Prepared in cooperation with the Northern Shenandoah Valley Regional Commission

Physical Habitat Classification and Instream Flow Modeling to Determine Habitat Availability During Low-Flow Periods, North Fork Shenandoah River, Virginia

Scientific Investigations Report 2006-5025

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

Cover photograph (left) of the upper section of the North Fork Shenandoah River near Cootes Store, Virginia, by Jennifer L. Krstolic, U.S. Geological Survey, October 15, 2002. Cover photograph (center) of the middle section of the North Fork Shenandoah River near Mount Jackson, Virginia, by Donald C. Hayes, U.S. Geological Survey, October 10, 2001. Cover photograph (right) of the lower section of the North Fork Shenandoah River near mouth, by Donald C. Hayes, U.S. Geological Survey, October 10, 2001.

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
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Information about water resources in Virginia is available online at http://va.water.usgs.gov

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (mi^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	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)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27), unless otherwise noted in the text or figures.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), unless otherwise noted in the text or figures.

Abbreviations:

DEQ	Virginia Department of Environmental Quality
GIS	Geographic Information System
GPS	Global Positioning System
HSC	Habitat Suitability Criteria
IFIM	Instream Flow Incremental Methodology
MANSQ	Manning Stage-Discharge
NSVRC	Northern Shenandoah Valley Regional Commission
NWIS	National Water Inventory System
PHABSIM	Physical Habitat Simulation Model
RHABSIM	River Habitat Simulation Model
SFZ	Stage of Zero Flow
SI	Suitability Index
USGS	U.S. Geological Survey
VAF	Velocity Adjustment Factors
VPI	Virginia Polytechnic Institute and State University
WSL	Water-Surface Elevation
WSP	Water-Surface Profile
WUA	Weighted usable-habitat area

Physical Habitat Classification and Instream Flow Modeling to Determine Habitat Availability During Low-Flow Periods, North Fork Shenandoah River, Virginia

By Jennifer L. Krstolic, Donald C. Hayes, and Peter H. Ruhl

Abstract

Increasing development and increasing water withdrawals for public, industrial, and agricultural water supply threaten to reduce streamflows in the Shenandoah River basin in Virginia. Water managers need more information to balance human water-supply needs with the daily streamflows necessary for maintaining the aquatic ecosystems. To meet the need for comprehensive information on hydrology, water supply, and instream-flow requirements of the Shenandoah River basin, the U.S. Geological Survey and the Northern Shenandoah Valley Regional Commission conducted a cooperative investigation of habitat availability during low-flow periods on the North Fork Shenandoah River.

Historic streamflow data and empirical data on physical habitat, river hydraulics, fish community structure, and recreation were used to develop a physical habitat simulation model. Hydraulic measurements were made during low, medium, and high flows in six reaches at a total of 36 transects that included riffles, runs, and pools, and that had a variety of substrates and cover types. Habitat suitability criteria for fish were developed from detailed fish-community sampling and microhabitat observations. Fish were grouped into four guilds of species and life stages with similar habitat requirements. Simulated habitat was considered in the context of seasonal flow regimes to show the availability of flows that sustain suitable habitat during months when precipitation and streamflow are scarce.

The North Fork Shenandoah River basin was divided into three management sections for analysis purposes: the upper section, middle section, and lower section. The months of July, August, and September were chosen to represent a low-flow period in the basin with low mean monthly flows, low precipitation, high temperatures, and high water withdrawals. Exceedance flows calculated from the combined data from these three months describe low-flow periods on the North Fork Shenandoah River. Long-term records from three streamflow-gaging stations were used to characterize the flow regime: North Fork Shenandoah River at Cootes Store, Va. (1925–2002), North Fork Shenandoah River at Mount Jackson, Va. (1943–2002), and North Fork Shenandoah River near Strasburg, Va. (1925–2002).

The predominant mesohabitat types (14 percent riffle, 67.3 percent run, and 18.7 percent pool) were classified along the entire river (100 miles) to assist in the selection of reaches for hydraulic and fish community data collection. The upper section has predominantly particle substrate, ranging in size from sand to boulders, and the shortest habitat units. The middle section is a transitional section with increased bedrock substrate and habitat unit length. The lower section has predominantly bedrock substrate and the longest habitat units in the river.

The model simulations show that weighted usable-habitat area in the upper management section is highest at flows higher than the 25-percent exceedance flow for July, August, and September. During these three months, total weighted usable-habitat area in this section is often less than the simulated maximum weighted usable-habitat area. Habitat area in the middle management section is highest at flows between the 25- and 75-percent exceedance flows for July, August, and September. In the middle section during these months, both the actual weighted usable-habitat area and the simulated maximum weighted usable-habitat area are associated with this flow range. Weighted usable-habitat area in the lower management section is highest at flows lower than the 75-percent exceedance flow for July, August, and September. In the lower section during these three months, some weighted usable-habitat area is available, but the normal range of flows does not include the simulated maximum weighted usable-habitat area.

A time-series habitat analysis associated with the historic streamflow, zero water withdrawals, and doubled water withdrawals was completed. During simulated historic drought periods, time-series habitat analysis shows weighted usable-habitat area to be limited for fast-generalist and pool-cover

guilds in the upper management section, for fast-generalist and pool-run guilds in the middle section, and for the pool-cover guild in the lower section. The zero water-withdrawal scenario during historic low-flow periods shows improvement in weighted usable-habitat area for fast-generalist guild species in the upper management section and for pool-cover guild species in the lower section. The double water-withdrawal scenario simulation shows a total loss of fast-generalist guild weighted usable-habitat area during historic low-flow periods in the upper management section and a small decline in pool-cover guild weighted usable-habitat area in the lower management section. Simulated weighted usable-habitat areas are close to the maximum weighted usable-habitat area during a normal or wet historic summer period.

Streamflows that provide habitat at levels similar to those provided by the normal flow range (between the 25- and 75-percent exceedance flows) were identified for each management section of the North Fork Shenandoah River. With the current flow regime, the model results indicate that weighted usable-habitat area does not become highly limited for fish until streamflows reach or fall below the 90-percent exceedance flows for multiple days in July, August, and September. During low-flow periods, weighted usable-habitat area is limited in the upper section, in particular. Water conservation measures and reduced withdrawals may help maintain flows that sustain habitat in the upper section and throughout the river during low-flow periods.

Introduction

The Shenandoah River basin in northwestern Virginia is an unregulated, rural basin with a growing population (30-percent growth 1980-2000) (Krstolic and Hayes, 2004) (fig. 1). Increasing development and increasing water withdrawals for public, industrial, and agricultural water supply threaten to reduce streamflows in the basin. Water-resources managers need more information to balance human water-supply needs with the daily streamflows necessary for maintaining the aquatic ecosystems of the basin. Prior to 1990, there was a scarcity of science-based information related to water-resources management in the Shenandoah basin. Since that time, groups from ten counties, incorporated cities, and towns in the Shenandoah River basin of Virginia and West Virginia (fig. 1) have begun working toward basinwide management of water resources. To meet the need for comprehensive information on hydrology, water supply, and instream-flow requirements of the Shenandoah River basin, the U.S. Geological Survey (USGS) and the Northern Shenandoah Valley Regional Commission (NSVRC) began a cooperative investigation of habitat availability during low-flow periods on the North Fork Shenandoah River in 1998. The overall study was enhanced through partnering with Virginia Polytechnic Institute and State University (VPI) in data collection and analysis.

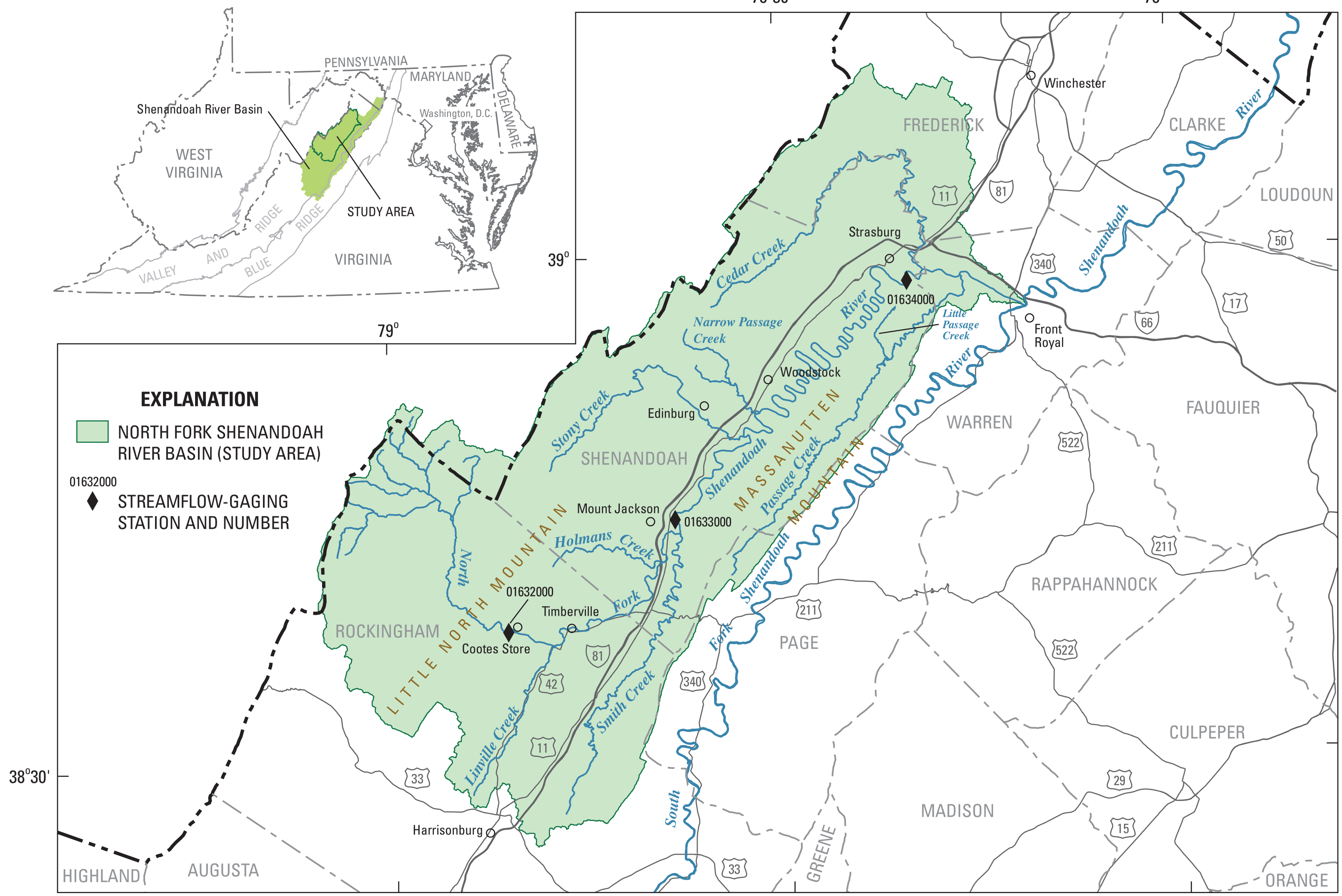
Zappia and Hayes (1998) related water availability to the physical habitat needs of fish and recreational uses in the Shenandoah River using Instream Flow Incremental Methodology (IFIM) techniques. Their study incorporated hydraulic information and literature-based fish habitat-suitability criteria to demonstrate the utility of scientific information for basinwide water-supply planning. Following Zappia and Hayes (1998) study on the main stem Shenandoah River, IFIM techniques were selected as the approach for the present study to investigate water availability and habitat on the North Fork Shenandoah River. There are two major tributaries to the Shenandoah River, however; the North Fork Shenandoah River was selected for study over the South Fork Shenandoah River because it has a growing population (67,551, 2000 U.S. Census) and the river discharge is less than that of the South Fork Shenandoah River, making water availability of greater concern.

The purpose of the present study is to enhance understanding of low-flow conditions, to relate water availability to physical habitat needs of fish, and to relate fish habitat to instream flows. It should be noted, however, that this study addresses fish habitat availability; habitat availability of other organisms was not investigated. The present study will provide scientific data to water-resources managers to assist them with setting target streamflows and selecting water-conservation goals. The methods and approach in this study can be applied to other basins in similar hydrogeologic settings.

The IFIM process usually includes the application and calibration of models such as the Physical Habitat Simulation Model (PHABSIM) (U.S. Geological Survey Fort Collins Science Center, 2001) or River Habitat Simulation Model (RHABSIM) (Thomas R. Payne and Associates, 1998), which are used to analyze hydraulic data along with the physical habitat requirements of aquatic organisms, or requirements of other instream and off-stream uses. The model output represents the habitat available for a selected set of streamflows.

Inputs to the PHABSIM and RHABSIM models include physical habitat data, micro-scale fish habitat-suitability criteria (HSC), hydraulic data, and stage-discharge ratings. Coarse physical habitat data is gathered along rivers or reaches of interest using mesohabitat mapping techniques. Mesohabitat data is as part of the process of determining the potential fish species composition, abundance, and size or age structure that the river can support (Simonson and others, 1993; Armstrong and Richards, 2001; Armstrong and others, 2003; Parsiewics and others, 2004; Sutton and Morris, 2004). Channel and riparian conditions within and upstream from a reach can have a profound effect on the habitat present (Vannote and others, 1980). Therefore, to accurately represent mesohabitat percentages for the reaches in the present study, the entire North Fork Shenandoah River was classified.

Prior to the start of present study, a detailed assessment of the fish community of the North Fork Shenandoah River had not been published. Data on fish species abundance and microhabitat preferences were necessary to model habitat availability representative of the fish species in the North Fork Shenan-



Base from U.S. Geological Survey Digital Line Graph, 1987, 1:2,000,000
Universal Transverse Mercator 17 projection, NAD 83, Central Meridian 81°00'W
Hydrography from U.S. Environmental Protection Agency Reach File Version 3.0, 1994, 1:100,000
Watershed boundary delineated from U.S. Geological Survey National Elevation Dataset digital elevation model, 2001, 30-meter resolution
City locations from U.S. Census Cartographic Boundary Files, Consolidated Cities, 2000, ~ 1:500,000
County boundaries from U.S. Geological Survey National Atlas coverage, 1995, 1:2,000,000
Roads from ESRI Streetmap USA, 2003

Figure 1. Location of the North Fork Shenandoah River Basin, Virginia (study area).

doah River. The VPI Department of Fisheries and Wildlife conducted a fish community assessment, and documented the physical microhabitats used by each species (Persinger, 2003) for the NSVRC. The community assessment also included the development of fish HSC to be used by the USGS in the IFIM modeling process.

Hydraulic data collection techniques provide habitat-specific stage and discharge relations needed for the IFIM modeling process. Measurements of depths, velocities, and water-surface elevations are typically used to establish ratings for a variety of habitat types. For the present study, hydraulic data were collected over a range of discharges by the USGS with the assistance of VPI. Hydraulic data were input to the RHABSIM model, a 1-dimensional water-surface profile model that uses stage-discharge ratings to simulate habitat conditions over a range of discharges. Because of the breadth of fish habitat conditions studied and the wide range of discharges modeled, the model results represent habitat and streamflow conditions that affect a large number of species on the North Fork Shenandoah River.

RHABSIM modeling results provide comprehensive information about low-flow physical habitat conditions based on the current, historic, and simulated future flow regimes. As flows are reduced water quality conditions can become a greater factor than the availability of habitat. To address this issue, a companion study was completed in July 1999 when the mean monthly streamflow was the lowest recorded since record-keeping began in 1925. Water-quality conditions documented in Krstolic and Hayes (2004) represent summer extreme low-flow conditions for the North Fork Shenandoah River. Krstolic and Hayes (2004) showed that most of the dissolved-oxygen concentrations at sites located in the upper reaches of the river were equal to or less than the State of Virginia's water-quality minimum, and most of the pH values at sites in the downstream portion of the river were greater than the state water-quality maximum. Water temperatures for one site in the lower portion of the river exceeded the state water-quality maximum. The present study examines habitat availability during low-flow periods to add to the understanding gained through water quality research presented in Krstolic and Hayes (2004).

The frequency of low-flow periods and increasing demands for water may affect instream flows and water-quality conditions throughout the North Fork Shenandoah River basin in the future. The model output, if used in conjunction with a socioeconomic analysis of water use and conservation, could be used by water-resources managers to make decisions about water-resources allocations that consider the habitat needs of fish and the water-use needs of humans. Similar studies that integrate habitat, instream flows, and water use are being incorporated into long-range water-resources plans in other basins in Virginia (Vadas and Weigmann, 1993). RHABSIM fish habitat results in combination with water-quality study results, current and projected water-use data, and projections about population growth could be helpful to water-resources managers in development of a plan to protect natural streamflow conditions, while meeting human water-supply needs within the North Fork Shenandoah River basin.

Purpose and Scope

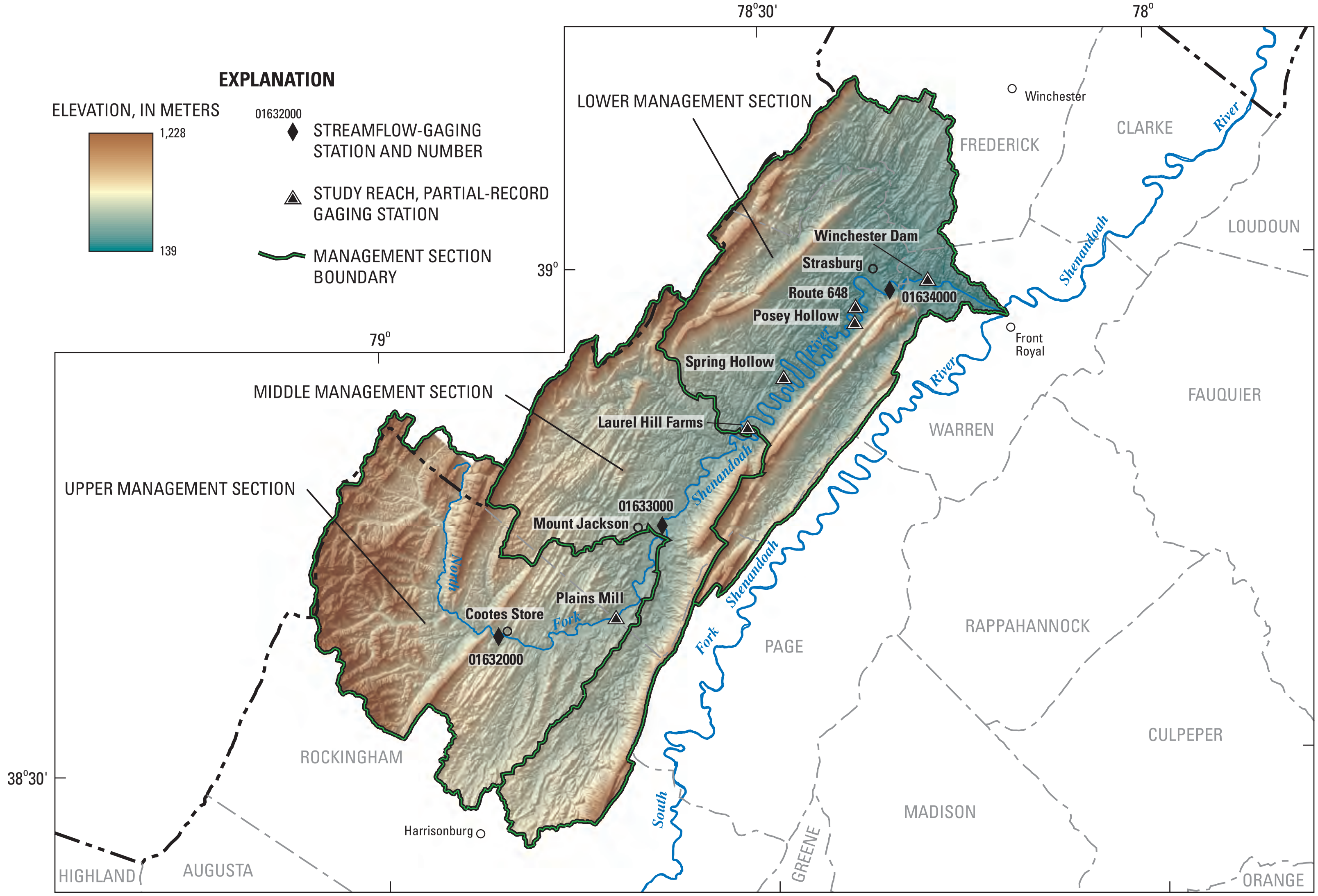
This report describes a classification of the mesohabitat of the North Fork Shenandoah River and documents the methods and findings of the habitat assessment and IFIM modeling process. The IFIM modeling process includes a synthesis of historic streamflow data, river hydraulics data, fish community structure data, fish habitat-suitability criteria, and recreational-use suitability criteria. The objectives of this investigation are to enhance understanding of summer low-flow conditions in the North Fork Shenandoah River, relate water availability to physical habitat needs of fish, and develop a relation for the availability of suitable fish habitat and instream flows. Selected withdrawal scenarios are simulated, including the effect that zero water withdrawals and double water withdrawals have on fish habitat.

Hydrogeology

The study area encompasses the main stem North Fork Shenandoah River from the headwaters near the Virginia border with West Virginia to the confluence with the South Fork Shenandoah River (fig. 1). The North Fork Shenandoah River has a drainage area of 1,033 mi^2. The North Fork Shenandoah River basin was divided into upper (miles 0–39.3), middle (miles 39.3–57.2), and lower (miles 57.2–107.3) sections for reporting study results (fig. 2). Streamflow-gaging stations are near the downstream end of each section: North Fork Shenandoah River at Cootes Store Va. (01632000), hereafter referred to as "Cootes Store"; North Fork Shenandoah River at Mount Jackson, Va. (01633000), hereafter referred to as "Mount Jackson"; and North Fork Shenandoah River near Strasburg, Va. (01634000), hereafter referred to as "Strasburg" (fig. 2). The drainage areas of these sections represent three hydrologically and geologically different areas within the basin, and are similar to basin divisions described by Hack and Young (1959).

The headwater streams that feed the North Fork Shenandoah River originate in West Virginia, but the main stem begins in Rockingham County, Va., and flows through Shenandoah and Warren Counties in Virginia (fig. 1). From the headwaters, the river flows east until Timberville, Va., where it turns and flows northeast parallel to Interstate 81 and Highway 11 to Strasburg, Va., and then turns east parallel to the Interstate 66 corridor to Front Royal, Va.

The North Fork Shenandoah River lies within the Valley and Ridge Physiographic Province. Basin topography is characterized by rolling hills and valleys, and is bordered on the eastern edge by Massanutten Mountain Range, which separates the North Fork Shenandoah River from the South Fork Shenandoah River (Virginia Department of Conservation and Economic Development, 1968) (fig. 1). The northeast-southwest trending ridges of the Valley and Ridge Physio-



Base from U.S. Geological Survey Digital Line Graph, 1987, 1:2,000,000
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Elevation from U.S. Geological Survey National Elevation Dataset digital elevation model, 2001, 30-meter resolution

Figure 2. Upper, middle, and lower management sections, location of study reaches, and topography in the North Fork Shenandoah River Basin, Virginia.

graphic Province are formed by resistant quartzite, sandstone, and conglomerates; the valleys are underlain by more readily weathered limestone, shale, and dolomite (Hack, 1965; Hayes, 1991). In the upper section, the North Fork Shenandoah River crosses the valleys and ridges on the west side of the basin, within mostly sandstone formations (Hack and Young, 1959). The river flows along the eastern side of the valley floor near Massanutten Mountain in wide, gradual meanders until it reaches Edinburg, Va. The upper and middle sections include karst topography within limestone and dolomite formations. The karst features include caves, sinkholes, and springs. Downstream of Edinburg, Va., the river enters the lower section and Seven Bends area where it is characterized by extremely narrow meanders, with 180-degree reversals, as it winds in and out of the ridges on the eastern side of the valley (Hack and Young, 1959; Krstolic and Hayes, 2004). In this section, the river follows fracture zones in the Martinsburg Shale (Hack and Young, 1959; Hack, 1965), which helped to form the river morphology unique to the Seven Bends area. The river has cut down to the bedrock within the middle and lower reaches, giving it a shallow and wide channel (Krstolic and Hayes, 2004).

