U.S. Department of the Interior
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A Demonstration of the Instream Flow Incremental Methodology, Shenandoah River, Virginia

Water-Resources Investigations Report 98-4157

Prepared in cooperation with the
LORD FAIRFAX PLANNING DISTRICT COMMISSION, VIRGINIA

science for a changing world

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By Humbert Zappia and D.C. Hayes

U.S. GEOLOGICAL SURVEY

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Richmond, Virginia
1998

U.S. DEPARTMENT OF THE INTERIOR
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PREFACE

This study and report could not have been accomplished without the continued cooperation and financial support of the following Virginia localities, agencies, and organizations to the Lord Fairfax District Planning Commission:

Winchester City, Va.,
Town of Berryville, Va.,
Town of Front Royal, Va.,
Town of Strasburg, Va.,
Town of Woodstock, Va.,
Clarke County, Va.,
Virginia Department of Environmental Quality,
Virginia Environmental Endowment,
Coalition of Area Environmental Organizations,
Coalition of Area River Recreational-Use Businesses.

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Velocity	
foot per second (ft/s)	0.3048	meter per second
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Current and projected demands on the water resources of the Shenandoah River have increased concerns for the potential effect of these demands on the natural integrity of the Shenandoah River system. The Instream Flow Incremental Method (IFIM) process attempts to integrate concepts of water-supply planning, analytical hydraulic engineering models, and empirically derived habitat versus flow functions to address water-use and instream-flow issues and questions concerning life-stage specific effects on selected species and the general well being of aquatic biological populations.

The demonstration project also sets the stage for the identification and compilation of the major instream-flow issues in the Shenandoah River Basin, development of the required multidisciplinary technical team to conduct more detailed studies, and development of basin specific habitat and flow requirements for fish species, species assemblages, and various water uses in the Shenandoah River Basin.This report presents the results of an IFIM demonstration project, conducted on the main stem Shenandoah River in Virginia, during 1996 and 1997, using the Physical Habitat Simulation System (PHABSIM) model.

Output from PHABSIM is used to address the general flow requirements for water supply and recreation and habitat for selected life stages of several fish species.The model output is only a small part of the information necessary for effective decision making and management of river resources. The information by itself is usually insufficient for formulation of recommendations regarding instream-flow requirements. Additional information, for example, can be obtained by analysis of habitat time-series data, habitat duration data, and habitat bottlenecks. Alternative-flow analysis and habitat-duration curves are presented.

INTRODUCTION

Because of current and projected demands on the water resources of the Shenandoah River, concerns have increased over the potential effects of these demands on the natural integrity of the Shenandoah River system. These concerns have been raised by a number of local, state, and federal agencies, as well as private citizen groups and other water-use organizations interested in preserving the natural integrity of the Shenandoah River. Because of the concern for the Shenandoah River system, a demonstration project was initiated in 1996 by the U.S. Geological Survey (USGS) in cooperation with the Lord Fairfax Planning District Commission. The demonstration project was conducted to show the utility of the Instream Flow Incremental Method (IFIM), developed by the U.S. Fish and Wildlife Service (USFWS) in addressing water-use and instream-flow issues. The demonstration project also was designed to set the stage for the identification and compilation of the major instream-flow issues in the Shenandoah River Basin, to develop the required multidisciplinary technical team to conduct more detailed studies, and to develop basin specific habitat and flow requirements for fish species, species assemblages, and various water uses in the Shenandoah River Basin.

Purpose and Scope

This report presents the results of an IFIM demonstration project conducted during 1996 and 1997 on the main stem Shenandoah River from the confluence of the North Fork and South Fork Shenandoah Rivers in Virginia to the confluence with the Potomac River in West Virginia. This report presents background information on the IFIM process, output from hydraulic and physical habitat simulation models, and additional information on analyzing the effect of alternative flows on habitat availability. The report relates model output to generalized flow requirements for water supply and recreation, and habitat for selected life stages of several fish species. A habitat-duration curve is developed through analysis of habitat time-series data for recreation.

Acknowledgments

The authors would like to thank the following individuals and organizations for their expertise, time, and moral and financial support in completing the demonstration project: Amy Derosier, USGS, Dr. Donald Orth, Virginia Technical Institute (VT); Mathew Chen, VT; Dr. Edward Pert, VT; Daryl Bowman and Larry Mohne, Virginia Department of Game and Inland Fish (VDGIF); and Lord Fairfax Planning District Commission. The authors also would like to thank all the members of the technical planning committee and technical advisory committee for their time and support, as well as their genuine interest in the health of the Shenandoah River Basin. The authors are especially thankful to all the land owners for their interest in the study and for freely giving access to the Shenandoah River.

DESCRIPTION OF THE SHENANDOAH RIVER BASIN

The Shenandoah River Basin lies in northwest Virginia (fig 1.) The basin is bounded by the Rappahannock River Basin to the east, the James River Basin to the south, and the Potomac River Basin to the west and north. The Shenandoah River Basin is drained by the Shenandoah River and its two major tributaries, the North Fork and South Fork Shenandoah Rivers. These three rivers flow northeast, parallel to the Blue Ridge Mountains, through the valleys of the Valley and Ridge Physiographic Province. The basin extends approximately 120 mi northeast from the headwaters in Augusta County, Va., to the Potomac River at Harpers Ferry, W. Va. The basin width averages 30 mi (Virginia State Water Control Board, 1988).

The Shenandoah River Basin exists almost entirely within the Valley and Ridge Physiographic Province, with the exception of a narrow strip along the eastern basin that is within the Blue Ridge Physiographic Province. The basin topography is characterized by rolling hills and valleys with the Blue Ridge Mountains along the eastern edge and the Massanutten Mountain Range dividing the North and South Fork Shenandoah River Basins (Virginia Department of Conservation and Economic Development, 1968).

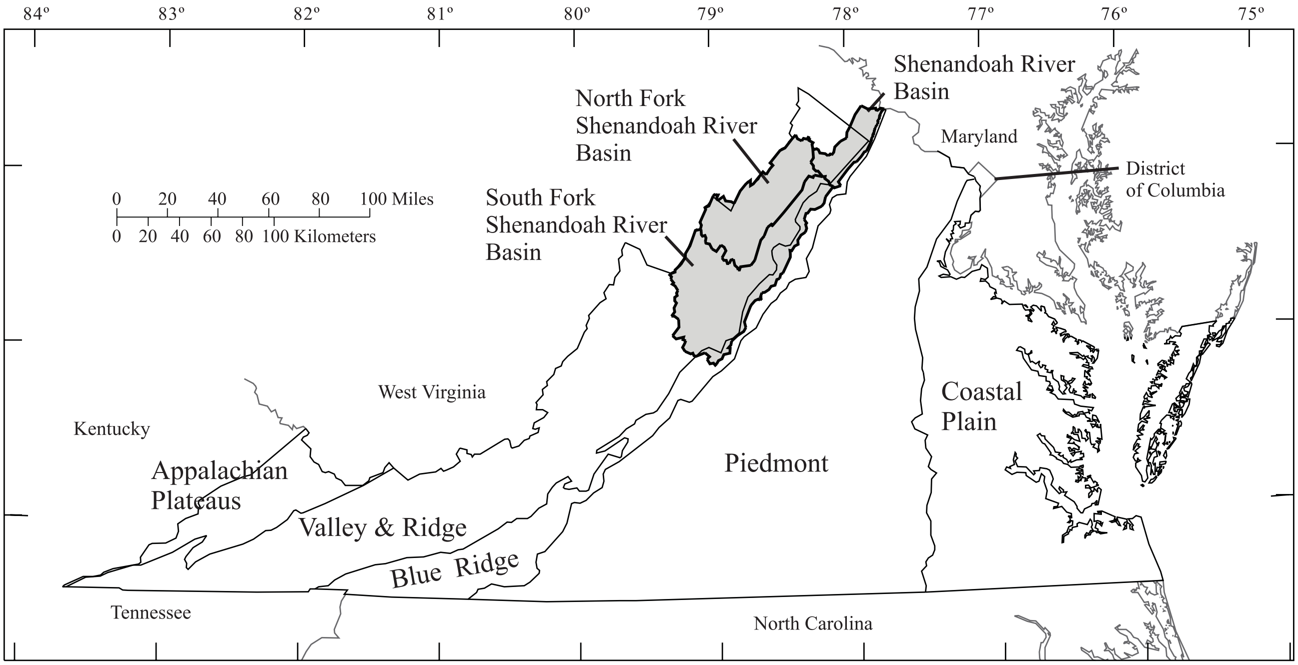

Figure 1. Shenandoah River Basin and physiographic provinces of Virginia.

The northeast-southwest trending ridges of the Valley and Ridge Physiographic Province are formed by resistant quartzite, sandstone, and conglomerates; the valleys are underlain by more readily weathered limestone, shale, and dolomite. The Blue Ridge Physiographic Province consists mainly of metamorphic and igneous rocks, with some sedimentary rock on the western slope (Hayes, 1991).

The Shenandoah River Basin is subject to greater extremes in temperature and precipitation than parts of Virginia east of the Blue Ridge Mountains. The average annual temperature is 51°F; extremes are well below 0°F and above 100°F. Annual precipitation averages approximately 39 in., and ranges from 35 in. to 50 in. (Virginia Department of Conservation and Economic Development, 1968). The greatest variation of precipitation within Virginia is in the Shenandoah River Basin where annual precipitation averages from 36 to 48 in. per year over 50 mi (Hayes, 1991). Annual snowfall averages approximately 35 in. in the mountains and is less in the valleys (Virginia Department of Conservation and Economic Development, 1968).

The Shenandoah River Basin is subject to strong frontal passages during the winter and thunderstorms during the summer. Prevailing wind from the southwest brings warm, moist air from the Gulf of Mexico in addition to moist air drawn in from the Atlantic Ocean. Strong cold fronts move across the basin from the northwest and clash with the warm, moist air, causing most of the basin's precipitation. Precipitation during the summer, generally caused by thunderstorms, is heavy but sporadic (Hayes, 1991).

Steep slopes in the mountains are characterized by thin soils, thus reducing the amount of ground-water storage and causing rapid runoff of surface water during storms. The geology of the western toe of the Blue Ridge is characterized by a thick mantle of residuum, talus, and alluvial deposits that overlay carbonate rocks on the eastern slope of the Valley and Ridge Physiographic Province. The residuum may exceed 600 ft in thickness and maintains base flows (Hayes, 1991; Nelms and others, 1997).

The flow-duration curve for the Shenandoah River at Millville, W. Va., is shown in figure 2. The flow-duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharges were equaled or exceeded for a given period. It also shows the integrated effect of various factors that affect runoff, such as climate, topography, and geology. If the discharge on which the flow-duration curve is based represents the long-term flow conditions of the stream, the curve may be used to estimate the percentage of time specified discharges will be equaled or exceeded in the future (Searcy, 1959). For example, the daily mean flow of 508 ft^3/s is equaled or exceeded 95 percent of the time and 1,630 ft^3/s is equaled or exceeded 50 percent of the time (fig. 2).

