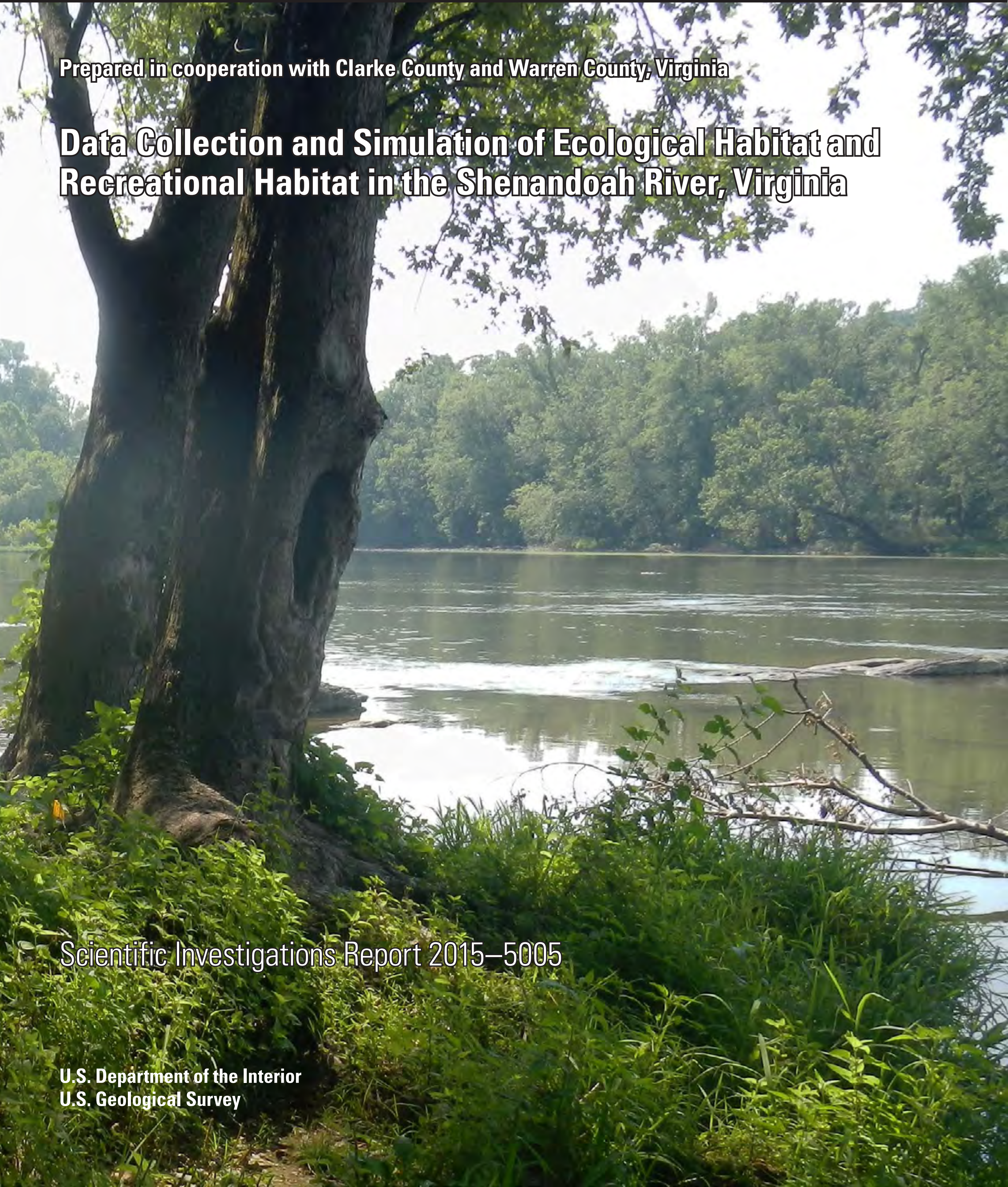


Prepared in cooperation with Clarke County and Warren County, Virginia

Data Collection and Simulation of Ecological Habitat and Recreational Habitat in the Shenandoah River, Virginia

Scientific Investigations Report 2015–5005

U.S. Department of the Interior
U.S. Geological Survey

Cover: View of the Shenandoah River from Lockes Mill boat landing. Photograph by Jennifer Krstolic, U.S. Geological Survey.

Data Collection and Simulation of Ecological Habitat and Recreational Habitat in the Shenandoah River, Virginia

By Jennifer L. Krstolic

Prepared in cooperation with Clarke County and Warren County, Virginia

Scientific Investigations Report 2015–5005

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

Suggested citation:
Krstolic, J.L., 2015, Data collection and simulation of ecological habitat and recreational habitat in the Shenandoah River, Virginia: U.S. Geological Survey Scientific Investigations Report 2015–5005, 30 p., *http://dx.doi.org/10.3133/sir20155005*.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

ADCP	acoustic Doppler current profiler
GPS	global positioning system
HABSIM	Habitat Simulation model
HSC	habitat-suitability criteria
JAS	July, August, September low-flow period. Signifies statistics were calculated only on the basis of data for those 3 months for the period of record
PHABSIM	Physical Habitat Simulation model
RHABSIM	River Habitat Simulation model
USGS	U.S. Geological Survey
VAF	velocity adjustment factor
WSL	water-surface level
WUA	weighted usable-habitat area, in square feet per 1,000 feet of stream

Data Collection and Simulation of Ecological Habitat and Recreational Habitat in the Shenandoah River, Virginia

By Jennifer L. Krstolic

Abstract

This report presents updates to methods, describes additional data collected, documents modeling results, and discusses implications from an updated habitat-flow model that can be used to predict ecological habitat for fish and recreational habitat for canoeing on the main stem Shenandoah River in Virginia. Given a 76-percent increase in population predictions for 2040 over 1995 records, increased water-withdrawal scenarios were evaluated to determine the effects on habitat and recreation in the Shenandoah River. Projected water demands for 2040 vary by watershed: the North Fork Shenandoah River shows a 55.9-percent increase, the South Fork Shenandoah River shows a 46.5-percent increase, and the main stem Shenandoah River shows a 52-percent increase; most localities are projected to approach the total permitted surface-water and groundwater withdrawals values by 2040, and a few localities are projected to exceed these values.

The habitat model used for this study evaluates the suitability of ecological habitat, represented by fish, and recreational habitat, represented by canoeing, based on depth, velocity, and substrate conditions, which are weighted for the physical habitat types (riffles, runs, or pools) present within a stretch of river. Weighted usable-habitat area in the Lockes Mill reach was maximized for adult smallmouth bass and sub-adult smallmouth bass (*Micropterus dolomieu*) and river chub (*Nocomis micropogon*) when streamflows were equal to median flow (900 cubic feet per second) for summer months. Ecological maximum weighted usable-habitat areas for smaller fish, such as spotfin or satinfin shiner (*Cyprinella* spp.), margined madtom (*Noturus insignis*), and juvenile redbreast sunfish (*Lepomis auritus*) occurred with 10th percentile flows (482 cubic feet per second) and lower. Recreational weighted usable-habitat areas for canoeing were maximized when streamflows were above the 75th percentile (1,410 cubic feet per second). During historic droughts, streamflows were less than the 10th percentile, and adult smallmouth bass and sub-adult smallmouth bass habitat was below normal for the majority of days during at least 2 months of the summer. When streamflows were less than the lowest 7-day average in a 10-year period, or 7Q10 flow (357 cubic feet per second), margined madtom, river chub, and sub-adult redbreast sunfish habitat areas were below normal as well. Streamflows that limit most fish species habitat availability range from 300 to 500 cubic feet per second. For the drought years simulated, flows that were equal to or less than the 10th percentile for summer months did not provide adequate depth for canoe passage through riffle habitats. A modeling limitation for higher flows than those studied during development of the habitat-suitability criteria is that modeled habitat availability will decrease as flows increase.

Time-series analyses were used to investigate changes in habitat availability with increased water withdrawals of 10, 20, and almost 50 percent (48.6 percent) up to the 2040 amounts projected by local water supply plans. Adult and sub-adult smallmouth bass frequently had habitat availability outside the normal range for habitat conditions during drought years, yet 10- or 20-percent increases in withdrawals did not contribute to a large reduction in habitat. When withdrawals were increased by 50 percent, there was an additional decrease in habitat. During 2002 drought scenarios, reduced habitat availability for sub-adult redbreast sunfish or river chub was only slightly evident with 50-percent increased withdrawal scenarios. Recreational habitat represented by canoeing decreased lower than normal during the 2002 drought. For a recent normal year, like 2012, increased water-withdrawal scenarios did not affect habitat availability for fish such as adult and sub-adult smallmouth bass, sub-adult redbreast sunfish, or river chub. Canoeing habitat availability was within the normal range most of 2012, and increased water-withdrawal scenarios showed almost no affect. For both ecological fish habitat and recreational canoeing habitat, the antecedent conditions (habitat within normal range of habitat or below normal) appear to govern whether additional water withdrawals will affect habitat availability. As human populations and water demands increase, many of the ecological or recreational stresses may be lessened by managing the timing of water withdrawals from the system.

Introduction

Demands on the water resources of the Shenandoah River have been an issue since the mid 1990s. In 1998, the U.S. Geological Survey (USGS) demonstrated the utility of developing predictive habitat models to address water-use and instream-flow issues and questions concerning fish and recreational habitat for the Shenandoah River (Zappia and Hayes, 1998). This previous work presented the framework for a physical habitat simulation model to be developed, and for habitat time-series analysis and alternative-flow scenario analysis to be conducted. Since the publication of habitat modeling results in Zappia and Hayes (1998), additional low-flow information and fish habitat-suitability criteria have become available. With recent population growth and projected increases in population and water withdrawals, Clarke and Warren Counties cooperated with the USGS to update the original habitat simulation model for the Shenandoah River to provide water-resource managers with current habitat time-series and alternate flow scenario information for decision-making related to drought management, water supply planning, and management of ecological and recreational habitat needs.

The total population of the Shenandoah River watershed in Virginia and West Virginia was 371,000 in 2010 (U.S. Census Bureau, 2011). This total watershed population was calculated using block group data within each hydrologic unit code (HUC) representing the major drainages in the Shenandoah River Basin: the South Fork Shenandoah River (population 263,000), the North Fork Shenandoah River (population 74,000), and the main stem Shenandoah River (population 34,000). In addition to people living in the watershed, 104,500 people living in Frederick County and the City of Winchester also rely on the Shenandoah River for some of their water supply, making a total of 475,500 people who use the Shenandoah River in some capacity. At the writing of Zappia and Hayes (1998), the 1995 Census reported only 294,000 people living in the Shenandoah River watershed (Solley and others, 1998) with an additional 74,500 people in Frederick County and the City of Winchester for a total of 368,500 people. The majority of people (178,000) resided in the South Fork Shenandoah River Basin, the North Fork Shenandoah River Basin (92,000), and the main stem Shenandoah River (24,000) (Solley and others, 1998).

Over the past 12 years, the number of people living in the vicinity of the Shenandoah River watershed has increased by 106,500 individuals—a 29-percent increase (Solley and others, 1998; U.S. Census Bureau, 2011). Water supply planning initiative reports predict population to increase over the next 20 years to approximately 649,000 (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011), representing a 76-percent increase from 1995 population levels. In an effort to plan for future water-use needs and maintain the Shenandoah River as an environmental resource, the main stem Shenandoah River habitat flow model was updated to incorporate new fish habitat-use data, low-flow calibration datasets, and future water-withdrawal scenarios. These scenarios may serve as general examples to other locals for potential habitat impacts to rivers of similar size as the Shenandoah River given predicted population growth and withdrawal requirements.

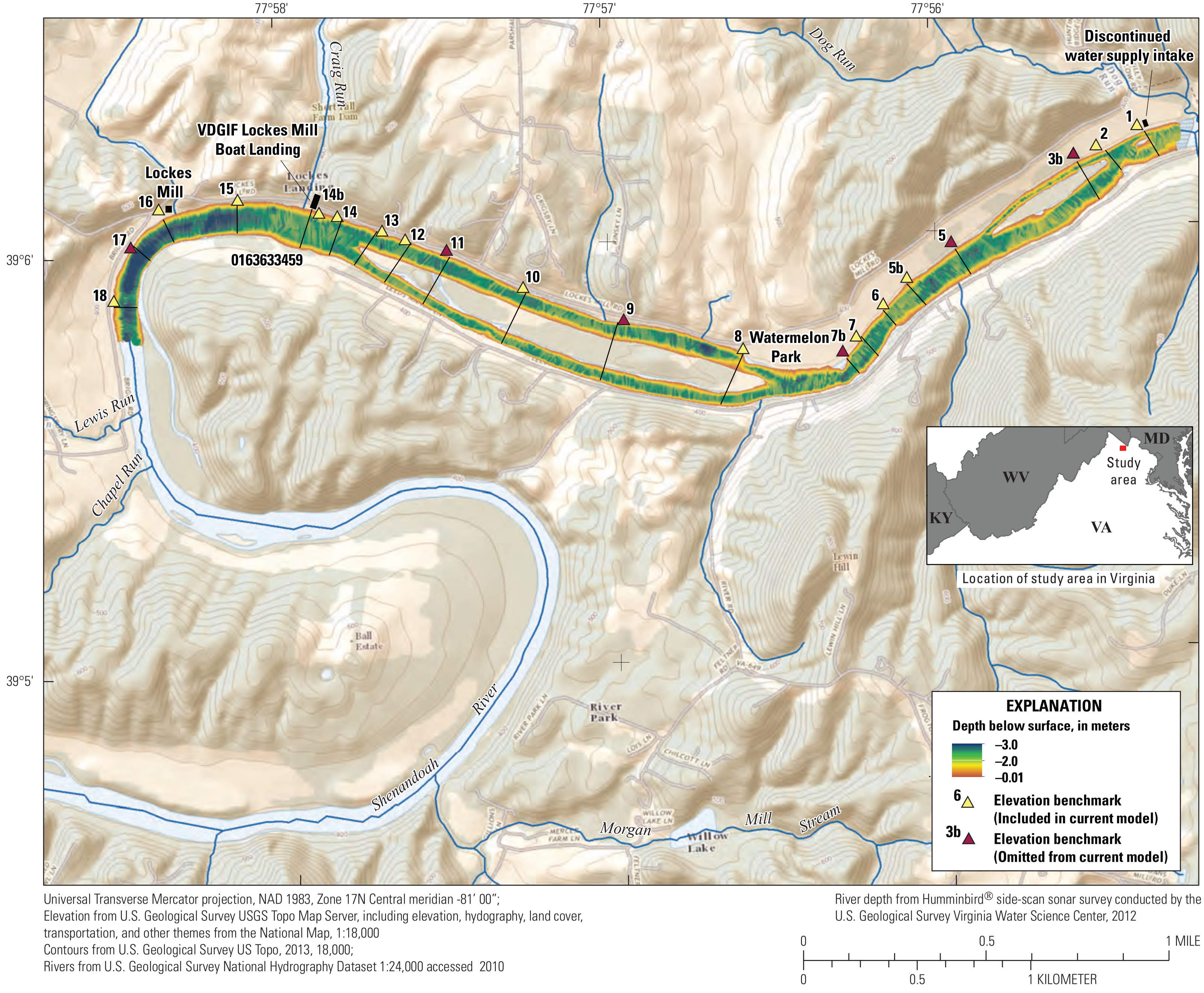
Purpose and Scope

The purpose of this report is to describe updates to methods, document modeling results, and discuss implications from an updated habitat-flow model for the main stem Shenandoah River. Since the initial investigation (Zappia and Hayes, 1998), new fish habitat-suitability criteria (Krstolic and Ramey, 2012) and water-withdrawal projections (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011) have been developed. Additionally, new data have been collected to improve and extend the model predictions for low-flow conditions. The objectives of the current investigation are to enhance the understanding of summer low-flow conditions in the main stem Shenandoah River relative to the physical habitat needs of fish and to analyze water use and recreation needs of humans, such as adequate conditions for canoe passage. Water-withdrawal scenarios similar to those developed for the North Fork and South Fork Shenandoah Rivers (Krstolic and others, 2006; Krstolic and Ramey, 2012) were completed for use by resource managers and planners for drought management and water supply planning.