Analysis of Historic Streamflow Data

Streamflows of the North Fork Shenandoah River basin have been monitored for more than 75 years. The long-term records from three streamflow-gaging stations (table 1) can be used to characterize the flow regime of the North Fork Shenandoah River. The station streamflow records represent slightly altered flow conditions owing to water withdrawals and return flows. Some of these withdrawals and returns are measured and documented and others are small, unregulated volumes that are not measured. The effect of water withdrawals on the North Fork Shenandoah River has not been assessed, but to this point (2004), streamflow records indicate that the river maintains a mostly natural flow regime.

Flow-duration curves can be used to describe the distribution of past flows and indicate the potential magnitude and frequency of occurrence of streamflows under similar climatic, land-use, and water-use conditions. A flow-duration curve is a cumulative frequency curve that shows the percentage of time specified discharges were equaled or exceeded during a given period, and combines the flow characteristics of a stream throughout the range of discharge, without regard to the sequence of occurrence (Searcy, 1969). The curves can be based on flows for the entire year or for specific time frames such as individual months or seasons.

Streamflows in the North Fork Shenandoah River fluctuate between flood-flow, normal-flow and low-flow conditions seasonally and yearly. Within the North Fork Shenandoah River basin, annual flow-duration curves representing the entire water year are used to calculate the daily mean flows equivalent to the 25- and 75-percent exceedance values (table 2, fig. 3), which are referred to in this report as the normal range of flows. This range only represents 50 percent of the data collected, so within a natural flow regime, the flow is outside of this range 50 percent of the time. The exceedance flows describe common flow patterns based on data collected throughout the entire period of record, and provide a standard for comparison with individual years or months. For this study, months with high temperatures, little precipitation (Southeast Regional Climate Center, 2003), low streamflow, and high water-use demands are of particular interest. Flow-duration curves representing the combined historic data from July, August, and September were selected to characterize the "low-flow period" exceedance flows for the North Fork Shenandoah basin (table 2). The 25- and 75-percent exceedance values for data from July, August, and September were used in this report to represent the normal range of flows for the low-flow period. Years having flows much lower than the normal range of flows for July, August, and September may be classified as dry years.

Table 1. Continuous monitoring streamflow-gaging stations on the North Fork Shenandoah River, Virginia.

[mi^2, square miles]

Station number	Station name	Drainage area (mi^2)	Operating agency	Period of record
01632000	North Fork Shenandoah River at Cootes Store, Va. (Cootes Store)	210	U.S. Geological Survey	1925–present
01633000	North Fork Shenandoah River at Mount Jackson, Va. (Mount Jackson)	506	Virginia Department of Environmental Quality	1943–present
01634000	North Fork Shenandoah River near Strasburg, Va. (Strasburg)	768	U.S. Geological Survey	1925–present

Table 2. Monthly, seasonal, and annual exceedance flows for three streamflow-gaging stations on the North Fork Shenandoah River, Virginia.

[ft³/s, cubic feet per second; Q.90–Q.25 =, value representing the 90-, 75-, 50-, or 25-percent exceedance value for the monthly, seasonal, or annual flows as noted; Values in bold type represent normal range of flows for the low-flow period]

Time period	Exceedance value	Cootes Store[1] 01632000 Discharge, in ft³/s	Mount Jackson[2] 01633000 Discharge, in ft³/s	Strasburg[1] 01634000 Discharge, in ft³/s
October	Q.90 =	2.3	32	88
	Q.75 =	4.5	45	113
	Q.50 =	12	74	156
	Q.25 =	50	153	267
November	Q.90 =	4.6	40	104
	Q.75 =	10	58	132
	Q.50 =	30	100	185
	Q.25 =	97	233	380
December	Q.90 =	7	47	113
	Q.75 =	27	77	161
	Q.50 =	73	184	305
	Q.25 =	168	383	561
January	Q.90 =	15	58	140
	Q.75 =	41	122	210
	Q.50 =	100	266	410
	Q.25 =	230	457	10,276
February	Q.90 =	27	89	164
	Q.75 =	66	194	315
	Q.50 =	147	360	565
	Q.25 =	299	640	946
March	Q.90 =	67	188	301
	Q.75 =	114	288	434
	Q.50 =	208	495	700
	Q.25 =	400	870	1,270
April	Q.90 =	59	156	288
	Q.75 =	89	234	394
	Q.50 =	167	383	604
	Q.25 =	348	706	1,090
May	Q.90 =	36	127	224
	Q.75 =	60	187	313
	Q.50 =	121	318	502
	Q.25 =	265	550	840
June	Q.90 =	14	68	150
	Q.75 =	23	109	206
	Q.50 =	44	169	300
	Q.25 =	99	279	471
July	Q.90 =	4	39	100
	Q.75 =	8.5	61	136
	Q.50 =	18	94	193

Table 2. Monthly, seasonal, and annual exceedance flows for three streamflow-gaging stations on the North Fork Shenandoah River, Virginia.—Continued

[ft^3/s, cubic feet per second; Q.90–Q.25 =, value representing the 90-, 75-, 50-, or 25-percent exceedance value for the monthly, seasonal, or annual flows as noted; Values in bold type represent normal range of flows for the low-flow period]

Time period	Exceedance value	Cootes Store[1] 01632000 Discharge, in ft^3/s	Mount Jackson[2] 01633000 Discharge, in ft^3/s	Strasburg[1] 01634000 Discharge, in ft^3/s
	Q.25 =	41	158	292
August	Q.90 =	1.4	26	84
	Q.75 =	3.5	44	115
	Q.50 =	13	74	169
	Q.25 =	46	169	300
September	Q.90 =	1.3	28	83
	Q.75 =	2.7	41	108
	Q.50 =	9.8	64	149
	Q.25 =	32	139	254
Annual	Q.90 =	4.6	43	110
	Q.75 =	15	76	160
	Q.50 =	61	182	310
	Q.25 =	178	418	630
July Aug Sept[3]	Q.90 =	1.6	30	87
	Q.75 =	**4.4**	**47**	**119**
	Q.50 =	14	78	171
	Q.25 =	**40**	**155**	**283**
Spring[4]	Q.90 =	48	147	260
	Q.75 =	86	230	373
	Q.50 =	164	388	590
	Q.25 =	338	710	1,060
Summer[5]	Q.90 =	3	36	99
	Q.75 =	9	62	143
	Q.50 =	23	112	214
	Q.25 =	64	207	367
Fall[6]	Q.90 =	2.1	32	90
	Q.75 =	5	47	118
	Q.50 =	15	78	163
	Q.25 =	58	172	296
Winter[7]	Q.90 =	14	58	130
	Q.75 =	40	119	210
	Q.50 =	101	268	416
	Q.25 =	231	520	758

[1]Historical data range 1925–2002.
[2]Historical data range 1944–2002.
[3]Reference low-flow months, July, August, and September.
[4]Spring months include March, April, and May.
[5]Summer months include June, July, and August.
[6]Fall months include September, October, and November.
[7]Winter months include December, January, and February.

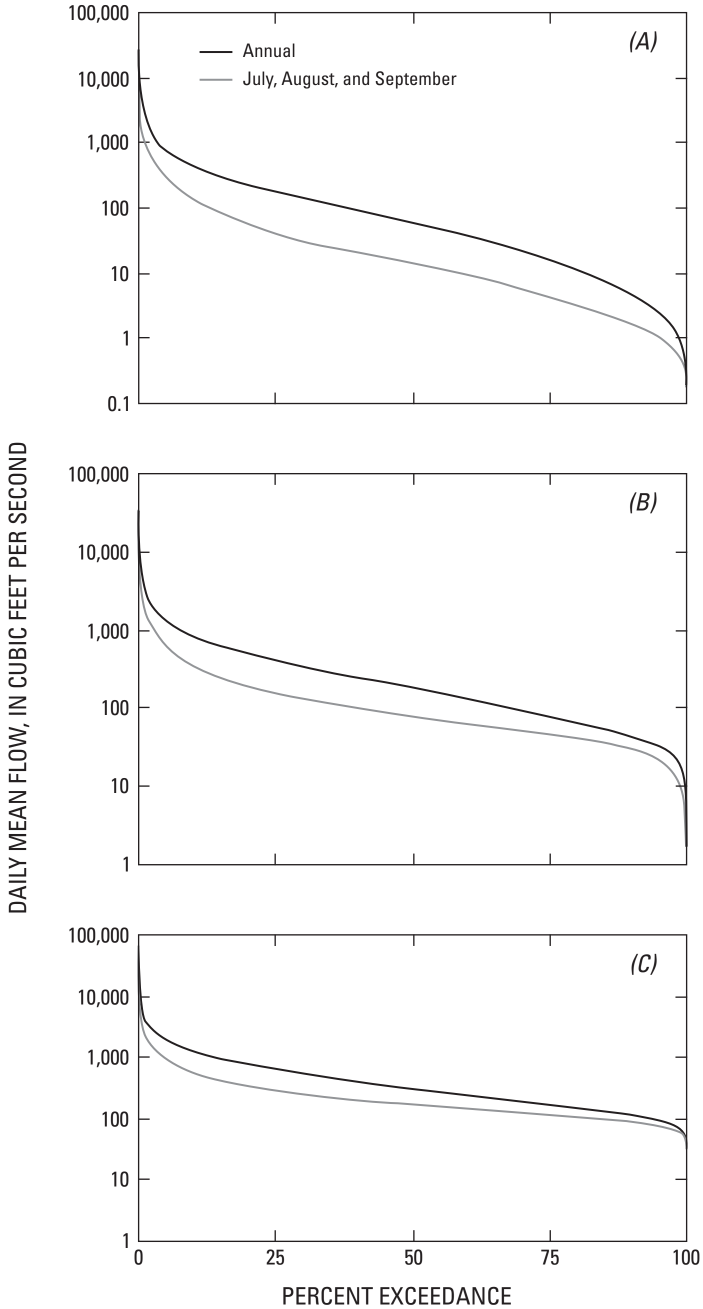

Figure 3. Annual and seasonal flow-duration curves for three streamflow-gaging stations on the North Fork Shenandoah River, Virginia: at Cootes Store, Va. (01632000) *(A)*; at Mount Jackson, Va. (01633000) *(B)*; near Strasburg, Va. (01634000) *(C)*.

The frequency and duration of low flows are important descriptors of low-flow conditions. Assessments of such hydrologic indices are important for understanding and predicting the effects of altered flow regimes on stream biota (Olden and Poff, 2003). The flow regime for the North Fork Shenandoah River can be further defined by examining the duration of the July, August, and September 25-, 50-, 75-, 90-, and 99- percent exceedance flows (table 3). By definition, 90-percent exceedance flows (whether annual, monthly, or seasonal) occur 10 percent of the time. In past dry years on the North Fork Shenandoah River, flows equal to or less than the 90-percent exceedance flow for July, August, and September occurred more than 50 percent of the time during low-flow months (table 4).

On average, daily values equal to or less than the 90-percent exceedance flows for July, August, and September for the Cootes Store, Mount Jackson, and Strasburg streamflow-gaging stations were recorded 1-4 days per month based upon the historic record for each station. During normal to wet years, these 90-percent exceedance flows are rare during July, August, and September, but during dry years or seasons, most daily mean flows are equal to or less than these values. Throughout the historic period, when daily mean flows equal to or less than the 90-percent exceedance flows for July, August, and September occur at least 50 percent of the time during some summer and fall months, it is likely that instream flows were limited (figures 4, 5, 6). This flow pattern occurred in the North Fork Shenandoah River basin in 1930, 1964–1966, 1999, and 2002. Many summer and fall months during these years had daily mean flows lower than the 90-percent exceedance flows for July, August, and September for 15 or more days per month (table 4). Although the analysis does not take into account whether the days below the exceedance flow were consecutive, it is likely that these low-flow days were consecutive because they occurred more than 15 days per month. Based on the historic streamflow data, dry periods meeting the above criteria occurred on approximately a 10- to 30-year cycle (figs. 3, 4, 5).

Aquatic biota have different seasonal flow needs related to the magnitude, frequency, and duration of flows (Poff and others, 1997; Richter and others, 1997, Richter and others, 2003). The normal range of flows for each season overlap, but the normal range of flows for winter and spring are substantially higher than the normal range of flows for summer and fall for the North Fork Shenandoah River (table 2). Low-flow statistics developed from the summer and fall months are not equivalent to those developed from winter and spring months. A streamflow that represents a low flow during one season can be a high flow during another. For example, a low flow of 48 ft^3/s at the Cootes Store station (table 2) would be expected infrequently during spring, but would be expected frequently during fall, and is within the high end of the normal range of flows for fall. Likewise, annual flow statistics do not adequately represent seasonal or monthly conditions. Streamflow statistics that describe the natural variations in flows for different seasons of the year are needed to fully describe natural flow regimes in an effort to understand how they affect the fish community.

Table 3. Average and maximum number of days in July, August, and September that streamflows were equal to or less than specified low-flow period exceedance values on the North Fork Shenandoah River, Virginia.

[avg, average number of days at the given exceedance flow; max, maximum number of days at the given exceedance flow]

Exceedance value	July avg	July max	August avg	August max	September avg	September max
Upper management section Cootes Store[1] 01632000						
25	23.6	31	23.3	31	23.9	30
50	9.9	31	14.5	31	15.7	30
75	2.7	31	8.0	31	9.3	30
90	1.0	25	3.5	31	4.2	30
99	0.0	0	0.5	11	0.3	12
Middle management section Mount Jackson[2] 01633000						
25	22.4	31	22.1	31	22.7	30
50	11.0	31	14.5	31	15.9	30
75	3.7	31	7.3	31	8.0	30
90	1.5	31	3.7	27	3.1	22
99	0.4	31	0.5	17	0.3	14
Lower management section Strasburg[1] 01634000						
25	22.4	31	22.7	31	23.4	30
50	11.4	31	14.1	31	16.3	30
75	4.2	31	7.1	31	8.4	30
90	1.9	31	3.2	30	3.4	27
99	0.4	22	0.4	22	0.3	10

[1] Historical data range 1925–2002.
[2] Historical data range 1943–2002.

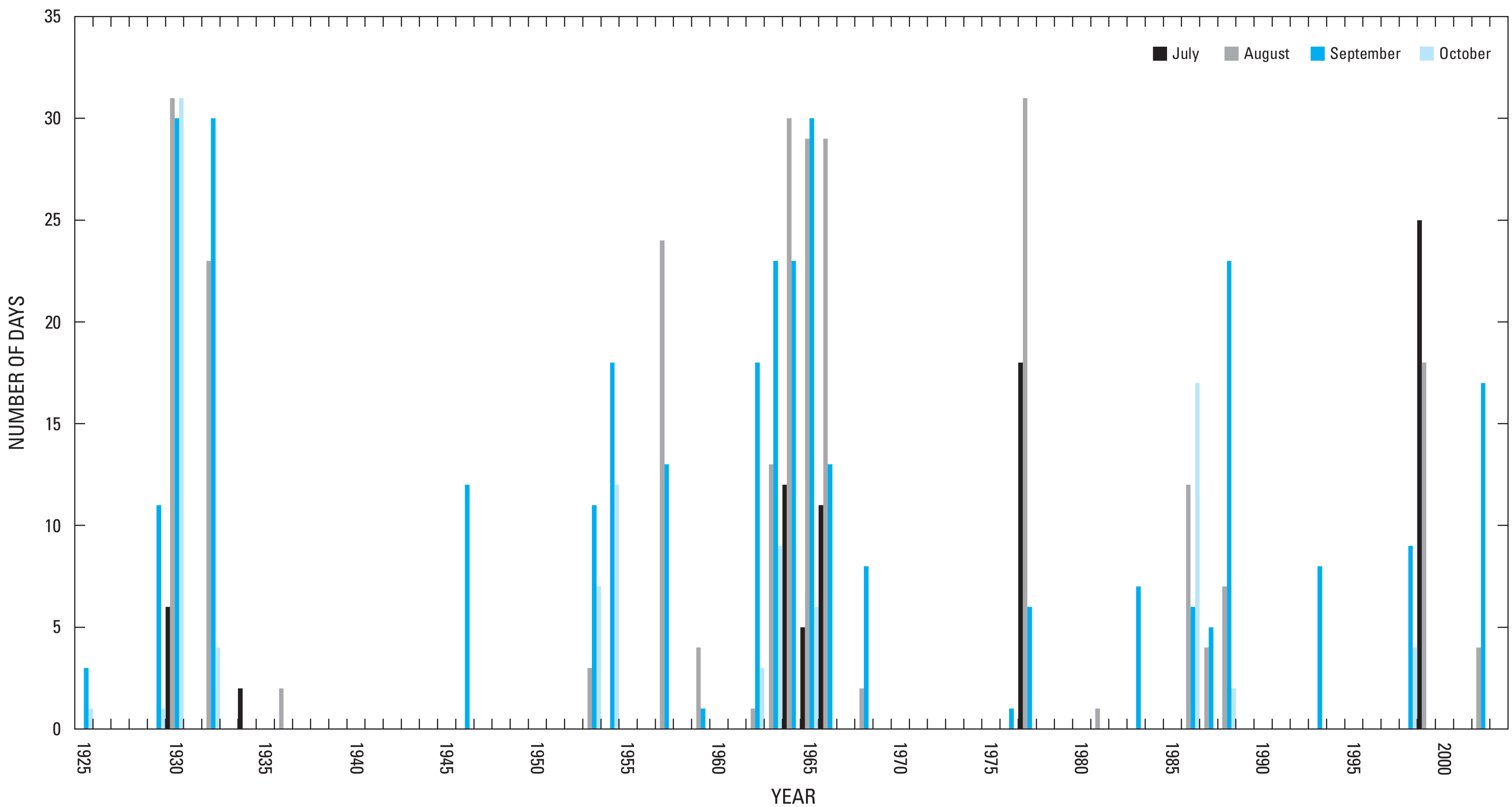

Figure 4. Number of days per summer month (July, August, September, and October) for the years 1995–2002 with streamflow values equal to or less than the 90-percent exceedance flow (1.6 cubic feet per second) for the Cootes Store streamflow-gaging station (01632000) on the North Fork Shenandoah River, Virginia.

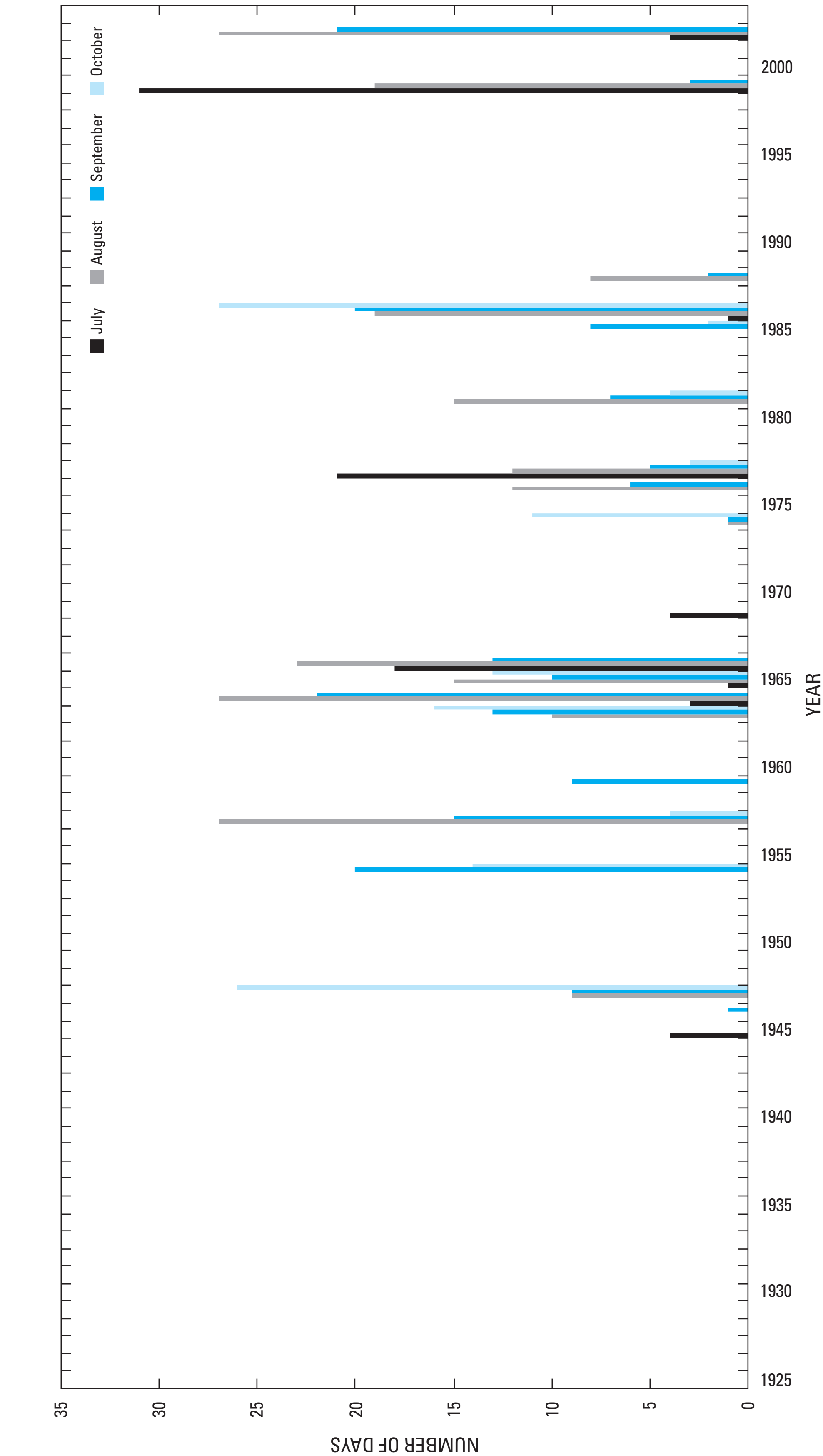

Figure 5. Number of days per summer month (July, August, September, and October) for the years 1943–2002 with streamflow values less than the 90-percent exceedance flow (30 cubic feet per second) for the Mount Jackson streamflow-gaging station (01633000) on the North Fork Shenandoah River, Virginia.