Land use in the Shenandoah River Basin creates the rural character for which the region is known. Approximately 59 percent of the area is forest and wetlands (U.S. Environmental Protection Agency, 1996). Approximately 38 percent of the area is agricultural with half in row crops and the other half in pasture,

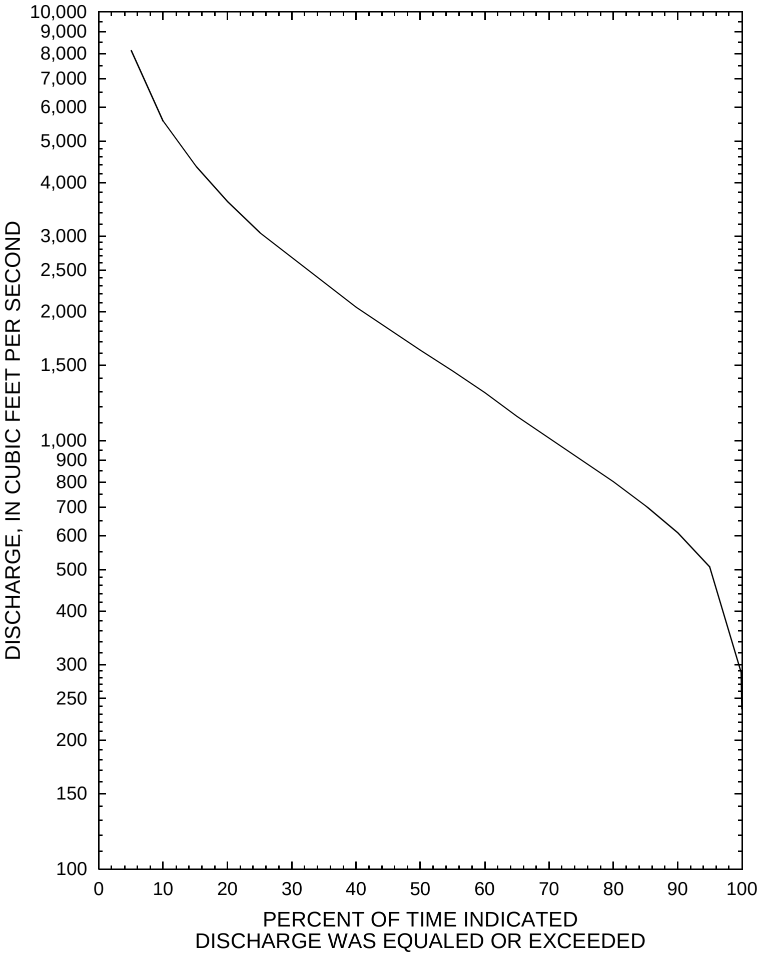

Figure 2. Flow-duration curve for the Shenandoah River at Millville, West Virginia, 1896-1996.

hay, or grass. Less than 3 percent of the area is developed.

Approximately 294,000 people live in the Shenandoah River Basin; the majority (178,000 persons) reside in the South Fork Shenandoah River Basin (Solley and others, 1998). The populations of the North Fork Shenandoah River Basin and the main stem Shenandoah River Basin are approximately 92,000 and 24,000 persons, respectively.

Water use is identified for each basin by groundwater and surface-water withdrawal (table 1). Forty percent of the offstream water use (all water-use categories except hydroelectric) in the Shenandoah River Basin is from surface-water sources. Seventy-two percent of the total water use in the main stem Shenandoah River Basin is withdrawn from surface-water sources. Thirty-one percent of the total water use in the South Fork Shenandoah River Basin is from surface-water sources; 55 percent of the total water use in the North Fork Shenandoah River Basin is from surface-water sources (Solley and others, 1998).

INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM)

Because of the large-scale development of reservoirs and other water-use projects over the last 70 years in the western United States and the resulting habitat loss, guidelines were developed by many states to protect remaining stream resources. Many assessment methods that rely on hydrologic and empirical habitat information have been developed. These methods usually produce single thresholds for minimum flow below which water may not be withdrawn for consumptive use (Stalnaker and others, 1995).

In the last 20 years, attention has shifted from establishing a threshold for minimum flow to methods capable of quantifying the effects of incremental changes in streamflow. Attention has shifted because single minimum instream flows are commonly inadequate to protect the aquatic resource. The IFIM that was developed under the guidance of the USFWS is a process utilizing various technical methodologies to

Table 1. Withdrawals for water-use categories for the Shenandoah River Basin, 1995

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

Water use	Main Stem Shenandoah River Basin		North Fork Shenandoah River Basin		South Fork Shenandoah River Basin	
	Ground water Mgal/d (ft^3/s)	Surface water Mgal/d (ft^3/s)	Ground water Mgal/d (ft^3/s)	Surface water Mgal/d (ft^3/s)	Ground water Mgal/d (ft^3/s)	Surface water Mgal/d (ft^3/s)
Public supply	0.15	2.92	2.67	7.75	14.9	10.42
	(0.23)	(4.52)	(4.13)	(12.0)	(23.0)	(16.1)
Commercial	.20	.07	.41	.29	1.53	.26
	(.31)	(.11)	(.63)	(.45)	(2.37)	(.40)
Domestic	1.02	.00	3.80	.00	4.90	.00
	(1.58)	(.00)	(5.88)	(.00)	(7.58)	(.00)
Industrial	.03	.04	1.27	.41	16.2	4.44
	(.05)	(.06)	(1.96)	(.63)	(25.0)	(6.87)
Livestock	.09	1.31	.74	1.86	.31	1.25
	(.14)	(2.03)	(1.14)	(2.88)	(.48)	(1.93)
Irrigation	.17	.00	.00	.61	.03	.78
	(.26)	(.00)	(.00)	(.94)	(.05)	(1.21)
Hydroelectric	.00	.00	.00	207	.00	796
	(.00)	(.00)	(.00)	(321)	(.00)	(1,230)
Total	1.66	4.34	8.89	217.92	37.87	813.15
	(2.57)	(6.72)	(13.74)	(337.90)	(58.48)	(1,256.51)

evaluate changes in the amount of estimated usable habitat for various species or groups of species as flow changes.

IFIM Process

The IFIM process attempts to integrate concepts of water-supply planning, analytical hydraulic engineering models, and empirically derived habitat versus flow functions to address questions concerning life-stage specific effects on selected species and the general well being of aquatic biological populations (Stalnaker and others, 1995). The IFIM process should be thought of as a water-management tool rather than an ecosystem model (Bovee, 1982). A key component of the IFIM process is the interaction and communication of all stakeholders or parties directly and indirectly affected by flow issues. Only through cooperation and communication can the stakeholders identify the problems and concerns, determine the effects of various alternatives through a technical analysis, and recommend and implement plans and policy to minimize adverse effects of low-flow periods.

When applying the IFIM process, various technical methods are available for long-range planning of instream flows, depending on the intensity and complexity of the issues being addressed (Stalnaker and others, 1995). The technical methods available for long-range planning of instream flows are (1) standard-setting techniques, (2) mid-range techniques, and (3) incremental techniques (Stalnaker and others, 1995). After application of one or more of these technical methods, specific recommendations for long-term planning can be made, and water-use limitations can be negotiated.

Standard-setting techniques are commonly used for instream flow issues of low-intensity, where minimal detail and effort are required. Standard-setting techniques are usually quick, reconnaissance-level, office type approaches, using existing information.

Mid-range techniques can require substantially more effort than standard-setting techniques but are applicable to flow issues of greater complexity. Mid-range techniques usually require the collection of hydrologic and biological data from specific study areas to determine the potential adverse effects of flow alteration.

When flow issues require intense negotiations and are extremely complex, incremental techniques are needed. Incremental techniques give a more complete picture of the effects of flow alteration than the best mid-range techniques. Incremental techniques require substantially more effort than other techniques, however, and are distributed over a much longer period of time (Stalnaker and others, 1995).

Instream Flow Technical Methods

This demonstration project utilized a mid-range technique on the Shenandoah River. The method applied required the use of hydraulic and habitat simulation models contained in the Physical Habitat Simulation System (PHABSIM) on a selected study reach on the Shenandoah River. The report gives examples of the types of simulation results obtained through the PHABSIM model as well as an example of a habitat-duration curve developed from the model output and discharge records.

Stream segments are the basic habitat subdivisions of a river when using the IFIM. The characteristic feature of a stream segment is uniform flow regime and geomorphology (slope, sinuosity, channel structure, geology, and land use). Flow regime normally is the primary factor for selecting the segment boundaries. The steady-state discharge at the upstream or downstream boundary should be within 10 percent of the discharge at any cross section in a segment. Stream segments may be relatively long parts of the stream (Bovee, [n.d.]a, Bovee, 1982).

Stream segments can be subdivided by either mesohabitat types or reaches. Mesohabitat types typically are the same order of magnitude in length as the channel width and are defined by the local channel slope, shape, structure, flow depth, and flow velocity. Riffles, runs, pools, bars, and divided channels are some stream features that are commonly classified as mesohabitat types. Each reach, sometimes called a representative reach, generally contains many or all of the mesohabitat types found in the segment and is typically one order of magnitude longer than the channel width for alluvial channels (10-15 stream widths in length) or one meander wave length for bedrock-controlled or colluvial channels. Data sampled at one or more reaches or at selected mesohabitats represent the hydraulic, geomorphologic, and habitat conditions within the stream segment (Bovee, [n.d.]a).

Leopold, and others (1964) noted that riffles tended to repeat every 7-10 channel widths in alluvial channels. This information was used to develop the underlying assumption of the representative reach that mesohabitat types are found in a repetitive pattern (Bovee, [n.d.]a). In a representative reach, each major mesohabitat type should be represented at least once and in the same proportion as in the stream segment (Bovee, [n.d.]a). Any reach selected within a stream segment, therefore, is theoretically very similar in habitat characteristics to any other reach selected within that segment. A reach selected at random would, therefore, be representative of the segment (Bovee, 1982). Use of the representative reach for representation of a stream segment works best in alluvial channels (Bovee, [n.d.]a).

In mesohabitat typing, all mesohabitat types in a stream segment are defined and inventoried to determine the proportion of the stream segment represented by each mesohabitat type. This approach was developed for stream segments where mesohabitat types occurred randomly with an irregular distribution throughout the stream segment, and use of the representative reach was inappropriate (Morhardt and others, 1983). Data are sampled to represent each mesohabitat type rather than the stream segment. The stream segment is represented by the data collected in each mesohabitat type, weighted by the proportion of the mesohabitat type in the stream segment (Bovee, [n.d.]a).

Whether the stream segment is represented by the representative reach or mesohabitat typing, PHABSIM is used to model the hydraulics and habitat conditions for selected discharges. Data collected by either method are used to calibrate the model. The calibrated model is then used to simulate hydraulic conditions at selected flows other than those directly measured. If the representative reach method is used, the PHABSIM model is used to analyze channel geometry, flow, and habitat through transects and stream cells established in the reach and to determine the relation between habitat and discharge for the reach. In the representative reach method, the sequence and spacing of mesohabitat types in the reach represent the sequence and spacing of mesohabitat types in the segment.

If the mesohabitat typing method is used, the PHABSIM model is used to analyze channel geometry, flow, and habitat through transects and stream cells established in the individual mesohabitat types. A synthetic reach is then developed where transects and stream cells in each mesohabitat type are weighted according to the proportion of that mesohabitat type in the segment. The relation between habitat and discharge for the stream segment is represented by the relation between habitat and discharge of the synthetic reach. The synthetic reach may represent the sequence of mesohabitat types in the segment, but it does not represent the actual spacing between transects.

The hydraulic part of the PHABSIM model requires two types of data for the simulation of flow in the stream (Bovee, [n.d.]b): (1) channel structure, and (2) hydraulic variables. Channel-structure data include channel geometry and substrate classification and distribution, as well as other structures relevant to the issues being addressed. Hydrologic variables include water-surface elevation, width, depth, velocity, wetted perimeter, discharge, and surface area. The hydraulic model simulates hydraulic variables at unmeasured discharges (Bovee, [n.d.]b). Simulated variables are used as a substitute for repeated empirical measurements at numerous flows (Bovee, [n.d.]c). Channel structure and hydraulic variables then can be used to generate a computerized “map” of a composite stream reach representing the study stream reach. The composite stream reach is depicted as a mosaic of stream cells (fig. 3). At any given discharge, each cell will have a unique combination of hydraulic and stream channel characteristics (Bovee, [n.d.]b).

Hydraulic simulation with PHABSIM assumes that channel geometry does not change with discharge

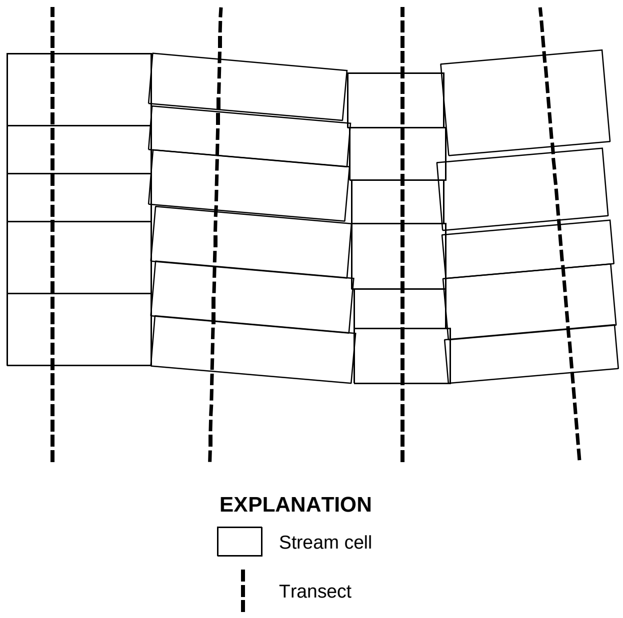

Figure 3. Schematic diagram of a composite stream reach depicting transects and stream cells. At any given flow, each cell will have a unique combination of hydrologic and stream-channel characteristics.

over the range of flows simulated. The results of the hydraulic calculations are water-surface elevations and velocities. Water depths used in the habitat programs are calculated from the water-surface elevations simulated in the hydraulic programs and the channel geometry. The water-surface elevation for a simulated discharge at a transect is used for all the cells in that transect. In contrast, velocities vary from cell to cell in the transect. The hydraulic model assumes water-surface elevations are independent of the velocity distribution in the channel (Bovee, [n.d.]c).

