
Stream Habitat Modeling to Support Water Management Decisions for the North Fork Shenandoah River, Virginia

FINAL REPORT

Prepared for

Northern Shenandoah Valley Regional Commission
North Fork Instream Flow Technical Advisory Committee

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EXECUTIVE SUMMARY

This four-year instream flow study was initiated to evaluate the hydraulics, habitat, and water quality of the North Fork Shenandoah River, Virginia, during low flow conditions. Virginia Tech in cooperation with the United States Geological Survey (USGS) collected hydraulic, fish habitat, and water quality data throughout the basin during periods of extreme drought in 1999 and 2002. This report summarizes the cumulative results, hydraulic, fish habitat, and water quality conditions in the North Fork Shenandoah River (NFSR). These results were used to establish a stepwise process for implementing aquatic conservation flow management in the NFSR basin and facilitate water use conservation measures at appropriate times during extreme droughts of the future. We applied the Instream Flow Incremental Methodology to provide a comparison of usable habitat conditions under baseline and alternative hydrologic time series corresponding to water use restrictions. Six study sites (with a total of 36 transects) were selected to characterize the mesohabitats (riffle, run, pool, and pocket run) of the entire river. Aquatic conservation thresholds were developed for three river reaches and were directly related to three long-term gauging stations: Cootes Store (mile 92 in Rockingham County), Mount Jackson (mile 70 in Shenandoah County), and Strasburg (mile 10 in Warren County).

Extreme droughts, such as the recent droughts (1999 to 2002), occur every 23 years on average and last an average of 2.5 years. Permitted public supply and commercial demands alone totaled 12.07 mgd (18.67 cfs), an increase of 50%

since 1995, and agricultural demands are poorly documented and no trend analysis was possible.

Habitat suitability criteria were developed onsite for groups of riffle, fast generalist, pool-run, and pool-cover fishes. Habitat responses to streams flow were quantified for these groups of fishes as well as for habitat conditions conducive to nuisance algal blooms. The river temperature model was calibrated to define the longitudinal temperature profile and identify critical or inhabitable stream reaches for aquatic organisms. Analyses suggest an overriding influence of prevailing weather and groundwater overwhelmed the effect of flow on water temperature; therefore temperature was not used as a criterion for developing aquatic conservation flow thresholds. Aquatic conservation flow threshold were derived from these habitat criteria as well as the water quality conditions during low flows in 1999 and 2002 and are recommended for implementation:

	Cootes Store	Mount Jackson	Strasburg
Normal	>100 cfs	>120 cfs	>150 cfs
Watch	<100	<120	<150
Warning	<60	<75	<90
Emergency	<25	<30	<65

During the drought of 1999, 37% of the daily minimum dissolved oxygen values fell below the state minimum dissolved oxygen standard of 4 mg/L. Nuisance levels of algae and aquatic vegetation were observed at most sites during summer 2002. Un-ionized ammonia levels measured during summer 2002 exceeded levels that are toxic to juvenile freshwater mussels. Water quality conditions in 2002 strongly support our determination that flow conditions during that time should be categorized as “Emergency” or “Warning” conditions for conservation measures. Implications of our findings and aquatic conservation flows for the three sites indicate that there will be more frequent warning and emergency conditions at the upper river (Cootes Store), then middle river (Mount Jackson), and the fewest warnings and emergency conditions in the lower river (Strasburg).

Several issues may complicate the straightforward adoption and successful implementation of the conservation flow thresholds developed in the study. These represent priority research needs for this basin and include: Nutrient Inputs, Hydrologic and Landscape Change, Habitat and Biological Change, Climate Change and Stream flow, Water Use and Conservation, Surface and Groundwater Interchange, and Stream and Riparian Restoration Activities.

Recommended Actions:

- Develop action plan for different aquatic conservation flow thresholds and adopt this as a clinical trial to improve water use conservation. Develop intensive monitoring system to accelerate data collection during warning, watch and emergency conditions.
- Extend study plan to SFSR to quantify water supply and demand balance throughout the SR Basin. Consider companion studies in other river basins.

- Develop a hydrologic model for entire basin to permit simultaneous calculations of many influences of water flows throughout basins.
- Continue to forge this partnership and new partnerships between scientists and other stakeholders in communities, government, private sector, and NGOs.

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CONVERSION FACTORS & ABBREVIATIONS

Multiply	By	To obtain
cubic feet per second (cfs)	0.02832	cubic meters per second (cms)
million gallons per day (mgd)	1.547	cubic feet per second (cfs)
feet (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

GLOSSARY

7Q10 flow: the lowest average flow for 7 consecutive days, which statistically occurs once every 10 years. Please refer to Minimum Instream Flow.

Climatic year: the 12-month period, April 1 through March 31. The water year is designated by the calendar year in which it begins; thus, the year beginning April 1, 2001, is called the "2001 climatic year." The climatic year is the reference for calculating extreme flow statistics.

Conservation flows: instream flow needed for some environmental need. Also called environmental flows

Cover: areas of shelter in the stream channel that provide aquatic organisms protection against predators and a place to rest and conserve energy by providing a reduction in velocity or visibility. Examples are logs, undercut banks, boulders, vegetation, etc.

Depth: the vertical distance from a point on the stream bed to the water surface.

Discharge: volume of water passing through a stream cross-section per unit of time.

Fishery: a population of fish preferred by anglers.

Fluvial generalist: an aquatic species that can use a wide habitat range of depths and velocities.

Fluvial specialist: an aquatic species that occupies a narrow habitat range of water depth and velocity; these species are most likely impacted by changes in instream flow.

Guilds: a group of species/life-stages that use similar areas (similar depth, velocity, substrate, cover, and temperature) for spawning, foraging, or refuge across time and space.

Habitat suitability curves: graphical description of how a species responds to changes in a habitat characteristic.

Mainstem: the main channel of a river system; all tributaries flow into it.

Mesohabitat: a section of stream that has similar depth and velocity within a reach. Examples are pools (deep and slow), riffles (shallow, fast), and runs (intermediate).

Minimum Instream Flow (MIF): the lowest stream flow required to protect some specified aquatic function; usually defined as the 7Q10 flow, which is less than optimal for aquatic organisms and processes. This is a legal term, not a biological one, and is the basis for issuing water permits in many states.

Pocket Run: unique mesohabitat of the North Fork Shenandoah; shallow areas of bedrock interspersed with deeper holes (pockets).

Pool: deep, slow current habitats with a concave bedform.

Riffle: shallow rapids, with turbulent flow; water surface is broken by substrate that is wholly or partially submerged; convex bedform.

Reach: a section of stream with all the mesohabitats present in a segment (see segment); usually 10-15x the average stream width.

Run: flat bedform with shallow depth; slightly turbulent flow; water surface is not broken by the bed substrate

Spatial: of or pertaining to space; a geographic location; has length, width, and depth.

Substrate: physical composition of the stream bottom (silt, sand, gravel, cobble, etc.).

Temporal: of or pertaining to time; a period of time.

Upper thermal limits: the threshold at which a species cannot survive for an extended period at greater temperatures.

Usable habitat: areas of stream in which a species can maintain itself for an extended period.

Velocity: distance water moves per unit time (i.e. feet per second).

Velocity shelter: physical habitat that provides refuge (i.e. eddies) from high velocity water.

Water quality: physical and chemical characteristics of the water, including but not limited to, temperature, acidity (pH), and dissolved oxygen (DO).

Water Year: the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the year ending September 30, 2002, is called the "2002 water year."

1 Introduction

In 1999, a four-year instream flow study was initiated to evaluate the hydraulics, habitat, and water quality of the North Fork Shenandoah River, Virginia, during low flow conditions. Using the principles of the instream flow incremental methodology (IFIM), Virginia Tech in cooperation with the United States Geological Survey (USGS) collected hydraulic, fish habitat, and water quality data throughout the basin. This report summarizes the cumulative results, hydraulic, fish habitat, and water quality, of this study and addresses the following research objectives:

Objective 1: Describe the baseline environmental setting of the North Fork Shenandoah River (NFSR).

Objective 2: Implement the physical data collection process associated with Physical Habitat Simulation System (PHABSIM) modeling.

Objective 3: Conduct PHABSIM modeling of hydraulic and fish habitat parameters for NFSR study sites.

Objective 4: Determine macrohabitat conditions (water quality and temperature) in the NFSR.

Objective 5: Establish a stepwise process for implementing aquatic conservation management in the NFSR basin.

Objective 6: Discuss future research needs.

The model results and conservation threshold identification process outlined in this report will provide biologists, water managers, county planners, and stakeholders with baseline information to identify conservation thresholds, institute conservation flow regulations, and thus, aid sustainable water allocation management in the Valley.

1.1 Justification

This research developed and tested mathematical models to describe expected changes in habitats and associated fish and aquatic life that could arise due to alternative water use practices, in particular instream flow protection. Many rural communities increasingly rely on fisheries and recreation for tourism income, both of which ultimately depend on a continued reliable supply of water. For a variety of reasons, fish and other aquatic taxa in rivers and streams have experienced significant declines (Allan and Flecker 1993). New water diversions or alternative water management may stir considerable debate, which often proceeds without any adequate analysis of expected losses to instream values, especially stream fish. Consequently, it is extremely difficult, if not impossible, to adequately trade-off benefits associated with offstream and instream uses of water. Yet this is precisely the charge given to water managers. Management decisions made today will affect the distribution of water-related benefits many years into the future. Furthermore, future trends in climate and population growth and redistribution will mean that analytical tools that address tradeoffs among various water uses will be increasingly valuable.

The Shenandoah River and its tributaries, the North Fork and South Fork, are great natural resources of the Commonwealth of Virginia. They represent an excellent model of a multiple use river. The mainstem Shenandoah River is a state scenic river. The river and its tributaries support an outstanding recreational fishery for local and regional citizens and is important habitat for numerous fishes and aquatic-dependent wildlife (e.g. herons, osprey, muskrat, and turtles). The river is also heavily used for drinking water, irrigation, industry, waste assimilation, hydroelectric power, and other economic uses. The population of the Shenandoah Valley continues to grow due to pleasant scenery, recreational amenities, and proximity to interstate highways and the Northern Virginia - DC metropolitan area. There is growing tension among residents that is rooted in the debate over limiting or managing growth in this region.

There has been widespread concern about low flow conditions on the Shenandoah River and its main tributaries. Low flows have prompted some municipalities to ask residents to conserve water due to the threat of water levels falling below intake levels. Low flows may also be linked to fish kills on the Shenandoah in 1988. Withdrawal of water from the North Fork for Winchester constitutes an interbasin transfer as return flows go to the Potomac River via Opequon; therefore, growth at this demand center would reduce flows downstream during droughts. The results of this study will permit municipalities and resource agencies to develop reasonable and defensible “protected” streamflow levels that would trigger voluntary conservation.

Only by understanding the responses of fish and other aquatic life to natural and human-induced flow changes can we begin to make good decisions about water uses in streams. Streams serve many functions in our society and the values, whether utilitarian, recreational, aesthetic, ecological, or scientific, touch the lives of all citizens. Water needs for basic human hygiene are surprisingly low; most water uses serve other functions, some of which are nonessential, and society and public servants can only make decisions regarding offstream uses when information is available on how values associated with instream uses vary with streamflow.

Drought can be defined as an unusually long period without rain. Lack of rain and drying out of water bodies can occur naturally every year and be highly predictable. Complete drying out or extremely low levels of water in naturally permanent water bodies occur much less frequently and are much less predictable. Nevertheless, while aquatic organisms must deal with similar problems in both situations, those adapted to predictable, relatively short-term dry periods may have different ways of dealing with these dry periods than those which can usually rely on permanent water. The frequency, duration and predictability of drying (or drought) events will have major influences on the types of organisms that can survive such events and their ability to recover from same. Human activities, particularly river regulation, deforestation and greenhouse emissions, undoubtedly affect the frequency and duration of drought episodes. Fish and aquatic invertebrates have numerous adaptations that permit them to withstand periods of drought. This research is a step in trying to understand the range of capabilities in our diverse riverine fauna. The stream fish fauna has representatives from a wide variety of life history strategies, habitat affinities, and trophic specializations. The plants and animals are linked together in a complex food web that has only been partially described. However, I have previously hypothesized that the production of larger, pool-dwelling fishes is largely dependent on production of current-dependent organisms (Orth 1995). The long-term scientific contribution of this research is creating and testing theories of how the fish populations interact, respond, and persist under natural and altered conditions.

1.1.1 Background on Instream Flow Research in Warmwater Streams

Higher order, often warmwater, streams are among the most altered aquatic ecosystems in the world; their aquatic resource values are heavily impacted by land use, road and bridge construction, mining, diversions and withdrawals, channelization, dams, and point-source discharges (Bryan and Rutherford 1993). Large-scale river regulation was underway 5000 years ago along the Nile, Tigris-Euphrates, and Indus rivers. Despite the wealth of studies on effects of various anthropogenic disturbances, the science of predicting biological responses to streamflow changes is immature. Therefore, policies on water withdrawals and assessments of the impacts of dam releases are often based on poor scientific understanding. Holistic streamflow management requires integration of flow regimes for at least five functions: 1) overbank flows to inundate riparian and floodplains zones, 2) floodflows to form floodplains, 3) in-channel flows to sustain the functioning of the instream system, 4) in-channel flows that meet critical fish requirements, and 5) surface and ground-water regimes to sustain the functioning of the hyporheic (stream-groundwater interface) system (Petts and Maddock 1994). In practice, policies are typically set without adequate knowledge of the requirements of each of these functions.

For most stream fishes and aquatic invertebrates there are few long-term studies of population dynamics in relation to streamflow. Major sustained changes in flow can bring reductions in some populations and barrier effects due to dams are most devastating for anadromous fish (Petts 1984). For resident fishes there are fewer studies. However, the debate over the relative strength of mechanisms controlling fish populations and assemblages is far from resolved. While some studies have demonstrated that fish assemblages in streams are stable and persistent despite large natural variation in streamflows (Meffe and Minckley 1987; Moyle and Vondracek 1985; Matthews 1988; Bass 1990), others found that normal spring flooding alters assemblages (Harrell 1978; Grossman et al. 1982; Ross and Baker 1983).

Extreme droughts certainly have a devastating effect on fish and aquatic invertebrates in streams. However, in the few studies where fish were monitored before and after severe drought, recovery occurred within 1 year (Larimore et al. 1959; Bayley and Osborne 1993). The rapid recovery is a result of upstream migration of cyprinids and suckers from downstream colonization sources; these populations are well adapted to drought cycles because they migrate to downstream wintering areas in fall and upstream in the spring. Other less mobile fishes, particularly darters, madtoms and sculpins may be more vulnerable to droughts.