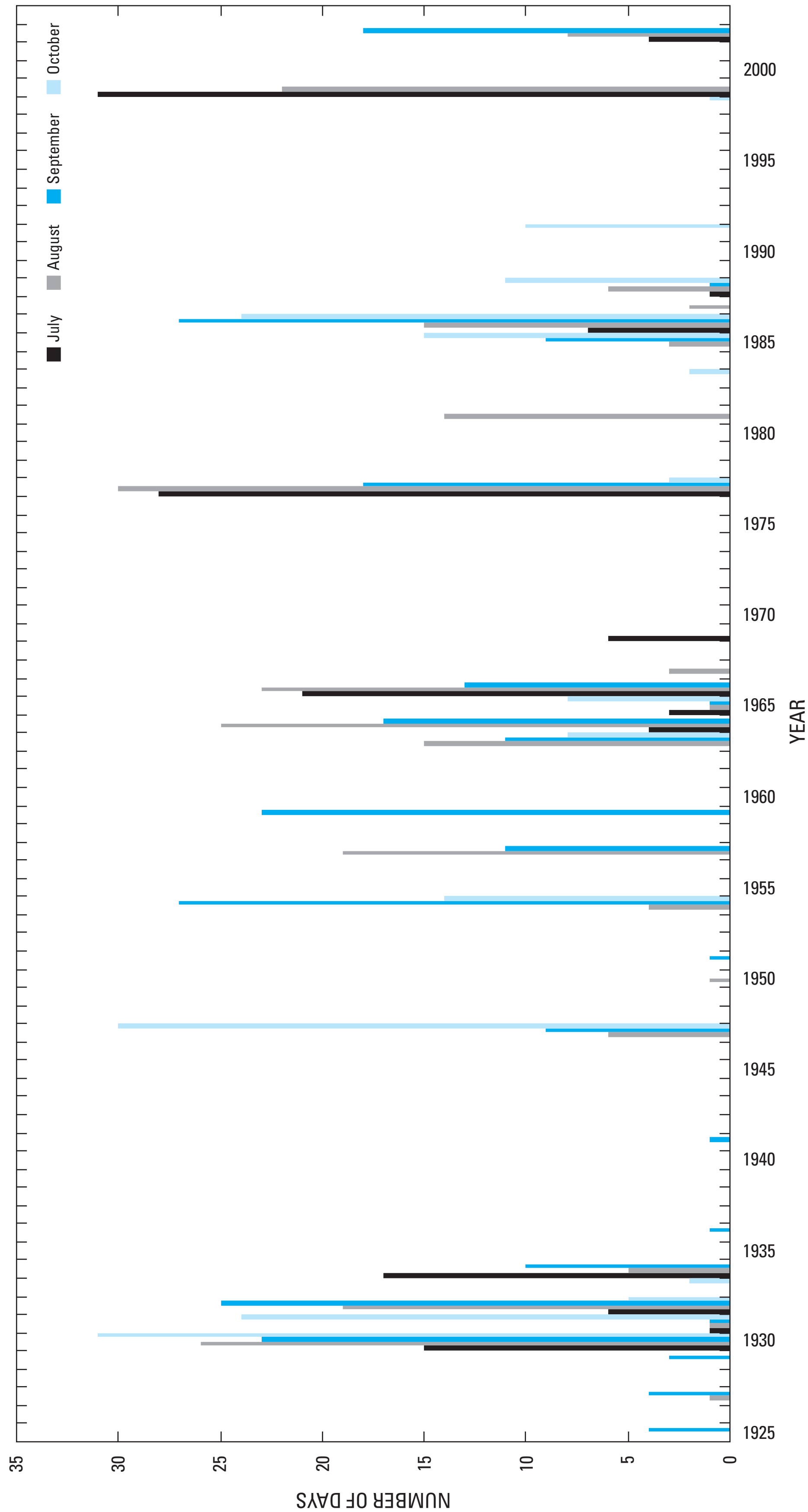

Figure 6. Number of days per summer month (July, August, September, and October) for the years 1925–2002 with streamflow values less than the 90-percent exceedance flow (87 cubic feet per second) for the Strasburg streamflow-gaging station (0163400) on the North Fork Shenandoah River, Virginia.

Table 4. The number of days flows were equal to or less than the 90-percent exceedance value for July, August, and September during dry years on the North Fork Shenandoah River, Virginia.

[n.d., no data, station was not in service during the year]

Year	July	Aug	Sept	3-month average	Percent of days
Cootes Store					
1930	6	31	30	22	72.0
1964	12	30	23	22	69.9
1965	5	29	30	21	68.8
1966	11	29	13	18	57.0
1999	25	18	0	14	46.2
2002	0	4	17	7	22.6
Mount Jackson					
1930	n. d.	n. d.	n. d.	n. d.	n. d.
1964	3	27	22	17	55.9
1965	1	15	10	9	28.0
1966	18	23	13	18	58.1
1999	31	19	3	18	57.0
2002	4	27	21	17	55.9
Strasburg					
1930	15	26	23	21	68.8
1964	4	25	17	15	49.5
1965	3	1	1	2	5.4
1966	21	23	13	19	61.3
1999	31	22	0	18	57.0
2002	4	8	18	10	32.3

Habitat Classification

Habitat classification on the North Fork Shenandoah River included data collection at three scales. Physical mesohabitat information at the scale of one river width was collected with mapping techniques in order to document variations in habitat from the headwaters to the mouth of the river. Site-specific transect data were collected at low, medium, and high flows to document variations of habitat with streamflow. Species-specific microhabitat use observations were made to document the instream conditions preferred by fish species on the North Fork Shenandoah River. When used together within the RHABSIM habitat modeling program, these data help in the determination of flows which provide suitable habitat for the fish of the North Fork Shenandoah River.

Mesohabitat Classification

Mesohabitats were classified and mapped to identify, describe, and quantify the mesohabitat types within the North Fork Shenandoah River. In this report, the term mesohabitat refers to a moderately large hydrogeomorphic habitat within a stream, such as a riffle, run, or pool, that has a relatively homogeneous channel shape and hydraulic characteristics and that behaves as a unit in response to changes in flow (Vadas, 1992; Vadas and Orth, 1998). Habitat data are collected primarily to document the relative quantity and quality of habitat availability for fish within a river (Simonson and others, 1993). Sharp changes in depth and (or) surface turbulence often delineate mesohabitat types (Vadas and Orth, 1998). The inventory of mesohabitats along the main stem of the North Fork Shenandoah River allowed for detailed hydrologic and fish community data collection to be prioritized within river reaches containing the predominant mesohabitat types, and assisted with weighting RHABSIM model transects to adequately simulate mesohabitat types in the river.

Methods

Mesohabitat mapping was conducted during low-flow periods between September 1998 and November 2002. During the data-collection period, flows ranged from 1.7 to 40 ft^3/s at Cootes Store, from 29 to 173 ft^3/s at Mount Jackson, and from 108 to 377 ft^3/s near Strasburg. Streamflow values during data collection ranged from the 50- to 95-percent annual exceedance values.

Mesohabitat mapping was conducted by canoe or on foot for the length of the North Fork Shenandoah River. As each change in mesohabitat type was encountered, the boundary location was recorded using a global positioning system (GPS) receiver. The mesohabitat type was noted, and mesohabitat length, average and maximum water depth, channel width, and bed substrate were measured or estimated visually. Mesohabitat length was estimated in the field (using the canoe as a scale reference) for mesohabitat less than 50 ft long, or measured with an infrared rangefinder (accuracy plus or minus 3 ft) or by using GPS-collected start and end points. As the canoe was paddled slowly through a habitat unit, water depth was measured with a surveyor's rod and channel width was measured with the infrared rangefinder. The predominant substrate type and particle size were estimated visually.

Mesohabitat was classified into three general categories-riffles, runs, and pools- which were further divided into two or more subcategories (Table 5). These categories are hierarchical and were developed based on lateral and hydraulic (depth-turbulence) characteristics that were visually assessed (after Vadas and Orth, 1998). Qualitative observations of water-surface gradient, water velocity, bed substrate type and size, and channel morphology were combined with depth measurements to classify each mesohabitat unit.

Table 5. Habitat type descriptions used for classification of mesohabitat on the North Fork Shenandoah River, Virginia.

Habitat type	Description
Riffle	Shallow rapids, with fast velocities, in an open stream where a turbulent water surface is created by obstructions that are wholly or partly submerged. Water depth is generally less than 1 foot deep.
Bedrock riffle	Formed by shallow water running over bedrock.
Particle riffle	Formed by a deposit of discrete particles such as boulders, small rocks (cobbles), gravel, and sand. Particle riffles are usually associated with islands or large channel bars.
Run	Swift moving areas characterized by predominantly smooth to slightly turbulent flow. The water surface is usually flat and is not broken by the substrate. Water depth is typically 1–4 feet deep.
Particle run	Formed by a gently sloping bed with a fairly consistent and uniform depth. Substrate is thin to thick deposits of cobbles, pebbles, gravel, and/or sand.
Bedrock run	Formed by a gently sloping bed with a fairly consistent and uniform depth. Substrate is bedrock with little silt or sand.
Pocket run	Characterized by shallow areas of bedrock interspersed with a mosaic of deeper holes or "pockets" that provide cover for fish. The pockets are more than 4 feet deep and generally 10–30 feet across. Pocket runs are distinguished from other runs in that they lack consistent and uniform depth. Pockets are encountered every 20 to 100 linear feet and found across the entire stream channel.
Pool	Areas with reduced or barely perceptible surface velocity, with a smooth, unbroken water surface. Water depth is greater than 4 feet deep.
Natural pool	Formed by a naturally occurring channel obstruction such as a bedrock control, island, large gravel bar, or a meander bend.
Artificial pool	Formed by an artificial channel obstruction such as a dam.
Backwater	Occurs along the edge of the channel. Backwaters are shallow pools that often occur on the downstream side of a large gravel bar or to one side of a mid-channel bar where water no longer flows around the bar.

The GPS-collected latitude and longitude coordinates were entered into a geographic information system (GIS) to create a GIS layer of mesohabitat boundary points. Short mesohabitat units (3-10 ft long) usually lacked GPS locations defining the beginning or end of the unit. Field notes were used to indicate where points should be added to complete the habitat boundary-point dataset. Points were added around meander bends and others were moved to mid channel to increase the accuracy of the length calculations. The adjusted GIS point layer was used to create a GIS line layer with accurate mesohabitat unit lengths and tabular information representing other measured parameters.

Results

Mesohabitat characteristics are reported for the upper, middle, and lower management sections of the North Fork Shenandoah River basin. For each mesohabitat type, the number of mesohabitat units, total length, percentage of the river length within the management section, and percent of the total river length are reported (table 6).

The habitat of the North Fork Shenandoah River is composed of 14.0 percent riffles, 67.3 percent runs, and 18.7 percent pools. Particle riffles are the most numerous riffle mesohabitat with 500 identified, followed by 155 bedrock riffles (table 6). The average length of particle and bedrock riffles is 114 ft and 143 ft respectively, but short riffles of about 3 ft in length are common. Most of the particle riffles are located along islands or narrow bends in the river. Particle runs are the most numerous run mesohabitat with 508 identified, followed by 256 bedrock runs, and 52 pocket runs (table 6). Most individual runs are greater than 300 ft in length, with average lengths of 344 ft, 765 ft, and 183 ft for particle, bedrock, and pocket runs, respectively. Natural pools are the most numerous pool mesohabitat with 102 identified, followed by 18 artificial pools, and 41 backwater areas (table 6). Where pools are present, they cover extensive sections of river, with average lengths of 559 ft, 2,083 ft, and 270 ft for natural pools, artificial pools, and backwater areas. Most artificial pools on the North Fork Shenandoah River are formed behind abandoned low bridges, and broken, small, low-head dams previously used to divert water to mill races for saw mills and grist mills during the late 1800's and early 1900's (Trout, 1997).

Substrate type and habitat-unit length differentiate the form and function of habitat between the upper, middle, and lower sections of the North Fork Shenandoah River. The upper section contains short mesohabitat units, with many repeating riffle, run, riffle sequences. Particle-substrate riffles and runs are most common. The source of the particle substrate is the siliceous rock from the headwater area that is transported great distances downstream from the source (Hack and Young, 1959). Although the river itself is flowing through a shale valley, the bedrock is soft relative to the sandstone coarse particulate substrate introduced from the tributaries. The shale bedrock is more easily eroded and broken up into small fragments that are carried away, resulting in a smaller percentage of shale particulate substrate on top of the bed relative to the sandstone substrate (Hack and Young, 1959).

The North Fork Shenandoah River receives flow from Smith Creek, Narrow Passage Creek, and Stony Creek in the middle section. Stony Creek marks the downstream end of the Seven Bends area, as the river transitions from the short, shallow mesohabitat units of the upper section into the longer mesohabitat units of the lower section. The upper and middle sections are covered primarily by cobbles and boulders. The middle management section is roughly half the total length of the upper section; however, the number of riffle habitat units (103) is one-fourth that of the upper section (406). The average length of an individual mesohabitat unit in the middle section is greater than the average length in the upper section, marking the transition between short, alternating sequences of riffles and runs to longer stretches of riffles and runs. Few pools or backwater mesohabitat units were identified in the middle section.

The lower section is the longest (50 mi), and contains long bedrock runs which frequently lead into artificial pools. In the meandering reaches of the lower section, the bed is mostly exposed bedrock (Hack and Young, 1959). There is less sandstone and other particle substrate on the bed in this section than in the upper or middle sections, which suggests that in the meandering reaches, greater energy has been expended in the excavation of rock by elongation of the channel than by the transportation of rock fragments (Hack and Young, 1959). The lower section of the North Fork Shenandoah River has seven artificial pools, which make up the longest individual mesohabitat units in this section and in the river (average 4,175 ft). The bedrock runs in this section are the second-longest individual mesohabitat units in the river (average 1,076 ft) and often lead up to the artificial pools.

Differences in the abundance and distribution of mesohabitat types from upstream to downstream can be seen by examining a plot of cumulative distribution of mesohabitat lengths (fig. 7). Particle riffles are more abundant than bedrock riffles throughout the river and especially within the upper and middle sections. Bedrock riffle mesohabitats are not abundant in the upper section, but increase in abundance in the middle and lower sections. Particle runs make up the greatest length of mesohabitat in the upper and middle sections, but are surpassed in length by bedrock runs in the lower section (fig. 7). The middle section is a transitional section between predominantly particle substrate in the upper section and bedrock substrate in the lower section. Natural pool mesohabitats are almost equally abundant in the upper, middle, and lower sections. Artificial pools have an irregular pattern of occurrence related to the presence of small dams along the river.

Table 6. Results of the mesohabitat classification and mapping for three management sections of the North Fork Shenandoah River, Virginia.

Habitat type	Upper section				Middle section				Lower section				Entire river			
	Number of units	Unit average length (feet)	Total length (miles)	Percentage of section	Number of units	Unit average length (feet)	Total length (miles)	Percentage of section	Number of units	Unit average length (feet)	Total length (miles)	Percentage of section	Number of units	Unit average length (feet)	Total length (miles)	Percentage of entire river
Particle riffle	354	96.9	6.5	18.5	71	111.5	1.5	12.3	75	197.1	2.8	11.1	500	114.0	10.8	14.0
Bedrock riffle	52	71.1	0.7		32	115.5	0.7		71	208.2	2.8		155	143.1	4.2	
Particle run	356	280.3	18.9		81	417.2	6.4		71	587.5	7.9		508	344.0	33.1	
Bedrock run	84	289.1	4.6	64.0	41	746.9	5.8	69.5	131	1,076.2	26.7	69.1	256	765.2	37.1	67.3
Pocket run	17	496.9	1.6		9	29.3	.05		26	20.3	0.1		52	182.8	1.8	
Natural pool	59	429.6	4.8		25	443.5	2.1		18	1,144.0	3.9		102	559.1	10.8	
Artificial pool	7	678.9	.9	17.5	4	924.0	.7	18.2	7	4,148.6	5.5	19.8	18	2,082.7	7.1	18.7
Backwater	25	253.4	1.2		8	264.0	.4		8	330.0	.5		41	270.4	2.1	
Totals	954	207,504[1]	39.3	100.0	271	92,928[1]	17.6	100.0	407	264,528[1]	50.1	100.0	1,632	564,960[1]	107.0	100.0

[1]Total length in feet within the section.

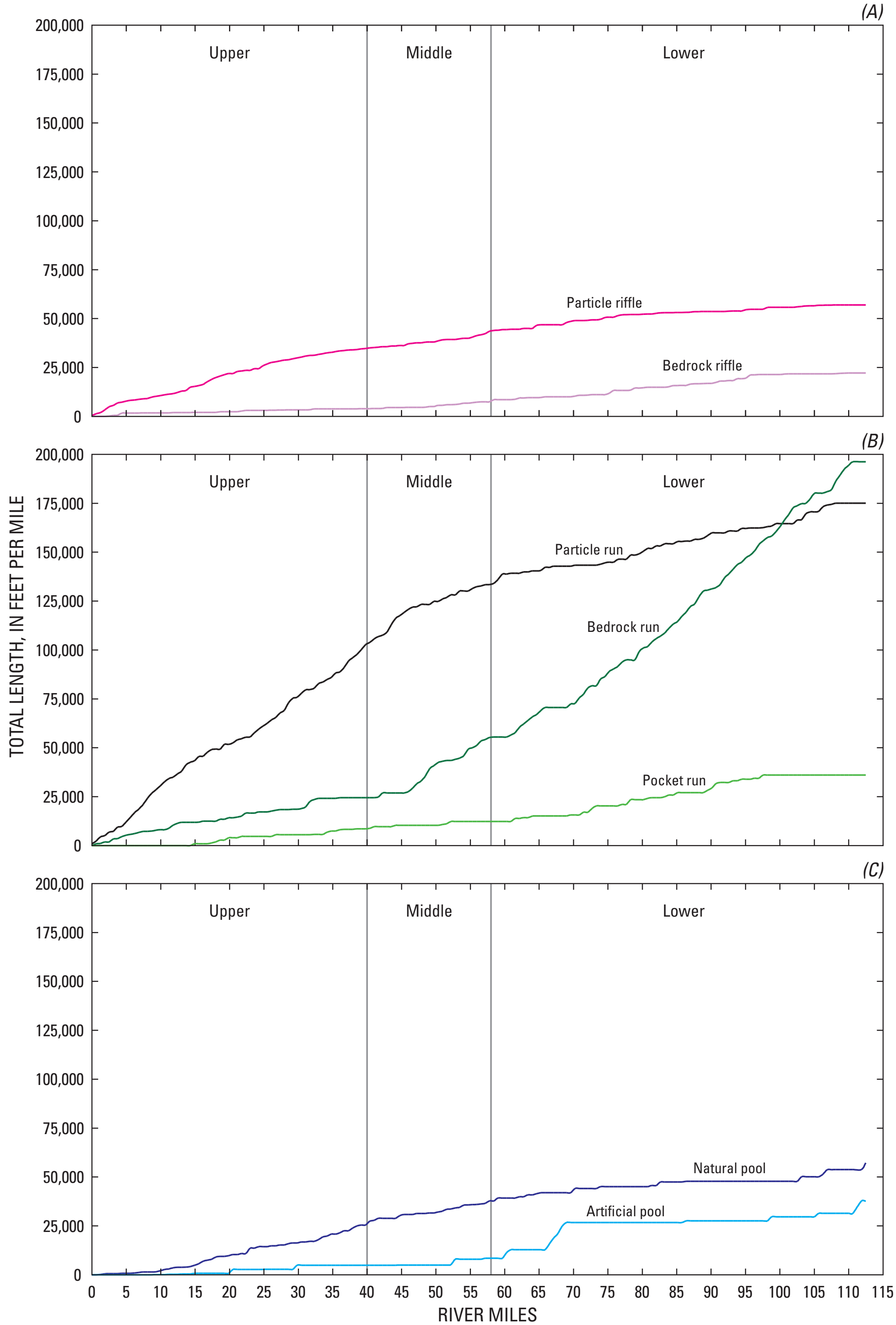

Figure 7. Cumulative length of riffle *(A)*, run *(B)*, and pool *(C)* mesohabitat types in the upper, middle, and lower management sections of the North Fork Shenandoah River, Virginia. River mile zero represents the confluence of smaller tributaries to form the headwaters of the North Fork Shenandoah River.

Hydraulic Data Collection in the Predominant Mesohabitat Types

Hydraulic data were used during model calibration and simulation to develop relations between water-surface elevation and discharge, and between water velocity and discharge. Data were collected on the North Fork Shenandoah River between April 1999 and November 2002.

Selection of Reaches

Six river reaches were selected for collection of hydraulic data on the North Fork Shenandoah River between Cootes Store, Va., and the confluence with Passage Creek. The reaches are referred to by place names of nearby features, and listed in order from upstream to downstream: Plains Mill, Laurel Hill Farms, Spring Hollow, Posey Hollow, Route 648, and Winchester Dam (fig. 2 and table 7). The predominant mesohabitat types in the river are represented in the reaches. The original scope of the project focused on the Seven Bends area of the North Fork Shenandoah River; therefore, five of the six reaches are in the northern end of the basin, in the middle and lower sections of the river. As the study progressed, the Plains Mill reach near Cootes Store, Va. was added to incorporate the upper section of the North Fork Shenandoah River (fig. 2).

Description of Reaches and Transects

Study reaches varied in length from 150 ft to 2000 ft, and in width from 100 ft to 200 ft. All reaches contained one or more mesohabitats, and three to eight semipermanent transects (following Bovee, 1997) (table 8). Transects were placed in sections of the river where the mesohabitat was homogeneous across the channel. Most reaches began with a downstream hydraulic control or riffle. The right bank and left bank were designated when looking downstream, with the right bank designated headpin and left bank designated tailpin in most cases. The ends of each transect were marked with rebar and labeled with numbered metal tags. Transects were extended out onto the floodplain to a level greater than bankfull. Verticals used in velocity, depth, and substrate measurements were spaced equally along each transect at constant intervals of either 3, 4, or 5 ft based upon the width of the river (following Bovee, 1997).

Standard PHABSIM data collection procedures (Bovee, 1997) were used to collect channel and floodplain topographic information for the model. Horizontal and vertical surveys of benchmarks, transect headpin and tailpin elevations, and channel features were conducted with a surveying level or a total station. The surveys provided information such as distance between transects, water-surface slope, bed-elevation profiles, stage-zero-flow elevation, water depths, and benchmark locations and elevations. The benchmarks used for the transect headpin and tailpin elevation surveys also served as benchmarks for water-surface elevation (WSL) measurements during hydraulic data collection.

Hydraulic Data Collection Methods

Hydraulic measurements were made in riffles, runs, and pools with a variety of substrates and cover types between April 1999 and November 2002. Each reach was visited a minimum of three times during hydraulic data collection to measure WSL, water depths, water velocities, transect discharges, and a best-estimate reach discharge during low-, medium,- and high-flow conditions. Hydraulic data collection was completed during wadeable flows, so the measurements are most reliable for low to normal flows. Some of the best-estimate discharges measured during the hydraulic data collection were close in value, but the range of flows measured for each reach were wide enough to develop a stage-discharge rating for the modeled flows. The best-estimate discharges measured for each reach were used as calibration discharges for the modeling phase of this research (table 9).

Table 7. Locations of river reaches studied during hydraulic data collection on the North Fork Shenandoah River, Virginia.

[Location information for the partial record station at each study reach (White and others, 2002). Reaches are presented in upstream to downstream order; DMS, degrees minutes seconds; NAD27, North American datum of 1927.]

Reach name	Station number	Latitude DMS (NAD27)	Longitude DMS (NAD27)
Plains Mill	01632530	38 38 56 W	78 42 25 N
Laurel Hill Farms	01633575	38 50 12 W	78 31 39 N
Spring Hollow	01633640	38 53 12 W	78 28 46 N
Posey Hollow	01633800	38 56 28 W	78 23 09 N
Route 648	01633820	38 57 15 W	78 23 03 N
Winchester Dam	01635210	38 58 52 W	78 17 25 N

Table 8. Mesohabitat types represented by transects in the hydraulic data-collection reaches on the North Fork Shenandoah River, Virginia.

[Transects are numbered in downstream to upstream order, beginning with number 1.]

Transect ID	Habitat type	Transect ID	Habitat type	Transect ID	Habitat type
Laurel Hill Farms		Spring Hollow		Posey Hollow	
5	Particle riffle	5	Particle riffle	5	Pocket run
4	Particle riffle	4	Particle riffle	4	Bedrock run
3	Particle run	3	Particle riffle	3	Bedrock run
2	Particle run	2	Particle riffle	2	Pocket run
1	Particle run	1	Particle run	1	Bedrock riffle
Plains Mill		Route 648		Winchester Dam	
7	Particle run	8	Bedrock run	3	Artificial pool
6	Particle run	7	Pocket run	2	Artificial pool
5	Particle run	6	Pocket run	1	Artificial pool
4	Natural pool	5	Bedrock run		
3B	Natural pool	4	Pocket run		
3A	Particle run	3	Pocket run		
3	Particle riffle	2	Bedrock run		
2	Natural pool	1	Bedrock riffle		
1A	Particle run				

Table 9. Best-estimate calibration discharges for each hydraulic data-collection reach on the North Fork Shenandoah River, Virginia.

