	0.91	1.06	1.00	0.12	0.00	1.01	0.99	0.01
Wills Cr	0.01	0.97	1.03	1.01	1.00	0.58	0.40	0.87	0.99	1.00	0.07	-0.14	1.04	0.94	-0.44
Cacapon R	0.00	1.00	1.00	1.01	0.99	0.58	0.52	0.81	1.12	1.00	0.00	0.18	1.02	0.98	-0.43
Potomac R at Hancock	0.03	1.03	1.00	0.91	1.06	0.82	0.84	0.90	1.04	1.00	0.00	0.05	1.01	0.99	-0.24

Note: Tbias, Qbias, Bbias, Sbias, and Wbias are relative bias for flows, quickflows, baseflows, summerflows, and winterflows, respectively. Wstat, Sstat, and Bstat are winter bias statistic, summer bias statistic, and baseflow statistic. QaveRI and BaveRI are the average quickflow recession index statistic and the average baseflow recession index statistic. Pbias and Vpbias are the peak bias and the volume of peak bias. Lo10 is the statistic of paired low flow bias.

Appendix E – Hydrologic Model

Thresholds of Flow Alteration Risk Identified by a Category and Regression Tree Analysis of the Potomac-Susquehanna Dataset

INTRODUCTION

As part of the ELOHA risk assessment and CART analysis methodology, a master data set of Potomac and Susquehanna basin sub-watersheds was created (Appendix C), candidate factors that may cause significant change in IHAs were tested, and risk thresholds estimated. The risk assessment methodology consisted of identifying possible risk factors in the Potomac and Susquehanna basins related to hydrologic alteration; identifying Potomac and Susquehanna sub-basins with streamflow records from 1984-2005; calculating the risk factors and associated hydrologic metrics for each sub-basin; and establishing low, medium, high, and severe risk categories utilizing Classification and Regression Tree (CART) analysis. A detailed description of these methods follows.

CONSTRUCT A COMBINED POTOMAC-SUSQUEHANNA DATA SET

With the assistance of Michele Dephilip and Tara Moberg of The Nature Conservancy (TNC) Pennsylvania chapter and Jennifer Hoffman of the Susquehanna River Basin Commission (SRBC), the Susquehanna basin was included in the Potomac analysis to increase sample size and statistical significance of results. Sub-basins were selected based on the locations of USGS gages with a minimum period of record from 1984-2005. Gages with greater than five years of missing data during the 1984-2005 period of record were not included in the analysis. Sub-basins are nested and cumulative (i.e. risks were calculated for the entire watershed upstream of the gage). The final Potomac-Susquehanna data set consisted of 40 Susquehanna and 65 Potomac watersheds of varying sizes and a broad range of land and water uses (Figure 1).

<u>Watershed Area and Size Classes</u>

Watersheds above each of the USGS gaging stations included in the Potomac-Susquehanna data set were delineated in a graphical information system (GIS) using the NHDPlus stream networks and their associated watersheds (USEPA 2005). Each watershed's area was calculated from the GIS layer and incorporated into the data set.

Most of the gaged watersheds in the Potomac-Susquehanna data set were larger than the headwater and small stream classes (<10 mi^2) of the Pennsylvania Aquatic Community Classification (PACC) and the combined headwater and creek classes (<38.61 mi^2) of the Northeastern Aquatic Habitat Classification System (NEAHCS). The PACC classification focuses on smaller waterbodies which usually do not have USGS gages. For this analysis, the NEAHCS classification system was modified to obtain n>10 in each watershed size category and a more even frequency distribution of sizes (Table 1). The Middle Potomac Sustainable Flows project Class 1 combined the NEAHCS headwater and creek classes; its Class 4 combined the NEAHCS medium mainstem river, large river, and great river classes. Classes 2 and 3 remained unchanged.

Slope

Slope was calculated for each sub-basin to assess the effects of slope on hydrologic metrics and risk factors. The National Elevation Dataset (NED) 30m resolution raster elevation grid was obtained for this purpose. ArcGIS 9.2 Spatial Analyst's Calculate Slope tool was utilized to convert the Digital Elevation Model (DEM) to slope in degrees. The slope of each 30m grid cell was calculated by identifying the maximum rate of elevation change between that cell and its 8 neighbors. Slope statistics for each sub-basin were then calculated using Spatial Analyst's Zonal Statistics tool. The tool provides a statistical summary of all 30m cells within a sub-basin. For the purposes of this analysis, minimum, maximum, mean, standard deviation, and range of slope values for each sub-basin were obtained.

Risk Factors

A series of risk factors were calculated for each of the 105 watersheds in the Potomac-Susquehanna data set. Risk factors were identified based on their ability to influence instream flows. Factors included urban, forest, and agricultural land uses; withdrawals; surface withdrawals; impoundments; consumptive use; impervious cover; and karst geology. Urban land use and percent impervious cover were considered because increases in impervious cover increase overall system flashiness, the volume of surface run-off, and storm peaks while decreasing the time to hydrograph peak among other hydrologic impact (Dunne and Leopold 1978); (Novotny and Olem 1994). Karst geology can also uniquely influence surface and groundwater hydrology (De Waele et al. 2009); (Legrand and Stringfield 1973). Procedures utilized to calculate risk factor values are described below. Impoundments can have widely varying impacts on downstream hydrology depending on size and operations. Moreover, both surface and groundwater withdrawals may limit the availability of water resources for instream uses, both human and ecological. Consumptive use is of particular interest because the water is not returned to the waterway and is effectively lost to downstream uses.

Land Use

The 30m resolution Chesapeake Bay Program (CBP) 2000 land use raster was utilized to calculate percent urban, percent forest, and percent agricultural areas within each sub-basin. Forested land uses were a combination of deciduous forests, evergreen forests, and mixed forests for the purposes of this analysis. Agricultural land uses included pasture, hay, and croplands. Urban areas included low, medium, high intensity developed, transportation, and urban treed and grassed. The ArcToolbox 'calculate area' tool was utilized to calculate land use areas for each sub-basin, which were subsequently converted to a percentage of the total area in Excel. The resulting land use percentages are shown in Table 2 of this report.

Impervious Cover

The ArcGIS 9.2 Zonal Statistics tool was utilized to calculate the mean percent impervious cover for each sub-basin based on the 30m resolution CBP 2000 impervious cover raster data set. The resulting impervious cover percentages are shown in Table 2.

Withdrawals

The ICPRB utilized withdrawal data for the year 2005 from Pennsylvania, West Virginia, Virginia, and Maryland. The data were formatted and combined into a single comprehensive database and imported into a GIS point shapefile using reported latitude and longitude values. Data quality control procedures were employed by comparing withdrawal attributes to Google Earth imagery. The Nature Conservancy utilized SRBC permitted withdrawal data to calculate withdrawal and consumptive use risk factors in the Susquehanna River basin. Due to potential over-estimation of permitted withdrawals in the Susquehanna permitted data set (when compared to actual withdrawals in the Potomac River basin), only Potomac data was utilized to identify low, medium, low, and high risk thresholds for withdrawal related factors using the CART analysis.

Withdrawal data were utilized to calculate withdrawals as a percent of 10th and 50th percentile flows (total withdrawals/[flow + total withdrawals]) and surface withdrawals as a percent of 10th and 50th percentile flows (surface withdrawals/[flow + total withdrawals]).

Consumptive Use

USGS Aggregate Water Use Data System (AWUDS)[1] county data from 1995 were obtained for all counties in the Potomac Basin. A consumptive use coefficient for each reported water use was estimated by dividing consumptive use by withdrawals. The average consumptive use coefficients by water use in the Potomac River basin are shown in Table 4. The consumptive use coefficients were multiplied by the 2005 total withdrawals (MG/year) for that water use type to estimate total consumptive use (MG/year) for each sub-basin. Consumptive uses for each sub-basin are shown in Appendix B of this report. Consumptive use values were calculated for the Susquehanna River basin based on permitted withdrawals and sector appropriate factors published in USGS 2005. Since permitted withdrawals may over-estimate actual use, Susquehanna consumptive use data were removed from the CART analysis.

Impoundments

Impoundments in the Potomac and Susquehanna basins were identified in the National Inventory of Dams (NID).[2] Potomac impoundments are shown in Figure 2. The total storage capacity of impoundments within each sub-basin was calculated by summing the NID reported normal storage capacities. The total storage capacity was then compared to the annual flow volume for 10th and 50th percentile flows in the sub-basin. Flows were calculated at sub-basin outlets using daily USGS gage data from 1984 - 2005. Impoundment risk factor values are shown in Appendix B of this report.

Karst Geology

The percentage of karst geology in Potomac and Susquehanna sub-basins were calculated using the US EPA's Region 3 ecoregion polygon shapefile in ArcGIS 9.2 (Figure 3). Three Level 4 ecoregions were identified; namely, Northern Limestone/Dolomite Valleys, Piedmont Limestone/Dolomite Lowlands, and Limestone Valleys and Coves. The 'tabulate area' tool was utilized to calculate the karst area of each sub-basin. The calculated karst areas were divided by the total area of each

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

[2] NID database: https://rsgis.crrel.usace.army.mil/apex/f?p=397:12:4227426315264309

respective sub-basin. Percentages of karst geology for each sub-basin are shown in Appendix B of this report.

Indicators of Hydrologic Alteration (IHA)

Eleven IHA metrics were selected to capture different portions of the hydrograph (Olden and Poff 2003). Selected metrics include mean flow, 3 day maximum, 1 day minimum, 3 day minimum, high pulse count, high pulse duration, low pulse duration, extreme low frequency, number of reversals, rise rate, and fall rate (Table 3). Information about the hydrologic and biologic importance of these indicators can be found in Apse et al. (2008).[3] The indicators were calculated for each of the 105 gaged watersheds over the 1984 – 2005 period of record using TNC's version 7.0 software (TNC 2007). Calculation details are described in Chapter 2 of Cummins et al. (2011) and in Appendix C of this report.

Precipitation-Adjusted IHAs

The Potomac and Susquehanna river basins are relatively "rich" in precipitation, but they exhibit a wide range in mean annual precipitation (32" – 55"). To investigate the possible effect of precipitation on the IHAs, four flow-based indicators—mean flow, 1-day and 3-day minimum flows, and 3-day maximum flow—were normalized to the mean annual precipitation in their watersheds. The 1971-2005 mean annual precipitation data from the NOAA network of Mid-Atlantic weather stations were used to create a spatial layer of mean annual precipitation for the Potomac and Susquehanna basins. Several methods were considered to interpolate the station precipitation data to a spatially explicit grid across the Potomac and Susquehanna Basins, including topo to raster, splining, thiessen polygons, and kriging. A verification data set of 13 precipitation stations was utilized to assess the accuracy of each method. Kriging was selected as it had an average percent error of 2.6%, lower than all three other methods (topo to raster had a 3.5% error, splining had a 4.55% error, and thiesson polygons had a 10.16% error at the validation points).

Kriging "assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. This method fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location" (ESRI, 2009). ArcMap 9.4 uses the following formula for kriging:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

where:

$Z(s_i)$ = the measured value at the i^{th} location.

λ_i = an unknown weight for the measured value at the i^{th} location.

s_0 = the prediction location.

N = the number of measured values.

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

The annual mean volume of water falling on each of the watersheds in the study was estimated from the spatial precipitation layer. The four IHAs with flow rate components (cfs) were divided by mean annual rainfall after converting all values to the same units. The resulting ratio (unitless) is thus weighting, or normalizing, the IHA relative to the precipitation falling on the watershed. Values of these normalized indicators are noted as such in Table 3 of this report.

CART ANALYSIS AND DEVELOPMENT OF RISK FACTOR THRESHOLDS

The ten risk factors were categorized by severe, high, medium, and low risk utilizing CART analysis, literature values, and the distribution of risk factor values. CART analysis was performed using S-PLUS software on IHA metrics for the 105 sub-basins with USGS gage data at the outlet (Appendix C of this report). IHA metrics were utilized as dependent variables to develop thresholds for the risk factor values (independent variables). CART analysis divides the data into consecutively smaller groups until the minimum sample size for each group is reached. The breaking points between groups are threshold values of the independent variables (risk factors) that minimize deviance within each group. The first threshold of the CART analysis, or primary break, is identified in the risk factor that can minimize deviance in the IHA statistic values. After the primary break is identified, the process continues until a terminal node is reached, where the minimum number of observations per group is reached or the deviance in the group is minimized.

"CART will usually over-fit the model, creating a tree that explains substantially all of the deviance in the original data, but in a manner specific to the particular data used to fit the tree. The tree must be pruned back, therefore, to a level where it can reasonably be expected to be robust (Lawrence and Wright 2001)." For this reason, mostly primary and secondary breaks were utilized in this analysis. The tree and statistical results for the 1 day minimum IHA metric with 5 observations before split and a minimum node size of 10 is provided in Figure 4 for example.

For this study, CART analysis was conducted for each IHA statistic using minimum number of observations before split equaled 2 and minimum node size equaled 4 except as described in run F and G. Several iterations of the CART analysis were conducted using sub-sets of the data. The strength in creating multiple trees for each independent variable is that consistent thresholds can be identified.

In cases where different risk factor thresholds were identified for different IHA metrics, thresholds were selected using 3 criteria (1) level of break (primary, secondary, etc.) – higher order breaks were given priority; (2) confirmation of value by other IHA metrics or within the same metric; and (3) resulting residual mean deviance values – lower deviance values were given priority.

The identified thresholds and rationale for each risk factor are given below. For thresholds identified using CART analysis, the residual mean deviance and the IHA statistics for which the threshold was identified are given. The sample size was105 for the geology and land use related factors because both Susquehanna and Potomac sub-basins were included. Only Potomac sub-basins were utilized in the CART analysis for withdrawal related risk factors because permitted water uses are available for the Susquehanna while actual water use is available for the Potomac (n=56, the sample size for 10th percentile risk factors may be lower due to missing observed flow data).

Several CART analysis runs were conducted to identify consistencies in the results. The strongest results are presented below along with a description of the runs that produced the results. If an earlier run was selected over a later run (ex. C instead of D), it is because there were either no thresholds found in the later run or they were fourth breaks or greater.

Description of the 7 CART runs:
a: ESWM CART results using Potomac only data (n=26) (Cummins et al. 2011). Independent variables include forest, impervious, urban, agriculture, karst geology, impoundments of 10th percentile flow, impoundments of 50th percentile flow.

b:ELOHA CART results using Potomac and Susquehanna data sets for non-withdrawal factors (n=105) and Potomac data set for withdrawal factors (n=56; n for 10th %ile risk factors may be lower due to missing observed flow data). For combined analysis, factors include forest, impervious, urban, agriculture, karst geology, impoundments of 10th percentile flow, impoundments of 50th percentile flow. For Potomac only analysis, factors include withdrawals, surface withdrawals, and consumptive use of 10th and 50th percentile flows.

c:ELOHA CART analysis as in b however a size class factor was included, a North Branch classification was included, and all coastal sub-basins were removed.

d:ELOHA CART analysis as in b however areas (sq. mi) were included, a regional factor was included, and IHA metrics with flows normalized for area and rainfall were used.

e:CART analysis of sub-basin area and region to each IHA metric. The purpose of this run was to determine whether the area or the physiographic region has a great influence on IHA metrics within the sub-basin. Only sub-basins with areas greater than 200 sq. mi. were included to remove regional bias because the majority of smaller sub-basins are located in the Potomac River basin. Coastal basins are not represented in this run because they are all less than 200 sq. mi.

f:CART analysis to determine whether watershed area is an important factor in classifying streams. The combined Potomac and Susquehanna data set was included. Size classes 1-4 were included. Coastal sub-basins were not included. A regional designation factor was not included. Minimum number of observations before split is 4 and minimum node size is 8. Factors included forest, impervious, agriculture, karst geology and area.

g: CART analysis to determine whether watershed area is an important factor in classifying streams. Only Potomac, non-coastal sub-basins were included. Includes size classes 1-4. Regional designations NB (North Branch = a) and O (Other = b). Minimum number of observations before split is 4 and minimum node size is 8. Factors include regional designations, area, forest, impervious, agriculture, karst geology, impoundments of 50th percentile flow, withdrawals of 50th percentile flow, surface withdrawals of 50th percentile flow, and consumptive use of 50th percentile flow.

CART Results

Percent Forest:

Low >77.91 (n=28) [C,D,G]

CART residual mean deviance = 46.46.

CART threshold is explained by number of reversals (secondary break)[C,D,G].

Medium 77.92 – 53.91 (n=48) [C,D,F,G]

CART residual mean deviance = 0.2722.

CART threshold is explained by high pulse duration (primary break)[C,G] and high pulse duration (secondary break)[D,F].

High 53.92 – 39.13 (n=14)[D]

CART residual mean deviance = 0.00048.

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

Severe <39.13 (n=17)

<u>Percent Impervious:</u>

Low <0.41 (n=33) [C,D,F]

CART residual mean deviance = 0.0016.

CART threshold is explained by 3 day maximum (primary break)[C,F] and mean flow (secondary break)[D].

Medium 0.42 – 3.81 (n=56)[C,D]

CART residual mean deviance = 0.002.

CART threshold is explained by 1 day minimum (secondary break)[C] and high pulse duration (secondary break)[D].

High 3.82 – 10.1 (n=10)[B,C,D]

CART residual mean deviance = 2.678.

CART threshold is explained by high pulse count (primary break)[B,C,D] and rise rate (primary break)[B].

Severe >10.1 (n=6)

<u>Percent Urban:</u>

Low <4.31 (n=38)[C]

CART residual mean deviance = 0.0021.

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

Medium 4.31 – 7.17 (n=25)[C,D]

CART residual mean deviance = 46.46.

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

High 7.17 – 42.92 (n=36)[C,D]

CART residual mean deviance = 0.0009.

CART threshold is explained by rise rate (primary).

Severe >42.92 (n=6)

<u>Percent Agriculture:</u>

Low <9.46 (n=20)[C,F]

CART residual mean deviance = 0.0193.

CART threshold is explained by mean flow (secondary break)[C,F] and 1 day minimum (secondary break)[F].

Medium 9.46 – 28.03 (n=57)[B,C,F]
CART residual mean deviance = 0.0003.
CART threshold is explained by fall rate (primary break)[B,F] and mean flow (primary break)[C,F] and extreme low frequency (secondary break)[F].
High 28.04 – 47.28 (n=19)[C,G]
CART residual mean deviance = 2.678.
CART threshold is explained by high pulse count (secondary break)[C,G].
Severe >47.29 (n=9)

Percent Karst:

Low <0.82 (n=59)[B,C,G]
CART residual mean deviance = 3.175.
CART threshold is explained by high pulse duration (secondary break)[B,C,G] and extreme low frequency (tertiary break)[G].
Medium 0.82 – 24.32 (n=18)[C,D,F]
CART residual mean deviance = 0.0021.
CART threshold is explained by 1 day minimum (primary break)[C,D,F] and 3 day minimum (primary break)[D,F].
High 24.33 – 44.06 (n=13)[C,D,F,G]
CART residual mean deviance = 0.708.
CART threshold is explained by extreme low frequency (primary break)[C,D,F,G].
Severe >44.06 (n=15)

Percent Impoundment of 10th Percentile Flows:

Low <0.025 (n=12)[C,D]
CART residual mean deviance = 0.00015.
CART threshold is explained by fall rate (tertiary break)[C] and fall rate (secondary break)[D].
Medium 0.025 – 4.05 (n=42)[D]
CART residual mean deviance = 0.2722.
CART threshold is explained by high pulse duration (secondary break).
High 4.06 – 26.19 (n=30)[C]
CART residual mean deviance = 0.0023.
CART threshold is explained by 3 day minimum (tertiary break).
Severe >26.19 (n=20)

Percent Impoundment of 50th Percentile Flows:

Low <0.22 (n=22)[C]
CART residual mean deviance = 0.0193.
CART threshold is explained by mean flow (secondary break).
Medium 0.22 – 9.48 (n=62)[C]
CART residual mean deviance = 46.46.
CART threshold is explained by number of reversals (secondary break).
High 9.48 – 22.91 (n=10)[C]

CART residual mean deviance = 0.0021.
CART threshold is explained by 1 day minimum (secondary break).
Severe >22.91 (n=11)

Percent Withdrawal of 10th Percentile Flows:

Low <0.24 (n=12)[C,D]
CART residual mean deviance = 0.0561.
CART threshold is explained by mean flow (secondary break)[C] and high pulse duration (secondary break)[D].
Medium 0.24 – 2.84 (n=11)[C,D]
CART residual mean deviance = 0.2748.
CART threshold is explained by low pulse duration (secondary break)[C] and extreme low frequency (secondary break)[D].
High 2.85 – 25.18 (n=23)[C,D]
CART residual mean deviance = 0.00016.
CART threshold is explained by fall rate (secondary break)C and 1 day minimum (fourth break)[D].
Severe >25.18 (n=9)

Percent Withdrawal of 50th Percentile Flows:

Low <1.42 (n=28)[C]
CART residual mean deviance = 0.3816.
CART threshold is explained by extreme low frequency (secondary break).
Medium 1.43 – 5.6 (n=11)[C,D]
CART residual mean deviance = 82.19.
CART threshold is explained by number of reversals (secondary break)[C] and extreme low frequency (fourth break)[D].
High 5.7 – 9.6 (n=8)[C]
CART residual mean deviance = 0.3816.
CART threshold is explained by extreme low frequency (primary break).
Severe >9.6 (n=9)

Percent Surface Withdrawal of 10th Percentile Flows:

Low <0.125 (n=17)[B,C,D]
CART residual mean deviance = 0.005.
CART threshold is explained by 1 day minimum (secondary break)[B], 3 day minimum (tertiary break)[B], high pulse duration (tertiary break)[C], and fall rate (fourth break)[D].
Medium 0.126 – 5.047 (n=24)[C,D]
CART residual mean deviance = 0.0019.
CART threshold is explained by rise rate (secondary break)[C] and low pulse duration (fifth break)[D].
High 5.048 – 72.48 (n=11)[C]
CART residual mean deviance = 82.19.
CART threshold is explained by number of reversals (tertiary break).