Artificial fluctuations in streamflow can dramatically alter fish faunas. Below hydroelectric dams with erratic water releases the shoreline in shallow-water habitats is rapidly relocated; fish assemblages are sparse and dominated by habitat generalists (Bain et al. 1988). Downstream from these dams the magnitude of flow fluctuations is reduced and fish assemblages become more abundant and diverse and fluvial specialists can persist (Kinsolving and Bain 1993; Scheidegger and Bain 1995). After instituting minimum flows below hydroelectric dams, the species richness doubled, abundance of fluvial specialists increased (Travnichek et al. 1995), and growth and condition increased (Weisburg and Burton 1993). After flow augmentation in a small creek in Pennsylvania, Normandeau Associates (1995) documented an increase in abundance of fish and benthic invertebrates, a decrease in incidence of black spot parasitism, and increases in growth rates of fishes.

To determine minimum acceptable flows we typically use hydrological approaches, habitat assessments based on empirical habitat-flow relationships, or physical habitat simulation (e.g., PHABSIM). Hydrological approaches are useful when long periods of reliable records exist for unregulated flows. However, these methods tend to be most useful when there are few controversies over the use of water and few water users. These methods all require more extensive field studies to verify the criteria developed for translating hydrologic statistics to instream flow requirements. In situations where the biota are nonnative or where water quality or channel form or substrata are altered from historical conditions, the hydrological approaches are not appropriate.

Habitat assessments based on empirical habitat-flow relationships can be used to develop reasonable flow recommendations. These require extensive databases and, consequently, models have been developed for only a few basins (Binns and Eiserman 1979; Milner et al. 1985; Petts et al. 1995). The Basque method, developed in northern Spain, develops instream flow protection standards based on the relation between diversity of fish and macroinvertebrates and the natural runoff for the low-flow periods (Docampo and de Bikuña 1993); similar efforts to determine empirical relations useful for instream flow management have been rare in North America.

Physical habitat simulation can be done with a variety of hydraulic modeling techniques and numerous approaches to fish-habitat modeling. PHABSIM is a set of complex modeling tools that are applied within the context of the Instream Flow Incremental Methodology (IFIM). IFIM is a problem-analysis framework for translating baseline and altered hydrology into descriptions of available or usable habitat for increments of instream flow. This information has great potential for contributing to compatible instream and offstream uses of water and developing plans to allow for rapid recovery of aquatic populations during favorable periods. However, successful applications require that the habitat analysis be calibrated with biological data on the well-being of fish populations and aquatic communities (Stalnaker et al. 1995). Without sufficient biological data on populations and communities and their responses to flow, the analysis of physical habitat will be inadequate foundation for negotiation over alternative water management schemes. The applications of IFIM have, therefore, encountered considerable debate because assumed relationships are seldom tested. Thus far, relations between available habitat measures and fish populations have been developed only for single-species populations (Nehring and Anderson 1993; Bovee et al. 1994).

PHABSIM is founded on the basic ecological principle most recently termed "hydraulic stream ecology" (Statzner et al. 1988). Because the difference between the speed of an organism and the medium in which it lives affects aspects of its energy budget, hydraulic conditions, such as velocity, depth, and complex hydraulic variables relate to the distribution of stream biota. PHABSIM consists of a series of computer models that are used to develop a prediction of usable habitat for fish or other biota as a function of discharge. It does this by coupling two models, one that simulates physical habitat preferences (habitat suitability criteria) and a hydraulic model which estimates how the available habitat space varies with discharge (Figure 1). Recently more complex hydraulic models have been adapted for this purpose (Leclerc et al. 1995) because of model limitations, particularly for low-gradient streams. However, the adequacy of biological models often limits the utility of PHABSIM and the field data requirements in large, heterogeneous stream reaches are sometimes prohibitive.

Virginia's state instream flow policies have forced regulators to deal with the issue of protecting aquatic ecosystems during low flows and placing conditions on water uses. The only published study that aimed at defining a relation between fish habitat and discharge for Virginia fishes was conducted in the upper James River basin by Orth and Leonard (1990). Although based only of fishes, their work suggested that hydrological approaches may serve as useful surrogates for early planning purposes. Clearly further research is needed in order to protect instream flows via drought management plans (Vadas and Weigmann 1993).

Further research and developments that may improve available tools for instream flow assessment include individual-based models (Jager et al. 1993), food-web models (Roell and Orth 1994), habitat-use guilds (Orth 1995), large-scale spatial relationships (Schlosser 1995), and community approaches. Most writers agree that current methods are too controversial for routine application without adequate on-site developing and testing of the biological models. Major concerns focus on habitat bottlenecks, nontransferable habitat suitability criteria, and approaches for dealing with water quality and biological constraints on species persistence. In smallmouth bass populations, stream flow may induce a habitat bottleneck on survival if frequent, variable high flows disrupt spawning (Lukas and Orth 1995); the timing and magnitude of flows is more important that absolute quantity of habitat for spawning. Without site-specific analyses, it is not possible to determine which life stages are influenced by habitat availability. The interaction of variables can result in changes in habitat preferences and render habitat suitability criteria from one stream inaccurate in others (Groshens and Orth 1993). Particularly relevant to drought management are the changes in temperature, dissolved oxygen, and community metabolism during extended periods of low flow. Mayfly nymphs and caddis fly larvae respond to lowered DO conditions by shifts in habitat selection and respiratory activity (Gore 1994). In species-rich assemblages the choice of a few species may have a large effect on the outcome of the study (Moyle and Baltz 1985). Consequently alternative approaches are needed, such as the application of habitat-use guilds instead of species-level habitat simulation (Leonard and Orth 1988; Lobb and Orth 1991; Vadas 1994), to simplify analysis and interpretation while at the same time protecting habitats for a wider variety of life forms. A recent broad-scale study showed that increased hydrologic variability was associated with fishes with generalized feeding strategies, generalized or silt substrata preferenda, and low-velocity preferenda (Poff and Allan 1995). Thus hydrological alterations (natural or anthropogenic) would be expected to alter the structure of fish assemblages. There is clearly a great need for development of more reliable methods that are rigorously tested against the biological variables they are intended to predict.

1.1.2 IFIM Approach for Shenandoah River

An IFIM study is designed to provide a comparison of usable habitat conditions under baseline and alternative hydrologic regimes. In the case of the Shenandoah River we can assume that the baseline hydrologic regime has changed and will change in the future due to increasing use. Since these withdrawals are relatively small in some river segments, the impacts will not affect timing and magnitude of flows during typical high-moderate flow seasons and may not significantly affect low flows in the main stem Shenandoah River at the present usage levels (Zappia and Hayes 1998). Therefore the impact that is of most interest for managers is the level of water withdrawals that would increase the length and severity of drought.

2 Objective 1: Environmental Setting

The environmental setting describes the North Fork Shenandoah's response to the physical and social landscape by evaluating the geomorphology, hydrology, and land and water use within the watershed. These processes are dynamic and represent a continuous temporal element. Fluvial geomorphology examines past processes that shape a landscape and influence a river's course, essentially how a river responds to its surrounding topography. Hydrology combines the landscape processes with climatic influences to describe the energy of the river, its historic and present flow dynamic. The interaction of geomorphology and hydrology produces the physical habitat available to aquatic organisms, while the hydrologic regime is an important determinant in the composition, structure, and function of aquatic ecosystems (Maddock 1999). Social and biological environment examines the social component of a river system, how human users influence the river, its processes, and fauna.

2.1 Fluvial Geomorphology

To evaluate the geomorphology of the Shenandoah Basin and the North Fork Shenandoah River we relied on a literature review of existing studies, specifically those conducted by Hack 1957 and 1965, and Hack and Young 1959.

The Shenandoah River drains approximately 3000 square miles and is the largest, southernmost tributary of the Potomac River, a tributary to the Chesapeake Bay. The Shenandoah River basin contains 59 subwatersheds, across nine counties and two states (Augusta, Rockingham, Shenandoah, Page, Warren, Frederick, and Clarke counties in Virginia; Hardy and Jefferson counties in West Virginia). The watershed is divided into 3 hydrologic units: the mainstem, the South Fork, and the North Fork, which is the focus of our study (Figure 2). The North Fork Shenandoah is a fifth order river that lies within the Valley and Ridge physiographic province of Virginia and drains approximately 1003 square miles. It is located in the northwestern portion of Virginia, and winds northeasterly for approximately 115 miles from its headwaters in West Virginia to its confluence with the South Fork (Figure 3).

The course of the North Fork Shenandoah River is a result of its adjustment to the local geology. The North Fork watershed is a mountainous landscape carved by erosional processes, such as the river itself, through geologic time (Hack 1965). The North Fork basin is underlain by sedimentary sequences of sandstone, quartzite, carbonate rocks (limestone and dolomite), and shale (Figure 4). The North Fork River valley is comprised of 3 distinct geologic regions: 1) the sandstone and shale sequences of upper river from the headwaters to Cootes Store, 2) the carbonate sequences from Cootes Store to Edinburg, and 3) the Martinsburg Shale region, commonly known as the Seven Bends, from Edinburg to Front Royal (Figure 4) (Hack and Young 1959).

A river approaches equilibrium by dispersing its energy throughout its course as it carves through the landscape. River slope or gradient is a function of discharge, bedrock composition, and bed material deposition (Hack 1957). In general, as slope decreases, discharge increases. North Fork basin elevations range from 2640 feet in the headwaters to 460 feet at its mouth. Average gradient of the NFSR is 5.5 ft/mile (Hack and Young 1959). The longitudinal profile is relatively smooth and exhibits the gentle concave profile of river in equilibrium (Hack and Young 1959; Morisawa 1968).

The river gradient is steep, through the ridge forming sandstone and quartzite sequences and shallows through the least resistant valley sequences of carbonate rocks (limestone and dolomite) and shale (Figure 5). Gradient in the sandstone reaches approximates seven times that of the shale reaches; this steepness is due to the river cutting through and transporting more resistant material (Hack 1965). Gravels, cobbles, and boulders comprise the bed substrate upstream of Edinburg, while the downstream, meandering reaches are dominated by bedrock. Elongate reaches joined by 180° bends characterize the 14 meandering miles of the Seven Bends region (Figure 3) (Hack and Young 1965).

Sinuosity is a measure of channel pattern and is defined as the ratio of channel distance to downvalley distance. Straight single channels (non-braided) have a low sinuosity, 1.0 – 1.5, while meandering channels have a moderate to high sinuosity, 1.5 – 4.0 (Gordon et al. 1992). NFSR sinuosity above Edinburg is 1.4 and increases to 3.4 in the Martinsburg Shale region. (Hack 1965). In the Seven Bends reach, the river must travel more than twice as far across the valley as it does downstream (Hack 1965). These meanders are formed as a result of the river cutting through the bedrock and jointing planes (zones of weakness) of the least resistant Martinsburg shale formation; these weak zones determine the course of the river (Hack 1965). Due to the carbonate sequences of the NFSR basin, solution is an important process (Hack 1965), creating the karst terrain and driving the close relationship of the river to groundwater sources.

2.2 Hydrology

Historic gauge station records are a valuable tool for evaluating streamflow and hydrologic processes in a watershed. Three long-term gauging stations, Cootes Store, Mount Jackson, and Strasburg, are located on the North Fork Shenandoah River (Figure 3). The Cootes Store gauge (#01632000) is the most upstream gauge located at river mile 92 in Rockingham County, Virginia. Cootes Store has an elevation of 1051 feet and a drainage area of 210 square miles. Established April 1, 1925, the gauge is an USGS maintained station. The Mount Jackson gauge (#01633000) is the mid-basin gauge located at river mile 70in Shenandoah County, Virginia. This gauge is maintained by the VDEQ and was established October 1, 1945. Mount Jackson’s elevation is 838 feet and drainage area is 506 square miles. The Strasburg gauge (#01634000) is the most downstream station located at river mile 10, at 494 feet elevation, with a drainage area of 768 square miles. This station is located in Warren County, Virginia, and is an USGS maintained gauge in operation since April 1, 1925. The relationship of drainage area to river length in the NFSR basin is described by the following equation:

$$L = 1.4\ A^{0.6}$$

where L is the river length in miles at a locality and A is the drainage area in square miles at the same locality (Hack 1957, 1965). In general, as drainage area increases along a river’s length, channel width and discharge also increase.

2.2.1 Methods

Individual gauge station records of daily mean streamflow over the period of analysis, April 1, 1925 to September 30, 2002, were downloaded from the USGS surface–water data website (USGS 2003). Long-term streamflow records were transferred into individual excel worksheets for each gauging station. The data were analyzed to produce mean daily streamflow hydrographs, monthly flow statistic curves, flow duration curves, and low flow statistic curves for the period of record at each gauge. The gauge hydrographs were produced by plotting mean daily discharge (cfs) values for the period of record at each gauge. A log scale improved the graphical display of the streamflow variability with time at each gauge (Figure 6, Table 1).

To generate the monthly flow statistic curves for each gauge, daily mean flow values for all years were entered into an excel worksheet and organized by month. Daily values for each month were sorted and ranked from lowest to highest mean daily flow. Exceedance probability was calculated for each ranked discharge value using,

$$\text{Exceedance Probability} = 1 - [i / (N + 1)]$$

where i = a value’s rank (from 1 to N) and N = the total number of values in the sample. Monthly Q25, Q50, and Q75 were plotted for each gauge station (Figure 7). Q50 represents the monthly median flow for the period of record; the discharge with a 0.50 probability of being equaled or exceeded. Q25 and Q75 is a measure of spread around the monthly median, or central, value. Period-of-record flow duration curves for each gauge were constructed using similar methods. Daily mean flow values for the period of gauge record were entered into an excel worksheet. Daily mean flow values were sorted and ranked from lowest to highest mean daily flow. Using the aforementioned equation, exceedance probability was calculated for each ranked value. Daily mean flow values were plotted against the exceedance probabilities to produce the flow duration curve (Figure 8).

For each gauge station, low flow analysis involved calculation of d-day flows, for averaging periods d = 1, 7, and 30, in an excel worksheet. The climatic year annual minima of these average values were used to produce a time series plot of annual d-day low flows. Low flow statistics, 7Q10 and 7Q30, for the period of record at each gauge were obtained from the USGS (D. C Hayes, USGS, personal communication) and added to the time series plot (Table 1, Figure 9). The 7Q10 and 7Q30 values are for diagnostic purposes only as they are unpublished and subject to USGS revision.