[Within each category (low, medium, and high) if more than one discharge is listed, data collection occured over multiple days. Transect data are represented by different discharges; ft^3/s, cubic feet per second]

Hydraulic Reach	Calibration discharge (ft^3/s)		
	Low	Medium	High
Plains Mill	22.5	109, 121	264, 308, 379, 438
Laurel Hill Farms	93.8	120	400
Spring Hollow	94.4	126	432
Posey Hollow	122	219	666
Route 648	83.34, 86.98	136	444, 526
Winchester Dam	195, 218	654, 696	1,430

For each day of data collection, WSLs were measured along one bank at each transect headpin or tailpin before and after data collection. WSLs were determined with a surveying level to the nearest 0.001 ft from a designated benchmark. A tagline was stretched across a transect, and water depths and velocities were recorded at the specified verticals for the reach. Velocity measurements were made using Price AA and Pygmy meters (to the nearest 0.01 ft/sec), or an electromagnetic flow-meter (to the nearest 0.1 ft/sec) mounted on a top-setting wading rod or hand line. Depth and velocity measurements followed USGS procedures for discharge measurements (Buchanan and Somers, 1969), except that the spacing between velocity readings, or verticals, was constant. Depth and velocity measurements from one transect per reach were used to calculate the best-estimate reach discharge. For reaches that did not have a transect suitable for discharge measurements, a discharge measurement was made downstream of the reach. Although complete hydraulic data collection could not always be accomplished at all transects at a reach in a single day, WSLs were measured for all transects in the reach.

Fish-Community Sampling and Microhabitat Observations

Typically, IFIM studies examine one or two species of importance and develop relations between the species habitat needs and discharge; these relations can then be used in the management of water levels in the stream. For the IFIM process to provide the most useful information on habitat for the North Fork Shenandoah River, which has a diverse fish community, all resident fish species and life stages need to be considered (Orth, 1987; Braaten and Berry, 1997; Persinger, 2003). In an effort to represent all species, but not model each species individually, fish were grouped into guilds (Vadas and Orth, 2000) for development of HSC. A fish guild is a group of fish or life stages that use microhabitats in a similar way. The combined abundance of species in a guild can reflect changes in limiting factors (Austin and others, 1994). For example, the combined abundance of riffle guild fish may be low if a limiting factor, such as water depth, has been lower than suitable for an extended period of time.

Community Sampling

Species composition and abundance on the North Fork Shenandoah River were described to document the fish and habitats utilized along the river. This portion of the study was conducted by VPI faculty, staff, and students from the Department of Fisheries and Wildlife during the summers of 2001 and 2002. Fish sampling was conducted at seven locations on the North Fork Shenandoah River, of which five also were used as hydraulic data collection sites (Persinger, 2003). Fish were sampled primarily by use of throwable anode electrofishing and underwater observation done by snorkeling during wadeable flows.

Thirty-seven species were identified and grouped into four guilds (Persinger, 2003) (table 10). Fish species and life stages were classified as members of the riffle guild, fast-generalist guild, pool-run guild, or pool-cover guild following guild structure adapted from Vadas and Orth (2000) (Persinger, 2003). The four guilds are organized along a continuum of habitat preference from fish preferring shallow depths with fast velocities, to deep depths with slow velocities. The riffle guild includes species of life stages that live in sections of the river with shallow depths and fast velocities. The fast-generalist guild includes species and life stages that live in sections with shallow to moderate depths and fast velocities. The fish in this group overlap in their velocity preferences with the riffle guild fish, and overlap in their depth preferences with the pool-run and pool-cover guilds. The pool-run guild includes species and life stages that prefer deeper depths with moderate velocities. The pool-cover guild includes species and life stages that prefer the lowest velocities and deepest depths, and generally utilize cover objects when present. Five species were considered members of more than one guild, depending upon the life stage of the fish (Persinger, 2003). For example, the spotfin shiner (*Cyprinella spiloptera*) was a member of the pool-cover guild during its juvenile and young-of-year life stages, but was a member of the fast-generalist guild as an adult (Persinger, 2003).

Microhabitat Observations

The physical microhabitat parameters of water depth, water velocity, and substrate type were measured at each location where a fish was observed. These parameters were arithmetically combined to describe the physical habitat conditions used by species of various life stages in the river. Depth was measured with a wading rod (to the nearest 0.10 ft). Water velocity was measured with an electromagnetic flow meter (to the nearest 0.10 ft/sec). Substrate within a 1-m^2 area around each fish observation location was assessed by assigning a channel index value–a composite measure of dominant substrate, subdominant substrate, embeddedness, and all cover items. Individual channel indexes were computed based on each substrate evaluation using a modified Wentworth classification scheme (Trihey and Wegner, 1981; Platts and others, 1983; Newcomb, 1992; Bovee, 1997). Substrate variables were recorded using a system of codes and quartiles and summarized as one number, the channel index (tables 11–13). For example, a location observed to have a dominant substrate of small cobble, subdominant substrate of large gravel, cover of a root wad and small-velocity shelter, and embeddedness of 10 percent would be coded as 08; 07; 08, 02; 1. The suite of codes was simplified to a 3-part numerical code, or channel index, based on dominant substrate (table 11), cover presence (0.1) or absence (0.0) (table 12), and embeddedness (quartile 1 = 0.01, quartile 2 = 0.02, quartile 3 = 0.03, quartile 4 = 0.04) (table 13). For the previous example, the computed channel index would be 8.11.

Table 10. Species and guild classification for fish identified in the North Fork Shenandoah River.

[Table modified from Persinger, 2003; J, juvenile; Y, young-of-year; A, Adult]

Species	Scientific name
Riffle guild	
Greenside darter	Etheostoma blennioides
Mottled sculpin	Cottus bairdi
Central stoneroller	Campostoma anomalum
Bluehead chub (J)	Nocomis leptocephalus
River chub (Y)	Nocomis micropogon
Longnose dace	Rhinichthys cataractae
Fast-generalist guild	
Potomac sculpin	Cottus girardi
Margined madtom	Noturus insignis
Roseyface shiner	Notropis rubellus
Comely shiner	Notropis amoenus
Satinfin shiner (A)	Cyprinella analostana
Spotfin shiner (A)	Cyprinella spiloptera
Bluehead chub (A)	Nocomis leptocephalus
Bull chub	Nocomis raneyi
Fallfish (J&Y)	Semotilus corporalis
Blacknose dace	Rhinichthys atrastulus
Pool-run guild	
Tessellated darter	Etheostoma olmstedi
Common shiner	Luxilus cornutus
River chub (A&J)	Nocomis micropogon
Fallfish (A)	Semotilus corporalis
Cutlips minnow	Exoglossum maxillingua
Rosyside dace	Clinostomus funduloides
Green sunfish (A&J)	Lepomis cyanellus
White sucker	Catostomus commersoni
Northern hog sucker	Hypentelium nigricans
Pool-cover guild	
Banded killifish	Fundulus diaphanus
Swallowtail shiner	Notropis procne
Spottail shiner	Notropis hudsonius
Satinfin shiner (J&Y)	Cyprinella analostana
Spotfin shiner (J&Y)	Cyprinella spiloptera
Bluehead chub (Y)	Nocomis leptocephalus
Bluntnose minnow (A)	Pimephales notatus
Bluntnose minnow (J&Y)	Pimephales notatus
Common carp	Cyprinus carpio
Green sunfish (Y)	Lepomis cyanellus
Pumpkinseed	Lepomis gibbosus
Bluegill	Lepomis macrochirus
Redbreast sunfish (A&J)	Lepomis auritus
Redbreast sunfish (Y)	Lepomis auritus
Largemouth bass	Micropterus salmoides
Smallmouth bass (A&J)	Micropterus dolomieu
Smallmouth bass (Y)	Micropterus dolomieu
Rock bass (A&J)	Ambloplites rupestris
Rock bass (Y)	Ambloplites rupestris
Brown bullhead	Ameiurus nebulosus
Yellow bullhead (A)	Ameiurus natalis
Yellow bullhead (J&Y)	Ameiurus natalis
Channel catfish	Ictalurus punctatus
American eel	Anguilla rostrata

Table 11. Substrate codes used to classify the dominant and subdominant substrate within fish study reaches and hydraulic data-collection transects on the North Fork Shenandoah River, Virginia.

[cm, centimeters; n.a., not applicable; <, less than; >, greater than]

Code[1]	Description	Sizes (cm)
01	Organic detritus	n.a.
02	Vegetation	n.a.
03	Silt	< 0.006
04	Sand	0.006–0.2
05	Small gravel	0.2–0.8
06	Medium gravel	0.9–2.5
07	Large gravel	2.6–5.1
08	Small cobble	5.2–12.8
09	Large cobble	12.9–25.6
10	Small boulder	25.7–51.2
11	Large boulder	> 51.2
12	Flat bedrock	n.a.
13	Tilted bedrock	n.a.

[1] From Trihey and Wegner, 1981; Platts and others, 1983; Newcomb, 1992; and Bovee, 1997.

Table 12. Codes used to describe the cover found around a fish observation site and within hydraulic data-collection transects on the North Fork Shenandoah River, Virginia.

[cm, centimeters; >, greater than]

Code[1]	Description
01	No cover
02	Small-velocity shelter (12.9–25.6 cm)
03	Medium-velocity shelter (25.7–51.2 cm)
04	Large-velocity shelter (> 51.2 cm)
05	Dense cluster of small sticks
06	Undercut boulder or log that provides overhead cover
07	Log jam
08	Root wad
09	8.0–25.0-cm logs
10	Weed bed / Submerged aquatic vegetation
11	Bedrock formation
12	Complex cover

[1] From Trihey and Wegner, 1981; Platts and others, 1983; Newcomb, 1992; and Bovee, 1997.

Table 13. Codes used to classify the percentage of fine particulate matter within a one square-meter area around a fish observation site, and within hydraulic data-collection transects on the North Fork Shenandoah River, Virginia.

[Fine particulate matter is defined as sand, silt and detritus.]

Code[1]	Fine particulate matter (Percent)	Description
1	0–25	Very few fines visible. If present, occur in very large interstitial spaces between large particles.
2	25–50	Fines present, filling large interstitial spaces. Few fines in smaller interstitial spaces.
3	50–75	Small particle interstitial spaces completely filled. Indistinct large particle boundaries.
4	75–100	Large and small materials nearly submerged in fines. Appears as sand bed with a few big rocks.

[1] From Trihey and Wegner, 1981; Platts and others, 1983; Newcomb, 1992; and Bovee, 1997.

Substrate variables for computing channel index values also were measured at each vertical along all transects of the six hydraulic data-collection reaches. The channel index values describe the study reach substrate, and are used as input for the North Fork Shenandoah River RHABSIM model.

Development of Fish Habitat-Suitability Curves

HSC are interpreted using a suitability index, or rank, on a scale of 0–1, where 1 is the most utilized or preferred habitat. HSC developed in this study are river-specific to fish in the North Fork Shenandoah River, and are most appropriate when used for studies of that river. The development of fish HSC was based primarily on detailed fish-community sampling, habitat observations, and analysis of collected data. The HSC curves represent the variables used to represent the microhabitat suitable for fish within the North Fork Shenandoah River, and were used in the modeling phase of this research.

For the fish within the four fish guilds described, the measurements of water depth, water velocity, and channel index for each species were placed into suitability ranks based on the nonparametric tolerance limits (Murphy, 1948; Somerville, 1958; Slauson, 1988) for the central 50 percent, 75 percent, and 90 percent of the data collected (Persinger, 2003). For example, for all the fish within one guild, the depths that represent the tolerance limits for the central 50 percent were ranked as 100-percent suitable, and received a value of 1. The depths that represent the tolerance limits for the central 75 percent were ranked as 50-percent suitable, and received a value of 0.5. Those which represent the tolerance limits for the central 90 percent were used to establish the cutoff between suitable and unsuitable habitat, and received a rank of 0.2.

The ranked habitat measures were summarized for each guild and used to create HSC for water depth, water velocity, and channel index for each fish guild (Persinger, 2003) (figs. 8–10). The fish sampling was completed during wadeable flows, so the habitat measures are most reliable for low to normal flows. Fish observations were not made in reaches that had water depths greater than 4 ft; therefore, the dataset used to create the fish HSC was not completely representative of the range of pool habitats found during the mesohabitat mapping. Consequently, the pool-cover guild depth-suitability curve developed by Persinger (2003) was altered for use in the modeling phase of this research so that all water depths greater than 4 ft were 100-percent suitable. No other alterations to the fish HSC were made.

Canoeing Suitability Curves

In addition to the fish HSC, depths and velocities suitable for recreation on the North Fork Shenandoah River were evaluated. HSC for canoeing were based only on water depths and velocities appropriate for canoeing (figs. 8-10) (Zappia and Hayes, 1998). Substrate or channel index was assumed 100-percent suitable for all substrates (fig. 10).

Instream Flow Modeling to Determine Fish Habitat Availability

The program RHABSIM 2.0 for DOS and Windows (Thomas R. Payne and Associates, 1998) was used for calibration and simulation of flow and habitat. The RHABSIM modeling process includes two calibration phases and three simulation phases. The WSL and velocity calibrations are completed first, followed by WSL, velocity, and habitat simulations. Calibration and simulation phases were performed separately for each reach, then habitat simulation results were combined for each of the three river management sections.

Model Calibration

The RHABSIM model calibration involves the datasets collected during the hydraulic data collection portion of the study. Calibration involves inputting topographic information for each study reach, WSLs, velocities, and discharge data for each hydraulic data-collection reach. The transect data is used to calculate stage-discharge ratings to enable simulation of depths and velocities for flows not measured during hydraulic data collection.

Inputs

For each reach and transect, the topographic elevation information derived from the horizontal and vertical surveys was input to the model as X, Y, Z coordinates. The X-value represents the distance along a transect from the headpin to the measurement vertical. The Y-value represents the distance upstream from the first transect. The most downstream transect has a Y-value of 0. The Z-value represents depth, and is calculated within the model from the bed elevation and WSL. Each X, Y, Z coordinate represents the middle point of one model cell for which a channel index value and three velocities were measured (appendix 1). The model cells within a transect represent an area half the distance to the next vertical in both directions, and a specified distance upstream and downstream of the transect.

In addition to cross-section elevation profiles for each transect, the model requires WSLs measured for each calibration discharge, average water-surface slope, and stage of zero flow (SZF) (appendix 1). Three best-estimate discharge measurements for each reach were used as calibration discharges in the RHABSIM model (table 9).

Water-Surface Elevation Calibration

Three WSL calibration models are available through RHABSIM: step backwater, or water-surface profile (WSP), channel conveyance, or Manning stage-discharge (MANSQ), and log-log regression, regression of the log of the SZF and log of the best-estimate discharge (Thomas R. Payne and

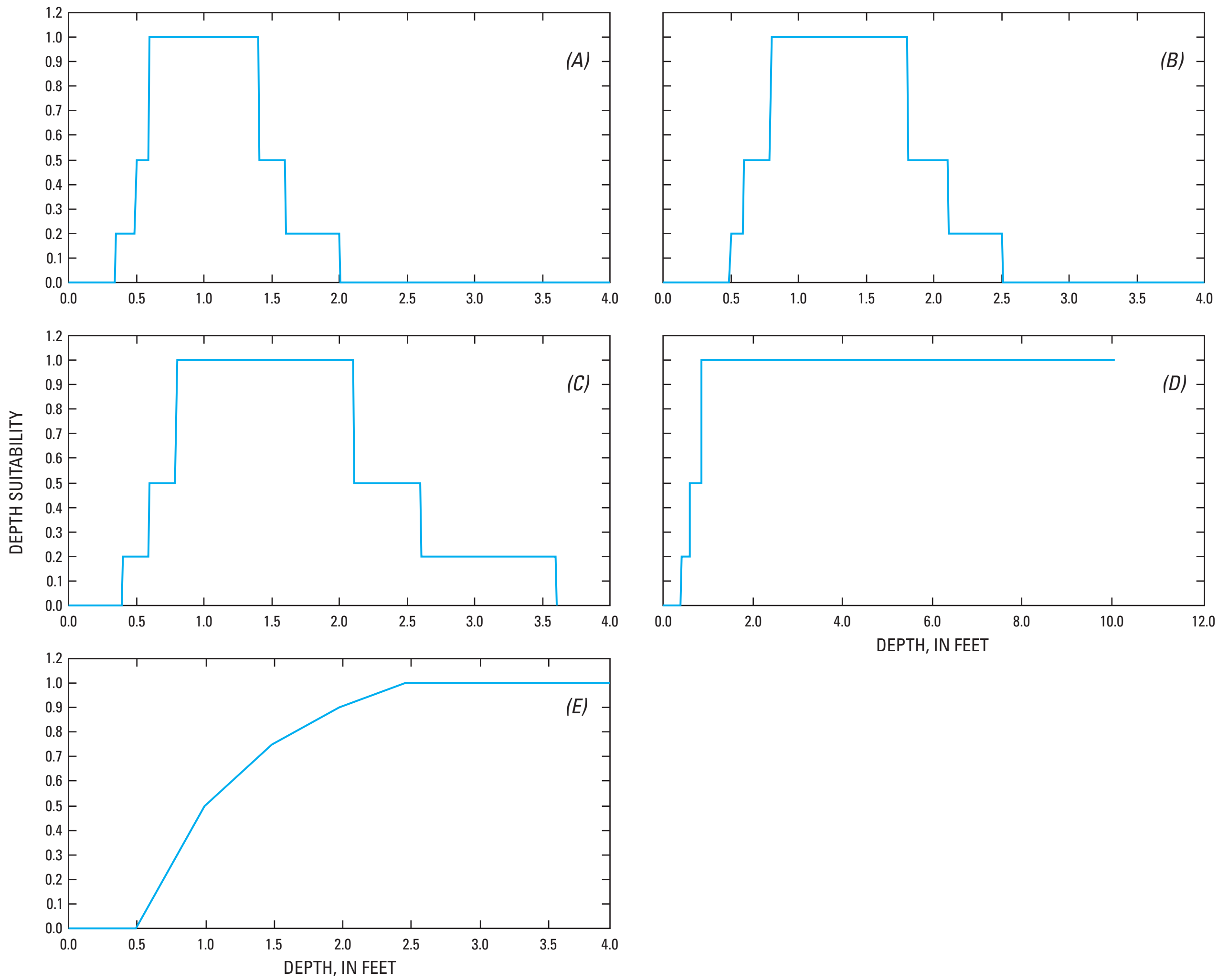

Figure 8. Fish habitat depth-suitability curves for riffle *(A)*, fast-generalist *(B)*, pool-run *(C)*, and pool-cover guilds *(D)*, and canoeing habitat depth-suitability curve *(E)* for the North Fork Shenandoah River, Virginia. Fish habitat suitability curves based on data from Persinger, 2003.

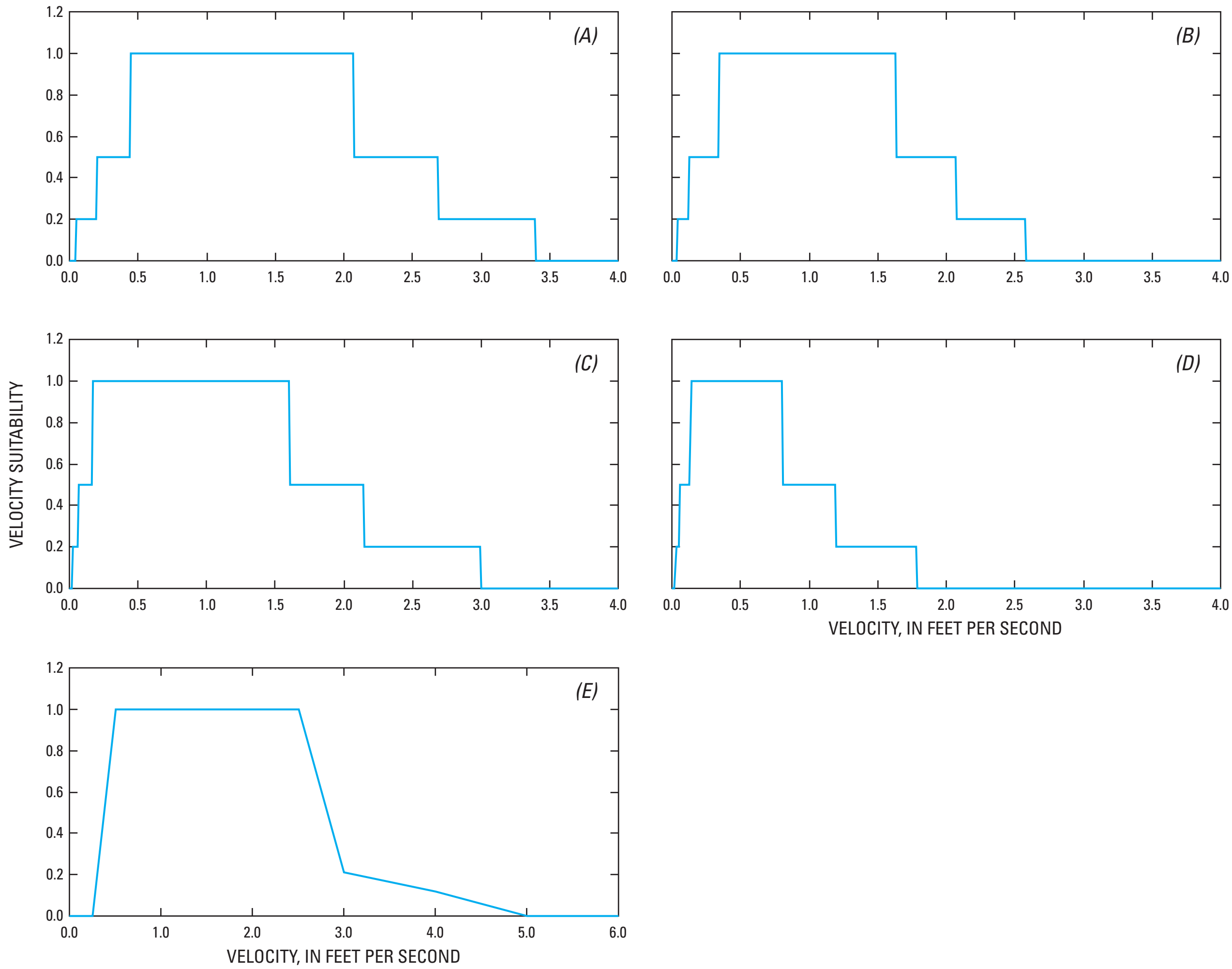

Figure 9. Fish habitat velocity-suitability curves for riffle *(A)*, fast-generalist *(B)*, pool-run *(C)*, and pool-cover guilds *(D)*, and canoeing habitat velocity-suitability curve *(E)* for the North Fork Shenandoah River, Virginia. Fish habitat suitability curves based on data from Persinger, 2003.