Three methods are available in the model for calculation of water-surface elevations: (1) direct stage-discharge relation or rating curve, (2) use of Manning's equation, and (3) the step-backwater method. Any single method or combination of methods can be used to determine water-surface elevations for simulated discharges through the reach. In the direct stage-discharge relation method and the Manning equation method, the transects are independent of each other. In the step-backwater method, the transects are not independent of each other (Bovee, [n.d.]c).

The PHABSIM model uses an empirically-derived rating curve to predict water-surface elevations from the stage-discharge relation. A least-squares regression is fit to three or more pairs of log-transformed stage-discharge data. In reality, the regression is performed on the water-surface elevation minus the stage of zero flow (Bovee, [n.d.]b).

The habitat part of the PHABSIM model requires hydraulic variables simulated in the hydraulic model and habitat suitability curves (SI's) developed by use of direct field observation or by expert opinion. SI's can be used to relate the adequacy of hydraulic conditions to provide usable habitat for aquatic biota or support the water use of interest. SI's and water-use flow requirements are combined with hydraulic conditions to rank the suitability of each stream cell in a computerized map for the aquatic biota or a water use of interest.

SI's are classified into four categories on the basis of their method of development. Category I SI's are very general and are based on information other than field observations from the study area. They are usually derived from scientific literature and from professional experience and judgement. Category I SI's should be used in low effort and intensity IFIM studies. Category II SI's (utilization curves) are intended to be realistic and are based on frequency analysis of field data from the study area. Category III SI's also are based on field data from the study area but have been corrected for environmental bias, such as the greater availability of one habitat type than another, and represent habitat preferences of the species in question. Category IV SI's (conditional preference curves) describe habitat requirements as a function of the interaction among many stream variables (Bovee, 1986; Twomey and others, 1984).

The relative rankings of the suitability of the stream cells in a computerized map generated by PHABSIM can be expressed as weighting factors ranging from 0 to 1. The weighing factors are based on a composite suitability index (CSI). A CSI can be mathematically calculated from a combination of several different habitat variables. Several aggregation techniques are available to determine a single CSI for a stream cell. This study uses a multiplicative aggregation given by:

$$CSI_i = V_i \times D_i \times S_i , \qquad (1)$$

where CSI_i is the composite suitability index for cell i,

V_i is the suitability index associated with the velocity in cell i,

D_i is the suitability index associated with the depth in cell i, and

S_i is the suitability index associated with the substrate type in cell i (Bovee, [n.d.]c).

When the weighting factors are multiplied by the surface area of the cell for a specified discharge, weighted usable area (WUA) is the result (Bovee, [n.d.]b). The WUA for a reach can be determined by summing the WUA of the individual cells at the specified discharge. A functional relation between discharge and habitat availability is produced by calculating the WUA at multiple discharges (fig. 4). In addition, the total suitable area can be determined by summing the area of all the cells in the reach that have a CSI greater than zero.

Other aggregation methods may be used to calculate the CSI for each cell. Two additional aggregation methods that are commonly used are the geometric mean and the limiting factor methods (Bovee, [n.d.]c).

In addition to WUA, each cell in the stream reach can be classified as being optimal, usable, suit-

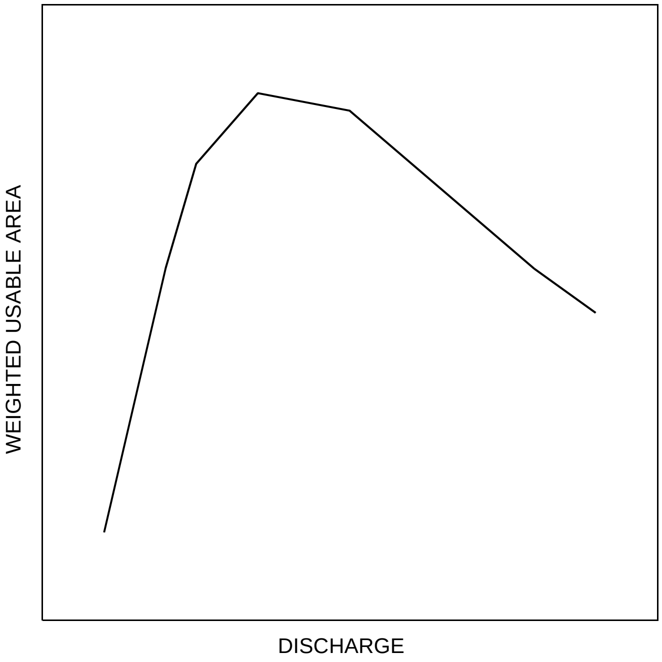

Figure 4. Generalized relation of weighted usable area to discharge.

able, or unsuitable for the species or water use of interest (Bovee, [n.d.]b). The stream cells are classified in this manner by comparing the habitat variables (depth, velocity, substrate) within the cells at a given discharge to habitat suitability criteria (HSC). A stream cell is considered optimal if all of its habitat variables are classified as optimal on the basis of their HSC's. A stream cell is considered usable if one or more of its habitat variables are classified as usable, but none are classified less than usable. A stream cell is considered suitable if one or more of its habitat variables are classified as suitable, but none are classified as unsuitable. A stream cell is considered unsuitable if one or more of its habitat variables are classified as unsuitable (Bovee, [n.d.]b).

HSC's are developed by various methods. One method that can be used classifies optimal habitat as the middle 50 percent of values where species were observed or water use is possible and corresponds to a range of SI's from 0.85 to 1.0. Usable habitat is classified as the central 75 percent of the values where species were observed or a water use is possible and corresponds to SI's greater than 0.25. Suitable habitat is classified as the full range of conditions where a species is observed or a water use is possible. Unsuitable habitat is considered everything else (Bovee, [n.d.]b).

Habitat time-series information is used to analyze the effect of various alternative-flow scenarios on habitat availability. Development of alternative-flow scenarios should be based on habitat requirements of multiple species and water uses, and the ability to alter the flow. Usually, multiple scenarios are developed and the effects on habitat analyzed to assist in addressing water-use and instream-flow issues. The alternative flow is often achieved through reduced water withdrawals and modified releases from impoundments.

Discharge records are combined with the habitat-discharge relation determined through PHABSIM to generate a habitat time series. One tool used to assist in the alternative-flow analysis is the habitat-duration curve. Habitat-duration curves are developed to summarize the availability of habitat over time and are produced in the same manner as the flow-duration curve except the time series of flow is replaced by the time series of available habitat.

APPLICATION OF THE IFIM TO THE SHENANDOAH RIVER

The demonstration project on the Shenandoah River began in 1996 and utilized a mid-range technique. The technique used a hydraulic model and habitat model contained in the PHABSIM on a study reach in the Shenandoah River Basin. This method gives an example of the types of results obtained through the IFIM process.

The main stem Shenandoah River was divided into three stream segments for application of the IFIM: (1) the upper stream segment, from the confluence of the North Fork and South Fork Shenandoah Rivers to the U.S. Highway 17 bridge; (2) the middle stream segment, from the U.S. Highway 17 bridge to the Virginia-West Virginia State line; and (3) the lower stream segment, from the Virginia-West Virginia State line to the confluence of the Shenandoah and Potomac Rivers (fig. 5). The segments are subdivided primarily on the basis of physical channel structure and flow regulation rather than on the basis of discharge. No major tributaries enter the river between the confluence of the North and South Forks and the confluence of the Shenandoah River with the Potomac River. During base flow, discharge in the Shenandoah River increases 15-20 percent over its entire length.

The upper stream segment is 18.1 mi in length and consists primarily of runs and pools. Approximately 8.7 mi of the stream are classified as run habitat and 8.4 mi are classified as pool habitat. Riffles, which are not numerous, are short and aligned perpendicular

Figure 5. Shenandoah River and stream segments.

to the channel. Approximately 1.0 mi of the stream is classified as riffle habitat. One island chain, approximately 1.3 mi in length, is in the segment. The uppermost pool is created by a power plant dam located approximately 3.5 mi below the confluence of the North and South Forks. The dam pools water upstream to the confluence and likely limits sediment transport through the segment.

The middle stream segment is 17.7 mi in length and consists of riffles, runs, and pools. Approximately 14.2 mi of the stream are classified as run habitat, and 1.9 mi are classified as pool habitat. Riffles are more numerous and longer than those in the upper stream segment. The riffles are formed either from bedrock outcrops or alluvium and may be aligned up to 30 degrees from perpendicular to the channel. Approximately 1.6 mi of the stream is classified as riffle habitat. Three island chains are in the segment; the average length is approximately 1.6 mi. No dams are within the segment, and dams upstream and downstream have little influence on flows. The Town of Berryville, Va., operates a water-supply intake on the west bank of the Shenandoah River approximately 0.5 mi upstream from the mouth of Craig Run. In addition, the Town of Berryville, Va., discharges treated wastewater approximately 1 mi upstream from the Virginia Highway 7 bridge over the Shenandoah River.

The lower stream segment is 16.8 mi in length and primarily consists of runs and riffles. Data are limited concerning pools. Total lengths of run, pool, and riffle habitat were not determined. From observation, riffle habitat is more abundant in the lower segment than in either of the other segments. The riffles are formed primarily from bedrock outcrops and are commonly aligned up to 45 degrees from perpendicular to the channel. One island chain, approximately 0.8 mi in length, is in the segment. A power plant dam is located 5.0 mi above the confluence of the Shenandoah and Potomac Rivers. The dam likely limits the flow and sediment transport through the segment.

Three mesohabitat types were identified when selecting stream segments: pools, riffles, and runs. For this study, definitions for each mesohabitat type are from Meador and others (1993). Pool habitat was delineated for the upper two segments of the Shenandoah by the VDGIF in a separate study to determine available muskellunge habitat in the Shenandoah Basin. The VDGIF pool-habitat data were used as a preliminary delineation of pool habitat for this study. Black and white aerial photos from the National Aerial Photography Program (1:40,000 scale) and USGS topographic maps (1:24,000 scale) were used for preliminary delineation of riffle habitat. Delineated pool and riffle habitats were transferred from the VDGIF study and aerial photos to the topographic maps for field verification.

Much of the river was observed from roads along either bank for verification of mesohabitat types. VDGIF pool-habitat delineations were not modified during the field verifications. Riffle-habitat delineations were modified during the field verification, usually by increasing the areas designated as riffle habitat. Any areas not delineated as pool or riffle habitat were considered run habitat. Total length of mesohabitat types delineated for the upper and middle stream segments of the Shenandoah River is summarized in table 2. Total length of mesohabitat types was not delineated for the lower stream segment because pool-habitat data were not available.

Table 2. Inventory of mesohabitat types for the upper and middle stream segments of the Shenandoah River

Mesohabitat type	Length in miles	Percentage of segment length
Upper stream segment		
Riffle	1.0	5.5
Run	8.7	48.1
Pool	8.4	46.4
Total	18.1	100
Middle stream segment		
Riffle	1.6	9.0
Run	14.2	80.3
Pool	1.9	10.7
Total	17.7	100

Selection of Study Reach and Transect Locations

The middle stream segment was selected for the study primarily because mesohabitat types tend to occur in a somewhat repetitive pattern and because of the limited flow regulation caused by dams. Dams in the upper and lower stream segments modified the flow and mesohabitat in their respective segments. Also, access to the river for data collection is available at three locations along the middle stream segment.