Gauge station data was also evaluated using the Indicators of Hydrologic Alteration software as a diagnostic tool to examine long-term trends in gauge data. This software calculates the ecologically critical hydrologic regime characteristics (magnitude, frequency, duration, timing, and rate of change) and analyzes temporal changes in these characteristics (Poff et al. 1997; Richter et al. 1997; Maddock 1999) (Tables 2 - 13).

2.2.2 Results and Discussion

The stream hydrograph indicates the pattern of streamflow variation over time. Long-term streamflow patterns are the result of many watershed factors influencing discharge, such as slope, watershed area, and landscape/geology acting on each gauge station sub-basin. Therefore, a hydrograph is an important forecasting tool for water supply planning (Morisawa 1968).

The Cootes Store hydrograph is more variable than the downstream gauges and indicates a strong response to headwater influences (Figure 6). The Cootes Store region exhibits a flashier response to hydrologic events due to its steeper gradient and narrower channel than the downstream reaches. Since a hydrograph reflects watershed characteristics that influence runoff (Morisawa 1968), the gradient and lithology of the Cootes Store valley may signal high runoff potential in this region. This character has important implications, especially in relation to non-point source pollution impacts. As the river widens and its gradient shallows, it is better able to buffer hydrologic influences, resulting in a muted response to extreme flow events, high and low, as evidenced at the Mount Jackson and Strasburg Gauges (Table 1, Figure 6).

Monthly flow statistic curves were also generated from gauge station data. These curves are an indicator of seasonal hydrologic patterns. Each curve exhibits the same seasonal response, with flows peaking in March, as a result of storm events and groundwater recharge, and declining during the low flow summer months (Figure 7).

Flow duration curves illustrate the percent of time a specific discharge is equaled or exceeded and as such, are important tools for determining temporal streamflow variability (Morisawa 1968; Hjelmfelt and Cassidy 1975; Dingman 2002). These curves depict historical, not year-to-year, variability of measured streamflows (Dingman 2002). The shape of flow duration curve reflects drainage basin characteristics. The steep slope of the Cootes Store curve indicates that there is greater runoff in this part of the basin compared to the Mount Jackson and Strasburg gauge sites, whose flattened curves are a response to increased surface or groundwater storage that equalizes flow (Figure 8) (Morisawa 1968).

To assess year-to-year variability, specifically in relation to low flow events, low flow statistic curves were generated for each gauge record. These curves illustrate the magnitude, frequency, and duration of low flow events at each gauge station (Figure 9). Critical low flow periods occur when low flow minimum discharge values fall below the 7Q10 and 7Q30 values for each gauge. The curves exhibit similar patterns with critical low flow periods approximately occurring from 1930-1933, 1964-1967, 1985-1987, 1999-2000, and 2002. Extreme drought or low flow events occur every 23 years on average and last and average of 2.5 years. These low flow curves will facilitate identification of water allocation alternatives that minimize those water uses that increase the magnitude or duration of low flow events.

For each series of gage records we calculated thirty-two hydrologic statistics to describe the historical flow regime. Furthermore, we used linear regression to test for changes over time. None of the thirty-two hydrologic statistics showed significant linear trends over time.

The North Fork Shenandoah River is the most critical water resource in the region. The NFSR basin provides only 20% of the mainstem discharge, but constitutes 60% of the region’s population. The NFSR provides many services, economic, recreational, and biological, to the residents and visitors of the Shenandoah Valley. Current projections of future population growth and water demand predict that water use will exceed supply by 2025 (Figure 10) (PA Consulting Group and Hazen and Sawyer 2001).

2.2.3 Demographics

The Shenandoah River basin supports an approximate, collective population of 444,100 (U.S. Census Bureau 2003). The Shenandoah River basin community is best described as a triumvirate of rural farmers (crop and cattle), wealthy landowners, and tourists. Median household income is approximately $34,700 and 10.4% of households are below poverty level (Figure 11) (U.S. Census Bureau 2003). Between 1970 and 1990, population growth increased by 34%, however land conversion for housing and urban development surpassed this growth (Chesapeake Bay Program 2004). Shenandoah River basin population density (people per square mile) is projected to increase 14% between 2000 and 2020. Housing density (residences per square mile) is projected to increase 17% between 2000 and 2020 (Chesapeake Bay Program 2004).

The NFSR basin supports a population of approximately 57,100 (U.S. Bureau of Census, 2000). From 1970 – 1990, NFSR basin population growth increased 53% (Jones et al. 1997). With the Valley's rural setting and close proximity to the Washington D. C. Metro area, further growth is inevitable. For 2000 – 2020, NFSR basin population growth is projected to increase 15%, with population density and housing density increasing 14% and 18%, respectively (Chesapeake Bay Program 2004).

2.2.4 Land Use and Water Quality

Over 250 years ago, the Shenandoah River and its mountainous setting drew German immigrant farmers from Pennsylvania to the Shenandoah Valley (Phillips 1996). Current Shenandoah basin land use, a mixture of 58% forested upland, 38% agriculture, and 3% developed land, reflects this agricultural heritage (Figure 12) (Chesapeake Bay Program 2004).

Designated Virginia's breadbasket, Shenandoah Valley counties are agriculturally diverse and consistently rank in the top five, statewide, for farm income, production, and acreage (Phillips 1996 and NASS 1999). In the Shenandoah Valley, 6,498 farms and orchards produced grain, feed (silage), cows (beef and dairy), poultry (meat and dairy), sheep, hogs, and fruit (apples, peaches, grapes for wine) on 1,063,477 acres, generating an annual cash receipt income of $819.5 million for 1997 (Table 14) (NASS 1999).

However, additional by-products of this agricultural productivity are nutrient and sediment inputs to the creeks, rivers, and springs of the Shenandoah River. Cropland agriculture practices account for the estimated 60% of nitrogen and 68% of phosphorus entering the Shenandoah River (Alliance for the Chesapeake Bay 2004). In 1999, the Virginia Department of Environmental Quality (VDEQ) and U.S. Environmental Protection Agency (EPA) designated approximately 746 miles of the Shenandoah River as impaired (Anonymous 2001). The State of

Our Rivers Report (2001) lists agricultural run-off and low flows as top watershed problems.

NFSR basin land use consists of 62% forested upland, 35% agriculture, and 2% developed land (Figure 12) (Chesapeake Bay Program 2004). Jones et al. (1997) used 33 landscape indicators to assess watershed condition in the NFSR basin and found that population change, ozone exposure index, riparian agriculture, vegetation index, and slope vegetation index are high risk indicators for adverse impacts on watershed condition (Table 15). Human use index, riparian forest, nitrogen loading, and potential soil loss are some of the moderately – high risk indicators for adverse impacts on NFSR watershed condition (Table 15) (Jones et al. 1997). In 1999, the DEQ and EPA designated approximately 126 miles of the North Fork Shenandoah River as impaired (Anonymous 2001). The prevalence of agriculture on steep slopes is the primary adverse impact on NFSR watershed condition (Jones et al. 1997). Critical tributaries of the NFSR include Holmans Creek, Linville Creek, and Mill Creek (Anonymous 2001).

2.2.5 Supply and Demand

Freshwater resources make up approximately 3% of the earth's water supply (97% is in oceans), with rivers accounting for 0.0001% of the total freshwater supply. Water use can be divided into two main categories: instream use and offstream use. Instream uses occur within the river channel. Offstream uses remove or divert water from the river and use it elsewhere. Based on USGS estimates of surface freshwater use in 1995, instream use (hydroelectric power) accounted for 3,160,000 mgd (million gallons per day) nationally (14,800 mgd in VA). Offstream use (irrigation/agriculture, public water supply, industry, and commercial) accounted for 264,000 mgd nationally (5,110 mgd in VA); 204,336 mgd were returned to a surface water or groundwater source after use (USGS 2002).

The NFSR is the source of supply for the towns of Winchester, Middletown, Strasburg, Woodstock, and Broadway. Permitted municipal and commercial water use averaged 0.78 mgd (1.16 cfs) in the NFSR basin from 1982 – 2002 (Figure 13) (R. Bodkin, VDEQ, personal communication). In 1995, surface water withdrawals for all water use categories (public supply, commercial, industrial, livestock, and irrigation) in the NFSR basin totaled 10.92 mgd (16.89 cfs), with public supply and commercial use accounting for 8.04 mgd (12.44 cfs) (Zappia and Hayes, 1998). In 2002, permitted public supply and commercial demands alone totaled 12.07 mgd (18.67 cfs) (R. Bodkin, VDEQ, personal communication), increasing 1.5 times (or 50%) from 1995. Based on the permitted withdrawal data, it is clear that surface water demands are increasing for the NFSR. However, there is uncertainty regarding total withdrawals, permitted and non-permitted, in the basin, especially for livestock and irrigational uses. As a result, these withdrawal figures are most likely an underestimate of total basin water withdrawals.

Agricultural, hydroelectrical, industrial, commercial, municipal, and recreational demands are quantifiable. However, biological demands are not easily accounted for due to the complex interactions of the riverine community (aquatic, terrestrial, riparian). Biological factors must be included in water use planning and management to maintain the integrity of the NFSR system.

NFSR basin biological demands include habitat for approximately 599 species of mammals, birds, amphibians, reptiles, insects, fish, crayfish, and mussels. The NFSR is home to approximately 43 fish species, 13 mussel species, and 8 crayfish species (VDGIF 2003). Several aquatic species are federal and/or state listed species.   The brook floater mussel, *Alasmidonta varicose*, is a federal species of concern and state endangered species and the Atlantic pigtoe, *Fusconaia masoni*, is a federal species of concern and state threatened species. The green floater, *Lasmigona subviridis*, yellow lampmussel, *Lampsilis cariosa*, and Tennessee pigtoe, *Fusconaia barnesiana*, are federal and state species of concern (VDGIF 2003). Although the roughhead shiner, *Notropis semperasper*, a federal and state species of concern and the Appalachia darter, *Percina gymnocephala*, a federal species of concern, are also included on the NFSR species list, based on systematics and distribution information, it is unlikely that either species occupies the NSFR or its tributaries (Jenkins and Burkhead 1994).

3 Objective 2: PHABSIM Physical Data Collection

Physical Habitat Simulation System (PHABSIM) modeling is an important tool in IFIM studies. The purpose of PHABSIM is to characterize the physical stream hydraulically and evaluate the relationship of stream flow (discharge) to habitat availability for aquatic resources (Figure 1) (Bovee 1997; Stalnaker et al. 1995,; Hardy 2000). The guiding assumption of PHABSIM is that aquatic resources are limited by the availability of physical habitat. As such, the end product of PHABSIM is a microhabitat index (weighted usable area, WUA) of available habitat at various discharges. However, it is important to note that this assumption is not always true, as aquatic resource benefits are the result of many factors, including but not limited to, habitat availability (Stalnaker et al. 1995; Hardy 2000). For this study, implementation of PHABSIM included 1) field data collection of channel characteristics, hydraulic properties, and fish habitat guild requirements to describe the NFSR, 2) hydraulic modeling, and 3) habitat modeling.

This section describes the consecutive physical data collection process, which included: 1) a mesohabitat inventory, 2) study reach and site delineation, 3) transect selection, 4) hydraulic data measurements, and 5) fish habitat data measurements.

3.1 Mesohabitat Inventory (J.L. Krstolic, USGS)

The initial effort of the study was to identify, describe, and quantify the relative amount of mesohabitat types that occur in the North Fork Shenandoah River. The term mesohabitat refers to intermediate-sized zones within a stream that have similar characteristics and tend to behave as a unit in response to changes in flow. Riffles, runs, and pools are examples of mesohabitat types. Mesohabitat features are smaller than a macrohabitat feature (a large area on the order of miles, such as the Seven Bends area), and larger than a microhabitat feature (a small area on the order of tenths of feet such as the space behind an individual boulder in the stream). Mesohabitat features are of moderate size, roughly on the order one stream width.

The mesohabitat inventory provides a base-line understanding of the physical characteristics of the river, and is necessary so that detailed hydrologic and habitat data collection efforts (1) target the most important mesohabitat types, (2) describe flow-habitat relations at similar locations, and (3) truly represent the physical stream (Moyle and Baltz 1985; Maddock 1999). Definition of the relation between instream flow and usable habitat within a particular mesohabitat type (e.g. riffles), combined with an inventory of mesohabitat type present in the river (number and length of riffles), can be used to estimate the net effect of incremental flow changes on that mesohabitat type throughout study area. The scope of this inventory includes the North Fork Shenandoah River, from the headwaters in West Virginia, to the confluence with the South Fork Shenandoah River in Virginia.

3.1.1 Methods

USGS personnel (D. Hayes, P. Ruhl, and J. Krstolic) canoed or walked the total river length to inventory NFSR mesohabitats. The inventory was conducted during periods of low flow between September 1998 and November 2002. During the inventory, stream flows ranged from 1.7 cubic feet per second (cfs) to 40 cfs at the USGS gauging station located at Cootes Store, Va., and from 111 cfs to 373 cfs at the USGS gauging station located at Strasburg, Va. These values represent approximately the 10th percentile of the flow duration curve for each gage, confirming that the data collection period was during low flows.

Three general categories were used to describe mesohabitat types: riffles, runs and pools (Table 16). Each general category was further divided into two or more subcategories (Table 17). These categories and subcategories were developed based on qualitative observations of general water-surface gradient, water velocity, bed substrate, and channel morphology. Riffles were described as shallow rapids, in an open stream where a turbulent water surface is created by obstructions that are wholly or partly submerged. Water depth in riffles was generally less than one foot deep. Runs were described as areas characterized by organized, predominantly smooth to slightly turbulent flow. The water surface was usually flat and was not broken by the substrate. Water depth in runs was generally between one and four feet deep. Pools were described as areas with reduced or barely perceptible surface velocity, as well as a smooth, unbroken water surface. Water depth in pools was greater than four feet deep.

As each change in mesohabitat type was encountered the location of the boundary was recorded using a Global Positioning System (GPS) receiver. The mesohabitat type was noted, and habitat characteristics described. Water depth, channel width, and bed substrate were measured or observed. Mesohabitat length was measured in the field in one of three ways. The length of mesohabitats less than 50 feet long was estimated using the length of the canoe as a reference. When a mesohabitat was longer than 50 feet and less than approximately 300 feet the length was measured with an infrared rangefinder (accuracy plus or minus three feet). The length of mesohabitats longer than approximately 300 feet were calculated based on the latitude-longitude coordinates of the boundaries. When a mesohabitat included a meander bend, the curvilinear channel length was accounted for by breaking the bend into several straight line-of-site sections and basing the calculation on a summation of the length of each section.

