SHENANDOAH NATIONAL PARK,

VIRGINIA

WATER RESOURCES SCOPING REPORT

David L. Vana-Miller and Don P. Weeks

Technical Report NPS/NRWRS/NRTR-2004/320

WATER RESOURCES DIVISION

National Park Service - Department of the Interior
Fort Collins - Denver - Washington

United States Department of the Interior • National Park Service

The National Park Service Water Resources Division is responsible for providing water resources management policy and guidelines, planning, technical assistance, training, and operational support to units of the National Park System. Program areas include water rights, water resources planning, regulatory guidance and review, hydrology, water quality, watershed management, watershed studies, and aquatic ecology.

Technical Reports

The National Park Service disseminates the results of biological, physical, and social research through the Natural Resources Technical Report Series. Natural resources inventories and monitoring activities, scientific literature reviews, bibliographies, and proceedings of technical workshops and conferences are also disseminated through this series.

Copies of this report are available from the following:

National Park Service (970) 225-3500
Water Resources Division
1201 Oak Ridge Drive, Suite 250
Fort Collins, CO 80525

National Park Service (303) 969-2130
Technical Information Center
Denver Service Center
P.O. Box 25287
Denver, CO 80225-0287

SHENANDOAH NATIONAL PARK

VIRGINIA

WATER RESOURCES SCOPING REPORT

David L. Vana-Miller[1] and Don P. Weeks[1]

Technical Report NPS/NRWRD/NRTR-2004/320

August, 2004

[1]Hydrologists, National Park Service, Water Resources Division, Denver, Colorado

United States Department of the Interior
National Park Service

Headwater streams and wetlands abound on the American landscape, providing key linkages between stream networks and surrounding land. Although often unnamed, unrecorded, and underappreciated, small headwater streams and wetlands -- including those that are dry for parts of the year -- are an integral part of our nation's river networks. Small wetlands, even those without visible surface connections, are joined to stream systems by ground water, sub-surface flows of water, and periodic surface flows. Current databases and maps do not adequately reflect the extent of headwater streams and associated wetlands. The resulting underestimate of the occurrence of such ecosystems hampers our ability to measure the key roles headwater streams play in maintaining quality of surface waters and diversity of life.

-- *Where Rivers are Born: The Scientific Imperative for Defending Small Streams and Wetlands*. Meyer et al. (2003)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

Any effort on a document of this magnitude is usually a cooperative venture. For the Water Resources Scoping Report for Shenandoah National Park that cooperation was especially strong and without it the Report would not have been possible.

Park staff were integral to this effort. Gordon Olson, Christi Gordon and Shane Spitzer were our points of contact at the park, and their coordination helped us pinpoint resources and expertise. A special thanks to Gordon for sending much needed publications from the park library; to Christi for providing the ever-important context of air quality at the park; and to Shane for providing recent water-based project proposals. Debbie Sanders coordinated all efforts to generate GIS-based graphics for the Report. The professional quality of those graphics enhances the look of the Report. Dave Demarest and Jim Atkinson provided resource materials and were most helpful with answers to many of our questions. Alan Williams provided information on the park's amphibian monitoring projects. Charlie Newton kindly provided aspects of the environmental audit for the park.

We thank Rick Webb of the University of Virginia for hosting the senior author during a Shenandoah Watershed Assessment Study fact-finding trip to the university. Rick has been instrumental in providing information, reports and publications when requested. The following individuals also kindly provided information for use in this Report: Karen Rice, Craig Snyder, John Young, and Robin Jung, U.S. Geological Survey; Donald Klemm, U.S. Environmental Protection Agency; and Michael Bank, University of Maine.

The following individuals provided review comments that improved an earlier version of this Report: Karen Rice, U.S. Geological Survey; Ellen Porter and Tamara Blett, Air Resources Division of the National Park Service; Mark Flora, Larry Martin and Gary Rosenlieb, Water Resources Division of the National Park Service; Alan Ellsworth, Northeast Regional Office of National Park Service; Gordon Olson, Shane Spitzer, James Atkinson, Dave Demarest, and Wendy Cass of Shenandoah National Park; and Rick Webb of the University of Virginia.

EXECUTIVE SUMMARY

Water Resource Scoping Reports (WRSRs) provide National Park Service (NPS) management with a better understanding of a park's water resources and the current issues it faces. These reports typically summarize existing hydrological information, identify and analyze major water resource issues, and determine if further development of the water-related issues, including recommended actions (project statements) that address the high-priortity issues, is warranted. This document provides for the first time under one cover a detailed summary and assessment of water resource information for the Shenandoah National Park.

For Shennadoah National Park, the number of water-related issues is low, but the complexity of most of those issues is high. We suggest that this WRSR meets the needs of current park management because of several factors including: 1) the existence of a longstanding, cooperative, water monitoring/research program between the park and the University of Virginia that has the ability to deal with the complexity of several of the issues; 2) the park is active with other cooperators and has already anticipated and developed recommended actions for several of the issues; and 3) the park has a well established long-term ecological monitoring program for aquatic biota. Therefore, on the one hand, we offer observations and suggestions that are often re-affirmations of past management decisions and, on the other, we provide recommendations that may serve as appropriate stimuli for project statements. The park is encouraged to seek technical assistance from the NPS Water Resources Division in the development of these water-related project statements.

Shenandoah National Park (SHEN), established in 1926, traverses a 70-mile segment of the Blue Ridge Mountains in the southern Appalachians of north-central Virginia. The Blue Ridge physiographic province is a narrow mountainous ridge between the *Valley and Ridge* province to the west and the *Piedmont* province to the east. The park ranges in width from 2 to 10 miles and encompasses approximately 200,000 acres (300 mi^2), 79,579 of which are designated wilderness. U.S. Highways 211 and 33 divide the park into three management districts. The 105-mile long Skyline Drive, which extends the entire length of the park and generally follows the topographic divide, provides the primary route of travel in the park.

The park is within the Chesapeake Bay airshed, a large geographic area which, because of topography, meteorology, and climate, routinely shares the same air mass. The airshed contains numerous major stationary sources of air pollutant emissions. Emissions from mobile sources (vehicles etc.) and many stationary sources are expected to increase with substantial growth in Virginia and other airshed states.

SHEN was targeted as one of the earliest atmospheric deposition, visibility, and air quality monitoring sites in the Class I national park network. SHEN is widely recognized as one of the Class I parks with resources most impaired by human-caused air pollution. In 1990, the U.S. Department of the Interior published in the Federal Register a Preliminary Notice of Adverse Impacts on Shenandoah's

visibility, streams and vegetation. The park's resources continue to be impacted by increasing numbers urban and rural emission sources, both local and regional.

Long-term air quality monitoring began at SHEN in 1981. The latest monitoring data available from the National Atmospheric Deposition Program/National Trends Network show that SHEN receives high wet deposition of sulfates and moderately high wet deposition of ammonium and nitrate compared to other locations in the eastern U.S. Among Class I parks, SHEN and Great Smoky Mountains National Park receive the highest sulfate and nitrate deposition.

In 1979, SHEN began a long-term cooperative agreement with the University of Virginia, known as the Shenandoah Watershed Study or SWAS, to monitor the acid-base status of two park streams and wet deposition in their respective watersheds. Since the mid-1990s this program has expanded to 14 streams. Today, SHEN maintains one of the most comprehensive long-term atmospheric deposition, air quality and related values monitoring programs of the 48 Class I national parks.

SHEN includes the headwaters of three river drainages -- the Shenandoah River to the west and the Rappahannock and James rivers to the east. There are 42 watersheds on the west side of SHEN and 28 on the east with about 72 perennial streams in the park. Watershed sizes range from 0.2 mi^2 to 12.1 mi^2. The most frequent watershed size is in the range of 1-2 mi^2 followed by the range of 4-5 mi^2. Of the 70 watersheds in SHEN, 44 are actively sampled by the park's Long Term Ecological Monitoring (LTEM) program; SWAS is part of the LTEM program.

The National Park Service Water Resources Division and Shenandoah National Park personnel held a water resources scoping workshop in Harrisonburg, VA on November 14, 2002. A total of 20 individuals, representing a mix of state and federal agencies, academic institutions, and environmental organizations, attended this workshop. The purpose of this workshop was twofold: 1) to familiarize the Water Resources Division with the water resource information for the park; and 2) to identify and prioritize water resource issues and management concerns.

A total of 31 water resource issues were identified at the scoping workshop, subsequently consolidated, and prioritized (via workshop attendee votes) into six high priority issues. These six issues have undergone some additional consolidation and transformation during the development of this report. The priorty issues identified during this workshop and discussed in this report include:

- Inventory and Classify Wetland Attributes – Basic wetland inventory maps prepared by the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI) program are available for SHEN. However, these maps grossly under-represent riverine wetlands. Additionally, many known wet areas, such as springs, are not delineated on the maps; seeps are not represented. Given the likelihood of many more potential wet areas, including springs and seeps, especially at the junctions of valley bottoms with their side slopes, it would appear SHEN needs to inventory and classify those remaining wet areas. This is more than apparent in the potential wet areas that were modeled in an on-going U.S. Geological Survey study.

  The intent of a proposed spring inventory study is to inventory and characterize, over a 2-year period, the physical, chemical and biological aspects of the known springs (70-100) throughout the park. However, the discrepancy between the number of known springs and the unsubstantiated 850 known surface-water sources cited in a 1972 publication is too large to ignore – and as the U.S. Geological study suggests, the number of potential spring/seep areas may exceed this number. Given that springs/seeps are distinct aquatic habitats often with individual uniqueness and that they may be experiencing loss of biodiversity from acidic deposition, it would appear important that SHEN attempt a complete inventory of springs/seeps.

  Once wet areas have been delineated, their physicochemical and biological characterizations are important to establish baseline conditions. This would provide the basis for any future wetland monitoring program. Such a characterization would depend on management needs and availability of resources.

- Re-evaluate Existing Water-Based Monitoring Programs – SHEN recently initiated a review of its long-term ecological monitoring program (LTEM). The only other SHEN LTEM review was conducted in 1996. Much has transpired within the SWAS program since 1996. We offer the following observations, suggestions, and/or recommendations for consideration during the LTEM review period.

  From our perspective the SWAS program has been and continues to be an effective 'partnership' for SHEN. Over the years, the design of the SWAS program evolved to reflect increased understanding of biogeochemical processes in SHEN watersheds. The current program appears to seek a balance between efficient use of available funding and effective detection and understanding of change. This balance is threatened by NPS budget erosion.

  SWAS watersheds make up only a fraction of the total number of watersheds in SHEN. This begs the question of what about the status and trend of water quality in the streams of other watersheds? Given current funding constraints, it would not appear possible to extend the SWAS program to streams in other watersheds. A solution may lie with the existing LTEM fish and aquatic macroinvertebrate monitoring programs.

The 1996 LTEM review recommended water quality sampling at headwater, middle, and lower stream reaches. This recommendation is rooted in the observation that acids deposited on the landscape can be partially neutralized by the time they reach lower elevations. We agree with the spirit and intent of this LTEM review recommendation, but given the reality of eroding budgets, it would not appear sustainable. We offer suggested revisions to the spatio-temporal framework of the SWAS sampling program.

The water monitoring program at SHEN appears to exist on ‘autopilot’ and park involvement is on an *ad hoc* basis. More often than not this leads to unlinked management and monitoring objectives. This and other weaknesses of the water monitoring program could be prevented if the program had access to a full or part-time NPS hydrologist.

- Restoration of Streams Impacted by Acidic Deposition – In 1999, the U.S. Forest Service began a restoration project in the St. Marys River, a nearby lotic system that has experienced the effects of acid deposition. To neutralize acidity temporarily (5-10 years), 140 tons of limestone sand were added to the river and five tributaries with the goal of improving ecosystem health and biodiversity. From 1998 to 2001 stream water quality improved (increased ANC) and macroinvertebrate and fish species richness increased.

  Stream liming does not qualify as ecosystem restoration because the fundamental impact of acidic deposition is degradation of watershed soil due to base cation depletion. Such a ‘restoration’ of the St. Marys River is an all too common ecological misstep by land management agencies concerned with only the short term.

- Impacts of Changing Chemical Composition of Streams on Aquatic Biota – Scientists now recognize that complete recovery of aquatic ecosystems will not occur until the sublethal effects of acidification on aquatic organisms are minimized or eliminated. Although seldom directly fatal for large-bodied aquatic organisms, sublethal chronic effects such as impacts on the food chain, biodiversity, and overall ecosystem health are key factors in determining the long-term impact of acid deposition on aquatic life.

  Given the ongoing review of SHEN’s LTEM program, it is appropriate to consider the incorporation of biological indicators into the program. In particular the fish and aquatic macroinvertebrate monitoring programs and past studies offer the ability to develop indicators of sublethal effects as well as multimetric indices.

In the future, the assessment of biogeochemical variability of SHEN's streams from the regional perspective of acidic deposition will, in all likelihood, need to be placed in the larger context of climate change. Current model projections predict that the climate of the Mid-Atlantic region will become warmer and wetter. A warmer atmosphere would influence the occurrence and severity of acidic deposition.

The potential effects of climate change on mercury toxicity and propagation through aquatic foodwebs could affect the contamination problem. Higher temperatures and metabolic rates will probably increase biomagnification and bioaccumulation rates, increasing contaminant levels in all organisms.

There would appear to be a need to develop analyses, experimental designs and aquatic indicators that distinguish between climatic and anthropogenic effects (acidic deposition) on SHEN's streams.

- <u>Inventory of Impacts on Water Quality</u> – There has been a lot of effort towards assessing the influences that atmospheric deposition has on water chemistry in SHEN. Equally important is an understanding of water quality impacts from the park's existing infrastructure and operations.

  In the original 1930s development and construction of SHEN, most buildings, campgrounds and other facilities were located and constructed in the higher altitudes along scenic Skyline Drive. These high-altitude locations are at the top of the watershed, maximizing the influence from contamination on SHEN's aquatic environments and water supplies down gradient. Many of the perennial streams in the park contain sensitive habitat for several species, including brook trout. Obviously, surface contaminants (accidental spills, untreated runoff, etc.) and shallow subsurface contaminants (leaking underground storage tanks, septic systems, etc.) can influence surface water chemistry in local streams, but ground water in SHEN is also very susceptible to contaminants. The relatively young age of ground water recorded at higher elevations in SHEN is indicative of fast ground water travel times and, therefore, high susceptibility to contamination from accidental spills or releases in the recharge area of aquifers.

  Other sources for pollutants include SHEN's maintenance facilities where hazardous materials are used and stored, septic systems, wastewater treatment plants, and activities such as building projects, washing operations, and visitor recreation (i.e., horseback riding). Two primary water quality concerns related to recreation trails in SHEN are: 1) accelerated sediment yields from trail erosion; and 2) bacteria contamination from horse and human sources.

- <u>Mercury Deposition</u> – Atmospheric deposition of mercury, listed as a priority pollutant by the U. S. Environmental Protection Agency, and its subsequent contamination of aquatic ecosystems has become a problem of national and global extent. Mercury deposited into lakes and streams undergoes aqueous phase chemical reactions to form toxic methylmercury, which is of greatest concern to human health. In the U.S., mercury makes more surface waters impaired for fishing than any other toxic contaminant. Currently, most states including Virginia have mercury fish consumption advisories – such advisories were few to nonexistent 15 years ago.

The chemistry of mercury is complex and its behavior difficult to predict in nature. Total mercury concentrations in the environment have not been found to be effective predictors of bioaccumulation in fish. Depending on physical, chemical and biological conditions at a site, mercury can remain largely tied up in sediments, released from particulate matter to other locations, or be taken up by aquatic biota where it may concentrate and become a threat to humans and other fish-eating animals. Although the precise factors controlling the accumulation of mercury in aquatic biota are not fully understood, it is clear that fish and other aquatic species are much more efficient in accumulating methylmercury than the inorganic forms that predominate in the environment. Thus, factors that influence the rate in which inorganic mercury is transformed to methylmercury also influence bioaccumulation as well.