A representative reach that includes many of the mesohabitat types found in the stream segment and was accessible was selected. The 3.2 mi long reach begins at a discontinued water-supply intake for the Town of Berryville, Va., approximately 2.5 mi upstream of the Virginia Highway 7 bridge over the Shenandoah River (fig. 6) and ends approximately 300 ft upstream of the existing water-supply intake for the Town of Berryville, Va. Riffle habitat constitutes approximately 12 percent of the reach length; run habitat constitutes approximately 73 percent of the reach length. The pool habitat constitutes approximately 15 percent of the reach length; however, only one pool is in the reach. On the basis of an average 400-ft width for the Shenandoah River, the desired length for a representative reach is 4,000-6,000 ft. The reach selected is considerably

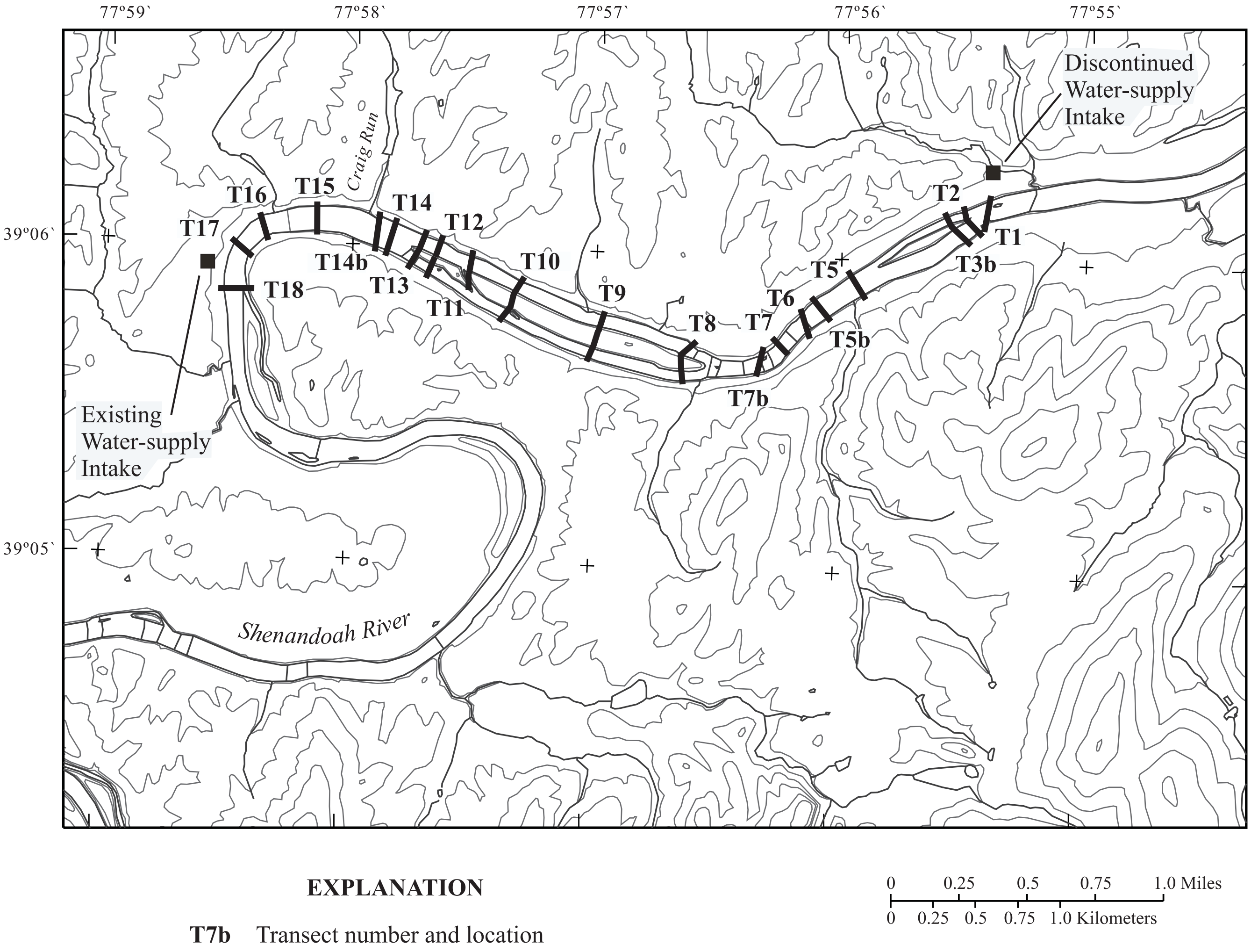

Figure 6. Study reach and transect locations.

longer because of the inconsistent channel structure, particularly in the riffle habitat. The only well defined riffle habitat that extends across the entire channel and that maintains hydraulic control through a wide range of base flows is located at the discontinued water intake for the Town of Berryville, Va. The first available pool habitat is located 3 mi upstream from this location.

Twenty transects were installed in the representative reach (fig. 6). Four transects were located in pool habitat, 10 transects were located in run habitat, and 6 transects were located in riffle habitat. Transects were established by use of guidelines in Bovee ([n.d.]a). Headpins, made from rebar about 2.0 ft in length, were installed along the north bank of each transect just above the bank-full stage elevation. Tailpins, made of the same type rebar, were installed along the south bank at similar bank-full stage elevations. Additional pins were installed on each side of the islands that divided the channel. Lag bolts placed in trees near the headpins of each transect were used as benchmarks. The lag bolts provided permanent vertical control for surveying the transect cross-section profile and water-surface elevations. Benchmarks also were established on the south bank where the channel was divided by islands.

Horizontal control for the transects was established by use of a Global Positioning System (GPS) to determine Universal Transverse Mercator (UTM) coordinates for two headpins. The remaining headpins, tailpins, and benchmarks were surveyed by use of a theodolite with electronic distance measuring equipment. Vertical control was established from a given elevation of a mill tailrace at transect 16. Levels were run to all benchmarks by use of the theodolite.

Calibration and Simulation of Hydraulic Conditions

Data were collected at verticals along transects to represent hydraulic and geomorphologic conditions in each cell in a reach. Water-surface elevations, or stage, were determined at each transect for several measured discharges (3,010, 1,900, and 907 ft^3/s). Some transects had one additional stage-discharge pair that was collected when cross-sectional data were collected at the verticals in the transect. At each vertical in a transect at a single discharge, depth, mean velocity, and substrate type were determined. Cell width was determined from the spacing of the verticals. Channel structure and hydraulic variables were collected by use of standard USGS discharge-measurement procedures described in Rantz and others (1982), except the data were collected at about 40 verticals at each transect rather than the recommended 25-30 verticals to better define the habitat areas near the bank. Substrate was classified as either silt or clay, sand, gravel, or bedrock. When more than one substrate type was observed at the vertical, such as gravel and bedrock, the coarser material was considered dominant. Substrate data were obtained by visual observation or by prodding the bottom with a measuring rod.

The direct stage-discharge relation method was used exclusively for calibration of water-surface elevations and discharges because multiple pairs of data were measured across a range of observed discharges, and because a major storm in September 1996 modified much of the channel geometry. About one third of the hydraulic data were collected after the storm, and adjustments for channel modifications were necessary. The stage-discharge relation was the best method for making these adjustments. The Manning's equation method was not used because many transects had section control during the lower flows and channel control during the higher flows. The stage-discharge relation method worked better in these flow conditions. The step-backwater method was not used because the distance separating the transects was too great for calibration and all controls in the reach needed to be defined by a transect. (Bovee, [n.d.]c).

In the direct stage-discharge relation method, calibration was performed by plotting the least-squares regression line and paired stage-discharge data to check the linearity of the relation. Adjustments were made to the stage of zero flow to reduce the error in the least-squares regression. At transects where the relation was not linear, the stage of zero flow was selected that would give the best fit at the lower discharges.

Velocities were calibrated by use of a single velocity data set collected at one of the three measured discharges according to the procedures outlined in Bovee (ed., [n.d.]b; [n.d.]c). A mean velocity was determined for each cell vertical in each transect. Manning's equation was used to calculate a roughness coefficient for each cell. When another discharge was simulated, PHABSIM obtains a new water-surface elevation corresponding to the new discharge from the stage-discharge relation. New depths were determined for each cell, the roughness coefficient was held constant, and a new mean velocity was computed. An estimated discharge was then computed by use of the new widths, depths, and velocities of all cells in the transect and compared to the simulated discharge. A velocity adjustment factor (VAF) was computed from the ratio of the simulated and estimated discharge. Corrected mean velocities were calculated by multiplying the new mean velocities by the VAF. The VAF is plotted against discharge as an indicator of model performance and should range between 0.2 and 5.0. The PHABSIM model is better at predicting velocities for discharges less than the discharge where the calibration velocities were measured (Bovee, [n.d.]b; Bovee, [n.d.]c).

A synthetic reach was developed from the available transects to represent the river segment rather than a representative reach because of the large spacing between the transects and the inability to calibrate the model to data collected at all the transects. The transect spacing caused cells to extend over large distances such that the data collected at a vertical did not accurately represent the habitat of the entire cell. Of the 20 transects located in the reach, 15 were used in the synthetic reach. The remaining five transects either had no depth and velocity data collected because of time constraints, or the hydraulic data could not be calibrated in the model because of flood damage to the channel or destruction of the transect location pins and benchmarks.

The synthetic reach was developed by use of four transects that represented riffle habitat, three transects that represent pool habitat, and eight transects that represent run habitat. The length of the synthetic reach was 1,000 ft, and cell lengths were defined so that each mesohabitat type represented the appropriate percentage of that habitat in the segment. Cells from the four transects representing riffle habitat were 9.0 percent of the synthetic reach. Cells from the three transects representing pool habitat were 10.7 percent of the reach, and cells from the eight transects representing run habitat were 80.3 percent of the reach.

After model calibration, hydraulic conditions were simulated for discharges ranging between 60 and 3,000 ft^3/s. Depths and mean velocities are computed for each cell at the simulated discharges. Substrate data determined in the field remained constant for all simulated discharges. The depth, velocity, and substrate type, as a function of discharge, are then integrated with habitat SI's to produce a measure of the relation between habitat and discharge (Bovee, [n.d.]c).

The minimum simulated flow of 60 ft^3/s is well below the recommend maximum extrapolation of 40 percent of the minimum measured flow (Bovee, [n.d.]c) or about 350 ft^3/s. Extrapolation to this extent is necessary for the purpose of the demonstration project because flows were never much lower than 900 ft^3/s during the data-collection period, and the size of the river is such that habitat is not significantly reduced until extreme low flows are encountered. The minimum flow of 60 ft^3/s was chosen because that is the approximate minimum flow for the period of record at the USGS discharge-measurement station, Shenandoah River at Millville, W. Va.

Simulation of Physical Habitat Requirements

After the hydraulic model has been calibrated and flow conditions simulated, the stage, velocity, depth, and substrate relations can then be used to determine the effect of different flows on various water uses and habitat availability. Flow requirements for water use and aquatic biota are typically developed for specific stream systems and study areas. For the purpose of the demonstration project, generalized information concerning selected water use and physical habitat flow requirements have been used in this report. This information has been drawn from a number of sources and is not known to be applicable to the Shenandoah River. The information presented for this demonstration should not be used to determine the actual relation between discharge, water use, and habitat availability in the Shenandoah River Basin.

Water Supply

The Town of Berryville, Va., withdraws water from the Shenandoah River upstream of Craig Run (fig. 6). The water-withdrawal system has a capacity of 0.864 Mgal/d (1.34 ft^3/s) and operates from an upper and lower intake. Although it is doubtful that the lower intake would ever be exposed, because it is at or below the level of the streambed, the upper intake could be above the water surface at some extreme low flow (table 3). If the upper intake is no longer submerged, the efficiency of withdrawal could decrease, and the ability to adequately supply water to the town's citizens could be reduced (Glenn Tillman, Director of Utilities, oral commun., 1998).

Table 3. Elevation of intakes and minimum discharge necessary for operation of the Town of Berryville, Va., withdrawal point
[<, less than]

Intake	Elevation in feet above sea level	Approximate discharge in cubic feet per second below which intake is unusable
Upper	378.7	700
Lower	375.7	<100

Recreation

Recreation activities require a minimum flow below which those activities are not possible. For example, canoeing may be impossible at discharges that produce significant areas in the stream that do not allow canoe passage or a WUA that equals zero (Nestler and others, 1985).