Description of the Study Area

The Shenandoah River watershed was described in Zappia and Hayes (1998) and other related publications (Krstolic and others, 2006; Krstolic and Ramey, 2012). Elements of the landscape that have changed since 1998 will be described as well as pertinent differences about study site information. Land use in the Shenandoah River Basin in 2006 was predominantly rural, with 56 percent forest and wetlands, 33 percent agricultural row crops and pasture, and almost 10 percent developed (Fry and others, 2011). A decrease in forest and agricultural land and an increase in developed land was evident from the 2006 National land cover dataset (Fry and others, 2011). In 1992, approximately 58 percent of the area was forest and wetlands, 38 percent agriculture, and less than 3 percent of the area was developed (Vogelmann and others, 2001).

The primary study site (Lockes Mill study reach) used in Zappia and Hayes (1998) was used for model development again in this investigation. This section of river stretches approximately 3.2 miles on the Shenandoah River including the Lockes Mill site and a Virginia Department of Game and Inland Fish (VDGIF) boat landing, to a historic inactive water intake downstream. Of the 20 initial transects surveyed for Zappia and Hayes (1998) only 14 were accessible and had adequate data to be included in the model update (fig. 1). A re-survey of depths using side-scan-sonar technology demonstrated that habitats had generally remained in the same locations as they were during the initial study.



Universal Transverse Mercator projection, NAD 1983, Zone 17N Central meridian -81′ 00″;
Elevation from U.S. Geological Survey USGS Topo Map Server, including elevation, hydrography, land cover, transportation, and other themes from the National Map, 1:18,000
Contours from U.S. Geological Survey US Topo, 2013, 18,000;
Rivers from U.S. Geological Survey National Hydrography Dataset 1:24,000 accessed 2010

River depth from Humminbird® side-scan sonar survey conducted by the U.S. Geological Survey Virginia Water Science Center, 2012

Figure 1. Lockes Mill study reach on the Shenandoah River at USGS station number 0163633459, transect and elevation control point locations, and water depth. (Water depths are from side-scan sonar survey)

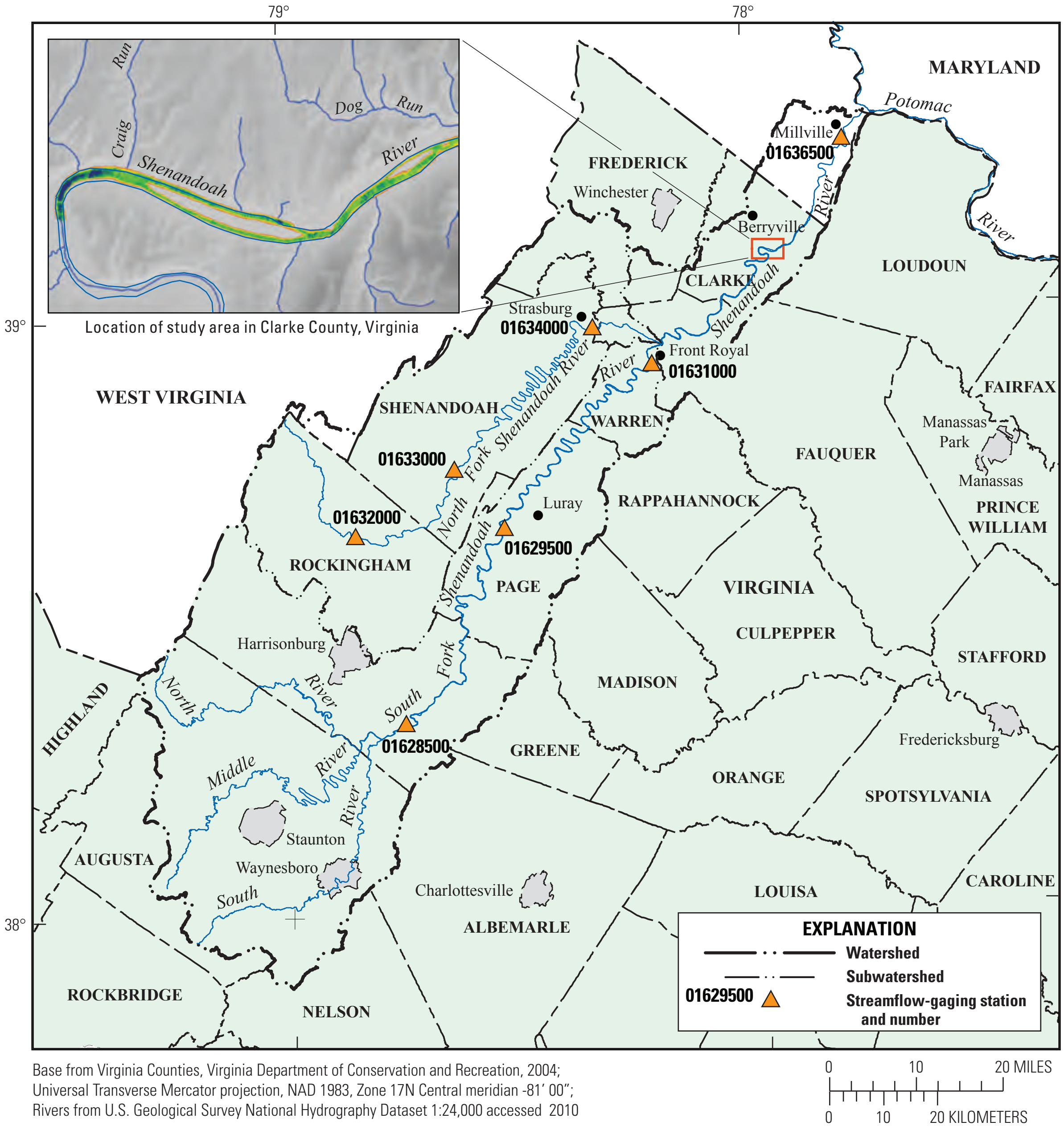
Analysis of Historic Streamflow

The Lockes Mill study reach (station number 0163633459) along the main stem Shenandoah River is located downstream from the confluence of the North Fork and South Fork Shenandoah Rivers and the Strasburg gage (01634000) and Front Royal gage (01631000) in Virginia, and is located upstream from the Shenandoah River at Millville, W. Va., gage (01636500) (fig. 2; table 1). The modeling results will be discussed in the context of the Millville gage, but the way in which the three gages relate to each other will be noted for reference. Published streamflow statistics for three streamflow-gaging stations are presented in this report for reference purposes. Table 2 presents annual flow statistics and seasonal flow statistics for the low-flow summer period of July, August, and September (JAS). The low-flow period as defined in this study and other USGS Shenandoah River Basin reports, represents the time of year when water supplies are most limited, air temperatures are highest, and the demand for water is greatest. Typically the flows in October are lower than in July and August; however, the irrigation demand and predation risk to young-of-year fish are of greater concern in earlier months. These flow statistics (table 2) represent a long-term record showing that the flow at Strasburg is approximately 35 percent of the flow at Front Royal, and the combined flow at Strasburg plus Front Royal is approximately 85 percent of the flow at Millville.

The Millville gage has a record of streamflow beginning in 1896, but has only been in continuous operation since 1930. On the basis of data from 1930 to 2002, the interquartile range (25th to 75th percentile) for annual flows at the Millville streamflow-gaging station ranged from 863 to 2,980 cubic feet per second (ft^3/s) or 558 to 1,926 million gallons per day (Mgal/d; Wiley, 2006). For this investigation, flow statistics were re-calculated for the date range from 1930 to 2012 and compared with those published in Wiley (2006) to confirm no major changes to the rating in recent years. Compared to the published values in Wiley (2006), each flow statistic was within 2 percent, and for flow statistics lower than the 50th percentile, the values were within 6 ft^3/s of the published statistics, so published statistics for Millville (1930–2002) were referenced throughout this report. Flows equal to or less than the 10th percentile for JAS have been used as a drought indicator in previous studies (Krstolic and others, 2006; Krstolic and Ramey, 2012) and will be evaluated as such for this study. The 10th percentile JAS flow for Millville is 482 ft^3/s or 312 Mgal/d (table 2) (Wiley, 2006). Of note is that the lowest 7-day average flow in a 10-year period (7Q10; 357 ft^3/s or 231 Mgal/d) is lower than the 10th and 5th percentile JAS flows for Millville (table 2) (Wiley, 2006). The 7Q10 historically has represented an extreme low-flow statistic.

Wiley (2006) compared the computed average low-flow statistics for 1930–2002 with each years' annual minimum-flow statistics to examine trends over time. For 15 streamflow gages across the State of West Virginia, the departure of annual minimum flows from the long-term average demonstrated an increase in minimum flows around 1970 (McCabe and Wolock, 2002; Wiley, 2006). These departures are considered negative if they are less than the long-term average low-flow statistic and positive if they are greater than the average low-flow statistic (Wiley, 2006). The primary cause for an increase in flows was attributed to climate variability (Wiley, 2006). For the streamflow-gaging station at Millville, a positive trend was noted for the entire time period when considering annual statistics. Increases in computed flow statistics generally were observed for statistics representing 1–7 day averages every 3 to 10 years. This indicates that the extreme low-flow statistics appear to be increasing with time.

Wiley (2006) compared the computed statistics for 1930–2002 with statistics for 10- to 20-year time periods to demonstrate how low-flow statistics vary through time and season. The lowest 7-day average flow in a 10-year period (7Q10) during the summer for Millville ranged from –28.4 to 12.1 percent of the 1930–2002 computed statistic depending on the time period examined. For a known drought period, 1963 to 1969, the 7Q10 was –28.4 percent lower than the long-term statistic. For 1943–1962 and 1970–1979, the summer JAS 7Q10 was 12.1 percent higher than the long-term statistic. These data demonstrate why it is important to monitor and assess long-term data in order to account for climactic variability. The lowest 30-day average flow in a 5-year period (30Q5) during the summer for Millville ranged from –28.3 to 17.1 percent of the 1930–2002 computed statistic depending on the time period examined. The only time the 30Q5 was lower than the long-term statistic was from 1963 to 1969. All other time periods examined were at least 3.7 percent higher (Wiley, 2006). The analysis of long-term streamflow indicates that minimum flows follow cyclical patterns associated with climate, and the minimum flows of a stream have regularly been 23–28 percent lower than the long-term average low-flow statistic since systematic streamgaging began.



Base from Virginia Counties, Virginia Department of Conservation and Recreation, 2004;
Universal Transverse Mercator projection, NAD 1983, Zone 17N Central meridian -81′ 00″;
Rivers from U.S. Geological Survey National Hydrography Dataset 1:24,000 accessed 2010

Figure 2. Map of study area and surrounding counties, watersheds, and streamflow-gaging stations within the Shenandoah Basin.

Table 1. Selected streamflow-gaging stations in the Shenandoah River Basin.

[mi², square mile]

Station number	Station name	Drainage area (mi²)	Operating agency	Period of record used in this study
01636500	Shenandoah River at Millville, W. Va.	3,041	U.S. Geological Survey	1930–2012
01631000	South Fork Shenandoah River at Front Royal, Va.	1,634	U.S. Geological Survey	1931–2008
01634000	North Fork Shenandoah River near Strasburg, Va.	770	U.S. Geological Survey	1925–2002

Table 2. Streamflow statistics for gages on the North Fork, South Fork, and main stem Shenandoah River.

[Annual statistics represent conditions over all months of the year. July–August–September statistics represent the 3-month average flow conditions. 7Q10 is the lowest 7-day average streamflow in a 10-year period. Monthly statistics are updated daily and are available for each streamflow-gaging station at *http://va.water.usgs.gov/duration_plots/dp_map_potomac.htm*]

Percentile	Strasburg[1] 01634000	Front Royal[2] 01631000	Millville[3] 01636500	Strasburg[1] 01634000	Front Royal[2] 01631000	Millville[3] 01636500
	Cubic feet per second			Million gallons per day		
			Annual			
95	1,910	4,650	8,040	1,234	3,005	5,196
90	1,240	3,160	5,480	801	2,042	3,542
75	630	1,760	2,980	407	1,138	1,926
50	310	948	1,590	200	613	1,028
25	160	533	863	103	344	558
10	110	386	585	71	249	378
5	90	328	482	58	212	312
7Q10[4]	65	247	357	42	160	231
			July–August–September			
95	947	2,360	3,730	612	1,525	2,411
90	566	1,490	2,440	366	963	1,577
75	367	831	1,410	237	537	911
50	214	557	900	138	360	582
25	143	420	641	92	271	414
10	99	330	482	64	213	312
5	75	290	416	48	187	269

[1] North Fork Shenandoah River near Strasburg, Va., period of record represents data from 1925 to 2002 (Krstolic and others, 2006).

[2] South Fork Shenandoah River at Front Royal, Va., period of record represents data from 1931 to 2008 (Krstolic and Ramey, 2012).

[3] Shenandoah River at Millville, W. Va., period of record represents data from 1930 to 2002 (Wiley, 2006).

[4] 7Q10 values for Strasburg and Front Royal are from Austin and others (2011); 7Q10 value for Millville is from Wiley (2006).

Water Withdrawals and Projections From the Water Supply Planning Initiative

The Shenandoah River watershed withdrawals for surface water and groundwater in 2005 were summarized on the basis of data reported to the Virginia Department of Environmental Quality (DEQ) in Krstolic and Ramey (2012). The 2005 water-use values are similar to the baseline water-use data compiled in the Upper Shenandoah River Basin Water Supply Plan (Central Shenandoah Planning District Commission, 2011) and the Northern Shenandoah Regional Water Supply Plan (Northern Shenandoah Valley Regional Commission, 2011). These plans used 2008 and 2006 data, respectively, to indicate current conditions and make predictions for daily average and peak water demand to the year 2040. The Krstolic and Ramey (2012) withdrawal calculation combined the permitted, reported values from DEQ as summarized and published in Kenny and others (2009) and the USGS-published countywide estimates for livestock and aquaculture (Lovelace, 2009a, 2009b) to ensure that agricultural withdrawals were represented. Aquaculture data are considered non-consumptive use by DEQ so it was omitted from the current investigation. Although agricultural users of greater than 300,000 gallons per month are reported, livestock and row crop spatial estimates are not part of the DEQ water-supply model, but represent agricultural uses that may go unreported. Therefore, the data for 2005 permitted and reported withdrawals (Kenny and others, 2009) were kept separate from the Lovelace (2009b) estimates for livestock, but were summed before calculating the 2040 projected demands (table 3). Summary data for 2005 water withdrawals for the North Fork, South Fork, and main stem Shenandoah River (table 3) represent “current” conditions for water supply for this investigation. The withdrawal values represent data from Virginia only, so the withdrawals may be underrepresented for the main stem Shenandoah River in Jefferson County, West Virginia. The withdrawal data and future water-withdrawal demands were used within the modeling phase without developing return-flow estimates. It is assumed that the current streamflow-gaging station records report daily values that already incorporate withdrawals and return flows. The withdrawal data are reported, tabulated, and verified through multiple sources, but returns would need to be estimated for future withdrawal regimes. Only withdrawals were considered for the modeling phase of this investigation, recognizing that this may represent a “worst case” scenario because there likely will be some portion of return flows from any consumptive-use withdrawal.