The GPS-collected latitude and longitude coordinates were input to a Geographic Information System (GIS) to map the location of mesohabitat boundaries. Short mesohabitat units usually lacked GPS locations for either the upstream or downstream boundaries, therefore; field notes were used to indicate where additional points should be added to complete the habitat description and inventory. To increase the accuracy of the length calculations, extra points were added around meander bends and some points were moved to mid-channel. Lengths were then re-calculated using the adjusted GIS point coverage.

3.1.2 Results and Discussion

As noted earlier, riffles were classified as particle or bedrock based upon their substrate types. The particle riffles were the most prominent riffle type with 513 identified, followed by 126 bedrock riffles, and 33 bedrock terrace riffles (Table 18). Most of the particle riffles were located along islands or narrow bends. Bedrock riffles spanned wide, shallow sections of river where bedrock ledges protrude, and the bedrock is tilted or dipped at an angle that interrupts the flow, causing turbulence. Both particle and bedrock riffles were short, generally less than 30 feet long, but commonly only three feet long. While the particle riffle is the most numerous habitat category, it only made up 10 percent of the total river length (Figure 14).

Runs make up the majority of habitat in the river. Particle runs were most numerous with 454 identified, followed by 329 bedrock runs, and 58 pocket runs (Table 18). Almost all run habitat types covered long stretches of the river. The average length of a pocket run was 620 feet, a bedrock run was 597 feet, and a particle run was 322 feet (Table 18). Sixty-nine percent of the North Fork Shenandoah River is made up of run habitat (Figure 14).

Pools are present in moderate number and are of varying size on the North Fork Shenandoah River. They are typically not very deep, with depths generally 10 feet or less. Most pools had bedrock substrate. The inventory identified 119 natural pools and 43 artificial pools (Table 18). The North Fork Shenandoah River has been historically used in a variety of economic endeavors. There have been saw mills and grist mills along the river since the 1800's. Small low head dams were used to divert water to mill races, and abandoned road crossings have become dams over time. Even though there are few hydroelectric plants and large dams, a substantial number of artificial pools were present. Overall, pools and backwaters made up 18 percent of the total river length (Figure 14).

3.2 Study Reach and Site Delineation

In June 2000, based on the initial phase of the mesohabitat inventory conducted by the USGS, 6 study sites (with a total of 36 transects) were selected to characterize the mesohabitats (riffle, run, pool, and pocket run) of the North Fork Shenandoah River. The 6 study sites, listed in upstream to downstream order, are Plains Mill, Laurel Hill Farm, Spring Hollow, Posey Hollow, Route 648, and Winchester Dam (Figure 15). Each site was associated with one of the 3

North Fork gauging stations based on gauge station hydrologic analysis (reference section 2.3.2), drainage area, tributary gains, mesohabitat composition and geomorphology. Thus, the study site(s) serves as a reference site(s) for the gauging station study reach. We feel these are the minimum number of sites needed to characterize the physical stream.

3.2.1 Cootes Store Reach

The Cootes Store study reach starts in the North Fork Shenandoah headwater region in West Virginia and extends to the confluence of Smith Creek (Figure 15). The reach is 39.3 miles in length and comprised of 17.5% pool habitat, 18.5% riffle habitat, and 64% run habitat. The Plains Mill site serves as the reference site for the Cootes Store reach. Plains Mill is located at river mile 81, 11 miles downstream of the Cootes Store gauge station. Plains Mill has a drainage area of 321 square miles, is 1905 feet (0.36 mi) in length, and is comprised of 16.6% pool habitat, 13.6% riffle habitat, and 69.8% run habitat (Plains Mill Site Profile, Appendix).

3.2.2 Mount Jackson Reach

The Mount Jackson study reach begins at the confluence with Smith Creek and extends to the confluence of Narrow Passage Creek (Figure 15). The reach is 17.6 miles in length and comprised of 18.2% pool habitat, 12.3% riffle habitat, and 69.5% run habitat. The Laurel Hill Farm site serves as the reference site for the Mount Jackson study reach. Laurel Hill Farm is located at river mile 55, 15 miles downstream of the Mount Jackson gauge station. Laurel Hill Farm has a drainage area of 653 square miles, is 333 feet (0.06 mi) in length, and comprised of 0% pool habitat, 18.9% riffle habitat, and 81.1% run habitat (Laurel Hill Farm Site Profile, Appendix). The site was selected because it is dominated by those mesohabitats most impacted by low flow conditions, riffles and runs.

3.2.3 Strasburg Reach

The Strasburg study reach begins at the confluence of Narrow Passage Creek and extends to the mouth (confluence with the South Fork Shenandoah) and encompasses the Seven Bends region of the North Fork Shenandoah (Section 2.3.1; Figure 15). The reach is 50.2 miles in length and comprised of 19.8% pool habitat, 11.1% riffle habitat, 68.9% run habitat, and 0.2% pocket run habitat. The Spring Hollow, Posey Hollow, Route 648, and Winchester Dam sites serve as the reference sites for the Strasburg study reach.

Spring Hollow is the most upstream site in the reach, located at river mile 42, 32 miles upstream of the Strasburg gauge station. Spring Hollow has a drainage area of 694 square miles, is 228 ft (0.04 mi) in length, and is comprised of 60.0% riffle habitat, 40.0% run habitat (Spring Hollow Site Profile, Appendix). The site was selected because it is dominated by those mesohabitats most impacted by low flow conditions, riffles and runs.

The Posey Hollow site is located at river mile 21, has a drainage area of 738 square miles, is 334 feet (0.06 mi) in length, and is comprised of 18.2% riffle habitat, 36.3% run habitat, and 45.6% pocket run habitat (Posey Hollow Site Profile, Appendix). This site was selected to highlight the unique pocket run mesohabitat found on the North Fork, in addition to the low flow intolerant habitats, riffle and run.

The Route 648 site is located at river mile 19, has a drainage area of 743 square miles, is 704 feet (0.13 mi) in length, and comprised of 7.5% riffle habitat, 72.5% run habitat, and 20.0% pocket run habitat (Route 648 Site Profile, Appendix). The Winchester Dam site is located at river mile 7, 3 miles downstream of the Strasburg gauge station. Winchester Dam has a drainage area of 932 square miles, is 155 feet in length and includes 100% artificial pool habitat, due to the low head dam just downstream of the study site (Winchester Dam Site Profile, Appendix).

3.3 Transect Selection

A transect (also called a cross-section) is a section across the stream channel that is perpendicular to the direction of flow (Figure 16). Transects were placed within the specific mesohabitat types (riffle, run, pool, pocket run) present at each study site according to methods outlined in Bovee (1997) and Trihey and Wegner (1981). Once transects were chosen, survey pins were placed along the left and right bank (identified looking downstream) to mark transect locations. Transects were numbered consecutively in the upstream direction. Temporary benchmarks were established at each site to serve as a vertical reference datum for the pins. Using a level and stadia rod, a closed-loop survey through all pins linked the transect elevations and distances to the benchmarks at each study site.

3.3.1 Results

A total of 36 transects were established across the 6 study sites. The Plains Mill site consists of 10 transects: 1 control, 1 riffle, 5 run, and 3 pool. Laurel Hill Farm is a riffle run complex site having 2 riffle and 3 run transects. Five transects, 4 riffle and 1 run, characterize the Spring Hollow site. Posey Hollow consists of 1 riffle, 2 pocket run, and 2 run transects. Route 648 is comprised of 1 riffle, 3 run, and 4 pocket run transects. The Winchester Dam site represents the pool mesohabitat type with 3 transects (Site Profiles, Appendix).

3.4 Hydraulic Data Collection

With the transects established, we commenced field data collection of 1) cross-sectional profiles, 2) channel index variables, 3) water surface elevations at target flows, and 4) water depths and velocities at target flows.

3.4.1 Cross-Sectional Profiles

In PHABSIM, the channel cross-section is described as a series of x and y coordinates, called verticals (Bovee 1997). The x-coordinate is the horizontal distance of a sample point, occurring at regular intervals (every 3ft, 4ft, 5ft, etc) along the transect. The x-coordinate distance is also referred to as the station. The y-coordinate is the channel bed elevation at each specified station (Figures 16 - 17).

Using a survey level and level rod, bed elevation (channel profile) was measured at each station along the transect tagline relative to the transect pins (Figure 17). Thirty to forty measurements (X, Y; vertical) were taken at each transect, and considered an adequate range to describe the channel morphology. Channel profile measurements were entered into the site-specific raw data import file for PHABWIN. With transects and verticals established, each study site is represented by a grid of equally spaced stream cells (Figure 18). At any given discharge, each cell along a transect will have a unique combination of hydraulic and habitat characteristics (channel index, water surface elevation, depth, and velocity). PHABWIN will model how the hydraulic and habitat characteristics vary in response to changes in flow.

3.4.2 Channel Index Variables

Channel index variables are those features that do not change directly as a function of flow. Channel index variables were measured at Plains Mill, Laurel Hill Farm, Spring Hollow, Posey Hollow, and Winchester Dam in August 2000 and at Route 648 in November 2000. As outlined in Bovee (1997), channel index variables were evaluated and recorded at each cell (defined as the mid-point between two adjacent hydraulic verticals) along the reach transects. For the purpose of this study, the channel index variables included substrate (dominant and subdominant), cover (all variables present), and embeddedness (percent).

Using a classification scheme adapted from Bovee (1997), Platts et al. (1983), Trihey and Wegner (1981), and Newcomb (1992) (Tables 19 - 21), individual channel indexes for each cell were recorded in field data notebooks. From the field notebooks, the cell channel index variables were transcribed in an excel spreadsheet using their associated codes and quartiles. For example, a cell having a dominant substrate of small cobble, subdominant substrate of large gravel, cover of a root wad and small velocity shelter, and embeddedness of 10% would be coded as 08; 07; 08,02; 1. Fish habitat measurements conducted during the summers of 2001 and 2002 used the same classification and coding system. As a result of the fish habitat analysis and suitability criteria development (Section 3.5.1), we simplified the suit of codes to a more meaningful metric (3 part numerical code) based on dominant substrate, cover [quantified as presence (0.1) or absence (0.0)], and embeddedness (quartile 1 = 0.01, quartile 2 = 0.02, quartile 3 = 0.03, quartile 4 = 0.04). Revisiting the aforementioned example, our final code for this cell would be 8.11. The finalized channel codes were imported into PHABWIN-2002 as a component of the raw data files.

3.4.3 Water Surface Elevation

The water surface elevation refers to the elevation of the water's surface in relation to an arbitrary datum (Figure 19). At each site transect and for each calibration discharge (target flow: low, medium, and high), water surface elevations were measured at the start and end of the each field day. Water surface elevations were measured along the right bank (looking downstream) with a survey level and level rod. The average water surface elevation was calculated for each transect and referenced to the site calibration discharge. The relationship between calibration discharges and water surface elevations is used to calibrate the hydraulic model and predict water surface elevations at unmeasured discharges for hydraulic simulation (Bovee 1997). Water surface elevation measurements for each target flow were entered as a component of the site-specific raw data import files.

3.4.4 Water Depth and Velocity Measurements

Water depth is the vertical distance from a point on the channel bed to the water surface. Velocity is the rate of flow at a depth in the stream. For each target flow (low, medium, and high), depth and velocity measurements were taken at each station along the individual transects (Figure 20). For shallow sections, depths approximately ≤ 5.5 ft, measurements were made by wading; for deeper sections, measurements were taken from a canoe or hobie cat®. Depths were measured in feet (ft) using the top set wading rod graduations. Velocities were measured in feet per second (ft/s) using Price AA, Pygmy, or Marsh-McBirney current meters that were suspended on a top set wading rod (4, 6, & 8 ft. lengths). For depths less than or equal to 2.5 ft, station mean column velocity was measured at the 0.6 water column depth. For depths greater than 2.5 ft, velocity was measured at the 0.8 and 0.2 depths and the average of these measurements was used as the station mean column velocity. Discharge for each cell is calculated as the product of measured station water depth, mean column velocity, and cell width. The sum of the transect cell discharges equals the total discharge for a given transect. Measured water depths and associated velocities are used in the calibration of the velocity model and simulation of velocity at unmeasured discharges. The depth and velocity measurements were entered as a component of the site-specific raw data input files.

3.5 Fish Habitat Data Collection

NFSR fish sampling sites ranged from 30 to 130 km of the river, upstream from its confluence with the South Fork Shenandoah River. The study sites were selected based on a mesohabitat assessment of the North Fork Shenandoah River, conducted during the fall of 1998 and spring of 1999 by Don Hayes and Peter Ruhl (United States Geologic Survey, Richmond, VA). Five sites sampled for the hydraulic model (Spring Hollow, Plains Mill, Laurel Hill Farm, Posey Hollow, and Route 648) were selected for fish sampling. The five reaches were used because they represented the habitat types of the river in proportions similar to the actual proportions found throughout the river. Four of these sites were sampled during summer 2001. Spring Hollow was sampled during the summer of 2002, along with two randomly selected sites, Covered Bridge and Edinburg.

Both sampling techniques, direct underwater observation and throwable anode electrofishing, were used for five of the seven sites on the river. During the summer of 2001, the Route 648 site was only sampled using direct underwater observation. Because of high water our field season came to an end before this site could be sampled using the throwable anode. During the summer of 2002, the Spring Hollow site was only sampled using the throwable anode. Snorkeling was not conducted here because the site is located directly below the outflow from a wastewater treatment plant

3.5.1 Field Data Collection

Direct underwater observation and electrofishing using a throwable anode were used to conduct fish and habitat sampling. Snorkeling surveys were conducted using slightly modified static-drop techniques described by Li (1988). For the snorkeling surveys the river was sampled in 30 m sections. The river was divided into lanes based on the visibility the day of sampling. The visibility was measured using the Secchi disk technique described by Ensign et al. (1995). After the river was divided into equally spaced lanes, two lanes in each 30 m section were chosen at random. Drop-lines were attached to a static line at the center of the two randomly selected lanes and left undisturbed for 30 minutes prior to beginning the sampling surveys (Figure 21).

At each fish location a marker (numbered float attached to a fishing weight) was dropped. The marker number, species, and notes on the fish’s behavior were relayed to a data recorder. All fish were identified to species except for the satinfin shiner (*Cyprinella analostana*) and the spotfin shiner (*Cyprinella spiloptera*). These two species were identified to genus because of the difficulty involved in field identification and will be referred to as *Cyprinella sp*. A detailed description of the snorkeling surveys can be found in Persinger (2003).