Research has revealed that the problems of acid deposition and mercury deposition are linked. Levels of mercury in fish tissue tend to be higher in more acidic water. Streams in SHEN vary considerably in terms of pH and other important water chemistry parameters due to variation in dominant bedrock types underlying individual watersheds. All streams in SHEN have low ionic strength. Streams underlain by siliciclastic bedrock have low ANC and consequently very low pH. As a result of low pH, these streams may be the most vulnerable to mercury contamination. Streams underlain by basaltic bedrock have higher ANC and pH whereas streams underlain by granitic bedrock have intermediate values for these parameters. Thus, bedrock distribution in SHEN may reflect a gradient in watershed response to atmospheric deposition of mercury. This is the rationale behind a proposed U.S. Geological study that will determine the distribution, abundance, and variability of mercury in fish in SHEN and to assess the relationship between stream water chemistry and mercury concentrations in brook trout.

The U.S. Geological Survey study is an appropriate and necessary first step in determining the extent and variability of mercury contamination in brook trout. However, understanding the variability of mercury concentrations in brook trout via bioaccumulation and biomagnification begs some basic questions. What are the sources and pathways of total mercury derived from atmospheric deposition to SHEN streams? What is the fate and transport of mercury in SHEN streams? These questions are similar to those questions that the SWAS program is attempting to answer with regard to acidic deposition and the biogeochemistry of forested catchments. Therefore, the understanding of mercury deposition and its fate and transport in streams would be a logical extension of the SWAS program.

INTRODUCTION

The objectives of this Water Resources Scoping Report (WRSR) include identifying major water resource-related issues and presentation of relevant information and management considerations to better assist National Park Service (NPS) managers with meeting their management objectives at Shenandoah National Park (SHEN).

The report is divided into five major sections. The first section includes a description of the applicable State and Federal legislation that provides the mandates and foundation for management decisions related to water resources. Additionally, it describes past and present land use and disturbance at SHEN.

The second section provides a discussion of the ecological setting that is necessary to interpret water resources and the impacts on them.

The third section contains a description of the park's hydrologic environment. This section provides the reader with an overview of the physical, chemical and biological aspects of SHEN's existing water resources.

The fourth section is the identification of significant water-related issues pertaining to SHEN management and begins to identify some of the "information needs" that will better assist NPS management in providing a greater level of water resource protection.

The fifth section consolidates for NPS management those recommendations proposed to address the water-related issues, thereby providing the NPS options to consider in future management actions. Many issue-specific recommendations previously proposed by NPS management via other SHEN documents (i.e., proposals for research/monitoring) are included.

The initial information-gathering effort for this report included a 5-day visit by the authors to SHEN in 2002. During this time, the authors conducted a 1-day, water resources scoping workshop. Attendance was solicited from various federal, state, and local agencies as well as the private sector. The results of this workshop provided the authors with a strong foundation, information- and issue-based, for the development of this WRSR. The senior author spent a second 5-day period at SHEN interviewing park staff and conducting an exhaustive review of park files. Furthermore, the senior author met with representatives of the Shenandoah Watershed Study (SWAS) from the University of Virginia. Information for this report was derived from these sources, as well as other federal and state agencies, and reviews of existing water resource information, both published and unpublished.

Location, Facilities and Recreation Opportunities

Shenandoah National Park traverses a 70-mile (linear) segment of the Blue Ridge Mountains in the southern Appalachians of north-central Virginia (Figure 1). The park rises above the Virginia Piedmont to its east and the Shenandoah Valley to its west. It ranges in width from 2 to 10 miles and encompasses approximately 200,000 acres (300 mi^2). U.S. Highways 211 and 33 divide the park into the north, central and south management districts (Figure 1). The 105-mile long Skyline Drive, which extends the entire length of the park and generally follows the topographic divide, provides the primary route of travel in the park.

In 1976 Congress designated 79,019 acres of SHEN as wilderness. In 1978 an additional 560 acres were designated as wilderness and today 40% of the park or 79,579 acres is wilderness (Figure 1).

There are four major campgrounds in the park: Mathews Arm (mile 22.1 – measured from northern to southern terminus along Skyline Drive); Big Meadows (mile 51.3); Lewis Mountain (mile 57.5) and Loft Mountain (mile 79.5). All except Mathews Arm have showers, laundry, and a camp store. No campground has hookups for water, electricity, or sewage, but Mathews Arm, Big Meadows and Loft Mountain have dump stations. Dundo Group Campground (mile 83.7) is a primitive campground for groups of eight or more and includes pit toilets and water.

Visitor services include food service at Elkwallow Wayside (mile 24.1), Skyland Lodge (mile 41.7 and 42.5), Big Meadows Wayside (mile 51.2), Big Meadows Lodge (mile 51.2) and Loft Mountain Wayside (mile 79.5). Motor fuel is available at Elkwallow, Big Meadows and Loft Mountain. Lodging is available at Skyland, Big Meadows, and Lewis Mountain Cabins (mile 57.5). There are three visitor centers – Dickey Ridge (mile 4.6), Harry K. Byrd, Sr. (mile 51) and Loft Mountain (79.5).

There are seven picnic areas that are open year-round – three of these are located at visitor centers. Restrooms with septic systems are present, but not open in the cold months.

The park has more than 500 miles of trails, including 101 miles of the Appalachian Trail. There are more than 150 miles of horse trails and Skyland Stables is open from May through October.

Total recreation visits in fiscal year 2002 were 1,511,016.

Legislation and Management

Numerous federal and state laws and executive orders mandate specific regulatory considerations with regard to protection and management of water-related resources in and adjacent to SHEN. Policies and guidelines of the NPS

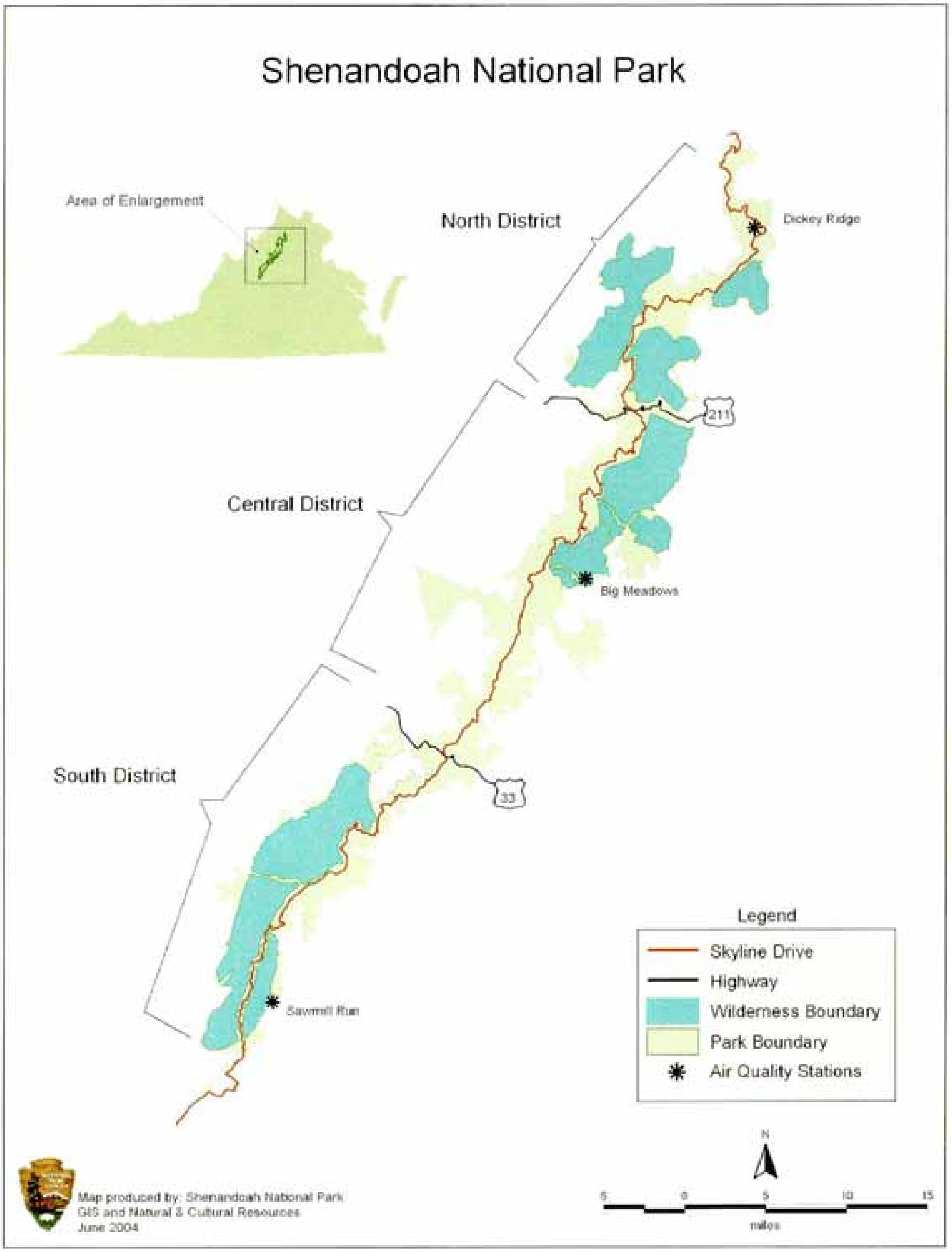


Figure 1. Shenandoah National Park.

require management of natural resources of the national park system to maintain, rehabilitate and perpetuate the inherent integrity of aquatic resources.

Many federal, state and local agencies and citizen's groups have an interest, mandated or otherwise, in the water resources of SHEN. Protection of water resources requires an understanding of the various policy, regulatory and management designations in order to facilitate coordination and cooperation among agencies and adjacent landowners.

Establishment of Shenandoah National Park

In 1924, the Southern Appalachian National Park Committee was appointed by the Secretary of the Interior to investigate the establishment of a park in the Appalachian range. The result of the committee's work was an act (43 Stat. 958) passed in February 1925 that directed the Secretary of the Interior to determine the boundaries and areas within the Blue Ridge Mountains of Virginia that could be recommended as Shenandoah National Park. Soon, considerable public support developed within the Commonwealth of Virginia for a large national park in the Blue Ridge Mountains.

In May 1926, Shenandoah National Park was established (44 Stat. 616) with the following provisions: lands could be secured by the United States only by public or private donation; the park include approximately 521,000 acres; and that the minimum area to be administered be 250,000 acres. The citizens of the Shenandoah Valley campaigned to raise the money to purchase the necessary land, which consisted of over 4,000 separate tracts. The Virginia General Assembly provided funds and passed a special law for the acquisition of the land to be donated to the NPS. The task proved complicated and costly, so Congress reduced the minimum requirements to 160,000 acres. By 1935 the deeds were ready, and the Commonwealth of Virginia donated approximately 176,500 acres to the Department of the Interior. Shenandoah National Park was dedicated on July 3, 1936.

The authorizing legislation does not address natural resources; however, additional legislation of August 19, 1937 addressed natural resources, but did not specifically mention water resources.

Federal

Legislation, executive orders, and policies that guide management of SHEN's aquatic resources include:

> The *National Park Service Organic Act* of 1916 established the NPS and mandated that it "shall promote and regulate the use of the federal areas known as national parks, monuments, and reservations by such means and measures as conform to the fundamental purpose of the said parks, monuments, and reservations, which purpose is to conserve the scenery

and the natural and historic objects and the wild life therein and to provide for the enjoyment of future generations."

The *General Authorities Act* of 1970 reinforced the 1916 *Organic Act* – all park lands are united by a common preservation purpose, regardless of title or designation. Hence, federal law protects all water resources in the national park system equally, and it is the fundamental duty of the NPS to protect those resources unless otherwise indicated by Congress.

The *Redwood National Park Act* (1978) amended the *General Authorities Act* of 1970 to mandate that all park system units be managed and protected "in light of the high public value and integrity of the national park system." Furthermore, no activities should be undertaken "in derogation of the values and purposes for which these various areas have been established", except where specifically authorized by law or as may have been or shall be directly and specifically provided for by Congress.

The *National Parks Omnibus Management Act* of 1998 attempts to improve the ability of the NPS to provide state-of-the-art management, protection, and interpretation of and research on the resources of the national park system by:

- Assuring that management of units of the national park system is enhanced by the availability and utilization of a broad program of the highest quality science and information;
- Authorizing the establishment of cooperative agreements with colleges and universities, including but not limited to land grant schools, in partnership with other Federal and State agencies, to establish cooperative study units to conduct multi-disciplinary research and develop integrated information products on the resources of the national park system, or of the larger region of which parks are a part;
- Undertaking a program of inventory and monitoring of national park system resources to establish baseline information and to provide information on the long-term trends in the condition of national park system resources, and;
- Taking such measures as are necessary to assure the full and proper utilization of the results of scientific study for park management decisions. In each case in which an action undertaken by the NPS may cause a significant adverse effect on a park resource, the administrative record shall reflect the manner in which unit resource studies have been considered. The trend in the condition of resources of the national park system shall be a significant factor in the annual performance.

Congress passed the *National Environmental Policy Act* (NEPA) in 1969, which requires that federal actions which may have significant environmental impacts shall: "utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decision making which may have an impact on man's environment."

The *Wilderness Act of 1964* established the National Wilderness Preservation System, composed of federal lands designated as wilderness areas. A wilderness, in contrast with those areas where man and his own works dominate the landscape, is "… an area where the earth and its community of life are untrammeled by man… an area of undeveloped federal land retaining its primeval character and influence… which is protected and managed so as to preserve its natural conditions that:

- appear to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable;
- provide outstanding opportunities for solitude or a primitive and unconfined type of recreation; and,
- has at least 5,000 acres of land or are of sufficient size as to make practicable their preservation and use in an unimpaired condition."

When the Wilderness Act established the National Wilderness Preservation System, most of the wilderness areas created under the Act were in the west. Areas in the east, such as SHEN, did not meet the definition of wilderness. In 1975, Congress passed the Eastern Wilderness Areas Act which included eastern wild areas, exhibiting elements of past human use but returning to a natural state, in the National Wilderness Preservation System.

The *Clean Air Act* of 1970 (as amended) regulates airborne emissions of a variety of pollutants from area, stationary, and mobile sources. The 1977 amendments created the 'Prevention of Significant Deteriortation' (PSD) program and designated specifically protected parks and wilderness areas as 'Class I' areas. The PSD program provides an opportunity for the NPS to assess potential water (and other) resource impacts from proposed new sources of air pollution in Class I areas such as SHEN. Such information is provided to State air regulators, as part of a formal process to inform them about emission levels or reductions needed to protect or improve water and other resources in the park.

The 1990 amendments to this act were intended primarily to fill the gaps in the earlier regulations, such as acid rain, ground level ozone, stratospheric ozone depletion and air toxics. The amendments identify a list of 189 hazardous air pollutants, such as mercury compounds, PCBs and dioxins, to name a few. The U.S. Environmental Protection Agency must study these chemicals, identify their sources, determine if emissions standards are warranted, and promulgate appropriate regulations.

The *Federal Water Pollution Control Act*, more commonly known as the *Clean Water Act*, was first promulgated in 1972 and amended several times since (e.g. 1977, 1987 and 1990). This law is designed to restore and maintain the chemical, physical and biological integrity of the nation's waters, including the waters of the national park system. To achieve this, the act called for a major grant program to assist in the construction of municipal sewage treatment facilities, and a program of effluent limitations designed to limit the amount of pollutants that could be discharged. Effluent limitations are the basis for permits issued for all point source discharges, known as the National Pollutant Discharge Elimination System (NPDES).

As part of the act, Congress recognized the primary role of the states in managing and regulating the nation's water quality. Section 313 requires that all federal agencies comply with the requirements of state law for water quality management, regardless of other jurisdictional status or landownership. States implement the protection of water quality under the authority granted by the Clean Water Act through best management practices and through water quality standards. Standards are based on the designated uses of a water body or segment of water, the water quality criteria necessary to protect that use or uses, and an anti-degradation provision to protect the existing water quality.

A state's antidegradation policy is a three-tiered approach to maintaining and protecting various levels of water quality. Minimally, the existing uses of a water segment and the quality level necessary to protect the uses must be maintained. The second level provides protection of existing water quality in segments where quality exceeds the fishable/swimmable goals of the Clean Water Act. The third level provides protection of the state's highest quality waters where ordinary use classifications may not suffice; these are classified as Outstanding National Resources Waters (ONRW). In Virginia the State designates Exceptional Waters, which are equivalent to ONRWs.