The water supply plans describe surface water and groundwater sources and frequently combine them when summarizing future demands. To gain a general understanding of the amount of increased water use for municipalities, comparisons were made for status of presently permitted withdrawals, current water use, and projected 2040 demand. On the basis of the reported withdrawals for 2006, average water withdrawals represent 50 percent of permitted withdrawals. Localities in the Shenandoah Valley have the legal permits to withdraw roughly twice the amount of water than were used in 2006. Six out of 13 localities in the North Fork and main stem Shenandoah River watersheds and five out of 13 other localities in the South Fork watershed project that daily average demands will equal or exceed 80 percent of their presently permitted withdrawals by the year 2040 (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011). Augusta County, Frederick County, Rockingham County, and the City of Harrisonburg each expect an increased water demand within the range of 4.4 to 6.5 Mgal/d by 2040. This equates to 74 to 250 percent of existing permitted capacity for those localities. Most localities approach their total permitted surface-water and groundwater values by 2040, and a few exceed them (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011).

The 2040 demand projections from the water supply plans were incorporated into the DEQ water supply model during 2013. The current and future water-use estimates in the DEQ model were preliminary as of September 2013 (Robert Burgholzer, Virginia Department of Environmental Quality, oral commun., 2013), but provide ratios of current (2006 or 2008) to future (2040) water demand for surface water that can be used to adjust the 2005 published water withdrawals for use in this investigation. The water supply plans (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011), as input to the DEQ water supply model, depict a wide range of surface-water withdrawals from the North Fork (55.9-percent increase), South Fork (46.5-percent increase), and main stem Shenandoah (52-percent increase) River watersheds. Cumulatively, the 2040 surface-water demand projections represent a 51-percent increase from 2005 surface-water withdrawals.

Table 3. Water-withdrawal totals for 2005 and projected estimates for 2040 for the Shenandoah River Basin.

[Mgal/d, million gallons per day]

USGS station number and name of watersheds in the Shenandoah River Basin	2040 estimates		2005 totals	2005 water-withdrawal data[3]	
	2040[1] surface-water with-drawals (Mgal/d)	Estimated percentage increase[2] (percent)	Permitted plus spatial estimate with-drawals (Mgal/d)	Permitted with-drawals in the DEQ and USGS databases (Mgal/d)	Spatial estimates for agricultural withdrawals (livestock and crop irrigation) (Mgal/d)
01632000 North Fork Shenandoah River at Cootes Store, Va.			0.75	0.00	0.75
01633000 North Fork Shenandoah River at Mount Jackson, Va.			2.69	1.75	0.94
– North Fork Shenandoah River at mouth			9.66	8.92	0.73
North Fork Shenandoah River cumulative totals	20.41	55.9	13.09	10.67	2.42
– South River at mouth			4.04	3.51	0.53
– Middle River at mouth			0.88	0.05	0.83
– North River at mouth			9.89	8.44	1.45
01628500 South Fork Shenandoah River near Lynnwood, Va.			0.10	0.00	0.10
01629500 South Fork Shenandoah River near Luray, Va.			1.29	0.38	0.91
– South Fork Shenandoah River at mouth			2.33	1.93	0.40
South Fork Shenandoah River cumulative totals	27.15	46.5	18.53	14.31	4.22
– Shenandoah River at West Virginia State line near Berryville, Va.	5.37	52.2	3.53	3.22	0.31
Basin totals	52.93		35.15	28.20	6.95

[1] Calculation of 2040 surface-water withdrawals = (2005 totals * Percent) + 2005 totals.

[2] Percentage increase from the Virginia Department of Environmental Quality water supply model (September 2013), which reflects the surface-water percentage increase in demand from the Upper and Northern Shenandoah water supply plans (Northern Shenandoah Valley Regional Commission, 2011; Central Shenandoah Planning District Commission, 2011).

[3] Permitted, location-specific withdrawal datasets, such as public water supply, commercial-industrial, thermoelectric, golf course irrigation, and mining (Kenny and others, 2009). Spatial estimates for county-level data include livestock (Lovelace, 2009b).

Hydraulic Data Collection Update

The majority of the data collected in 1996 and 1997 were input to the updated habitat-flow model for the Shenandoah River. Previously surveyed transect streambed elevations for each variably sized model cell, water-surface levels, velocity, discharge, and elevation control points were utilized along with new water-surface level and discharge data collected in 2011 and 2012. Transect elevation control points were verified, and new water-surface-level datasets were compared with historic datasets to ensure accuracy. The historic data and recently collected data were combined to create an updated habitat-flow model with an extended representation of low-flow conditions and new fish habitat-suitability criteria (Krstolic and Ramey, 2012).

A few challenges complicated the modeling phase of the Zappia and Hayes (1998) investigation. The primary complication was a change in the channel topography due to a flood in September 1996, which altered the channel geometry near transects 5b, 7b, 8, and 13. The flood occurred after the two high-flow discharge measurements had been made and water-surface-level data had been collected, but the velocity and depth (channel elevation) surveys had not been completed. For the original model this meant that the depth and velocity profile after the storm did not match what the stage-discharge relation would have predicted for discharge. The stage-discharge relation for measurements prior to the storm was adjusted to fit the new channel geometry within the Zappia and Hayes (1998) model, so that subsequent measurements would fit within that relation. The transect water-surface level (WSL) above and below the adjusted transects were taken into account to ensure the slope was realistic. Because the model stage-discharge relation was adjusted to post-flood conditions, it was assumed that new data collected for extending the low-flow portion of the rating could be verified against the original relation and utilized for development of a new model.

Establishing New Elevation Control Points

It was necessary to verify existing horizontal and vertical control points for the transects along the Lockes Mill study reach so that water-surface profiles could be surveyed and used for additional calibration datasets for the habitat-flow model. Fifteen years had passed since the initial investigation, and only 8 of the original 26 transect elevation control marks (benchmarks) were found to be in usable condition. The benchmarks were lag bolts in trees, most of which were in areas of substantial growth, but the lag bolts were found to be stable and accessible. New transect benchmarks were established at each transect when necessary, and the few remaining headpins or tail pins from the original study were found to be unusable for establishing new control, but they were marked for reference purposes. The original survey control was based off of Global Positioning System (GPS) coordinates and elevation for the Lockes Mill tailrace near transect 16. This location was re-surveyed with survey-grade GPS and post processed through the National Geodetic Survey (2012) Online Positioning User Service (OPUS), resulting in an elevation within 0.09 feet (ft) of the original survey elevation and within 0.07 ft of the tax map survey provided by the landowner. The mill tailrace is a cobblestone structure that did not have a clear marking for the exact location of the original survey, so the accuracy of the GPS survey confirmed that the tail race is a good control feature to verify the new elevations surveyed for this update. New control points were installed and surveyed with GPS along the boat launch and the road near the VDGIF Lockes Mill landing. The new control points were in view of the transect 14b benchmark, which was at the boat launch and was still in good condition from the original survey (fig. 1). The transect 14b benchmark was used as a verification for each new survey conducted.

Total station surveys of the newly installed and existing original benchmarks were conducted in 2011 beginning from the two newly installed control points, extending upstream on the left bank, extending downstream on the left bank, and across the river to the right bank from Watermelon Park near transect 7. The four separate surveys used the two new control points along the boat launch as starting elevations and included surveys of the benchmark 14b lag bolt and the mill tailrace for elevation verification.

Elevations for the transect 14b benchmark from the four surveys were compared with the original survey elevation from 1996. For each survey, any of the eight intact original transect benchmarks available were also surveyed and the updated elevations were compared with the original elevations. To assure the continuity between original and updated elevations, all new survey benchmark elevations were adjusted to match original elevations on the basis of the difference between transect 14b original and updated elevations or other original benchmarks. The difference between updated and original benchmarks resulted in survey adjustment factors ranging from 0.25 to 0.90 ft. These updated benchmark elevations were used as control points for new WSL measurements, but no new transect elevation surveys were conducted.

Discharge and Water-Surface-Level Data Collection

Discharge and WSL data were collected in July 2012 at a measured discharge of 970 ft^3/s, and in September 2012 at 620 ft^3/s. Digital auto level equipment (Sokia SDL30) and traditional leveling equipment (Zeiss) were used to survey water-surface profiles from transect 18 to transect 1. Data were recorded digitally in the field with hand-held Trimble data storage devices. Discharge measurements were made upstream from the VDGIF Lockes Mill boat landing by using a power boat and acoustic Doppler current profiler (ADCP) running WinRiver II software (Turnipseed and Sauer, 2010). Discharge was measured in the morning and the afternoon each day that a WSL survey was conducted, unless the WSL survey was completed before midday. A survey of WSL at transect 14b accompanied each discharge measurement to monitor for changes in stage.

As an additional verification for changes in stage during each data-collection period, continuous HOBO U2 (2008–10, Onset Computer Corporation) water-level and temperature loggers were deployed at the upstream and downstream ends of the study reach and in the middle at transect 8 on both banks. The loggers were placed at least 1 ft below the water surface to ensure they would be submerged the entire time. Two HOBO monitors were placed above water on land surface at either end of the study reach for barometric pressure compensation calculations. In July 2012 the total change in stage increased slightly overnight and decreased on the second day of data collection, with a maximum range of values less than 0.06 ft. Discharge ranged from 959 to 1,043 ft^3/s during the July surveys. The upstream monitor showed the least amount of variation because it was located in a pool near the water intake. The left bank monitors at transect 8 and transect 1 had the greatest amount of variability because they were located in or near riffle habitats. In September 2012 stage dropped during data collection, although the stage did not change more than 0.076 ft. Discharge measurements ranged from 612 to 618 ft^3/s during the September surveys.

Water-Surface-Level Adjustments

Water-surface levels were surveyed using elevation control points that had not yet been adjusted to match the Zappia and Hayes (1998) published elevations. The resulting WSLs were adjusted using the same factors used to adjust the benchmark elevations. The WSLs from transect 18 to transect 1 from the historic and the current surveys plot as would be expected for the range of discharges surveyed. The WSLs associated with the 970 ft^3/s discharge measurement in 2012 served as a confirmation of accuracy as they plotted close to WSLs associated with the 907 ft^3/s discharge measurement from 1997.

Fish-Community Data and Dominant Substrate

The initial investigation on the Shenandoah River (Zappia and Hayes, 1998) included flow requirements for aquatic biota drawn from a number of sources that were not known to be applicable to the Shenandoah River. The purpose of that investigation was to demonstrate the utility of the instream flow process in this region, and the reader was originally cautioned to regard it as such. For this update, fish habitat-suitability criteria are available. Habitat-suitability criteria were developed for the fish community of the South Fork Shenandoah River in 2008 and 2009 (Ramey, 2009; Krstolic and Ramey, 2012, tables 10, 11). Fish observations were made using three sampling techniques, and the habitats of each species were documented for flows representing the 10th percentile to the 75th percentile JAS flow range on the South Fork Shenandoah River. Habitat-suitability criteria (Ramey, 2009; Krstolic and Ramey, 2012) from the South Fork Shenandoah River were used for modeling at Lockes Mill because the depths and velocity range was quite similar to study sites on the South Fork Shenandoah River. Krstolic and Ramey (2012) used dominant substrate as a measure of habitat differentiation during the River Habitat Simulation (RHABSIM) software model process (Thomas R. Payne and Associates, 1998). Dominant substrate data were available for the main stem Shenandoah River; however, fewer classes of substrate were recorded by Zappia and Hayes (1998). Krstolic and Ramey (2012) recorded substrate classes for various sizes of gravel (fine, small, large), cobble (small and large), and boulder (small and large), and Zappia and Hayes (1998) simply recorded clay/silt, sand, gravel, and bedrock. The South Fork Shenandoah fish habitat-suitability criteria had to be generalized to represent dominant substrate data available for evaluation on the main stem Shenandoah River (table 4).

Table 4. Substrate-suitability indices for the Lockes Mill study reach (0163633459), main stem Shenandoah River, Virginia.

[1 indicates 100% suitable, 0.75 indicates 75% suitable, 0.5 indicates 50% suitable, and 0 indicates not suitable]

Numeric code	Main stem substrate category	Substrate-suitability index						
		Sub-adult smallmouth bass	Adult smallmouth bass	Juvenile redbreast sunfish	Sub-adult redbreast sunfish	*Cyprinella* spp.	Margined madtom	River chub
20	Clay/Silt	0	1	0.5	0.5	0	0.000	0
26	Clay/gravel	0	1	0	0.5	0	0.000	0
29	Clay/bedrock	0	0.5	0.5	0.5	0	0.000	0
30	Sand	0.5	0.5	0	0	0	0.000	0
36	Sand/gravel	0.5	0.5	0	0	0	0.000	0
39	Sand/bedrock	0	0	0	0	0	0.000	0
60	Gravel/cobble	1	1	1	1	0.75	0.75	0.75
63	Gravel/sand	0.5	0	0	0	0	0.00	0
69	Gravel/bedrock	0.5	0	0.5	0	0.5	0.5	0.5
90	Boulder/bedrock	1	0.5	0.5	1	1	1.000	1
93	Bedrock/sand	0	0	0	0	0	0.000	0
96	Bedrock/gravel	0.5	1	0	1	1	1.000	1

Using RHABSIM Modeling to Determine Fish Habitat Availability and Recreation Conditions

The program RHABSIM 3.0 for DOS and Windows (Thomas R. Payne and Associates, 1998) was used for calibration and simulation of flow and habitat. The methods used in the RHABSIM modeling process were similar to methods used in Krstolic and Ramey (2012) and Krstolic and others (2006), with calibrations of WSL and velocity used to simulate WSL, velocity, and habitat for a wide range of flows. Calibration and simulation were completed in one model for the Lockes Mill Shenandoah River study reach.