After the survey was completed, we returned to the location of each marker and measured the habitat. The dominant substrate, subdominant substrate (Table 19), embeddedness (Table 20), and cover (Table 21) were described within a one meter square area around the fish location using a modified version of the Wentworth classification system (reference Section 3.4.2). Water column depth (m) was measured using a top-setting wading rod. Mean water column velocity (m/s) was measured with a Model 2000 Marsh McBirney electronic flow meter.

Electrofishing using a throwable anode was also used to gather fish habitat use data. The design of the throwable anode (Figure 22) was based on the systems described by Monahan (1991) and Bovee (1997). A detailed description of the throwable anode and sampling methodology used in this study can be found in Persinger (2003). The technique for using the system was based on the procedures described by Bovee (1997). The river was divided into five equal sized lanes and sampled using a modified version of the diamond-sampling pattern (Figure 21). The sampled reach was approached from downstream. A 60 m section of the river was sampled at a time and the anode was thrown 25 times. Collected fish were identified to species and the marker number and species information was recorded. The group would then proceed to the area just downstream of the next sampling site and repeat the procedure. At the end of a run the crew would return to all marked locations and measure the same habitat variables that were recorded during the snorkeling surveys.

3.5.2 Guild Approach

Habitat data used in any IFIM study should represent the entire aquatic community (Moyle and Baltz 1985; Orth 1987; Gan and McMahon 1990). In warmwater stream systems with high species richness, such as the North Fork Shenandoah River having habitat information for only one or two species limits the usefulness of the model output produced by PHABSIM. If only a small portion of the community is represented, then flows thought to protect the integrity of the system may actually be detrimental to it (Bain et al 1988; Lobb and Orth 1991; Aadland 1993). Several approaches have been proposed for filling the need to describe the habitat of the entire community. One proposed approach to this problem is using habitat guilds to represent the habitat needs of the aquatic community (Orth 1987; Leonard and Orth 1988; Lobb and Orth 1991; Aadland 1993).

Using guilds to simplify fish diversity has become a common practice in fish community studies (Austen et al. 1994; Vadas and Orth 2000). An approach to using guilds would be to treat the guilds as super species and establish criteria for the guild itself (Austen et al. 1994). In this way all members of the guild are being represented by the guild criteria. Several different guild structures have been proposed for use in instream flow studies with the number of guilds being used varying from four to seven (Bain et al. 1988; Lobb and Orth 1991; Aadland 1993; Vadas and Orth 1997; Vadas and Orth 2000).

The habitat guild structure that was used in this study is a modified version of one developed for the Roanoke River, VA (Vadas and Orth 1997, 2000). Vadas and Orth (2000) used a guild structure containing four rheophilic (fast-riffle, riffle/run, fast generalist, and shallow-rheophilic) and three limnophilic guilds (pool/run, open-pool, and pool-cover) habitat guilds (Figure 23). The guilds used in this study are riffle, fast generalist, pool-run, and pool-cover (Figure 23). Three of the guilds used are a combination of two guilds described by Vadas and Orth (2000) and the other is their pool-run guild. The riffle guild used in this study is a combination of the fast-riffle and riffle/run guilds. These two guilds were combined into one riffle guild because of the large overlap in the habitat described by the guilds and because of the low number of species occurring in these two guilds. The fast generalist guild used in this study is a combination of the fast generalist and shallow-rheophilic guilds. These two guilds were combined due to their similarity and a lack of species fitting into the shallow-rheophilic guild. The pool-cover guild used in this study is a combination of the open pool and pool-cover guilds. These two guilds were combined due to their similarity and a lack of species fitting into the open pool guild.

Prior to sampling, the species were placed into the four habitat guilds based on placement in the Vadas and Orth (2000) study or on habitat information taken from literature about the adult life stage. The species placement and guild structure were tested because of the lack of good habitat information on many species in the literature and because a habitat guild structure has never been transferred between systems before. Species placement in each of the four guilds was then finalized (Table 23) based on the testing done in Persinger (2003).

3.5.3 Habitat Suitability Criteria

The data collected for all species assigned to a given guild were combined to form the data set that was used to develop the habitat suitability criteria for the guild. Habitat suitability criteria were developed for depth, velocity, substrate, embeddedness, and cover presence for each habitat guild. In addition the mean and standard deviation was calculated for the depth (Table 24) and velocity (Table 25) data of each guild (Figure 24).

Two techniques were used for developing the habitat suitability criteria. Nonparametric tolerance limits were used to create criteria for the continuous variables depth, and velocity (Table 26). Strauss Linear Index was used to create habitat suitability criteria for the categorical variables substrate, embeddedness, and cover presence. The substrate variable is a combination of the measures of dominant substrate and subdominant substrate taken in the field. Detailed description of how nonparametric tolerance limits and Strauss Linear Index were used to establish habitat suitability criteria for the habitat guilds can be found elsewhere (Persinger 2003).

The riffle and fast generalist guilds are using a smaller range of depth and shallower depths than the pool-run and pool-cover guilds, as you would expect (Figure 25). The velocity criteria for the guilds (Figure 26) indicate that the riffle guild is using the widest range and fastest velocities. The pool-run and fast generalist guilds are using the intermediate velocities and the pool-cover is using the slowest velocities. Optimal substrate habitat for riffle guild ranges from small cobble to small boulder with suitable habitat ranging from large gravel to flat bedrock (Figure 27). The optimal substrate habitat for the fast generalist ranges from small cobble to small boulder with suitable habitat ranging from small gravel to flat bedrock (Figure 27). Pool-run guild optimal substrate ranges from large cobble to small boulder with suitable habitat ranging from small cobble to tilted bedrock (Figure 28). Small cobble is the optimal habitat for the pool-cover guild and all other substrate types except tilted bedrock is considered suitable (Figure 28).

The riffle, fast generalist and pool-run guilds all have the same criteria for embeddedness with 0-25% embeddedness being optimal habitat and anything more embedded considered unsuitable (Figure 29). The pool-cover guild has an optimal embeddedness of 25-50% embedded with anything greater than 25% being suitable (Figure 29). All four guilds need at least some type of cover for the habitat to be suitable using cover presence versus cover absence all four guilds showed a preference for cover (Figure 30).

The criteria development results give a good picture of the habitat use of each of the habitat guilds. The riffle guild prefers shallow, fast water with low embeddedness, cobble sized substrate, and nearby cover. The fast generalist guild prefers locations with medium depths and velocities, cobble to boulder-sized substrate, low embeddedness, and nearby cover. The pool-run guild prefers locations with deeper depths, medium velocities, cobble to boulder-sized substrate, low embeddedness, and nearby cover. The pool-cover guild prefers deeper, slower water with embedded substrate and nearby cover.

4 Objective 3: PHABSIM Microhabitat Modeling

Microhabitat refers to the small-scale hydraulic and physical habitat river features that determine the specific location or home range of aquatic organisms (Figure 1) (Hardy 2000). PHABSIM modeling includes hydraulic and habitat simulation of a stream reach using hydraulic variables (section 3.4) and habitat suitability criteria (section 3.5) (Milhous et al 1989). For a detailed discussion of

PHABSIM, see Milhous et al. 1989, Stalnaker et al. 1995, and Bovee 1997. Five of the six study sites, Plains Mill, Laurel Hill Farm, Spring Hollow, Posey Hollow, and Route 648, were modeled in PHABSIM. The Winchester Dam site was not modeled, as this site is not habitat limited during low flow conditions.

4.1 Hydraulic Modeling

The purpose of hydraulic modeling in PHABSIM is to determine the response of depth and velocity as a function of discharge. Hydraulic modeling in PHABWIN is a two-step process: 1) calibration and simulation of water surface elevations and 2) calibration and simulation of velocities (Figure 31).

4.1.1 Raw Data Input

Hydraulic calibration and simulation was conducted using windows – based PHABSIM software, PHABWIN-2002, and the process outlined in Hardy 2000. Raw data files were imported into PHABWIN-2002. Upon import, all data in the raw data input window was checked for accuracy. The water surface elevation (WSL) modeling wizard was selected. The WSL and stage of zero flow (SZF) were set to the average and user-defined values (values contained in the imported raw data files), respectively for each calibration/target flow set (calset). Best discharge (Q) groups were set for each cross-section and calset. Best Q for each cross-section and calset was defined as the discharge measured at the designated representative transect for each site (Site Profiles, Appendix). Twenty-seven base simulation flows, ranging from 5 to 700 cfs, were used for each site to encompass measured discharges and sufficient low discharge values to model low flow response. For individual sites, the site calibration discharges (calset 1, calset 2, calset 3) were included in the simulation flow range, so each site was modeled with at least 30 simulation flows (the 27 base simulation flows plus the calibration discharges). Once the simulation flow range was set, the water surface model was selected for the site.

4.1.2 Water Surface Elevation Modeling

PHABSIM employs one of three hydraulic models to calibrate and simulate WSL's: 1) IFG4, 2) MANSQ, or 3) WSP. IFG4 uses a stage-discharge regression to calculate WSL at each cross section. MANSQ uses Manning's equation as,

$$Q = [(1.49/n) \text{ x } S^{1/2}] \text{ x } A \text{ x } R^{2/3}$$

where Q = discharge, n = roughness coefficient, S = slope, A = cross section area, and R = hydraulic radius, to calculate WSL at each cross section. Manning's N describes the roughness or resistance to flow within a channel (Hardy 2000). WSP, the water surface profile model, uses a step backwater method and Manning's equation to determine how the longitudinal profile of water surface elevation changes across cross sections and discharges (Milhous et al. 1989; Hardy 2000).

For this study, either the WSP or the MANSQ model served as the water surface elevation model. The WSP model assumes that the water surface elevation is controlled by hydrologic conditions at a downstream cross section. Therefore, the WSP model was selected for those sites, Route 648 and Posey Hollow, which experienced a backwater effect due to mesohabitat composition and transect location. The WSP model treats the cross sections dependently, using one model to evaluate water surface elevations across all transects within a site. The high calibration discharge (calset 3) was chosen as the initial calibration discharge for calibrating Manning's N to the longitudinal profiles for all cross sections. Manning's N values were selected based on calculated N values for each transect (Site Profiles, Appendix). Roughness modifiers (RMOD's) were selected for the remaining calibration discharges, calset 1 (low) and calset 2 (medium), to modify the initial calibration discharge Manning's N values to improve prediction of WSL's at calset 1 and 2 (Hardy 2000). Using the guiding principle that roughness increases with decreasing discharge and a trial and error approach, RMOD's were selected to improve the model predictability (Site Profiles, Appendix).

To evaluate the calibration results of the WSL model, the observed and predicted WSL's were viewed on the longitudinal profile graph and examined for anomalies (water flowing uphill). If the calibration results were unsatisfactory (WSL error > 0.05 ft), N values and RMOD's were adjusted (within the range of measured values) to recalibrate the model. If the calibration results were satisfactory, WSL simulation proceeded using the WSL modeling wizard.

The MANSQ model assumes that the condition of the channel controls the water surface elevation and that no backwater effect occurs between site transects. The MANSQ model was selected for those sites with a composite of riffles and runs that did not calibrate well with the WSP model, Spring Hollow, Laurel Hill Farm, and Plains Mill. The MANSQ model is a channel conveyance model that treats each site transect independently, therefore water surface elevation is evaluated on a transect by transect basis. A MANSQ model was defined for each cross section at a site. Calset 3 (high flow) was chosen as the initial calset and calsets 1 and 2 were selected as the remaining calibration discharges for calibrating the WSL profile. The default modeling parameters for MANSQ were selected and beta coefficients were set using a trial and error process for each cross-section to minimize the difference in the observed and predicted WSL's (target difference $\leq$ 0.05 ft) (Site Profiles, Appendix). After the beta coefficients were set for each cross-section, the WSL calibration results were evaluated on the longitudinal profile graph.

Validation is a mandatory component of model calibration and simulation (Mayer and Butler 1993). WSL calibration results for each site were exported from the PHABWIN output (scratch) file into an excel spreadsheet. The average Manning's N value (across cross sections) for each calibration flow was plotted against discharge. An acceptable plot exhibited a decrease in Manning's N values with increasing discharge. In addition, WSL calibration results, observed and predicted, for each calibration discharge set were entered into excel and model performance was tested using the modeling efficiency statistic (EF) (Mayer and Butler 1993). Modelling Efficiency, EF, is a statistic that directly relates model predictions to the observed data. EF is a goodness of fit statistic where,

$$EF = 1 - \Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \overline{y_i})^2$$

and y_i = the observed value, y_i = the predicted value, and y_i = the observed value mean (Mayer and Butler 1993). Model simulations with a negative EF value are rejected and EF values approaching 1 indicate near perfect model simulations (Mayer and Butler 1993). If validation results were satisfactory, simulation flow analysis commenced in the WSL modeling wizard. Upon completion of the WSL model calibration and simulation, the velocity model was run for each site.

4.1.3 Velocity Modeling

PHABSIM uses the IFG4 model to predict cell velocities as discharge changes. The velocity model treats each cross-section at a site independently. Route 648, Posey Hollow, Spring Hollow, Laurel Hill Farm, and Plains Mill were each calibrated using a mixed velocity model approach. For each site, three velocity models were selected. Model 1 used all cross sections and calQ 1 for the low flows of the simulation range (minimum – Q1), model 2 used all cross sections and calQ 2 for the medium flows of the simulation range (Q1 – Q3), and model 3 used all cross sections and calQ 3 for the high flows of the simulation range (Q3 – maximum). No Manning's N options were selected for the calibration and simulation runs.

Calibration results were viewed in the Bed Profile window. In addition, velocity calibration results for each site were entered into excel and model performance was tested using the modeling efficiency statistic (Mayer and Butler 1986). Route 648 cross sections 5 and 7 failed the test (negative EF value) at the high calibration flow (calQ3). However, the mixed velocity model for this site was maintained, as depth and velocity data was collected at these cross sections on a different day than cross sections 1 – 4 and 6. The site discharge difference across those days (444 cfs for XS 5, 7 and 526 cfs for XS 1 – 4, 6) resulted in the poor agreement. Several Plains Mill cross sections failed the test (had negative EF values) and as a result indicated that a mixed velocity model approach was not appropriate for this site. As a result, the velocity model was recalibrated using a high calibration velocity approach; one velocity model across all cross sections and simulation flows, using calQ 3 for calibration (Plains Mill Site Profile, Appendix). These results were checked using the modeling efficiency statistic and only one cross section, XS 8, failed (Plains Mill Site Profile, Appendix).