Severe >72.48 (n=3)

Percent Surface Withdrawal of 50th Percentile Flows:

Low <0.041 (n=16)[C,D,G]
CART residual mean deviance = 0.0001.
CART threshold is explained by 1 day minimum (primary break)[C,G], 3 day minimum (primary break)[C,G], 3 day minimum (tertiary break)[D], and 1 day minimum (tertiary break)[D].
Medium 0.041 – 4.47 (n=31)[C]
CART residual mean deviance = 0.4855.
CART threshold is explained by high pulse duration (secondary break).
High >4.47 (n=10)

Percent Consumptive Use of 10th Percentile Flows:

Low <0.009 (n=9)[C,D]
CART residual mean deviance = 7.254.
CART threshold is explained by low pulse duration (primary break)[C] and high pulse duration (tertiary break)[D].
Medium 0.009 – 2.67 (n=33)[C,D]
CART residual mean deviance = 0.3816.
CART threshold is explained by extreme low frequency (tertiary break)[C] and high pulse duration (fifth break)[D].
High 2.68 – 4.73 (n=10)[C]
CART residual mean deviance = 0.0032.
CART threshold is explained by 1 day minimum (tertiary break)[C] and 3 day minimum (tertiary break)[C].
Severe >4.73 (n=3)

Percent Consumptive Use of 50th Percentile Flows:

Low <0.012 (n=18)[C]
CART residual mean deviance = 0.0032.
CART threshold is explained by 1 day minimum (secondary break) and 3 day minimum (secondary break).
Medium 0.013 – 1.89 (n=32)[C,G]
CART residual mean deviance = 0.0561.
CART threshold is explained by mean annual flow (secondary break)[C] and number of reversals (tertiary break)[G].
High >1.89 (n=6)

Region/Area only CART[E]

Region code: a=Appalachian, b=Appalachian/Ridge and Valley, c=Piedmont, d=Piedmont/Appalachian/Ridge and Valley, e=Piedmont/Ridge and Valley, f=Ridge and Valley.

Extreme low frequency: primary break area<25045, secondary break region (b,d,e,f)
Fall rate: primary break: region a,b; secondary breaks at area 25045 and area 1016.62
High pulse count: primary break region a,b,d,f; secondary breaks at area 843.83 and 400.587
High pulse duration: primary break at region c,e; secondary break at area 935.744
Low pulse duration: primary break area 213.274; secondary break area 353.196
Mean flow: primary break region c,d,e,f; secondary breaks at area 248.459 and 1563.6
Number of reversals: primary break area 25045; secondary break area 2369
Rise rate: primary break region d,f; secondary breaks at area 503.974 and 841.569
1 day min: primary break at region a,c,d,f; secondary breaks at area 219.17 and 609.033
3 day max: primary break at area 215.5; secondary breaks at area 208.274 and region b,c,d,e,f
3 day min: primary break at region a,c,d,f; secondary breaks at area 219.17 and 609.033

CONCLUSIONS

The CART analysis identified thresholds for each risk factor that optimized group homogeneity. Breaks for several risk factors were repeated throughout multiple CART runs, including percent forest, percent urban, percent impervious cover, and percent karst, strengthening confidence in the identified threshold and in their significance for altering hydrology in the Potomac River basin. Other risk factor thresholds were weaker, particularly those associated with water use and impoundments, and varied between CART analyses. Thresholds identified during the CART analysis were subsequently utilized in combination with the regressions and scatter plots to revise and finalize risk categories.

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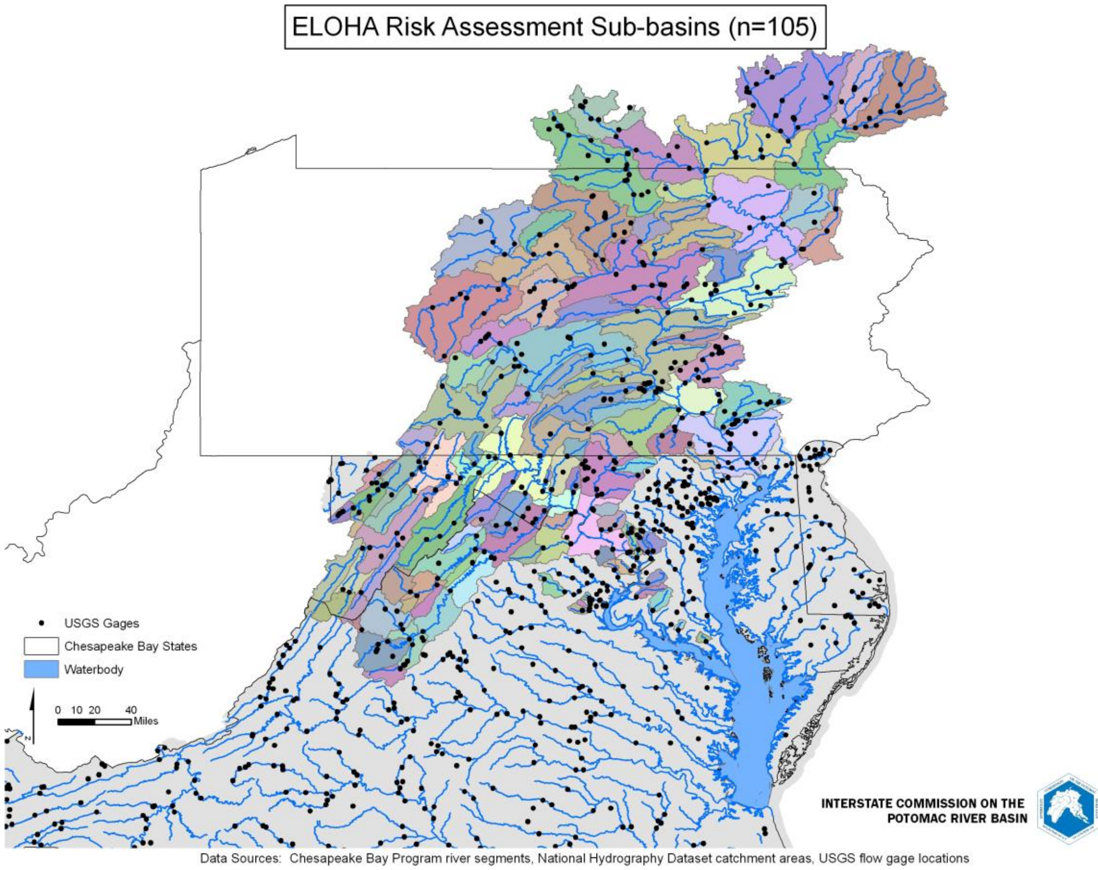

Figure 1. Sub-basins under consideration in the Potomac and Susquehanna Basins.

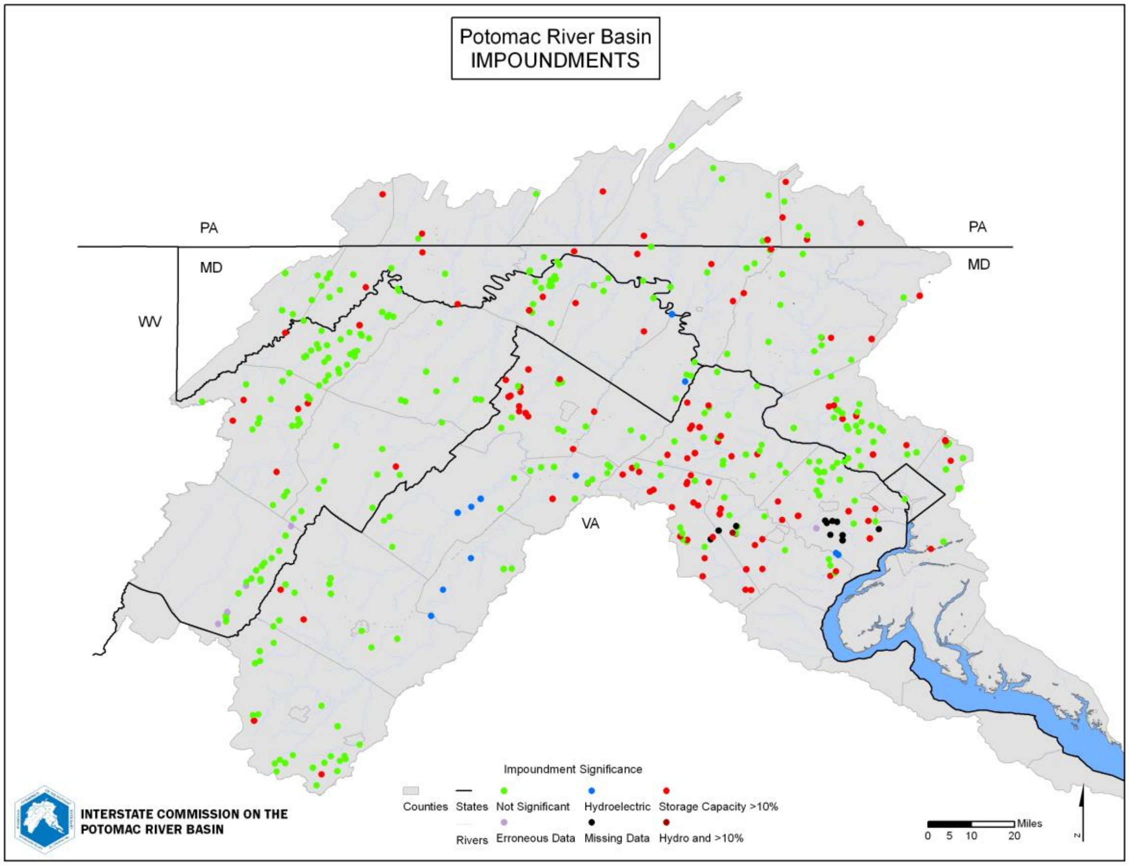

Figure 2. Impoundments in the Potomac Basin.

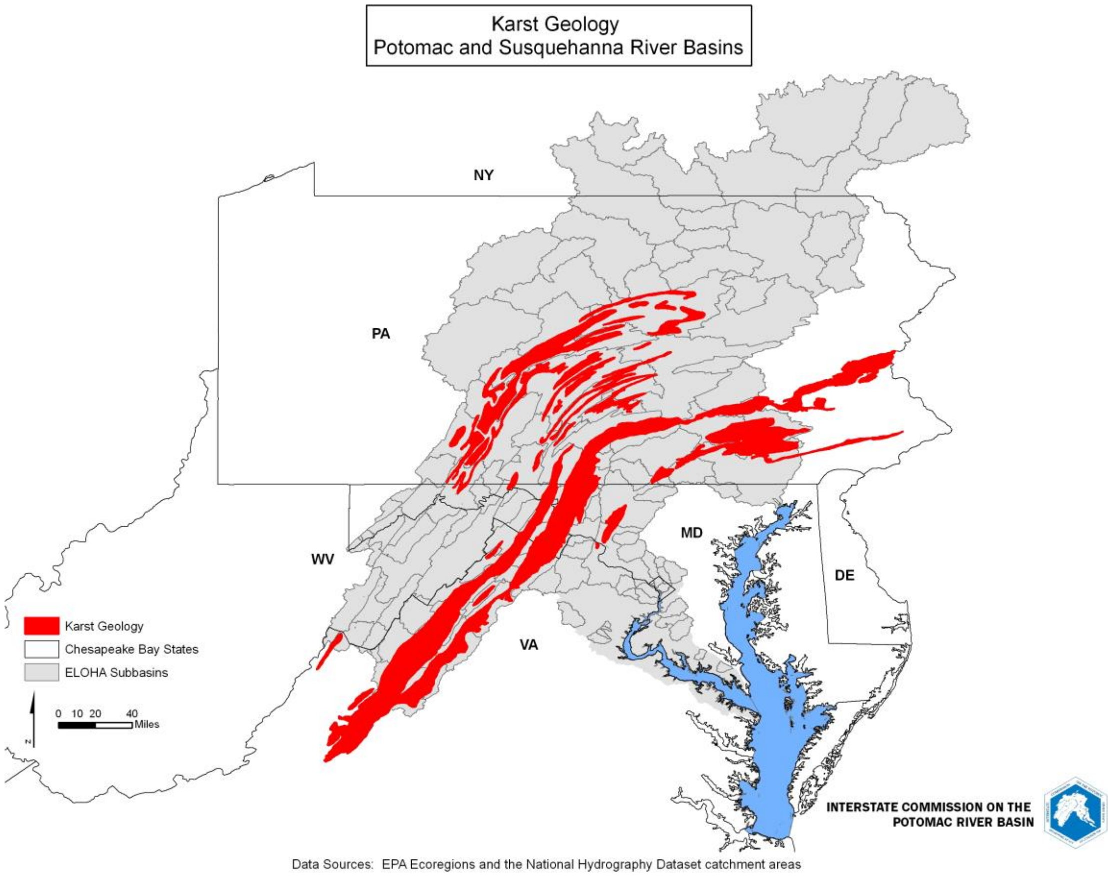

Figure 3. Areas with karst geology in the Potomac and Susquehanna River Basins.

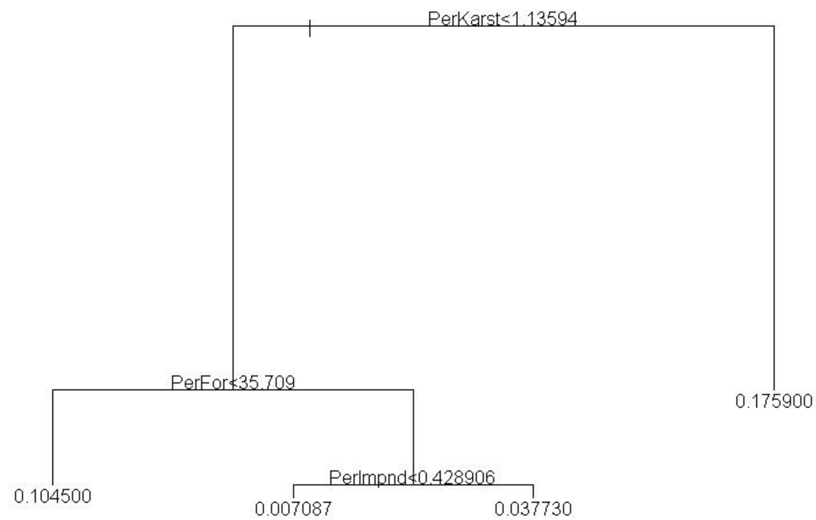

Figure 4. Example CART output.

Table 1. Counts of all gaged watersheds in the Potomac-Susquehanna data set, grouped by size class.

		Potomac (n=65)	Susquehanna (n=40)	Totals (n=105)
NEAHCS Size Class (mi^2)	Description (Class Designation)			
<3.86	Headwaters (1a)	1		1
3.86 – <38.6	Creeks (1b)	9	-	9
38.6 – <200	Small Rivers (2)	28	3	31
200 – <1,000	Medium Tributary Rivers (3a)	17	24	41
1,000 – <3,861	Medium Mainstem Rivers (3b)	6	6	12
3,861 - <9,653	Large Rivers (4)	2	2	4
≥9,653	Great Rivers (5)	2	5	7
PACC Size Class (mi^2)				
<2	Headwater Stream (1)	-	-	-
2 – <10	Small Streams (2)	2	-	2
10 – <100	Mid-reach Streams (3)	26	1	27
>100	Large Streams and Rivers (4)	37	39	76
PSC (mi^2)				
<38.6	Headwaters and Small Streams (1)	10	-	10
38.6 - <200	Large Streams (2)	28	3	31
200 - <1000	Small (Wadeable) Rivers (3)	17	24	41
≥ 1000	Medium and Large Rivers (4)	10	13	23

Note: Size classifications utilized include the Northeastern Aquatic Habitat Classification System (NEAHCS), the Pennsylvania Aquatic Community Classification (PACC), and the Middle Potomac Sustainable Flows Project Size Classes (PSC). Only watersheds with USGS stream gages at their outlets and 1984-2005 data were included in the data set.

Table 2. Calculated risk factor values for the Potomac-Susquehanna gaged watersheds.
Column Headers: Pot-Sus, indicates Potomac (P) or Susquehanna (S) river basin; Region (Reg) codes; Area, watershed square miles; Urban, percent urban land cover; Ag, percent agricultural land cover; For, percent forest cover; Imperv, percent impervious surface cover; W10, total withdrawals as a percent of the 10th percentile flow; W50, total withdrawals as a percent of the median (50th%ile) flow; Sw10, surface withdrawals as a percent of the 10th percentile flow; Sw50, surface withdrawals as a percent of the median (50th%ile) flow; Impnd10, impoundment storage capacity as a percent of the 10th percentile flow; Impnd50, impoundment storage capacity as a percent of the median (50th%ile) flow; Cu10, consumptive use as a percent of the 10th percentile flow; Cu50, consumptive use as a percent of the median (50th%ile) flow.
Region (Reg) codes: Ridge and Valley (R), Coastal (C), Piedmont (P), Appalachian (A), Piedmont/Ridge and Valley (PR), Appalachian/Ridge and Valley (AR), Coastal/Piedmont (CP), and Piedmont/Appalachian/Ridge and Valley (PAR).

Tributary	Pot - Sus	Reg	Area	Urban	Ag	For	Imperv	Karst	W10	W50	Sw10	Sw50	Impnd10	Impnd 50	Cu10	Cu50
Conococheague Creek	P	R	498.81	9.49	42.62	46.35	2.77	31.52	10.72	4.62	5.21	2.24	5.17	2.08	3.48	1.50
Catoctin Creek, MD	P	R	67.16	13.49	33.13	52.91	1.05	0.00	3.92	1.33	1.54	0.52	0.81	0.27	1.87	0.64
North East Branch Annacostia River	P	C	73.77	69.66	2.71	23.70	19.93	0.00	2.27	1.07	0.73	0.35	3.14	1.46	1.16	0.55
Great Seneca Creek	P	P	101.78	39.01	23.01	31.08	9.00	0.00	0.23	0.11	0.23	0.11	49.56	24.58	0.18	0.09
Aquia Creek	P	P	35.90	8.98	9.79	76.17	1.50	0.00	13.94	4.93	5.66	3.25	5.95	1.91	0.01	0.00
St Clement Creek	P	C	18.40	16.45	27.51	53.24	0.96	0.00	0.37	0.14	0.00	0.00	0.00	0.00	0.14	0.05
St Marys River	P	C	24.46	22.65	6.97	56.51	4.02	0.00	21.74	8.92	0.00	0.00	91.19	32.14	4.65	1.91
Passage	P	R	87.81	1.76	7.46	90.38	0.09	23.73	9.09	3.03	9.09	3.03	0.63	0.20	7.23	2.41
Zekiah Swamp Run	P	C	79.63	21.11	14.79	58.48	2.80	0.00	19.59	6.99	0.32	0.11	0.19	0.06	4.60	1.64
Difficult Run	P	P	57.84	46.83	12.84	37.19	11.19	0.00	3.01	1.35	2.62	1.18	62.82	27.74	1.08	0.49
Accotink Creek	P	P	23.94	90.37	0.87	6.87	25.05	0.00	1.09	0.41	0.00	0.00	0.38	0.14	0.23	0.09
Quantico	P	P	7.30	2.88	1.80	89.67	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U1_Tonoloway	P	R	10.77	2.30	16.13	81.51	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
McMillan	P	A	2.71	10.36	22.41	67.04	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Smith Creek	P	R	94.92	5.00	43.25	51.52	0.83	71.16	1.05	0.39	1.05	0.39	0.00	0.00	0.50	0.18
Linville	P	R	45.11	5.73	65.53	28.26	1.31	98.62	0.58	0.22	0.00	0.00	0.00	0.00	0.14	0.05
NF_SouthBranch	P	R	310.07	2.02	7.60	86.72	0.29	0.00	NA	0.02	NA	0.02	NA	0.00	NA	0.01
Hogue Creek	P	R	16.02	12.15	9.39	77.83	0.08	36.30	0.00	0.00	0.00	0.00	31.55	9.37	0.00	0.00
Marsh Run	P	R	17.85	31.83	44.10	23.60	5.61	0.39	0.58	0.17	0.00	0.00	0.00	0.00	0.22	0.06
Bennett Creek	P	P	62.79	19.31	38.68	38.21	1.78	0.00	1.64	0.70	0.22	0.09	0.55	0.23	0.98	0.42
U1_NorthRiver	P	R	22.65	0.34	0.00	99.35	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Middle River	P	R	374.39	8.27	47.27	43.17	1.39	71.74	4.31	1.89	0.10	0.05	0.46	0.20	1.01	0.44