For Exceptional Waters, water quality controls are applied on pollutant sources such that water quality is not lowered in these waters. Specifically, for these waters the level of water quality necessary to protect existing uses shall be maintained and protected. Where designated uses are not attained, there shall be no lowering of water quality with respect to the pollutant or pollutants that are causing the nonattainment. A short-term, temporary lowering of water quality in the park may be permitted by the State on a case by case basis. Conversely, where the quality of water is better than the water quality standards, that water shall be considered high quality and that quality shall be maintained and protected.

Section 303 of the Clean Water Act requires the promulgation of water quality standards by the states. Additionally, each state is required to review its water quality standards at least once every three years. This section also requires the listing of those waters where effluent limitations are not stringent enough to implement any water quality standard [so called 303(d) list]. Each state must establish, for each of the waters on the 303 (d) list, total maximum daily loads (TMDLs) for applicable pollutants.

Section 404 of the Clean Water Act requires that a permit be issued for discharge of dredged or fill materials in waters of the U.S., including wetlands. The U.S. Army Corps of Engineers administers the Section 404 permit program with oversight and veto powers held by the U.S. Environmental Protection Agency.

The 1987 amendment to the Clean Water Act that established a stringent nonpoint source control mandate. Subsequent amendments further developed this mandate by requiring that states develop regulatory controls over nonpoint sources of pollution and over storm water runoff from industrial, municipal, and construction activities. Many of the NPS's construction activities are regulated by the Clean Water Act under the storm water permitting requirements.

The *Endangered Species Act* of 1973 requires the NPS to identify and promote the conservation of all federally listed endangered, threatened, or candidate species within any park unit boundary. This act requires all entities using federal funding to consult with the Secretary of Interior on activities that potentially impact endangered flora and fauna. It requires agencies to protect endangered and threatened species as well as designated critical habitats. While not required by legislation, it is NPS policy to also identify state and locally listed species of concern and support the preservation and restoration of those species and their habitats.

Executive Order 13112: *Invasive Species* complements and builds upon existing federal authority (e.g., Endangered Species Act, Nonindigenous Aquatic Nuisance Prevention and Control Act, Lacy Act, and Federal Plant Pest Act) to aid in the prevention and control of invasive species. This Executive Order established an Invasive Species Council. This Council developed a National Invasive Species Management Plan.

Executive Order 11990: *Wetlands Protection* directs the NPS to 1) provide leadership and to take action to minimize the destruction, loss, or degradation of wetlands; 2) preserve and enhance the natural and beneficial values of wetlands; and 3) avoid direct or indirect support of new construction in wetlands unless there are no practicable alternatives to such construction and the proposed action includes all practicable measures to minimize harm to wetlands.

Executive Order 11988: *Floodplain Management* states that the objective is, "…to avoid to the extent possible the long- and short-term adverse impacts associated with the occupancy and modification of floodplains and to avoid direct and indirect support of floodplain development wherever there is a practicable alternative." For non-repetitive actions, the E.O. states that all proposed facilities must be located outside the limits of the

100-year floodplain. If there were no practicable alternative to construction within the floodplain, adverse impacts would be minimized during the design of the project.

National Park Service Management Policies and Guidelines (2001) provide broad policy guidance for the management of units of the national park system. Topics include park planning, land protection, natural and cultural resource management, wilderness preservation and management, interpretation and education, special uses of the parks, park facilities design, and concessions management.

With respect to water resources, it is the policy of the NPS to determine the quality of park surface and ground water resources and avoid, whenever possible, the pollution of park waters by human activities occurring within and outside of parks. In particular, the NPS will work with appropriate governmental bodies to obtain the highest possible standards available under the Clean Water Act for protection of park waters; take all necessary actions to maintain or restore the quality of surface and ground waters within the parks consistent with the Clean Water Act and all applicable laws and regulations; and, enter into agreements with other agencies and governing bodies, as appropriate, to secure their cooperation in maintaining or restoring the quality of park water resources.

The NPS will manage watersheds as complete hydrologic systems, and minimize human disturbance to the natural upland processes that deliver water, sediment and woody debris to streams. The National Park Service will manage streams to protect stream processes that create habitat features such as floodplains, riparian systems, woody debris accumulations, terraces, gravel bars, riffles and pools.

The NPS will achieve the protection of watershed and stream features primarily by avoiding impacts to watershed and riparian vegetation and by allowing natural fluvial processes to proceed unimpeded. When conflicts between infrastructure (such as bridges) and stream processes are unavoidable, park managers will first consider relocating or redesigning facilities, rather than manipulating streams. Where stream manipulation is unavoidable, managers will use techniques that are visually non-obtrusive and that protect natural processes to the greatest extent practicable.

Recommended procedures for implementing service-wide policies are described in the NPS Directives System. The guidelines most directly pertaining to actions affecting water resources include:

> Director’s Order #2: Park Planning;
> Director’s Order #12: Conservation Planning, Environmental Impact Analysis, and Decision-making;
> Director’s Order #77-1: Wetland Protection;
> Director’s Order #77-2: Floodplain Management;
> Director’s Order #83: Public Health;

NPS-75: Natural Resource Inventory and Monitoring; and
NPS-77: Natural Resources Management.

The latter two represent guidelines from an older system that have not been converted to the Directives System.

Based on these legislative mandates and NPS policies, SHEN's Resource Management Plan (NPS 1998) denotes the following objective – the ecological integrity of this portion of the Blue Ridge/Central Appalachian biome is protected, maintained, and restored, as appropriate.

The 5-year Strategic Plan for SHEN (NPS 2000) incorporates the servicewide mission goals of "Natural and cultural resources and associated values are protected, restored, and maintained in good condition and managed within their broader ecosystem and cultural context" and "Vital signs for natural resource monitoring are identified and the monitoring program is maintained." Tiering off from the former goal is the long-term goal of having water quality in SHEN remain stable or improve. These goals are directly related to the comprehensive management of water resources in SHEN. Although not mentioned in the Strategic Plan, the servicewide goal of "The NPS contributes to knowledge about natural and cultural resources and associated values; management decisions about resources and visitors are based on adequate scholarly and scientific information" directly relates to the water resource inventory work being conducted in SHEN.

State of Virginia

State water quality laws and regulations can be found on the worldwide web at < http://www.deq.state.va.us/regulations/xwaterregs.html >.

Land Use and Land Disturbance

There is important heuristic value in understanding historical land use and natural land disturbance in a watershed context. This importance has to do with physical and biological legacies. Legacies are the physical remnants or signatures of past natural or anthropogenic disturbances (Naiman *et al.* 1995). Legacies have a profound influence on current and future environmental conditions. Natural legacies comprise the present habitat and biota resulting from past events such as glaciation, floods, and sedimentation. Past legacies of an anthropogenic origin include farming, logging, and mining.

The inherited properties (i.e., legacies) of ecological systems determine the directions and rates of ecosystem responses to a disturbance or stress, such as acidic deposition. Legacies influence the direction and rate of change; subsequent disturbances that occur at various times and spatial scales also are influential. Knowledge of disturbances, legacies, and lag times is crucial to achieving predictive understanding (Naiman *et al.* 1995). That is, the understanding of how past events and processes have led to current legacies or environmental conditions can contribute to predicting the responses of freshwater systems to contemporary disturbances or stresses.

Historical Perspective

Archeological evidence indicates that as early as 8000 BC paleo-Indians, primarily hunters and gatherers, were using the Blue Ridge Mountains. By 1000 AD agricultural communities had developed in the surrounding valleys and use of the mountains was limited to brief hunting trips.

The first European record of exploration of the Blue Ridge was in 1669. During the 18th century, people moved into the Piedmont from the Tidewater Region and into the Shenandoah Valley from Pennsylvania. By 1800 settlement of the valleys was fairly complete.

During the 19th century, settlement progressed into the mountain hollows as land in the lowlands became scarce. The suitability of land for farming determined the locations of most home sites in the park (Gathright 1976). For example, little farming occurred in the southwestern portion of the park with its steep slopes and thin and rocky soils (Lynch and Dise 1985; Figures 2a, b, c).

Logging began in the early 19th century and was intense during the first two decades of the 20th century. Most of the timber in the area of SHEN had been cut approximately every 30 years (Lambert 1989). Coupled with the outbreak of chestnut blight, logging removed much of the older timber prior to park formation.

Mining activities were also conducted through the latter half of the 19th century for iron, manganese, and copper, mainly in the southwestern portions of the park.

Logging, mining, and farming ceased after the establishment of the park in 1935 (Lynch and Dise 1985).

As the population increased in the mountains, much of the land supporting it degraded. In many areas game was hunted out, pastures overgrazed, soil depleted and timber logged out. At the turn of the 20th century, societal and technological changes in the area around the mountains made the mountain economy more tenuous. The population reached its peak about 1900. The 400-500 families living in the hollows in 1930 represented half of what were there 30 years prior. The distribution in SHEN of this population’s legacies (buildings, roads, and trails) is shown in Figures 2a, b, c.

The establishment of SHEN in 1926 did not provide for the expenditure of federal funds for land purchase. Over a period of 10 years private donations and a major expenditure by the Commonwealth of Virginia secured the land necessary to officially establish the national park in 1935. In the meantime, the Skyline Drive was funded and construction began in 1931. In 1933, the Civilian Conservation

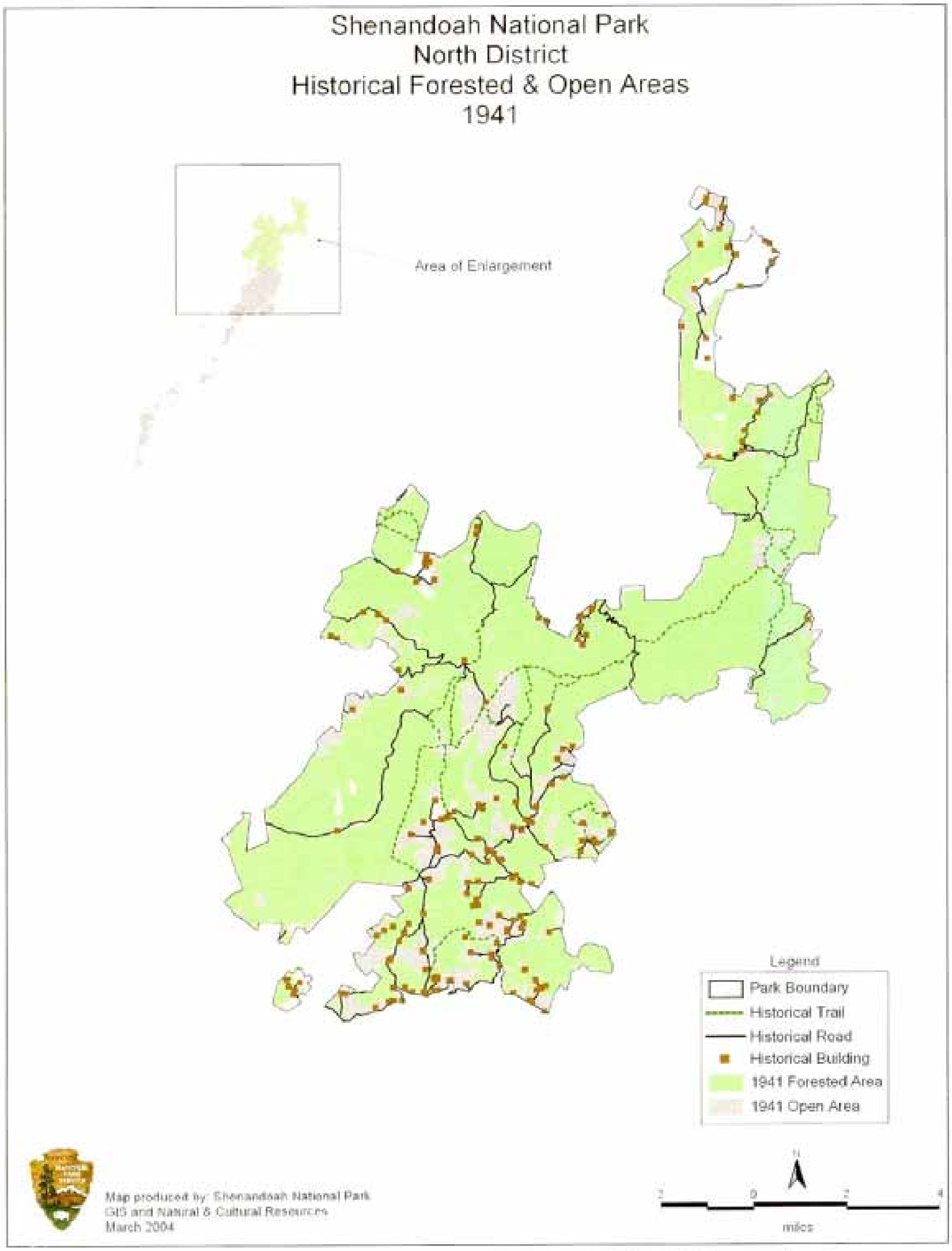


Figure 2a. Forested and open areas in 1941 in Shenandoah National Park, North District.

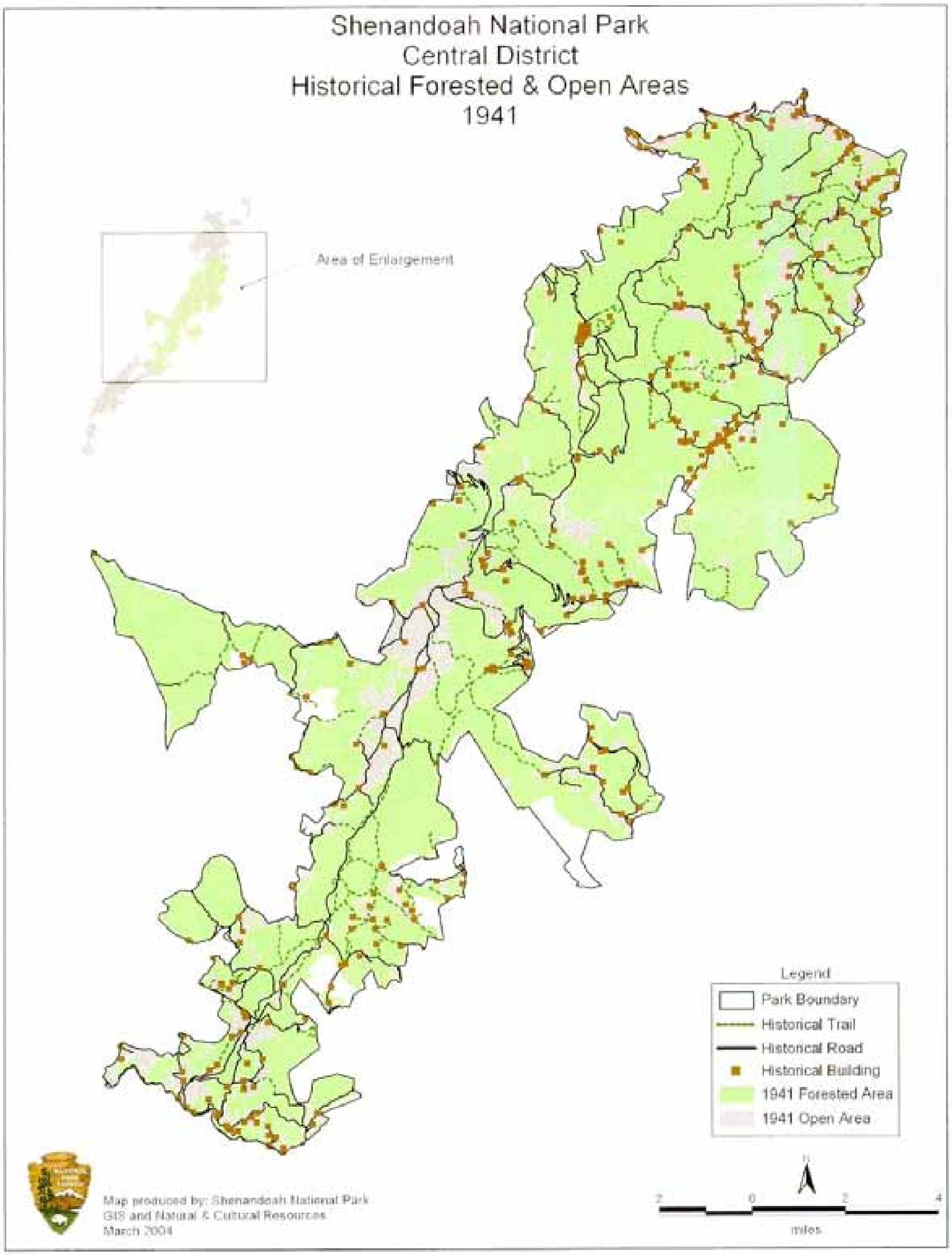


Figure 2b. Forested and open areas in 1941 in Shenandoah National Park, Central District.