Once the calibration results proved acceptable, through positive EF values, the simulation analysis proceeded in the velocity modeling wizard (Site Profiles, Appendix). Velocity adjustment factor (VAF) results were evaluated for velocity simulation predictability. VAF is an adjustment factor in the velocity simulation process and is the ratio of predicted simulation discharge to observed/measured discharge. VAF results were imported from the PHABWIN scratch file, plotted within a site excel worksheet, and checked for the relationship of increasing cross sectional VAF's with increasing discharge (from calset 1 to calset 3). With hydraulic model calibration and simulation complete, a depth and velocity - discharge relationship is established for each study site that will facilitate habitat modeling.

4.2 Habitat Modeling

PHABWIN merges the hydraulic modeling output with habitat suitability curves to determine available habitat response as a function of discharge (Figure

31). With the hydraulic models calibrated and simulated, habitat analysis commenced in PHABWIN-2002. The PHABSIM habitat model uses the hydraulic model output, combined with the measured fish habitat parameters to calculate a microhabitat index for target species (in our case, fish habitat guilds) at each site. Habitat modeling is a two-step process involving 1) microhabitat index (WUA) calculation and curve generation using the HABTAE modeling wizard and 2) Time Series modeling.

4.2.1 Methods

Since site transects were selected based on a habitat mapping approach, weighting factors were calculated for individual site transects to approximate the habitat composition of the study reach (section 3.2), except for the last site transect (most upstream cross section), which was assigned a value of 0.0 (Site Profiles, Appendix). For each site, weighting factors were entered into the PHABWIN raw data input screen. Suitability curve files were created for each guild and representative species (Section 3.5) and imported into PHABWIN as FISHCRV files according to Hardy 2000. For the purpose of this report, only the guild criteria will be discussed. For further information on the representative species criteria, please refer to Persinger 2003.

As a result of low flow conditions during summer 2002, large algal mats were prevalent in the NFSR (Section 5). An algae-midge guild suitability curve was developed, based on professional judgment, to model algal bloom potential in the NFSR across the simulation flows (Figure 32). Using the HABTAE modeling wizard, all guild suitability curve sets, fish and algae, were selected for each site, default modeling options were chosen, and the habitat simulations completed to produce guild microhabitat index (WUA) curves. Habitat index (WUA) curves for each guild at a site were examined for conservation thresholds.

4.2.2 Results

Since we are concerned with low flow conditions on the NFSR, it is important to focus on the left side of the WUA graphs, specifically evaluating decreases in the habitat index with decreasing simulation flows (thus reading the graph from right to left). This process facilitates the identification of habitat limitation thresholds, where biological demands and aquatic ecosystem processes are compromised due to reduced streamflow and water quality.

Cootes Store Reach: Plains Mill Site

The Plains Mill site is a composite of run, pool, and riffle mesohabitats. Due to the habitat diversity (mesohabitat types, depth, velocity, and channel index) at this site, the model predicts habitat index curves for all guilds (Figure 33). Although the magnitude of each fish habitat guild curves varies, their overall shape is similar. All fish habitat guilds exhibit a similar response to reduced discharge, with the microhabitat index decreasing sharply at approximately 50 cfs (Figure 33). This guild microhabitat index decrease is further compounded by a simultaneous steep increase in the algae microhabitat index (Figure 33). As a result, fish habitat is limited by quantity and quality during low flow conditions at the Plains Mill site.

Mount Jackson Reach: Laurel Hill Farm Site

Although Laurel Hill Farm is a riffle run complex site, the model predicted a habitat – flow function for all guilds (Figure 34). The shallow to moderate depth, moderate to high velocities, and predominance of small cobble and tilted bedrock at Laurel Hill Farm are well suited for the riffle, fast generalist, and pool run guilds (section 3.5, Persinger 2003) resulting in similar habitat predictions for these guilds (Figure 34). The model predicts a high habitat – flow relationship for the pool cover guild which is most likely driven by the presence of cover items, moderate embeddedness, and small cobble substrate (Figure 34, section 3.5, Persinger 2003). All fish habitat guilds exhibit a similar response to reduced discharge, with the microhabitat index decreasing at approximately 50 cfs, with a concurrent increase in algae microhabitat index (Figure 34).

Strasburg Reach: Spring Hollow Site

Spring Hollow is also characterized by riffles and runs, and like the Laurel Hill Farm site, the model predicted habitat – flow relationships for all guilds. The shallow to moderate depths, moderate to high velocities, and bedrock and cobble substrate creates compatible habitat for the riffle and fast generalist guilds, that is less suitable for the pool cover guild (Figure 35, section 3.5, Persinger 2003). The microhabitat for the riffle, fast generalist, and pool – run guilds decreases sharply at approximately 50 cfs, while the pool – cover guild microhabitat index decreases at approximately 10 cfs (Figure 35). The algae – midge guild microhabitat index increases at approximately 10 cfs (Figure 35). The minor response of the algae – midge guild at the Spring Hollow site is possibly due to the lack of suitable slow velocity, deep water habitat necessary for algal bloom growth and midge hatch (Figure 32).

Strasburg Reach: Posey Hollow

Posey Hollow is comprised of riffle, run, and pocket run habitat. The deeper water depths, moderate velocities, and tilted bedrock substrate provides suitable habitat for the pool – run guild and somewhat suitable habitat for the pool – cover guild (Figure 36, section 3.5, Persinger 2003). However, this combination of habitat features is narrowly suitable for the fast generalist guild and unsuitable for the riffle guild, those guilds most impacted during low flow conditions (Figure 36). The pool – run microhabitat index decreases sharply at approximately 70 cfs with a concurrent increase in the algae – midge microhabitat index (Figure 36).

Strasburg Reach: Route 648

Route 648 is also characterized by riffle, run, and pocket run habitats, with deeper water depths, moderate velocities, and tilted bedrock substrate. Similar to the Posey Hollow site, the model predicted microhabitat – discharge relationships for the pool – run and pool – cover guilds that are less suitable for the fast generalist guild and unsuitable for the riffle guild (Figure 37). The pool – run and fast generalist guilds exhibit declines in microhabitat index at approximately 90 cfs (Figure 37). The pool – cover guild exhibits a decline in microhabitat index at approximately 140 cfs. Due to the predominance of deep, slow moving water at the Route 648 site, the model predicts an increase in algae – midge microhabitat index at approximately 250 cfs.

4.3 Time Series Modeling

Upon habitat modeling completion, habitat – flow relationships are established for all guilds at each site. To examine temporal variability in the guild specific habitat – flow relationships at each site, the habitat data was analyzed using a time series approach. Time series analysis included 1) selection of flow time series for each study site, and 2) habitat time series modeling using WinHabTime software.

4.3.1 Selection of Flow Time Series

Since the focus of this study is habitat response due to low flow conditions, summer 1999 and summer 2002 daily mean discharge data were selected for time series analysis (Figure 38). This data was selected because it represented the most recent flow - limiting, critical periods in recorded flow history at each NFSR gauging station. Summer was defined as the period from June 1 through September 30. Since daily discharge data was not available for each study site, summer 1999 and 2002 daily mean discharge data for each gauge was weighted to its representative site(s), so modeled habitat - flow time series relationships reflect site discharge response. We used linear regression to explain the relationship of gauge station discharge (variable X) to representative site discharge (variable Y). Site discharge measured on a specific day (section 3.4) was plotted against gauge discharge for that same day, with a trendline plotted through the points (Figure 39). Due to the low sample sizes, ranging from three data points at Laurel Hill Farm to eight data points at Plains Mill, all the graphs exhibited a good fit with R^2 values greater than 0.94. The R^2 value is the fraction of variance shared by the gauge station discharge (X) and site discharge (Y). Summer 1999 and 2002 daily mean discharge values were entered into site specific excel worksheets and weighted daily mean discharge values for each gauge station were calculated using the best fit linear regression line equations (Figure 39).

To establish alternative flow time series, we referenced the permitted water withdrawal data for the NFSR (section 2.3) and developed incremental water management scenarios ranging from non - restriction to maximum restriction. Using the increase rate in permitted municipal and commercial withdrawals from 1995 to 2002, we multiplied total 1995 NFSR water use (16.9 cfs) by 1.5 to obtain a total 2002 NFSR water use estimate of 25.3 cfs. Since 2002 water use data was not available for all use categories, this estimate assumes that all water use categories increased by the same rate from 1995 to 2002. In site specific excel worksheets, we established seven water allocation strategies by adding percentages (0, 10, 25, 50, 75, 90, 100) of the 2002 NFSR withdrawal estimate (25.3 cfs) back to the summer 1999 and 2002 daily mean discharge values for each site, thus simulating management scenarios of no restriction (0% of withdrawals added to the discharge) to maximum restriction (100% of withdrawals, 25.3 cfs, added to the discharge). A total of fourteen site specific flow time series, for each period (summer 1999, summer 2002) and water allocation scenario (0, 10, 25, 50, 75, 90, 100), were exported from excel and saved as ASCII text files for import into time series software.

4.3.2 Habitat Time Series Modeling

Habitat time series modeling in WinHabTime involved a four step process of 1) importing HABTAE modeling results, 2) defining biologically significant periods, 3) running habitat time series, and 4) computing and evaluating habitat/flow metric summaries. Site–specific HABTAE modeling results and flow time series were imported into WinHabTime software according to Hardy 2000. For each site, one biologically significant period was defined, starting on June 1 and ending on September 30. Habitat time series was run for the fourteen flow scenarios for each site. Mean daily discharge habitat time series curves were generated for each guild at a study site using the habitat time series metric module (Figures 44 – 66).

4.3.3 Results

For ease of presentation, only the no restriction (0% withdrawals added to the mean daily discharge) and maximum restriction (100% withdrawals added) allocation scenarios are displayed on the times series graphs (Figures 44 – 63). This range serves as an allocation continuum, in which incremental changes in restriction result in incremental changes in microhabitat index. Appendix A contains comprehensive tables of allocation scenario time series results for each site (Tables A1 – A47).

The allocation scenarios resulted in the greatest benefit for the riffle guild (Figures 40, 45, 50) and fast generalist guild (Figures 41, 46, 51, 55, 59), respectively. The allocation scenarios resulted in only minor benefits for the pool – run guild (Figures 42, 47, 52, 56, 60) and pool – cover guild (Figures 43, 48, 53, 57, 61). The algae – midge guild demonstrated the greatest habitat index reduction with increased flow (Figures 44, 49, 54, 58, 62). All guilds exhibited sharp microhabitat declines in response to low flow events (September 8 – 10, 1999, and September 28, 2002), regardless of allocation scenario. However, restrictions enacted prior to low flow events may reduce the magnitude and duration of these events and mitigate water quality conditions (i.e. reduced algal bloom potential); thus alleviating stressors, flow and water quality, to the aquatic community during critical low flow periods.

5 Objective 4: Macrohabitat Investigation: water quality and temperature

Macrohabitat analysis is an important component of instream flow assessments (Bovee 1982, Moyle and Baltz 1985, Orth and Leonard 1990). Macrohabitat refers to reach scale, habitat conditions in a river that determine the longitudinal distribution of aquatic organisms (Figure 1) (Hardy 2000). During low channel flows, aquatic organisms can be challenged by a lack of suitable physical habitat, deteriorating water quality, or both. To meet the management needs of the NFSR, an understanding of water quality during low flows is needed to properly frame research conclusions. However, only limited data on water quality during a severe drought is available for the NFSR. The water quality investigation involved 1) measurement of water quality parameters and 2) stream temperature modeling.

5.1 Water Quality Parameter Measurements

5.1.1 Methods

M. Chan (Virginia Tech) and D. Hayes (USGS) conducted a preliminary water quality study on the NFSR in 1999 to determine longitudinal trends in water temperature, dissolved oxygen, and pH in the NFSR during severe drought. During July 12 – 30, 1999, temperature, dissolved oxygen (DO measured as mg/L and percent saturation), and pH data were collected at 52 sites using Y.S.I. 6-series, multi-parameter probes. Sites were located from Cootes Store in the headwaters downstream to Passage Creek, just above the confluence with the South Fork Shenandoah River. Pre-dawn and mid-day point sampling was conducted at 34 sites, while continuous monitoring was conducted at 18 sites, every half hour for one to eight days. For the purpose of this report, only data results for sites ranging from Cootes Store to Strasburg (sites 1 – 29) will be presented, as this sampling scale is consistent with the microhabitat study (Sections 3.2 and 3.5). For a detailed discussion on the 1999 water quality study, refer to Krstolic and Hayes (2004).

In September 2000, temperature data loggers (Hobo® H8 Pro temperature model H08-001-02 and Stowaway® XTI Internal/External temperature model XTI-08-05) housed in submersible polycarbonate cases, were deployed at each of the NFSR gauging stations, Cootes Store, Mount Jackson, and Strasburg, to record hourly average water temperature (°C). At each site, the temperature loggers were placed mid-channel and attached to weighted airline cable or chain secured to a tree along river’s edge. In April 2001, a relative humidity and temperature data logger (Hobo® H8 Pro RH/Temp model H08-032-08) was established at the Laurel Hill Farm study site to record hourly average air temperature (°C) and relative humidity. The RH/Temperature logger was mounted inside a protective cover (4 in. PVC cap, painted brown to reduce UV reflection) and secured to a streamside tree (approximately 6 feet above ground surface and 50 feet from water's edge). Logger data was downloaded periodically using Boxcar® Pro 4.0 software. All loggers were retrieved from the NFSR sites in January 2003.

J. Lozinski (Virginia Tech) conducted a follow-up water quality investigation in summer 2002. A total of nine sites were sampled along the NFSR during eight sampling trips during June 20 – August 14, 2002. Sample site locations ranged from Cootes Store to Strasburg, with four of the nine sites corresponding to the 1999 locations, sites 1, 15, 24, and 29 (Figure 63). Dissolved oxygen, water and air temperature, pH, un-ionized ammonia, and orthophospate levels were measured during six of the eight sampling trips. DO and temperature data was collected during a minimum-maximum study on August 13, 2002 (sites 1, A, B, C, and 15) and August 14, 2002 (sites D, 24, E, and 29) during pre-dawn (for minimum measurements) and late afternoon (for maximum measurements) (Figure 63). At each site, a hand-held digital YSI meter was used to measure dissolved oxygen concentrations (mg/L) and water temperature (°C) in the center of the river, mid water column. pH was measured with a QuickCheck® digital pH meter, mid-channel, mid-water column at each site. Un-ionized ammonia (NH_3) and orthophosphate (PO_4-3) were measured using colorimetric tests with

Chemets® Self-Filling Ampules field test kits. Recorded water quality measurements from summers 1999 and 2002 were compared with state water quality criteria.