Model Calibration

The RHABSIM model calibration incorporates datasets representing topographic information for each transect, WSLs, velocities, and discharge data for the study reach. The transect data are used to calculate stage-discharge ratings to enable simulation of depths and velocities for flows not measured during hydraulic data collection. The Physical Habitat Simulation (PHABSIM) model developed in Zappia and Hayes (1998) was available and imported to RHABSIM so that the same transect topographic information and streambed substrate data could be utilized. The high-flow datasets representing 1,900 ft^3/s and 3,200 ft^3/s that had been collected in 1996 prior to the flood and the adjusted WSL, as they were corrected by Zappia and Hayes (1998), were used in their original format. New low-flow discharge and WSLs collected in 2012 representing 620 ft^3/s and 970 ft^3/s were added the model. The previously collected 907 ft^3/s calibration dataset was omitted because it was similar to the more recent data collected. Other data elements that were updated include the distance and average slope between transects. The RHABSIM interface includes tools to examine the stage-discharge relation for each transect individually and the slope profiles for all transects. The tools were used to verify the ratings for each transect; two transects were identified that did not fit the WSL slope profiles of the other transects. The historic WSL for transects 5 and 3b as represented in the original PHABSIM model were more than 2 ft above the recent survey elevations and were omitted from the model update. The calibration technique for the original model was used to examine each transect individually and did not require the WSL slope profile to be consistent upstream or downstream from the transect in question. It is possible that calibration adjustments for transects 5 and 3b altered the streambed elevation, making the data incomparable to the recent measurements. The recently surveyed WSLs for the 620 ft^3/s and 970 ft^3/s discharge datasets were consistent throughout the study reach, and the slopes paralleled the Zappia and Hayes (1998) data quite well.

Water-Surface-Level Calibration

The WSL calibration method was the same for each transect throughout the reach. Given the large distance between transects, each transect was calibrated separately using the Log-Log regression approach (Thomas R. Payne and Associates, 1998), which creates a stage-discharge rating for each transect. The rating is then used to predict WSLs for simulated discharges that were not measured during the study. The predicted values were compared with the field-measured WSLs with relatively good agreement. Differences between predicted and observed WSLs ranged from 0.02 to 0.15 ft for pools and runs, and from 0.05 to 0.43 ft for riffles. Riffle WSLs are much more challenging to sample, which makes it difficult to get accurate measurements and predictions, especially over such a large date range. The WSL for the 1,900 ft^3/s calibration discharge was frequently predicted higher than what was observed. Since the two highest calibration flows were measured in 1996 prior to the flood, it is likely that the discrepancies are related to the adjustments that were made to the stage-discharge relation after the channel was altered.

Velocity Calibration

Velocity data were not re-surveyed for this model update. The historic data that matched the streambed topography were used. Velocity calibration procedures were similar to those used with the North Fork Shenandoah and South Fork Shenandoah models (Krstolic and Ramey, 2012; Krstolic and others, 2006). The 1-velocity calibration method (Thomas R. Payne and Associates, 1998) was selected for all transects. Cell-by-cell roughness values were adjusted to ensure a good match between the simulated velocity and discharge, and the measured velocity and best-estimate discharge calibration datasets. The model-calculated discharge for each transect was compared to best-estimate calibration discharge for the reach to obtain velocity adjustment factors (VAF) for each calibration discharge. After VAF were determined for calibration discharges, they were incrementally increased for each simulation discharge. Measured velocities in the velocity calibration dataset were used as a template and adjusted on the basis of the predicted depths from WSL simulations and the VAF to simulate velocities.

Habitat Simulation and Development of Weighted Usable-Habitat Area Curves

RHABSIM model cells were centered on the verticals where depths and velocities were collected at varying intervals along each transect. The length of model cells was varied based on the kind of habitat represented along the transect and the percentage of the reach upstream or downstream from the transect that contained the same habitat type. Transect weighting factors (app. 1) were used to determine model cell lengths and ultimately areas of available habitat.

The WSL and velocity simulations and the fish habitat-suitability criteria (HSC), developed by Ramey (2009) and Krstolic and Ramey (2012), and canoeing HSC (Milhouse, 1990; Zappia and Hayes, 1998) were input to the Habitat Simulation Model (HABSIM) of RHABSIM (Thomas R. Payne and Associates, 1998). HABSIM uses the HSC suitable ranges for water depths, water velocities, and dominant substrate to assign individual suitability ranks (on a scale from 0.0 to 1.0) for depth, velocity, and substrate in each model cell. Following Krstolic and others (2006) and Krstolic and Ramey (2012), multiplicative aggregation (Waddle, 2001) was used to calculate the composite habitat-suitability rank for each cell between 0.0 and 1.0. The area of all suitable habitat cells within a reach was summed for a total weighted usable-habitat area (WUA). The process was repeated for each species or life stage of fish and for canoeing over all simulation flows, and a functional relation between habitat and discharge was defined and expressed in the form of WUA curves. For canoeing, only depth and velocity were of concern. The velocity had upper and lower limits defining optimal, suitable, and unsuitable velocity. Flows that are faster than 5 feet per second are considered unsuitable and could be unsafe for inexperienced paddlers. For higher flows, fast velocities with low HSC ranks combined with depths with suitable HSC result in reduced WUA. Adequate water depth to avoid scraping bottom is a major consideration when paddling; therefore, habitat simulations for canoeing had additional restrictions placed on depth to include only cells that are 1-ft deep or greater.

Habitat-Discharge Relations for Lockes Mill Study Reach and the Millville Streamflow-Gaging Station

Habitat was simulated for a range of flows from 60 to 5,000 ft^3/s at Lockes Mill study reach for seven species and life stages of fish and for recreation. These flows are equivalent to a range of 70 to 5,850 ft^3/s at the Millville gage. Because it is advantageous to discuss habitat data in the context of long-term historical streamflow data, the Millville-equivalent flows were used as input to the time-series analysis. The WUA data represent total physical habitat available per a simulated 1,000-ft reach of stream with habitats present in the study reach for a given streamflow (table 5; fig. 3).

The WUA curves (fig. 3) help depict the streamflows associated with maximum values of WUAs for each species and for recreation and how WUA increases or decreases as flows change. It should be noted that the WUA curves are bell-shaped, having lower WUA at the highest flows—a maximum associated with median to low-flow conditions—and decreasing WUA as flows decrease. The WUA curves have similar patterns for species of similar size or life stage as opposed to patterns grouping game or grouping non-game species together. For example, the maximum WUA for adult smallmouth bass and sub-adult smallmouth bass (*Micropterus dolomieu*) and river chub (*Nocomis micropogon*) all appear to be associated with the median flow for JAS (900 ft^3/s). Sub-adult redbreast sunfish (*Lepomis auritus*) maximum WUA is associated with the 25th percentile flow (641 ft^3/s), which is still within the normal range of flows for JAS. Smaller fish, such as spotfin or satinfin shiner (*Cyprinella* spp.), margined madtom (*Noturus insignis*), and juvenile redbreast sunfish (*Micropterus dolomieu*) maximum WUA were associated with the 10th percentile flows and lower. The maximum or optimum habitat is related to streamflows that consistently provide depths with an optimal range for species (table 5). Smaller fish or earlier life stage habitat requirements are optimized with depths less than 2 ft, and larger adult fish habitat requirements are optimized with depths greater than 2 ft. Canoeing WUA is maximized when streamflows are above the 75th percentile, near 2,000 ft^3/sec. At discharges greater than 2,000 ft^3/s, the velocity becomes faster than considered suitable for canoeing safely. Although the depth is adequate, the velocity could increase to a level that could make canoeing dangerous. For all species of fish considered during this investigation, except juvenile redbreast sunfish, habitat was maximized with streamflows between 482 and 900 ft^3/s at Millville, representing the 10th percentile to the 50th percentile flows for JAS (fig. 3).

Table 5. Weighted usable-habitat area in square feet per 1,000 feet of stream for the Lockes Mill study reach, main stem Shenandoah River, Virginia.

[ft^3/s, cubic feet per second; Mgal/d, million gallons per day]

Calculated[1] Millville equivalent daily discharge (ft^3/s)	Millville equivalent daily discharge (Mgal/d)	Simulated discharge (ft^3/s)	Fish species weighted usable-habitat area							Canoeing
			Sub-adult smallmouth bass	Adult smallmouth bass	Juvenile redbreast sunfish	Sub-adult redbreast sunfish	*Cyprinella* spp.	Margined madtom	River chub	
70	45	60	7,154	11,866	58,599	26,234	15,511	44,065	40,746	6,222
117	76	100	27,612	17,695	77,500	53,848	35,913	65,396	59,556	26,610
234	151	200	74,235	35,020	107,398	91,504	102,765	87,364	103,516	92,462
351	227	300	107,873	50,988	118,366	100,548	129,657	124,052	147,316	139,005
468	302	400	139,293	60,193	111,628	108,528	141,287	134,599	165,469	181,275
585	378	500	162,788	67,827	102,436	115,064	141,222	136,150	171,726	222,073
725	469	620	168,082	71,669	78,961	116,148	133,606	134,522	174,546	261,763
819	529	700	173,820	74,021	67,328	114,672	122,932	128,202	177,394	283,911
936	605	800	175,798	76,014	63,425	110,794	120,135	120,926	172,184	306,915
1,135	734	970	163,148	71,512	46,061	109,384	106,235	107,486	153,090	333,866
1,170	756	1,000	158,047	70,969	40,713	108,167	99,624	104,887	150,095	337,306
2,223	1,437	1,900	101,625	47,200	13,226	67,558	33,722	57,295	71,516	363,230
2,340	1,512	2,000	91,601	45,153	12,250	60,338	31,617	54,914	67,370	362,219
3,522	2,276	3,010	57,807	30,356	5,010	33,316	9,615	28,304	25,999	324,184
4,680	3,025	4,000	43,748	23,842	2,933	23,381	4,218	11,948	13,582	277,800
5,850	3,781	5,000	28,565	19,130	2,111	15,738	667	8,254	7,802	242,973

[1] The ratio of measured discharge at Lockes Mill to daily mean discharge for Millville was calculated for all days which had pairs of data. The value of 1.17 was used to calculate the equivalent daily discharge at Millville from the measured or simulated flows at Lockes Mill study site.

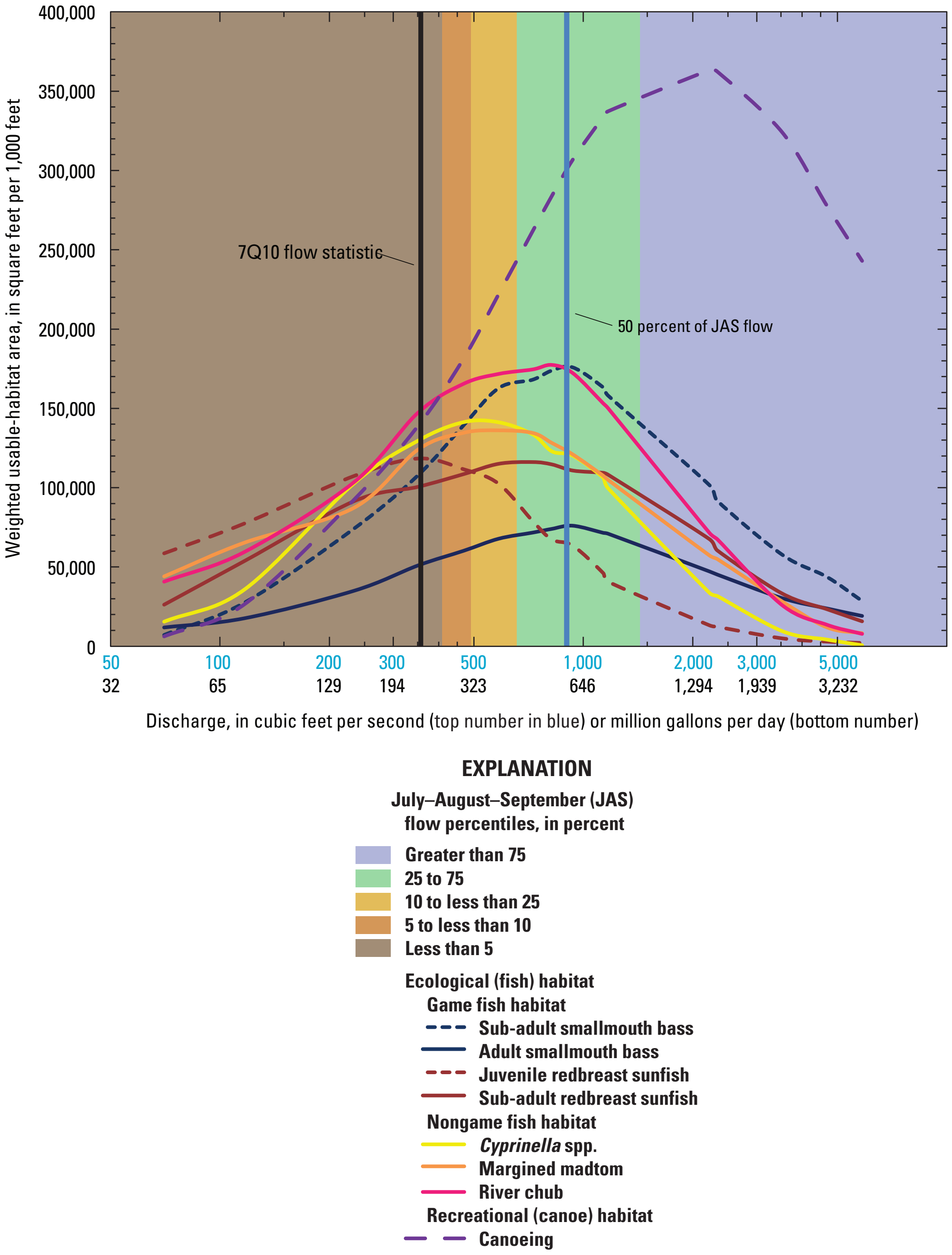


Figure 3. Weighted usable-habitat area of ecological and recreational habitat for the Lockes Mill study reach on the Shenandoah River, Virginia. Flow percentiles are based on data from the Millville streamflow-gaging station (01636500) from 1930 to 2002 for streamflows during the months of July, August, and September. These statistics represent the expected range of flows and are based on the historic streamflow record.

Habitat Time-Series Scenario Analysis for Low-Flow Periods

For management purposes it is important to understand what the normal range of habitat conditions would be for each species of interest and which species habitat area may become limited during droughts. Time-series analysis allows the evaluation of habitat over the historic streamflow record to simulate past and future habitat conditions on the basis of the current understanding of WUA and streamflow.

Habitat Duration for Summer Months of the Historic Record

Habitat-duration plots were constructed for each species or life stage by assigning usable habitat area to each discharge value for the period of record for Millville from 1930 to 2012. Habitat values for JAS were then ordered and ranked, and the percentage of time the habitat value was equaled or exceeded was calculated. Habitat-duration statistics describe the most common and least common habitat conditions, and can be used to define a normal range of available habitat area for each species or life stage of fish (fig. 4). The normal range of habitat for summer months (JAS) represented by the 25th to 75th percentiles of available habitat is depicted on time-series plots for context. Figure 4 illustrates the differing amounts of habitat available for each species during summer months in the main stem Shenandoah River. Typically the least amount of habitat area is available for adult smallmouth bass and sub-adult redbreast sunfish, which have narrow ranges of available habitat area. River chub and sub-adult smallmouth bass tend to have the most available habitat within the study reach in the summer, and *Cyprinella* spp., margined madtom, and juvenile redbreast sunfish have wide ranges of available habitat.