13

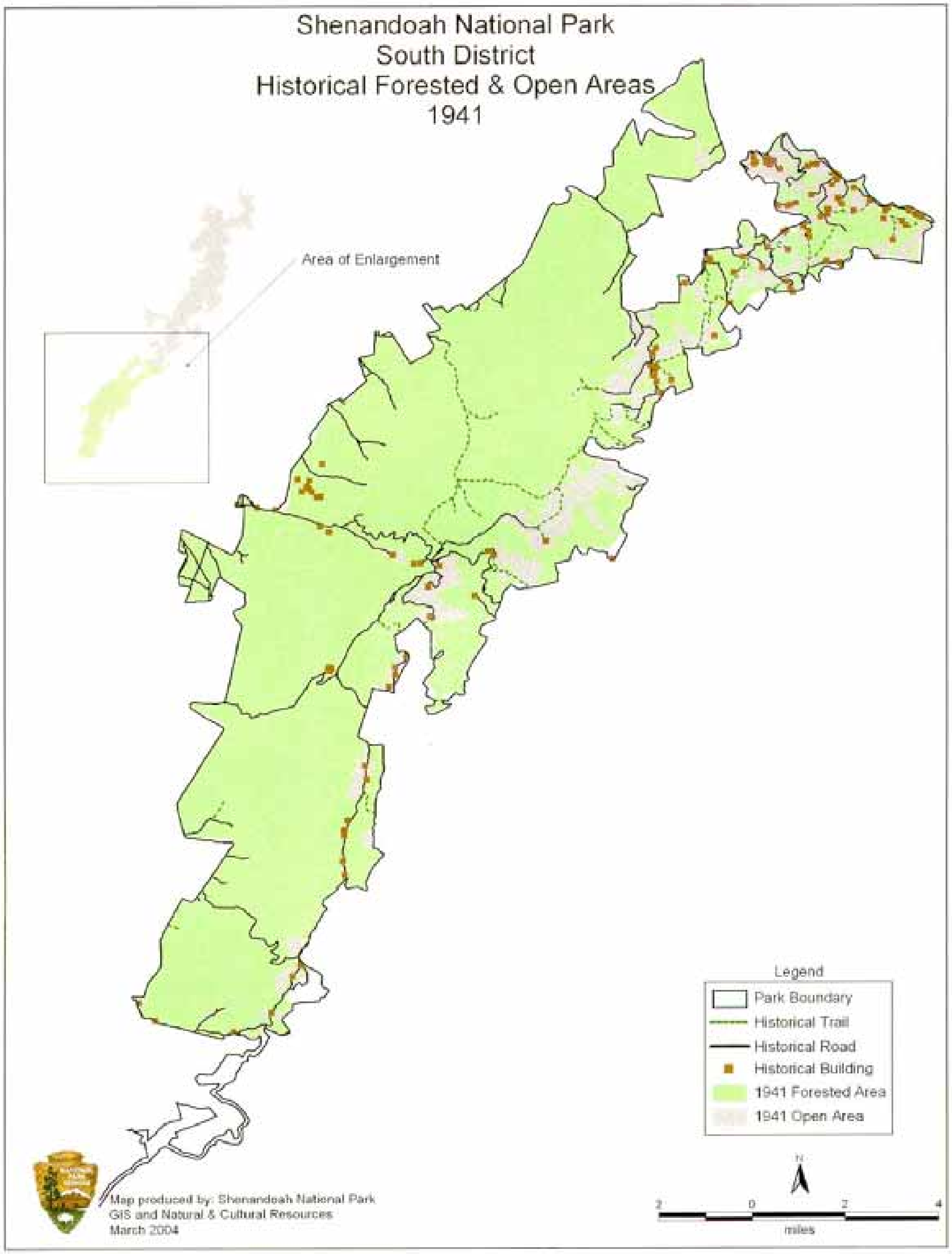


Figure 2c. Forested and open areas in 1941 in Shenandoah National Park, South District.

Corps (CCC) established six camps in the park and constructed most of the facilities necessary for visitor service. Of the people still living in the mountains, many sold their land to the Commonwealth and moved out on their own, while the remainder were placed in resettlement camps outside the park.

Since becoming a national park, much of the land has returned to a natural state. The park is now about 95% forested -- approximately half of the forest area was cleared at the time of park formation. Historical forested and open areas in SHEN in 1941 (Figures 2a, b, c) further demonstrate the consistent progression of all open areas to forest since the park was established in 1935. Animals that were greatly reduced or extirpated have returned or have been reintroduced. The streams in SHEN now do not show any obvious signs of previous land use. So complete was the regeneration in the first four decades of the park that in 1976 Congress designated 79,072 acres of the SHEN as wilderness area (Lambert 1989).

Because of the importance of understanding biological and physical legacies, Fievet *et al.* (2003) describe in detail the historical land use and disturbance history for the 14 watersheds in SWAS. This description includes maps that depict changes in forest cover and open area, forest types of 1941 and 1985 (see Figures 9a,b, and c for the current distribution of forest types in these 14 watersheds), historical fires, roads, buildings and open areas, and current roads, buildings, and open areas. The earliest information (circa 1934; see Table 1) is based on records and maps created just prior to the establishment of SHEN in 1935.

Present Day

There are several major paved roads. Skyline Drive runs the length of the park for approximately 105 mi and US Routes 211 and 33 run east and west. There are visitor centers, restaurants, lodges, cottages, gift stores and gas stations located along Skyline Drive, all of which are potential sources of nonpoint source pollution. U.S. Routes 211 and 33 are salted by the Virginia Department of Transportation during winter to prevent icing; parts of Skyline Drive are also salted. SHEN has an extensive network of unpaved roads that is used for management activities, fire control, and rescue operations. Although visitors cannot drive vehicles on these roads, sediment enters streams as a result of erosion on these often steep roads. In addition, there are over 497 mi of hiking trails, including some horse trails, and a 94.5-mile stretch of the Appalachian Trail. Trails are another potential source of sediment in SHEN streams.

The invasion of non-native insects and pathogens during the 20th century seriously impacted the vegetation communities in the park. The chestnut blight (*Endothia parasitica*) entered the U.S. in the early part of the 20th century. All chestnut trees in the park were affected by the disease, and by 1940 only

Table 1. Open area and lengths of roads and trails in 1934 in 14 watersheds of Shenandoah National Park. After Fievet *et al.* (2003).

Watershed	**Watershed Area (Ac)**	**Open Area (Ac)**	**Percent Open Area**	**Length Good Road/ Hwy (m)**	**Length Poor Road (m)**	**Length Trail (m)**
Jeremy's Run	5442.98	267.87	4.92	0.00	11111.11	7668.63
N.F. Thornton River	4723.30	1850.75	39.18	2545.88	15835.78	8193.95
Piney River	3118.05	587.23	18.83	3405.85	9771.15	8876.60
Hazel Run	3277.67	462.83	14.12	2108.93	15129.47	12837.50
North Fork Dry Run	572.59	1.24	0.22	733.86	707.52	1042.23
Brokenback Run	2441.45	373.68	15.31	69.21	8760.98	7384.94
White Oak Canyon Run	3488.40	123.40	3.54	5707.65	14973.24	4086.46
Rose River	5878.71	1309.77	22.28	21029.09	6779.62	17020.80
Staunton River	2600.49	328.35	12.63	0.00	5505.61	3184.50
Two Mile Run	1375.55	0.00	0.00	0.00	0.00	0.00
Deep Run	772.97	0.00	0.00	0.00	2734.23	0.00
White Oak Run	1262.61	7.73	0.61	0.00	527.53	0.00
Paine Run	3066.63	2.50	0.08	5794.58	600.53	214.07
Meadow Run	2193.78	0.00	0.00	0.00	1984.86	1352.15

remnant chestnut sprout growth existed. The loss of this tree species had a large impact on the structure and composition of park forests because some stands had 50% or greater numbers of chestnuts.

In 1986, the infestation of gypsy moth (*Lymantria dispar*) began in the park. Because the preferred food of the gypsy moth is oak, the predominate oak forests of the park were vulnerable to widespread impact; 39,536 acres of oak forest were defoliated in 1989. Repeated defoliations, coupled with several years of drought, caused widespread oak mortality in the late 1980s and early 1990s. The introduction in the early 1990s of a fungus that attacks gypsy moth larvae has helped to reduce oak defoliation and/or mortality. The non-native hemlock woolly adelgid (*Adelges tsuga*) and the native southern pine beetle (*Dendroctonus frontalis*) have had smaller-scale impacts on park forests. However, the former has resulted in the loss of greater than 80% of the park’s eastern hemlocks.

Based on records kept since 1935, SHEN averages eight naturally occurring fires per year. These fires tend to remain small, and are easily suppressed except during times of drought. Large fires within the park, the latest in 2000, are primarily human caused.

ECOLOGICAL SETTING

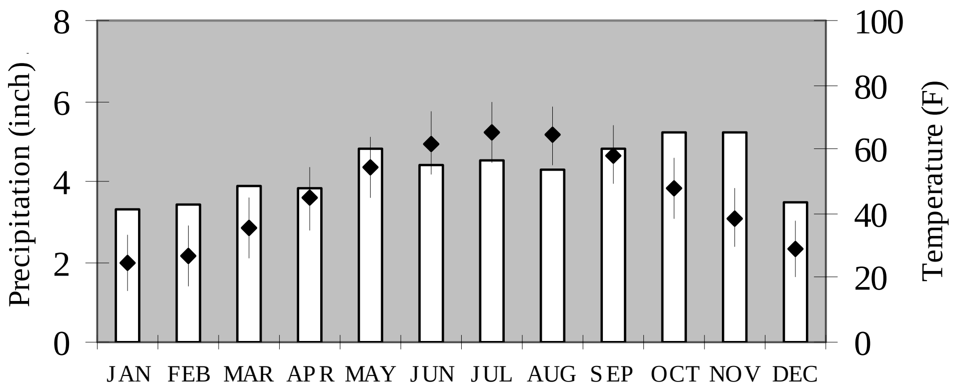
Climate

The Atlantic Ocean, and in particular the Gulf Stream, plays an important role in Virginia's precipitation regime (Sullivan *et al.* 2003). The climate in SHEN is dominated by winter storms that track from the west and north, and moist tropical air masses from the Gulf of Mexico and Atlantic Ocean during the remainder of the year. During the winter, large scale low-pressure systems predominate, producing gentle and evenly distributed precipitation that lasts for many hours. In contrast, summer precipitation often occurs as local showers and thunderstorms with high intensity, short duration, and limited areal distribution. Topography affects the distribution of precipitation in SHEN (see Physiography section). Because of "rain shadow" effects, precipitation amounts are smallest in the northeastern part of the park and largest in the southwestern part. Cooling of an air mass as it is mechanically lifted over the mountain barrier may result in orographic precipitation. During the passage of frontal and nonfrontal systems, the orographic effect can enhance precipitation at the higher elevations, leaving the foothills and upslope areas drier. The net effect of mountains in SHEN is to increase precipitation by 4 to 5 inches per year for every 1,000-foot increase in elevation (Lynch 1987). This is illustrated in Figure 3, which presents climate data (1961-1990) from two locations, Big Meadows and Luray. The weather station at Big Meadows is located inside the park boundary at an elevation of 3536 feet above mean sea level (msl). The Luray weather station is located immediately west of the park at a lower elevation, 1197 feet (msl). At Big Meadows, the average annual rainfall is 51.2 inches. At the lower elevation (Luray), average annual rainfall drops to 39.1 inches. Average monthly air temperatures range from 24.8° F in January to 65.5° F in July at Big Meadows. Warmer temperatures occur at the lower elevations. Average monthly air temperatures at Luray range from 41.9° F in January to 85.5° F in July.

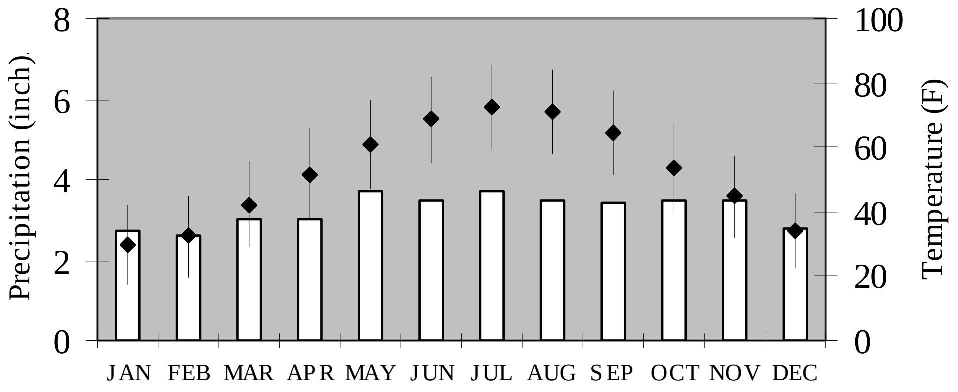
Air Quality

SHEN is within the Chesapeake Bay airshed, a large geographic area which, because of topography, meteorology, and climate routinely shares the same air mass. The airshed contains numerous major stationary sources of air pollutant emissions. Emissions from mobile sources (vehicles etc.) and many stationary sources are expected to increase with substantial growth in Virginia and other airshed states; however, in-park emissions comprise less than 1% of total human-made emissions from the surrounding eight counties (Sullivan *et al.* 2003).

The park is located downwind from the following major industrial and urban areas: Ohio River Valley; northeastern West Virginia; and southwestern Pennsylvania. Emission sources within 125 miles cause greater visibility and acidic deposition impacts at SHEN, on a per ton basis, than more distant sources (Sullivan *et al.* 2003).



Big Meadows



Luray

Figure 3. Monthly Mean Precipitation (bars) and Air Temperature Range (diamond-whiskers) (1961-1990), Big Meadows and Luray, Virginia (National Climate Data Center, 2003).

SHEN was targeted as one of the earliest atmospheric deposition, visibility, and air quality monitoring sites in the Class I national park network. SHEN is widely recognized as one of two Class I parks (the other being Great Smoky Mountains National Park) with resources most impaired by human-caused air pollution. In 1990, the U.S. Department of the Interior published a Preliminary Notice of Adverse Impacts on Shenandoah's visibility, streams and vegetation in the Federal Register. The park's resources continue to be impacted by increasing numbers of local and regional, urban and rural emission sources.

Long-term air quality monitoring began at SHEN in 1981 although data collection was uneven prior to 1988. This program originally consisted of ground-level ozone, sulfur and nitrogen wet deposition, and the size, concentration and chemical composition of airborne particulate matter that degrades visibility. The park's long-term monitoring program has since been expanded to include meteorology, sulfur dioxide, dry deposition, optical visibility, and, effective October 2002, wet deposition of mercury (Sullivan *et al.* 2003). Two monitoring locations, Dickey Ridge (North District) and Sawmill Run (South District) were closed after 1994, but the Big Meadows site (Central District) continues in operation (Figure 1). In 1979, SHEN began a long-term cooperative agreement with scientists at the University of Virginia to monitor the acid-base status of two park streams and wet deposition in their respective watersheds. Since the mid-1990s this program was expanded to 14 streams. Today, SHEN maintains one of the most comprehensive long-term atmospheric deposition, air quality and related values monitoring programs of the 48 Class I national parks. SHEN's strong scientific foundation coupled with a solid legal and policy foundation enhances NPS capability to uphold its "affirmative responsibility" to restore and protect Air Quality Related Values (AQRVs) in SHEN from the harmful effects of human-caused air pollution. AQRVs are those resources that may be affected by air quality, including vegetation, wildlife, soils, water quality, and visibility.