5.1.2 Results

Dissolved Oxygen

Similar patterns of extreme high and low DO concentrations exist in the 1999 and 2002 data. Worst-case scenarios show DO levels changing by 10.5 mg/L in 1999 and 8.5 mg/L in 2002 within 12 hours. The average DO, calculated from both 1999 and 2002 minimum-maximum studies, was plotted with error bars to depict the minimum and maximum values at each site (Figures 64 – 65). In July 1999, 37% fell below the state minimum dissolved oxygen standard of 4 mg/L. In 2002, DO was not observed below the standard at any of the nine sites during the minimum-maximum study on August 13, 2002. However, Site 24 at Rt. 661 approached the state minimum standard with a measurement of 4.45 mg/L. Percent saturation was also plotted (Figures 66 - 67) for 1999 and 2002 minimum-maximum DO study data. DO saturation data reveal that only 13.7% of the July 27 – 29, 1999, samples (Figure 66) and 35.2% of August 13 - 14, 2002, samples (Figure 67) fall within the optimal percent saturation range (80 – 120%).

pH

In both 1999 and 2002 studies, pH values were lower in the upstream sites and increased with downstream distance (Figures 68 - 69). In July 1999, 25% of the sample sites exceeded the state pH standard of 9.0 (Figure 68). In the 2002 study, 22% of the sample sites exceeded the state pH standard (Figure 69). Both years' data show an increasing trend in pH from Mount Jackson (site 15) to Strasburg (site 29) (Figures 68 – 69). Prevalent algal growth and aquatic vegetation at sites downstream of Mount Jackson may contribute to this increase in pH (Figure 70).

Temperature

During the July 1999 minimum – maximum study, 11% of the sample sites exceeded the Virginia water quality standard for maximum temperature of 31°C. The state standard was not exceeded at either the Cootes Store or Mount Jackson site during June, July, August, or September 2002 (Figures A1 – A9, Appendix). However, water temperatures at the Strasburg site exceeded the 31°C maximum standard nine times in July and four times in August (Figures A9 – A12, Appendix). Plotting recorded water temperature data, recorded air temperature (at Laurel Hill Farm), and USGS discharge data, NFSR water temperatures at all three sites continued to correspond to air temperature, despite watershed streamflow variation (Figures 71 – 73).

Un-ionized Ammonia (UIA)

UIA levels from the June – August 2002 sampling period were high at all sites in the NFSR (Figure 74). In addition to the 2002 un-ionized ammonia data, a recent study by Mummert et al. (2003) reported that a substantially high proportion of samples from the NFSR contained UIA levels above the estimated safe environmental threshold (0.01 mg/L) for juvenile mussel habitats. These samples were also above the mean 96h LC50s (0.10 – 0.12 mg/L) for the juvenile rainbow mussel, *Villosa iris*, and the mean 96h LC50s (0.23 – 0.28 mg/L) for the juvenile wavy–rayed lampmussel, *Lampsilis fasciola*.

Orthophosphate

Orthophosphate (PO4-3) levels at all NFSR study sites exceeded EPA recommendations of 0.1 mg/L (Figure 79). Average orthophosphate concentrations were highest at Site A, with measurements ranging from 0.20 to 8.00 mg/L (Figure 75). This site is directly downstream from a poultry processing plant.

5.2 Stream Temperature Modeling

The temperature-modeling portion of this study was completed using the Stream Network Temperature Model (SNTEMP), created by Dr. Fred Theurer of the U.S. Soil Conservation Service (SCS). SNTEMP is an integral tool of IFIM studies (Bovee et al. 1998), and was used to evaluate the effects of low flow on water temperature in the NFSR.

SNTEMP is a steady state model for branched stream networks that predicts the daily mean, minimum, and maximum water temperatures as a function of stream distance and environmental heat flux. SNTEMP is comprised of six modules: heat flux, heat transport, solar model, shade model, meteorological model, and the regression model. The heat flux module is designed to simulate energy balances between eight components: solar radiation, atmospheric radiation, vegetative and topographic radiation, evaporation, convection, conduction, friction, and water's back radiation. The heat transport model predicts average mean daily and diurnal water temperatures as a function of stream distance. The solar module predicts solar radiation on the receiving water body, and the shade module predicts the interception of solar radiation due to vegetation and topography. The meteorological module predicts changes in air temperature, relative humidity and atmospheric pressure. A built-in regression model is also included with the ability to fill in or smooth small portions of data with missing water temperature values.

SNTEMP is a DOS program run by nine input files (Figure 76) consisting of stream geometry, hydrology, and meteorology data. Files were created using the SNTEMP Self-Study Guide's detailed instructional tables, listing record and field positions for each file type. Within each file, nodes define areas of the stream network. Nodes used in modeling the NFSR were Headwater (H), Validation (V), Diversion (D), Point load (P), Change (C), Output (O), and End (E). Tributaries within the stream network can also be included as Point loads (P) or as Junctions (J), however, temperature data was not available for accurate tributary modeling. TDATCHK.EXE, an associated program of SNTEMP, was used to ensure correct formatting of all files.

5.2.1 Description of Study Sites

The North Fork Shenandoah River was divided into 13 reaches to be modeled by SNTEMP. The modeled area, 126.5 river kilometers, begins 0.1 km upstream of the USGS Cootes Store gage (#01632000) and continues downstream to model-rkm 0.0 at the USGS Strasburg gage site (#01634000).

There were 34 nodes modeled in SNTEMP, consisting of 1 Headwater (H) node, 3 Validation (V) nodes, 4 Diversion (D) nodes, 4 Point load (P) nodes, 12

Change (C) nodes, 16 Output (O) nodes, and 1 End (E) node (Figure 81). The H node was located at model-rkm 126.5, 0.1 model-rkm above the Cootes Store site (model-rkm 126.4). The H node marked the upstream boundary of the mainstem, while the E node was located at Strasburg (model-rkm 0.0), marking the downstream boundary of the mainstem. The three V nodes each located at USGS gauging stations recording hourly discharge data (Cootes Store, model-rkm 126.4, Mount Jackson, model-rkm 92.5, and Strasburg, model-rkm 0.0).

Four permitted withdrawers and four of the most prominent dischargers (>0.50 MGD design flow) along the NFSR were included in the modeling process. Included in the model were those withdrawers with reported 2002 average monthly withdrawal rates available: Town of Broadway (model-rkm 121.0), Food Processors Water Coop. (model-rkm 119.5), Town of Woodstock (model-rkm 62.1), and Town of Strasburg (model-rkm 4.3) (Figure 81). Point discharges (P) require both daily effluent flow and temperature data. Dischargers include the North Fork Modular (SIL Cleanwater), comprised of Wampler, Rocco/Shadybrook Farms processing plants as well as wastewater from the Towns of Broadway and Timberville (model-rkm 118.0), the New Market Wastewater Treatment Plant (model-rkm 107.80), the Woodstock Wastewater Treatment Plant (model-rkm 48.90), and the Strasburg Wastewater Treatment Plant (model-rkm 2.5) (Figure 77). Suitable change (C) nodes were determined from topographic maps along with NFSR habitat, geographic information systems (GIS) data provided by the USGS. C nodes marked upstream ends of reaches with new hydraulic or stream shading properties, and were important indicators of the 13 reach boundaries used in SNTEMP. Output (O) nodes indicated areas of temperature outputs requested from the model. Sixteen outputs were requested; 13 outputs correspond to the average distance between each of the 13 reaches, and an additional 3 outputs correspond to the three temperature validation sites.

5.2.2 Collection and Derivation of Model Parameters

The six categories of model parameters include stream geometry and time, shade, meteorological, flow, and water/streambed temperature. Parameters were obtained by derivation/collection techniques, or documented typical default values were used. SNTEMP parameters were collected according to methods documented in Bartholow (1989) and Krause (2002).

Stream Geometry and Time Parameters

Reach elevations and mean basin elevation were determined from topographic maps, and were important for calculating elements related to friction heat convection, solar radiation, air temperature, and relative humidity (Bartholow 1989). Site latitude and longitude readings orient SNTEMP to the position of the stream on the earth’s surface. Mean basin latitude and longitude (38.75, -75.6) were also determined using topographic maps. SNTEMP requires site-specific latitudes, which were determined using www.topozone.com to obtain the most accurate readings. Latitude in decimal degrees were converted to radians using the conversion factor of 1 degree = 0.017453293 Radians. The simulation period included the summer months at risk for high water temperatures and low streamflows, June 1, 2002 through September 30, 2002, as defined by Julian date (day 152 through day 273). The modeled reach distances were used in calculation of heat transport and measured with the aid of the DeLorme® 3-D TopoQuad software. The Strasburg gage was chosen as the End node (model-rkm 0.0). River kilometers were measured and counted upstream from the End node to the Headwater node (model-rkm 126.5).

To obtain travel time, Bartholow (1989) suggests that SNTEMP functions with either a constant travel time or a constant Manning's n. Manning's n values were estimated using Table II-I "Values of Manning's "n" roughness coefficient" from the QUAL2E user's guide (EPA 1995). Lower values were used (~ 0.028 – 0.037) for clean and straight areas of the river, while higher values (0.113) were used for very weedy, winding and overgrown areas farther downstream along the Seven Bends area.

Based on procedures in Bartholow (1989), stream average width was calculated for those NFSR sections with available data (Plains Mill model-rkm 109.1, Laurel Hill Farm model-rkm 70.4, Spring Hollow model-rkm 48.6, Posey Hollow model-rkm 17.1, and Rt. 648 model-rkm 10.6).

Shade Parameters

Stream shading can influence water temperature significantly for low flow streams in midsummer (Bartholow 1989). Shade parameters were collected for use in the SNTEMP Shade File, KVRFSHD.prn. Parameters included site latitude, stream reach azimuth, stream width, topographic altitude, and vegetation crown, height, offset and density.

Stream reach azimuth, the orientation of the stream with respect to due south, was calculated using DeLorme® topomap software (1999) and methods outlined by Bartholow (1989). Topographic altitude, vegetation height, vegetation crown, and vegetation offset data were obtained for both east and west stream banks at 13 randomly selected sites using a clinometer, standard measuring tape, and procedures described by Bartholow (1989). To determine shade quality, vegetation density was measured using a light meter and 18% photographic gray card.

Meteorological Parameters

Air temperature is an important parameter in stream temperature modeling (Bartholow 1989). A logger stationed at Laurel Hill Farm recorded air temperature and relative humidity to provide site-specific data. Wet bulb temperature, barometric pressure, wind speed, and percent possible sun data were obtained from the Elkins, WV weather station.

Dust coefficient and ground reflectivity were estimated from Tables II.1 and II.2 in Theurer et al. (1984). An average of summer dust coefficient estimates for the Washington, D.C. area (0.09) was chosen for this study. The ground reflectivity value, 0.21, is an average of the ground condition values for meadows and fields (0.14), vegetation, early summer, leaves with high water content (0.19), and vegetation, late summer, leaves with low water content (0.29).

Stream Temperature Parameters

Submersible water temperature loggers were positioned at the three USGS gage stations along the NFSR: Strasburg, Mount Jackson, and Cootes Store. Hourly temperature data were downloaded from the loggers and used in SNTEMP to predict temperatures at specified outputs along the NFSR.

Flow Parameters

Daily mean flow data (cms) for each of the NFSR gauging stations, Cootes Store, Mount Jackson, and Strasburg, was downloaded from the USGS surface-water data website (USGS 2003).

Model Calibration and Validation

Calibration and validation began once all data was entered into SNTEMP. SNTEMP was calibrated by comparing predicted temperatures to observed temperatures for the NFSR gage stations, Cootes Store, Mount Jackson, and Strasburg. In addition, model parameters were adjusted within realistic boundaries to determine proper calibration values (Bartholow 1989). Typically, one parameter was adjusted while holding all others constant to determine the effect of the altered parameter. Calibration was complete when the parameters produced an output with less than 10% of the predicted temperatures within ± 2.5°C of the observed temperatures, combined with the best model validation results. For model validation, goodness-of-fit was determined by plotting predicted versus observed values, and fitting a regression line through point (0,0) (Figure 78). An R^2 value of 0.827 suggests that predicted values are closely related to the observed data.

5.2.3 SNTEMP Modeling Results

Modeling Mean Daily River Temperature

Temperatures were predicted using the calibrated data set exhibiting a positive modeling efficiency statistic and the best R^2. Predictions made at the Cootes Store site (model-rkm 126.4) were within ± 0.25°C of the observed data

(Figure 79). The Cootes Store average mean daily temperature during June through September 2002 was 23.33°C. The high and low mean daily temperatures were 27.67°C on July 4, 2002, and 17.18°C on September 27, 2002, respectively. Mount Jackson's predictions were also similar to observed data; less than 8.0% of the predicted values deviated by ± 2.5°C, and less than 2.5% of the predicted values deviated by ± 3.0°C (Figure 80). The Mount Jackson average mean daily temperature during June through September 2002 was 23.42°C. The high and low mean daily temperatures were 28.43°C on July 4, 2002, and 17.18°C on September 26, 2002, respectively. At the Strasburg site, less than 4.5% of the temperature predictions were ± 2.5°C from the observed temperatures and less than 2.5% differed by ± 3.0°C (Figure 81). The Strasburg average mean daily temperature during June through September 2002 was 25.06°C. The high and low mean daily temperatures were 29.24°C on July 4, 2002, and 18.13°C on September 28, 2002, respectively.

To create a temperature profile for the river, temperature outputs were analyzed along thirteen additional NFSR reaches, in addition to the model outputs at the three gauging stations. The river temperature profile identifies temperature trends and indicates critical or inhabitable stream reaches for aquatic organisms. Three distinct temperature peaks are evident in the upstream, middle, and downstream reaches (Figure 82). The model predicted high average temperatures within the NFSR during July and August, with temperatures ranging between 23.0°C and 27.5°C.