There are flows that are greater than the minimum flow, at which the recreation is possible, but substantially degraded. Examples of degraded conditions for canoeing may include stream segments where depths across the stream are so shallow as to require significant amounts of portage or where velocities are so reduced as to require constant paddling.

Generalized habitat SI's for canoeing in a river are presented in figure 7. The curves represent generalized depth, velocity, and substrate requirements for canoeing. Optimal, usable, suitable, and unsuitable values for depth, velocity, and substrate habitat variables for canoe operations are listed in table 4.

Optimal depths are water depths greater than or equal to 1.8 ft. Optimal velocities range from approximately 0.5 to 2.6 ft/s. All substrates types are assumed suitable for canoeing. Discharges producing sub-optimal habitat characteristics may prevent or substantially degrade the recreation activity.

Table 4. Depth, velocity, and substrate requirements for canoeing in a river[1]

[ft, feet; ft/s, feet per second; cm, centimeters: ≥, greater than or equal to; <, less than; >, greater than]

Habitat variable	Optimal ranges	Usable ranges	Suitable ranges	Unsuitable ranges
Depth (ft)	≥1.8	≥0.8	≥0.5	<0.5
Velocity (ft/s)	0.5-2.6	0.3-3.0	0.3-5.0	<0.3 and >5.0
Substrate (diameter in cm)	All assumed suitable	All assumed suitable	All assumed suitable	All assumed suitable

[1] Habitat suitability information presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Values extrapolated from Milhouse, 1990

Aquatic Biota

Aquatic biota, such as selected fish species, have specific habitat requirements for various life stages and activities. These requirements commonly are combinations of velocity, depth, and substrate, as well as other factors. When discharges are substantially altered, the appropriate combination of habitat characteristics necessary for success of these species may be absent or reduced to levels that limit the population.

It is also important to realize that adverse effects to organisms other than the species of interest, caused by flow alterations, can reduce the success of the species or population of interest. These adverse effects can occur because of the complex interactions between species and groups of species. These interactions can include predator-prey relations, life stage-host specific interactions, and habitat use and food source competition.

To demonstrate the potential effects of flow on fish species, information on habitat requirements for a minnow species (blacknose dace), a bottom dwelling species (white sucker), and a top predator (muskellunge) are presented.

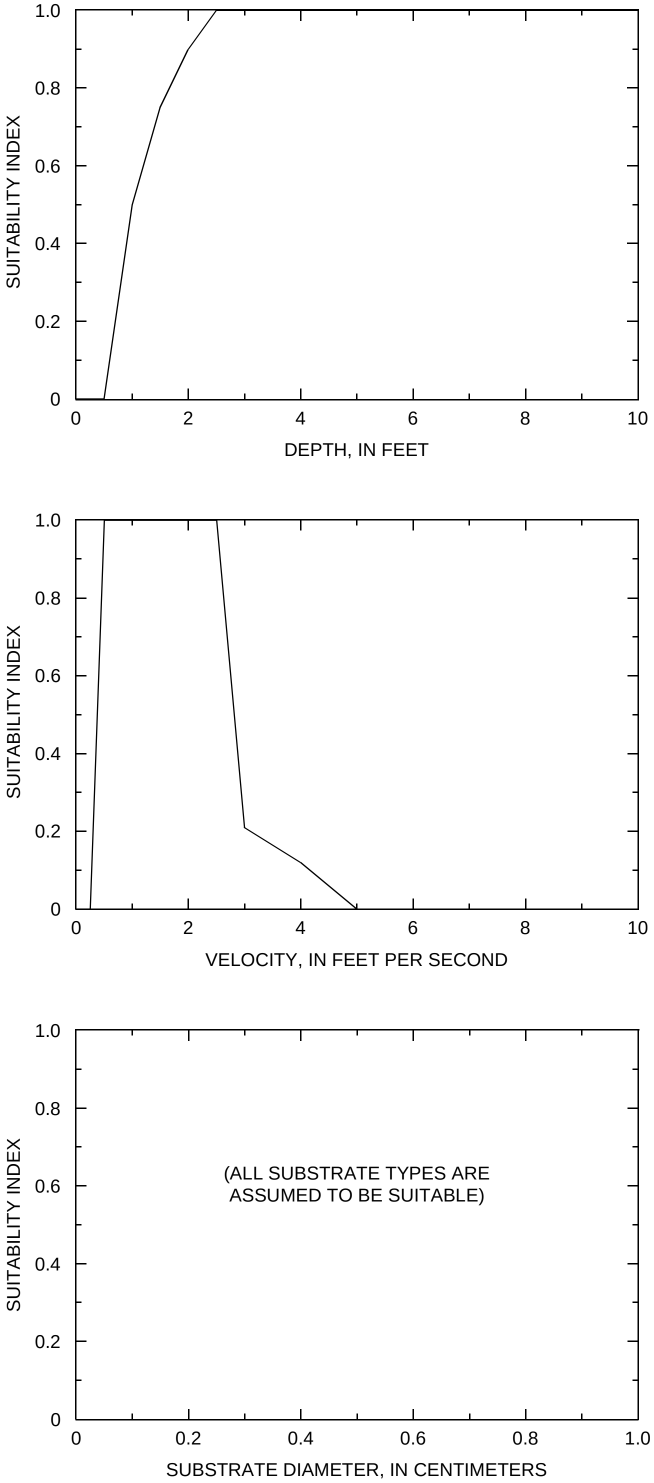

Figure 7. Generalized habitat suitability curves for canoeing on a river. [Habitat suitability curves presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Curves were taken from Milhouse, 1990.]

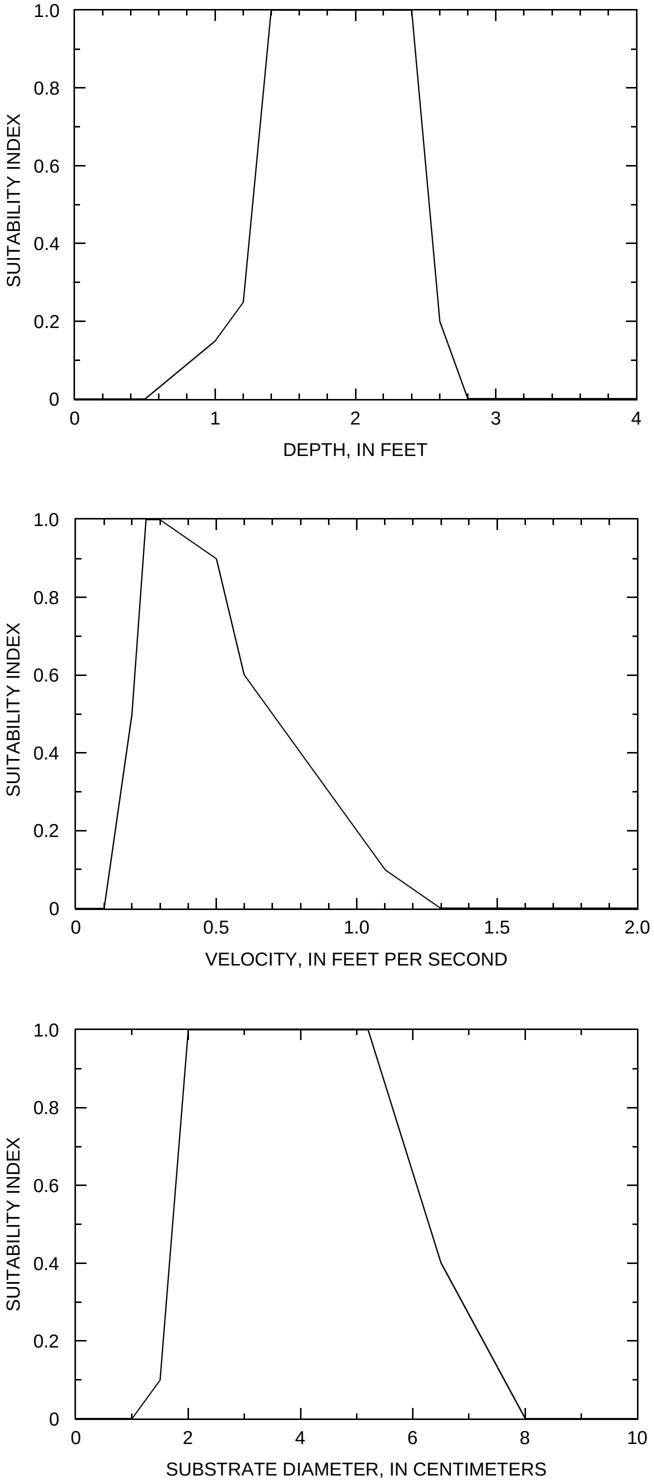

Figure 8. Generalized habitat suitability curves for juvenile and adult blacknose dace (*Rhinichthys atratulus*). [Habitat suitability curves presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Curves were taken from Sheppard, D., and Johnson, J., 1984. Unpublished (J.W. Terrell, U.S. Fish and Wildlife Service, written commun., 1997).]

Blacknose dace

Blacknose dace (*Rhinichthys atratulus*) are distributed from Manitoba to Nebraska, east to the Maritime Provinces and south along both sides of the Appalachian Mountains to Georgia and Alabama (Lee and others, 1980). Blacknose dace are mature at 2 years of age, are short lived, and are primarily insectivores.

On the basis of the literature, adult blacknose dace are found in pools but may be found in other habitats (J.W. Terrell, U.S. Fish and Wildlife Service, written commun., 1997). Adult dace are typical in rocky and gravelly streams; the highest densities are found over gravel-cobble substrates.

Habitat SI's for blacknose dace (fig. 8) represent generalized depth, velocity, and substrate requirements for juvenile and adult blacknose dace. Optimal, usable, suitable, and unsuitable values for depth, velocity, and substrate habitat variables for juvenile and adult blacknose dace are listed in table 5.

Optimal depths for blacknose dace range from about 1.4 to 2.4 ft. Optimal velocities range from approximately 0.2 to 0.5 ft/s, and optimal substrate diameter ranged from about 1.9 to 5.2 cm. Discharges producing sub-optimal habitat characteristics can limit the habitat available for blacknose dace and can adversely affect this species. The potential adverse effects may be the result of limited spawning habitat, forage area, and cover available to escape predators.

Table 5. Depth, velocity, and substrate requirements for juvenile and adult blacknose dace (*Rhinichthys atratulus*)[1]

[ft, feet; ft/s, feet per second; cm, centimeters; <, less than; >, greater than]

Habitat variable	Optimal ranges	Usable ranges	Suitable ranges	Unsuitable ranges
Depth (ft)	1.4-2.4	1.2-2.6	0.5-2.8	<0.5 and >2.8
Velocity (ft/s)	0.2-0.5	0.2-1.0	0.1-1.3	<0.1 and >1.3
Substrate (diameter in cm)	1.9-5.5	1.6-7.1	1.0-8.0	<1.0 and >8.0

[1] Habitat suitability information presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Values extrapolated from Sheppard, D., and Johnson, J., 1984. Unpublished (Terrell, J.W., U.S. Fish and Wildlife Service, written commun., 1997).

White sucker

The white sucker (*Catostomus commersoni*) is distributed from the Mackenzie River, Hudson Bay drainage, and the Labrador Peninsula; south along the Atlantic Coast to western Georgia; along the northern extremes of the Gulf States to Northern Oklahoma. Its range extends north through eastern Colorado, Wyoming, Montana, Alberta, north-central British Colombia and the southeastern Yukon territory (Twomey and others, 1984).

White suckers can tolerate a broad range of environmental conditions. Male white suckers reach maturity between 2 and 6 years of age. Female white suckers usually mature 1 to 2 years later than males. Adult white suckers (greater than 150 mm total length) primarily inhabit pools and are common in areas with slow to moderate velocity. Smaller individuals can be found in a greater variety of habitats than adults.

Habitat SI's for the white sucker (fig. 9) represent generalized depth, velocity, and substrate requirements for the adult white sucker. Optimal, usable, suitable, and unsuitable values for depth, velocity, and substrate habitat variables for the adult white sucker are listed in table 6.