Tributary	Pot - Sus	Reg	Area	Urban	Ag	For	Imperv	Karst	W10	W50	Sw10	Sw50	Impnd10	Impnd 50	Cu10	Cu50
Big Pipe Creek	P	P	101.25	15.12	54.04	29.50	1.82	0.00	2.97	1.34	0.22	0.10	0.00	0.00	0.77	0.35
Cedar Run	P	P	92.51	9.93	47.28	40.12	1.57	0.00	24.17	6.78	18.25	5.12	44.71	10.20	5.15	1.45
Cedar Creek	P	R	102.08	2.97	5.07	90.51	0.05	5.70	0.00	0.00	0.00	0.00	1.86	0.67	0.00	0.00
North River	P	R	375.24	6.39	29.10	63.80	1.98	45.05	15.05	6.45	11.74	5.04	10.39	4.05	3.46	1.48
Patterson Creek	P	R	218.34	2.88	18.60	78.23	0.32	0.00	0.22	0.05	0.00	0.00	52.11	12.45	0.05	0.01
Savage River	P	R	46.20	4.48	13.33	81.33	0.32	0.00	4.34	1.35	0.00	0.00	1.01	0.31	0.93	0.29
South River	P	R	125.16	6.28	21.26	69.08	0.82	52.72	12.51	6.04	1.81	0.87	3.70	1.66	2.68	1.29
Stony River	P	A	47.41	1.40	13.71	76.60	0.61	0.00	99.04	96.83	99.04	96.83	404.68	119.49	2.48	2.42
U1_NorthBranch	P	A	72.19	5.53	14.48	77.60	0.40	0.00	26.19	12.27	1.07	0.50	0.00	0.00	4.53	2.12
U1_NorthFork	P	R	211.55	1.72	3.35	91.82	0.20	0.71	0.00	0.00	0.00	0.00	2.36	0.56	0.00	0.00
U1_SForkSouthBranch	P	R	102.48	2.27	5.53	88.89	0.19	0.00	0.27	0.09	0.27	0.09	103.48	33.64	0.10	0.03
U1_SouthBranch	P	R	174.51	2.43	27.17	70.28	0.24	8.99	0.82	0.36	0.82	0.36	0.00	0.00	0.18	0.08
Upper Goose Creek	P	P	118.67	3.71	47.04	48.94	0.37	0.00	0.17	0.04	0.00	0.00	4.81	1.12	0.04	0.01
Upper Monocacy River	P	PR	172.88	10.80	50.99	32.23	3.16	1.25	14.16	4.43	4.76	1.49	13.44	3.77	3.52	1.10
Upper Opequon	P	R	58.26	15.53	38.23	45.26	3.25	49.43	0.00	0.00	0.00	0.00	1.75	0.65	0.00	0.00
Wills Creek	P	AR	188.20	2.65	13.11	84.09	0.19	0.00	0.26	0.09	0.25	0.09	0.05	0.02	0.06	0.02
Savage River Dam	P	R	104.35	3.53	9.53	85.74	0.19	0.00	3.28	1.50	2.07	0.95	55.64	24.92	0.00	0.00
NW_L1_Anacostia	P	CP	51.97	75.32	4.57	17.28	22.20	0.00	1.25	0.56	0.70	0.32	0.92	0.41	0.00	0.00
Goose Creek	P	P	331.17	4.30	50.48	44.53	0.49	0.00	2.40	0.68	0.12	0.04	11.46	3.19	0.00	0.00
Opequon Creek	P	R	277.61	12.65	37.75	48.72	2.76	63.07	14.12	6.93	7.97	3.91	0.25	0.11	0.01	0.01
U3_SouthFork	P	R	1073.24	7.59	36.27	54.92	1.56	59.30	11.83	5.54	4.31	2.02	4.10	1.79	0.01	0.00
Monocacy	P	PR	811.48	16.13	48.43	32.31	3.22	5.79	15.76	6.45	7.54	3.09	4.21	1.55	0.01	0.00
U1_SouthFork	P	R	1368.58	6.98	33.72	58.15	1.37	56.55	12.69	6.06	3.31	1.58	3.78	1.68	3.10	1.48
U2_NorthBranch	P	AR	406.59	4.32	11.66	81.20	0.34	0.00	87.55	76.67	86.68	75.91	88.16	41.21	3.04	2.66
U2_NorthFork	P	R	509.14	3.90	30.94	63.58	0.68	46.99	5.64	1.83	3.58	1.16	0.70	0.22	1.34	0.43
U2_SForkSouthBranch	P	R	276.92	2.17	5.18	89.62	0.19	0.00	0.10	0.04	0.10	0.04	64.48	22.43	0.04	0.01
U2_SouthBranch	P	R	650.34	2.39	13.77	81.43	0.30	2.41	1.24	0.48	1.22	0.47	0.00	0.00	0.30	0.12
U3_NorthBranch	P	AR	871.66	7.36	11.23	79.65	0.72	0.00	81.16	64.89	80.32	64.22	54.54	23.40	2.84	2.27
U2_SouthFork	P	AR	1644.2	6.69	31.72	60.41	1.24	52.89	11.63	5.66	3.33	1.62	3.55	1.62	0.01	0.00
Antietam Creek	P	R	290.92	17.00	40.71	37.99	4.42	71.05	10.89	5.96	2.74	1.50	1.87	0.97	2.79	1.53
Cacapon River	P	R	681.67	1.00	9.33	87.50	0.16	0.00	0.16	0.06	0.09	0.03	2.64	0.98	0.03	0.01

Tributary	Pot - Sus	Reg	Area	Urban	Ag	For	Imperv	Karst	W10	W50	Sw10	Sw50	Impnd10	Impnd 50	Cu10	Cu50
Cameron Run	P	CP	45.79	84.98	0.35	3.38	30.59	0.00	1.61	0.68	0.79	0.34	51.89	21.88	0.41	0.17
Catoctin Creek, VA	P	P	92.48	3.17	53.48	40.06	0.77	0.00	10.02	3.15	1.99	0.62	3.90	1.14	3.35	1.05
North Fork, Shenandoah	P	R	927.49	4.70	28.37	65.54	0.69	45.40	6.69	2.64	3.38	1.33	1.90	0.72	1.59	0.62
Piscataway Creek	P	C	68.81	38.26	8.63	45.19	8.77	0.00	12.24	4.16	0.00	0.00	1.64	0.51	3.04	1.03
Rock Creek	P	P	76.23	69.85	5.13	16.00	23.25	0.00	0.77	0.35	0.37	0.17	11.22	5.00	0.55	0.25
South Branch Potomac River	P	R	1481.98	1.55	13.40	81.78	0.42	0.97	4.90	1.90	4.89	1.90	9.07	3.41	1.16	0.45
South Fork, Shenandoah	P	R	2130.24	7.39	31.52	59.86	1.25	52.67	9.63	4.30	4.27	1.91	3.21	1.35	2.39	1.07
Potomac River @ Hancock	P	AR	4095.88	4.13	11.82	82.42	0.46	1.59	61.33	39.08	60.70	38.68	25.84	10.45	2.37	1.51
Potomac River @ Little Falls	P	PAR	11578.2	9.04	26.13	63.01	1.67	21.83	57.51	32.29	55.21	31.00	15.00	5.29	4.94	2.77
Potomac River @ Paw Paw	P	AR	3120.45	4.50	12.79	80.99	0.54	1.83	65.30	43.02	64.63	42.58	30.30	12.16	2.50	1.65
Potomac River @ Point of Rocks	P	R	9658.07	6.60	23.16	68.76	1.07	25.36	46.39	26.29	44.02	24.95	13.62	5.62	2.49	1.41
Potomac River @ Shepherdstown	P	R	5982.41	5.72	17.42	75.29	0.89	11.21	57.21	33.42	55.84	32.62	20.24	7.60	2.50	1.46
Susquehanna River At Unadilla NY	S	A	982.00	3.66	23.14	69.30	0.31	0.00	0.62	0.26	0.00	0.00	100.11	41.28	0.23	0.10
Unadilla River At Rockdale NY	S	A	520.00	2.65	27.49	66.79	0.27	0.00	0.23	0.09	0.00	0.00	1.51	0.61	0.05	0.02
Susquehanna River At Conklin NY	S	A	2232.00	3.46	22.18	71.11	0.36	0.00	0.73	0.30	0.00	0.00	47.98	19.85	0.16	0.07
Chenango River Near Chenango Forks NY	S	A	1483.00	3.95	24.68	68.06	0.53	0.00	4.49	2.03	2.34	1.06	5.85	2.58	1.10	0.50
Tioga River Near Erwins NY	S	A	1377.00	3.91	20.37	74.57	0.59	0.00	2.41	0.92	0.68	0.26	13.54	5.11	0.50	0.19
Cohocton River Near Campbell NY	S	A	470.00	4.26	18.69	73.54	0.83	0.00	3.84	1.56	1.11	0.45	80.18	31.75	0.82	0.33
Chemung River At Chemung NY	S	A	2506.00	5.12	19.74	73.46	1.00	0.00	6.74	2.66	0.96	0.38	24.55	9.28	1.50	0.59
Susquehanna River at Towanda, PA	S	A	7797.00	4.88	21.27	71.39	0.85	0.00	8.36	3.69	5.55	2.45	22.57	9.47	1.99	0.88
Towanda Creek near Monroeton, PA	S	A	215.00	2.75	24.16	72.15	0.36	0.00	6.63	2.40	6.63	2.40	1.80	0.62	1.15	0.42
Tunkhannock Creek	S	A	383.00	6.02	22.11	68.83	0.66	0.00	11.22	4.57	10.69	4.36	8.90	3.37	2.93	1.19

Tributary	Pot - Sus	Reg	Area	Urban	Ag	For	Imperv	Karst	W10	W50	Sw10	Sw50	Impnd10	Impnd 50	Cu10	Cu50
near Tunkhannock, PA																
Lackawanna River at Old Forge, PA	S	A	332.00	23.38	13.70	59.36	5.87	0.00	0.09	0.04	0.00	0.00	50.16	20.16	0.02	0.01
Susquehanna River at Wilkes-Barre, PA	S	A	9960.00	5.75	21.19	70.56	1.05	0.00	7.83	3.48	5.55	2.46	19.82	8.41	1.90	0.84
Fishing Creek near Bloomsburg, PA	S	AR	274.00	3.91	17.52	76.82	0.33	0.00	0.13	0.05	0.13	0.05	2.18	0.83	0.02	0.01
Susquehanna River at Danville, PA	S	A	11220.0	6.28	20.80	70.34	1.17	0.00	9.90	4.53	7.73	3.54	17.76	7.68	2.43	1.11
WB Susquehanna River at Karthaus, PA	S	A	1462.00	6.21	12.02	79.93	0.43	0.00	36.90	18.29	25.77	12.77	44.91	17.19	7.18	3.56
Sinnemahoning Creek at Sinnemahoning, PA	S	A	685.00	2.79	1.99	94.85	0.10	0.00	2.89	1.01	1.17	0.41	1.30	0.45	0.51	0.18
Kettle Creek near Westport, PA	S	A	233.00	1.53	1.84	96.07	0.02	0.00	0.00	0.00	0.00	0.00	2.75	0.97	0.00	0.00
Bald Eagle Creek near Beech Creek Station, PA	S	A	562.00	8.30	11.98	77.81	1.19	24.90	16.11	8.75	6.28	3.41	14.00	6.99	3.72	2.02
Pine Creek bl L Pine Creek near Waterville, PA	S	A	944.00	2.60	6.64	89.97	0.20	0.16	2.59	0.97	1.18	0.44	1.20	0.44	0.56	0.21
Lycoming Creek near Trout Run, PA	S	A	173.00	1.74	12.67	84.93	0.13	0.00	0.00	0.00	0.00	0.00	0.76	0.26	0.00	0.00
Loyalsock Creek at Loyalsockville, PA	S	A	435.00	2.85	9.57	86.02	0.27	0.22	0.05	0.02	0.05	0.02	2.47	0.91	0.01	0.00
West Branch Susquehanna River at Lewisburg, PA	S	A	6847.00	4.89	10.46	83.33	0.61	5.65	1.94	0.83	0.82	0.35	4.08	1.72	0.42	0.18
Penns Creek at Penns Creek, PA	S	R	301.00	3.35	20.14	75.54	0.39	26.90	0.99	0.43	0.30	0.13	1.51	0.66	0.21	0.09
East Mahantango Creek near Dalmatia, PA	S	R	162.00	6.34	26.61	65.97	1.27	0.00	2.35	0.88	0.56	0.21	0.09	0.03	0.56	0.21
Frankstown Br Juniata River at Williamsburg, PA	S	R	291.00	14.82	15.93	68.06	3.17	30.27	16.23	8.27	15.38	7.84	10.18	4.74	3.47	1.77
Little Juniata River at Spruce Creek, PA	S	R	220.00	7.38	18.53	73.41	1.29	43.06	2.58	1.31	1.96	0.99	3.41	1.70	0.55	0.28
Juniata River at	S	R	816.00	8.75	17.16	73.14	1.60	36.43	6.77	3.43	6.06	3.07	4.97	2.43	1.61	0.82

Tributary	Pot - Sus	Reg	Area	Urban	Ag	For	Imperv	Karst	W10	W50	Sw10	Sw50	Impnd10	Impnd 50	Cu10	Cu50
Huntingdon, PA																
Rays Br Juniata R bl Rays Dam nr Huntingdon, PA	S	R	960.00	5.64	19.28	72.80	0.70	23.04	2.15	1.05	1.22	0.59	211.98	102.18	0.58	0.28
Aughwick Creek near Three Springs, PA	S	R	205.00	4.08	11.61	83.44	0.33	6.92	0.00	0.00	0.00	0.00	2.96	0.84	0.00	0.00
Juniata River at Newport, PA	S	R	3354.00	6.45	18.33	73.82	1.01	26.90	3.84	1.72	3.05	1.37	56.11	24.64	0.92	0.41
Sherman Creek at Shermans Dale, PA	S	R	200.00	3.82	21.20	74.22	0.60	36.18	0.56	0.20	0.00	0.00	0.10	0.04	0.12	0.04
Conodoguinet Creek near Hogestown, PA	S	R	470.00	11.05	43.32	44.26	3.16	32.03	6.86	2.89	0.94	0.40	2.32	0.94	1.98	0.83
Susquehanna River at Harrisburg, PA	S	AR	24100.0	6.27	17.93	73.72	1.14	6.92	12.14	5.87	10.18	4.92	16.22	7.32	2.94	1.42
Yellow Breeches Creek near Camp Hill, PA	S	PR	216.00	14.28	25.24	58.82	4.37	37.32	5.92	3.46	3.65	2.13	0.70	0.40	1.34	0.78
Swatara Creek near Hershey, PA	S	R	483.00	13.75	27.69	55.98	4.01	11.64	6.10	2.43	0.87	0.35	7.06	2.71	2.26	0.90
West Conewago Creek near Manchester, PA	S	P	510.00	13.02	47.92	35.77	3.93	5.91	29.52	12.01	25.15	10.23	14.88	4.85	7.96	3.24
Susquehanna River at Marietta, PA	S	AR	25990.0	6.88	19.11	71.83	1.38	7.71	19.68	9.91	17.83	8.97	15.09	6.77	4.81	2.42
Conestoga River at Conestoga, PA	S	P	470.00	23.32	47.92	25.93	7.59	63.56	12.21	6.13	3.85	1.94	1.60	0.75	3.79	1.90
Susquehanna River at Conowingo, MD	S	AR	27100.0	7.54	21.08	69.08	1.59	8.96	2.67	1.09	0.10	0.04	24.02	9.60	0.64	0.26
Deer Creek at Rocks, MD	S	P	94.40	12.91	49.40	36.25	1.36	0.00	0.21	0.11	0.00	0.00	0.47	0.25	0.04	0.02

Table 3. Flow metrics for the Potomac-Susquehanna gaged watersheds.
See Supplemental Table A in report and documentation in Appendix C for metric definitions and units.

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
Conococheague Creek	7.00	10.00	4.00	0.09	-0.05	101.00	1.50	0.42	0.060	0.061	3.59
Catoctin Creek, MD	6.25	11.00	2.00	0.10	-0.06	102.00	1.50	0.38	0.008	0.009	3.47
North East Branch Annacostia River	5.00	30.50	2.00	0.33	-0.09	123.00	4.00	0.39	0.041	0.045	3.50
Great Seneca Creek	4.00	20.00	2.00	0.14	-0.07	122.00	1.50	0.41	0.084	0.090	3.40
Aquia Creek	6.00	19.00	2.50	0.13	-0.06	113.00	1.00	0.29	0.005	0.007	2.73
St Clement Creek	5.00	19.00	2.00	0.15	-0.08	116.00	0.50	0.31	0.004	0.005	2.79
St Marys River	5.00	17.00	3.00	0.12	-0.08	115.00	1.50	0.35	0.026	0.028	4.06
Passage	7.00	11.00	4.00	0.05	-0.04	98.50	1.50	0.33	0.012	0.013	4.18
Zekiah Swamp Run	6.50	17.50	3.00	0.19	-0.08	95.50	1.00	0.35	0.000	0.000	3.00
Difficult Run	4.50	27.50	2.00	0.24	-0.07	124.00	1.50	0.37	0.046	0.049	2.96
Accotink Creek	3.50	39.00	2.00	0.42	-0.08	137.00	3.50	0.40	0.012	0.013	4.85
Quantico	5.50	17.50	2.00	0.10	-0.05	114.50	1.00	0.33	0.004	0.005	3.92
U1_Tonoloway	8.00	10.00	5.50	0.09	-0.06	101.50	3.00	0.46	0.003	0.003	4.97
McMillan	7.00	13.00	4.00	0.27	-0.14	106.00	0.50	0.48	0.008	0.009	3.33
Smith Creek	8.00	9.00	3.50	0.04	-0.03	97.00	1.00	0.29	0.046	0.047	2.37
Linville	9.00	8.00	4.00	0.04	-0.04	101.00	1.00	0.30	0.048	0.049	2.38
NF_SouthBranch	5.50	12.00	4.00	0.12	-0.07	91.50	1.50	0.43	0.013	0.014	3.15
Hogue Creek	6.00	11.00	4.00	0.06	-0.05	107.50	3.00	0.36	0.021	0.021	4.31
Marsh Run	5.00	5.00	2.00	0.05	-0.03	105.50	1.50	0.21	0.022	0.023	0.81
Bennett Creek	6.00	14.00	2.00	0.11	-0.06	115.50	1.50	0.37	0.042	0.043	3.12
U1_NorthRiver	20.00	9.00	7.00	0.09	-0.04	71.00	1.00	0.45	0.010	0.010	4.94
Middle River	8.00	8.50	4.00	0.05	-0.03	104.00	0.00	0.30	0.073	0.074	2.23
Big Pipe Creek	7.00	18.50	2.00	0.13	-0.06	119.00	1.50	0.38	0.056	0.059	2.80
Cedar Run	4.75	14.00	3.00	0.09	-0.05	116.00	1.00	0.30	0.002	0.003	3.16

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
Cedar Creek	6.00	10.50	3.25	0.08	-0.05	107.50	3.00	0.40	0.031	0.033	4.87
North River	9.00	8.50	7.00	0.06	-0.04	98.00	0.00	0.39	0.058	0.059	3.15
Patterson Creek	6.00	7.50	6.00	0.05	-0.03	80.00	1.00	0.29	0.010	0.010	2.42
Savage River	6.75	11.50	5.00	0.20	-0.09	94.00	1.50	0.56	0.017	0.017	4.90
South River	6.00	9.00	4.50	0.08	-0.05	93.00	0.00	0.40	0.080	0.082	3.57
Stony River	4.50	15.50	4.00	0.18	-0.11	128.50	5.50	0.61	0.026	0.027	5.08
U1_NorthBranch	4.00	17.00	3.00	0.32	-0.19	124.00	5.50	0.69	0.058	0.067	4.08
U1_NorthFork	17.00	10.00	5.75	0.06	-0.03	84.00	0.50	0.36	0.005	0.005	5.12
U1_SForkSouthBranch	5.50	9.00	6.00	0.06	-0.04	84.00	2.00	0.38	0.020	0.020	5.02
U1_SouthBranch	7.00	9.00	6.00	0.09	-0.05	100.00	3.00	0.36	0.052	0.052	2.98
Upper Goose Creek	4.25	9.00	2.75	0.08	-0.06	104.00	1.00	0.37	0.002	0.003	3.40
Upper Monocacy River	7.00	18.50	3.00	0.11	-0.06	110.00	2.00	0.41	0.008	0.009	4.56
Upper Opequon	4.00	13.50	3.00	0.10	-0.05	98.00	0.50	0.34	0.057	0.057	4.36
Wills Creek	6.00	9.00	6.00	0.15	-0.09	97.50	1.00	0.66	0.047	0.047	5.52
Savage River Dam	14.50	9.00	8.00	0.12	-0.12	55.50	1.00	0.56	0.107	0.119	4.50
NW_L1_Anacostia	4.00	32.50	2.00	0.22	-0.10	138.00	4.50	0.33	0.033	0.036	2.80
Goose Creek	6.25	12.00	2.75	0.08	-0.05	106.00	1.00	0.35	0.005	0.006	3.00
Opequon Creek	6.00	10.50	3.00	0.05	-0.03	109.50	0.00	0.35	0.073	0.074	5.08
U3_SouthFork	11.00	8.00	5.25	0.06	-0.03	97.50	0.00	0.34	0.074	0.074	2.84
Monocacy	7.75	14.00	3.00	0.12	-0.06	106.00	1.50	0.39	0.037	0.038	3.52
U1_SouthFork	9.25	8.50	6.25	0.04	-0.04	98.00	0.50	0.36	0.076	0.076	3.32
U2_NorthBranch	8.50	8.00	7.00	0.08	-0.04	104.50	0.00	0.58	0.175	0.175	3.67
U2_NorthFork	9.00	9.50	4.75	0.04	-0.03	92.00	1.00	0.31	0.025	0.026	3.12
U2_SForkSouthBranch	8.00	9.00	6.25	0.05	-0.03	78.00	2.00	0.34	0.019	0.020	3.74
U2_SouthBranch	7.00	9.00	5.00	0.08	-0.05	91.50	2.00	0.41	0.040	0.040	3.14
U3_NorthBranch	5.75	9.50	5.50	0.08	-0.06	113.00	0.50	0.53	0.108	0.111	3.32