Upstream, temperatures show an increasing trend between model-rkms 126.4 and 114.0. This trend is likely attributable to the combination of impacts from the Town of Broadway (model-rkm 121.0) and the Food Processors Water Coop withdrawals (model-rkm 119.5) along with the industrial discharge from the North Fork Modular (model-rkm 118.0). Together, the Town of Broadway and the Water Coop's withdrawals averaged 0.038 cms/day, whereas the NF Modular discharged an average 0.078 cms/day at an average temperature of 25.5°C. The NF Modular's 2002 records for July and August, the months with the highest temperature predictions, discharges and temperatures increased with an average of 0.1 cms/day at 26.8°C in July and 0.072 cms/day at 27.41°C in August. A short distance below the NF Modular, temperatures began to decrease. The New Market Wastewater Treatment Plant (located at model-rkm 107.9) reported 2002 discharge was approximately 4°C cooler than NF Modular's discharge, and may be the source of the temperature decrease downstream of NF Modular. Temperatures remained fairly constant with a slight increase between model-rkms 89.5 and 51.0. In the Seven Bends section of the NFSR, temperatures rose again forming the third peak. During the summer of 2002 submerged aquatic vegetation was abundant along this stretch. It is possible that the river meanders, combined with the aquatic vegetation, produced a low velocity, high water temperature environment.

Modeling Maximum River Temperature

In addition to mean daily temperature predictions, maximum temperatures were predicted for the months of June, July, August, and September 2002

(Figures 83 - 86). The Virginia Department of Environmental Quality (VDEQ) standard maximum temperature for mountainous streams is 31°C (State Water Control Board 2003). Maximum temperatures at the Cootes Store and Strasburg sites exceeded the maximum temperature standard for the end of June 2002 and nearly one-third of July 2002. Maximum temperatures during August at Cootes Store and Strasburg ranged predominantly between 29°C and 32°C. During September 2002, all maximum temperature predictions for Cootes Store, Mount Jackson, and Strasburg fell below the state standard. Throughout the study period, Mount Jackson temperatures never exceeded the state standard. The average maximum river temperature profile (Figure 87) showed a similar trend to the average mean daily river temperature profile (Figure 82), with peaks of increased temperatures upstream, midstream, and downstream. Average maximum temperatures were approximately 3°C greater than average mean daily temperatures at each site.

Air Temperature and Groundwater Affect on NFSR Water Temperature

Comparing observed average water temperature, average air temperature, and average flow for summer 2002, NFSR water temperature is more influenced by air temperature than flow (Figure 88). In addition, groundwater influences (spring discharge) throughout the basin may mitigate summer water temperatures and create zones of cooler water temperatures for fish. This thermal refugia may provide critical fish habitat during low flow periods. Higher flows may increase average temperatures, diminishing thermal refugia due to mixing between small amounts of cooler groundwater inflows and larger amounts of upstream warm water.

6 Objective 5: Aquatic Conservation Management

The purpose of this research was to investigate the stream flow in the North Fork Shenandoah River to determine the instream flow needs and facilitate future water supply planning in such a way as to minimize the risk of future water shortages. The drought of 1999 and 2002 generated action of state, regional, and local levels focused on water issues. If population growth continues as projected in the basin, the severity of surface and groundwater shortages may become even more acute unless a sustainable approach to water management is adopted now. Because it has been approximately 20 years since Virginia did statewide water planning, water supply planning has re-emerged as a high priority for the Commonwealth. The General Assembly approved SB1221 in 2003. This legislation reactivated the Water Policy Technical Advisory Committee, which will develop criteria and requirements for local water plans.

The research described in this report makes the North Fork Shenandoah River the first river in Virginia where quantitative analyses on instream habitat conditions permit definition of aquatic conservation flows. Preliminary definitions will have to be used in other rivers to define watch, warning and emergency drought conditions*. The general application of these drought triggers is as follows:

(a) Watch—initiate actions to anticipate future restrictions.

(b) Warning—drought conditions present—require implementation of water use restrictions.

(c) Emergency—unrestricted use is not possible. Mandatory use restrictions in place.

*See www.deq.state.va.us/info/drought_response_plan.pdf

A variety of methodologies could be employed to identify the way that stream flow change influences natural ecosystems (Orth and Leonard 1990; Petts and Maddock 1994; Leclerc et al. 1995; Stalnaker et al. 1995; Richter et al. 1997; Bovee et al. 1998; King and Louw 1998; Railsback 2001; King et al. 2003; Thorme 2003). Many of the technical assumptions and approaches differ; however, we have adopted a framework for problem-solving that can be traced from the Instream Flow Incremental Methodology (Stalnaker et al. 1995) to the 6-step process for ecologically sustainable water management (Richter et al. 2003). The process for ecologically sustainable water management involves six steps:

(1) Estimating ecosystems flow requirements.

(2) Determining human influences on the flow regime.

(3) Identifying incompatibilities between human and ecosystem needs.

(4) Collaboratively searching for solutions.

(5) Conducting water management experiments.

(6) Designing and implementing an adaptive water management plan.

This research provides initial estimates of ecosystem flow requirements (step 1), determines the human influence of withdrawal on flow (step 2) and identifies the incompatibilities between human and ecosystem needs (step 3). The estimation of ecosystem flow requirements was based upon the hydraulic and physical habitat modeling and temperature and water quality modeling, all of which focused solely on in channel instream flow needs during extended drought conditions. Our assumption is that future water withdrawals will not affect timing and magnitude of flows during typical high-to-moderate flow seasons.

Extreme drought conditions experienced in 1999-2000 and 2002 are relatively rare events. We determined that on average these extreme droughts occur every 23 years and last 2.5 years.

There were several criteria or assumptions that we used in selecting aquatic conservation flow triggers. The first four are habitat based criteria.

1) Algal blooms and associated nuisance levels of aquatic vegetation and aquatic insects (midges and mosquitoes) are associated with extended periods of unsuitable microhabitat (Figures 33-37).
2) Fish kills are associated with high levels of ammonia, and widely fluctuating pH and dissolved oxygen levels as observed in 1999 and 2002.
3) Aquatic life forms associated with fast-riffle guild are most sensitive to reductions in low flow as measured by microhabitat indices (Figures 33-37).
4) Aquatic conservation triggers must permit the enhancement of habitat if withdrawal is restricted. These effects were quantified for the droughts of 1999 and 2002 (Figures 40-62).

Other criteria were more practical concerns:

5) Aquatic conservation flows must be based on measurable and easy to implement discharge values.
6) Aquatic conservation flow triggers must be consistent with existing state policy. Emergency triggers cannot be less than the 7-d 1-in-10-year low flow because these values are determinants of waste assimilation capacity and water quality standards.
7) Triggers are not equal categories of flow in order to permit sufficient number of days for watch conditions to be communicated before more restrictive conditions occur.

	Cootes Store	Mount Jackson	Strasburg
Normal	>100 cfs	>120 cfs	>150 cfs
Watch	<100	<120	<150
Warning	<60	<75	<90
Emergency	<25	<30	<65

These aquatic conservation flow triggers result in more warning and emergency conditions at Cootes Store than at Mount Jackson, and in turn Strasburg. Therefore, the potential for new water withdrawals is limited to the Strasburg reach.

Determining Human Influence

Agricultural activities, in particular fertilizer application and animal manure, on steep slopes in the watershed, especially tributaries (Holmes, Linville, and Mill Creeks) are prevalent impacts on NFSR water quality. This has a direct influence on water quantity requirements. Effects of water withdrawals on stream flow characteristics were less obvious than the water quality, despite documentable increases in permitted water demands (12.07 mgd in 2002) and unknown changes in withdrawals for livestock in irrigation.

7 Objective 6: Additional Research Needs

A major paradigm shift has occurred in water resources management since the 1970s. Ecological considerations, such as environmental or conservation flows are equally important as other water management goals (e.g. risk of future water shortage). In the past, the terminology was different as we used 'minimum instream flow' to indicate that this flow level was a compliance factor which was only considered after a water development plan was completed. We now recognize that there are real limits to water use and different approaches are needed to resolve competing needs (Brooks 2003; Gleick 2003; Poff et al. 2003). Future research and management actions will be more complex and holistic. Gleick (2001) advocated a soft-path approach for water management. This approach seeks to improve the productivity of water use rather than seek the unattainable endless supply of new water. With this approach, water services and qualities are matched to users' needs rather than simply delivering quantities of water. Furthermore, the soft path uses collaborative negotiation to include the local communities in decisions about water management, allocation, and use.

We advocate that this approach to management of North Fork Shenandoah River follow steps 4, 5, and 6 of Richter et al (2003), and adopt this soft path by concentrating on demand side of water management. Localities should research many of the water use and conservation strategies currently available and applied globally (see Vickers 2001). Globally the net productivity of water has increase via new and improved technology (Gleick 2003; Hutson et al. 2004). Consequently, future projections of water supply needs based on an assumption of new increase in water use efficiency will be overstated.

Several issues may complicate the straightforward adoption of the conservation flow thresholds developed in the study.

(1) Nutrient Inputs

(2) Hydrologic and Landscape Change

(3) Habitat and Biological Change

(4) Climate Change and Streamflow

(5) Water Use and Conservation

(6) Stream and Riparian Restoration Activities

Nutrient Inputs

Nitrogen enrichment is usually attributed to nonpoint source pollution from agricultural production areas where applied inorganic fertilizers or animal wastes leach or move via surface runoff (Hubbard et al. 2004). This is a major source of pollution contributing to nutrient loading in the Chesapeake Bay (USEPA 2000). Future urbanization and continuation of animal feeding operations and fertilizer applications in the North Fork watershed will increase movement of nitrogen in this watershed either from upland soils through riparian zone, into stream, or vertically through the vadose zone into groundwater. The relative importance of row crop and animal feeding and processing to nitrogen loading is worth of additional research focused on understanding the processes regulating nitrogen so that cost effective methods can be developed to reduce nitrogen loading. Short-term trend analysis indicates that nitrogen levels in Virginia are not declining (Zipper et al. 2002) despite two decades of concerted efforts to reduce nutrients to Chesapeake Bay.

Restoration and protections of extensive riparian forested zones that can continue to serve as nutrient filters should be targeted in the North Fork Shenandoah River Watershed. These actions can provide a focus for community involvement and education while providing long-term changes that can be evaluated via periodic research studies on nutrient loading. The high organic content and anaerobic conditions both facilitated by appropriate forest planting in seasonally saturated riparian zones, may provide nitrogen sinks where denitrification is enhanced (Ambus and Lowrance. 1991). Furthermore, the predominance of stream impairment in the NFSR watershed via fecal coliform bacteria suggests that more aggressive management practices must be researched and tested to simultaneously sequester nitrogen and fecal coliform bacteria for reduction and processing. Research is needed to identify appropriate target treatment areas and management strategies relative to pollution potential on smaller tracts of land.

Hydrologic and Landuse Change

Despite expectations to the contrary, we did not observe long term hydrologic changes in low flow or high flow statistics based on analysis of U. S. Geological Survey gaging records of 70+ years. The deforestation and sediment loss from this basin likely occurred over 150 years before the present thereby changing the soil character long before gaging records began. Furthermore, the combination of climatic cycles and land use change make the empirical detection of these changes very unlikely. Recent studies suggest that the effect of conversion of land from forest to agriculture and urban uses reduce base flows and increase peak flows, leading to a number of indirect effects temperature and biological processing of nutrients and organic matter (Sponseller et al. 2001; Krause et al. 2004; Sweeney et al. 2004).

Habitat and Biological Change

Although there are few historical data on biological conditions in the NFSR, we suspect that there is a legacy effect of past water quality that resulted in a loss of the native mussel fauna and their nutrient processing role. The filtering capability of native mussels likely played on important role in the processing of nutrients and organic matter. The recent drought with its extended low flow created conditions that favored establishment of attached algal and macrophyte communities in the channel. These biological changes during droughts certainly play a critical role in the daily cycle of pH, dissolved oxygen, and toxicity of a contaminants, including ammonia. Furthermore, the chronic stressors in the NFSR are not restricted to low flow conditions. Fish kills have been documented in years that are characterized as low flow as well has high flow. Fish kills were documented by the Department of Environmental Quality in 2004 and fish with lesions indicative of chronic stress were observed despite normal or high flow conditions. Consequently, the management of water withdrawals is unlikely to solve the chronic stress problems in the NFSR. We recommend that research be initiated to evaluate multiple stressors and their effects on multiple aquatic taxa in the NFSR and identify key sources that need to be reduced.

Climate Change and Streamflow

In the twentieth century droughts became longer and heavier rains more frequent in some regions of the U.S. (Karl et al. 1995a, 1995b). The effect of climate change on hydrologic patterns is regionally variable (Vorosmarty et al. 2000. While our analyses did not detect these changes in the NFSR, the prudent planner should develop contingency plans for longer periods of droughts than what have occurred in the past. Global warming may cause species redistribution and make the upper reaches even more critical in providing limited refugia.

Water Use and Conservation

Further research is needed on the efficacy of nonmarket and market incentives that could facilitate the change in water demands needed in the NFSR. While water withdrawals in the U.S. have stabilized (3% change from

1985-2000), productivity of water use has increased (Hutson et al. 2004). The increase in productivity of water use is a result of periods of scarcity. Currently there are no ongoing research efforts to evaluate the efficiency of current water use in the basin. Incentives for water conservation will need to be developed for the multiple water users if the projected population growth in the basin is to be sustained without importing water from the South Fork Shenandoah River.

Stream and Riparian Restoration

The North Fork Shenandoah River watershed is altered by a combination of low dams, roads, urbanization, and intensive agriculture operations. The combination of effects has resulted in segments that are not functioning adequately to provide optimal ecosystem services. Although it was beyond the scope of this study to do a complete watershed assessment and stream habitat assessment we do recommend additional research on the following issues in the NFSR. The functionality of existing dams and barriers should be evaluated to consider management options for barrier mitigation. This would eliminate fragmentation of certain populations and facilitate more rapid recolonization after fish kills and other chronic stress periods. Furthermore, the deforestation causes local bank erosion and changes in channel morphology. Studies in Pennsylvania documented the effects of deforestation and subsequent channel change on a suite of ecosystem functions, including nutrient processing (Sweeney et al. 2004). This research supported the need for management of forested buffer zones along streams (Osborne and Kovocic 1993). In addition, the watershed development has likely affected to functionality and formation and maintainance of wetland ecosystems. We recommend a study to inventory and delineate wetlands in the basin with the intent of protection and enhancement of their extent. Furthermore, the use of land terracing or contouring and other best management practices should be evaluated for reducing the nutrient loads to the NFSR.

Recommended Actions:

- Develop action plan for different aquatic conservation flow thresholds and adopt this as a clinical trial to improve water use conservation. Develop intensive monitoring system to accelerate data collection during warning, watch and emergency conditions.
- Extend study plan to SFSR to quantify water supply and demand balance throughout the SR Basin. Consider companion studies in other river basins.
- Develop a hydrologic model for entire basin to permit simultaneous calculations of many influences of water flows throughout basins.
- Continue to forge this partnership and new partnerships between scientists and other stakeholders in communities, government, private sector, and non governmental organizations.

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