Optimal depths for adult white sucker range from about 2.0 to 5.2 ft. Optimal velocities range from approximately 0.2 to 0.6 ft/s. All substrate types are assumed suitable for adult white sucker. Discharges producing sub-optimal habitat characteristics may adversely affect this species by reducing forage area for adults, reducing cover available to escape predators, and during the right season, limiting movement and spawning.

Table 6. Depth, velocity, and substrate requirements for adult white sucker (*Catostomus commersoni*)[1]

[ft, feet; ft/s, feet per second; cm, centimeters; <, less than; >, greater than]

Habitat variable	Optimal ranges	Usable ranges	Suitable ranges	Unsuitable ranges
Depth (ft)	2.0-5.2	1.0-13.1	0.5-16.4	<0.5 and >16.4
Velocity (ft/s)	0.2-0.6	0.1-1.1	0.0-1.3	>1.3
Substrate (diameter in cm)	All assumed suitable	All assumed suitable	All assumed suitable	All assumed suitable

[1] Habitat suitability information presented for demonstration only, and are not known to be applicable to the Shenandoah River Basin. Values were extrapolated from Twomey and others (1984).

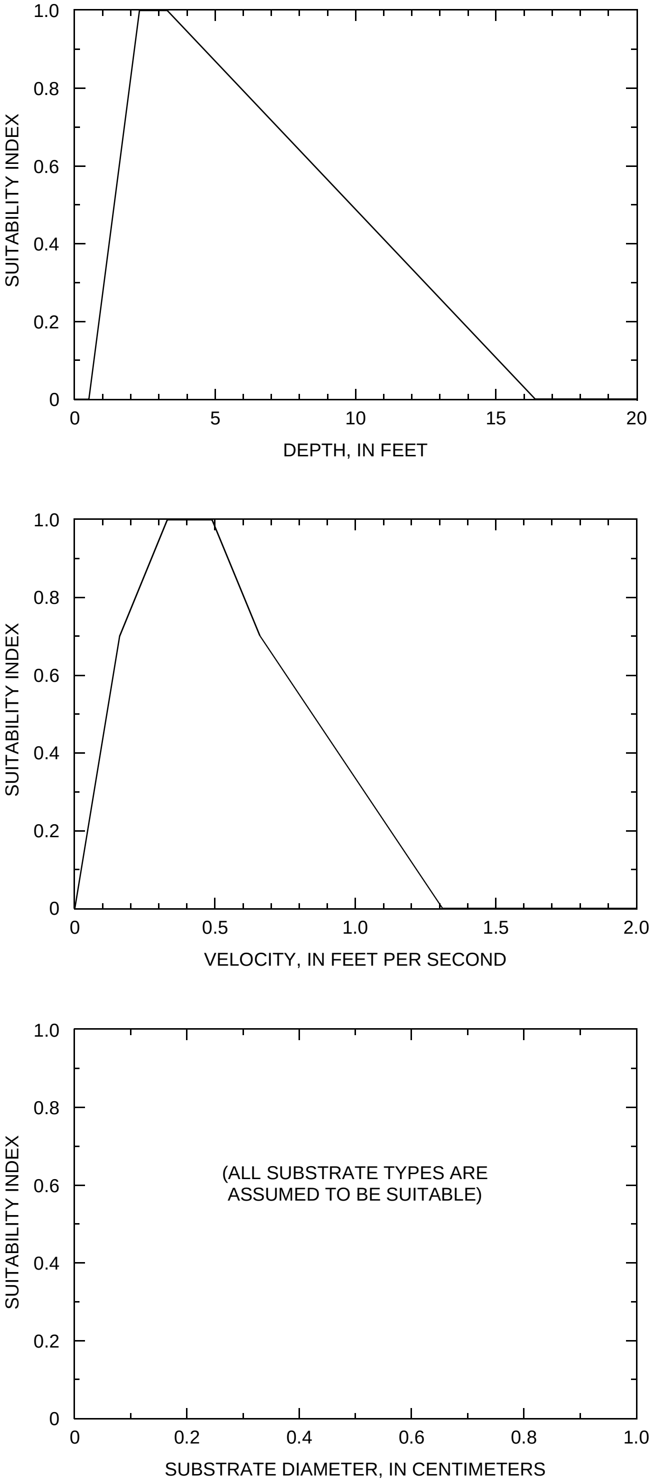

Figure 9. Generalized habitat suitability curves for adult white sucker (*Catostomus commersoni*). [Habitat suitability curves presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Curves were taken from Twomey and others, 1984.]

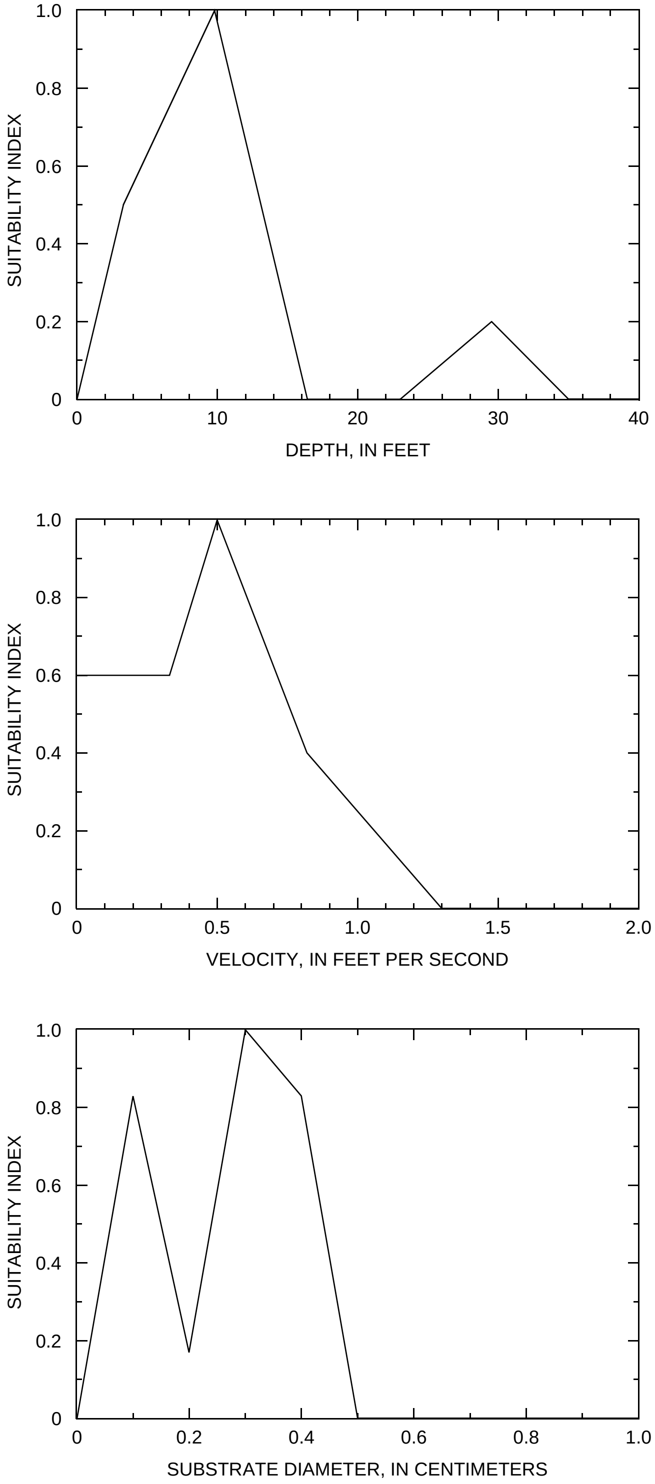

Figure 10. Generalized habitat suitability curves for juvenile and adult muskellunge (*Esox masquinongy*). [Habitat suitability curves presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Curves were taken from a paper by Leclerc, 1983, (J.W. Terrell, U.S. Fish and Wildlife Service, Written commun., 1997).]

Muskellunge

The original native range of muskellunge (*Esox masquinongy*) was restricted to the fresh waters of eastern North America. Its range extends from Quebec through western Vermont, south to Tennessee west of the Appalachian Mountains. The range extends north from Tennessee into the Great Lake States and Southern Manitoba, excluding the Mississippi River (Scott and Crossman, 1973). Muskellunge have been introduced in recent years into many streams and states, including the Shenandoah River in Virginia.

The growth rate of muskellunge is highly variable. Sexual maturity may depend on the growth rate and sex of the individual. Males have been observed to mature at 3 to 4 years of age, whereas some females have been observed to mature at 4 to 5 years of age (Scott and Crossman, 1973).

Muskellunge are found in a variety of river and lake types and are commonly associated with submerged structures (weeds, trees, overhangs). In streams, muskellunge are found in association with pools, low gradient stream reaches, and fallen trees (J.W. Terrell, U.S. Fish and Wildlife Service, written commun., 1997).

Habitat SI’s for muskellunge (fig. 10) represent generalized depth, velocity, and substrate requirements for juvenile and adult muskellunge. Optimal, usable, suitable, and unsuitable values for depth, velocity, and substrate habitat variables for juvenile and adult muskellunge are listed in table 7.

Optimal depths for juvenile and adult muskellunge ranged from about 7.8 to 10.8 ft. Optimal velocities ranged from approximately 0.4 to 0.6 ft/s, and optimal substrate ranged from about 0.3 to 0.4 cm in diameter. Discharges producing sub-optimal habitat characteristics may limit the habitat available for juvenile and adult muskellunge and may adversely affect this species. Potential adverse effects can include reduced cover available for the species. The availability of cover is key to successful feeding of muskellunge because it typically ambushes its prey. Also, the reduction in available cover and shallow depths may prevent juvenile fish from escaping predation from birds such as heron.

Habitat Time Series and Alternative-Flow Scenario

After the relations between flow and available habitat were determined through the PHABSIM model,

Table 7. Depth, velocity, and substrate requirements for juvenile and adult muskellunge (*Esox masquinongy*)[1]

[ft, feet; ft/s, feet per second; cm, centimeters; >, greater than; ≤, less than or equal to]

Habitat variable	Optimal ranges	Usable ranges	Suitable ranges	Unsuitable ranges
Depth (ft)	7.8-10.8	1.6-14.8	0.1-16.4 and 23.0-35.0	16.4-23.0 and >35.0
Velocity (ft/s)	0.4-0.6	0.0-1.0	0.0-1.3	>1.3
Substrate (diameter in cm)	0.3-0.4	0.1-0.2 and 0.2-0.5	≤0.5	>0.5

[1] Habitat suitability information presented for demonstration only and are not known to be applicable to the Shenandoah River Basin. Values were extrapolated from a paper by Leclerc, 1983, (J.W. Terrell, U.S. Fish and Wildlife Service, written commun., 1997).

discharge records were incorporated to display the availability of habitat over time. The habitat time-series data can be analyzed with the same methods used to analyze discharge time-series data, and the effects of various alternative-flow scenarios on habitat availability can be determined. For this demonstration project, an alternative-flow scenario was developed such that when flows decrease below 1,000 ft^3/s, the flow was increased by 10 percent.

Daily values of discharge were retrieved for the Shenandoah River at Millville, W.Va., for the period of record 1896-1996. Daily values of the alternative flow were then determined for the same period. From the habitat-discharge relation, daily values of available habitat were computed for the historic flows and alternative flows. For the demonstration project, only one alternative-flow scenario was developed and only the habitat-discharge relation for canoeing was used to determine habitat time series. Habitat-duration curves for canoeing were developed from the historic flow and the alternative flow data.

SIMULATION RESULTS AND ANALYSIS

The output provided by the PHABSIM model is only a small part of the information necessary for effective decision making and management of river resources. The information by itself is usually insufficient for formulation of recommendations regarding instream flow requirements (Bovee, 1982). The output can be viewed for the entire segment or for the individual transects. The output is considered an overall description of the habitat-discharge relation when viewed in reference to the stream segment; or it can assist in locating critical local points, or bottlenecks, that disrupt habitat continuity within the segment when viewed in reference to individual transects. Several important concepts related to the habitat-discharge relation should be considered during analysis: (1) a flow that is beneficial to one life stage, species, or water use may be detrimental to another life stage, species, or water use, (2) various life stages, species, or water uses may require different amounts of water at different times of the year, (3) a flow that maximizes habitat in one part of the stream may reduce habitat in another part of the same stream, and (4) increased flows may not increase habitat. Graphs of the relation between discharge and habitat are useful because they show changes in physical habitat for each water use, life stage, and species evaluated as the discharge increases or decreases (Bovee, 1982).