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
U2_SouthFork	9.00	8.00	7.00	0.03	-0.04	108.00	1.00	0.34	0.069	0.071	2.80
Antietam Creek	5.75	7.00	3.00	0.06	-0.03	107.00	1.00	0.35	0.102	0.104	1.91
Cacapon River	10.75	9.00	5.00	0.03	-0.04	85.50	2.00	0.32	0.031	0.032	3.07
Cameron Run	3.50	37.50	2.00	0.23	-0.07	135.00	0.50	0.26	0.022	0.023	2.24
Catoctin Creek, VA	6.75	13.00	2.00	0.08	-0.05	104.00	1.00	0.35	0.011	0.012	4.18
North Fork, Shenandoah	7.50	9.00	4.25	0.03	-0.03	104.50	1.00	0.26	0.038	0.039	1.95
Piscataway Creek	4.50	21.00	2.00	0.14	-0.04	119.00	2.00	0.20	0.000	0.000	1.45
Rock Creek	4.00	29.00	2.00	0.30	-0.07	124.00	3.50	0.28	0.028	0.029	1.96
South Branch Potomac River	8.25	9.00	5.50	0.05	-0.03	87.00	2.00	0.34	0.028	0.028	2.95
South Fork, Shenandoah	10.50	8.50	6.25	0.04	-0.05	102.00	0.00	0.47	0.084	0.090	3.24
Potomac River @ Hancock	8.00	8.00	6.00	0.05	-0.04	87.50	2.00	0.37	0.047	0.047	2.62
Potomac River @ Little Falls	10.00	7.00	6.50	0.04	-0.04	98.00	1.00	0.36	0.028	0.030	2.55
Potomac River @ Paw Paw	8.50	8.50	5.25	0.06	-0.05	92.00	2.50	0.39	0.052	0.053	2.87
Potomac River @ Point of Rocks	12.00	7.50	6.25	0.04	-0.04	98.00	2.50	0.36	0.052	0.054	2.49
Potomac River @ Shepherdstown	5.75	7.00	5.50	0.05	-0.05	100.50	2.50	0.41	0.051	0.056	2.71
Susquehanna River At Unadilla NY	6.00	8.00	4.25	0.12	-0.09	113.50	3.50	0.65	0.047	0.050	3.57
Unadilla River At Rockdale NY	9.00	12.00	4.50	0.15	-0.08	99.00	4.00	0.55	0.050	0.051	3.62
Susquehanna River At Conklin NY	7.00	9.50	6.00	0.11	-0.09	100.50	2.00	0.53	0.035	0.036	3.93
Chenango River Near Chenango Forks NY	7.00	10.50	4.75	0.13	-0.08	96.00	2.50	0.56	0.044	0.045	3.69

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
Tioga River Near Erwins NY	8.75	13.00	3.75	0.07	-0.05	105.00	3.00	0.43	0.027	0.027	3.76
Cohocton River Near Campbell NY	11.00	11.00	4.00	0.09	-0.05	104.00	3.00	0.43	0.025	0.026	3.43
Chemung River At Chemung NY	16.00	12.00	4.75	0.07	-0.05	94.00	3.00	0.44	0.029	0.030	4.11
Susquehanna River at Towanda, PA	6.25	9.00	5.25	0.09	-0.07	89.00	2.00	0.51	0.037	0.038	3.70
Towanda Creek near Monroeton, PA	5.50	12.00	4.00	0.13	-0.06	100.50	3.00	0.52	0.012	0.013	6.20
Tunkhannock Creek near Tunkhannock, PA	6.00	13.00	4.00	0.11	-0.08	107.50	4.50	0.47	0.024	0.025	4.20
Lackawanna River at Old Forge, PA	4.00	11.00	5.00	0.12	-0.09	118.00	5.00	0.44	0.038	0.039	3.56
Susquehanna River at Wilkes-Barre, PA	7.00	8.50	6.25	0.09	-0.06	89.50	2.00	0.51	0.042	0.043	3.39
Fishing Creek near Bloomsburg, PA	5.25	13.00	4.75	0.19	-0.10	99.50	2.00	0.58	0.034	0.035	5.29
Susquehanna River at Danville, PA	9.25	8.00	7.00	0.09	-0.07	88.00	2.00	0.50	0.048	0.049	3.16
WB Susquehanna River at Karthaus, PA	7.00	12.00	4.50	0.12	-0.10	95.00	4.00	0.55	0.054	0.055	3.04
Sinnemahoning Creek at Sinnemahoning, PA	7.50	11.00	6.00	0.17	-0.10	99.00	4.00	0.55	0.018	0.019	4.19
Kettle Creek near Westport, PA	4.50	9.00	8.00	0.11	-0.09	102.50	2.50	0.56	0.017	0.018	4.98
Bald Eagle Creek near Beech Creek Station, PA	7.50	10.50	6.00	0.11	-0.07	90.50	2.00	0.46	0.095	0.097	2.08
Pine Creek bl L Pine Creek near Waterville, PA	9.00	9.00	9.00	0.08	-0.07	93.00	3.00	0.54	0.025	0.025	4.57

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
Lycoming Creek near Trout Run, PA	6.00	11.00	5.00	0.15	-0.08	98.00	4.00	0.62	0.023	0.028	6.10
Loyalsock Creek at Loyalsockville, PA	6.00	13.00	4.50	0.15	-0.10	101.00	2.00	0.62	0.032	0.033	5.36
West Branch Susquehanna River at Lewisburg, PA	11.00	9.50	7.25	0.11	-0.07	82.50	2.50	0.54	0.049	0.051	3.48
Penns Creek at Penns Creek, PA	10.50	10.00	4.00	0.12	-0.07	98.00	2.50	0.50	0.056	0.057	3.68
East Mahantango Creek near Dalmatia, PA	6.25	11.50	4.00	0.13	-0.09	100.00	3.00	0.46	0.028	0.028	3.97
Frankstown Br Juniata River at Williamsburg, PA	5.50	12.00	4.25	0.12	-0.07	113.00	4.00	0.48	0.077	0.078	3.76
Little Juniata River at Spruce Creek, PA	5.50	11.50	4.25	0.16	-0.09	112.50	4.00	0.60	0.108	0.108	3.85
Juniata River at Huntingdon, PA	4.50	11.50	4.00	0.09	-0.08	134.00	5.00	0.48	0.090	0.096	3.03
Rays Br Juniata R bl Rays Dam nr Huntingdon, PA	15.75	8.00	7.25	0.06	-0.08	96.00	3.00	0.44	0.070	0.071	3.87
Aughwick Creek near Three Springs, PA	9.50	10.50	5.25	0.10	-0.06	98.00	2.00	0.43	0.013	0.013	4.40
Juniata River at Newport, PA	8.00	9.00	6.00	0.06	-0.05	98.00	3.50	0.45	0.065	0.066	2.90
Sherman Creek at Shermans Dale, PA	6.50	13.00	3.00	0.14	-0.07	106.00	2.00	0.51	0.035	0.036	4.74
Conodoguinet Creek near Hogestown, PA	8.00	10.50	4.25	0.09	-0.05	99.00	2.00	0.42	0.056	0.057	2.81
Susquehanna River at Harrisburg, PA	6.25	8.00	6.50	0.08	-0.06	82.50	2.00	0.49	0.058	0.059	2.80

Tributary	Low pulse dur	High pulse cnt	High pulse dur	Rise rate	Fall rate	Num of rev	Ext low freq	Mean flow (normalized to rainfall&area)	1 day min (normalized to rainfall&area)	3 day min (normalized to rainfall&area)	3 day max (normalized to rainfall&area)
Yellow Breeches Creek near Camp Hill, PA	7.00	11.50	2.00	0.08	-0.05	111.00	3.00	0.46	0.160	0.161	2.46
Swatara Creek near Hershey, PA	7.50	13.50	3.50	0.14	-0.10	113.50	4.00	0.51	0.048	0.051	3.71
West Conewago Creek near Manchester, PA	7.00	15.00	3.00	0.12	-0.07	103.00	3.50	0.42	0.022	0.023	4.05
Susquehanna River at Marietta, PA	7.50	8.00	6.00	0.07	-0.06	90.50	2.00	0.50	0.059	0.061	2.74
Conestoga River at Conestoga, PA	5.00	16.00	2.00	0.13	-0.07	114.00	3.00	0.43	0.079	0.080	3.25
Susquehanna River at Conowingo, MD	2.00	10.00	5.00	0.18	-0.17	172.50	10.00	0.50	0.037	0.052	2.64
Deer Creek at Rocks, MD	5.25	17.00	2.00	0.13	-0.06	120.00	3.00	0.42	0.110	0.112	2.16

Table 4. Average consumptive use coefficients.

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

Appendix E – Hydrologic Model

Baseline Land Use

Introduction to modeling baseline land uses

Baseline hydrologic conditions were defined as "modeled current conditions with the influence of water withdrawals, impoundments, and biologically significant hydrologic alterations due to land use removed via modeling." The purpose of this section is to describe the process by which baseline land uses for each of the 747 watersheds draining to a biological sampling point were generated for use in the hydrologic models, both HSPF and WOOOMM. In general, baseline land use calculations modified the current land uses in the CBP HSPF model (Table 1) to meet criteria established for baseline conditions, >78% forest and <0.35% impervious cover .

Methods

To calculate baseline land uses for each of the watersheds draining to a biological monitoring point, a spreadsheet was developed to modify current land use conditions to meet baseline criteria by HSPF land-river segment. Forested land use ("for") was adjusted to 78%. The two impervious cover land uses ("imh", "iml") were kept in their original proportions but adjusted to equal 0.35% of the total land use. All other land uses were adjusted to equal the remaining 21.65% of the land use, while keeping their proportions the same as the "current" scenario.

Land river segments within watersheds that exceed the minimum land use requirements for baseline conditions, those with greater than 78% forest and/or less than 0.35% impervious cover, retained the land use characteristics exceeding the baseline criteria. Without this distinction (if the baseline flows for all land river segments within each watershed were calculated utilizing 78% forest and 0.35% impervious cover), some components would appear to become more altered under baseline conditions due to decreases in percent forest and increases in impervious cover. Example baseline land use calculations are provided in Tables 2 and 3.

Discussion

Because of the assignment of land uses based on land-river segments, if all land-river segments in a watershed are >78% forest and <0.35% impervious, the watershed will exhibit no changes in land use between current and baseline scenarios. However, if one or more land-river segments in a watershed do not meet the criteria (i.e. <78% forest and/or >0.35% impervious), the watershed will show alteration between the two scenarios regardless of whether the total percent forest in the watershed is >78% and the total percent impervious cover in the watershed is <0.35% impervious cover. The change in land use for the entire watershed will be sum of any changes for all land-river segments. For a watershed to have no change in land use, all land-river segments in the watershed must have >78% forest and <0.35% impervious.

The baseline land uses resulting from this analysis will provide a point of reference for estimations of hydrologic alteration.

Table 1. Land use definitions.

LUCode	LuDescription
afo	Animal Feeding Operations
hom	High Till Crop without manure
hwm	High Till Crop with manure
lwm	Low Till Crop with Manure
nhi	High Till Crop with Manure and Nutrient Management
nho	High Till Crop with Nutrient Management but without manure
nlo	Low Till Crop with manure and Nutrient Management
urs	Nursery
alf	Alfalfa
hyo	Hay without nutrients
hyw	Hay with nutrients
nal	Alfalfa with Nutrient Management
nhy	Hay with nutrients and Nutrient Management
bar	Bare-construction
puh	High Intensity Pervious Urban
pul	Low Intensity Pervious Urban
imh	High Intensity Impervious Urban
iml	Low Intensity Impervious Urban
ext	Extractive
for	Forest
hvf	Harvested Forest
npa	Pasture with Nutrient Management
pas	Pasture
trp	Trampled Pasture
wat	Water

Table 2. Current land uses for one watershed draining to a biological monitoring point (858.5 acres).

uniqueid	afo	alf	bar	ext	for	hom	hvf	hwm	hyo	hyw	imh	iml	lwm	nal	nhi	nho	nhy	nlo	npa	pas	puh	pul	trp	urs	wat
382925907842100	2.4	44.8	0.0	0.0	205.0	5.2	2.1	12.4	20.5	111.1	4.96	1.74	51.4	0.0	6.3	0.2	30.2	18.5	39.8	242.7	21.1	26.8	11.3	0.0	0.0

Note: Unmanaged forest land shown in green and urban impervious land uses shown in pink. Under current conditions, forest accounts for approximately 24% of the total area while urban impervious land uses occupy 0.78% of the watershed. All values are in acres and are rounded to the tenth of an acre for the purposes of this example.

Table 3. Baseline land uses for the same watershed as previous table (858.5 acres).

uniqueid	afo	alf	bar	ext	for	hom	hvf	hwm	hyo	hyw	imh	iml	lwm	nal	nhi	nho	nhy	nlo	npa	pas	puh	pul	trp	urs	wat
382925907842100	0.7	12.9	0.0	0.0	669.6	1.5	0.6	3.6	5.9	31.9	2.22	0.78	14.8	0	1.8	0.1	8.7	5.3	11.4	69.7	6.1	7.7	3.2	0.0	0.0

Note: Unmanaged forest land shown in green and urban impervious land uses shown in pink. Under baseline conditions, forest accounts for 78% of the watershed and urban impervious accounts for 0.35% of the watershed. Note: the proportion of each urban impervious land uses remained the same in relation to each other and the proportion of non-forested, pervious land uses remained the same in relation to each other while the total percentage of the watershed containing those land uses changed. All values are in acres and are rounded to the tenth of an acre for the purposes of this example.

Appendix E – Hydrologic Model

Baseline Scenario

Introduction

This section documents the process of estimating baseline flows at the river segment scale utilizing the Chesapeake Bay Program (CBP) Phase 5.2 model. The resulting time series were utilized for comparison of baseline to future scenarios, which were only run in the CBP model. Baseline flows were estimated for all Potomac river segments EXCEPT (1) segments in the coastal plain; (2) tidal river segments because they do not contain simulated rivers; and/or (3) segments draining directly to a tidal segment that do not contain biological monitoring locations (Figure 1).

The baseline scenario 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." Within the CBP modeling environment, this process includes setting all discharge and withdrawal input time series to zero, redefining reservoir segments as river segments, and adjusting land uses to meet established criteria.

Methods

Removal of Impoundments

In the CBP Phase 5.2 model, reservoir segments are designated utilizing a "flag" in the river parameter file, gen_info_{scenario}.csv. The segment's hydrologic function table (FTABLE) is also designed to reflect the hydrologic function of a reservoir rather than a river reach (EPA 2007). In order to remove the 17 Potomac impoundments in the resegmented model, the reservoir flag was removed in the input geometry file and a river FTABLE was developed for each segment utilizing the USGS XSECT program (Moyer and Benentt 2007). XSECT is "a computer program that requires nine input variables used to represent channel morphology. These input variables are reach length, upstream and downstream elevation, channel bottom width, channel bankfull width, channel bankfull stage, slope of the floodplain, and Manning's roughness coefficient for the channel and floodplain." Inputs for the USGS XSECT program were developed utilizing 30m DEMs, CBP river reaches, and empirically developed values for simulated river segments.

Removal of Withdrawals and Point Sources

Point sources of flow to the simulated river and withdrawals of flow from the simulated river are incorporated into the model in Watershed Data Management (WDM) format. WDMs are a binary input file used to store input time series for HSPF. The CBP model code requires that a WDM be present for each simulated river segment for both point sources and withdrawals; however, they do not need to contain data. In order to remove the effects of withdrawals and point sources, therefore, blank WDM files were substituted for the withdrawal and point source input time series.

Baseline Land Uses

Based on regression and CART analysis in the Potomac and Susquehanna basins, the criteria for baseline land use were established at 78% forest and 0.35% impervious cover (see Appendix E file Pot-Susq_CART_analysis_011712.doc). To calculate baseline land uses, a spreadsheet was developed to adjust current land uses to "baseline" conditions by land-river segment. Forested land use (“for”) was adjusted to 78%. The two impervious cover land uses (“imh”, “iml”) were kept in their original proportions but adjusted to equal 0.35% of the total land use. All other land uses were adjusted to equal the remaining 21.65% of the land use, while keeping their proportions the same as the "current" scenario.

Watersheds that exceed the minimum land use requirements for baseline conditions, those with greater than 78% forest and/or less than 0.35% impervious cover, retained the land use characteristics exceeding the baseline criteria. Without this distinction (if the baseline flows for all watersheds are calculated utilizing 78% forest and 0.35% impervious cover), some watersheds would appear to become more altered under baseline conditions due to decreases in percent forest and increases in impervious cover. For an example of the calculation methods used to develop the baseline input time series, see the task A-3.10 memo.

This methodology was utilized to calculate baseline land uses for the series of input spreadsheets required in the CBP Phase 5.2 model. The years 2002, 1997, 1995, 1992, 1987, and 1982 have an input land use spreadsheet to define land use changes over the simulation time period. Model scripts interpolate between the input data sets for intermediate years.

Results

Reference Watersheds

Reference watersheds are areas where the current condition IS a baseline condition. Because baseline criteria were established by assessing reference watersheds, it was expected that reference watersheds would show zero (or very small) alteration between current and baseline conditions.[1] Curves were developed utilizing simulated data from 1984-2005. Simulated current, simulated baseline, and observed flows are provided below for several Potomac reference watersheds (Figures 2 – 5). This sub-set of reference watersheds was selected for presentation here because they roughly correspond to simulated river segment outlets for direct comparison with model results.

Non-reference Watersheds

Non-reference watersheds selected for presentation here have varying degrees of hydrologic alteration when comparing current and baseline flows (Figures 6-9). This is due to the unique conditions of each particular watershed and the impacts of removing impoundments, discharges, withdrawals, and adjusting land use to baseline conditions. As with the selected reference watersheds, this sub-set of watersheds was selected for presentation here because these watersheds roughly correspond to simulated river segment outlets for direct comparison with model results.

Significant Impoundments

The CBP Phase 5 model was previously re-segmented to include 12 additional “significant” impoundments. Impoundments were identified as “significant” using the following criteria: (1) water was impounded to generate hydroelectricity; (2) reservoir normal storage capacity was greater than 10% of the mean flow; or (3) both 1 and 2. For more information, see memo regarding re-segmentation at impoundments. For a sub-set of impoundments, the simulated baseline, simulated

[1] Simulated baseline and current conditions are indistinguishable in all but one of the reference watersheds selected for this preliminary analysis.

current, and observed flows are shown below (Figures 10-12). The curves were developed for simulated river segments immediately downstream from the reservoir segments.

Discussion

CBP baseline model outputs were utilized to calculate alteration from current and future scenarios at the river segment scale. Simulated baseline time series were developed for the 747 WOOOMM watersheds; however these flows were not appropriate for calculation of alteration in future scenarios since the future scenarios were only run in the HSPF model. By comparing scenarios (e.g. baseline to current) from only one model at a time, alteration from differences in model output was not erroneously included in the results.

References

EPA. 2007. BASINS technical note 1: Creating Hydraulic Function Tables (FTABLES) for reservoirs in BASINS. U.S. Environmental Protection Agency. Retrieved from http://www.epa.gov/waterscience/basins/docs/tecnote1.pdf.

Moyer, D., and M. Benentt. 2007. Development of relations of stream stage to channel geometry and discharge for stream segments simulated with Hydrologic Simulation Program - Fortran (HSPF), Chesapeake Bay Watershed and Adjacent Parts of Virginia, Maryland, and Delaware. USGS Scientific INvestigations Report, USGS. Retrieved from http://pubs.usgs.gov/sir/2007/5135/pdf/SIR2007-5135.pdf.

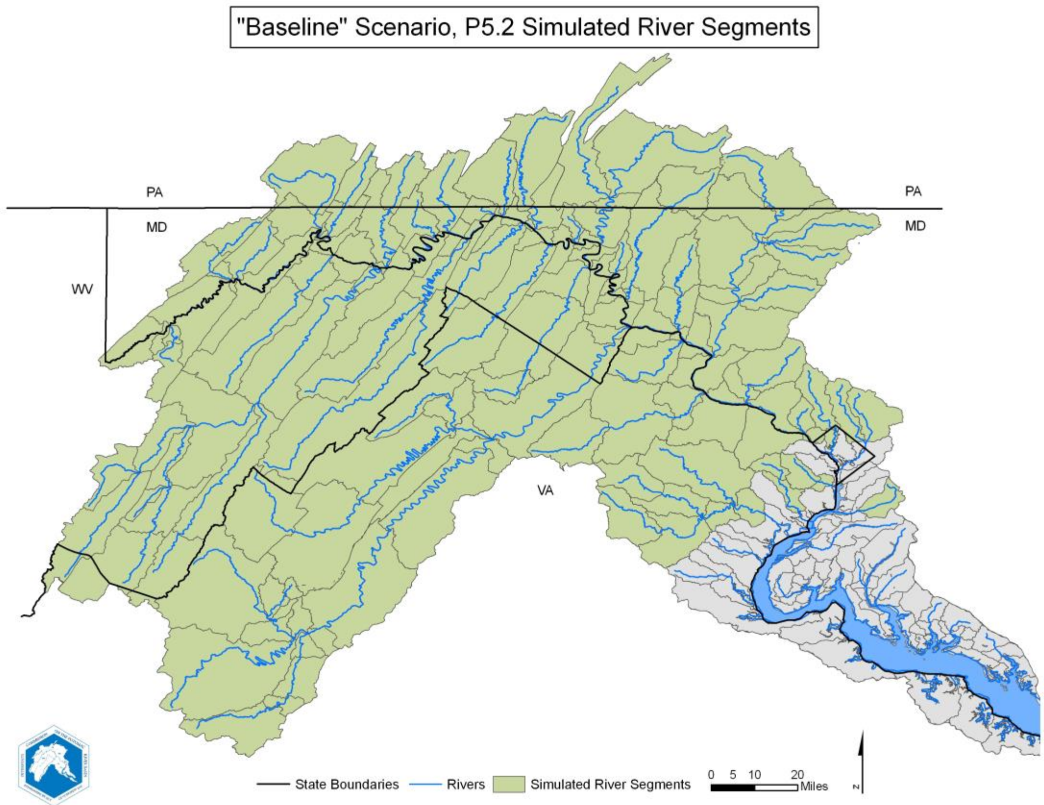

Figure 1. CBP river segments for which baseline flows were estimated.