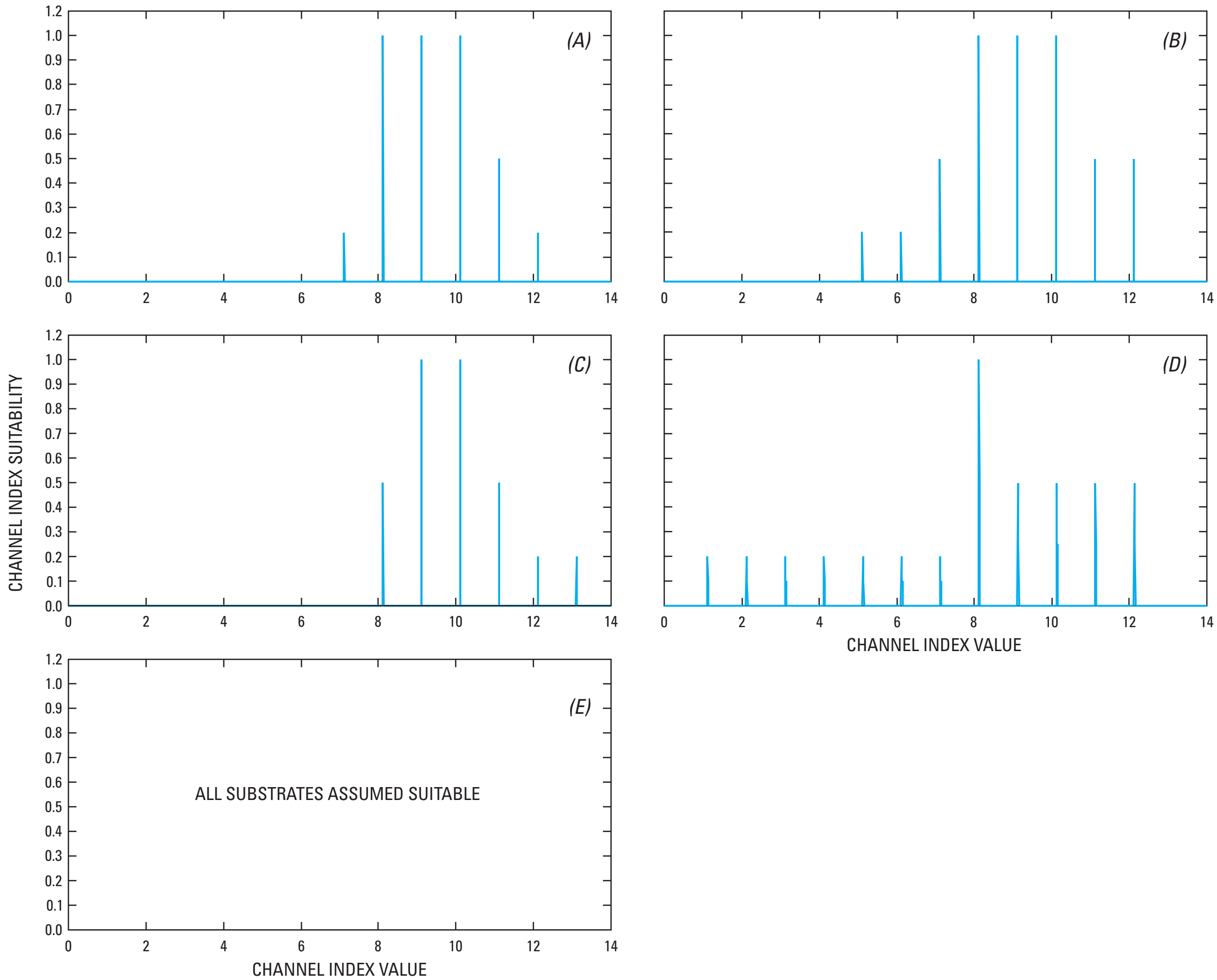

Figure 10. Fish habitat channel index-suitability curves for riffle *(A)*, fast-generalist *(B)*, pool-run *(C)*, and pool-cover fish guilds *(D)*, and canoeing habitat channel index-suitability curve *(E)* for the North Fork Shenandoah River, Virginia. Fish habitat suitability curves based on data from Persinger, 2003.

Associates, 1998; U.S. Geological Survey, 2001). WSL models were selected for each reach based on reach habitat conditions and hydraulic properties (table 14). Each model used the measured (observed) WSL, calibration discharges, and n-values or beta-values (as specified by the particular model) to produce a simulated WSL. The model calibration was an iterative process, with new n-values or beta-values selected to minimize the difference between the observed and simulated WSL (U.S. Geological Survey, 2001). For most transects, the difference between observed and simulated WSL was less than 0.05 ft (appendix 1). When the differences were as great as 0.08 ft, transects were located within riffle habitats with steep water-surface slopes, or along steep streambanks where WSL measurements were difficult.

When the WSL model calibration parameters were finalized and the WSLs had been simulated for the calibration discharges, the model was used to simulate WSLs for a set of 30 discharges representative of the flows within each management section of the river (table 15). The model simulation flows were corrected for drainage area differences between the hydraulic data-collection reach and the station with which it is associated (table 16). For example, at Route 648, the drainage area is 3.7 percent less than the drainage area at the Strasburg station; therefore, to represent 300 ft^3/s discharge at the Strasburg station, an equivalent discharge of 289 ft^3/s was simulated in the RHABSIM model.

Velocity Calibration

Three methods are available within RHABSIM for velocity calibration: 1-velocity, regression, or depth. Various velocity calibrations and simulations were run to compare observed and simulated velocities, with the 1-velocity method selected for all reaches and transects. The velocity dataset that produced the least difference between the best-estimate discharge and model-calculated discharge was selected as the primary dataset to calibrate the velocity model (table 17). The selected dataset was generally the velocity dataset for the highest calibration discharge. The velocity model calculates a transect discharge using observed velocities and calculated depths from the difference between the WSL and channel bed elevations. The transect discharge is compared with calibration discharges for the reach to obtain velocity adjustment factors (VAF). VAF are used to simulate velocity for the 30 simulation flows.

Habitat Simulation and Development of Weighted Usable-Habitat Area Curves

The WSL and velocity simulations and the fish and canoeing HSC were input to the Habitat Simulation Model (HABSIM) (Thomas R. Payne and Associates, 1998). HABSIM calculates a composite suitability index (SI) for each model cell by evaluating the simulated attributes (water depths, water velocities, and channel index values) against the HSC (U.S. Geological Survey, 2001). Multiplicative aggregation (U.S. Geological Survey, 2001) was used to calculate the SI for each cell. SI for all cells within a reach were summed for a total weighted usable-habitat area (WUA). The process was repeated for each guild and canoeing over 30 simulation flows, and a functional relation between habitat and discharge was defined and expressed in the form of WUA curves.

As with the mesohabitat classification, the North Fork Shenandoah River basin was divided into upper, middle, and lower sections that are associated with the streamflow-gaging stations (Cootes Store, Mount Jackson, Strasburg) near the downstream end of each section. From one station to the next downstream, the drainage area for each station more than doubles (table 1) (U.S. Geological Survey, 2003). The median annual exceedance flows increase approximately two-fold from one station to the next downstream (61 ft^3/s, 182 ft^3/s, and 310 ft^3/s for the Cootes Store, Mount Jackson, and Strasburg stations, respectively). The distance between stream-

Table 14. Water-surface calibration method used in RHABSIM for each hydraulic data-collection reach on the North Fork Shenandoah River, Virginia.

[When two methods are listed, one method was used for the first transect and another method was used for the rest of the transects. RHABSIM, River Habitat Simulation Model; WSL, water-surface elevation; ft^3/s, cubic feet per second; WSP, water-surface profile method; MANSQ, Manning stage-discharge method; Log-log regression, regression of the log of the stage zero flow and log of the best-estimate discharge]

Hydraulic Reach	WSL calibration method[1]	Calibration discharge (ft3/s)
Plains Mill	Log-log regression	all
Laurel Hill Farms	MANSQ	400
Spring Hollow	MANSQ	432
Posey Hollow	Log-log regression cross section 1, WSP	666
Route 648	Log-log regression cross section 1, WSP	86.98
Winchester Dam	Log-log regression cross section 1, WSP	218

[1] Thomas R. Payne and Associates, 1998.

Table 15. Simulation flows for the hydraulic data-collection reaches in the upper, middle, and lower management sections of the North Fork Shenandoah River, Virginia

[Equivalent flow, flow at each reach that was adjusted by drainage area to represent flow at the station; Bold values represent calibration discharges; ft³/s, cubic feet per second.]

Upper management section		Middle management section		Lower management section				
Cootes Store	Plains Mill	Mount Jackson	Laurel Hill Farms	Strasburg	Spring Hollow	Posey Hollow	Route 648	Winchester Dam
Flow (ft³/s)	Equivalent flow (ft³/s)	Flow (ft³/s)	Equivalent flow (ft³/s)	Flow (ft³/s)	Equivalent flow (ft³/s)	Equivalent flow (ft³/s)	Equivalent flow (ft³/s)	Equivalent flow (ft³/s)
0.2[a]	0.3	1[b]	1	25[c]	23	24	24	30
0.5	.8	2	3	35	32	33	34	42
1	2	4	5	45	41	43	43	54
2	3	6	8	55	50	53	53	66
4	6	8	10	65	59	62	63	79
6	9	10	13	75	68	72	72	91
8	12	15	19	87	78	83	**83.3**	105
10	15	20	26	90	81	86	**87.0**	109
15	**22.5**	25	32	105	**94.4**	100	101	127
20	30	35	45	128	115	**122**	123	155
25	38	45	58	141	**126**	135	**136**	170
30	46	55	71	162	146	155	156	**195**
35	53	65	83	180	162	172	173	**218**
40	61	73	**93.8**	230	207	**219**	221	278
45	68	85	109	275	248	263	265	332
50	76	94	**120**	300	270	287	289	363
60.75	**92.5**	110	141	350	315	335	337	423
71.7	**109**	130	167	375	338	359	361	453
80	**121**	150	192	400	360	383	385	484
90	137	175	224	461	415	441	**444**	557
100	152	200	256	480	**432**	459	462	580
120	183	235	301	500	450	479	482	605
173.5	**264**	275	353	546	491	523	**526**	**654**
202.4	**308**	312	**400**	575	518	550	554	**696**
249	**379**	350	449	600	540	574	578	725
288	**438**	400	513	650	585	622	626	786
350	533	450	577	696	626	**666**	670	841
400	609	500	641	800	720	766	770	967
450	685	525	673	900	810	861	867	1,088
500	761[a]	550	705[b]	1,180	1,062	1,129	1,136	**1,430**[c]

[a] The simulation discharges for the upper management section represent a range between the lowest historic mean daily flow recorded at Cootes Store, and 1.74 times the highest measured flow at the Plains Mill study reach.

[b] The simulation discharges for the middle management section represent a range between 0.55 times the lowest historic mean daily flow recorded at Mount Jackson, and 1.76 times the highest measured flow at the Laurel Hill farms study reach.

[c] The simulation discharges for the lower management section represent a range between 0.75 times the lowest historic mean daily flow recorded at Strasburg, and the highest measured flow at the Winchester Dam study reach.

Table 16. Drainage-area-based correction factors for relating discharge measured at hydraulic data-collection reaches to discharge measured at streamflow-gaging stations on the North Fork Shenandoah River, Virginia.

[Simulated discharges for each streamflow-gaging station were multiplied by the percent difference in drainage area between the station and the ungaged reach to correct for flow differences.]

River management section and associated streamflow-gaging station	Reach	Drainage area difference (percent)
Upper–Cootes Store	Plains Mill	53.2
Middle–Mount Jackson	Laurel Hill Farms	28.2
Lower–Strasburg	Spring Hollow	-10.0
Lower–Strasburg	Posey Hollow	-4.3
Lower–Strasburg	Route 648	-3.7
Lower–Strasburg	Winchester Dam	20.9

Table 17. Velocity calibration discharges used in RHABSIM for each hydraulic data-collection reach and transect on the North Fork Shenandoah River, Virginia.

[RHABSIM, River Habitat Simulation Model; ft^3/s, cubic feet per second]

Reach	Transect	Calibration discharge (ft^3/s)
Plains Mill	1a, 5	379
Plains Mill	2, 3b, 4	264
Plains Mill	3, 3a, 7	308
Plains Mill	6	438
Laurel Hill Farms	1–5	400
Spring Hollow	1–5	432
Posey Hollow	1–5	666
Route 648	1, 6, 8	444
Route 648	2, 3, 5, 7	526
Route 648	4	136
Winchester Dam	1–3	1,430

flow-gaging stations and substantial increases in drainage area and discharge support the decision to run RHABSIM model simulations for three sections of the river.

The habitat-discharge relation for the upper management section was created using data collected at the Plains Mill reach. The flows were corrected for drainage area differences between the Cootes Store station and the reach (tables 15 and 16), and transects were weighted to represent mesohabitat percentages in the upper section of the North Fork Shenandoah River (appendix 1). The Plains Mill reach contains nine transects which were placed in riffle, pool, and run habitats with a variety of substrate and cover types (table 8). The complex nature of the reach and variety of water-surface slopes made it difficult to calibrate, so modeling results may not be as representative as results for the more downstream sections.

The habitat-discharge relation for the middle management section was created using data collected at the Laurel Hill Farms reach. The flows were corrected for drainage area differences between the Mount Jackson station and the reach (tables 15 and 16), and transects were weighted to represent mesohabitat percentages in the middle section of the North Fork Shenandoah River (appendix 1). Laurel Hill Farms was the only reach near the Mount Jackson station. Transects were placed only in riffles and runs in this reach; therefore, the WUA curves are most representative of these mesohabitats.

The habitat-discharge relation for the lower management section was created using data collected at the Spring Hollow, Posey Hollow, Route 648, and Winchester Dam reaches. The flows were corrected for drainage area differences between the Strasburg station and each reach (tables 15 and 16), and transects were weighted to represent mesohabitat percentages in the lower section of the North Fork Shenandoah River (appendix 1).

Transect weighting factors are used in RHABSIM to ensure that the amount of habitat represented by each reach corresponds to the amount of mesohabitat in that section of the river (appendix 1). For the upper section, Plains Mill transects were weighted to represent the percentages of riffles, runs, and pools in that section (table 6). The middle section weighting factors were assigned in the same way. For the lower section, weighting factors were distributed among all transects in the four reaches to accurately represent the mesohabitat percentages in that section (table 6). Riffle habitat is present in the Posey Hollow, Spring Hollow, and Route 648 reaches; therefore, weighting factors were distributed among all riffle habitats in the three reaches. Most of the pool habitat within the study reaches in the lower section was artificial pool located in the Winchester Dam site. In an effort to include transects that represent natural pools, pocket run habitat was grouped with pool habitat. In general, depths in the holes of pocket runs were closer to the range of depths for pools than runs. The pool habitat was represented by transects in the Winchester Dam and Route 648 reaches, and run habitat represented by transects in Posey Hollow, Spring Hollow and Route 648 reaches. Because simulation flows had been corrected for drainage area and transects weighted for lower section mesohabitat, the resulting individual WUA curves from all four reaches could be combined to produce a composite set of WUA curves for the lower management section.

Habitat-Discharge Relations for the Management Sections

The habitat-discharge relations for the upper and middle sections of the North Fork Shenandoah River are each derived from one study reach, but the relations for the lower management section represent a composite of four study reaches. For the lower section, each reach was modeled individually and WUA summed, so the WUA will be greater in magnitude than in the upper and middle sections. For management and comparison purposes, however, the general trend of the WUA curves is more important than the magnitude. The magnitude reflects the WUA in the study reaches, but is not directly representative of the actual WUA in the rest of river. The WUA for each river management section is represented by four habitat-discharge relations for fish: riffle guild, fast-generalist guild, pool-run guild, and pool-cover guild, and one habitat-discharge relation for canoeing. These relations consist of the simulated discharge and corresponding habitat value (tables 18–20, figs. 11–13).

The canoeing-discharge relations are slightly different than the fish habitat-discharge relations. Canoeing suitability was evaluated based upon depths and velocities, with all substrates assumed suitable (Fig. 10).

The RHABSIM modeling and data analysis resulted in a series of graphs, or WUA curves, that illustrate relations between discharge and habitat area. The highest point, or peak, for each WUA curve represents the discharge with the maximum WUA for each guild analyzed. Each guild will have slightly different maximum WUA, based on the fish HSC evaluated and the microhabitat conditions of each study reach. Therefore, the discharge with the maximum WUA for one guild may not represent the maximum WUA for other guilds. The maximum, inflection points, and percentiles of the WUA curves are typically evaluated as potential flow targets at the level of protection desired, or as points above which greater amounts of flow only provide minor gains in usable habitat (Sutton and Morris, 2004). At any point in time, a given streamflow may be more suitable for some species or life-stages but less suitable for others. In streams with more than one species of interest, the challenge is to evaluate the effects of any recommended flows on all species (Sutton and Morris, 2004).

A relatively simple analysis would identify the peak of the WUA curve as a flow target, regarding more habitat as desirable and less habitat as undesirable. The relation between discharge and habitat is complex; however, and it is important to understand the factors that affect WUA amounts and the relation between WUA and the hydrologic regime. WUA is consistently low during high flows, increases as flows decrease to normal or low-flow conditions, then decreases during extreme low-flow conditions. These general patterns are explained partially by considering the fish HSC for depth and velocity. The right side of the curves represents high flows having deep water depths and fast velocities, conditions which are not ranked as highly suitable for any fish guilds. As flows decrease, water depths and water velocities decrease, creating habitat conditions that are ranked suitable for more species—typically pool-cover and pool-run guilds. As flows continue to decrease, depths and velocities become more suitable to all guilds, and the WUA increases up to the maximum. The flows associated with the maximum WUA are different for each guild within each management section. For fish guilds that have shallow water depths rated highly suitable, lower flows can provide more habitat. At some point, each fish guild will be limited by water depths or velocities (or lack thereof), and WUA curves will sharply decrease. Flows with shallow water depths and either fast or slow water velocities are represented on the left side of the curves, and represent a decrease in habitat suitability and availability.

The WUA curves are compared to the natural hydrograph to understand the relations between habitat suitability and the distribution of streamflows within and between years. The WUA curves represent the habitat associated with the range of simulated flows, regardless of month or season. Within one year, for example, normal summer flows may not provide the maximum WUA that could be obtained during spring flows. During dry years flows that provide the maximum WUA may not be attainable, or will be much less frequent than during wet years (Sutton and Morris, 2004). Understanding the frequency of flows that provide WUA should provide a framework for assessing future habitat conditions during seasons, and during wet, normal, and dry years.

Upper Section

For the upper management section near the Cootes Store station, WUA (fig. 11) was simulated for flows between 0.2 and 500 ft^3/s. The range of simulation flows represents flows much higher and lower than the normal range of flows for July, August, and September (4.4–40 ft^3/s) to adequately describe the relation between habitat and discharge. Three out of four guilds have limited WUA at high flows in the range of 300–500 ft^3/s. The pool-cover guild WUA is not limited at high flows. During high-flow periods the majority of the main channel has low WUA for the riffle, fast-generalist, and pool-run guilds. Water velocities and depths are much greater during periods of high flow, and fish and other aquatic organisms may move to edge areas to find shelter from swift velocities. During moderate to low flows, the WUA for the riffle and fast-generalist guilds appears to be more abundant than for the pool-run and pool-cover guilds.

The upper section of the North Fork Shenandoah River shows more variation in the habitat-discharge relation among guilds than the other two downstream sections. For the upper management section, flows that sustain maximum WUA are close to 42 ft^3/s for all guilds, a flow that approximately correlates to the 25-percent exceedance flow for July, August, and September. The pool-cover and pool-run WUA curves are similar in shape (fig. 11). WUA for these two guilds gradually increases as flows decline from the highest simulated flow, 500 ft^3/s, to 100 ft^3/s. Flows between 100 and 40 ft^3/s provide

Table 18. Weighted usable-habitat area in square feet per 1,000 feet of stream for the upper management section of the North Fork Shenandoah River, Virginia.

[ft^3/s, cubic feet per second]

Cootes Store discharge (ft^3/s)	Fish guild				Canoeing
	Riffle	Fast-generalist	Pool-run	Pool-cover	
0.2	0	0	0	0	0
0.5	124	0	43	29	0
1	312	19	688	151	0
2	1,715	702	1,322	423	9
4	4,251	1,989	3,140	1,929	457
6	5,575	5,873	6,030	3,593	1,419
8	8,320	7,769	6,957	5,101	2,701
10	10,524	8,765	8,046	6,462	3,978
15	14,124	12,620	10,598	8,683	6,769
20	17,088	15,373	12,410	10,946	9,634
25	19,361	17,307	13,551	12,860	12,470
30	20,808	20,011	14,915	14,803	15,381
35	21,553	21,736	15,884	16,243	18,231
40	22,342	22,851	16,376	17,747	21,240
45	20,355	23,326	16,524	18,367	24,198
50	19,001	24,919	17,419	19,446	27,202
60.75	17,693	24,901	17,507	19,654	33,814
71.7	16,161	22,764	17,211	19,845	40,682
80	14,711	22,760	16,933	20,216	46,072
90	12,556	21,244	16,987	19,547	53,117
100	11,478	19,615	16,139	19,681	59,231
120	9,094	16,304	13,134	19,450	70,361
173.5	3,350	10,875	9,811	17,649	88,676
202.4	2,239	8,008	7,532	17,454	94,775
249	1,235	4,113	5,652	14,958	101,531
288	564	2,528	3,691	12,670	104,497
350	272	1,054	2,261	10,904	105,945
400	54	645	1,846	8,622	104,805
450	54	389	1,382	7,103	102,642
500	22	151	919	6469	100,359

Table 19. Weighted usable-habitat area in square feet per 1,000 feet of stream for the middle management section of the North Fork Shenandoah River, Virginia.

[ft^3/s, cubic feet per second]

Mount Jackson discharge (ft^3/s)	Fish guild				Canoeing
	Riffle	Fast-generalist	Pool-run	Pool-cover	
1	25	25	86	561	0
2	143	62	307	1,683	10
4	184	150	658	3,641	155
6	518	358	1,070	5,934	436
8	848	420	1,464	6,933	983
10	944	457	1,702	7,779	1,735
15	1,891	1,108	2,513	9,533	4,502
20	2,466	1,644	3,281	11,870	8,387
25	4,180	2,839	4,114	12,099	12,550
35	5,743	3,745	5,679	14,438	20,705
45	5,997	5,101	6,963	14,861	28,495
55	6,561	6,141	7,812	16,157	36,228
65	6,832	6,849	8,486	17,324	43,323
73	7,136	7,071	9,582	16,559	48,684
85	7,489	7,138	9,751	16,939	55,503
94	7,560	7,219	9,616	14,942	60,019
110	7,511	6,646	9,391	13,678	67,690
130	7,390	5,872	9,141	12,078	75,309
150	6,320	5,929	8,842	10,465	81,857
175	5,424	5,311	8,392	9,376	88,058
200	3,548	4,324	7,640	7,490	93,084
235	2,782	2,316	6,132	6,506	98,963
275	2,113	1,970	5,156	4,858	104,146
312	1,321	1,306	4,716	4,443	107,258
350	1,030	690	3,553	3,959	109,685
400	630	549	2,387	2,622	111,942
450	433	356	1,645	2,066	113,299
500	282	306	1,306	1,929	113,684
525	282	306	1,163	1,919	113,401
550	282	306	951	1,566	112,487

Table 20. Weighted usable-habitat area in square feet per 1,000 feet of stream for the lower management section of the North Fork Shenandoah River, Virginia.