The primary output of PHABSIM is WUA and associated discharge; however, any input, calibration, or simulated data also can be used as an analysis tool. The output also can be used with additional flow or time-series information to enhance the overall analysis. This report focuses on the relation between habitat (WUA) and discharge and includes information on the relation of available habitat with time and habitat duration.

Water Supply

The ability to withdraw water from a stream is limited by flow at a specific location and not flow within a stream reach. The hydraulic and flow simulations in the PHABSIM model are useful for determining flows at which the ability to withdraw water from a stream is limited. The intakes for the Town of Berryville, Va., water supply are located about 300 ft downstream from transect 18 (fig. 6). Because of the proximity of the intakes to transect 18, the information collected at transect 18 was used in the analysis of flow and withdrawal limits at the intakes. Comparing the elevations of the intakes to the stage-discharge relation at transect 18, the upper intake will become exposed at a discharge of about 700 ft^3/s, and the lower intake may become noneffective at a discharge less than 100 ft^3/s.

An analysis of the flow duration of the discharge-measurement station at Shenandoah River at Millville, W. Va., indicates that the flow in the Shenandoah will be greater than or equal to 700 ft^3/s 85 percent of the time, and the flow will be greater than or equal to 100 ft^3/s more than 99 percent of the time. On the basis of this analysis of historical information, there were periods during which flows would have left the upper intake exposed, indicating the possibility for future limiting of water withdrawals.

Recreation

On the basis of the generalized flow requirements used in this demonstration project, WUA for canoeing decreases slowly below a discharge of 2,200 ft^3/s, from a peak of about 400,000 ft^2 per 1,000 linear ft of river (fig. 11). The amount of WUA for canoeing decreases rapidly as discharge decreases from 1,200 ft^3/s. The rapid decrease in WUA at the lower discharges is because of the rapid decreases in depth in the stream cells with decreasing discharge (fig. 7).

In addition, WUA begins to decrease for canoeing above a discharge of 2,200 ft^3/s. The decrease in WUA at the higher discharges is because of increased velocity in the stream cells.

An analysis of the flow duration of the discharge-measurement station at Shenandoah River at Millville, W. Va., indicates that the flow in the Shenandoah will be greater than or equal to 1,200 ft^3/s 63 percent of the time. On the basis of this analysis of historical information and the generalized flow requirements for canoeing, low flows occurred during about 37 percent of the period of record, which could have affected the quality of the recreation experience.

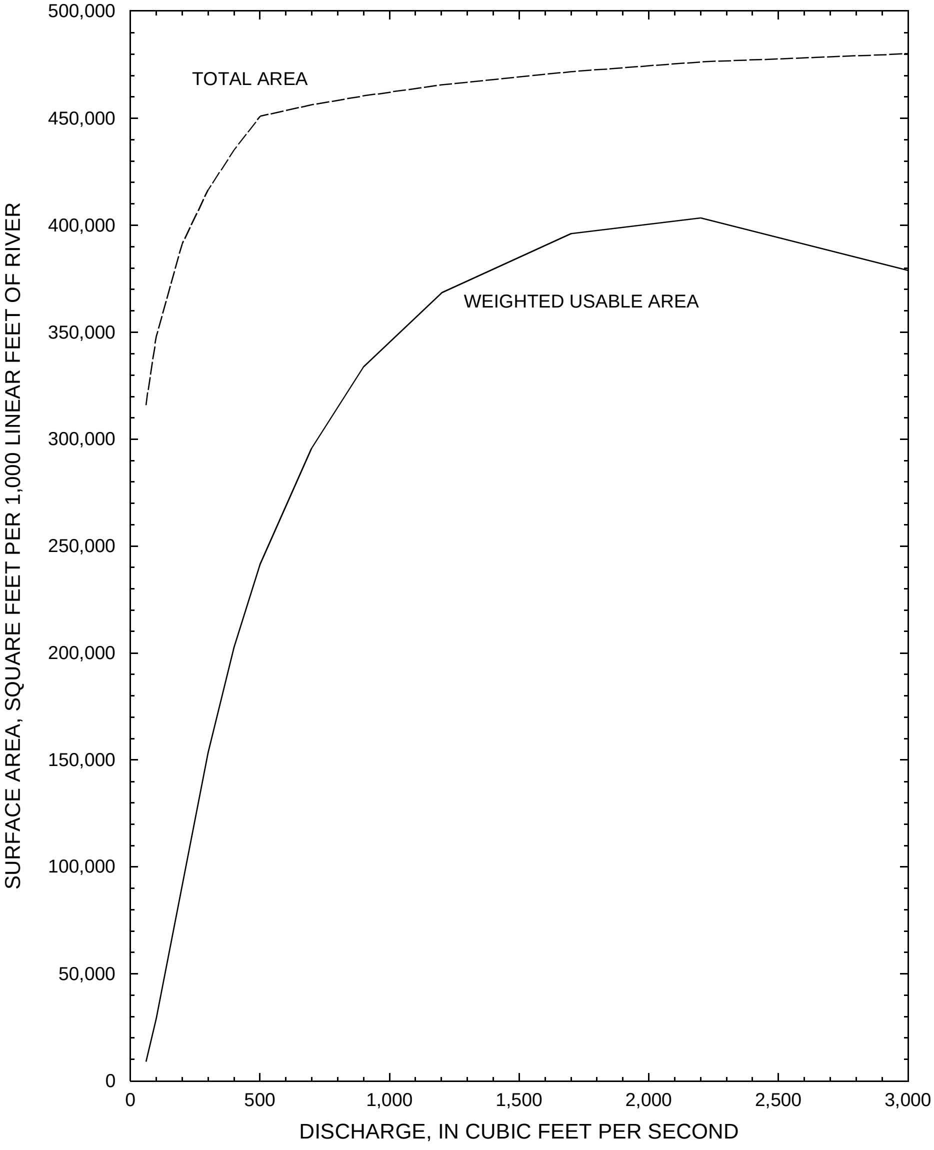

Figure 11. Relation of discharge to surface area for canoeing. [Information presented for demonstration only and is not known to be applicable to the Shenandoah River Basin.]

Aquatic Biota

The total amount of suitable habitat available for a given species, life stage, or group of species is dependent, at least in part, on the velocities, depths, and substrate types required to support the organisms of interest. Habitat availability and suitability can be linked to instream flow. It is important to note that although habitat may be available for specific species, habitat may be limited for other organisms important to the success of the specific species of interest.

Blacknose dace

On the basis of the generalized habitat requirements used in this demonstration project, the amount of WUA for juvenile and adult blacknose dace decreases rapidly from a peak of about 42,000 ft^2 per 1,000 linear ft of river as discharge decreases from 300 ft^3/s (fig. 12). Above 300

ft^3/s, the amount of WUA declines slowly as discharge increases.

Significant amounts of habitat for juvenile and adult blacknose dace are available only over a small range of discharge because of the narrow ranges of depth and velocity that are suitable for adult blacknose dace (fig. 8).

An analysis of the flow duration of the discharge-measurement station at Shenandoah River at Millville, W. Va., indicates that the flow in the Shenandoah will be greater than or equal to 300 ft^3/s 98 percent of the time. On the basis of this analysis of historical information and the generalized flow requirements for blacknose dace, low flows occurred during about 2 percent of the period of record, which could have limited the availability of habitat.

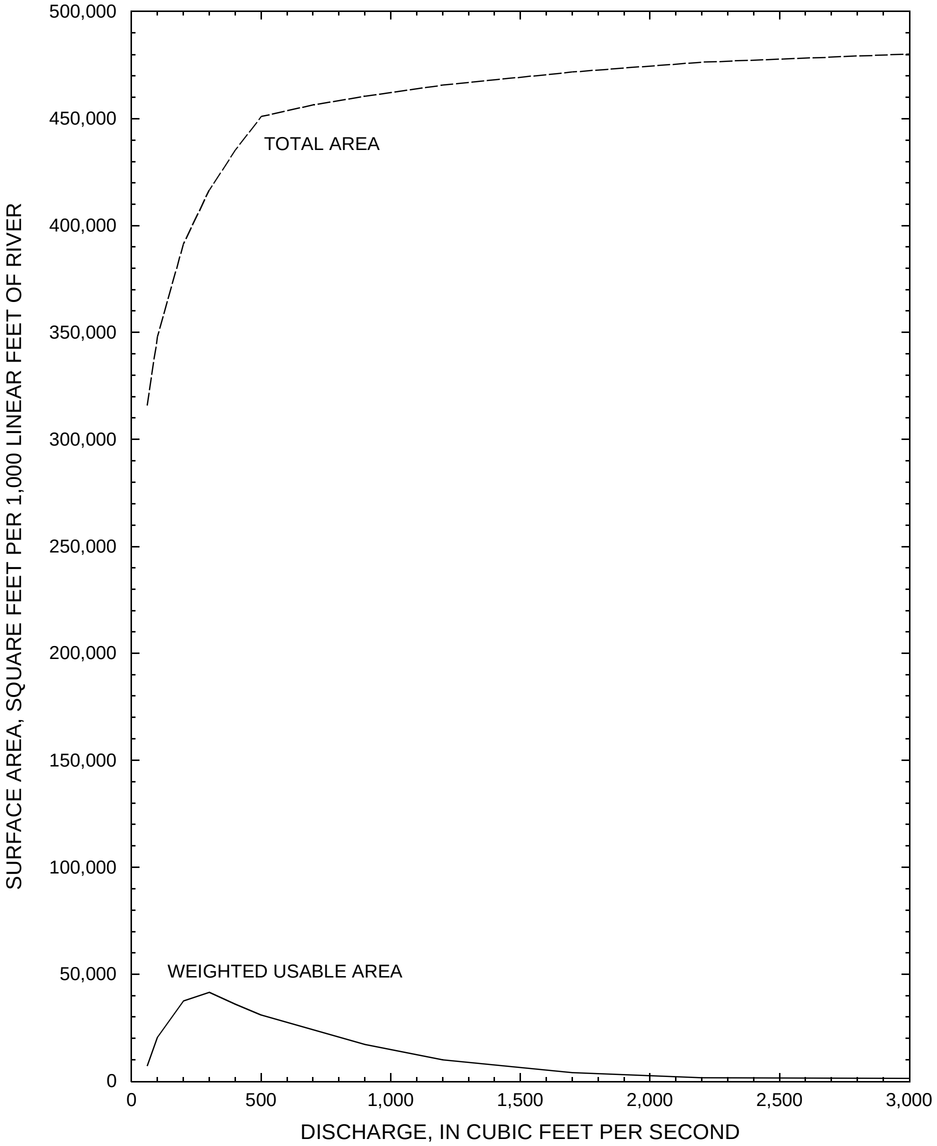

Figure 12. Relation of discharge to surface area for juvenile and adult blacknose dace habitat. [Information presented for demonstration only and is not known to be applicable to the Shenandoah River Basin.]

White sucker

On the basis of the generalized habitat requirements used in this demonstration project, the amount of WUA for adult white sucker decreases rapidly from a peak of about 170,000 ft^2 per 1,000 linear ft of river as discharge decreases from 500 ft^3/s (fig. 13). Above 500 ft^3/s, the amount of WUA declines slowly as discharge continues to increase.

The shape of the discharge-WUA curve for the white sucker is similar to the shape of the curve for the blacknose dace but with five times the WUA for any selected discharge. The two species have similar velocity requirements, however, the white sucker can tolerate a much wider range of depths and substrates (fig. 9). The decrease in WUA at the higher discharges is because of higher velocities, unsuitable for adult white sucker.

An analysis of the flow duration of the discharge-measurement station at Shenandoah River at Millville, W. Va., indicates that the flow in the Shenandoah will be greater than or equal to 500 ft^3/s 94 percent of the time. On the basis of this analysis of historical information and the generalized flow requirements for blacknose dace, low flows occurred during about 6 percent of the period of record, which could have limited the availability of habitat.