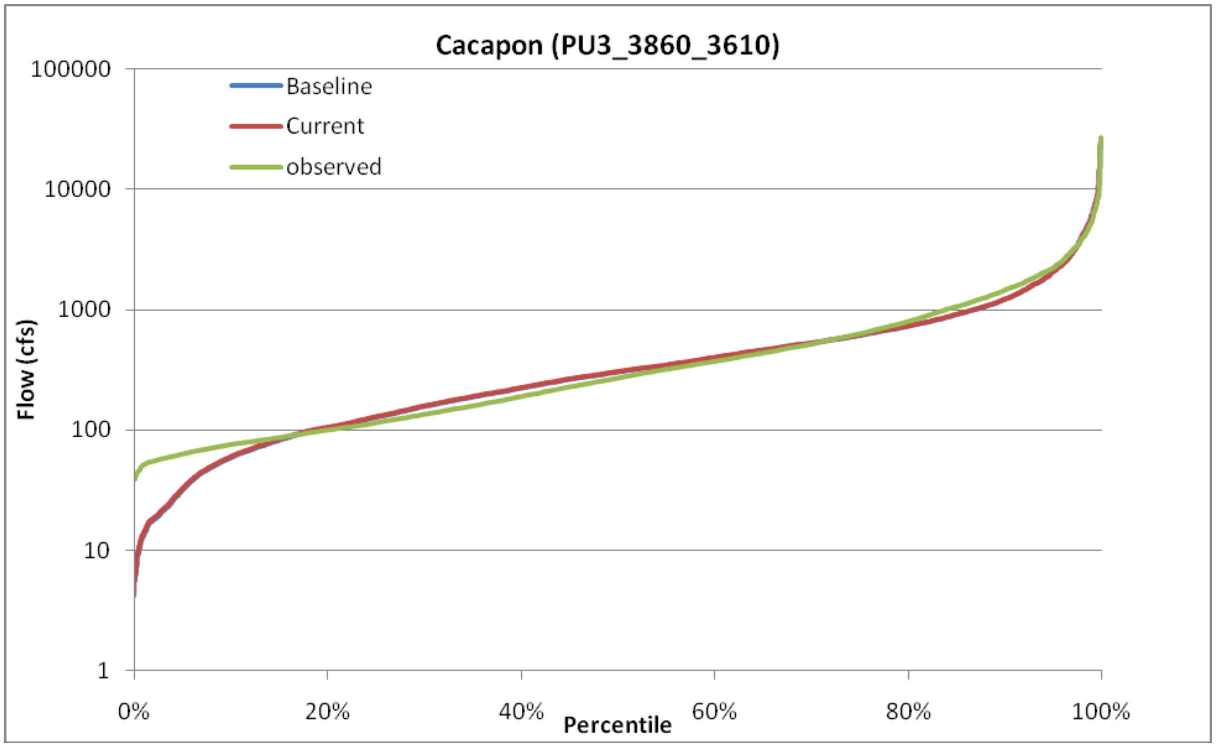

Figure 2. Cacapon watershed. The observed time series from the USGS gage at the Cacapon watershed outlet is missing data from water year 1996.

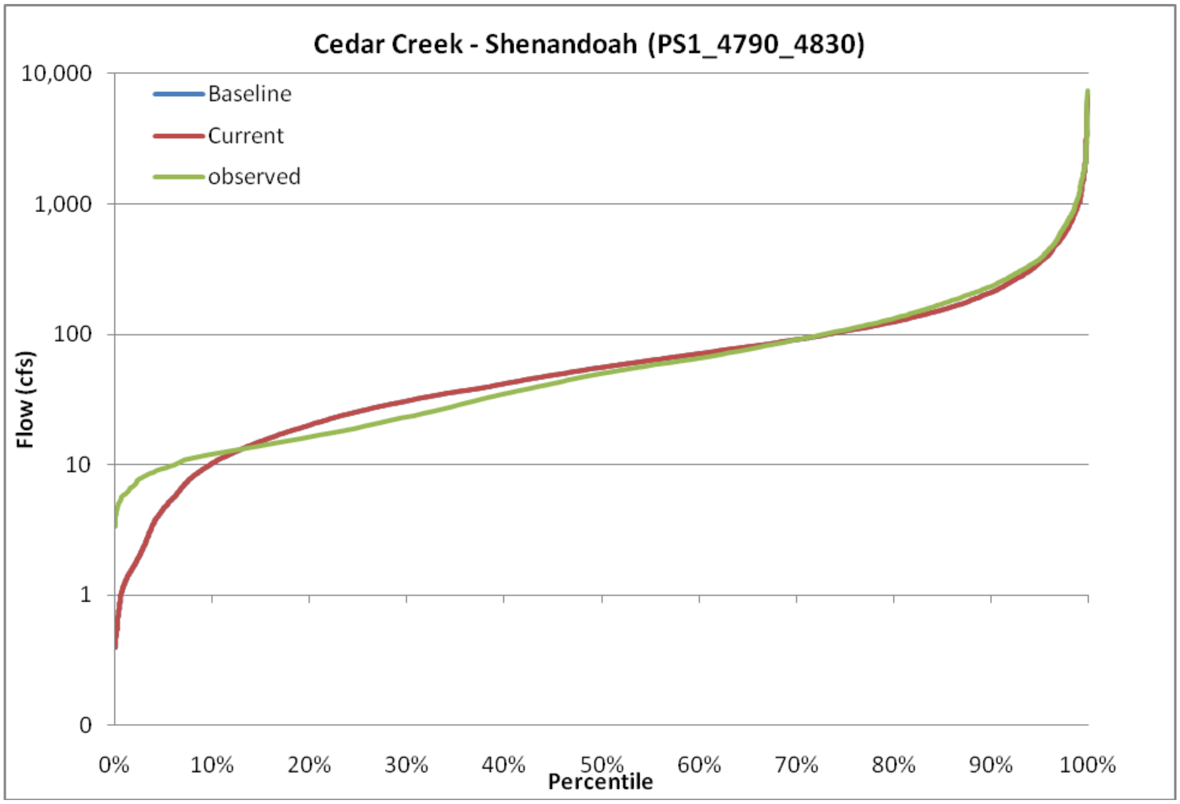

Figure 3. Cedar Creek sub-watershed of the Shenandoah.

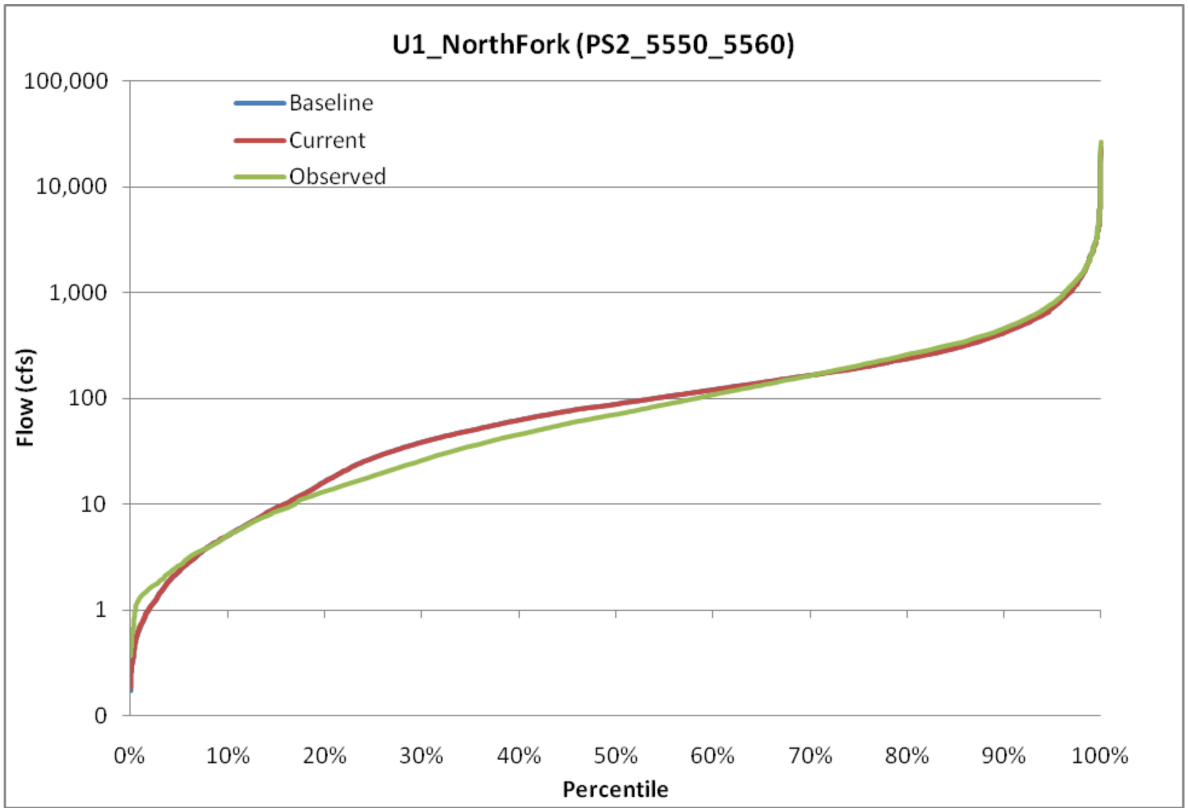

Figure 4. Upper North Fork watershed.

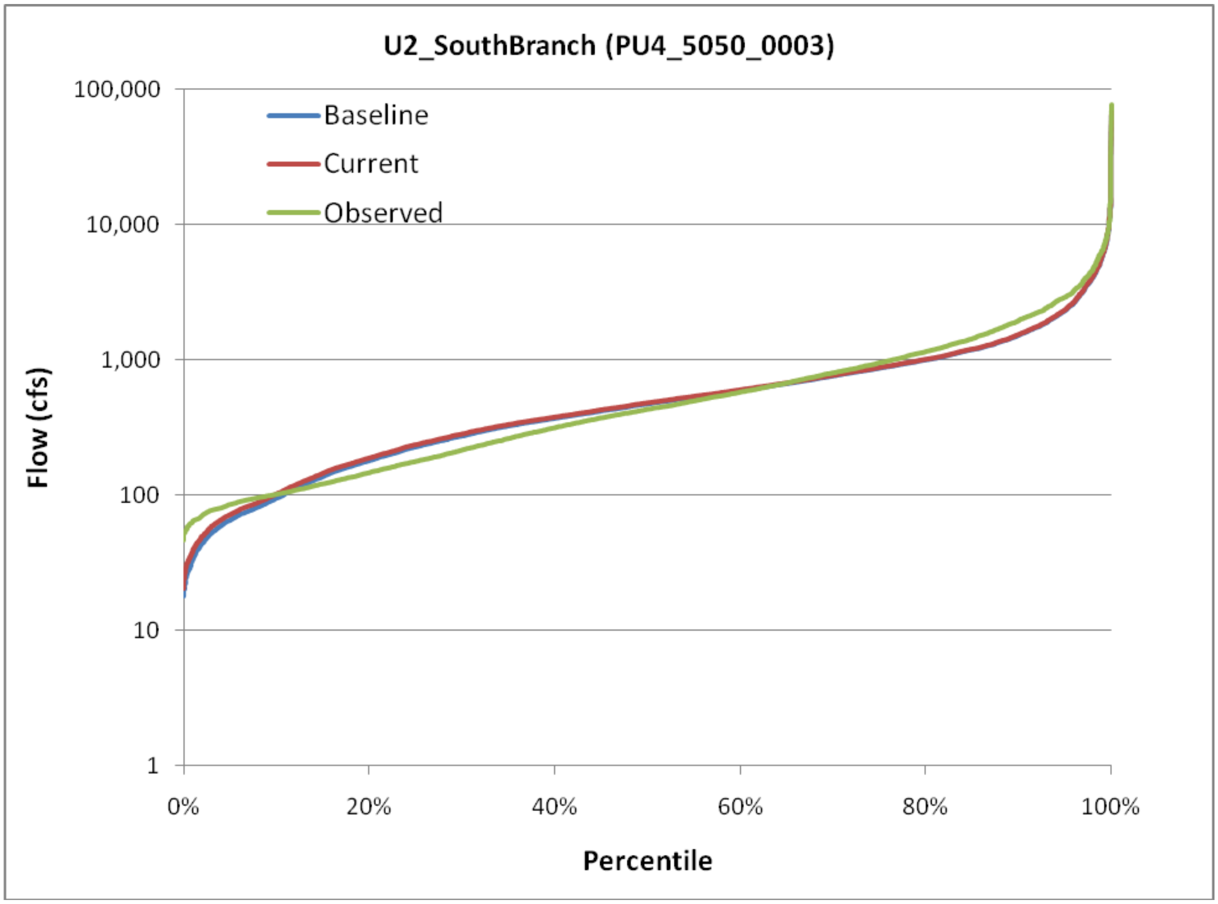

Figure 5. Upper South Branch watershed. Baseline and current conditions are indistinguishable in this watershed above approximately 40th percentile flows. Low flows decrease under baseline conditions.

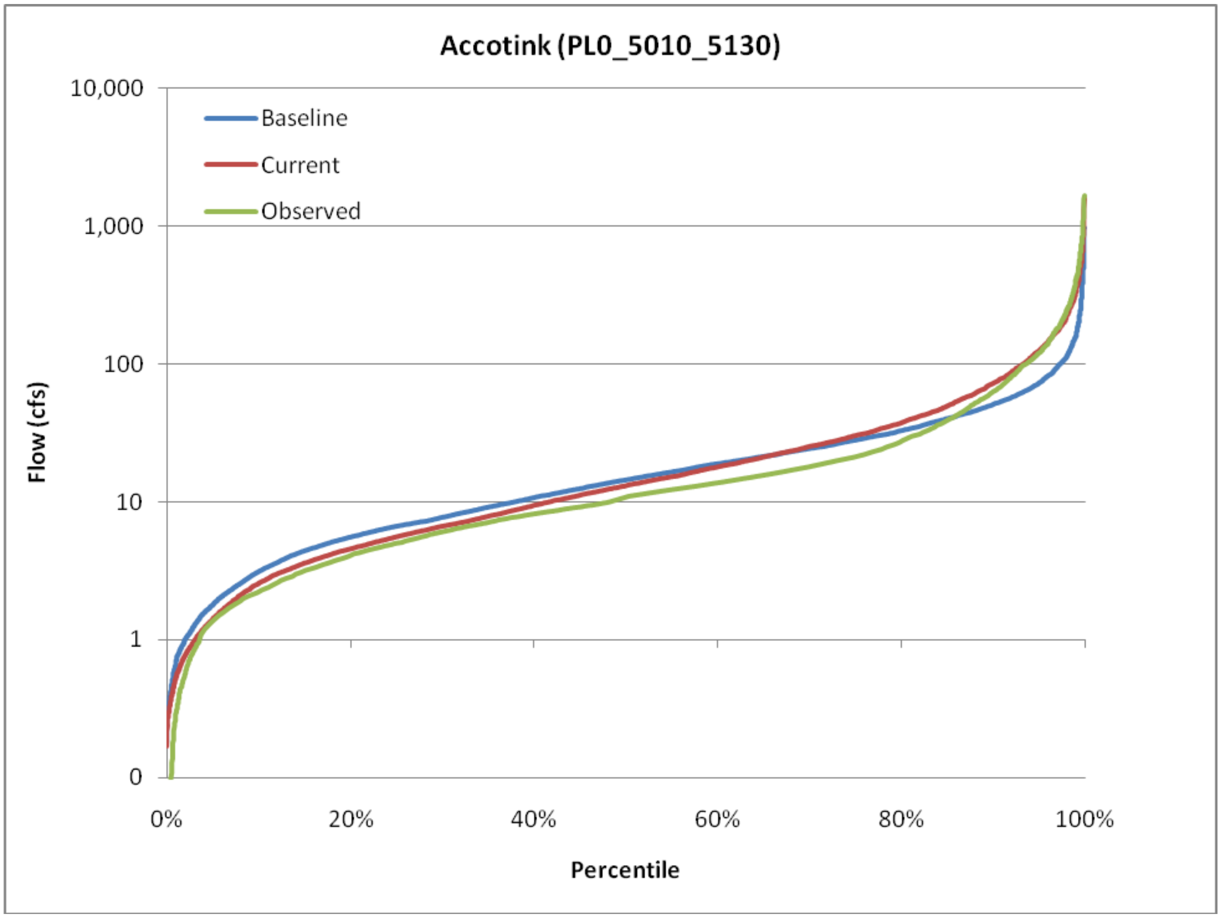

Figure 6. Accotink watershed. The Accotink watershed is just over 90% urban and has approximately 25% impervious cover.

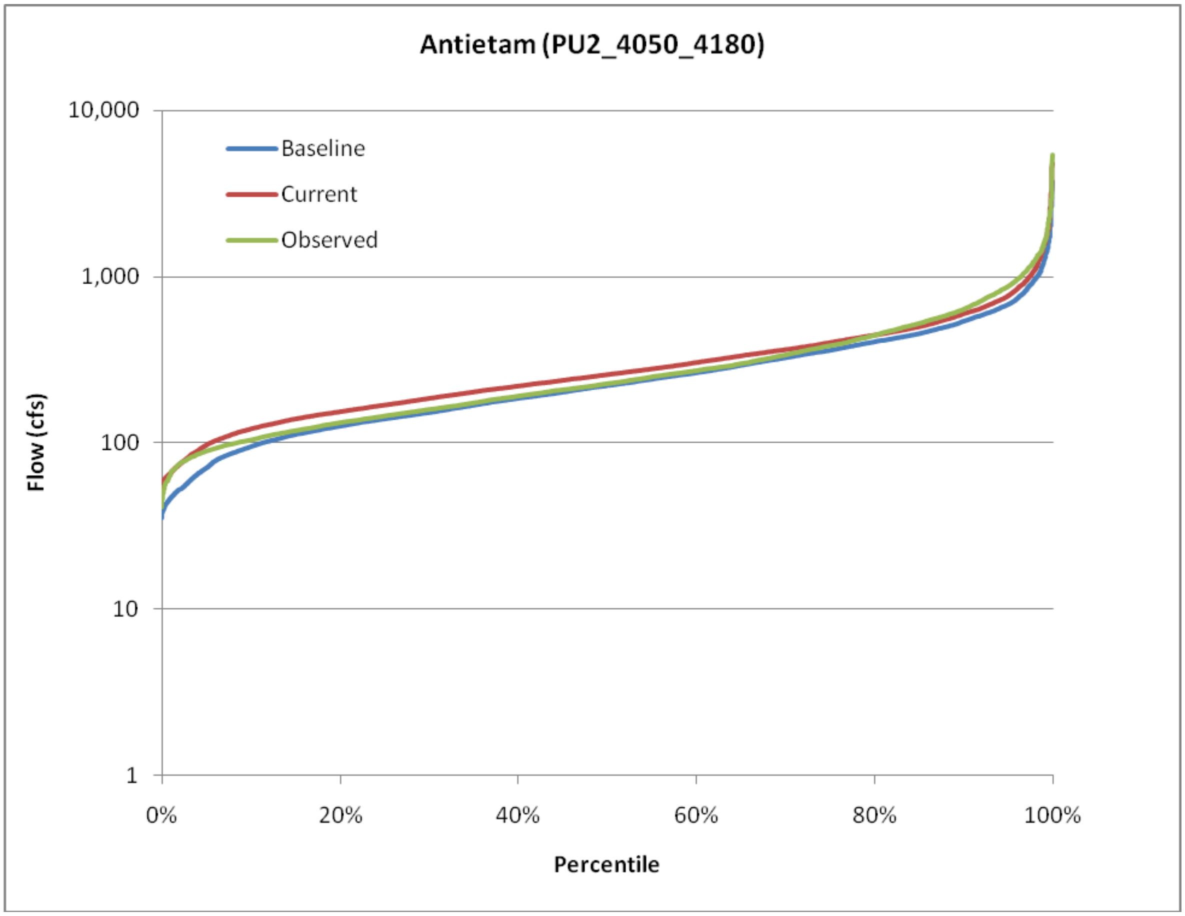

Figure 7. Antietam watershed. Land uses in this watershed are 4% impervious cover and 38% forest, 40% agriculture, and 38% forest. Withdrawals are equal to 6% of the median flows under current conditions.