[ft^3/s, cubic feet per second]

Strasburg discharge (ft^3/s)	Fish guild				Canoeing
	Riffle	Fast-generalist	Pool-run	Pool-cover	
25	9,544	7,592	17,321	7,525	6,932
35	12,920	11,002	22,423	8,098	11,090
45	15,245	13,902	26,750	8,405	18,132
55	15,550	15,061	28,760	9,671	28,418
65	16,788	16,358	30,733	12,844	42,044
75	17,157	17,225	32,557	12,975	59,288
87	17,782	18,300	33,617	13,522	83,836
90	17,849	18,482	33,051	13,654	90,634
105	18,551	18,498	32,728	14,144	120,425
128	18,229	17,162	31,793	14,493	172,104
141	18,035	16,716	30,509	14,813	199,798
162	15,709	12,288	26,412	14,829	248,441
180	14,664	11,920	25,468	14,726	288,750
230	11,859	11,359	23,620	14,916	369,386
275	10,224	9,169	22,117	15,185	415,184
300	7,776	7,005	21,143	15,470	427,793
350	4,464	5,012	17,530	15,517	441,082
375	4,016	4,722	16,331	15,090	444,836
400	3,613	4,216	15,075	14,378	447,465
461	2,231	2,409	12,903	10,984	449,179
480	1,889	1,988	12,426	10,957	451,667
500	1,786	1,905	11,510	10,771	452,527
546	1,316	1,626	9,310	10,670	454,895
575	1,149	1,286	8,619	10,575	456,922
600	1,208	1,103	8,223	10,521	458,343
650	884	906	6,531	9,592	460,612
696	781	753	5,993	8,590	461,278
800	274	624	4,015	7,564	462,742
900	238	537	2,795	6,961	461,047
1,180	118	216	1,364	5,515	435,799

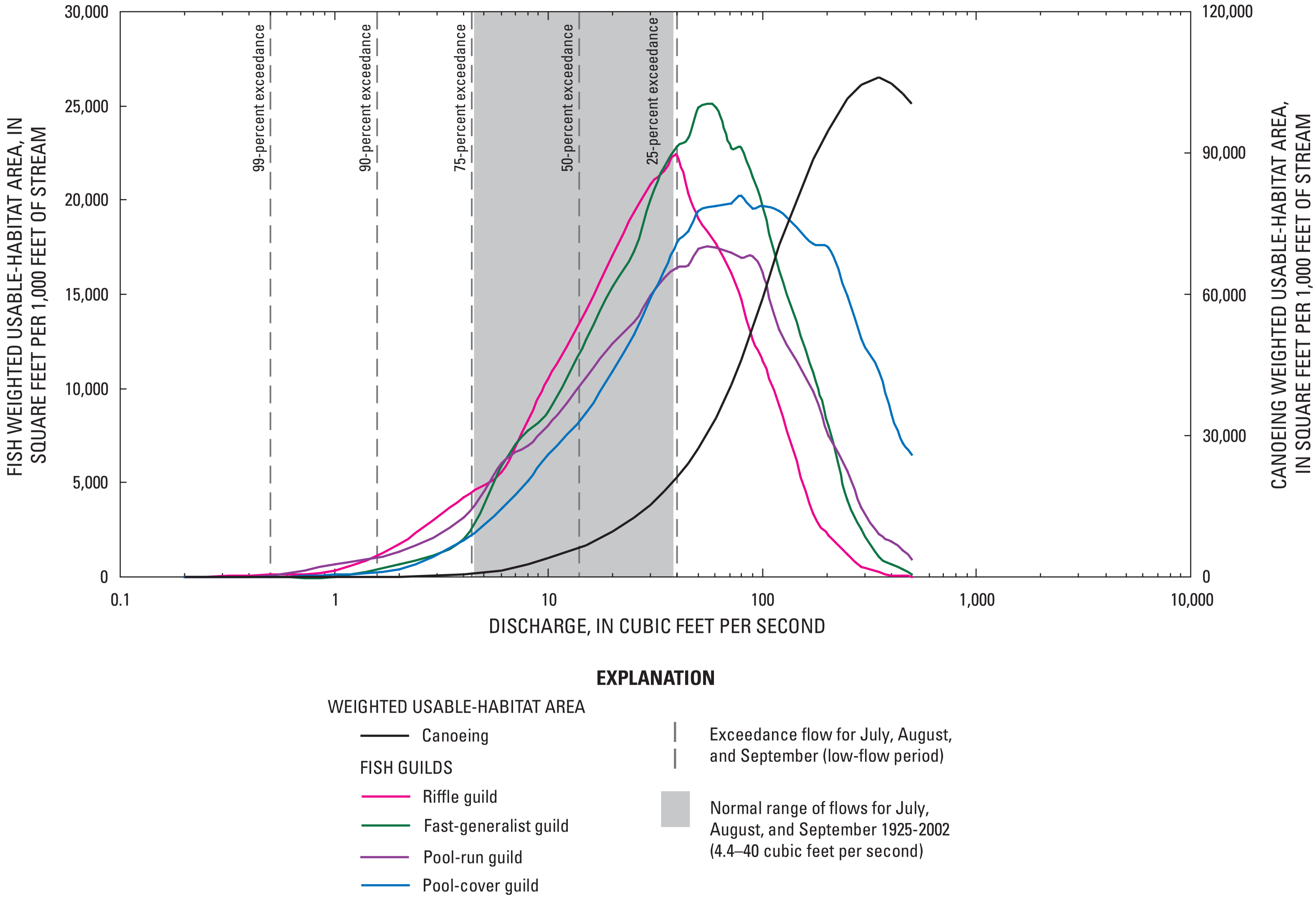

Figure 11. Weighted usable-habitat area for the upper management section of the North Fork Shenandoah River, Virginia.

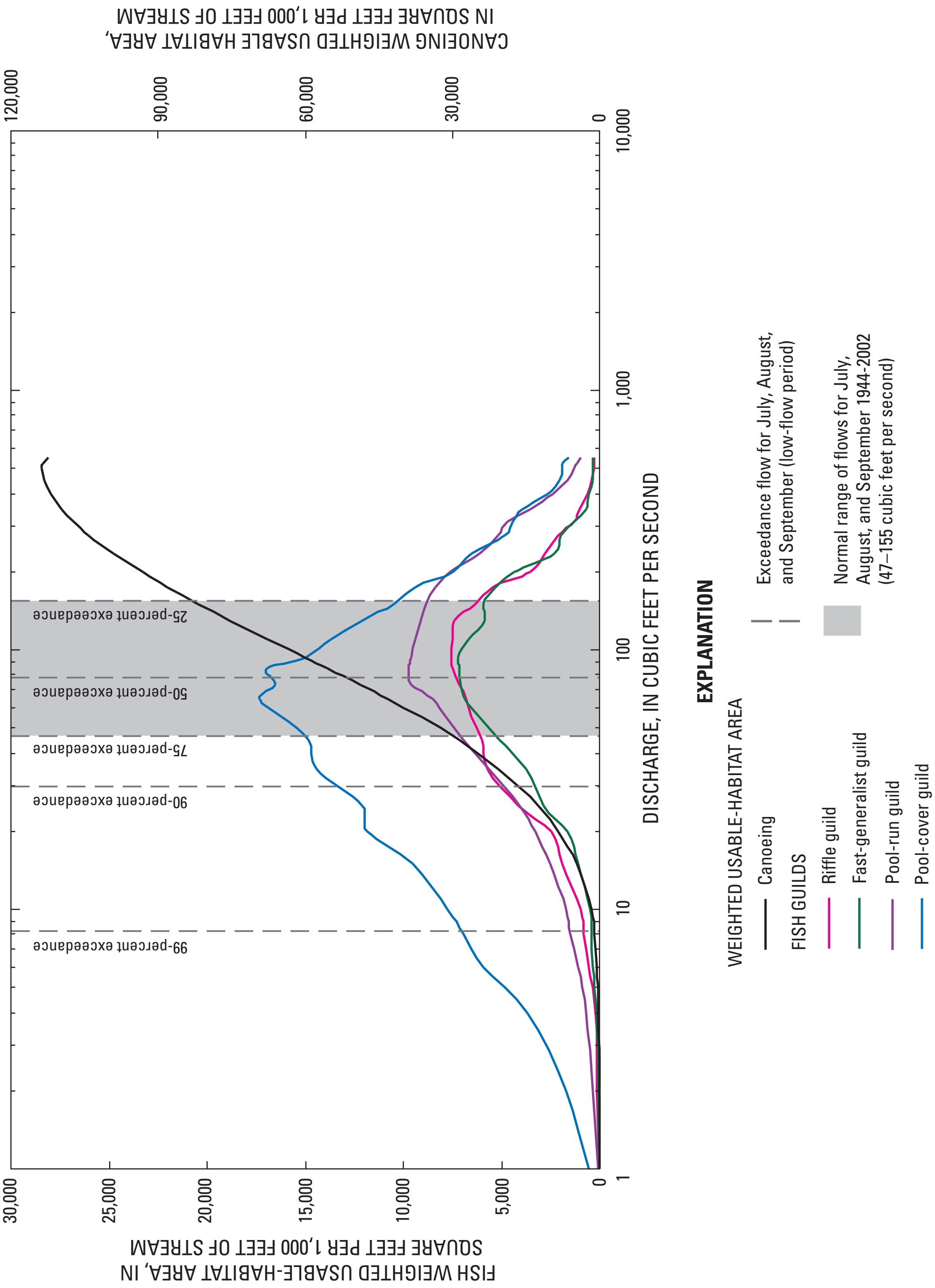

Figure 12. Weighted usable-habitat area for the middle management section of the North Fork Shenandoah River, Virginia.

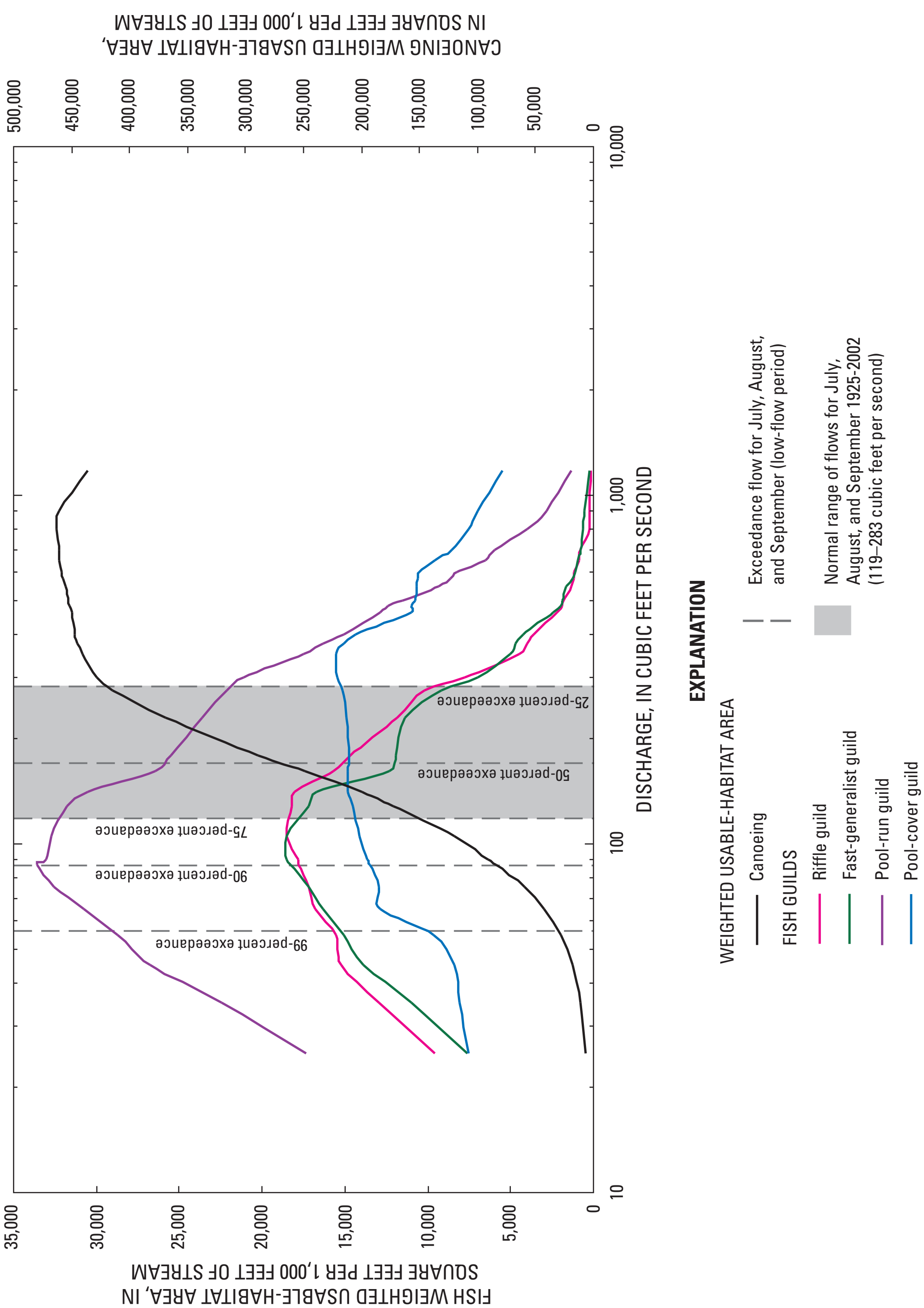

Figure 13. Weighted usable-habitat area for the lower management section of the North Fork Shenandoah River, Virginia.

the maximum and constant amount of WUA for pool-cover and pool-run guilds; WUA sharply decreases with flows less than 40 ft^3/s. Fast-generalist WUA (fig. 11) steeply increases as flows decline from 500 to 60 ft^3/s. Flows between 60 and 50 ft^3/s provide the maximum WUA, and then WUA sharply decreases with flows less than 40 ft^3/s. Riffle guild WUA (fig. 11) gradually increases as flows decrease from the highest simulated flow to 40 ft^3/s, which is the flow with the maximum WUA. At flows less than 40 ft^3/s riffle WUA declines. Riffle WUA remains the most abundant of all four guilds in the upper management section. WUA is limited at and below the 90-percent exceedance flow (1.6 ft^3/s) (fig. 11).

To illustrate the amount of WUA commonly expected for each guild during the low-flow period, the normal range of flows (4.4–40 ft^3/s), the 50-percent exceedance flow (14 ft^3/s), and the 90-percent exceedance flow (1.6 ft^3/s) for July, August, and September flows were plotted over each set of WUA curves (fig. 11). The normal range of flows for July, August, and September only includes the maximum WUA for the riffle guild. During the low-flow period it is common for the actual WUA to be less than the maximum simulated WUA in late summer and early fall for all guilds. With the steep decline in WUA within the normal range of flows during July, August, and September, it is also likely that habitat conditions are dynamic during the low-flow period in the upper section of the North Fork Shenandoah River.

For the upper management section, canoeing suitability is at a maximum at 350 ft^3/sec. At this flow riffles, runs, and pools have suitable depths and velocities for canoeing. At 100 ft^3/sec approximately half the amount of canoeing WUA is available than is with 350 ft^3/sec. During summer, these flows occur less than 25-percent of the time based on the exceedance flows for July, August, and September (table 2).

Middle Section

For the middle management section near the Mount Jackson station, WUA (fig. 12) was simulated for flows between 1 and 550 ft^3/s. The range of flows represents flows much higher and lower than the normal range of flows for July, August, and September (47–155 ft^3/s) to adequately describe the relation between habitat and discharge. For all four fish guilds WUA is limited at high flows in the range of 300–550 ft^3/s because the water depths and velocities are outside the suitable range. During moderate and low flows habitat is abundant in similar amounts for all four fish guilds.

The middle management section of the North Fork Shenandoah River shows little variation in the habitat-discharge relations for all four guilds. The flows that sustain maximum WUA for all guilds are between 70 and 80 ft^3/s, a flow that approximately correlates with the 50-percent exceedance flow for July, August, and September. For all guilds, as flows declined from highest measured flow, 550 ft^3/s, to 80 ft^3/s, WUA steeply increases. WUA decreases with flows less than 75 ft^3/s, and is highly limited at and below the 99-percent exceedance flow (8 ft^3/s).

There is more WUA for the pool-cover guild than for the three other fish guilds in the middle management section. Depths, velocities, and substrates were most suitable to fish in the pool-cover guild (fig. 12); however, fish from the other guilds are also supported. It is possible that substrate and cover suitability may be a limiting factor for the riffle, fast-generalist, and pool-run guilds in the middle section, but not for the pool-cover guild.

To illustrate the amount of WUA commonly expected for each guild during the low-flow period, the normal range of flows (47–155 ft^3/s), the 50-percent exceedance flow (78 ft^3/s), and the 90-percent exceedance flow (30 ft^3/s) for July, August, and September flows were plotted over each set of WUA curves (fig. 12). Unlike the upper and lower sections, the normal range of flows for July, August, and September includes the maximum WUA for all fish guilds in this section. Within this range, the WUA does not change much with changes in flow. At flows less than the 75-percent exceedance flow, WUA decreases at a similar rate for all guilds.

For the middle management section, canoeing suitability is at a maximum at 500 ft^3/sec. At 100 ft^3/sec approximately half the amount of canoeing WUA is available than is with 500 ft^3/sec. During summer, these flows occur more than 50-percent of the time based on the exceedance flows for July, August, and September (table 2).

Lower Section

For the lower management section near the Strasburg station, WUA (fig. 13) was simulated for flows between 25 and 1,180 ft^3/s. The range of flows represents flows much higher and lower than the normal range of flows for July, August, and September (119–283 ft^3/s) to adequately describe the relation between habitat and discharge. For all four fish guilds, the WUA is limited at high flows in the range of 500–1,180 ft^3/s. As with the upper section during high-flow periods, edge and backwater areas contain suitable habitat, but the majority of the main channel sustains small amounts of WUA. During moderate and low-flow periods habitat for pool-cover and pool-run is most abundant.

For the riffle, fast-generalist, and pool-run guilds of the lower section of the North Fork Shenandoah River, flows that sustain maximum WUA range between 90 and 100 ft^3/s (fig. 13), which approximately correlates to the 90-percent exceedance flow for July, August, and September. The WUA for these three guilds increases from the highest simulated flow, 1180 ft^3/s, to 100 ft^3/s. With flows below 90 ft^3/s WUA decreases more gradually than the upper or middle sections. For the pool-cover guild, WUA is at a maximum at 500 ft^3/s, and is maintained at a constant level with only slight decreases between 500 and 65 ft^3/s. WUA for the pool-cover guild decreases steeply between 65 and 25 ft^3/s. For the lower section, the amount of WUA, represented by the magnitude or height of the curves, is substantially greater for the pool-run guild than for the other three guilds. WUA for all fish guilds is limited below the 99-percent exceedance flow (56 ft^3/s).

To illustrate the amount of WUA commonly expected for each guild during the low-flow period, the normal range of flows (119–283 ft^3/s), the 50-percent exceedance flow (171 ft^3/s), and the 90-percent exceedance flow (87 ft^3/s) for July, August, and September flows were plotted over each set of WUA curves (fig. 13). The normal range of flows for July, August, and September does not include the maximum WUA for any guild. Habitat appears to be more abundant for flows less than the 75-percent exceedance flow. However, the habitat may be composed of mostly disconnected patches and edge areas, and the potential water-quality problems within the shallow habitats make the habitat suitability questionable.

For the lower management section, canoeing suitability is at a maximum at 800 ft^3/sec. At 162 ft^3/sec approximately half the amount of canoeing WUA is available than is with 800 ft^3/sec. During summer, these flows occur more than 50-percent of the time based on the exceedance flows for July, August, and September (table 2).

Time-Series Analysis for Low-Flow Periods

A time-series analysis was completed to overlay the habitat-discharge relations on the entire historic streamflow record to show how WUA may have fluctuated daily, seasonally, and during low-flow periods. Two different withdrawal scenarios were simulated to show how WUA may be affected by various water-withdrawal practices.

Discharge data for each of the three stations were obtained (U.S. Geological Survey, 2003) for the period of record through water year 2001 (ending September 30, 2002). To simulate the withdrawal scenarios, discharge datasets were created from the historic data to represent streamflows with zero water withdrawals and double water withdrawals for each management section.

No major dams are present on the North Fork Shenandoah River; therefore, the primary way that humans affect instream flows is related to water withdrawals and returns for municipal, industrial, and agricultural uses. Water suppliers, cities, counties, industries, farmers, and individuals report their monthly water use to the Virginia Department of Environmental Quality (DEQ). Reported agricultural water use is much lower than municipal and industrial water use in the North Fork Shenandoah River basin (Virginia DEQ, written commun., February 15, 2005). Agricultural withdrawals in Virginia are reported on a volunteer, survey basis, so the accuracy of the values is uncertain. The reported surface-water withdrawals for agriculture have occurred in June, July, August, and September in the North Fork Shenandoah River basin. Based on five years of data (1998-2002), the average daily water withdrawals on the North Fork Shenandoah River for all uses are 3.0 ft^3/s, 0.3 ft^3/s, and 14.5 ft^3/s for the upper, middle, and lower management sections respectively. Due to the general nature of the location information for water withdrawals, the middle management section does not appear to have large withdrawal volumes. The 0.3 ft^3/s value is likely too low, but is the best estimate available at present.

The average daily water withdrawals (1998-2002) were added back to the historic daily mean flow data for the months of June, July, August, and September to create a zero water-withdrawal scenario (in which no water is removed from the river). For each respective section of the river, withdrawal amounts were added cumulatively (3.0 ft^3/s, 3.3 ft^3/s, and 17.8 ft^3/s). This scenario simulates the potential success of water conservation measures in maintaining WUA during low-flow periods. The second flow scenario involves doubling water withdrawals to simulate the potential effects of increased water use on WUA. The cumulative daily withdrawal values were subtracted from the historic daily mean flow data. Because the discharge data already includes current water withdrawals, subtracting withdrawal amounts of 3.0 ft^3/s, 3.3 ft^3/s, and 17.8 ft^3/s from respective management sections represents a doubling of water use.

The discharge datasets and habitat-discharge relations were entered into and evaluated with a time-series analysis spreadsheet (James Henriksen, U.S. Geological Survey, written comun., 2002). The spreadsheet contains algorithms to assign the WUA value to each daily mean flow value for the historic period. The time-series analysis produces simulated, daily variations of WUA for the entire period of record. For dry years noted earlier (Historic Flow Summary) the time-series results were examined to identify flows that limit the WUA for fish and to identify fish guilds that are most affected. The time-series results were also examined to identify and describe the range of habitat conditions for each fish guild.

The habitat time-series analysis shows the daily and seasonal variation of habitat with flow, as well as times when WUA is limited during dry periods (figs. 14-16). Flow is closely linked to habitat availability, and during dry months (approximately July through November), a decrease in flow generally corresponds to a decrease in WUA, and an increase in flow corresponds to an increase in WUA. This habitat area increase may occur because during low flows, an increase due to rainfall or run-off creates more moderately shallow areas of run and riffle habitat. During wet months of the year (approximately December through June), increases in flow (peaks of the hydrograph) frequently correspond to decreases in WUA. This WUA decrease may occur because during high flows, riffles and runs are inundated and much of the river becomes run habitat with fast velocities, which is not suitable for many species.

The flow corresponding to the maximum WUA represents a boundary between whether WUA increases or decreases with increased flow. When flows are lower than the flow corresponding to the maximum WUA, and there is an increase due to rainfall or run off, WUA increases. When flows are higher than the flow corresponding to the maximum WUA, and there is an increase due to rainfall or run off, WUA decreases. A flow roughly corresponding to the maximum WUA for all guilds was selected and is noted on each times-series graph (figs. 14-16).