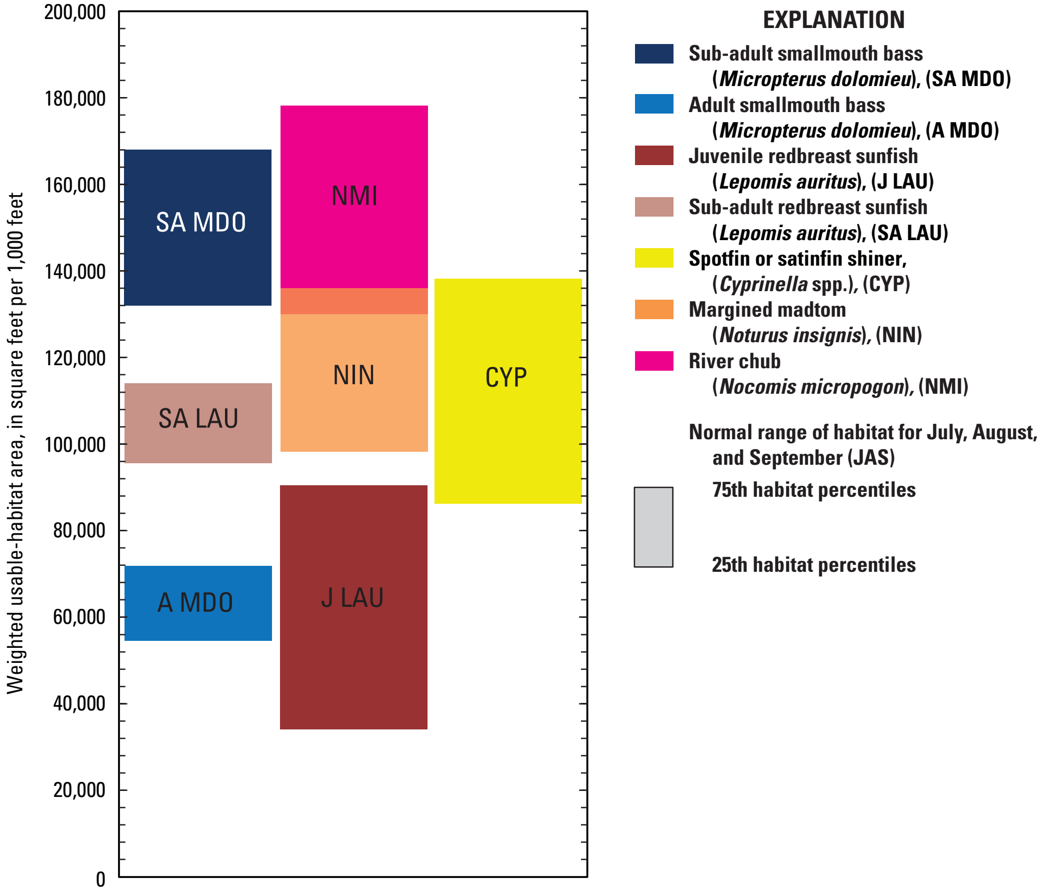


Figure 4. Normal range of weighted usable-habitat area during July, August, and September for each fish species or life stage. (Shaded boxes represent 25th to 75th habitat percentiles calculated from a time-series association of the weighted usable-habitat area curves to the historic streamflow record at Millville, West Virginia).

Times-Series Scenarios for Historic Droughts and Normal Summers

Time-series plots of the habitat availability were calculated from the discharge-habitat relations and applied to historic daily flows for the streamflow-gaging station at Millville following Krstolic and Ramey (2012) to provide a picture of habitat availability during a selected set of summer flow periods. Drought years were examined as examples of times when habitat was potentially limited so that species and habitats affected by drought could be identified. This assessment sought to describe the flow conditions that were potentially stressful for fish or recreation habitat availability and to contrast those conditions with normal or optimal habitat availability. The results and descriptions are interpretations of the WUA curves, the time-series plots, and the historic flow record. The scenarios presented in this report are for informational purposes only, and any selection of flow thresholds and desired habitat availability during drought or low-flow periods would be at the discretion of resource managers, planners, and policy makers in the Shenandoah Valley.

For each species, life stage, or canoeing, daily and monthly habitat was examined for drought years (1963, 1977, 1999, and 2002) and one normal flow year (2012). The normal range (25th to 75th percentile range) of flows for the streamflow-gaging station at Millville for JAS (from 1930 to 2002) is 641 to 1,410 ft^3/s (table 2). During the selected drought years examined for this study (1963, 1977, 1999, and 2002), the monthly mean flows ranged from 392 ft^3/s to 595 ft^3/s during June, July, August, and September which is below the normal range of flows for JAS. During 2012, monthly mean flows ranged from 776 ft^3/s to 1,199 ft^3/s, which is within the normal range of flows for JAS (table 2). For management purposes it may be useful to evaluate habitat availability on a daily or monthly basis so information is presented in both formats.

Daily Summaries

During historic droughts, daily changes in habitat in response to changes in streamflow demonstrated that adult smallmouth bass and sub-adult smallmouth bass habitat was frequently below normal. When streamflows were close to the 10th percentile JAS flow (less than 500 ft^3/s or 323 Mgal/d) during 2002 (fig. 5), 1999 (fig. 6), 1977, and 1963, adult and sub-adult smallmouth bass available habitat was below normal for the majority of days during at least 2 months of the summer. Streamflows were less than the 7Q10 flow (357 ft^3/s or 231 Mgal/day) for 15 days during summer months of 1999. These extreme low-flow conditions also resulted in habitat decreases below the 25th percentile of available habitat for margined madtom, river chub, and sub-adult redbreast sunfish. Except for the decreases in available habitat described above, available fish habitat in the Shenandoah River near Lockes Mill during historic droughts was within a normal range for a given species or life stage. Flows that limit most species habitat ranged from 300 ft^3/s to 500 ft^3/s, with particular strain to larger game species like adult smallmouth bass. In general, if flows were greater than the 10th percentile JAS flow, available habitat for all species studied was at least suitable.

As was the case on the South Fork Shenandoah River during historic droughts, adequate flows for suitable canoeing rarely occurred on the main stem Shenandoah River. On the basis of the habitat modeling results in the Lockes Mill section of the Shenandoah River, streamflow must be at least 500 ft^3/s to ensure average depths of at least 1 ft for paddling. Flows equal to or less than the 10th percentile flow for JAS do not provide adequate depth for passage through riffle habitats. For the time-series scenarios for 2002 and 1999, conditions for canoeing were outside the normal range (figs. 5*B* and 6*B*) for the majority of days during JAS. Flows during 2012 were adequate to support canoeing at the end of July, most of August, and some of September (fig. 7*B*) because streamflows were greater than the 25th percentile JAS flow (641 ft^3/s) during that time. Although recreation is certainly a consideration for water-resources management, when flows are only slightly higher than the 10th percentile flow for JAS and decreasing as they were during the drought years examined, canoe paddling is unlikely to be successful.

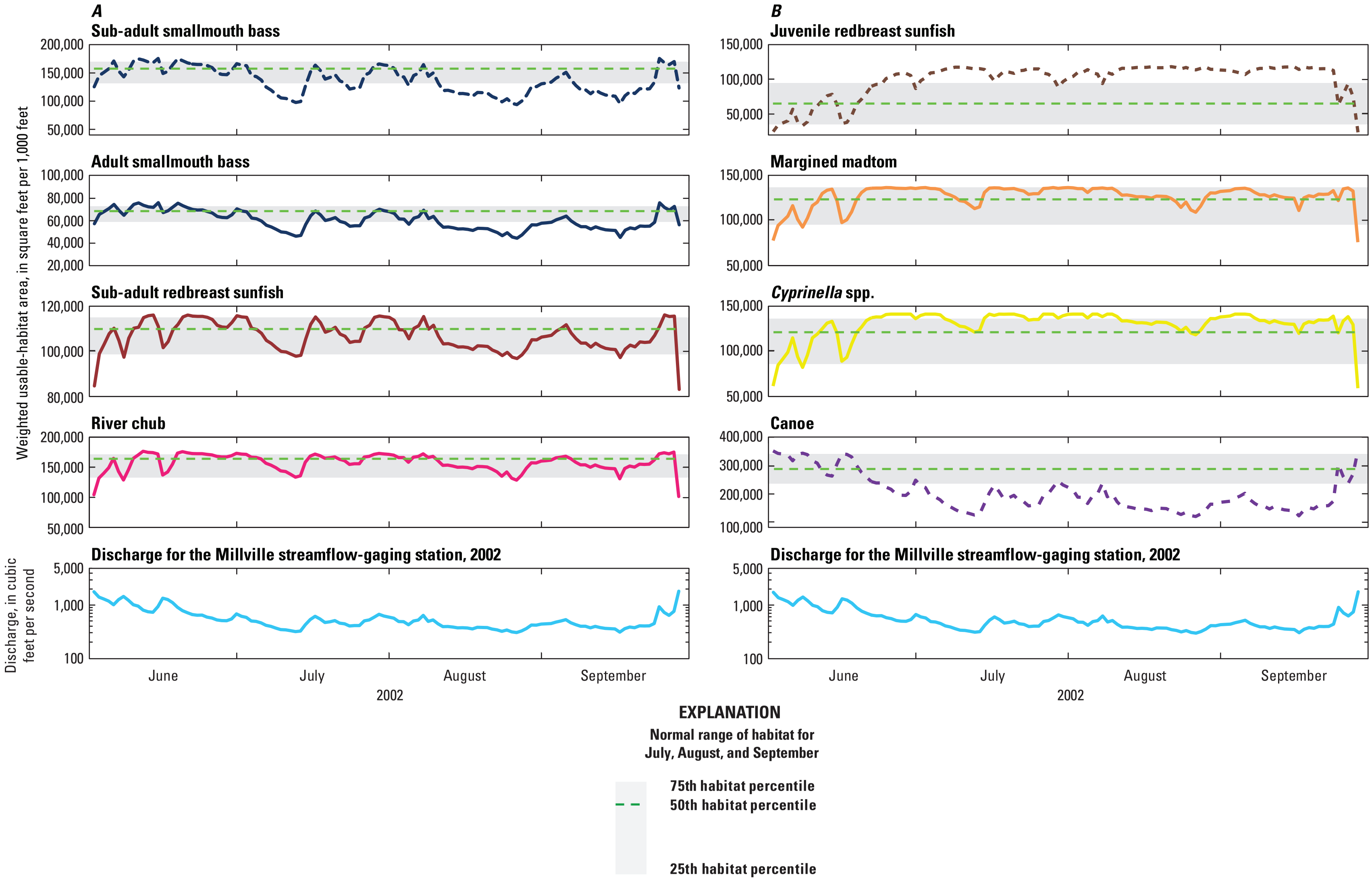


Figure 5. Habitat time series for the Lockes Mill study reach (0163633459) during 2002. (*A*) adult and sub-adult smallmouth bass, sub-adult redbreast sunfish, and river chub weighted usable-habitat area and daily mean discharge for the river at Millville (01636500); (*B*) juvenile redbreast sunfish, margined madtom, *Cyprinella* spp., and canoeing weighted usable-habitat area, and daily mean discharge for the river at Millville (01636500).

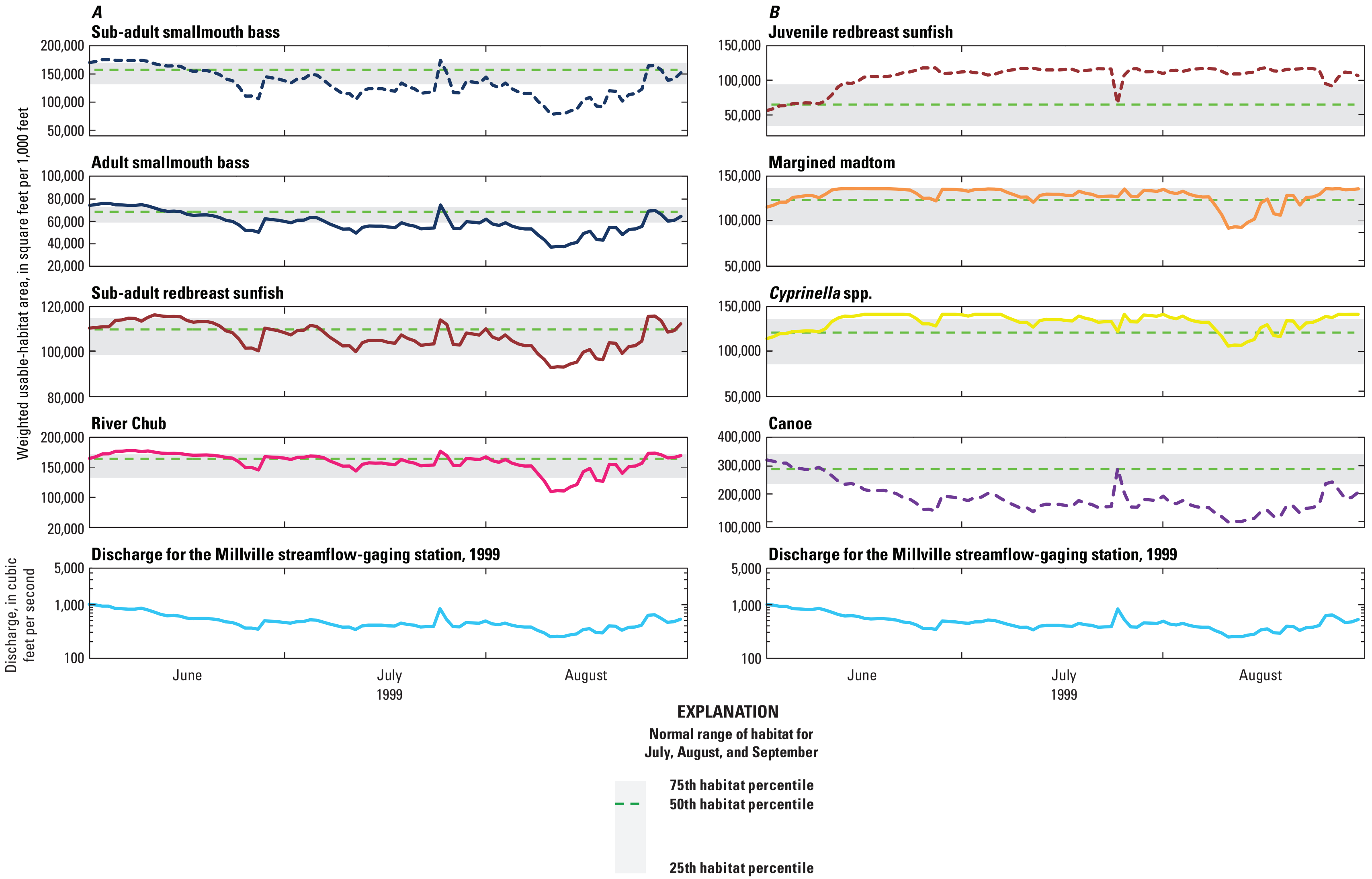


Figure 6. Habitat time series for the Lockes Mill study reach (0163633459) during 1999. (*A*) adult and sub-adult smallmouth bass, sub-adult redbreast sunfish, and river chub weighted usable-habitat area and daily mean discharge for the river at Millville (01636500); (*B*) juvenile redbreast sunfish, margined madtom, *Cyprinella* spp., and canoeing weighted usable-habitat area, and daily mean discharge for the river at Millville (01636500).