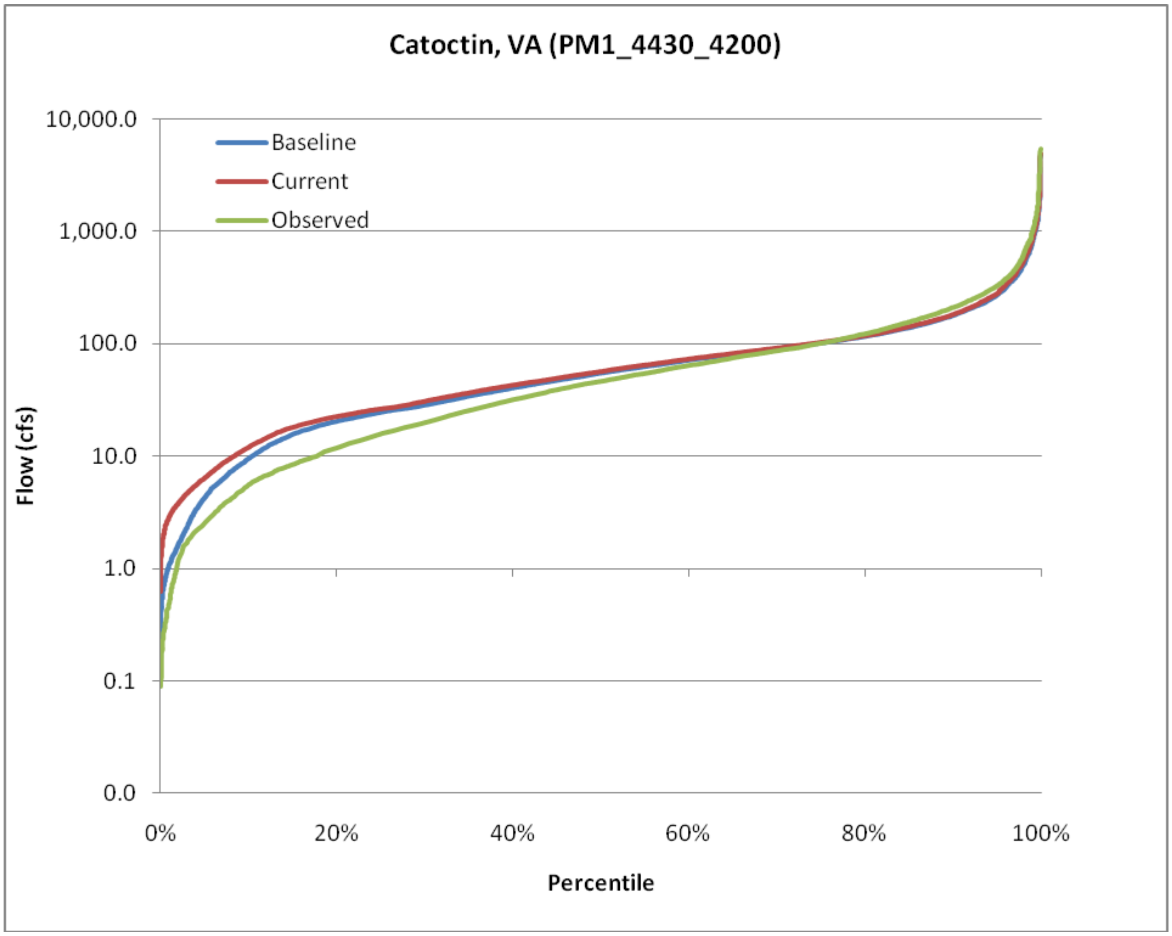

Figure 8. Catoctin Creek watershed, VA. The Catoctin Creek watershed is 53% agriculture and 40% forested.

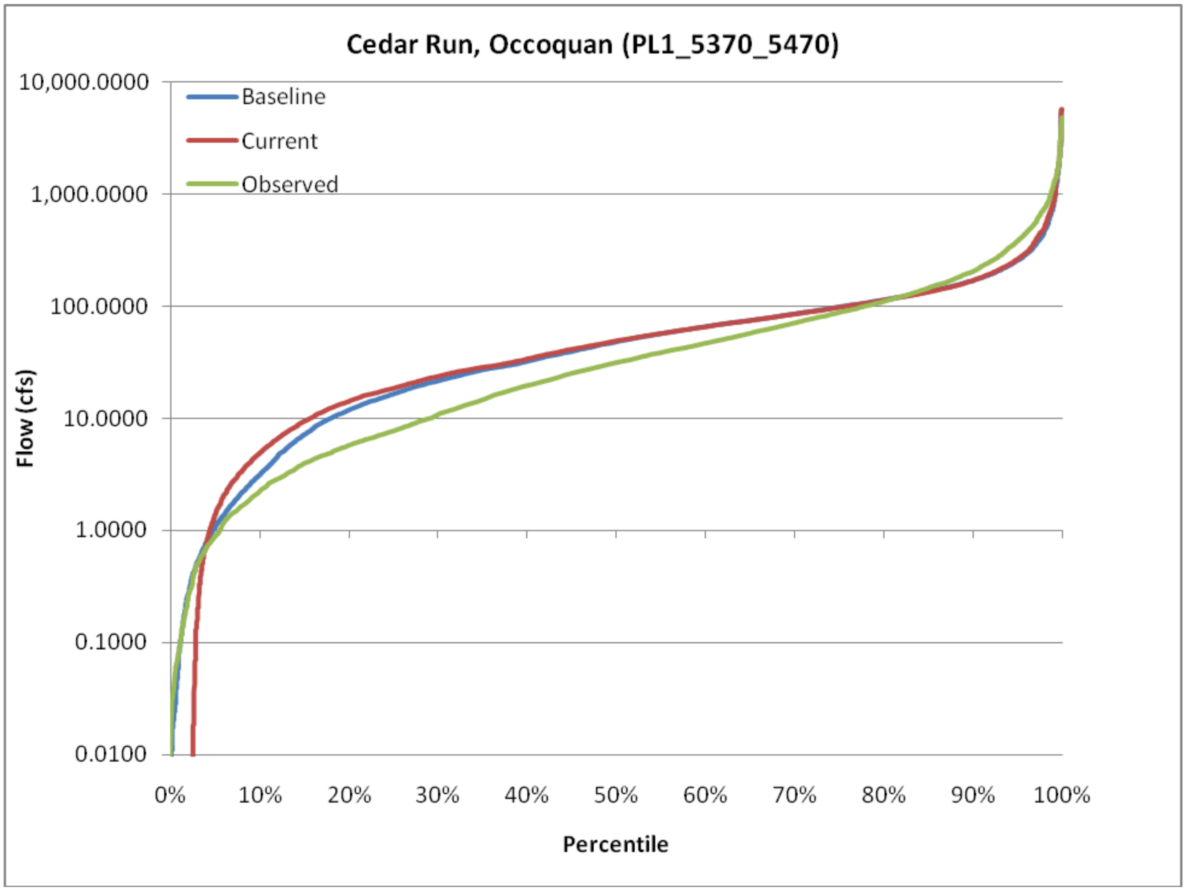

Figure 9. Cedar Run sub-watershed of the Occoquan. This watershed is 47% agriculture, 10% urban, and 40% forest under current conditions. Withdrawals are approximately 7% of the median flow.

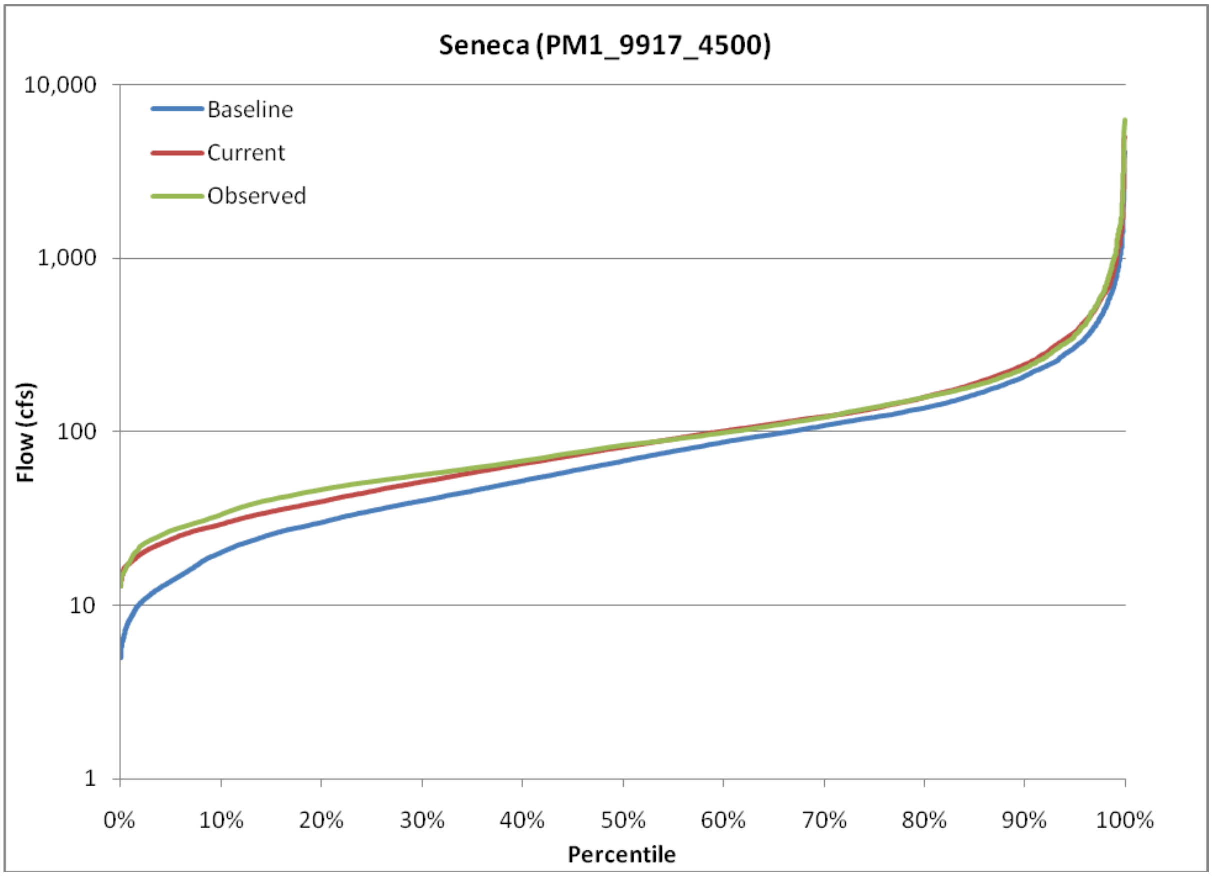

Figure 10. Great Seneca Creek watershed.

Note: Little Seneca Dam has a minimum flowby requirement of 1.1 million gallons per day and has historically made low flow releases to meet flowby requirements at Little Falls. Land uses in the watershed are 39% urban, 9% impervious, 23% agriculture, and 31% forest.

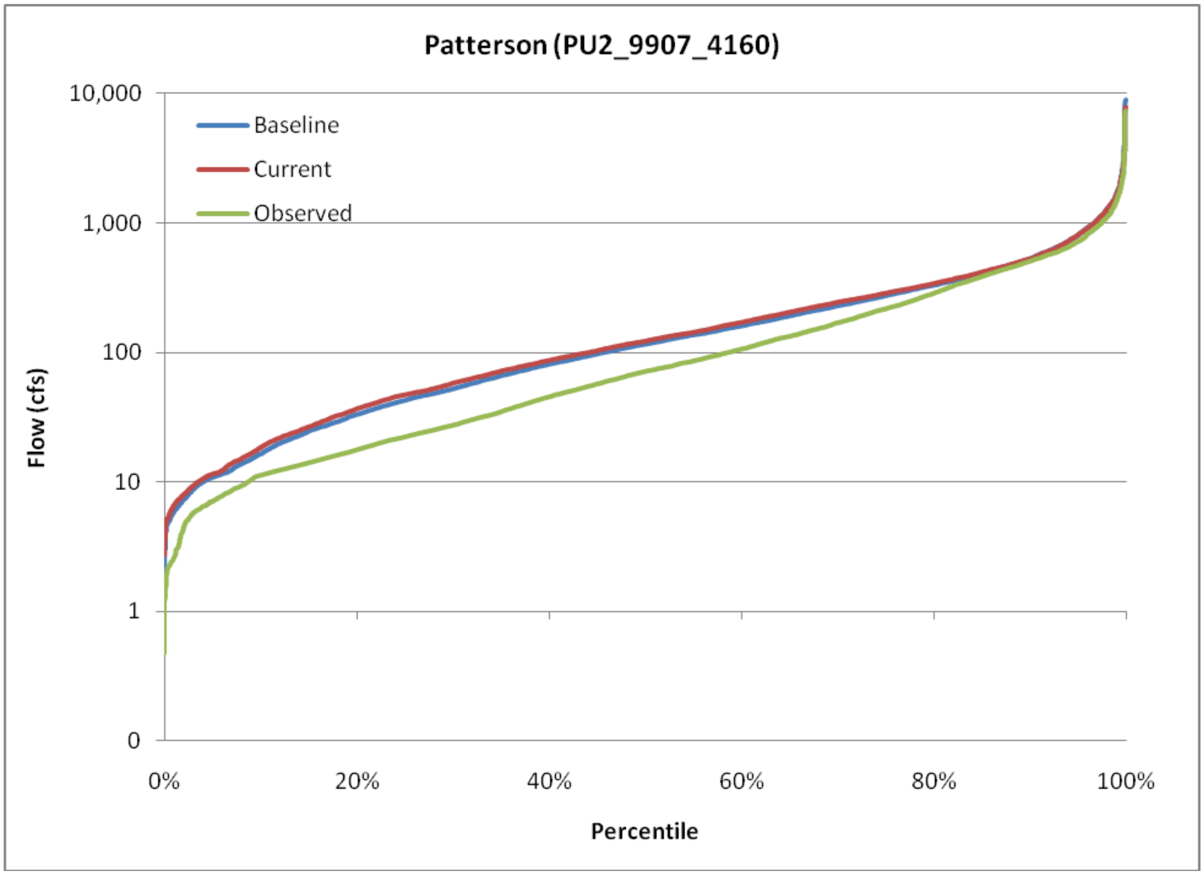

Figure 11. Patterson Creek watershed.

Note: Baseline and current conditions in the Patterson Creek watershed are very similar. The two impoundments upstream of this river segment are Patterson No.4 and Patterson No. 41. The drainage areas to these reservoirs occupy only a small percentage of the total drainage area in the Patterson Creek watershed. Moreover, the Patterson Creek land uses are borderline reference conditions.

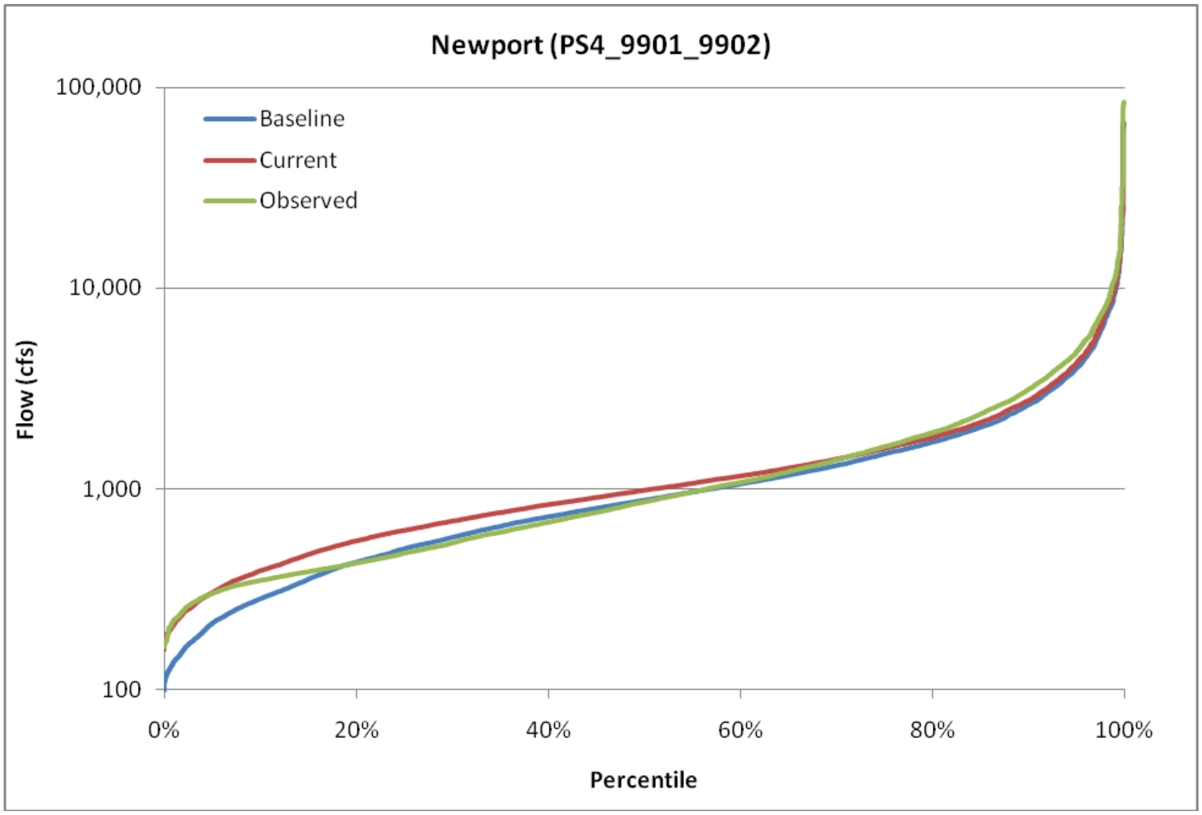

Figure 12. Newport Dam, Shenandoah watershed.

Note: The Newport Dam is used for hydroelectric purposes and has a normal storage of 1,090 acre-feet. The watershed draining this segment is composed of 7% urban, 34% agriculture, 58% forest, and is estimated to be 1.4% impervious cover. Karst geology is present in 57% of this watershed. Withdrawals are equal to approximately 6% of the median flow.

Appendix E – Hydrologic Model

WOOOMM Module

Introduction

This memo documents efforts to transition from the Chesapeake Bay Program (CBP) Phase 5 HSPF modeling environment to the VA Department of Environmental Quality (VADEQ) WOOOMM (Online Object Oriented Meta-Model) environment. The WOOOMM was selected for the ELOHA process because it can simulate flows at any stream location within a CBP river segment. WOOOMM is able to simulate flows at any stream location by combining several model components including the CBP Phase 5 model, a channel routing routine, and a USGS channel morphology model.[1,2] This WOOOMM capability enables flow simulation at biological monitoring points throughout the study area (Figure 1), locations for which flows are needed to conduct the alteration assessment, Task A-5. In selected test cases, WOOOMM was also shown to more accurately reproduce observed flows at the sub-river segment scale when compared with other methods (Table 1).

In total, 747 watersheds that drain to 869 biological monitoring points were selected for use in the assessment of hydrologic alteration (REPORT APPENDIX E – Watershed_delineation_011712.pdf). Hydrologic alteration under baseline, current, and alternate future scenarios will be estimated for these watersheds. Required WOOOMM input data sets for each watershed include direct runoff segment ID, area characteristics, physiographic province, nested shed codes, channel slope, channel length, and land use among others. For each model scenario (e.g. baseline, current, future), additional inputs may include withdrawals, discharges, and impoundments.

Some biological monitoring points did not require explicit simulation within the WOOOMM modeling environment because they either (1) were located near the outlet of a CBP river segment, or (2) were located so close to another biological monitoring point that the delineated watersheds were identical for modeling purposes. This is the reason there is a difference in the number of watersheds and the number of biological monitoring points in the study.

Terminating CBP River Segment ID

The WOOOMM model requires an ID for the terminating CBP river segment for each watershed. For watersheds that exist solely within one river segment, including all Class 1 and 2 watersheds, the terminating river segment is the only river segment. Larger watersheds may cross several CBP river segments. In such cases, the terminating river segment is the CBP river segment in which the biological monitoring point (i.e. the watershed outlet) is located. The direct runoff segment ID was obtained utilizing the biological monitoring point shapefile, the CBP river segment shapefile, and the

[1] The WOOOMM model is available online at http://deq1.bse.vt.edu/wooomm/login.php.

[2] A WOOOMM tutorial is available online at http://deq1.bse.vt.edu/wooomm/doc/tutorial_02.html.

GIS Join by Spatial Location tool. In this way, the river segment that contains the biological monitoring point was associated with each watershed unique ID.

CBP River Segment Cumulative Upstream Area

The cumulative upstream area for the terminal river segment was obtained from the model input geometry file for the CBP river segments. The spreadsheet can be found in the CBP model folder hierarchy at model\p52\config\catalog\geo\{scenario}\watershed_area.csv.

Watershed Area

Several area-related characteristics were calculated as inputs for the WOOOMM model; namely, the total area of each watershed, the area of each watershed not contained in any other watershed, and the area of CBP river segments not explicitly simulated in a watershed terminating in that segment. Examples of these types of areas are shown in Figure 2.

The total area of each watershed draining to a biological monitoring point was calculated utilizing the watershed boundary polygons and the Calculate Geometry tool in GIS. A description of how the watershed boundary shapefile was created is available in the REPORT APPENDIX E – Watershed_delineation_011712.pdf. The watershed areas vary widely (0.2 – 3,050 sq. mi.). The median watershed size is 3.6 sq. mi. Resulting watershed areas are shown in Figure 3.

Due to the WOOOMM simulation order, the area of each watershed not contained in any other watershed within the CBP terminating river segment was calculated. Utilizing this information, the WOOOMM model simulates the upstream, smallest watersheds first and methodically continues downstream, adding only the area for each watershed that has not been previously simulated within another watershed. The area of the CBP river segment that was not explicitly simulated in a watershed terminating in that segment was also necessary to determine flow generation to downstream river segments (Figure 2). A polygon shapefile of these areas was obtained by Erasing the watershed area shapefile from the CBP river segment shapefile, resulting in a shapefile of CBP river segments not located in a watershed local drainage area.

Dominant Physiographic Province

Four EPA Level III ecoregions were represented by the watersheds draining to biological monitoring points; namely, Valley and Ridge (66%), Piedmont (30%), Coastal Plain (3%), and Appalachians (1%). The dominant physiographic province is required input for the WOOOMM model because regression equations in the USGS channel morphology model vary by physiographic province. To obtain this characteristic for each watershed, the watershed shapefile was Intersected with the EPA's ecoregion layer, described in (Woods et al. 1999). The result was a polygon for each unique watershed/ecoregion combination. Areas for these combinations were calculated with the "Calculate Geometry" tool. The dominant ecoregion was identified for each watershed in Excel utilizing the resulting areas.

Nested Shed Codes

Watersheds draining to biological monitoring points are nested. Nested shed codes were developed to differentiate the 'level' within the nested hierarchy for each watershed. Figure 4 is an example of this nested watershed hierarchy and the associated nested shed codes for CBP river segment PM2_2860_3040, containing Marsh Creek, Rock Creek, and Alloway Creek in the upper Monocacy watershed. The GIS attribute files were imported to Excel for each watershed polygon. Watershed characteristics including size, area, and location were utilized to construct a table of the watersheds contained in each watershed. A marco was created to read the table and construct the corresponding nested codes.