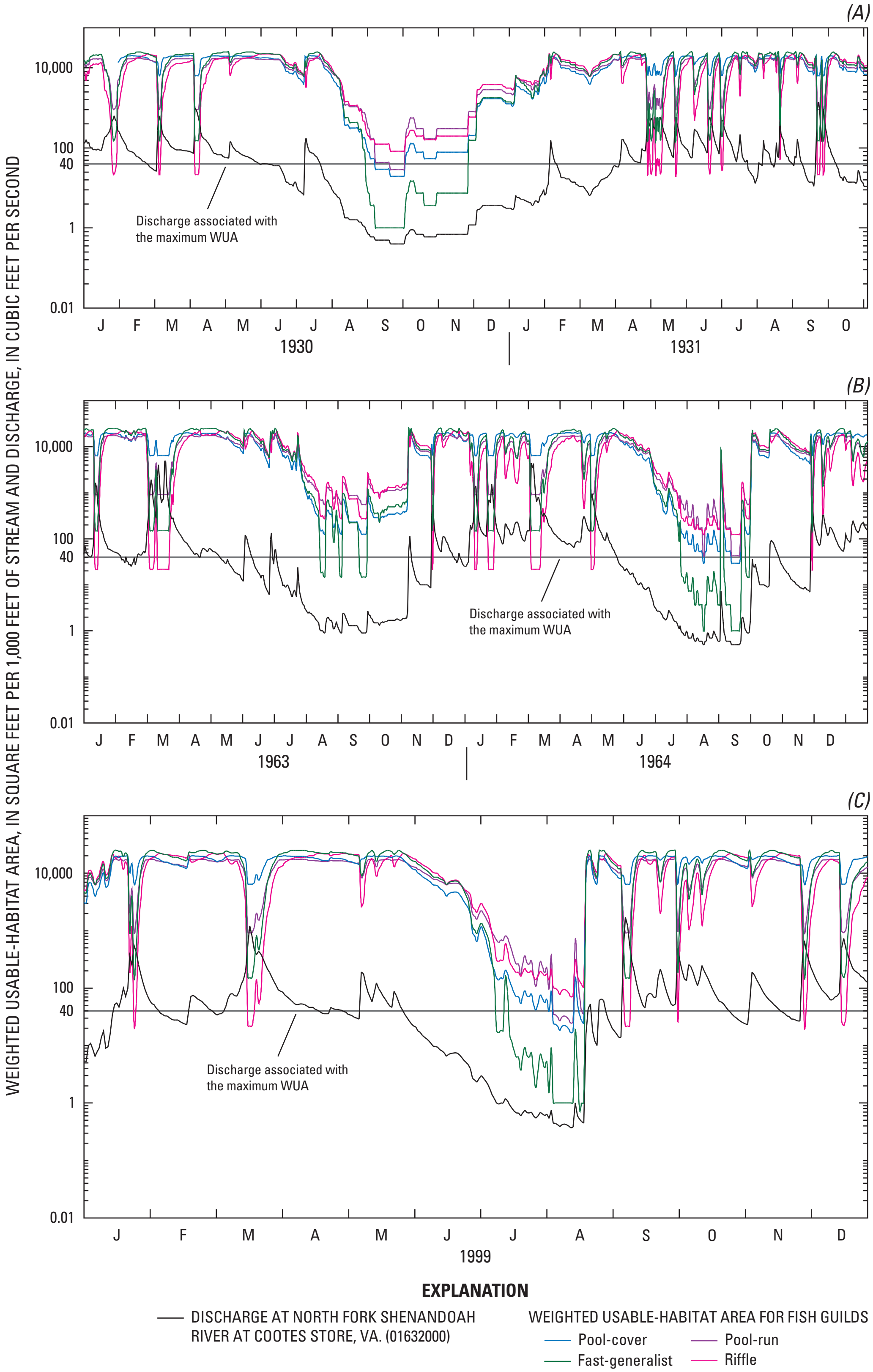

Figure 14. Daily mean discharge and weighted usable-habitat area (WUA) for fish guilds in the upper management section of the North Fork Shenandoah River, Virginia for the 1930 low-flow period *(A)*, 1964 low-flow period *(B)*, and 1999 low-flow period *(C)*. Discharge associated with the maximum WUA for all fish guilds in this section of the river is indicated.

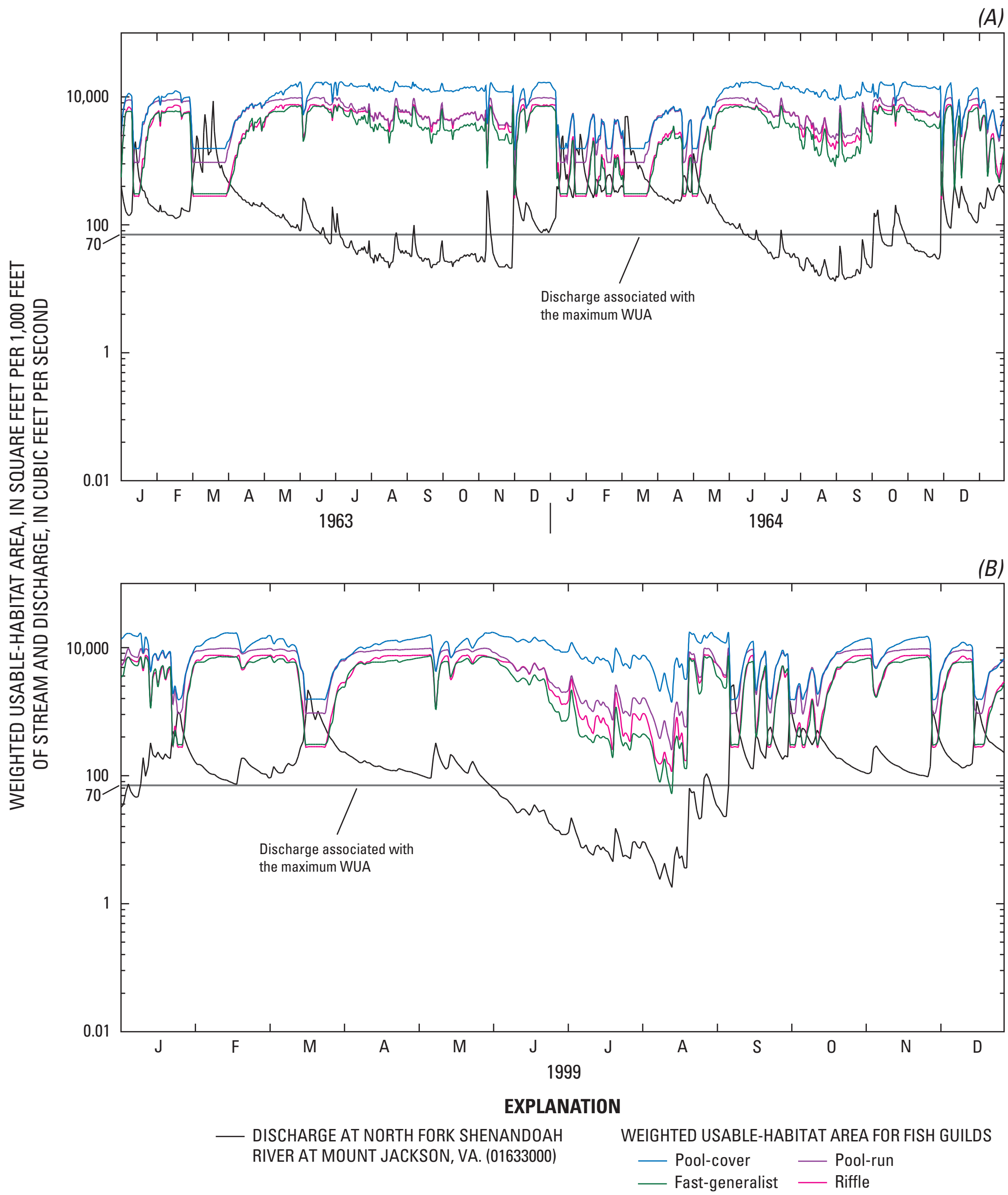

Figure 15. Daily mean discharge and weighted usable-habitat area (WUA) for fish guilds in the middle management section of the North Fork Shenandoah River, Virginia for the 1964 low-flow period *(A)*, 1999 low-flow period *(B)*. Discharge associated with the maximum WUA for all fish guilds in this section of the river is indicated.

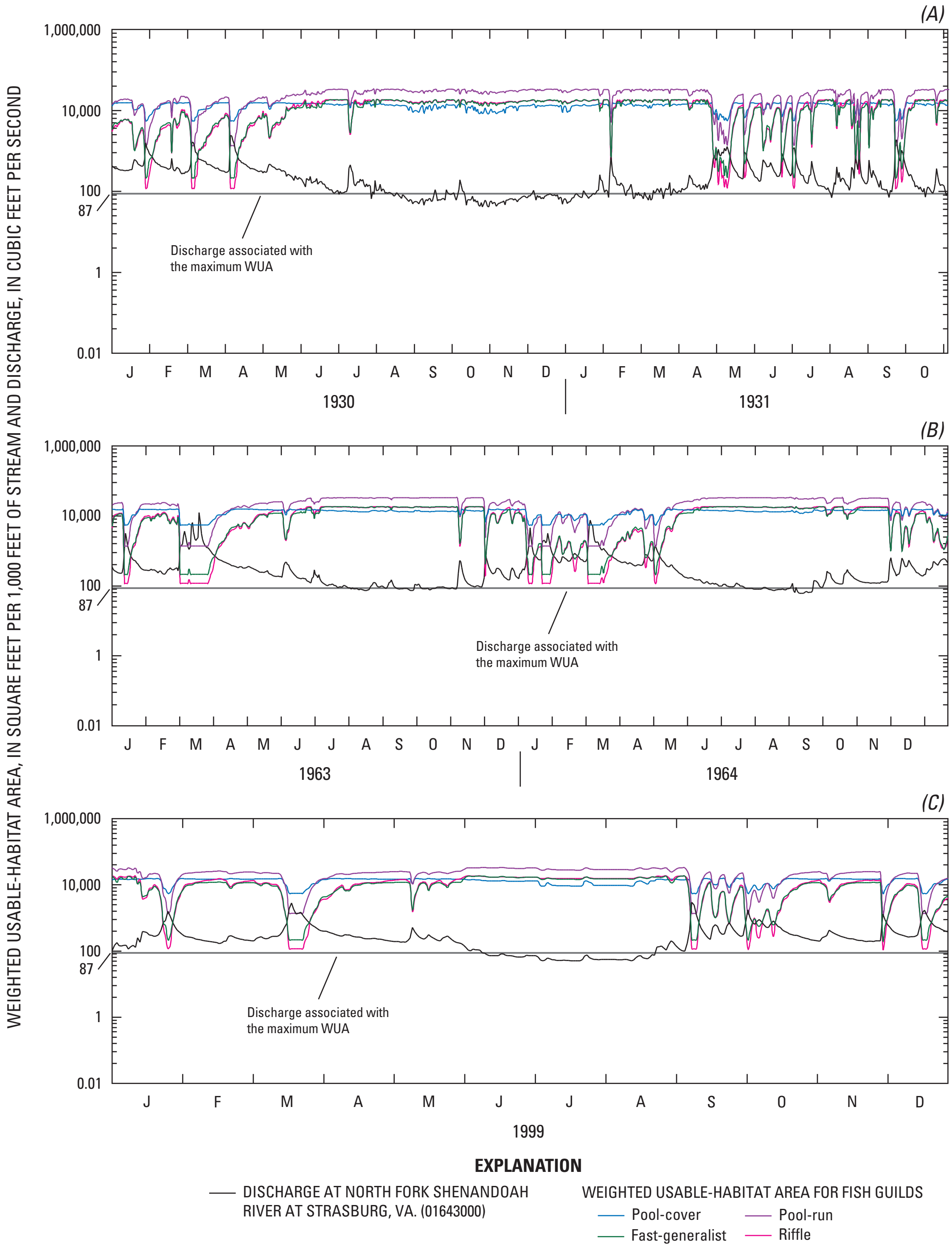

Figure 16. Daily mean discharge and weighted usable-habitat area (WUA) for fish guilds in the lower management section of the North Fork Shenandoah River, Virginia for the 1930 low-flow period *(A)*, 1964 low-flow period *(B)*, and 1999 low-flow period *(C)*. Discharge associated with the maximum WUA for all fish guilds in this section of the river is indicated.

The magnitude of habitat decline during natural dry periods can be seen in the time-series habitat values associated with extreme low flows recorded for the upper section of the North Fork Shenandoah River (fig. 14). The maximum WUA is available at a range between 40 and 55 ft^3/s for all four fish guilds. The 40 ft^3/s flow marked on figure 14 indicates the boundary below which WUA decreases with decreases in flow. This flow is equivalent to the 25-percent exceedance flow for the low-flow period and is the upper end of the normal range of flows for July, August, and September. The time-series graphs show that during extended periods with flows much lower than the normal range of flows, habitat can be highly limited (fig. 14).

In the upper management section, the fast-generalist and pool-cover guilds showed the greatest response to decreases in flow. The WUA for these two guilds was lowest during July, August, and September of 1930, 1963, and 1964, and during July and August of 1999 (fig. 14). The WUA for the fast-generalist guild decreased more than that for other guilds during previous low-flow periods. This implies that run habitat and run-dwelling fish species in the upper management section are most vulnerable to habitat loss during low-flow periods. Were water-withdrawals to increase during these times in the upper section, habitat conditions would be limited more frequently. During wet months (December-June), WUA is relatively constant and sustained. With large rain events WUA for riffle and fast-generalist guilds decline, probably indicating that the habitats are washed out in deep, fast flows. Overall, wet months sustained higher WUA than dry months in the upper management section of the North Fork Shenandoah River.

The magnitude of habitat decline during natural dry periods can be seen in the time-series habitat values associated with extreme low flows recorded for the middle management section of the North Fork Shenandoah River (fig. 15). The maximum WUA is available at approximately 70 ft^3/s for all four fish guilds (fig. 15). This is close to the median flow for July, August, and September. In the middle management section when flows are 70 ft^3/s and decreasing, WUA for the riffle, fast-generalist, and pool-run guilds will also decrease. Sustained low-flows below this value in 1999 showed great habitat decline, and even some decline in pool-cover guild habitat area in August of 1999 when flows were less than 10 ft^3/s (fig. 15).

In the middle management section, the fast-generalist, riffle, and pool-run guilds showed the greatest response to decreases in flow. The WUA for these three guilds was lowest during July, August, and September of 1964, and during June, July, and August of 1999 (fig. 15). The WUA for the fast-generalist guild decreased more than that for other guilds during low-flow periods. The WUA for riffle and pool-run guilds was more abundant than that for the fast-generalist guild, but the pattern of habitat decline in response to changes in flow was similar. The pool-cover guild WUA remained constant and did not show much response during past low-flow periods. During wet months (December-June), WUA remained constant. The WUA during wet months was frequently less than during dry months. Larger volumes of water in this section of the river may lead to habitat conditions that are too deep or fast for many fish, but is a normal habitat condition based upon seasonal patterns of flow.

All four fish guilds within the lower management section were relatively unaffected by low flows shown in the time-series graphs (fig. 16). Based on the WUA curves (fig. 13), this section should not show a great loss in habitat until flows are below the 90-percent exceedance value (87 ft^3/s). Flows during the dry years examined dropped below this value infrequently (fig. 16). Because of the abundance of runs and pools in this section, and because pool-cover maximum WUA (fig. 13) is available over a wide range of flows, WUA in the lower management section will react slowly to changes in flow. Water quality during low flows is a concern, however. Lower flows and lower water depths may promote algal growth. During field data collection for a 1999 water-quality study of the North Fork Shenandoah River (Krstolic and Hayes, 2004), large filamentous mats of algae were observed in July. In conjunction with extreme low flows, dissolved oxygen levels can decline or fluctuate widely, as was observed in July 1999. As within the middle management section, during wet months (December-June), WUA in the lower management section was frequently less than during dry months. The WUA for the riffle and fast-generalist guilds varied much more widely during wet months than the WUA for the pool-run or pool-cover guilds. Seasonal patterns of habitat availability are representative of natural variations in flow.

Simulations of the zero water-withdrawal and double water-withdrawal scenarios were conducted for the entire period of record; however, the recent dry period of 1999 was selected to illustrate the pattern of WUA loss or gain represented by these simulations. The zero water-withdrawal scenario (adding back water withdrawals for June, July, August, and September) showed improvement in habitat availability for the fast-generalist guild species in the upper management section (fig. 17). All guilds showed improvements in WUA, but the fast-generalist guild showed the greatest response in the upper section. Water withdrawals are so minimal in the middle management section that the simulation showed little improvement. For the lower management section, reduced water use showed some improvement in pool-cover guild WUA (fig. 18). The zero-withdrawal scenario represents the upper limit for habitat availability during dry periods for all guilds.

The double water-withdrawal scenario showed a total loss of fast-generalist guild WUA during July to mid-August of 1999 in the upper section (fig. 17). By subtracting 3.0 ft^3/s from the historic discharge data, most of the simulated daily mean flows were equal to or less than 0.5 ft^3/s during this time period. With simulated daily mean flows close to 0.0 ft^3/s, the corresponding simulated WUA was equal to zero. This scenario demonstrates the scarcity of water in the upper section of the North Fork Shenandoah River. The double water-withdrawal scenario for the middle section did not have much effect on simulated WUA. In the lower section, the double

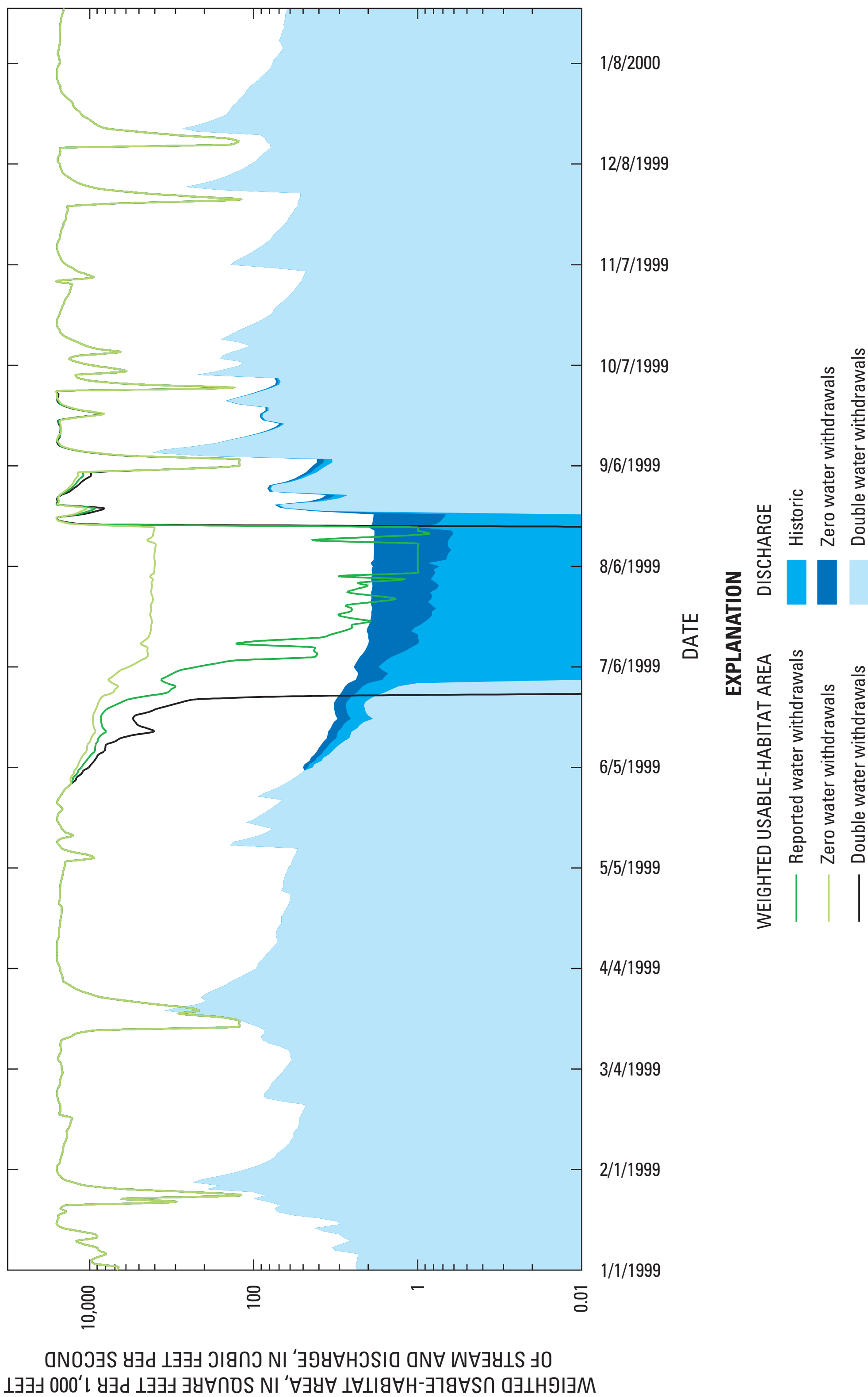

Figure 17. Weighted usable-habitat area for the fast-generalist fish guild under three different water-withdrawal scenarios in 1999 in the upper management section of the North Fork Shenandoah River, Virginia.

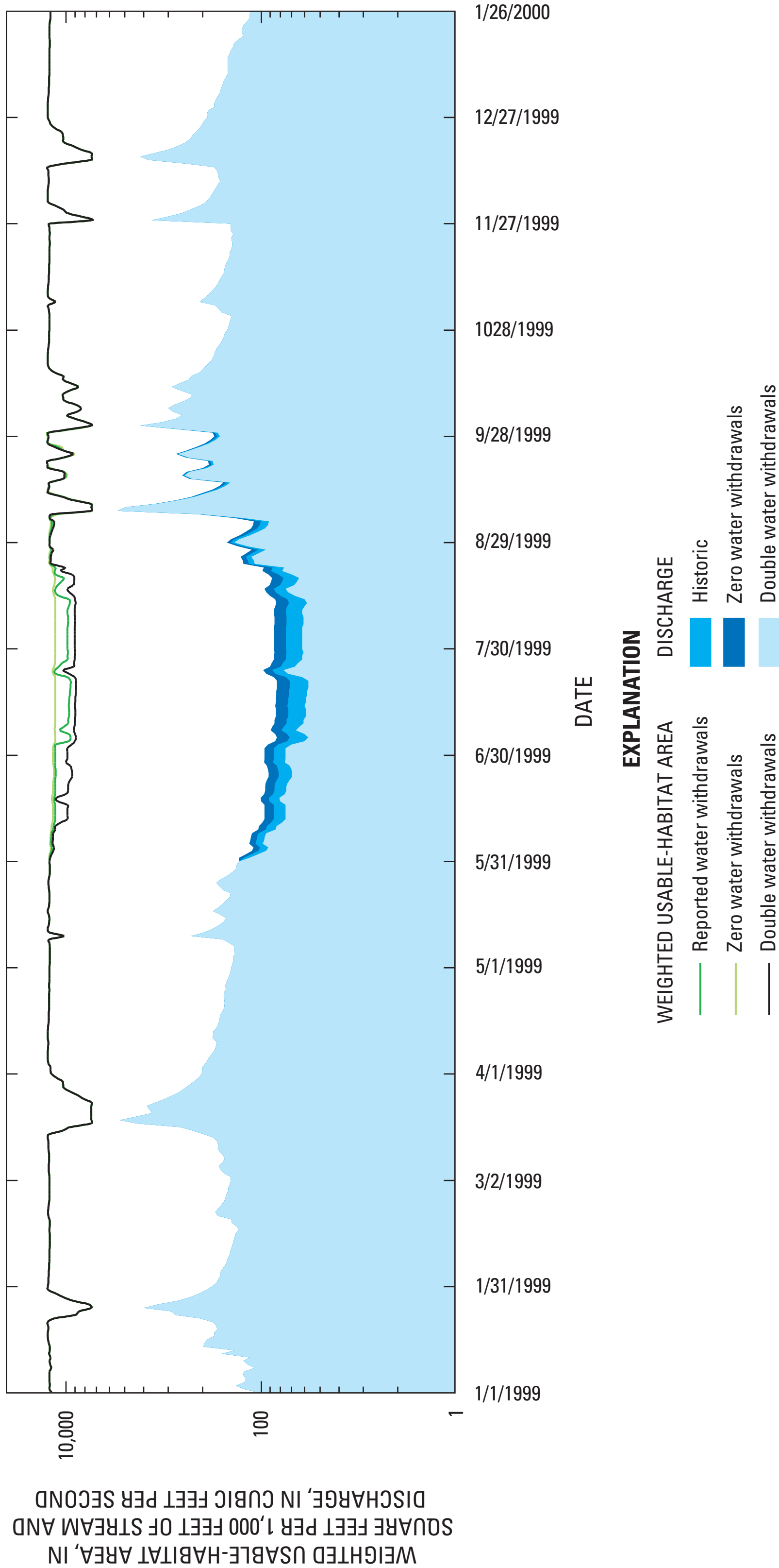

Figure 18. Weighted usable-habitat area for the pool-cover fish guild under three different water-withdrawal scenarios in 1999 in the lower management section of the North Fork Shenandoah River, Virginia.

water-withdrawal scenario showed a small decline in habitat availability for pool-cover guild species (fig. 18). Doubling of water withdrawals in this section of the North Fork Shenandoah River should have less effect on WUA than in the upper section.