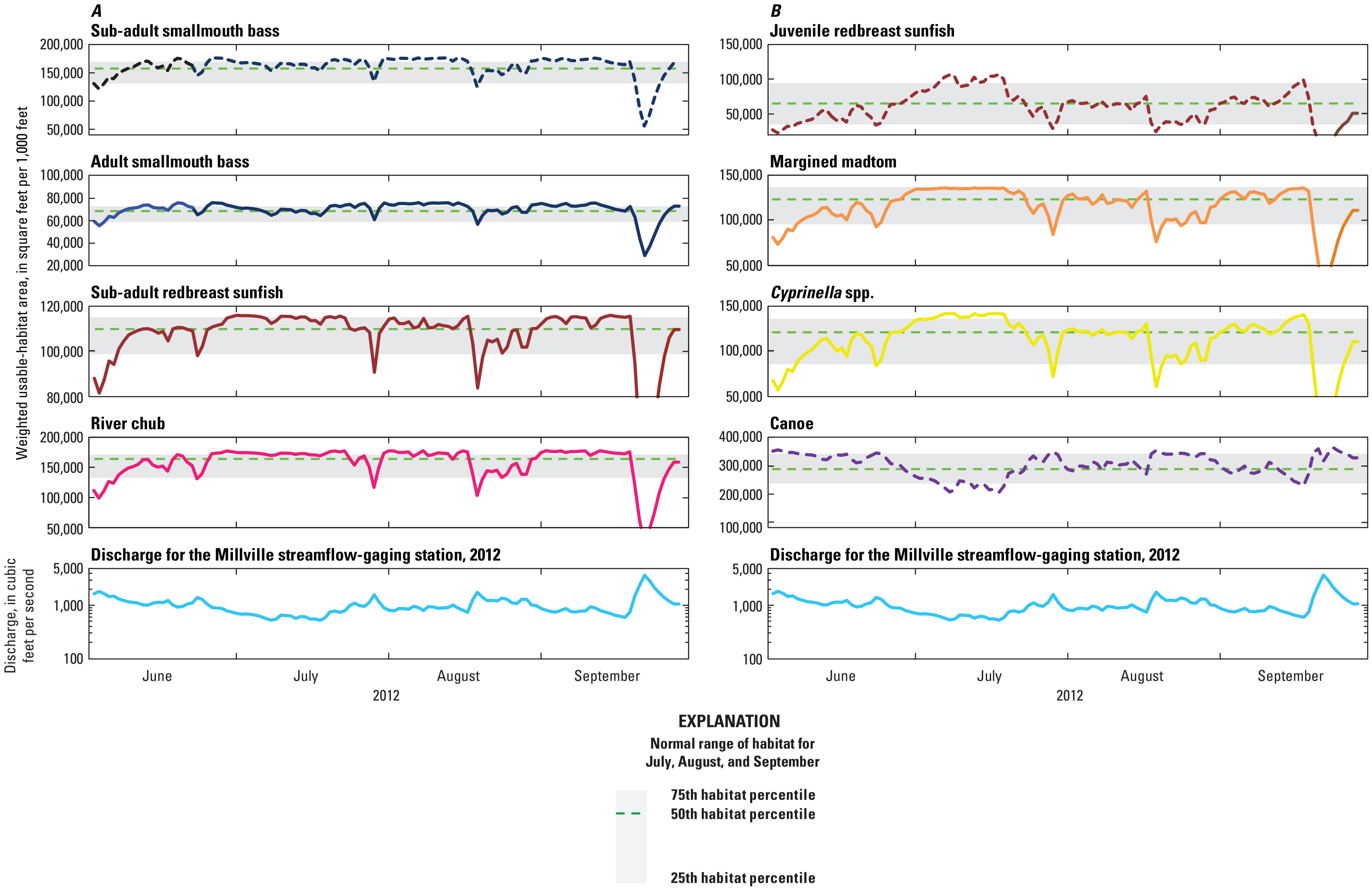


Figure 7. Habitat time series for the Lockes Mill study reach (0163633459) during 2012. (*A*) adult and sub-adult smallmouth bass, sub-adult redbreast sunfish, and river chub weighted usable-habitat area and daily mean discharge for the river at Millville (01636500); (*B*) juvenile redbreast sunfish, margined madtom, *Cyprinella* spp., and canoeing weighted usable-habitat area, and daily mean discharge for the river at Millville (01636500).

Monthly Summaries

Bar charts summarizing the number of days each month that habitat was within the normal range for each species or life stage and canoeing (table 6) were constructed from time-series daily data for JAS 1963, 1999, 2002, and 2012 (fig. 8). For smaller species, redbreast sunfish, *Cyprinella* spp., margined madtom, and river chub, habitat conditions were within a normal range almost all months during the selected drought years (fig. 8). Adult and sub-adult smallmouth bass and canoeing habitat was lower than the 25th percentile of habitat more than half the days of each month during 1963, 1999, and 2002. The habitat conditions for fish and canoeing were possibly as close to ideal as possible in July and August 2012 because all species of fish were within the normal habitat range for 28–31 days and canoeing was within the normal range for 20–31 days.

During wet conditions in September 1999 and 2012, available fish habitat did not follow the same patterns as might be expected with increases in flow. For example, when the maximum flow for September 1999 was 9,650 ft^3/s (fig. 8), the number of days that habitat was within the normal range was six or less for all fish species. The decreased habitat availability with higher streamflows is related to storm flow. This demonstrates a modeling limitation for the habitat-suitability criteria, because higher flows represent fast velocities or depths outside those values studied during the development of the fish HSC. For species that prefer shallow habitats, high flows can intermittently create instream habitat conditions outside the optimal or suitable ranges for depth or velocity. Canoe mean monthly suitability responded to flow changes as would be expected, increasing with more flow and decreasing with less flow.

These monthly count summary statistics could be developed on an on-going basis and integrated with the DEQ water supply planning initiative by applying the habitat-discharge relation to daily values of streamflow from USGS streamflow-gaging stations throughout the Shenandoah Basin. The available daily habitat can be compared with the normal habitat range (table 6) determined in this investigation and counted if the criteria are met. The monthly count summary statistics should also be considered in the context of the maximum and mean monthly flow for each month. The reader is encouraged to be mindful of the upper limits indicated by the HSC so that incorrect assumptions are avoided.

Table 6. Normal range of weighted usable-habitat area in square feet per 1,000 feet of stream for July, August, and September for each species and canoeing for the Shenandoah River.

Habitat percentile	Fish species weighted usable-habitat area							Canoeing
	Sub-adult small mouth bass	Adult small mouth bass	Juvenile redbreast sunfish	Sub-adult readbreast sunfish	*Cyprinella* spp.	Margined madtom	River chub	
75	168,915	72,538	93,909	114,639	135,852	134,562	173,092	338,045
50	157,512	68,347	65,160	109,924	121,187	122,978	164,383	288,040
25	131,256	58,777	34,970	98,770	85,856	94,944	132,931	236,207

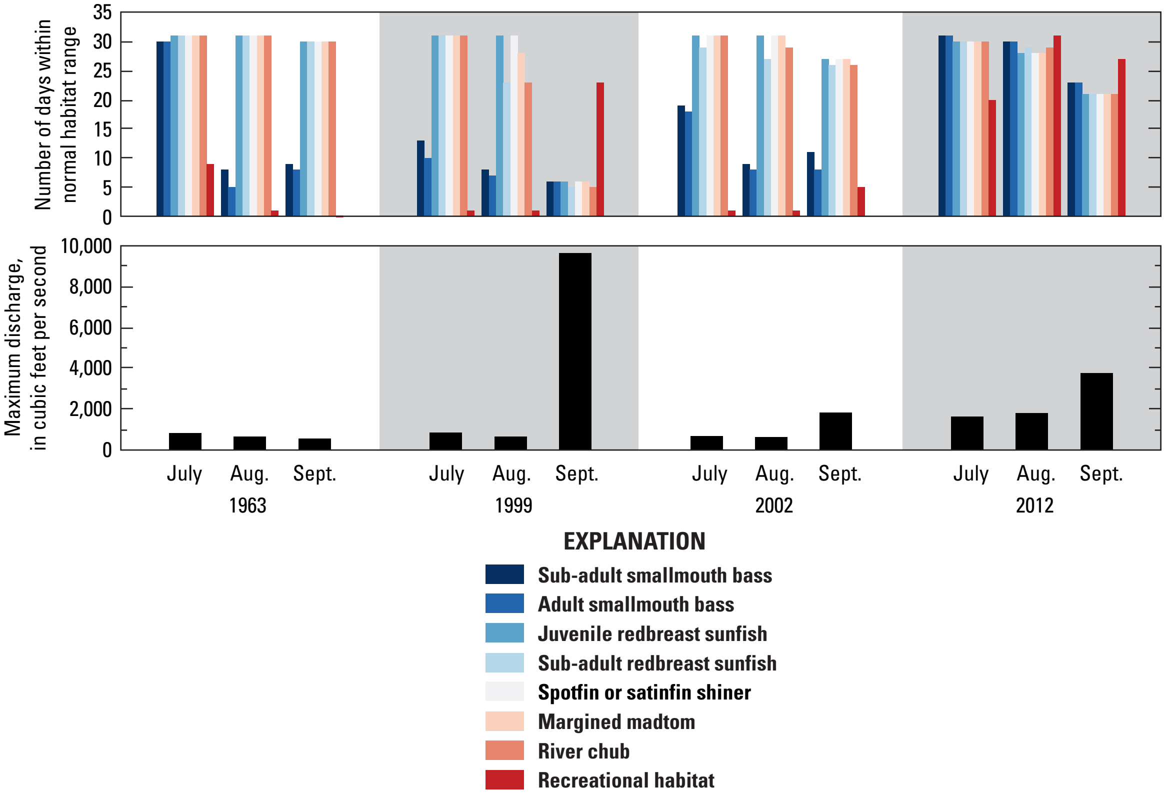


Figure 8. Number of days per month when habitat for fish or canoeing was within the normal range during 1963, 1999, 2002, and 2012.

Increased Water-Use Scenario Results

Time-series analyses were used to investigate changes in habitat availability with increased water use up to the 2040 amounts projected by local water supply plans (Central Shenandoah Planning District Commission, 2011; Northern Shenandoah Valley Regional Commission, 2011). On the basis of the estimates for water use and population growth, cumulative water-withdrawal increases of 10, 20, and almost 50 percent (48.6 percent) were applied to the Millville streamflow record. These percentage increases in water withdrawals equate to a maximum reduction in streamflow of 26.7 ft^3/s or 17.3 Mgal/d more than the present withdrawals when the 2040 estimated water-withdrawal totals for the basin are considered. As with the time-series analysis, years with extreme drought, moderate drought, and normal recent conditions were examined to determine potential effects on available habitat. Scenarios were run for both game and non-game fish ecological habitat and canoeing recreational habitat availability with increased water withdrawals.

While scenarios were run for each species that was modeled, only the species with somewhat obvious declines in habitat availability with increased withdrawals are discussed in this section. Adult and sub-adult smallmouth bass frequently had habitat availability outside the normal range for habitat conditions during drought years such as 2002, yet 10- or 20-percent increases in withdrawals did not contribute to a large reduction in usable habitat (fig. 9*A, B*). When withdrawals were increased by 50 percent and habitat conditions were outside the normal range, there was an additional decrease in usable habitat (fig. 9*A*). During 2002 drought scenarios, reduced habitat availability for sub-adult redbreast sunfish or river chub was only slightly evident with 50-percent increased withdrawal scenarios (fig. 9*C, D*). This result is not surprising because the habitat availability primarily is based on suitability criteria that assess changes in depth or velocity as primary habitat indicators. For a river as large as the Shenandoah River, a reduction of 17.3 Mgal/d equates to a decrease in depth of less than 0.02 ft. For a recent normal year like 2012, increased water-use scenarios did not affect habitat availability for fish such as adult and sub-adult smallmouth bass, sub-adult redbreast sunfish, or river chub (fig. 10).

For recreational habitat represented by canoeing, drought conditions that were already much lower than the normal range for canoeing were decreased with increases in withdrawals. For the 2002 drought, the increased withdrawals contributed to a constant decrease as habitat continued to drop lower than normal (fig. 11*A*). In contrast, canoeing habitat availability was within the normal range for most of 2012, and any increased water-withdrawal scenario applied to that time series of habitat showed almost no affect (fig. 11*B*).

The increased water-withdrawal scenarios confirm that habitat availability will be reduced with increased water withdrawals. Although short-term investigations in the Shenandoah River Basin have not confirmed whether habitat and flow alteration could affect fish species diversity or abundance, investigations in other basins have shown reductions in abundance, demographic parameters, and species diversity with respect to decreases in flow magnitude of base flow, mean discharge, or total discharge (Poff and Zimmerman, 2010). Most of the studies summarized in Poff and Zimmerman (2010) represented large alterations and lacked data for moderate ranges of flow alteration, so more work is needed to ascertain whether there is a threshold response with lower levels of alteration. One study quantified the response of fluvial fish to environmental or anthropogenic variables (Armstrong and others, 2011) and found that a one-unit (1 percent) alteration in the August median flow resulted in a 0.9-percent decrease in relative abundance of fish (in counts per hour). The 50-percent water-withdrawal increase scenario could result in as much as a 3-percent reduction in the median JAS flow statistic if water returns were minimal. If Armstrong and others (2011) calculations were applicable to the Shenandoah River, the relative abundance of fish could be reduced by 2.7 percent.

These scenarios illustrate the importance of the timing of water withdrawals for maintaining habitat and sustaining flows during low-flow conditions. For both ecological fish habitat and recreational canoeing habitat, the antecedent conditions (habitat within normal range of habitat or below normal) appear to govern whether additional water withdrawals will affect habitat availability. The increased water-withdrawal scenarios contributed to greater reductions in habitat if streamflow was already below normal. Potential management strategies toward maintaining flows and habitat in the normal range could include withdrawing water to off-stream storage prior to low-flow months or preferentially withdrawing during storms in the summer. Implementing water-conservation practices during drought and repairing water delivery system leaks to improve efficiency, thus reducing water withdrawals, are both strategies that would proactively work toward maintaining the flow regime and available habitat. As the population and water demands increase, many of the ecological or recreational stresses may be lessened by managing the timing of water withdrawals and working to keep the projected withdrawals as low as possible.