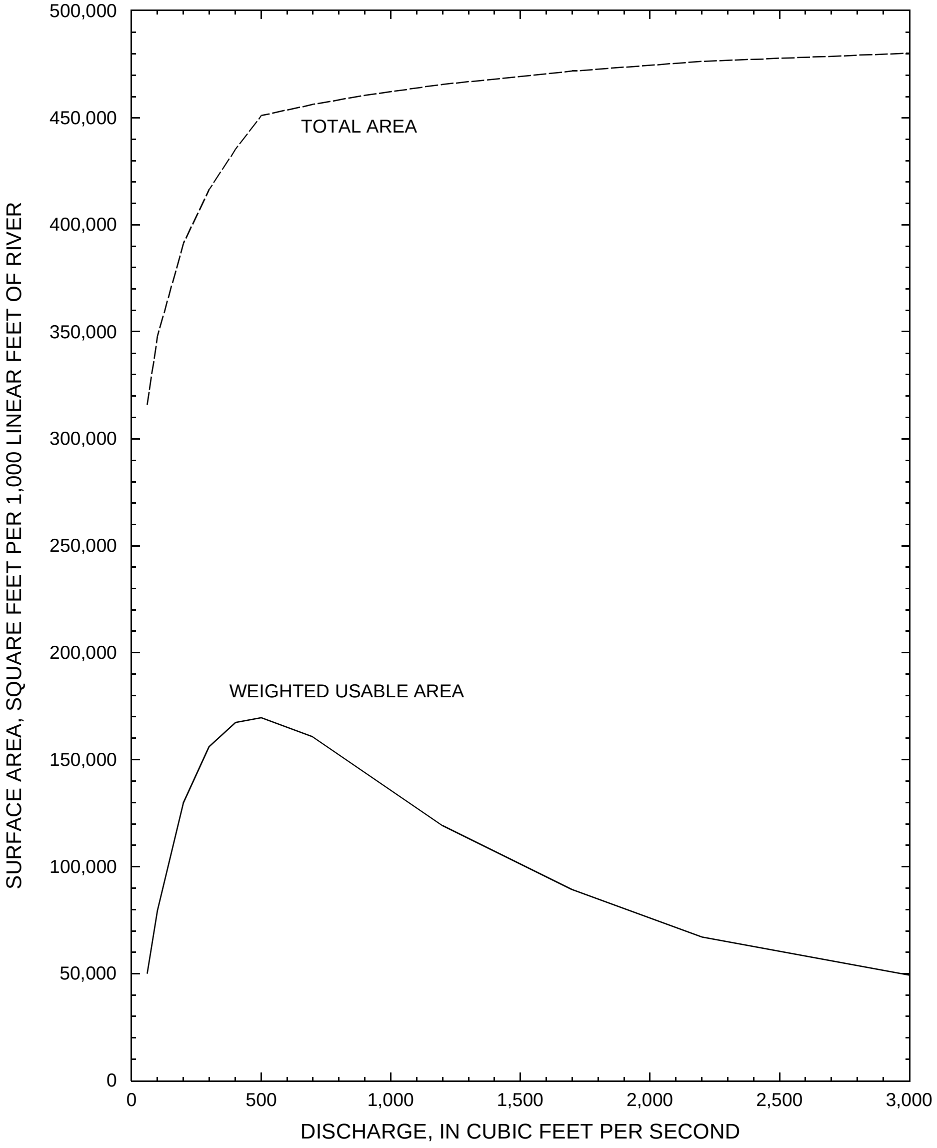

Figure 13. Relation of discharge to surface area for adult white sucker habitat. [Information presented for demonstration only and is not known to be applicable to the Shenandoah River Basin.]

Muskellunge

On the basis of the generalized habitat requirements used in this demonstration project, very little habitat is available at any discharge for adult and juvenile muskellunge (fig 14). However, the amount of WUA available is fairly constant across the entire range of simulated discharges. Muskellunge can tolerate a wide range of depths but tolerate a relatively narrow range of velocities and substrate types (fig. 10).

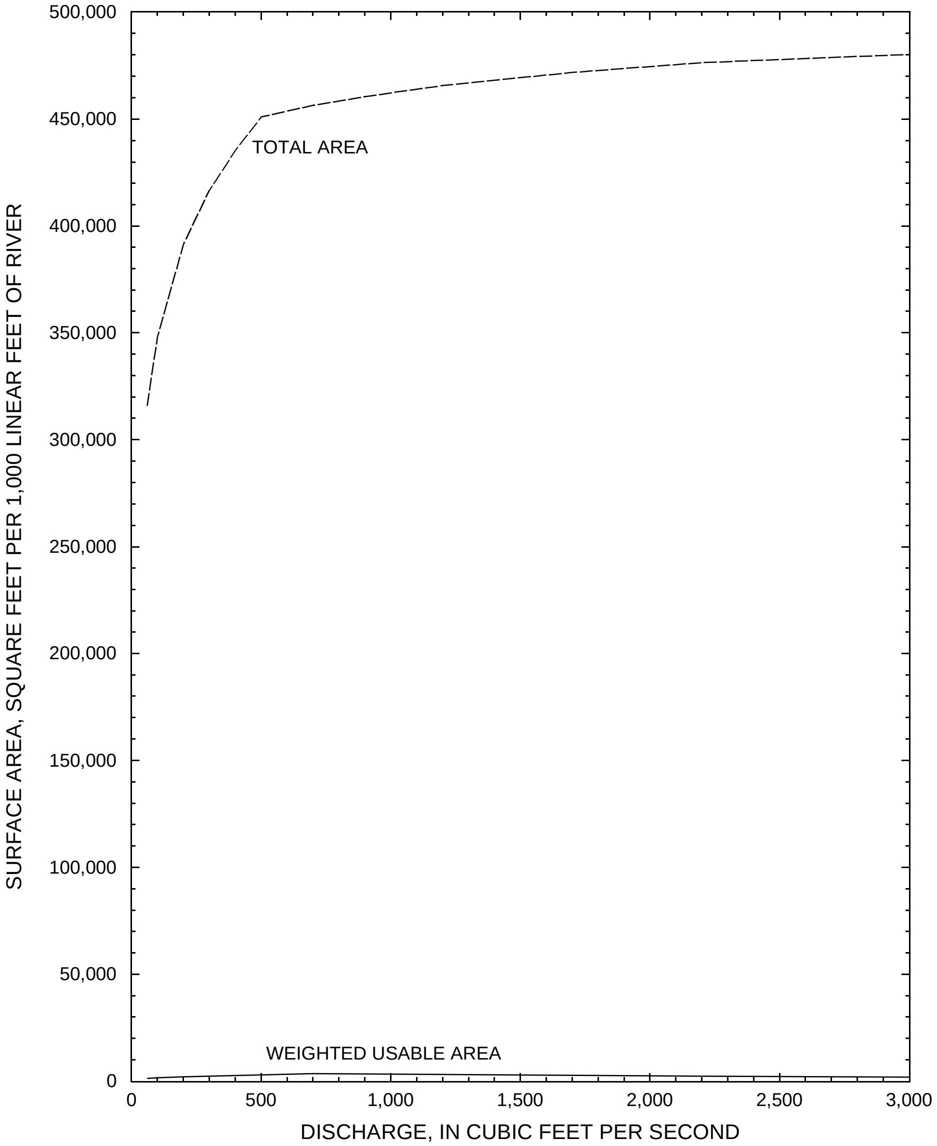

Figure 14. Relation of discharge to surface area for juvenile and adult muskellunge habitat. [Information presented for demonstration only and is not known to be applicable to the Shenandoah River Basin.]

Alternative Flow Analysis

Habitat-time series and habitat-duration curves developed from various alternative flows for all studied species or water uses can be analyzed to determine the possible habitat gains or losses for each alternative flow and the frequency at which they will occur. On the basis of generalized habitat-discharge relations for canoeing and the historic and alternative flows used in this demonstration project, figure 15 shows the comparison of the habitat-duration curves developed from the habitat-time series for the historic flow and alternative-flow scenario discussed in the section ‘Habitat Time Series and Alternative-Flow Scenario.’ Approximately 15,000 ft^2 per 1,000 linear ft of river more of canoe habitat are available when the alternative flow is maintained above the historic flow.

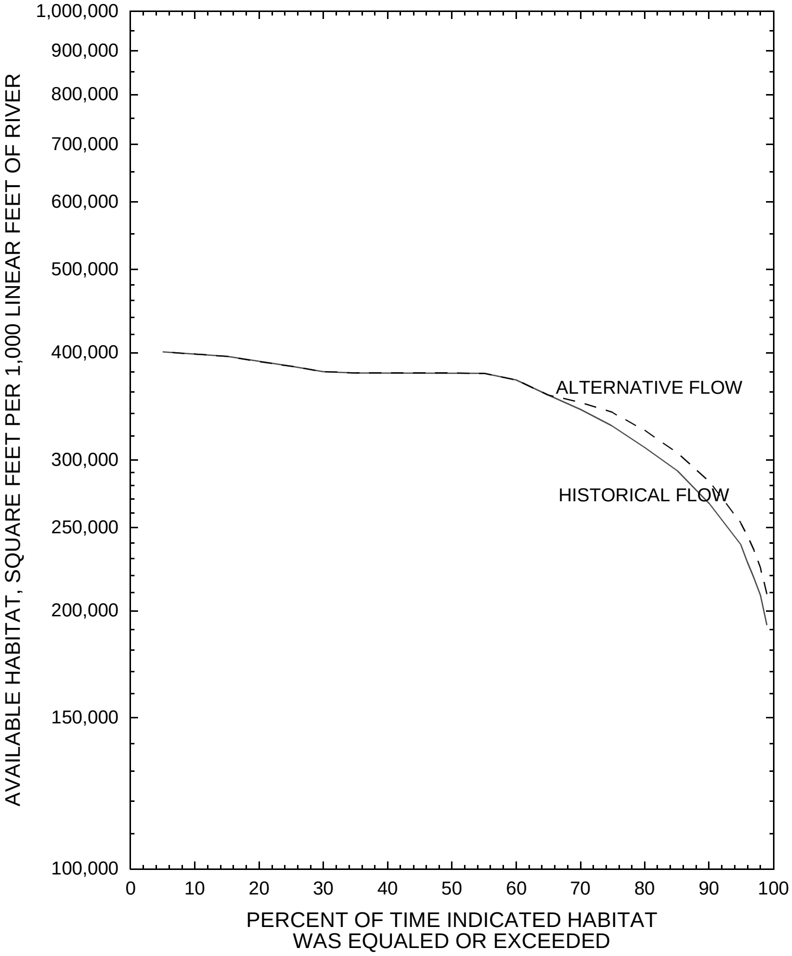

Figure 15. Habitat-duration curves for canoeing based on discharge from the Shenandoah River at Millville, West Virginia, 1896-1996.

SUMMARY AND CONCLUSIONS

As urban and rural growth continues, competition for clean water expands into stream areas previously capable of meeting local water-use demands. Conflicts among instream and offstream users of streamflow increase as flow decreases.

A study was conducted on the main stem Shenandoah River in Virginia to demonstrate the ability of IFIM to (1) supply information about the potential effect of decreased flows on water supply, recreation, and habitat availability for selected species, (2) bring together stakeholders and other parties that may be directly affected by decreased flows because of increased water demands on the Shenandoah River, and (3) begin to assemble the appropriate technical team and methodologies to address these issues.

The demonstration clearly identifies some of the utility in using PHABSIM to potentially identify critical low-flow periods, where additional flow reductions may adversely affect water use, recreation, and aquatic species. In addition, the habitat - time series shows the change in habitat availability associated with an alternative-flow scenario. Further work needs to be conducted to address the specific water issues within this basin and to identify critical flow periods, on the basis of specific flow requirements for the Shenandoah River basin.

Output provided by the PHABSIM model is only a small part of the information necessary for effective decision making and management of river resources. The information by itself is usually insufficient for formulation of recommendations regarding instream flow requirements. Additional information, for example, can be obtained by analysis of habitat time-series data, habitat duration data, and habitat bottlenecks.

Regardless of the method used, the IFIM process attempts to quantify the effects of incremental changes in streamflow, of which a key component is the interaction and communication of all parties directly and indirectly affected by flow issues.

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