These two withdrawal scenarios show that an increase in the frequency of low flows below the flows that correspond to the maximum WUA would cause more habitat losses for riverine fish, but that conservation measures may help to lessen the effect on habitat during low-flow periods. Fish populations can recover from the effects of droughts over time and with low-flow periods occurring about every 10–30 years, the stress to the aquatic community likely would not cause permanent damage. Many of the flows discussed in this report represent natural flows that occur during frequently low-flow periods, yet rarely during normal years. However, if water withdrawals were to cause consistent, annual, drought-like conditions, fish populations could be affected year round and it is uncertain how well the aquatic community would recover.

Summary and Conclusions

The objective of this study was to collect hydrologic, biologic, and habitat data for the North Fork Shenandoah River basin, focusing on availability of suitable habitat and maintenance of streamflows during low-flow periods. Study components included documentation of the mesohabitat distribution, analysis of historic streamflow data, collection of empirical river hydraulics data and fish community structure data, and development of fish habitat-suitability criteria and recreational-use suitability-criteria, all of which supported model development and time-series analysis of weighted usable area for the North Fork Shenandoah River. Since 1998 the U.S. Geological Survey has been working in cooperation with the Northern Shenandoah Valley Regional Commission on the present study and has partnered in data collection and analysis with Virginia Polytechnic Institute and State University. The North Fork Shenandoah River basin was the major focus of this study because the water supply is less than the other major tributary of the Shenandoah River, the South Fork Shenandoah River, and because 21 percent of the Shenandoah River basin population resides in the North Fork Shenandoah River basin. Maintaining health of the aquatic ecosystem, in concert with supplying water to a growing population and industry base, is of concern to local water-resoureces managers.

A modeling approach using empirical fish habitat requirements and physical stream habitat availability was selected. The RHABSIM model inputs include physical habitat data, microscale fish habitat-suitability criteria, and hydraulic data including water-surface elevation, depth, velocity, substrate, and discharge measurements. The large size of the basin (1,033 mi^2) necessitated its division into three management sections for analysis purposes: the upper section, middle section, and lower section. The three sections are associated with the streamflow-gaging stations near the downstream end of each section: at Cootes Store, Va., at Mount Jackson, Va., and near Strasburg, Va.

Despite past mill dams, some channelization for transportation, and the current water- withdrawal levels, streamflow of North Fork Shenandoah River varies with the seasons and weather, with high flows during winter and spring and lower flows during summer and fall. Within each management section, the historic streamflows were analyzed to determine the months with the lowest flows throughout the year. Flow statistics for the months of July, August, and September were used as a reference point to low-flow months, and the effect that flow reductions have on habitat during these months was assessed. Past low-flow years, when water was scarce throughout the basin, can be identified from the historic record when daily mean flows equal to or less than the 90-percent exceedance flow occurred an average of 50 percent of days during July, August, September, or October. The impact water withdrawals have on the system has not been assessed, but to this point (2004), the river is maintaining a fairly natural flow regime related to water availability, and during normal climatic years is largely unaffected by the withdrawals. This study focused on periods when streamflow is extremely low, when it may be difficult to achieve a balance between sustaining the aquatic community and using water to support the needs of people.

Mesohabitat classification and mapping were completed to identify, describe, and quantify the mesohabitat types within the North Fork Shenandoah River. This inventory of mesohabitat along the entire river allowed RHABSIM model transects to be weighted to adequately represent mesohabitat types of the river. The general categories of habitat along the entire North Fork Shenandoah River include 14 percent riffle, 67.3 percent run, and 18.7 percent pool. The percentages of rifle, run, and pool habitat are similar in each management section; however, mesohabitat unit length and substrate composition vary by section. In the upper section, the mesohabitat units are short, with many repeating riffle, run, riffle sequences. Particle-substrate riffles and runs are most common. The average length of an individual mesohabitat unit in the middle section is greater than the average length in the upper section, marking the transition between short, alternating sequences of riffles and runs, to longer stretches of riffles and runs. Few pools or backwater mesohabitat units were identified in the middle section. The lower section of the North Fork Shenandoah River is defined by long runs and artificial pools, which make up the longest individual mesohabitat units in the river. The extensive runs and artificial pools make the lower section slower to react to decreases in flow than the upstream sections.

The mesohabitat classification assisted with the selection of hydraulic data-collection reaches and fish-sampling sites. Six hydraulic data-collection reaches and 36 transects were included in the study. Each river management section contained at least one reach, and the lower section contained four reaches. Hydraulic measurements included water depths, water velocities, transect discharges, and a best-estimate reach discharge during wadeable low-, medium-, and high-flow conditions in riffles, runs, and pools with a variety of substrates. Habitat-suitability criteria of fish are based on detailed fish-community sampling on the North Fork Shenandoah River, habitat observations, and analysis of collected data. To provide information that will describe the habitat utilized by multiple species and life stages of the fish community, fish species were grouped into guilds for development of habitat suitability criteria.

Standard RHABSIM procedures were followed for each reach during calibration and simulation of water-surface elevations and velocities, and during habitat simulation. Habitat-discharge relations, or weighted usable-habitat area curves (WUA), were developed during habitat simulation. WUA curves were presented in the context of the normal flow regime for late summer and early fall. Understanding the availability of habitat during normal- and low-flow conditions on the North Fork Shenandoah River should aid water-resources managers in the creation of realistic management goals. The RHABSIM modeling results can be used to identify flow scenarios that limit or support WUA, and to identify which fish guilds are most affected in each river management section.

The upper management section has the least amount of flow, so it was expected that habitat within this reach would be most affected during low-flow periods. WUA is at a maximum at 42 ft^3/s, a flow that approximately correlates to the 25-percent exceedance flow for July, August, and September. Habitat area is limited at and below the 90-percent exceedance flow (1.6 ft^3/s). For most years, it is common in late summer and early fall for the river to sustain WUA less than the maximum WUA.

The middle management section is transitional between the headwaters in the upper section and the mouth in the lower section. It is the most diverse section of the North Fork Shenandoah River based on flow and mesohabitat, indicating that it may support fish within all guilds. The flows that sustain maximum WUA for all guilds are between 70 and 80 ft^3/s. These flows are within the normal range of flows for July, August, and September, indicating that the flows are available 50 percent of the time. WUA decreases with flows less than 75 ft^3/s, and is very limited at and below the 99-percent exceedance flow for July, August, and September (8 ft^3/s)

The lower section contains the longest and widest runs and pools. For the riffle, fast-generalist, and pool-run guilds, WUA is at a maximum at flows between 90 and 100 ft^3/s. In the lower management section, the curve for the pool-run guild contains substantially greater area than the other three guild curves. For the pool-cover guild, WUA is at a maximum at 500 ft^3/s. The WUA for the pool-cover guild is maintained at a constant level, with only slight decreases between 500 and 65 ft^3/s. WUA decreases and becomes limited at and below the 99-percent exceedance flow for July, August, and September.

The dynamic nature of WUA within the constructs of daily flow changes can be illustrated with time-series analysis. The habitat-discharge relation was overlain on the historic streamflow record, and two withdrawal scenarios were evaluated: zero water withdrawals and double water withdrawals. Flow is closely linked to habitat availability, and as the river enters a dry period, a reduction in flow generally corresponds to a reduction in WUA, and an increase in flow corresponds to an increase in WUA. During previous dry periods, time-series analysis showed that habitat availability was limited for fast-generalist and pool-cover guilds in the upper management section; for riffle, fast-generalist, and pool-run guilds in the middle section; and for no guilds in the lower section.

The zero water-withdrawal scenario (adding back water withdrawals for June, July, August, and September) showed increased WUA for fast-generalist guild species in the upper management section. In the upper section, all guilds showed improvements in WUA, but the fast-generalist guild showed the greatest response. Water withdrawals were so minimal in the middle management section that little improvement was shown. For the lower management section, there was some increase in WUA for the pool-cover guild WUA.

The double water-withdrawal scenario (subtracting water withdrawals for June, July, August, and September) showed a total loss of fast-generalist guild WUA during July to mid-August of 1999 in the upper management section. Most of the simulated daily mean flows were equal to or less than 0.5 ft^3/s during this time period, with the corresponding WUA close to zero. This scenario confirms the scarcity of water in the upper section of the North Fork Shenandoah River. Because of minimal reported water withdrawals, the double water-withdrawal scenario did not have much of an effect on simulated WUA in the middle section. The double water-withdrawal scenario showed a small decline in habitat availability for pool-cover guild species in the lower management section. Doubling of water withdrawals in this section of the North Fork Shenandoah River should have less of an effect on WUA than in the upper section.

These withdrawal scenarios show that an increase in the frequency of low flows below the flows that correspond to the maximum WUA would cause more habitat losses for riverine fish, but that water conservation measures may help to lessen the effect on habitat during low-flow periods. Decreases in flow during the high-flow season by water withdrawal and storage techniques likely would not cause more habitat losses for fish.

With the current flow regime, the model results indicate that habitat availability does not become very limited until the 90-percent exceedance flows for July, August, and September are maintained for continuous periods; however, to support quality habitat requires the maintenance of streamflows within the normal range of flows for each management section. For the upper section, maximum WUA is available at flows close to 40 ft^3/s. For July, August, and September the normal range of flows is between 4.4 and 40 ft^3/s, and the 90-percent exceedance flow is 1.6 ft^3/s. With current water withdrawals, during normal to wet years, flows naturally will remain within the range of 4.4 and 40 ft^3/s. However, during dry years, or with increased water withdrawals, flows lower than the normal range of flows would likely be maintained for continuous periods. Maintaining flows lower than the normal range of flows each summer would consistently cause decreased WUA in this section. A reduction of flows to maintain the river at one given flow could cause a decline in the variety of habitats present and may contribute to water-quality problems.

Seasonal instream conditions, current water withdrawals, and future water-use demands are all factors that can affect WUA and the extent to which a river can support a diverse fish community. Information on current and future water withdrawals and a better understanding of low-flow stream and habitat conditions, would be useful to water-resources managers in the development of a management plan for the North Fork Shenandoah River.

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Appendix 1. RHABSIM Model-Calibration Data from the Hydraulic Data-Collection Reaches

Appendix 1. RHABSIM model-calibration data from the hydraulic data-collection reaches.

[WSL, water-surface elevation; ft, feet; ft^3/s, cubic feet per second; verticals, number of measurement points along the transect; slope, average water-surface slope for all discharges measured; SZF, stage zero flow; n.d., no data; ft/s, feet per second]

Transect identification	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] (percent)	SZF[1] (ft)	Average depth (ft)	Wetted width (ft)	Manning's n[3]	Velocity mean (ft/s)
						Plains Mill						
	96.35	96.34	22.5	18					1.65	96.03	0.48	0.14
	97.03	97.05	109	106					2.24	100.65	.17	.48
1	97.11	97.10	121	n.d.[2]	35	0.1	0.0011	94.24	2.31	101.17	.17	.52
	97.50	97.54	264	n.d.[2]					2.63	103.98	.10	.97
	97.81	97.77	379	357					2.87	106.63	.08	1.24
	96.35	96.33	22.5	21					2.87	100.67	1.28	.08
	97.03	96.95	109	n.d.[2]					3.39	105.92	.37	.30
2	96.92	97.03	92.5	77	37	0	.0011	94.24	3.31	105.08	.41	.27
	97.46	97.52	264	264					3.73	108.49	.18	.65
	97.81	97.74	379	n.d.[2]					4.01	110.56	.15	.85
	97.05	97.05	22.5	22					0.60	81.12	.16	.46
	97.73	97.71	109	n.d.[2]					1.05	107.25	.11	.97
3	97.75	97.77	121	139	43	1	.0046	95.92	1.06	108.14	.10	1.06
	98.29	98.35	308	311					1.35	133.11	.07	1.71
	98.55	98.50	379	n.d.[2]					1.57	136.28	.08	1.77
	97.25	97.24	22.5	13					1.18	100.40	.15	.19
	97.92	97.95	109	105					1.64	118.02	.06	.56
3A	98.03	98.01	121	n.d.[2]	44	1	.0003	95.92	1.74	119.09	.06	.58
	98.60	98.62	308	295					2.22	124.29	.04	1.12
	98.81	98.78	379	n.d.[2]					2.40	126.12	.04	1.25
	97.24	97.23	22.5	17					3.41	122.62	1.08	.05
	97.93	97.94	109	96					3.97	127.08	.30	.22
3B	97.99	98.00	121	n.d.[2]	45	.2	.0003	95.92	4.02	127.41	.28	.24
	98.46	98.49	264	280					4.40	129.98	.15	.46
	98.80	98.76	379	n.d.[2]					4.67	132.00	.12	.61
	97.25	97.25	22.5	12					3.32	135.49	1.15	.05
	97.95	97.96	109	99					3.89	140.49	.32	.20
4	98.05	98.02	121	n.d.[2]	43	.5	.0003	95.92	3.96	141.72	.30	.22
	98.47	98.52	264	254					4.30	144.43	.16	.43
	98.83	98.79	379	n.d.[2]					4.61	146.18	.13	.56
	97.53	97.49	22.5	20					0.57	111.31	.04	.35
	98.05	98.12	109	n.d.[2]					0.85	153.53	.02	.84
5	98.14	98.18	121	134	49	.1	.0002	96.47	0.94	154.39	.02	.83
	98.61	98.63	264	n.d.[2]					1.37	158.61	.02	1.22
	98.98	98.88	379	382					1.73	160.36	.02	1.37
	97.62	97.57	22.5	24					2.08	125.95	.40	.09
	98.11	98.21	109	n.d.[2]					2.51	129.14	.12	.34
6	98.21	98.26	121	115	43	.1	.0002	96.47	2.60	129.79	.11	.36
	99.11	98.96	438	437					3.41	133.70	.05	.96
	99.02	99.07	379	n.d.[2]					3.33	133.36	.06	.85

Appendix 1. RHABSIM model-calibration data from the hydraulic data-collection reaches.—Continued

[WSL, water-surface elevation; ft, feet; ft^3/s, cubic feet per second; verticals, number of measurement points along the transect; slope, average water-surface slope for all discharges measured; SZF, stage zero flow; n.d., no data; ft/s, feet per second]

Transect identification	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] (percent)	SZF[1] (ft)	Average depth (ft)	Wetted width (ft)	Manning's n[3]	Velocity mean (ft/s)
	97.70	97.69	22.5	11					0.71	64.62	0.03	.49
	98.31	98.34	109	n.d.[2]					1.00	96.73	.02	1.13
7	98.44	98.39	121	129	39	.5	.0002	96.47	1.07	102.43	.02	1.10
	98.86	98.94	308	273					1.31	120.94	.01	1.94
	99.15	99.09	379	n.d.[2]					1.59	122.17	.01	1.95
Spring Hollow												
	95.52	95.57	94.4	87					.98	70.25	.05	1.37
1	95.76	95.70	126	125	45	0.77	.0020	93.80	1.15	74.40	.05	1.47
	96.46	96.46	432	407					1.63	87.60	.03	3.03
	95.71	95.74	94.4	99					.93	66.58	.06	1.52
2	95.92	95.89	126	128	47	.5	.0048	94.30	1.07	71.62	.07	1.64
	96.71	96.71	432	423					1.70	80.23	.05	3.17
	95.97	95.99	94.4	96					.76	75.63	.05	1.64
3	96.16	96.11	126	136	46	.5	.0048	94.60	.92	78.00	.06	1.76
	96.84	96.84	432	405					1.46	87.84	.04	3.37
	96.13	96.15	94.4	108					.78	74.85	.05	1.62
4	96.29	96.27	126	132	44	.5	.0048	94.80	.87	80.99	.05	1.79
	96.97	96.97	432	389					1.38	94.55	.04	3.31
	96.45	96.45	94.4	100					.90	99.43	.09	1.06
5	96.55	96.56	126	131	50	.5	.0048	95.20	.99	100.29	.08	1.27
	97.16	97.16	432	369					1.53	106.03	.05	2.66
Laurel Hill Farms												
	96.51	96.51	93.8	94					1.24	140.77	.07	0.54
1	96.66	96.66	120	121	47	0.5	.0004	95.50	1.38	142.27	.06	.61
	97.64	97.64	400	405					2.27	149.42	.05	1.18
	96.57	96.58	93.8	91					.90	138.10	.04	.75
2	96.73	96.72	120	111	50	.5	.0004	95.50	1.04	141.38	.04	.82
	97.69	97.69	400	415					1.93	148.95	.03	1.39
	96.78	96.78	93.8	98					.73	135.20	.03	.95
3	96.85	96.90	120	116	49	1	.0004	95.50	.79	136.34	.02	1.11
	97.72	97.72	400	411					1.61	142.31	.02	1.75
4	97.04	97.03	93.8	109					.96	119.47	.10	.82
	97.10	97.13	120	135	46	.5	.0035	95.50	1.01	120.67	.09	.98
	97.72	97.72	400	376					1.49	134.88	.06	1.99
5	97.64	97.63	93.8	193					1.02	144.50	0.37	.64
	97.68	97.69	120	186	46	.5	.0246	95.50	1.06	145.50	.31	.78
	98.00	98.00	400	388					1.36	148.25	.14	1.98

Appendix 1. RHABSIM model-calibration data from the hydraulic data-collection reaches.—Continued

[WSL, water-surface elevation; ft, feet; ft^3/s, cubic feet per second; verticals, number of measurement points along the transect; slope, average water-surface slope for all discharges measured; SZF, stage zero flow; n.d., no data; ft/s, feet per second]

Transect identification	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] (percent)	SZF[1] (ft)	Average depth (ft)	Wetted width (ft)	Manning's n[3]	Velocity mean (ft/s)
Route 648												
	89.50	89.53	83.34	n.d.[2]					0.76	135.25	0.48	0.81
	89.51	89.55	86.98	133					.77	135.40	0.48	.83
1	89.93	89.76	136.00	144	36	0	.1008	88.11	1.16	140.40	0.62	.84
	90.38	90.50	444.00	481					1.58	142.99	0.33	1.97
	90.62	90.63	526.00	n.d.[2]					1.81	144.02	0.35	2.02
	89.58	89.58	83.34	88					1.44	140.18	0.55	.41
	89.60	89.60	86.98	n.d.[2]					1.46	140.33	0.54	.42
2	90.00	90.00	136.00	135	34	1	.0142	88.11	1.82	143.34	0.51	.52
	90.48	90.48	444.00	n.d.[2]					2.28	144.86	0.23	1.34
	90.69	90.69	526.00	523					2.49	145.33	0.22	1.45
	89.59	89.59	83.34	112					2.11	131.79	0.97	.30
	89.60	89.61	86.98	n.d.[2]					2.12	131.83	0.94	.31
3	90.01	90.01	136.00	138	35	1	.0142	88.11	2.50	133.58	0.80	.41
	90.50	90.55	444.00	n.d.[2]					2.95	135.68	0.33	1.11
	90.76	90.77	526.00	617					3.19	136.79	0.32	1.21
	89.61	89.59	83.34	n.d.[2]					2.69	119.11	1.31	.26
	89.62	89.61	86.98	n.d.[2]					2.70	119.17	1.27	.27
4	90.04	90.02	136.00	126	32	0	.0142	88.11	3.06	121.76	1.02	.37
	90.60	90.59	444.00	n.d.[2]					3.52	125.70	0.41	1.00
	90.81	90.82	526.00	n.d.[2]					3.67	127.62	0.37	1.12
	89.61	89.60	83.34	n.d.[2]					1.96	134.59	0.88	.32
	89.62	89.62	86.98	106					1.97	134.74	0.85	.33
5	90.05	90.02	136.00	128	36	1	.0142	88.11	2.35	137.82	0.74	.42
	90.66	90.61	444.00	n.d.[2]					2.89	141.68	0.33	1.08
	90.82	90.84	526.00	544					3.03	142.69	0.30	1.22
	89.62	89.60	83.34	98					2.52	123.88	1.35	.27
	89.64	89.62	86.98	n.d.[2]					2.53	124.40	1.31	.28
6	90.07	90.03	136.00	124	37	.2	.0171	88.11	2.76	134.32	1.04	.37
	90.66	90.64	444.00	469					3.17	142.97	0.43	.98
	90.89	90.87	526.00	n.d.[2]					3.36	144.51	0.40	1.08
	89.65	89.60	83.34	92					1.58	137.59	0.69	.38
	89.64	89.63	86.98	n.d.[2]					1.57	137.50	0.65	.40
7	90.07	90.04	136.00	138	37	.8	.0171	88.11	1.95	141.25	0.62	.49
	90.66	90.68	444.00	n.d.[2]					2.49	144.55	0.29	1.23
	90.93	90.91	526.00	573					2.74	145.87	0.29	1.32
	89.66	89.61	83.34	85					2.21	147.14	1.29	.26
	89.66	89.63	86.98	n.d.[2]					2.21	147.14	1.23	.27
8	90.09	90.05	136.00	129	39	.5	.0171	88.11	2.57	151.31	1.04	.35
	90.69	90.73	444.00	439					3.10	155.09	0.45	.92
	90.93	90.97	526.00	n.d.[2]					3.31	156.44	0.43	1.02

Appendix 1. RHABSIM model-calibration data from the hydraulic data-collection reaches.—Continued

[WSL, water-surface elevation; ft, feet; ft^3/s, cubic feet per second; verticals, number of measurement points along the transect; slope, average water-surface slope for all discharges measured; SZF, stage zero flow; n.d., no data; ft/s, feet per second]

Transect identification	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] (percent)	SZF[1] (ft)	Average depth (ft)	Wetted width (ft)	Manning's n[3]	Velocity mean (ft/s)
						Posey Hollow						
	91.35	91.39	122	104					0s.93	180.65	0.05	0.73
1	91.77	91.66	219	239	43	0	.0006	89.7	1.33	184.55	.05	.89
	92.23	92.30	666	525					1.78	185.83	.03	2.01
	91.38	91.41	122	174					2.22	170.24	.19	.32
2	91.84	91.83	219	229	42	0.1	.0006	89.7	2.65	172.66	.14	.48
	92.32	92.33	666	761					3.10	174.21	.06	1.23
	91.38	91.42	122	127					2.35	171.12	.20	.30
3	91.85	91.85	219	220	41	0.5	.0006	89.7	2.77	174.64	.15	.45
	92.34	92.36	666	671					3.23	176.03	.07	1.17
	91.47	91.47	122	127					1.72	171.08	.12	.41
4	91.93	91.90	219	220	41	0.8	.0006	89.7	2.15	173.57	.10	.59
	92.39	92.42	666	738					2.59	175.22	.05	1.47
	91.53	91.48	122	142					2.87	184.53	.39	.23
5	91.98	91.91	219	203	44	0.2	.0009	89.7	3.26	188.04	.28	.36
	95.50	92.45	666	812					3.66	188.96	.11	.96
						Winchester Dam						
	95.39	95.37	195	130					3.81	173.18	.43	0.30
	95.40	95.41	218	178					3.82	173.23	.39	.33
1	95.88	95.90	654	752	41	0.5	.0012	94.00	4.24	175.62	.16	.88
	95.92	95.94	696	n.d.[2]					4.28	175.82	.15	.93
	96.39	96.36	1430	1436					4.69	178.16	.09	1.71
	95.40	95.39	195	183					3.70	169.25	.40	.31
	95.41	95.40	218	168					3.71	169.27	.36	.35
2	95.88	95.88	654	n.d.[2]	42	.5	.0012	94.00	4.15	170.44	.15	.92
	95.94	95.92	696	802					4.21	170.59	.14	.97
	96.40	96.40	1430	1404					4.64	171.73	.08	1.79
	95.41	95.39	195	120					4.30	168.31	.51	.27
	95.42	95.40	218	220					4.31	168.34	.46	.30
3	95.89	95.89	654	n.d.[2]	42	.5	.0012	94.00	4.75	169.52	.18	.81
	95.95	95.93	696	773					4.81	169.66	.17	.85
	96.40	96.42	1430	1379					5.23	170.70	.10	1.60

[1] Value calculated from field measurements.

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

[3] Manning's n calculated with average slope for the reach where $n = 1.486/V * R^{2/3} * S^{1/2}$ (n, coefficient of roughness; V, mean channel velocity; R, hydraulic radius, in this case, average depth; S, slope)