Atmospheric Deposition

Atmospheric deposition is the process by which airborne particles and gases are deposited on the earth's surface either through precipitation (called wet deposition) or as a result of atmospheric processes, such as settling (called dry deposition). Sulfates and nitrates are the principal constituents of wet or atmospheric deposition, commonly called acidic deposition or acid rain – they cause changes in water and soil chemistry, which, in turn, affect biological communities.

Emissions of sulfur dioxide and nitrogen oxides from the burning of fossil fuels are the primary sources of acidic deposition in the U.S. The generation of electric power (a stationary source) accounts for 60% of all sulfur dioxide and 26% of all nitrogen oxide emissions (USEPA 2000). Nitrogen oxide emissions are dominated by mobile sources (e.g., automobiles).

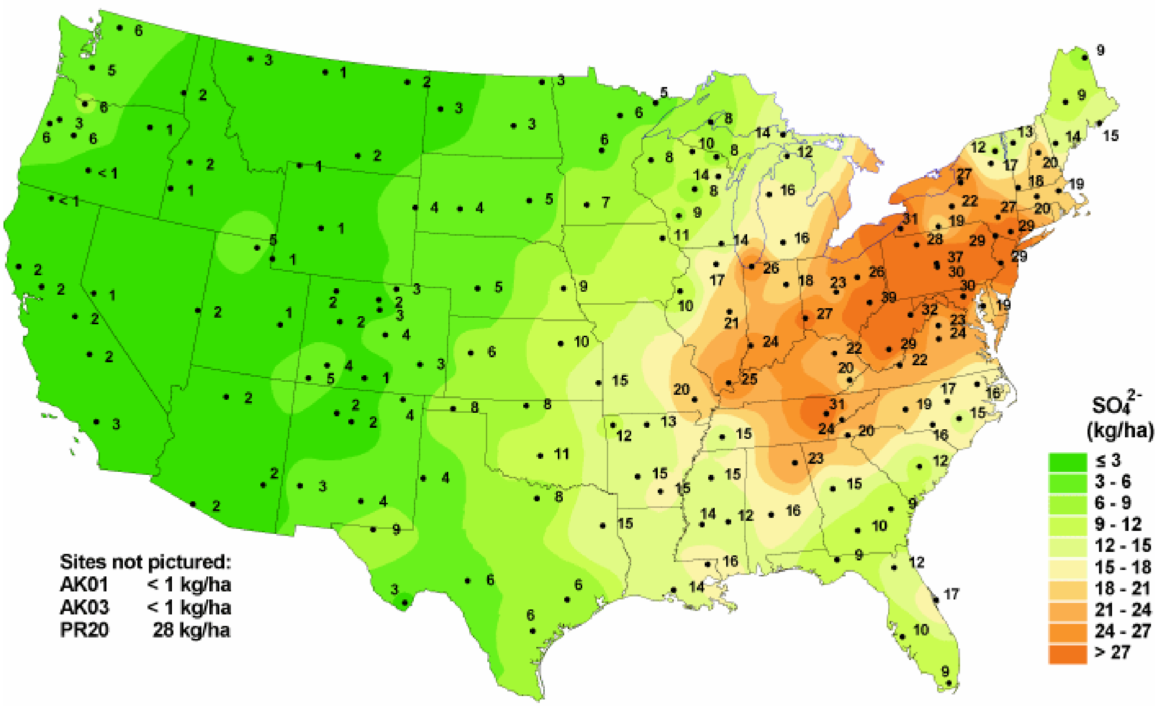
Webb (2003) gives the following history and future projection of acidic deposition in the US:

> A substantial change occurred in both the level and trend of acid-forming emissions during the past few decades, largely in response to regulatory controls. U.S. emissions of sulfur dioxide and nitrogen oxide peaked around 1970 after increasing amid fluctuations since the late 1800s (Husar *et al.* 1991). Annual emissions of sulfur dioxide then declined about 38% between 1973 and 1998, while emissions of nitrogen oxides leveled off at about the 1973 level (USEPA 2000). Sulfur dioxide emissions can be expected to decline another 14 percent from the 1973 levels by 2010, the target year for compliance with the sulfur emissions cap set by the 1990 CAAA [Clean Air Act Amendments]. However, the 1990 CAAA did not set a cap on nitrogen emissions which are expected to increase in the future with increasing fossil fuel consumption (NAPAP 1993; 1998).
>
> Reductions in the sulfur component of acidic deposition have generally followed the reductions in sulfur dioxide emissions. Deposition of sulfate in precipitation in the mid-Appalachian region declined by 23 percent between the periods of 1983-94 and 1995-98 (USGAO 2000). Legislated reductions of sulfur dioxide emissions have thus achieved reductions in sulfur deposition and additional reductions can be anticipated through 2010.
>
> However, the more critical issue relative to ecosystem effects is the magnitude of anthropogenic emissions in relation to natural emissions. Anthropogenic nitrogen emissions are presently 9 times the natural background level and are expected to increase. Estimates of natural sulfur emissions in the US are in the range of 1-5 percent of total sulfur emissions (NAPAP 1990). Assuming that as much as 5 percent of the sulfur dioxide emitted in 1973 (total annual level of 317 million tons) was derived from non-anthropogenic sources, the natural emission level for sulfur expressed as sulfur dioxide is about 1.6 million tons/yr. When fully implemented in 2010 the 1990 CAAA will cap anthropogenic sulfur dioxide emissions at 15.4 million tons/yr, a value nine times the natural background level. Thus even with anticipated emission reductions emissions of acid forming compounds, and hence acidic deposition, will continue to far exceed natural levels.

The primary source of long-term information on wet deposition is the National Atmospheric Deposition Program/National Trends Network (NADP/NTN). The NPS has 42 NTN sites located in national park units. One of these sites is the Big Meadows area of SHEN.

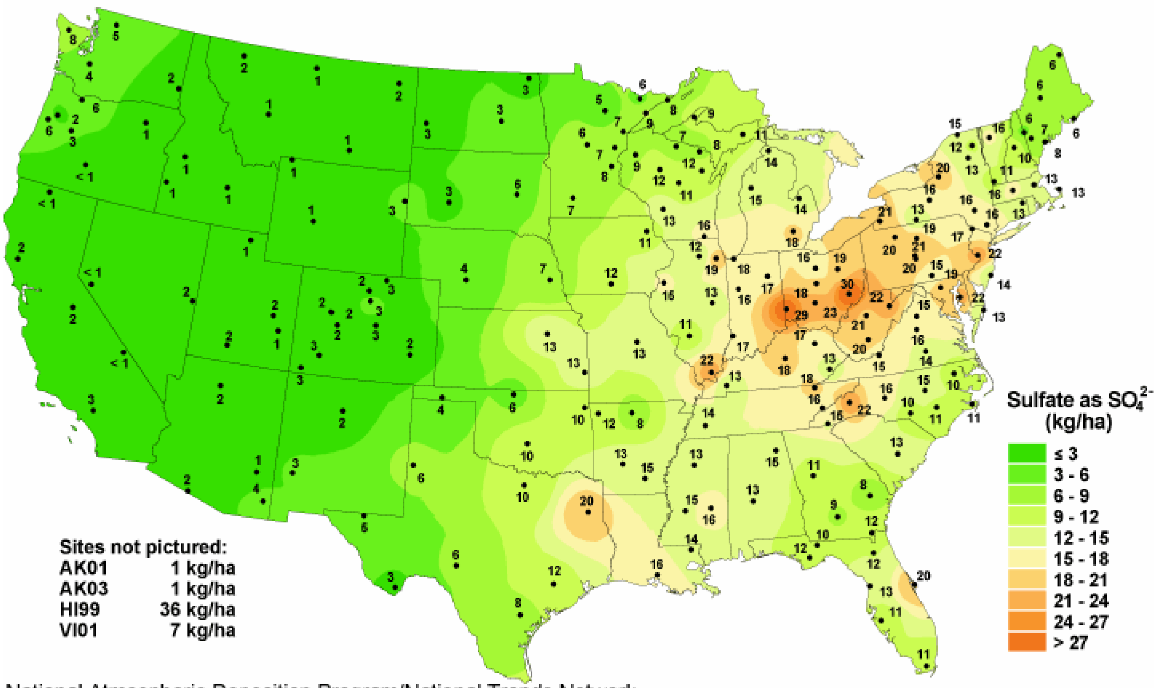
Annual data available from the NADP/NTN monitoring program for 1996 and 2001 show that SHEN receives high wet deposition of sulfates and moderately high wet deposition of ammonium and nitrate compared to other locations in the eastern U.S. (Figures 4a, b). Among Class I parks, SHEN and Great Smoky Mountains National Park receive the highest sulfate and nitrate deposition. Sulfur and nitrogen wet deposition values tend to be higher to the west and north of SHEN, but lower to the southeast of the park.

Sulfate ion wet deposition, 1996



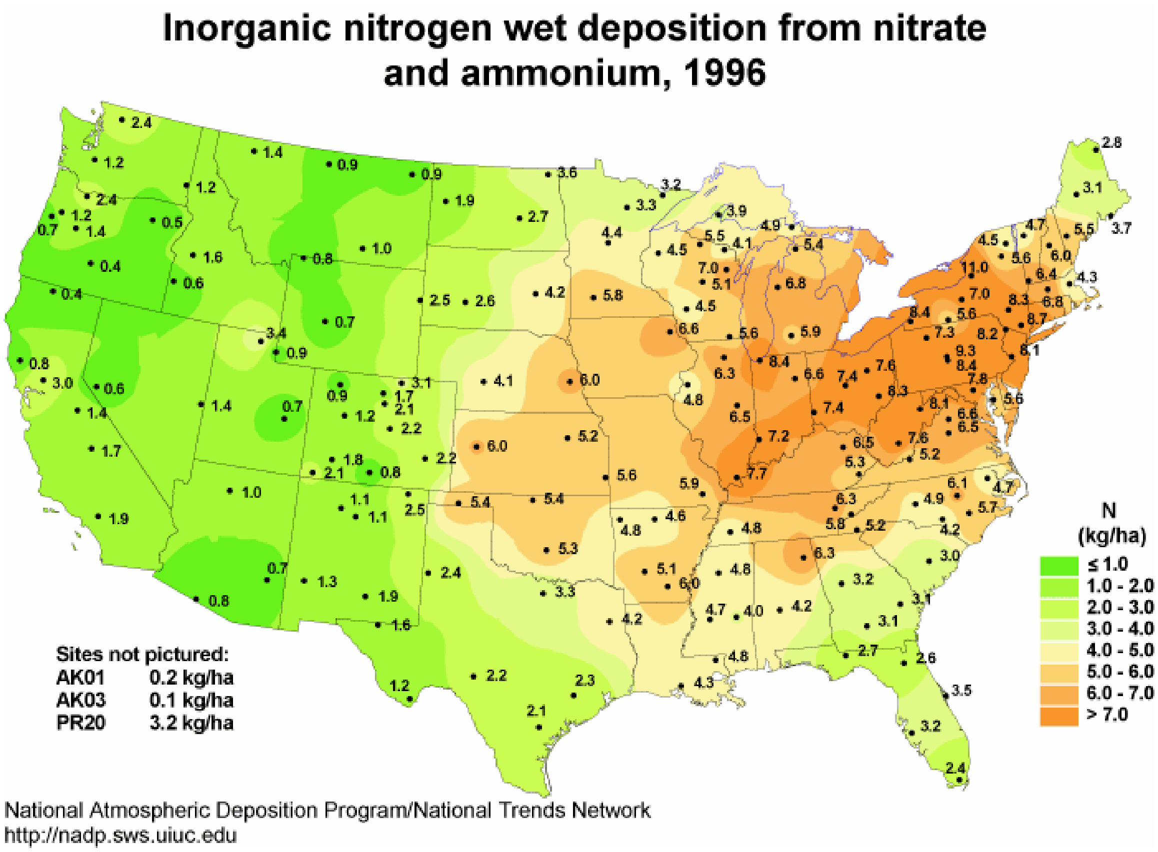
National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Sulfate ion wet deposition, 2001



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Figure 4a. Sulfate ion wet deposition across the U.S., 1996 and 2001.



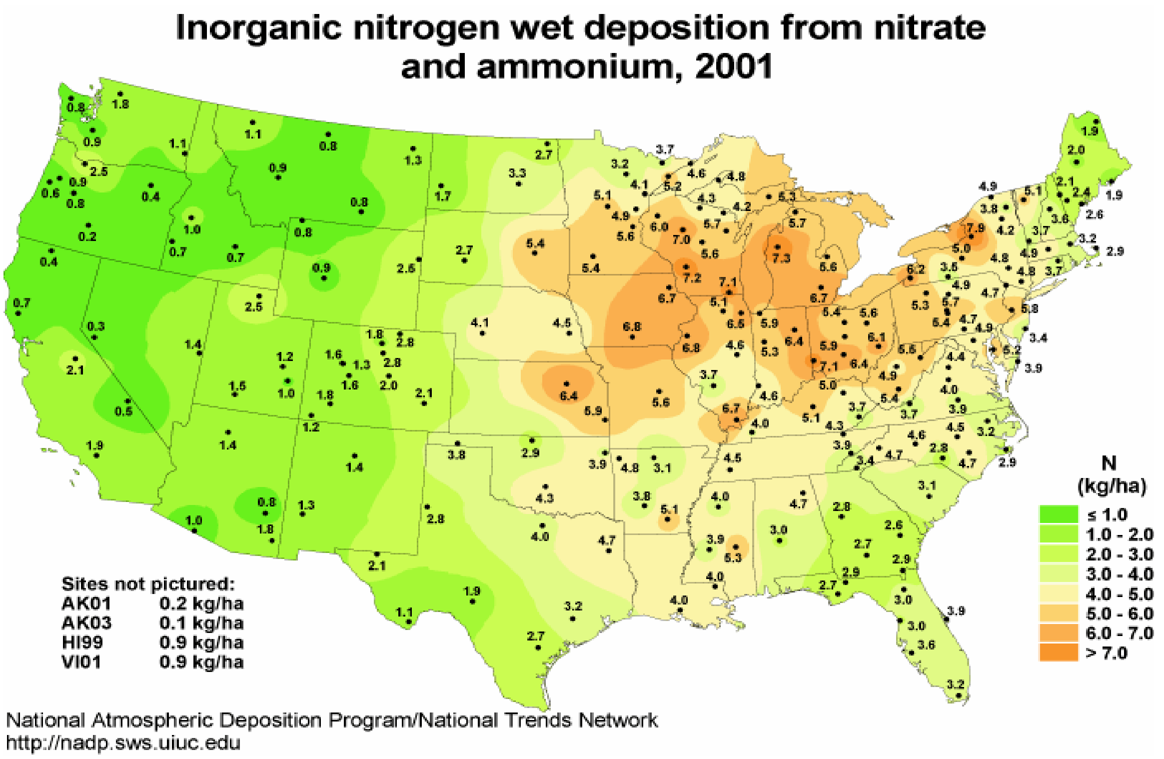


Figure 4b. Inorganic nitrogen wet deposition from nitrate and ammonium across the U.S., 1996 and 2001.

Sulfate deposition in SHEN shows a substantial reduction in 2001 compared to 1996 (Figure 4a). This has generally followed the recent legislated reductions in SO_2 emissions as discussed above.

Over the 1981 to 2000 period of record, wet nitrogen deposition at Big Meadows has varied substantially. There is no indication of large long-term increases or decreases in wet nitrogen deposition, although there has been a short-term decline over the last 5 years (Figure 4b).

The concentrations of major ions measured in precipitation and quantity of precipitation at the Big Meadows site (1981-2000) are given in Table 2.
This site had mean sulfate, nitrate, and sum of base cation concentrations equal to 31, 14, and 9 μeq/L, respectively. In contrast the White Oak Run (1980-2000) and North Fork Dry Run (1987-2000) sites (both operated by the U. of Virginia as part of the SWAS program) had mean sulfate, nitrate, and sum of base cation concentrations equal to 47, 20, and 17 μeq/L (White Oak Run) and 40, 18, 16 μeq/L (North Fork Dry Run), respectively.

Average total (wet and dry) sulfur and nitrogen deposition at the Big Meadows site for the period 1995-1998 was 10.5 kg/ha/yr and 8.6 kg/ha/yr, respectively (Sullivan *et al.* 2003). Sulfur deposition decreases from north to south in the park by less than 12%; given the resolution of a meteorological model, any east-west differences could not be determined (Sullivan *et al.* 2003), although they could be significant, given elevational change and orographic effects.