Local River Reach Characteristics

Local river reaches are defined by the main river stem for each watershed's local area. The main stem segments were identified from the National Hydrography Dataset (NHD) stream layer. Examples of local river reaches in a portion of the Shenandoah watershed are shown in Figure 5.

Channel Slope

For each watershed draining to a biological monitoring point, the local river reach slope was calculated. This value is utilized by the USGS channel morphology model component of WOOOMM as well as in the channel routing routine. Channel slope was estimated in GIS utilizing the National Elevation Dataset's (NED) 30 meter resolution Digital Elevation Model (DEM) and the NHD stream layer. The elevation grid was converted to a slope grid using the Surface Analysis Slope tool within Spatial Analyst. The resulting slope grid was clipped to the stream layer and, utilizing Spatial Analyst's Zonal Statistics, the average channel slope within each watershed draining to a biological monitoring point was calculated.

Channel Length

Channel length is necessary for the channel routing and channel morphology routines in the WOOOMM model. Lengths were calculated by intersecting the local river reaches with the local areas of watersheds draining to biological monitoring points. This operation resulted in a single stream shapefile with the attributes of both the watershed and the stream. Within the attribute table, the length of the streamlines were then calculated using the Calculate Geometry tool and summed for each watershed to obtain the total mainstem length.

Current and Baseline Land Uses

Methods used to obtain the baseline land uses for each watershed are described in Appendix E (Baseline Landuse). To calculate the current land uses, the area of each University of Maryland's RESAC land use category for the year 2000 was calculated using a GIS area tabulation function. The RESAC land use categories were adjusted to the CBP Phase 5 land use types, as required by the WOOOMM model, utilizing an optimization routine. The optimization included the following 3 steps for each watershed by CBP land-river segment:

1) Sum the total area of the 6 major land use groups (forest, crop, developed, barren, extraction, and water) in the Phase 5 land-river segment and in the RESAC data for the watershed;
2) Calculate the fraction of each of the 25 Phase 5 land use types within the larger land use groupings for each of the watershed's Phase 5 land-river segments; and
3) Utilize Eq. 1 to obtain the area for each Phase 5 land use type in the watershed by land-river segment.[3]

[3] The land use group adjustment factor (*f*) is calculated by an Excel marco performing a Goal-Seeking function to set the total of the new land use type areas equal the total RESAC area.

$$A = (l_{P5}/L_{P5}) * (L_R/L_{P5}) * f \qquad \text{(Eq. 1)}$$

l_{P5} = Phase 5 land use type area
L_{P5} = Phase 5 land use group area
L_R = RESAC land use group area
f = land use group adjustment factor

Withdrawal and Discharge Databases

The VADEQ WOOOMM model can incorporate withdrawals and discharges based on location (i.e. latitude and longitude) instead of using the spatially aggregated WDM[4] binary time series format required by the CBP HSPF model. To this end, a point source database was developed utilizing the Bay Program Nutrient Point Source Database.[5] The developed database contains two related tables. One table includes the National Pollution Discharge Elimination System (NPDES) permit numbers and the latitude and longitude of the respective discharges. The other table contains the NPDES number and the monthly discharge time series from 1984-2005 for the location. A total of 227 permitted dischargers are represented in the database. Similarly, a spatially explicit withdrawal database was developed utilizing the ICPRB 2005 withdrawal database (developed by J. Palmer 2009). Only surface withdrawals were included in the simulation, as information on the effects of individual groundwater withdrawals on surface water flow is unknown. This is standard practice as the CBP HSPF model also does not include groundwater withdrawals.

Discussion

The input files described in this document were utilized to define the watersheds draining to biological monitoring points within the WOOOMM modeling environment. Scripts were developed by R. Burgholzer, VADEQ, to pull this information from their original shapefile, spreadsheet, and database formats into the model to develop a folder hierarchy of the nested watersheds containing the respective input data. The model was then run under current and baseline conditions (no impoundments, withdrawals, or discharges; greater than or equal to 78% forested land use; and impervious less than or equal to 0.35%). The model output time series were utilized to estimate hydrologic alteration for each watershed.

References

Woods, A.J., J.M. Omernik, and D.D. Brown. 1999. Level III and IV ecoregions of Delaware, Maryland, Pennsylvania, Virginia, and West Virginia. Page 57. EPA, Corvallis, OR.

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[4] Watershed Data Management (WDM) is a binary input file used to store input time series for HSPF such as precipitation, flows, and withdrawals, among others.

[5] http://www.chesapeakebay.net/data_pointsource.aspx

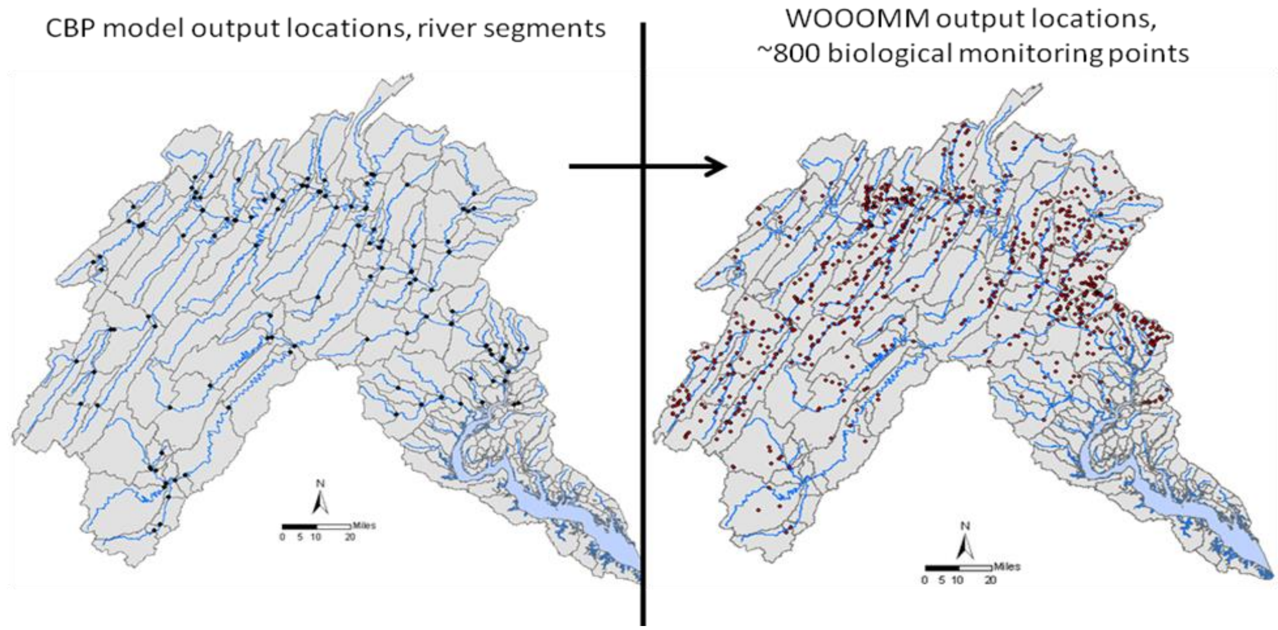

Figure 1. The map of the Potomac River basin on the left has CBP river segment outlets marked with black points. Utilizing the WOOOMM model, flows can be simulated within river segments. The map of the Potomac River basin on the right shows biological monitoring points for which flows were simulated in the WOOOMM model.

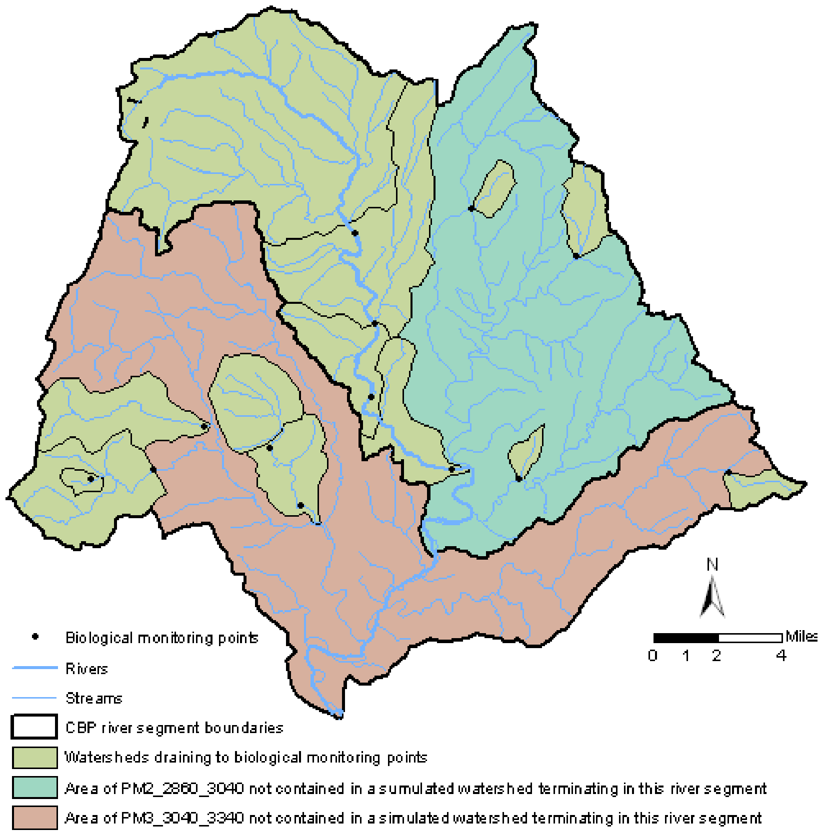

Figure 2. Watershed area characteristics for two CBP river segments in the Upper Monocacy watershed.

Note: The light green areas show the local drainage areas. These areas do not overlap (i.e. a downstream watershed's local drainage area does not include the area of upstream watersheds). The total watershed area utilizes these same watershed boundaries, however, they are overlapping. That is, the total watershed area does include the area of upstream, nested watersheds. The blue and pink areas are the portions of the CBP river segments (outlined in bolded black) that are not explicitly simulated by any watershed contained therein.

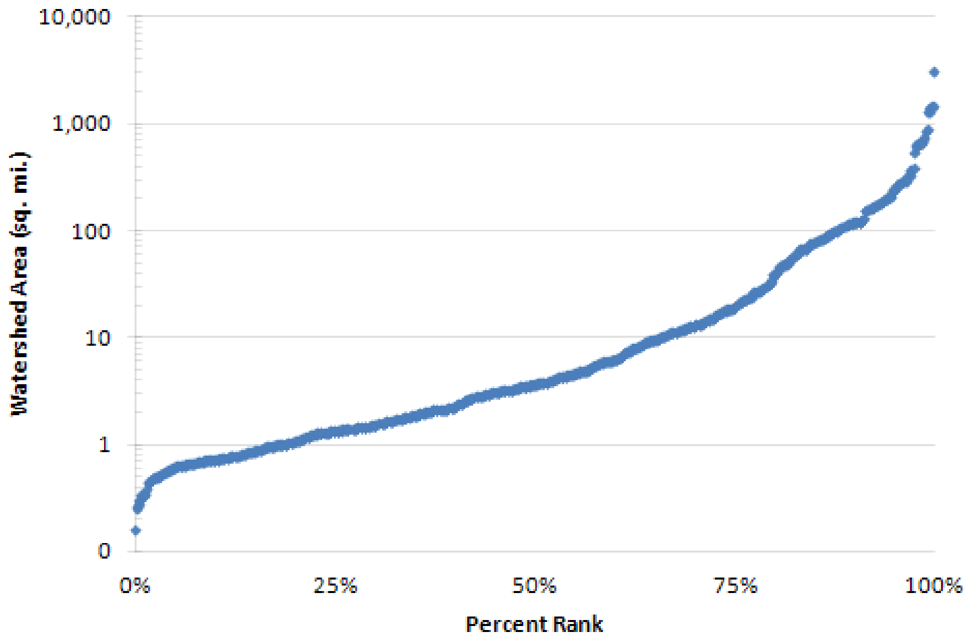

Figure 3. Contributing areas of watersheds draining to biological monitoring points (n=747).

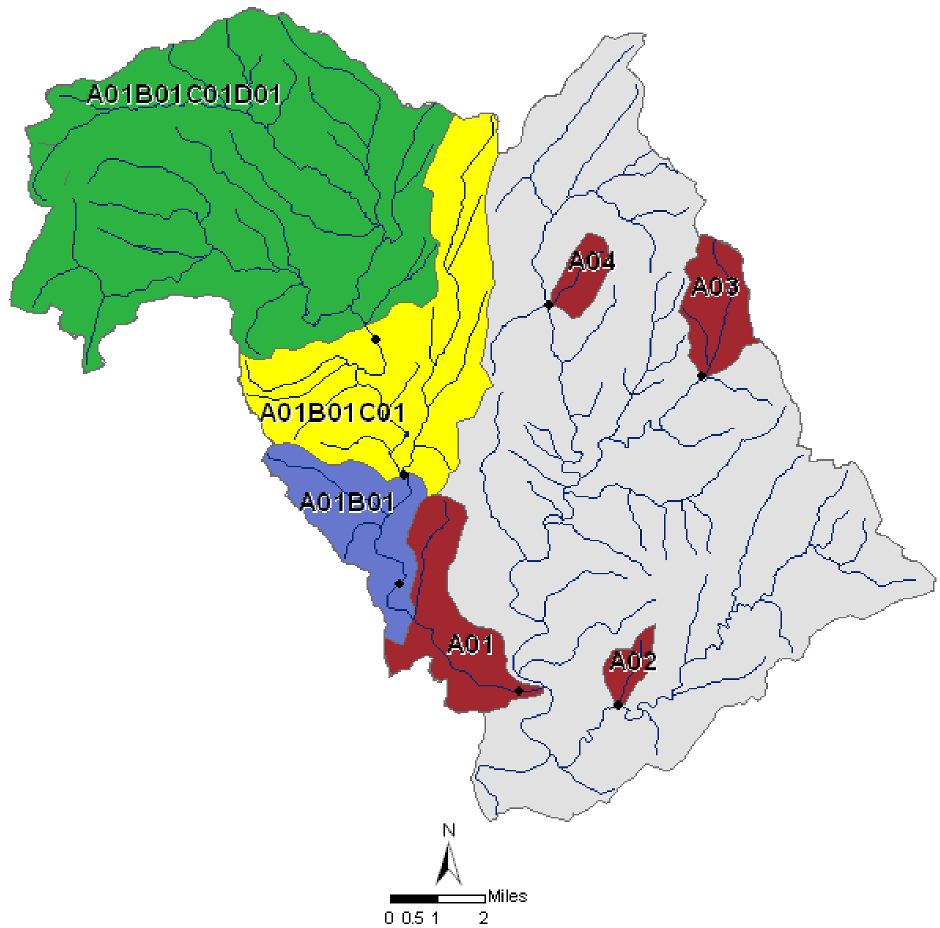

Figure 4. Nested shed codes for CBP river segment PM2_2860_3040.

Note: The light gray area is the portion of the river segment not explicitly simulated as part of a watershed terminating within the river segment. The different colors are utilized to denote watershed level. Level A watersheds are shown in dark red; Level B watersheds are shown in blue; Level C watersheds in yellow; and Level D watersheds in green. These watersheds are nested, meaning that the total area of watershed A01 includes the area of all watersheds beginning with A01.

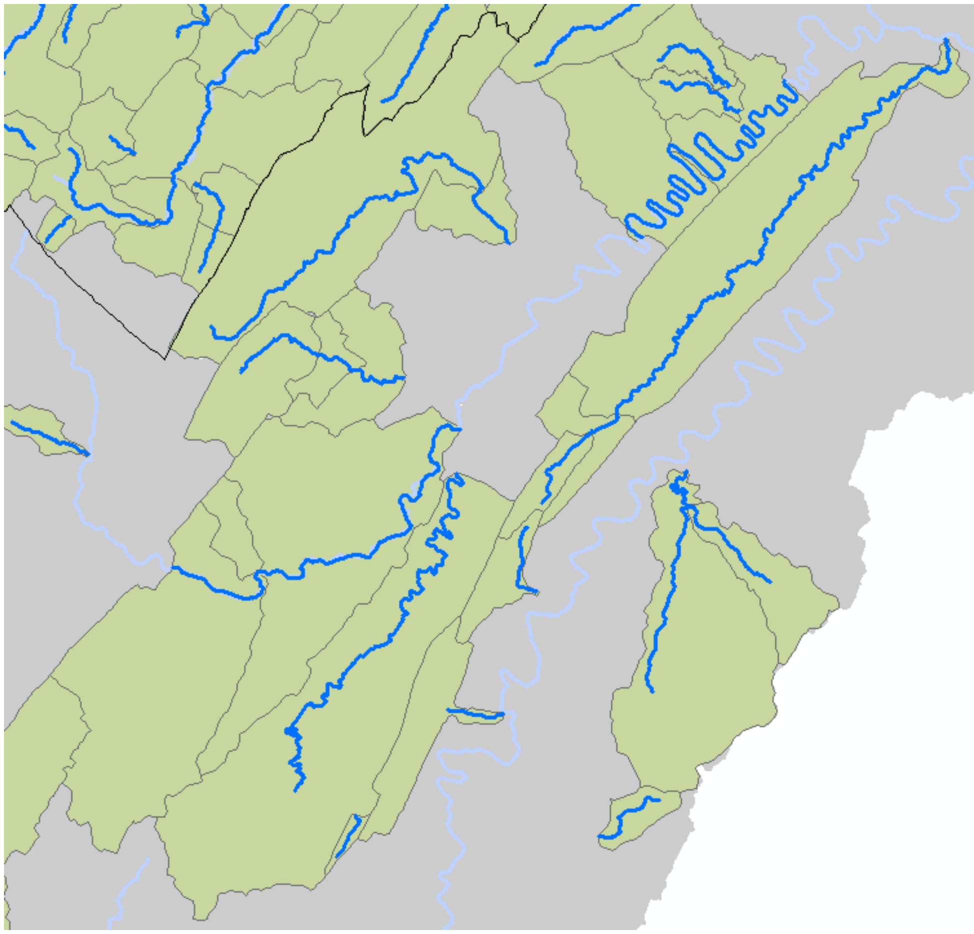

Figure 5. Local river reaches in a portion of the Shenandoah River watershed.

Note: The dark blue lines are the local river reaches. The light blue lines are the CBP Phase 5 river reaches. Green polygons are the local areas of watersheds draining to biological monitoring points. The area with a white background in the bottom right hand corner of the figure is outside of the Potomac River basin.

Table 1. Comparison of observed flows with WOOOMM simulated and HSPF simulated flows in select test watersheds (cfs).

Tributary	USGS Gage	Area Weighted HSPF	WOOOMM
Bennett Creek	72	**74.22**	59.5
Linville Creek	39.7	41.92	**38.6**
Marsh Run	11.3	18.71	**16.8**
McMillan Fork	4.62	5.91	**4.7**
North River	30	17.61	**21.5**
Smith Creek	79.4	86.92	**75.5**
Tonoloway	14.3	**12.51**	11.7

Appendix E – Hydrologic Model

Evaluations of CBP Phase 5 model and VADEQ WOOOMM module

Introduction

The Chesapeake Bay Program (CBP) Phase 5 model and VADEQ's WOOOMM (Online Object-Oriented Meta-Model) were assessed for effectiveness in modeling the hydrology of the Potomac River basin. According to the Middle Potomac Watershed Assessment's Project Management Plan, a model was to be selected "based on its ability to inform assessment activities such as sustainable flow analyses and development of a future Potomac basin comprehensive water resource plan." To this end, model errors were quantified under the standard Phase 5 conditions, all forested conditions, and for baseflow simulation. Further, methods for estimating flows upstream of existing river segment outlets, the traditional model computation locations, were evaluated utilizing the Phase 5 model and WOOOMM.

CBP Phase 5

Phase 5 simulated flows were compared to USGS observed data at 59 calibration sites in the Potomac River basin (Figure 1). The Phase 5 model was assessed utilizing nine IHA metrics, selected in collaboration with The Nature Conservancy, to represent ecologically important portions of the hydrograph. The metrics include 3 day minimum, 1 day minimum, 3 day maximum, low pulse duration, high pulse count, high pulse duration, number of reversals, extreme low frequency, and mean annual flow. Baseflow simulation was also assessed. The Phase 5 model estimates baseflow for both simulated and observed flows at the 59 calibration stations using the USGS PART method as part of the standardized model output (Rutledge 1998).

Comparisons of simulated to observed data (Figure 2) show under-simulation of low flows (with a median under-simulation of 3 day minimum by 43% and 1 day minimum of 44%) and over-simulation low pulse duration by a median of 36%. Simulation of 3 day maximums and mean flows were more accurate, with median errors of 13 and 0%, respectively. Baseflow, as estimated by the PART method, was over-simulated by a median of 3%.

Relative error between observed and simulated data was also assessed for each IHA metric in comparison to watershed area and mean annual flow to determine if the size or flow in a river segment influences simulation errors. Resulting r-squared values were small for all IHA metrics for area and size correlations. Number of reversals had the strongest correlation, with an r-squared of 0.196 (Figure 3).

Further investigations were conducted to assess baseflow simulation in the Phase 5 model. Figure 4 shows the baseflow errors at each calibration station over a USGS grid depicting baseflow contribution to total flow. Overall, there was little correlation (R^2 =0 .028) between percent baseflow contribution to total flow and simulation error.