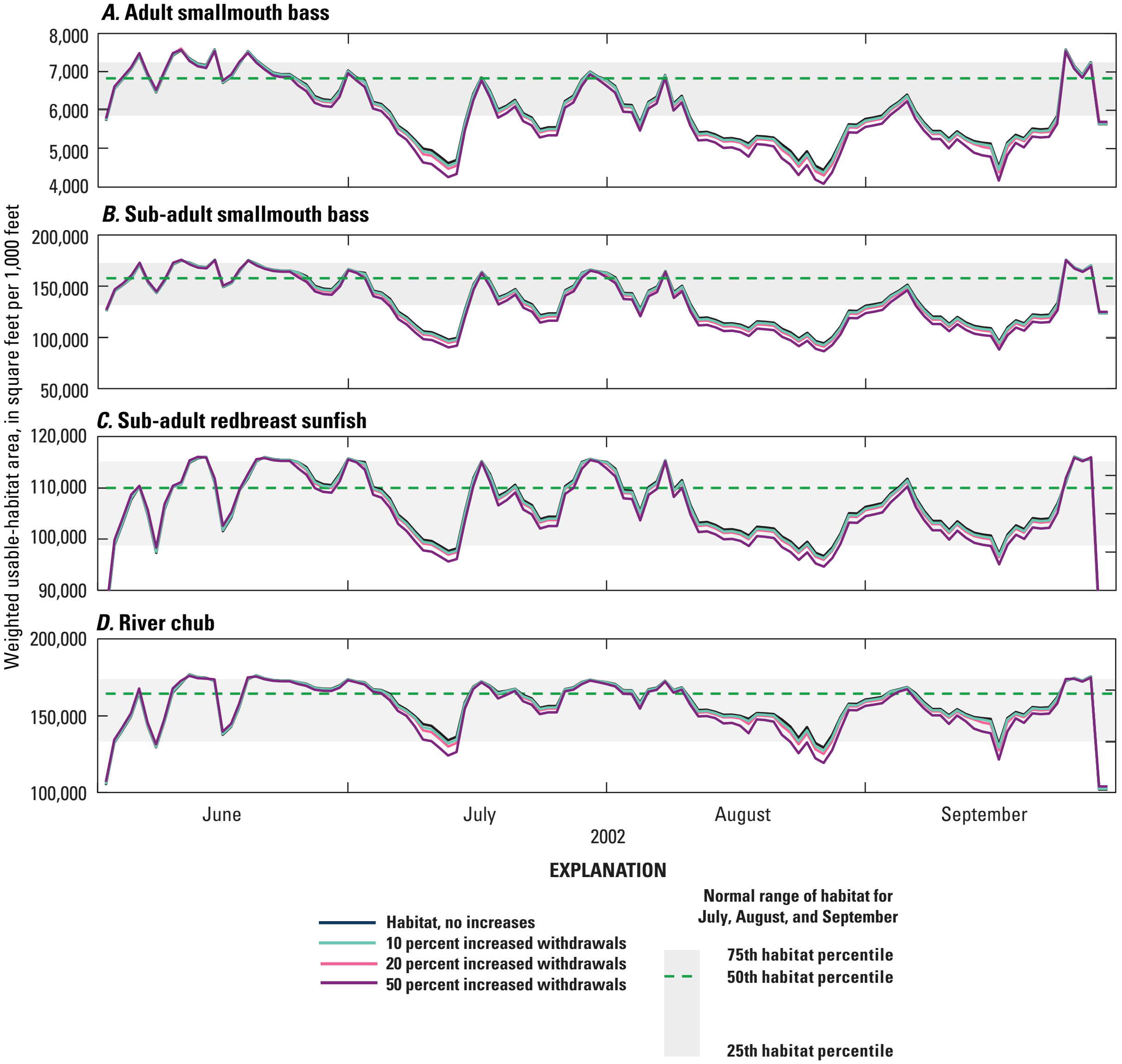


Figure 9. Habitat time-series increased water-withdrawal scenarios for the Shenandoah River at Millville, West Virginia, during 2002. (*A*) adult smallmouth bass, (*B*) sub-adult smallmouth bass, (*C*) sub-adult redbreast sunfish, and (*D*) river chub weighted usable-habitat area with 10-, 20-, and 50-percent increase in water use.

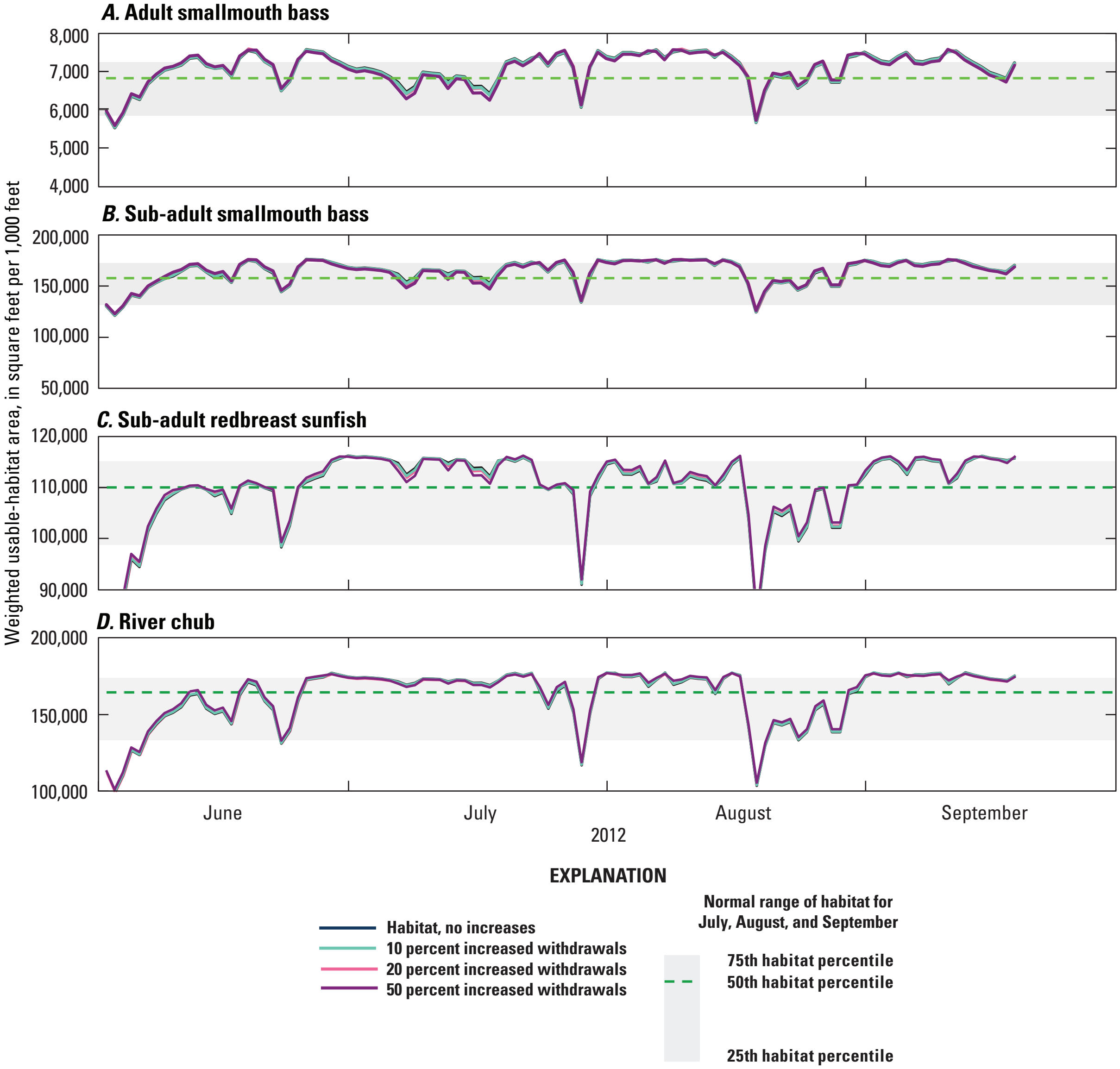


Figure 10. Habitat time-series increased water-withdrawal scenarios for the Shenandoah River at Millville, West Virginia, during 2012. (*A*) adult smallmouth bass, (*B*) sub-adult smallmouth bass, (*C*) sub-adult redbreast sunfish, and (*D*) river chub weighted usable-habitat area with 10-, 20-, and 50-percent increase in water use.

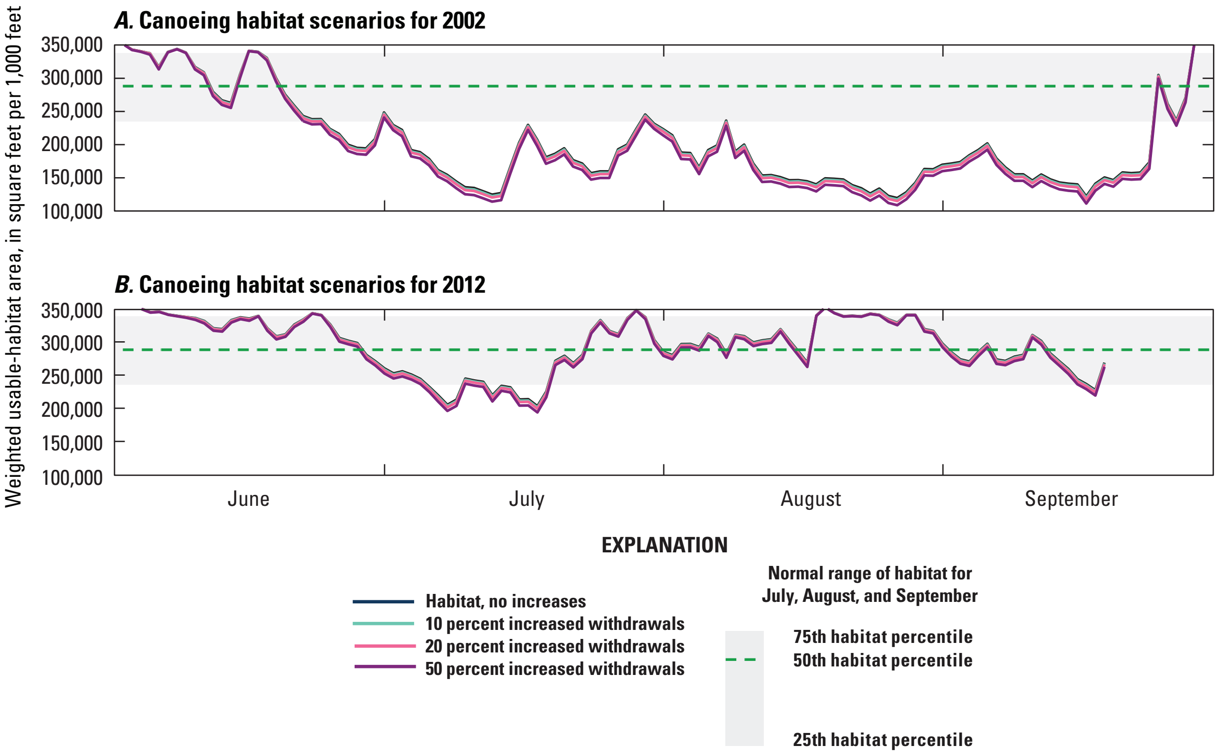


Figure 11. Canoeing recreational habitat time-series increased water-withdrawal scenarios, main stem Shenandoah River, based on (*A*) 2002 flow data, and (*B*) 2012 flow data.

Summary and Conclusions

This report describes updates to methods, documents modeling results, and discusses implications from an updated habitat-flow model for the main stem Shenandoah River in Virginia. The 2010 population within the Shenandoah River watershed and adjacent areas that used water from the river represented a 29-percent increase from 1995 records, and the 2040 predicted population represents a 76-percent increase from 1995 records. Given that water withdrawals are also predicted to increase with population, there has been interest in assessing how increases in withdrawals may affect habitat and recreation in the Shenandoah River. Water withdrawals for 2005 were compared with projected water demands for 2040 from the recently completed water supply planning initiative documents written by the two planning district commissions within the Shenandoah River Basin. Most localities projected demands that approach their total presently permitted surface-water and groundwater withdrawal values by 2040, and a few are projected to exceed them. The projected surface-water withdrawals vary by watershed, the North Fork Shenandoah River shows a 55.9-percent increase, the South Fork Shenandoah River shows a 46.5-percent increase, and the main stem Shenandoah River shows a 52-percent increase. Cumulatively, the 2040 surface-water withdrawal values represent a 51-percent increase from 2005 surface-water withdrawals. This equates to adjusted daily mean flows for the Shenandoah River at Millville, West Virginia, that are 17.3 Mgal/d (26.7 ft^3/s) less than they were in 2005.

Seasonal flow statistics for the Shenandoah River at Millville for the low-flow summer period of July, August, and September (JAS) were of interest for understanding effects on habitat with increases in water withdrawals during low-flow periods. Long-term record flow statistics for streamflow-gaging stations in the Shenandoah River Basin show the flow at Strasburg is approximately 35 percent of the flow at Front Royal, and the combined flow of Strasburg plus Front Royal is approximately 85 percent of the flow at Millville. Flows equal to or less than the 10th percentile for JAS (482 ft^3/s or 312 Mgal/d) were evaluated as drought indicators for this study.

New water-withdrawal projections were complemented by additional low-flow water-surface level (WSL) profiles and discharge data to enhance the habitat simulation model. It was necessary to verify and install new elevation control points along the Lockes Mill study reach, with updated elevations adjusted to the previous study values. New discharge and WSL profile data were collected and combined with the two high-flow datasets previously published in an early model from 1998. After the data were combined, the model was re-calibrated, and a new habitat-discharge relation was developed for ecological habitat for fish and recreational habitat for canoeing.

The habitat-discharge relation weighted usable-habitat area (WUA) curves have similar patterns for species of similar size or life stage as opposed to patterns grouping game or grouping non-game species together. For example, the maximum WUA for adult smallmouth bass, sub-adult smallmouth bass, and river chub all appear to be associated with the median flow for JAS (900 ft^3/s). Smaller fish, such as *Cyprinella* spp., margined madtom, and juvenile redbreast sunfish maximum WUA were associated with the 10th percentile flows and lower. Canoeing WUA is maximized when streamflows are above the 75th percentile, near 2,000 ft^3/s.

To place the habitat-discharge relation in context, time series of habitat were used to calculate habitat-duration statistics to define normal habitat availability for the summer months. Habitat-duration statistics describe the availability of usable habitat for a given species for a range of streamflow, given the known physical conditions of the reach. The range of available habitat for adult smallmouth bass and sub-adult redbreast sunfish at the Lockes Mill study reach is narrow compared to other fish species, predominantly because these fish favor deeper pool habitats that are not as common as run habitats within the study reach.

Time-series plots of the habitat availability and daily streamflow during drought years illustrate how ecological or recreational habitat conditions may be affected by drought. For each fish species, life stage, and for canoeing, daily habitat availability was examined for drought years (1963, 1977, 1999, and 2002) and one normal flow year (2012). During historic droughts, streamflows were less than the 10th percentile flow (500 ft^3/s or 323 Mgal/d), and adult smallmouth bass and sub-adult smallmouth bass habitats were below normal for the majority of days during at least 2 months of the summer. When streamflows were less than the 7Q10 flow (357 ft^3/s or 231 Mgal/d), margined madtom, river chub, and sub-adult redbreast sunfish habitats were below normal as well. Streamflows that limit most fish species habitat availability range from 300 to 500 ft^3/s. Although recreation is a consideration for water-resources management, when flows are only slightly higher than the 10th percentile flow for JAS, canoe paddling is unlikely to be successful because flows equal to or less than the 10th percentile do not provide adequate depth for passage through riffles. Flows during 2012 were adequate to support canoeing because streamflows were greater than the 25th percentile JAS flow (641 ft^3/s) during that time.

For smaller species, redbreast sunfish, *Cyprinella* spp., margined madtom, and river chub, habitat conditions were within a normal range almost all days of each summer month during selected drought years 1963, 1999, and 2002. Whereas, adult and sub-adult smallmouth bass and canoeing habitat was lower than the normal range of habitat the majority of days during summer months of 1963, 1999, and 2002. Ideal habitat conditions for fish and canoeing were represented by model simulations for July and August 2012. However, in September 1999 when the maximum flow for the month was 9,650 ft^3/s, habitat was only within the normal range six days or less for all fish. Storm flows occurred with faster velocities or deeper depths than those studied during the development of the fish habitat-suitability criteria, thus demonstrating a modeling limitation represented by flows outside the study range.