While past atmospheric deposition was dominated by sulfur deposition, recent research indicates a growing importance of nitrogen deposition as a component of acidification (Bulger *et al.* 1999; Galloway *et al.* 2003). Nitrogen effects are more complicated because, unlike sulfur, nitrogen is an important and sometimes limiting plant nutrient. When nitrogen deposition exceeds the levels at which plants can assimilate it, increased nitrate can result in stream acidification. In the Northeast, surface water acidification resulting from nitrogen deposition has been characterized as a seasonal and episodic phenomenon associated with high stream flows, in contrast to the chronic acidification associated with sulfur (Driscoll *et al.* 2003). Interestingly, for 83 streams in the Northeast with estimates for nitrate export, nitrate export increased steeply with nitrogen deposition above 6.8 kg/ha/yr at the base of the watershed or about 10 kg/ha/yr for the whole watershed (Aber *et al.* 2003; compare with average nitrogen deposition of 8.6 kg/ha/yr for Big Meadows site). This relationship between nitrogen deposition and nitrate export for the Northeast is quite similar to the relationship observed for European forests, despite differences in forest types and management (Dise and Wright 1995).

Table 2. Precipitation volume and measured concentrations of major ions in precipitation at the Big Meadows monitoring site within SHEN. After Sullivan *et al.* (2003). ppt = precipation.

Year	ppt (cm)	Concentration of Ion in Precipitation								pH
		Ca	Mg	Na	K	NH_4	SO_4	NO_3	Cl	
		(μeq/L)								
Big Meadows (Center of Central District, 3524 ft)										
1981	93.3	6.1	4.2	5.6	0.7	10.7	40.2	13.7	5.3	4.5
82	122.6	6.1	2.6	5.8	1.4	13.0	49.6	18.5	4.3	4.4
83	183.4	3.1	2.0	5.2	0.5	8.7	29.4	11.9	7.1	4.6
84	144.2	3.6	1.6	3.4	2.2	16.6	37.0	13.1	4.9	4.6
85	151.0	3.0	1.6	2.2	0.3	6.5	34.0	11.5	3.0	4.5
86	104.5	2.7	1.3	2.6	0.3	9.6	40.1	15.4	2.9	4.4
87	51.7	2.5	1.1	3.0	0.2	4.6	19.6	9.9	3.4	4.7
88	108.2	3.4	1.6	3.0	0.3	7.0	31.2	14.3	3.4	4.6
89	150.7	3.1	1.5	4.3	0.4	13.9	40.4	17.5	5.0	4.4
90	157.5	2.6	1.4	4.2	0.4	10.9	31.2	12.9	5.4	4.6
91	107.5	2.6	0.9	2.6	0.7	12.1	34.5	15.0	3.8	4.5
92	169.1	1.7	1.1	4.3	0.3	8.0	23.0	9.9	4.9	4.7
93	150.8	1.8	0.7	2.0	0.2	10.9	30.9	13.2	2.5	4.5
94	137.6	3.1	1.0	2.6	0.4	12.0	29.2	14.0	3.0	4.6
95	193.5	2.1	2.1	11.4	0.3	8.1	17.0	10.1	9.6	4.8
96	171.2	2.9	1.2	4.4	0.3	11.5	28.4	15.9	4.8	4.5
97	126.5	2.3	0.8	2.3	0.2	11.2	29.3	14.7	2.9	4.6
98	131.6	2.5	0.9	2.7	0.4	12.3	27.0	13.6	3.5	4.6
99	141.1	3.4	1.7	4.1	0.4	10.4	27.7	12.7	5.2	4.6
2000	110.7	2.9	0.9	2.1	0.3	11.2	26.3	13.8	2.9	4.6
Mean	135.3	3.1	1.5	3.9	0.5	10.5	31.3	13.6	4.4	4.6

Physiography

SHEN lies entirely within the *Northern Blue Ridge* subprovince of the *Blue Ridge* physiographic region (Lynch 1987). The Blue Ridge physiographic province (area = 3,000mi^2) is a narrow mountainous ridge between the *Valley and Ridge* province to the west and the *Piedmont* physiographic province to the east (Figure 5). The *Northern Blue Ridge* subprovince is characterized by a rugged landscape with steep slopes, narrow ridges, broad mountains, and high relief (Bailey 1999). Park elevations range from 550 feet (msl) in the northwest corner of the SHEN to 4050 feet (msl) atop Hawksbill Mountain in the central part of the park. In the northern part of the park, base-level elevations along the Blue Ridge foothills average 850 feet (msl) on the west and 800 feet (msl) on the east, and peak elevations as high as 3474 feet (msl) at the top of Hogback Mountain. The average relief is less than 2000 feet. The topography is similar in the southern portion of SHEN, with higher base-level elevations (1400 and 1000 feet on the west and east, respectively), which reduces the average relief to 1500 feet (msl). The highest elevation in the southern portion of the park is 3587 feet (msl) atop Loft Mountain. In the central part of SHEN, several peaks have elevations higher than 3000 feet (msl), including Hawksbill Mountain, producing an average relief above 2000 feet. Base-level elevations in the central district of the park are 1150 feet (msl) on the west and 900 feet (msl) on the east (DeKay 1972).

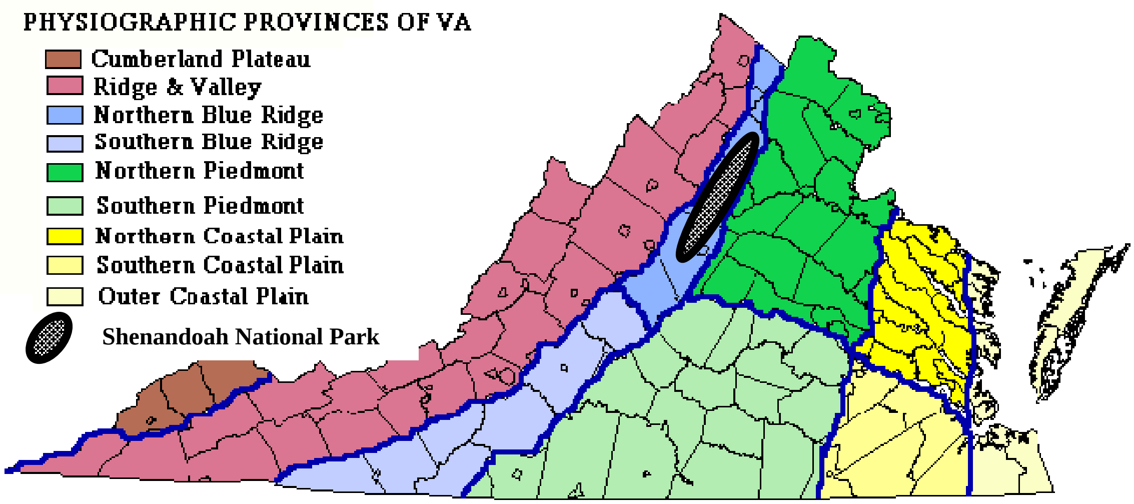


Figure 5. Physiographic Provinces of Virginia. Modified from http://www.dcr.state.va.us/dnh/environ.htm.

Geology

The geology of SHEN is the result of several erosional, depositional, tectonic, and volcanic events that began in the Precambrian and continued through the Ordovician Period (Lynch 1987). The geology of the park represents one of its most outstanding natural resources. Exposed formations of the Blue Ridge Mountains are among the oldest in North America.

Sullivan *et al.* (2003) provide the following geological description for SHEN:

> There are seven principal rock types that form the bedrock of the area (Figure 6). There are granitic rocks, know as Old Rag Granite and the Pedlar Formation, which exceed one billion years in age. They cover about 8% and 25% of the park area, respectively. The 600-million year old Swift Run Formation is a conglomerate of debris from granitic rocks and the volcanism, which laid down the Catoctin Formation. The Catoctin Formation is comprised of many layers of metamorphosed volcanic rocks from a series

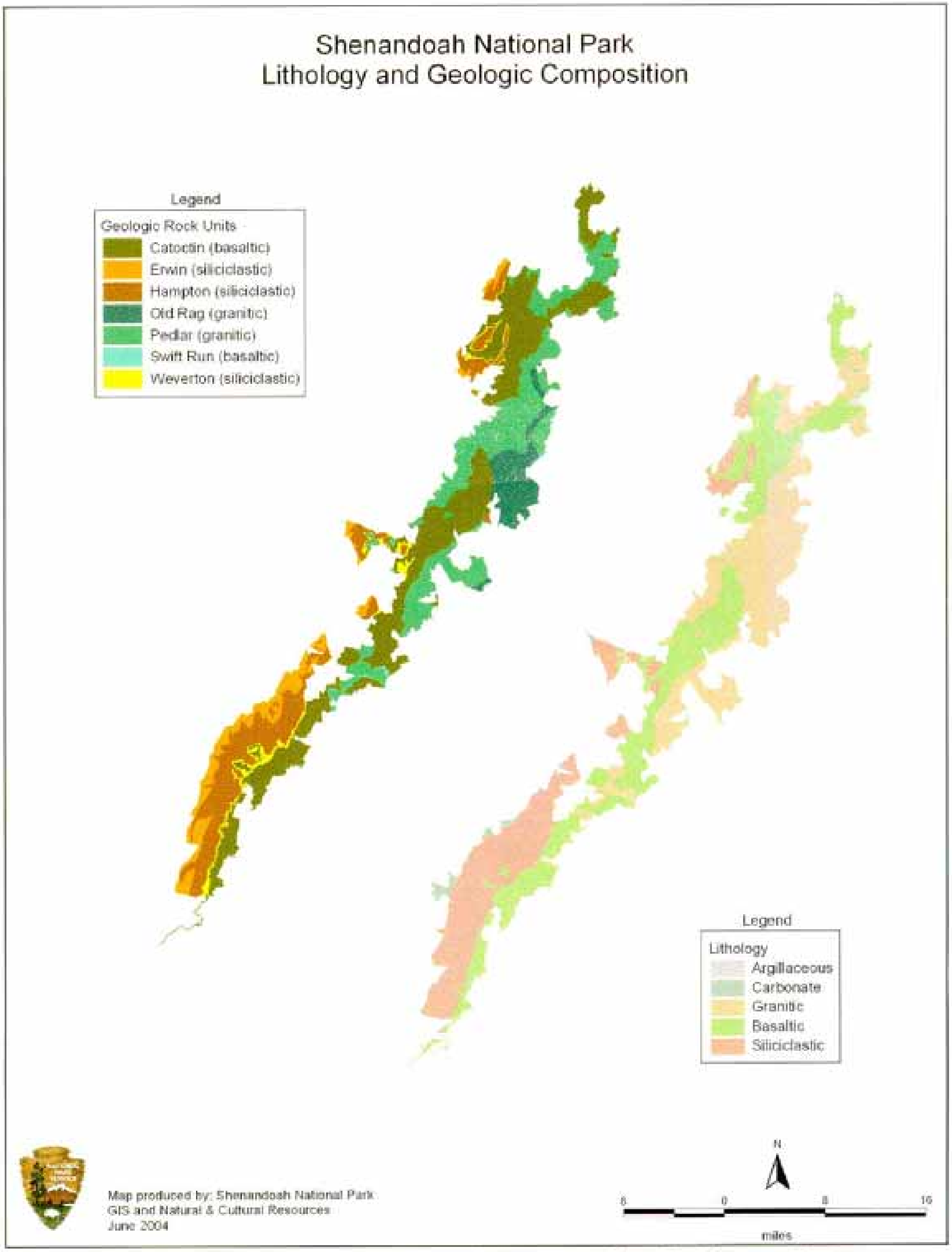


Figure 6. Lithology and geologic composition in Shenandoah National Park.

> of eruptions 600-million years ago. At least 12 of these layers have been identified in SHEN. Covering about 38% of SHEN, the Catoctin Formation dominates the central and northern parts of SHEN, producing many of the cliff faces and waterfalls in the park. The other three rock types found in SHEN are metamorphosed sedimentary rocks, about 500 million years old. The Weverton, Hampton (Harpers), and Erwin (Antietam) members of the Chilhowee Formation are exposed along the western slopes in the southern portions of SHEN. The Hampton Member is a thick deposit of phyllite and shale in lower sections and interbedded metasandstone and phyllite with intermittent quartzite in the upper sections. The Weverton Member is a sequence of interbedded quartzite, phyllite, and metasandstone with limited distribution in the park. The Antietam Formation is composed of light gray quartzite and quartz-rich clastics, which may be sparsely interbedded with less resistant metasandstone and phyllite. This resistant formation produces the sharp peaks in the southwestern part of the park.

The exposed geological formations in SHEN can be classified into three basic types of rock; granitic, basaltic, and siliciclastic (sedimentary rocks that contain abundant silica or sand). Siliciclastic rock types are most sensitive to acidification, followed by granitic rock types. Basaltic rock types are relatively insensitive. Each type covers approximately one-third of the park (Figure 6). There are also minor amounts of argillaceous and carbonate rock types.

Relationships between water chemistry and geology within SHEN have been known for some time. Lynch and Dise (1985) found silica, base cations, and acid neutralizing capacity (ANC) to be strongly related to the distribution of geologic formations. Bricker and Rice (1989) further established that the composition of the underlying bedrock to be one of the factors controlling stream chemistry. ANC is a measure of the concentration of acid that can be neutralized by the dissolved cations in a body of water. The effects of acidification were often greatest in watersheds underlain by the Antietam (Erwin) Formation, which had stream water pH averaging 5.0 and ANC averaging 7.0 µeq/L (Lynch and Dise 1985). Lynch and Dise also found that flow-weighted stream water ANC decreased in order of the underlying geologic formation as follows:

> basaltic (Catoctin formation) > granitic (Pedlar and Old Rag formations) > siliciclastic (Hampton and Antietam formations)

The significance of the bedrock association with acid-base status is further revealed by plotting pH versus ANC (Figure 7). In addition to the bedrock related gradient in ANC and pH, there is also a bedrock related gradient in stream water sensitivity to change in pH. Because of the nonlinear relationship between ANC and pH, a given ANC loss in streams associated with siliciclastic and granitic rock results in a larger depression in pH than occurs given the same ANC loss in streams associated with basaltic rock.