All Forest Scenario

Developing an ELOHA baseline scenario included adjustment of land uses to remove hydrologic alterations caused by land uses. To this end, an assessment was conducted to test the effects of forested land uses on flow simulation in the Potomac. Figure 5 and 6 show the forested areas in the Potomac and the effects of an all forest simulation on selected river segments. As expected, the all forested simulation had the most impact on mean annual flow in currently un-forested areas. Mean annual flows were reduced under the all forest scenario in all simulated river segments. The maximum reduction was just over 25% while the minimum reduction was approximately 1%.

Figure 7 depicts the differences in the all forested scenario to the "current" land use for ten IHA statistics. The 3 and 1 day minimums, 3 day maximums, date of minimum, high pulse count, number of reversals, and mean annual flow decreased under forested conditions. The remaining statistics increased under the all forested scenario.

The percent differences by watershed area and mean annual flow were also calculated for each IHA metric. This analysis was conducted to see if there are greater model sensitivities to land use in river segments of differing flow regimes and contributing areas. Low r-squared values were found for all IHA metrics for both watershed area and flow plots. Low pulse duration had the highest r-squared value for correlation with watershed area, 0.18 (Figure 8).

VADEQ's Online Object Oriented Meta-Model (WOOOMM)

Estimation of flows at ungaged locations using VADEQ's Online Object Oriented Meta Model (WOOOMM) was tested in 6 watersheds, ranging in size from 3 square miles to 63 square miles. WOOOMM results were compared to three other methods including area-weighting USGS gage data, area-weighting CBP model output, and area-weighting CBP model output by land use.

The monthly Nash Sutcliffe efficiency values are provided in Table 1 for the test cases. Results for two of the watersheds, Linville and Bennett, are provided here. For Linville Creek, a 45 sq mi watershed in Virginia with a mean annual flow of 40 cfs, the WOOOMM method was able to estimate mean annual flows within 3% for the 2000-2005 time period. Flows in Bennett Creek, a tributary to the Monocacy in Maryland with a watershed area of 63 sq mi and a mean annual flow of 72 cfs, were estimated within 2% of USGS observed flows using WOOOMM routing and the simulated output from the HSPF river segment. In both Linville and Bennett Creeks, simulation errors were smallest using the WOOOMM method.

Conclusion

The CBP HSPF model is a useful tool for simulation of current conditions and provides the capability of scenario development in the Potomac River basin, including simulation of a baseline scenario with increases in forested conditions. Combining the CBP HSPF capabilities and the capability of the WOOOMM model to divide these flows into contributing ungaged areas will be a powerful estimation of hydrologic alteration in the Potomac River basin.

References

Rutledge, A. 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data - update. Page 43. Water Resources Investigations Report, USGS.

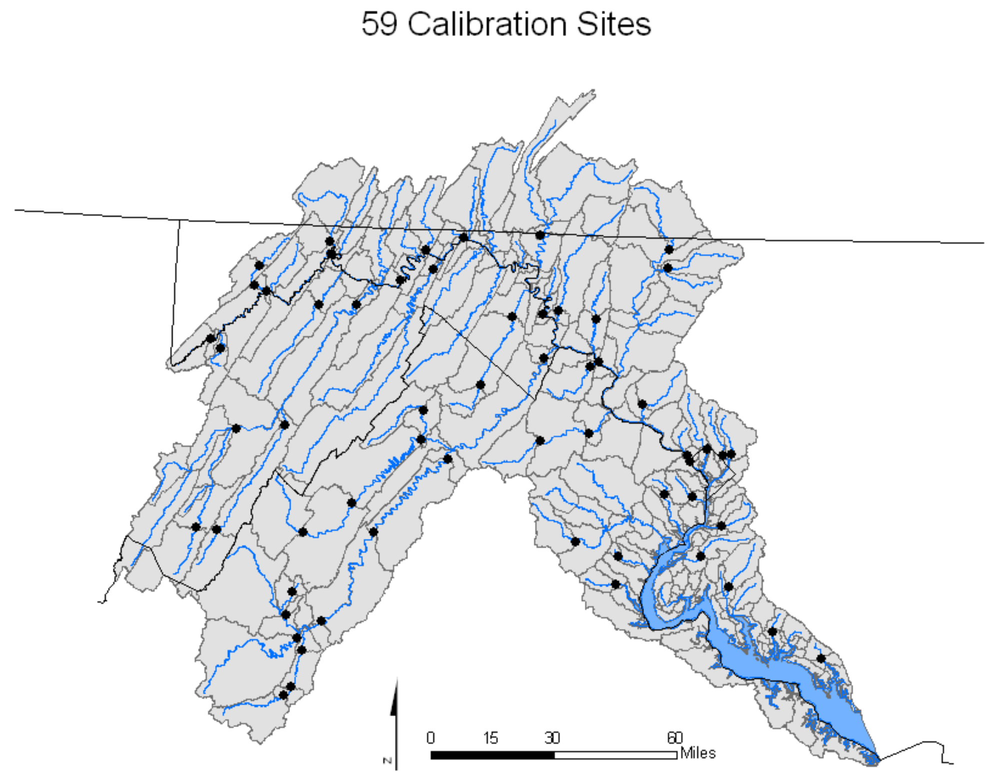

Figure 1. Locations of the 59 calibration sites utilized to compare simulated and observed flows in the Potomac River basin.

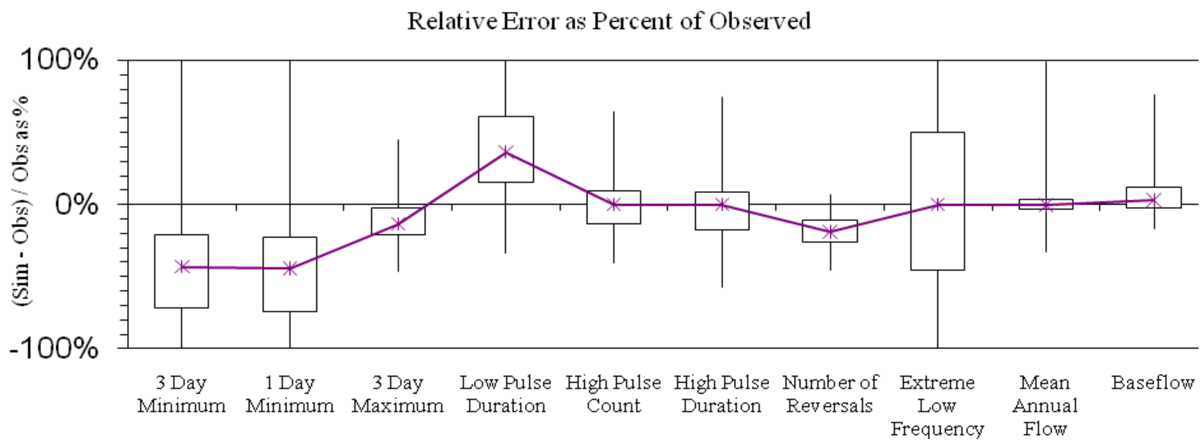

Figure 2. Comparison of observed and Phase 5 simulated flows at 59 calibration stations.

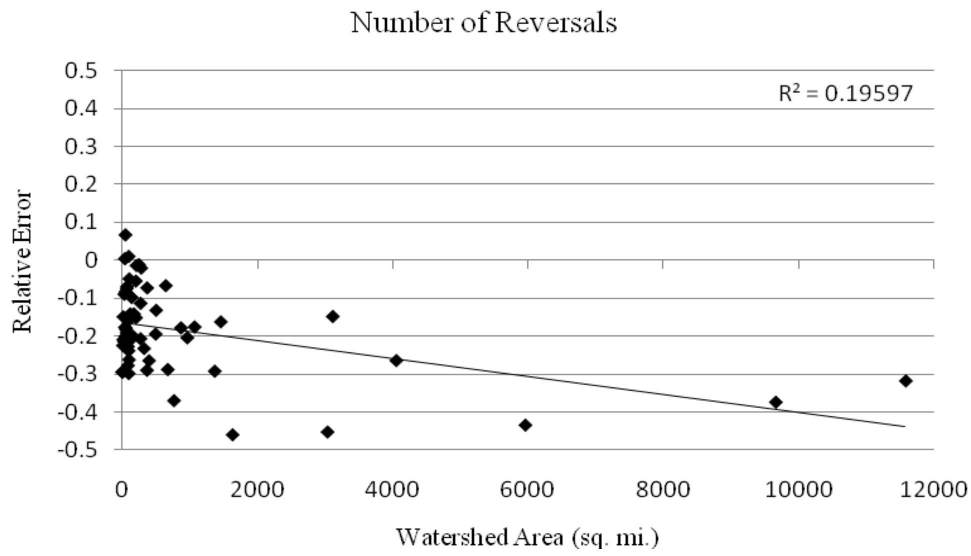

Figure 3. Correlation of relative error in number of reversals flow metric with

Note: Number of reversals had the highest correlation of relative error and watershed area and mean annual flow (mean annual flow not shown here).

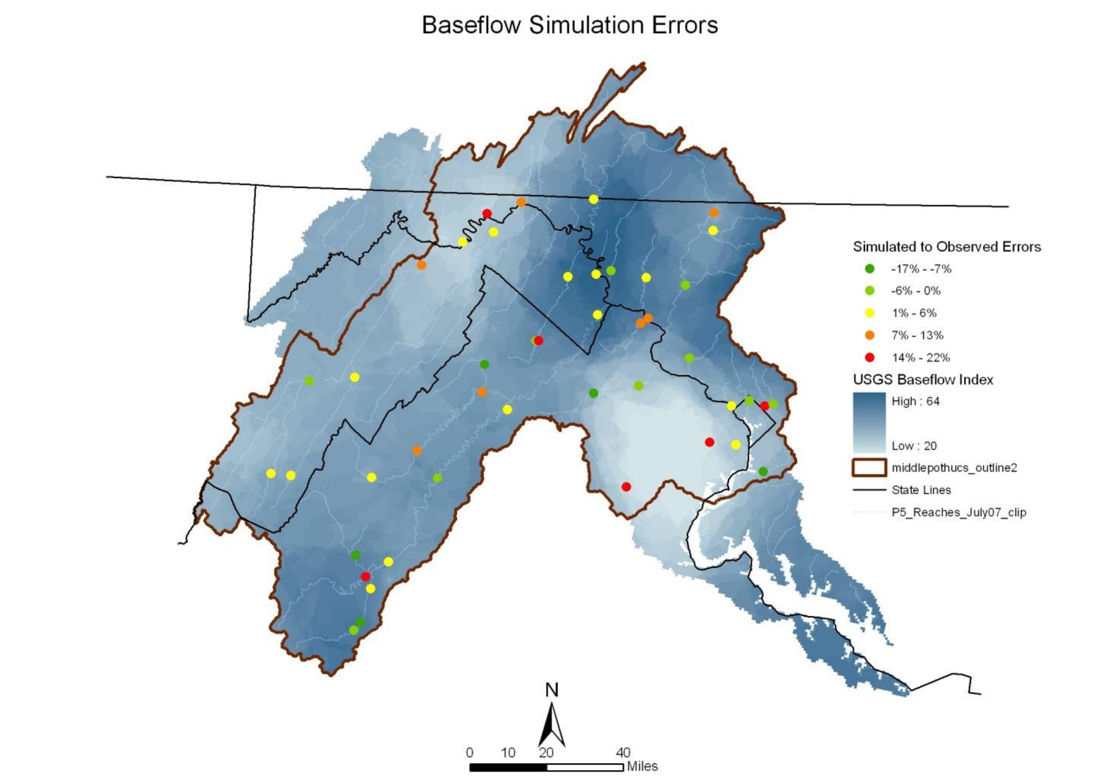

Figure 4. Baseflow simulation errors in the Potomac Basin.

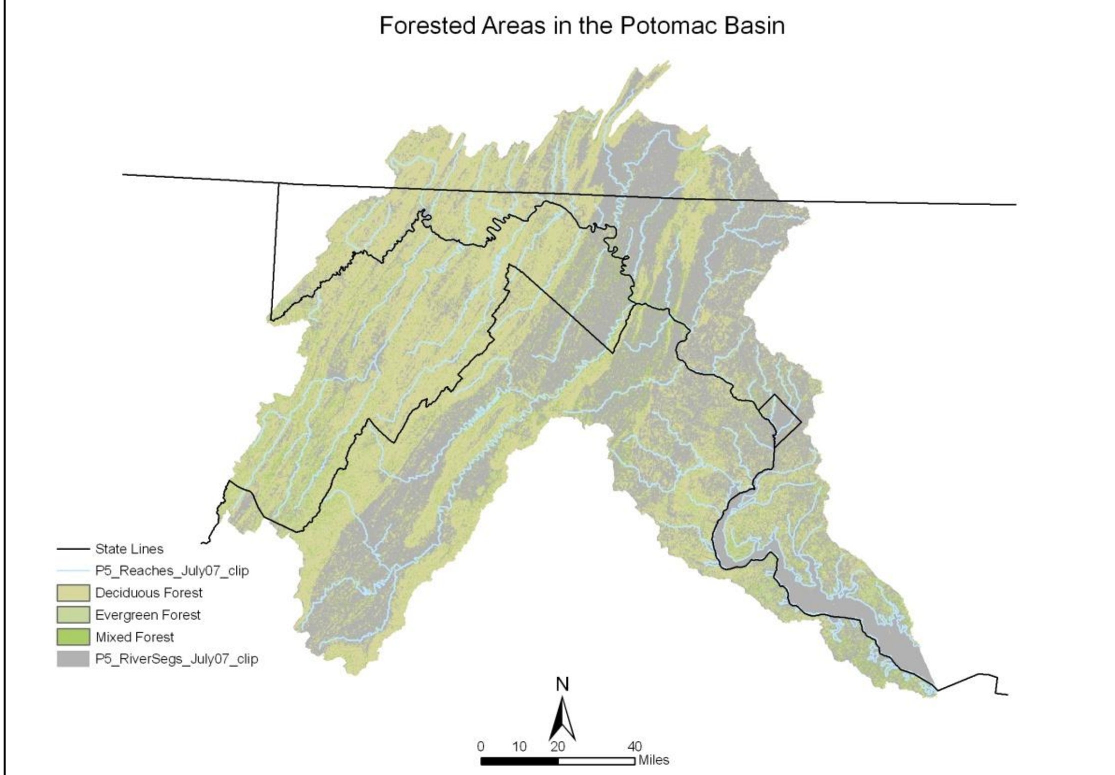

Figure 5. Forested areas in the Potomac Basin.

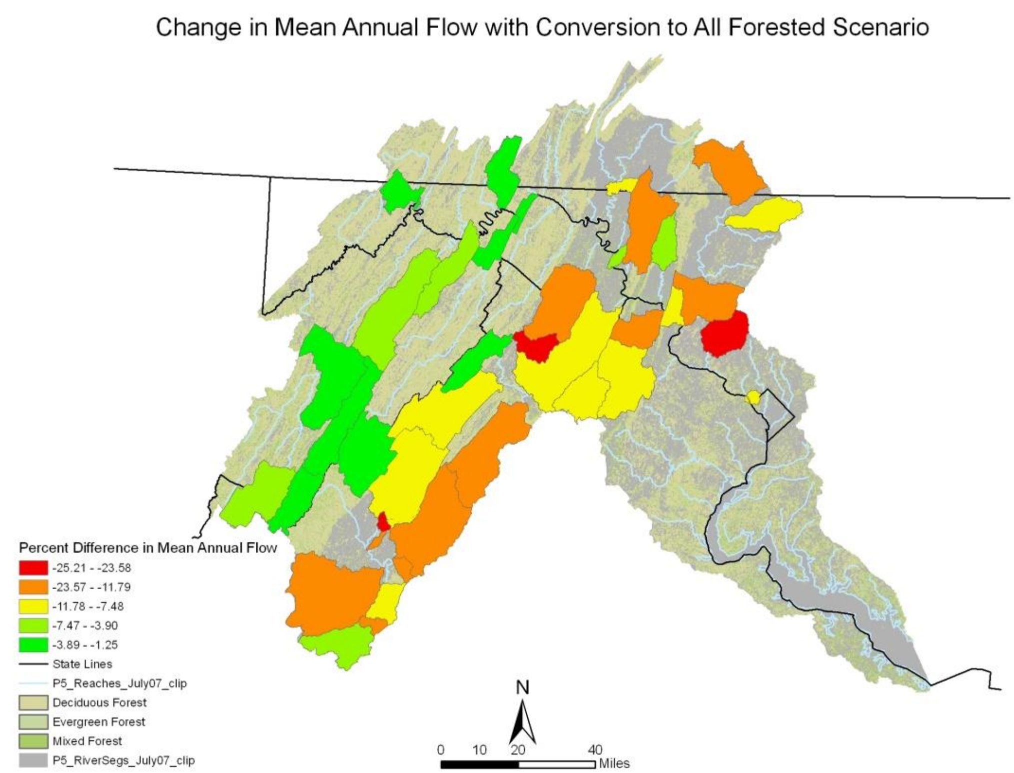

Figure 6. Change in mean annual flow under all forest scenario.

Note: the spatial extent of this analysis was limited to the highlighted river segments.

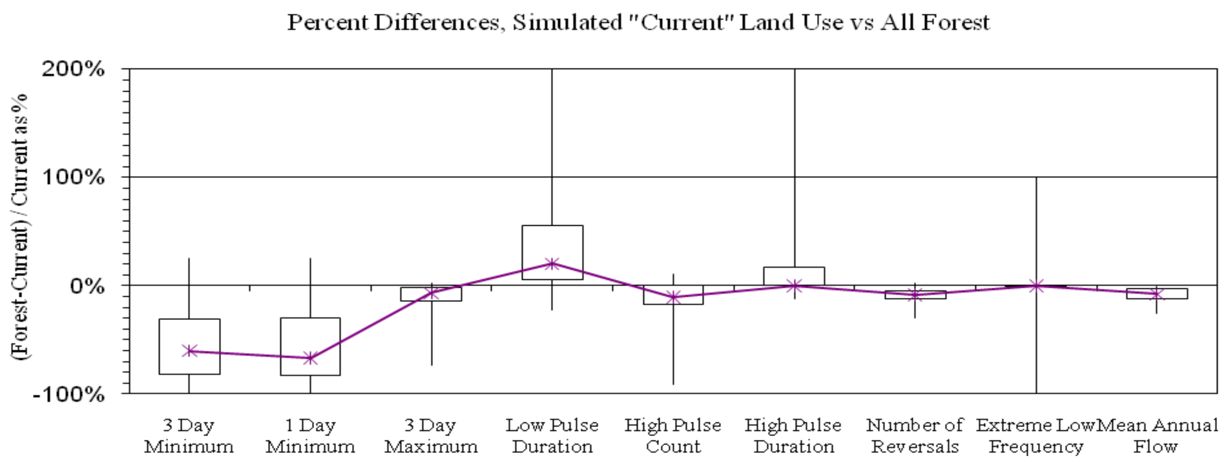

Figure 7. Boxplots of percent differences in current land uses compared to the all forest scenario for selected IHA metrics.

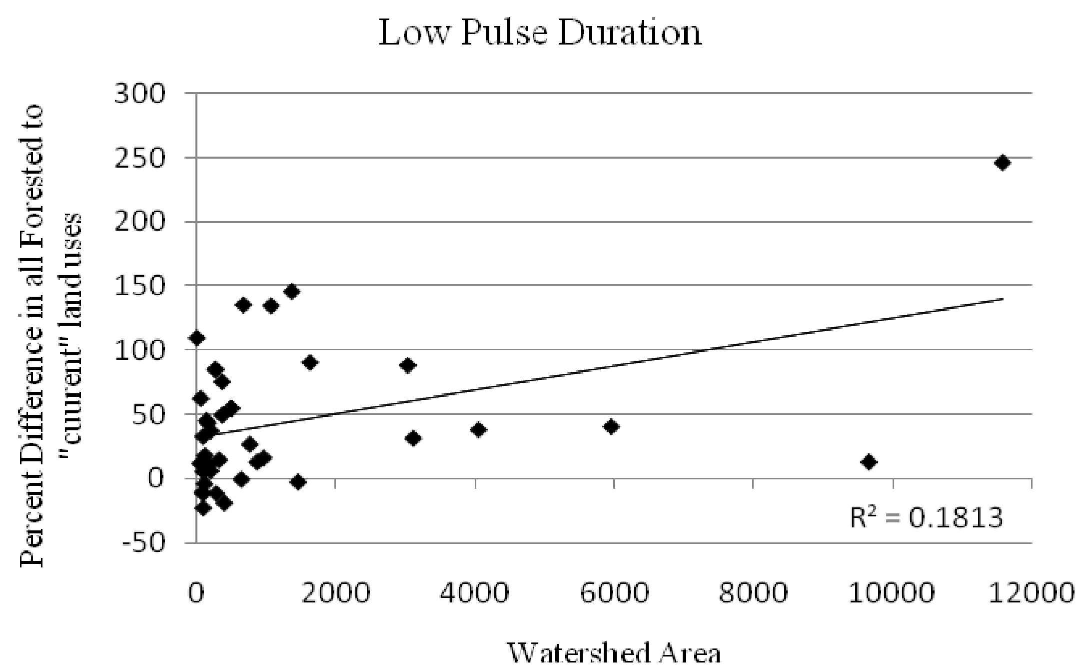

Figure 8. Correlation of percent differences in low pulse duration under current and all forested scenarios compared to watershed area.

Table 1. Monthly Nash Sutcliffe values were calculated for the test watersheds, shown in the table below.

Tributary	State	Area (sq. mi.)	Average Annual Flow (cfs)	Monthly NSE	R
Tonoloway Creek	PA	11	14	0.63	0.96
McMillan Fork	MD	3	5	0.92	0.97
North River	VA	23	30	0.32	0.79
Marsh Run	MD	18	11	-0.92	0.99
Linville Creek	VA	45	40	0.77	0.93
Bennett Creek	MD	63	72	0.75	0.97