Time-series analyses were used to investigate changes in habitat availability with increased water use of 10, 20, and almost 50 percent (48.6 percent) up to the 2040 amounts projected by local water supply plans of the two planning district commissions within the Shenandoah River Basin. These percentage increases in water withdrawals equate to 17.3 Mgal/d more than the present withdrawals when the 2040 estimated water-withdrawal totals for the basin are considered.

Increased water-withdrawal scenarios were run for both game and non-game fish ecological-habitat availability and canoeing recreational-habitat availability. Adult and sub-adult smallmouth bass habitat availability frequently was outside the normal range for habitat conditions during drought years, yet only when withdrawals were increased by 50 percent during drought years, were large reductions in habitat evident. For small species such as sub-adult redbreast sunfish or river chub that were usually within the normal range for habitat conditions, 2002 drought scenarios plus 50-percent increased withdrawal scenarios resulted in only slightly reduced habitat availability. For a recent normal year, like 2012, the increased water-use scenarios did not affect habitat availability for fish.

Recreational habitat represented by canoeing decreased with increases in withdrawals. For the 2002 drought, the increased withdrawals contributed to a constant decrease as habitat continued to drop lower than normal. In contrast, canoeing habitat availability was within the normal range for most of 2012, and any increased water-withdrawal scenario applied to that time series of habitat showed almost no affect.

The increased water-withdrawal scenarios confirm that habitat availability will be reduced during drought years with increased water withdrawals. While short-term investigations in the Shenandoah River Basin have not confirmed whether habitat and flow alteration could affect fish species diversity or abundance, investigations in other basins increasingly support this assertion. A study of fluvial fish assemblages in Massachusetts demonstrated decreases in relative abundance of fish in response to anthropogenic alteration to August median flows. In applying similar methods to those used in Massachusetts to the Shenandoah River, a 50-percent water-withdrawal increase could result in a 2.7 percent reduction in relative abundance of fish.

These increased water-withdrawal scenarios in this investigation illustrate the importance of the timing of water withdrawals for maintaining habitat and sustaining flows during low-flow conditions. For all simulations of habitat, the antecedent conditions (habitat within normal range of habitat or below normal) appear to govern whether additional water withdrawals will affect habitat availability. Withdrawing water to off-stream storage prior to low-flow months, preferentially withdrawing water during storms in the summer, and implementing water-conservation practices during droughts are management strategies which may help to maintain flows and habitat in the normal range. As the population and water demand increase, many of the ecological or recreational stresses may be lessened by managing the timing of water withdrawals and implementing proactive conservation strategies to keep the projected withdrawals as low as possible.

Acknowledgments

The author thanks the cooperators, Clarke and Warren Counties, for support of this scientific work. We also thank the Northern Shenandoah Valley Regional Commission and Central Shenandoah Planning District for their continued support and interest in this work. The continued interest and feedback received from policy makers, planners, utility managers, State agency staff, and private citizens enhanced the study process.

Appreciation is extended to local landowners for allowing access to the river from their properties. Watermelon Park allowed access to the river along the campground that facilitated re-visiting historic monitoring locations.

Vital field assistance was provided by the lead technician for the project, Roger Moberg (USGS, Richmond, Va.) and other experienced technicians and hydrologists: Brent Banks, Carlos Rodriguez, James Duda, Karl Dydak, Geoff Austin, Russ Lotspeich, Don Hayes, and Gary Speiran (USGS, Richmond, Va.). Additional field assistance was provided by Jon Campbell (USGS, Reston, Va.). The author also thanks the peer reviewers who increased the effectiveness of this document.

References Cited

Armstrong, D.S., Richards, T.A., and Levin, S.B., 2011, Factors influencing riverine fish assemblages in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2011–5193, 59 p. (Also available at *http://pubs.usgs.gov/sir/2011/5193/*.)

Austin, S.H., Krstolic, J.L., and Wiegand, Ute, 2011, Low-flow characteristics of Virginia streams: U.S. Geological Survey Scientific Investigations Report 2011–5143, 122 p. + 9 tables on CD. (Also available online at *http://pubs.usgs.gov/sir/2011/5143/*.)

Central Shenandoah Planning District Commission, 2011, Upper Shenandoah water supply plan and drought preparedness and response plan: Staunton, Va., Central Shenandoah Planning District Commission, accessed January 14, 2014, at *http://www.cspdc.org/programs/environment/programs_environment.htm*.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011, Completion of the 2006 National Land Cover Database for the conterminous United States: Photogrammetric Engineering & Remote Sensing, v. 77, no. 9, p. 858–864.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

Krstolic, J.L., and Ramey, R.C., 2012, South Fork Shenandoah River habitat-flow modeling to determine ecological and recreational characteristics during low-flow periods: U.S. Geological Survey Scientific Investigations Report 2012–5081, 64 p. (Available online at *http://pubs.usgs.gov/sir/2012/5081/*.)

Krstolic, J.L., Hayes, D.C., and Ruhl, P.M., 2006, Physical habitat classification and instream flow modeling to determine habitat availability during low-flow periods, North Fork Shenandoah River, Virginia: U.S. Geological Survey Scientific Investigations Report 2006–5025, 63 p.

Lovelace, J.K., 2009a, Methods for estimating water withdrawals for aquaculture in the United States, 2005: U.S. Geological Survey Scientific Investigations Report 2009–5042, 13 p.

Lovelace, J.K., 2009b, Methods for estimating water withdrawals for livestock in the United States, 2005: U.S. Geological Survey Scientific Investigations Report 2009–5041, 7 p.

McCabe, G.J., and Wolock, D.M., 2002, A step increase in streamflow in the conterminous United States: Geophysical Research Letters, v. 29, no. 24, p. 38–1—38–4.

Milhouse, R.T., 1990, Recreational river space as related to discharge in the Salmon River, Oswego, County, New York: US Fish and Wildlife Service, Draft Report, 56 p.

National Geodetic Survey, 2012, OPUS—Online Positioning User Service, National Geodetic Survey, accessed January 24, 2014, at *http://www.ngs.noaa.gov/OPUS/about.jsp#*.

Northern Shenandoah Valley Regional Commission, 2011, Northern Shenandoah regional water supply plan, submitted to Virginia Department of Environmental Quality, September 2011, 127 p.

Onset Computer Corporation, 2008–10, HOBO U2 data loggers and HOBOware software, accessed April 4, 2014, at *http://www.onsetcomp.com/*.

Poff, N.L., and Zimmerman, J.K.H., 2010, Ecological responses to altered flow regimes—A literature review to inform the science and management of environmental flows: Freshwater Biology, v. 55, p. 194–205.

Ramey, R.C., 2009, Habitat suitability criteria for fishes of the South Fork of the Shenandoah River and an investigation into observer effects associated with two techniques of underwater observation: Richmond, Va., Virginia Commonwealth University, Master's thesis, 123 p.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 76 p.

Thomas R. Payne and Associates, 1998, User's manual—RHABSIM [Riverine Habitat Simulation software] 2.0 for Dos and Windows, variously paged.

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods, book 3, chap. A8, 87 p.

U.S. Census Bureau, 2011, 2010 Census centers of population by census block group, accessed June 21, 2011, at *http://www.census.gov/geo/www/2010census/centerpop2010/blkgrp/bgcenters.html.*

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and Van Driel, J.N., 2001, Completion of the 1990's National Land Cover Data Set for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 67, p. 650-662, accessed November 5, 2014, at *http://www.mrlc.gov/nlcd1992.php*.

Waddle, T.J., ed., 2001, PHABSIM [Physical Habitat Simulation model] for Windows—User's manual and exercises: Fort Collins, Colo.: U.S. Geological Survey Open-File Report 01–340, 288 p., accessed April 9, 2014, at *http://www.mesc.usgs.gov/Products/Publications/pub_abstract.asp?PubID=15000*.

Wiley, J.B., 2006, Low-flow analysis and selected flow statistics representative of 1930–2002 for streamflow-gaging stations in or near West Virginia: U.S. Geological Survey Scientific Investigations Report 2006–5002, 190 p.

Zappia, Humbert, and Hayes, D.C., 1998, A demonstration of the instream flow incremental methodology, Shenandoah River, Virginia: U.S. Geological Survey Water-Resources Investigations Report 98–4157, 24 p.

Appendix. RHABSIM model calibration data from the hydraulic data collected at the Lockes Mill study reach (0163633459), main stem Shenandoah River, Virginia.

[Calculated discharge is an RHABSIM calculated value. SZF, stage zero flow; WSL, water-surface level; slope, average water-surface slope for all discharges measured; verticals, number of measurement points along the transect; ND, no data collected]

Transect	Observed WSL[1] (ft)	Simulated WSL (ft)	Reach calibration discharge[1] (ft^3/s)	Model-calculated discharge (ft^3/s)	Verticals	Transect weighting factor	Slope[1] (ratio)	SZF[1] (ft)	Average Depth	Wetted Width	Velocity mean
1	372.2	372.09	3,010	ND	74	0.31	0.000	368.8	2.21	526.51	ND[2]
	371.48	371.63	1,900	ND					1.67	477.55	ND[2]
	371.01	371.07	970	1,106.7					1.37	427.77	1.57
	370.85	370.75	620	ND					1.29	402.22	ND[2]
2	373.12	373.06	3,010	ND	67	0.06	0.000	369.4	2.92	490.88	ND[2]
	372.54	372.61	1,900	ND					2.37	485.66	ND[2]
	371.95	372.04	970	945.9					1.81	480.35	1.06
	371.82	371.72	620	ND					1.68	479.15	ND[2]
5b	373.85	373.86	3,010	ND	43	0.4	0.001	371	1.89	440.46	ND[2]
	nd		nd	ND					nd	nd	ND[2]
	373.47	373.44	970	1,334.5					1.55	430.39	1.66
	373.28	373.3	620	ND					1.37	425.35	ND[2]
6	375.03	374.9	3,010	ND	45	0.01	0.001	371.3	2.79	384.07	ND[2]
	374.2	374.44	1,900	2,018.4					2.07	366.98	2.35
	373.89	373.86	970	ND					1.8	359.04	ND[2]
	373.61	373.54	620	ND					1.54	356.17	ND[2]
7	375.86	375.81	3,010	ND	41	0.25	0.001	371.3	3.71	312.91	ND[2]
	375.2	375.24	1,900	2,037.4					3.08	309.46	1.89
	374.44	374.53	970	ND					2.38	303.6	ND[2]
	374.2	374.13	620	ND					2.15	301.22	ND[2]
8	377.12	377.04	3,010	ND	78	0.01	0.000	372	3.41	503.65	ND[2]
	376.43	376.52	1,900	ND					2.8	490.11	ND[2]
	375.8	375.87	970	1,005.8					2.24	477.13	1.19
	375.56	375.48	620	ND					2.03	471.28	ND[2]
10	378.38	378.32	3,010	ND	53	0.33	0.001	374.8	2.8	525.68	ND[2]
	377.88	377.89	2,330	2,305.2					2.31	522.94	1.7
	377.77	377.84	1,900	ND					2.21	521.78	ND[2]
	377.15	377.25	970	ND					1.61	515.25	ND[2]
	377.02	376.92	620	ND					1.49	513.9	ND[2]
12	380.02	379.95	3,010	ND	62	1	0.000	377.1	3.27	519.31	ND[2]
	379.65	379.6	2,150	2,148.4					2.92	515.76	1.33
	379.48	379.56	1,900	ND					2.77	512.18	ND[2]
	379.03	379.09	970	ND					2.38	501.61	ND[2]
	378.9	378.83	620	ND					2.26	498.55	ND[2]
13	380.6	380.42	3,010	ND	75	0.06	0.000	376	3.79	525.07	ND[2]
	379.88	379.86	2,390	2,406.2					3.15	512.88	1.41
	379.45	379.79	1,900	ND					2.75	507.61	ND[2]
	378.95	379.03	970	ND					2.35	489.17	ND[2]
	378.83	378.61	620	ND					2.24	486.9	ND[2]

Appendix. RHABSIM model calibration data from the hydraulic data collected at the Lockes Mill study reach (0163633459), main stem Shenandoah River, Virginia.—Continued

[Calculated discharge is an RHABSIM calculated value. SZF, stage zero flow; WSL, water-surface level; slope, average water-surface slope for all discharges measured; verticals, number of measurement points along the transect; ND, no data collected]

Transect	Observed WSL[1] (ft)	Simulated WSL (ft)	Reach calibration discharge[1] (ft^3/s)	Model-calculated discharge (ft^3/s)	Verticals	Transect weighting factor	Slope[1] (ratio)	SZF[1] (ft)	Average Depth	Wetted Width	Velocity mean
14	380.72	380.52	3,010	ND	47	1	0.001	375.6	4.29	569.01	ND[2]
	379.76	379.95	2,240	2,260.9					3.38	562.46	1.2
	379.45	379.88	1,900	ND					3.09	558.24	ND[2]
	379.06	379.09	970	ND					2.73	552.72	ND[2]
	378.89	378.65	620	ND					2.57	549.43	ND[2]
14b[3]	380.25	380.15	3,010	ND	26	0	0.000	375.6	2.3	597.06	ND[2]
	379.6	379.75	1,900	ND					1.78	559.48	ND[2]
	379.21	379.25	970	ND					1.49	524.6	ND[2]
	379.04	378.95	620	ND					1.37	509.95	ND[2]
15	380.42	380.33	3,010	ND	40	0.1	0.000	376.5	5.26	491.5	ND[2]
	380.18	379.92	2,200	2,187.1					5.03	490.92	0.87
	379.75	379.87	1,900	ND					4.62	489.3	ND[2]
	379.24	379.3	970	ND					4.12	487.37	ND[2]
	379.07	378.98	620	ND					3.95	486.7	ND[2]
16	380.7	380.61	3,010	3,007.9	50	0.1	0.000	376.5	5.76	401	1.16
	380.03	380.16	1,900	ND					5.12	399.01	ND[2]
	379.56	379.6	970	ND					4.67	397.61	ND[2]
	379.36	379.28	620	ND					4.48	396.39	ND[2]
18	380.71	380.6	3,010	ND	52	1	0.000	376.5	4.92	403.1	ND[2]
	379.96	380.11	1,900	1,860.6					4.2	400.84	0.95
	379.45	379.5	970	ND					3.71	398.74	ND[2]
	379.25	379.16	620	ND					3.52	397.93	ND[2]

[1] Value calculated from field measurements.

[2] No velocity dataset collected for this water-surface level.

[3] No velocity datasets were collected for any discharges that were simulated, so the model could not calculate discharge. The transect was weighted 0, so it does not factor into the habitat calculations but remains as part of the study for reference, water-surface calibration, and because it is central to the elevation control network.

Approved for publication January 8, 2015
For further information about this publication contact:

Director
U.S. Geological Survey
Virginia Water Science Center
1730 East Parham Road
Richmond, VA 23228
http://va.water.usgs.gov/

Prepared by the Raleigh Publishing Service Center

Krstolic—**Data Collection and Simulation of Ecological Habitat and Recreational Habitat in the Shenandoah River, Virginia**—Scientific Investigations Report 2015–5005

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20155005