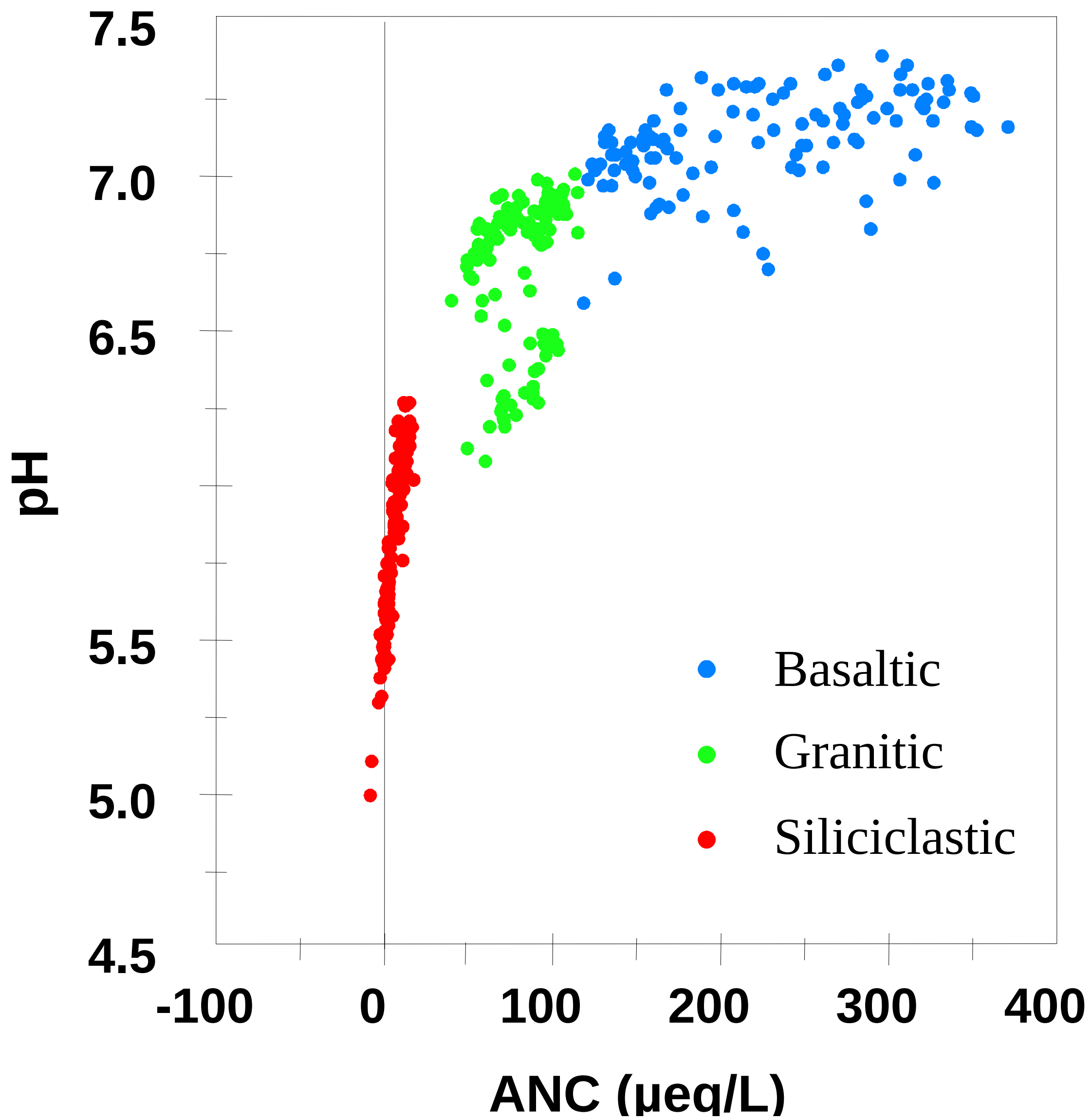


Figure 7. The relationship between pH and ANC from a subset of a spring 1992 survey associated with single bedrock classes. The line marks 0.0 ANC, the division between (+) and (-) ANC. Note that the pH change for a given ANC change varies for stream waters associated with different bedrock. Modified from Bulger *et al.* (1999).

Structurally, the Blue Ridge is composed of complexly folded and faulted igneous and metamorphic rocks. Structural features in the geology of SHEN were created by tectonic events that occurred throughout the Paleozoic Era. The results of compressional forces of folding are preserved as large asymmetrical folds in the southwest part of the park. The geologic development of the Blue Ridge was heavily influenced by faulting. There are two major types of faults within the park. The first type includes high-angle reverse and thrust faults, which typically have a northeast-southwest trend and dip to the southeast. Displacement of thousands of feet along these faults has thrust Precambrian and

Cambrian rocks over Paleozoic carbonate rocks. The second type comprises very high-angle transverse faults trending northwest. These faults have a vertical displacement of less than 500 feet (Lynch 1987).

The geology of the Blue Ridge greatly influenced the location of the settlements and life of the settlers. The early mountain settlers selected home sites where water, gentle slopes, and fertile soils were present (Gathright 1976).

Soils

The distribution of soil types in Virginia, including SHEN, is closely related to bedrock distribution (U.S. Department of Agriculture 1979). Soils in SHEN are derived from in-situ weathering of bedrock or transport of weathered material from upslope positions (Elder and Pettry 1975; Carter 1961; Hockman *et al.* 1979; Lynch and Dise 1985). The predominant soil associations include the Myersville-Catoctin, Porters-Halewood, Lew-Cataska-Harleton, and Hazleton-Drall. Colluvial fans, talus deposits, and exposed rock are also common. Soils in SHEN are generally classified as well-drained and medium to very strongly acidic (Lynch and Dise 1985).

The amount of cations a soil can hold is described as cation exchange capacity (CEC). It refers to the basic cations (Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}) and the acidic cations (H^{+} and Al^{+3}).   The larger the number the more cations the soil can hold. A clay soil will have a larger CEC than a sandy soil. A common measure of base cation availability in soils is the percent base saturation, which represents the fraction of exchange sites occupied by base cations in soils. Soil acidity is the amount of the total CEC occupied by the acidic cations. Base saturation values in the range of 10-20% have been cited as threshold values for incomplete acid neutralization and leaching of aluminum from soil and surface waters (Ruess and Johnson 1986; Binkley *et al.* 1989; Cronan and Schofield 1990). In 2000, the University of Virginia collected and analyzed soil samples at 79 sites within the park. The samples were collected from 14 different watersheds. The soils within watersheds situated primarily on siliciclastic bedrock generally showed the lowest soil pH (median 4.4 to 4.5), cation exchange capacity (median 3.5 to 7.5 cmol/kg), and base saturation (median 8 to 15%). Values for watersheds having soils primarily on granitic bedrock were generally intermediate, and basaltic watersheds were higher in all three parameters (Table 3). The present low base cation availability in soils of watersheds underlain by siliciclastic or granitic bedrock is probably due to a combination of low base cation content of the parent bedrock and depletion by previous land use and decades of accelerated leaching by acidic deposition (Sullivan *et al.* 2003).

Stream water ANC varies in predictable ways in the SHEN streams, depending on the characteristics of the underlying soils and bedrock (Lynch and Dise 1985). Geology, soils and water chemistry are all closely interrelated within SHEN. For example, Sullivan *et al.* (2003) found a clear relationship between stream water ANC and measured soil base saturation among the park’s watersheds. All

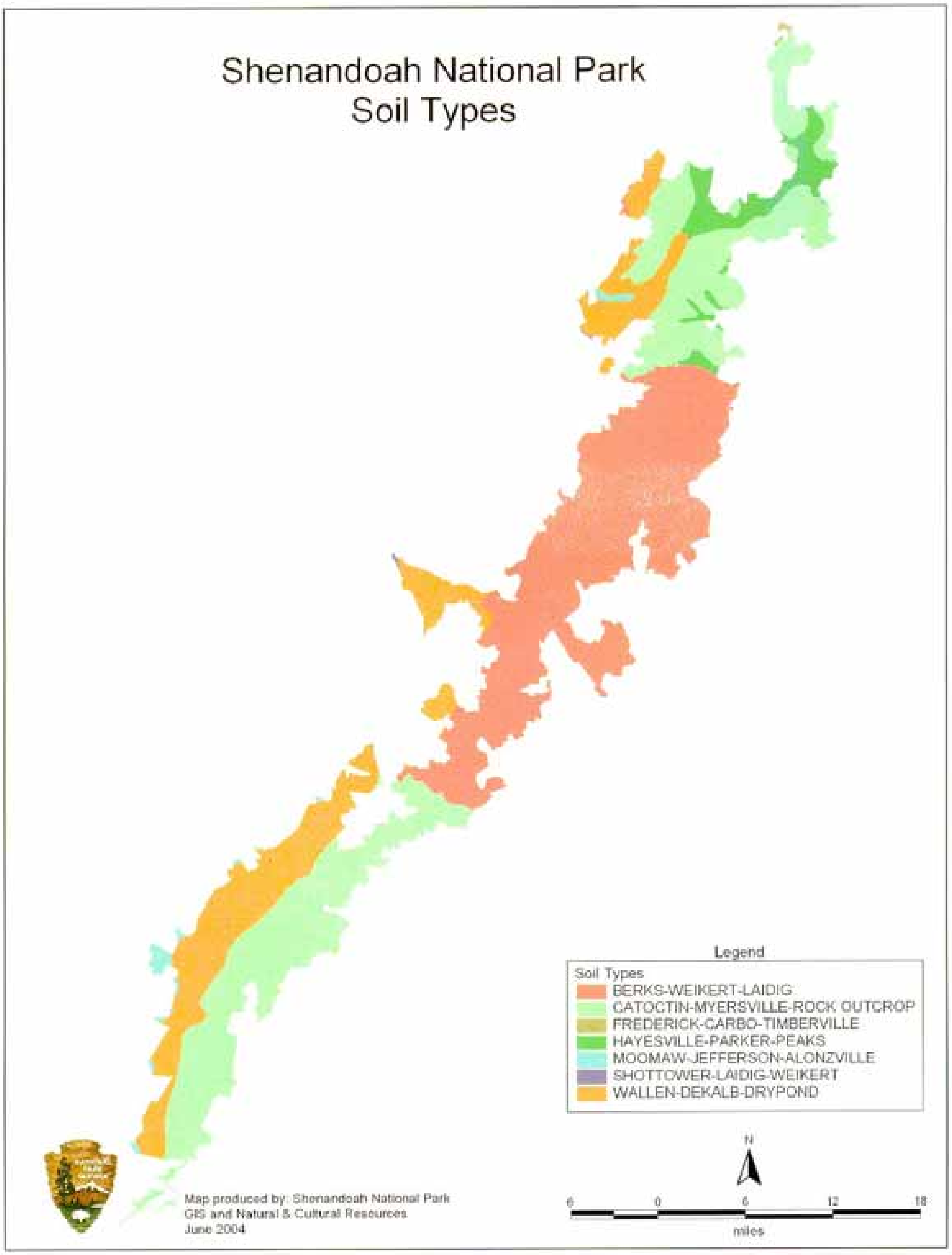
Table 3. Interquartile distribution of pH, cation exchange capacity (CEC), and percent base saturation for soil samples collected in SHEN study watersheds during the 2000 soil survey (Sullivan *et al.* 2003). Abreviations are as follows n= number of samples; Med= median

Site ID	Watershed	n	pH			CEC (cmol/kg)			Percent Base Saturation		
			25th	Med	75th	25th	Med	75th	25th	Med	75th
Siliciclastic Bedrock Class											
VT35	Paine Run	6	4.4	4.5	4.7	3.7	5.7	5.7	7.1	10.0	24.9
WOR1	White Oak Run	6	4.3	4.4	4.4	4.8	7.5	7.8	5.3	7.5	8.5
DR01	Deep Run	5	4.3	4.4	4.5	3.9	5.0	5.8	7.2	8.9	10.8
VT36	Meadow Run	6	4.4	4.4	4.5	3.1	3.5	7.6	7.8	8.7	11.3
VT53	Twomile Run	5	4.3	4.5	4.5	4.6	6.0	6.9	11.7	12.3	13.6
Granitic Bedrock Class											
VT59	Staunton River	6	4.7	4.8	4.9	6.5	7.5	9.2	9.1	13.9	29.5
NFDR	NF of Dry Run	5	4.4	4.5	4.7	7.3	8.0	9.2	7.5	10.8	12.4
VT58	Brokenback Run	5	4.6	4.7	4.7	7.3	8.4	9.6	6.0	6.7	9.7
VT62	Hazel River	4	4.5	4.7	4.8	5.3	5.3	6.5	12.3	12.8	21.6
Basaltic Bedrock Class											
VT60	Piney River	6	4.7	5.0	5.3	7.3	7.7	10.0	17.0	24.0	57.0
VT66	Rose River	8	4.8	5.0	5.3	7.3	10.1	10.7	19.1	38.0	63.5
VT75	White Oak Canyon	6	4.9	5.1	5.5	7.1	7.5	9.3	15.6	32.8	43.4
VT61	NF of Thornton River	7	5.1	5.2	5.3	7.7	9.6	10.8	35.6	54.4	71.2
VT51	Jeremys Run	4	4.7	5.0	5.3	6.3	7.6	7.7	15.0	22.8	46.1

Note: Watersheds are stratified according to the predominant bedrock class present in each watershed.

watersheds characterized by soil base saturation < 15% had average stream water ANC < 100 µeq/L. Watersheds with higher soil base saturation (> 22%) were dominated by basaltic bedrock and had average stream water ANC > 100 µeq/L. Lowest base saturation values (7 to 14%) were found in the siliciclastic and granitic watersheds.

Although soil acidification can occur in response to acidic deposition, soil acidification is also a natural process (Binkley *et al.* 1989). Three soil types present in the park (Wallen-DeKalb-Drypond, Moomaw-Jefferson-Alonzville, and Shottower-Laidid-Weikert) are associated with high percentages of acidic streams and streams having low ANC (Sullivan *et al.* 2003). Within the park, these soil types are most common in the South District, but are found within all districts along the western slope of the mountains (Figure 8). The Waller-DeKalb-Drypond type is the most common of the three within SHEN, and the most prevalent soil type along the western slope. Forest soils within SHEN have



Map produced by: Shenandoah National Park
GIS and Natural & Cultural Resources
June 2004

Figure 8. Soil types in Shenandoah National Park.

probably acidified to some degree in response to acidic deposition (Sullivan *et al.* 2003).

Vegetation

The eastern deciduous forest of SHEN is in a transitional zone between northern and southern vegetation types; northern species dominate higher elevations and north-facing slopes, and central hardwood forest species are prominent at lower elevations or more southerly slopes.

There are seven primary forest types within the park (Table 4; Figures 9a, b, c). The chestnut oak (*Quercus prinus*) forest type, occupying low to mid-elevation drier slopes with a southern or southwestern aspect, is the most prevalent. Red Oak (*Q. rubra*) is its primary associate. The yellow (or tulip) poplar (*Liriodendron tulipifera*) forest type occurs most frequently at lower elevations of north and east facing slopes of relatively moist drainages in the North and Central districts. Common associates are yellow birch (*Betula alleghaniensis*), eastern hemlock (*Tsuga canadensis*), white pine *(Pinus strobus*) and white oak (*Q. alba*). The richest and most diverse forest type, occupying mesic habitats in hollows or coves of valley bottoms, is the cove hardwood forest. No single species dominates this type, but rather a complex number of species are associated, including basswood (*Tilia americana*), yellow birch, sweet birch *(B. lenta*), butternut (*Juglans cinerea*), American elm (*Ulmus americana*), slippery elm (*U. rubra*), red maple (*Acer rubrum*), sugar maple (*A. saccharum*), umbrella magnolia (*Magnolia tripetala*), red and white oaks, white pine, hemlock and tulip poplar. Red Oak stands are less common but occur over a broad range of environmental conditions, occupying some of the most mesic ridge tops and side slopes. Mockernut hickory (*Carya tomentosa*), pignut hickory (*C. glabra*), chestnut oak, and white oak are common associates. The red oak forest type occurs more frequently on the finer textured soils derived from basaltic greenstone parent

Table 4. Forest types of Shenandoah National Park (after Teetor 1988).

Forest Type	Acreage	Percent of Park
Chestnut Oak	94,145	49
Cove Hardwood	28,630	15
Red Oak	18,345	10
Yellow Poplar	29,830	16
Pine	10,780	6
Black Locust	7,910	4
Hemlock	1,105	1

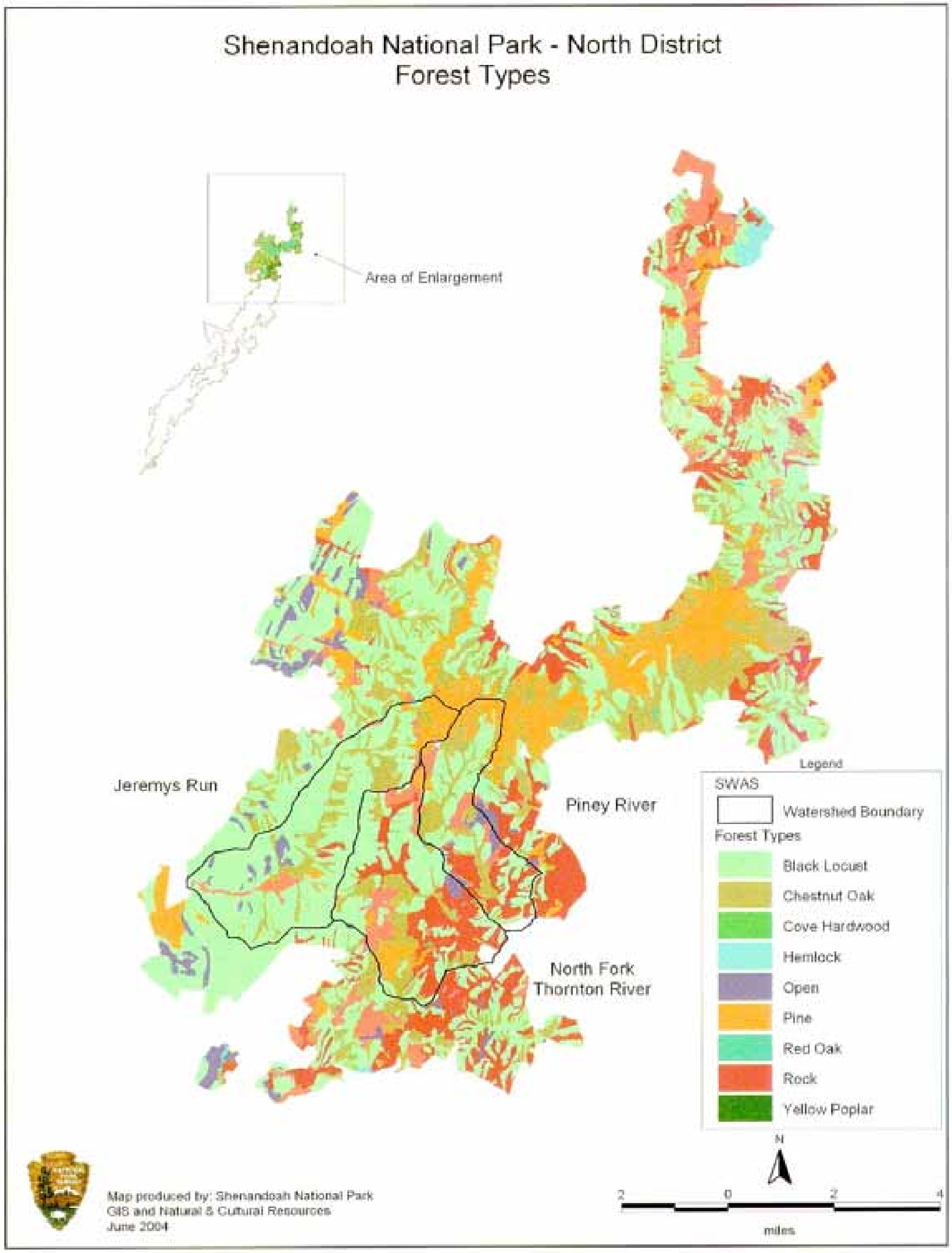


Figure 9a. Forest types in Shenandoah National Park, North District.

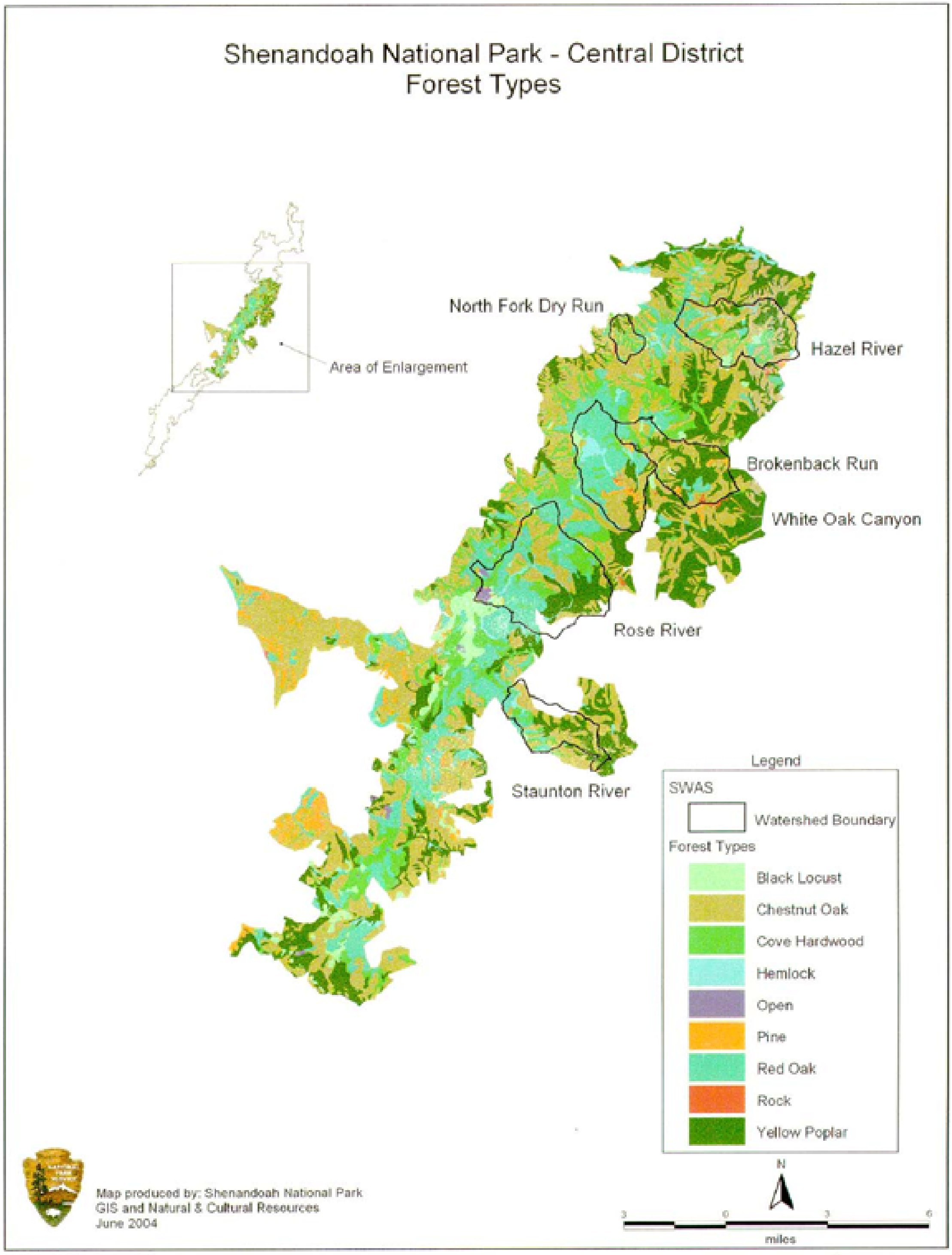


Figure 9b. Forest types in Shenandoah National Park, Central District.

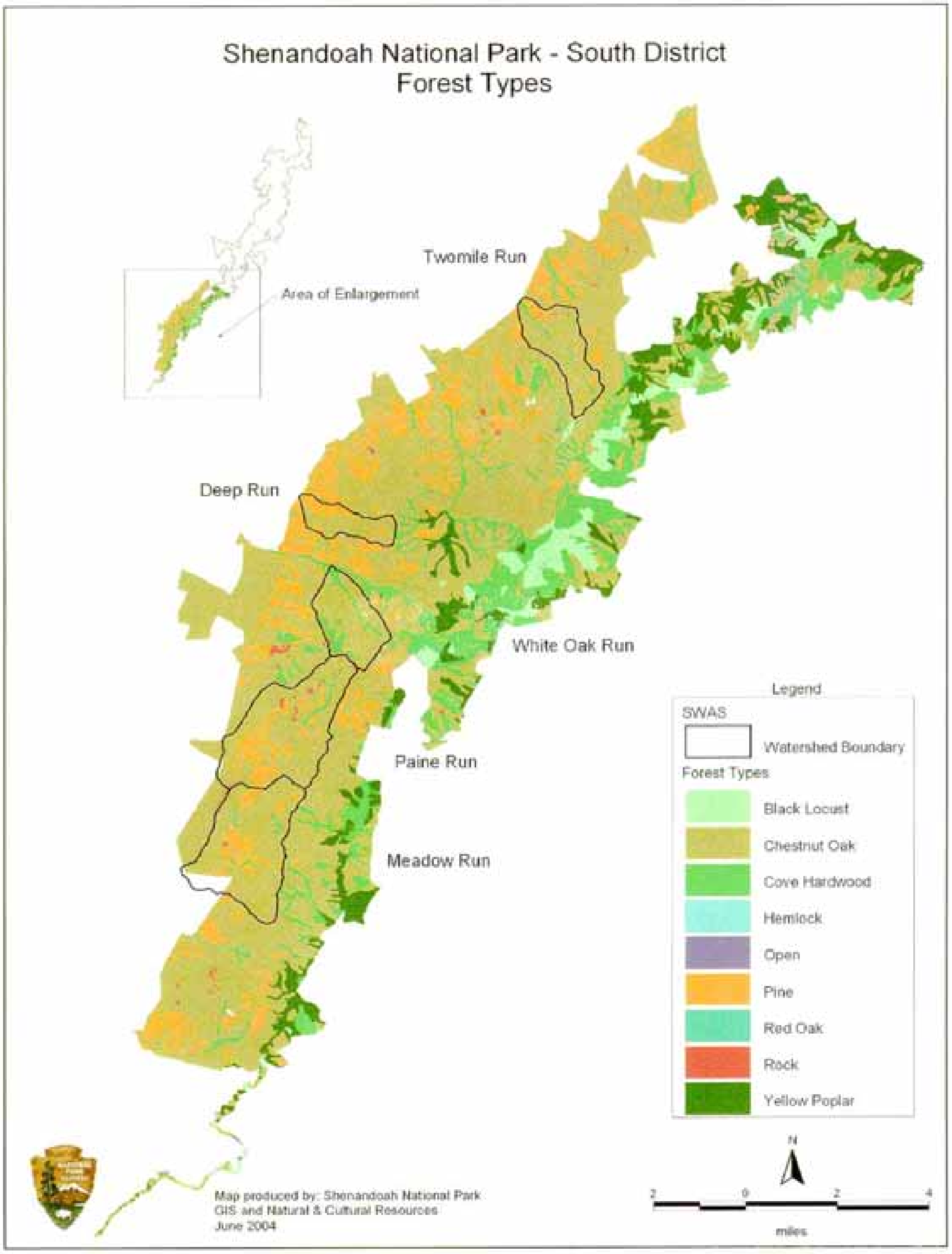


Figure 9c. Forest types in Shenandoah National Park, South District.

material. The pine forest type is composed of eastern white pine, Virginia pine (*P. virginiana*), and pitch pine (*P. rigida*), all of which are primarily successional and found on previously disturbed sites. Black locust (*Robinia pseudoacacia*) is an early seral stage forest type found primarily in recently disturbed areas. Associated species are black cherry (*Prunus serotina*), the non-native tree of heaven (*Ailanthus altissima*), and Virginia pine. Eastern hemlock was found in pure stands on moist sites associated with spring seeps, streams, north facing slopes and shaded drainage bottoms. This forest type is exhibiting a severe decline caused by the non-native insect, hemlock woolly adelgid.

DESCRIPTION OF THE HYDROLOGIC ENVIRONMENT

Hydrology

SHEN, located along the crest of the Blue Ridge Mountains, includes the headwaters of three river drainages; the Shenandoah River to the west and the Rappahannock and James rivers to the east. There are 42 watersheds on the west side of SHEN and 28 on the east with about 72 perennial streams in the park. Of the 70 watersheds in SHEN, 44 are actively sampled for water quality parameters by the park's Long Term Ecological Monitoring (LTEM) program; SWAS is part of the LTEM program. Figure 10 delineates those LTEM watersheds and provides watershed sizes. Watershed sizes range from 0.2 mi^2 (Dry Run) to 12.1 mi^2 (Big Run). The most frequent watershed size is in the range of 1-2 mi^2 followed by the range of 4-5 mi^2.

East slope streams tend to be larger and more dendritic, fed by one or more perennial tributaries and a number of associated springs; in contrast, west slope streams tend to be more linear (trellis) and fed by fewer springs as most originate from much dryer south and west facing ridges (Figure 11 a, b, c). The lengths of those portions of streams that flow in SHEN range from 3.1 to 5 miles. A chief feature of these high elevation streams is high gradient, with pools interspersed with riffles, rapids, cascades and falls, and bottoms chiefly of large gravel, rubble, boulder, and bedrock. In many places streams drop over ledges creating waterfalls up to 85 feet. Most streams are heavily shaded and cool or even cold in the summer and are typically clear with rain-caused turbidity quickly disappearing.

The watershed network can be partitioned into two systems, headwater and network systems, on the basis of process characteristics (Gomi *et al.* 2003). Headwater systems contain four topographic units with distinctive biological and hydrological processes: 1) hill slopes; 2) zero-order basins; 3) ephemeral or temporal channels emerging from zero-order basins, termed transitional channels; and 4) first and second-order stream channels depending on linkages from hill slopes to channels. Hill slopes have either divergent or straight contour lines, typically with no channelized flow. A zero-order basin is defined as an unchannelized hollow with convergent contour lines. Although saturated overland flow may be observed in zero-order basins and at the foot of hill slopes

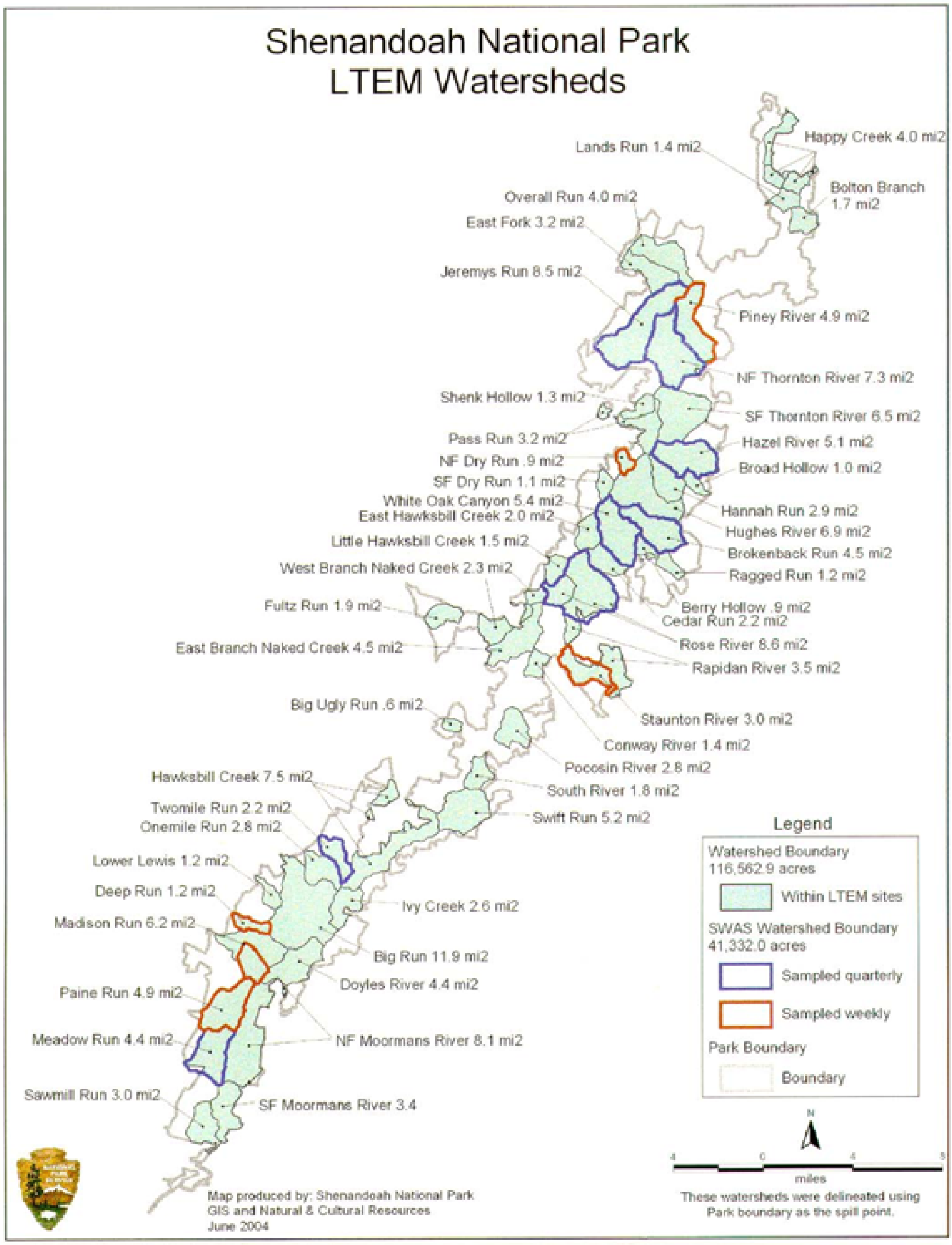


Figure 10. Delineation and site of watersheds sampled by the Shenandoah National Park LTEM program.

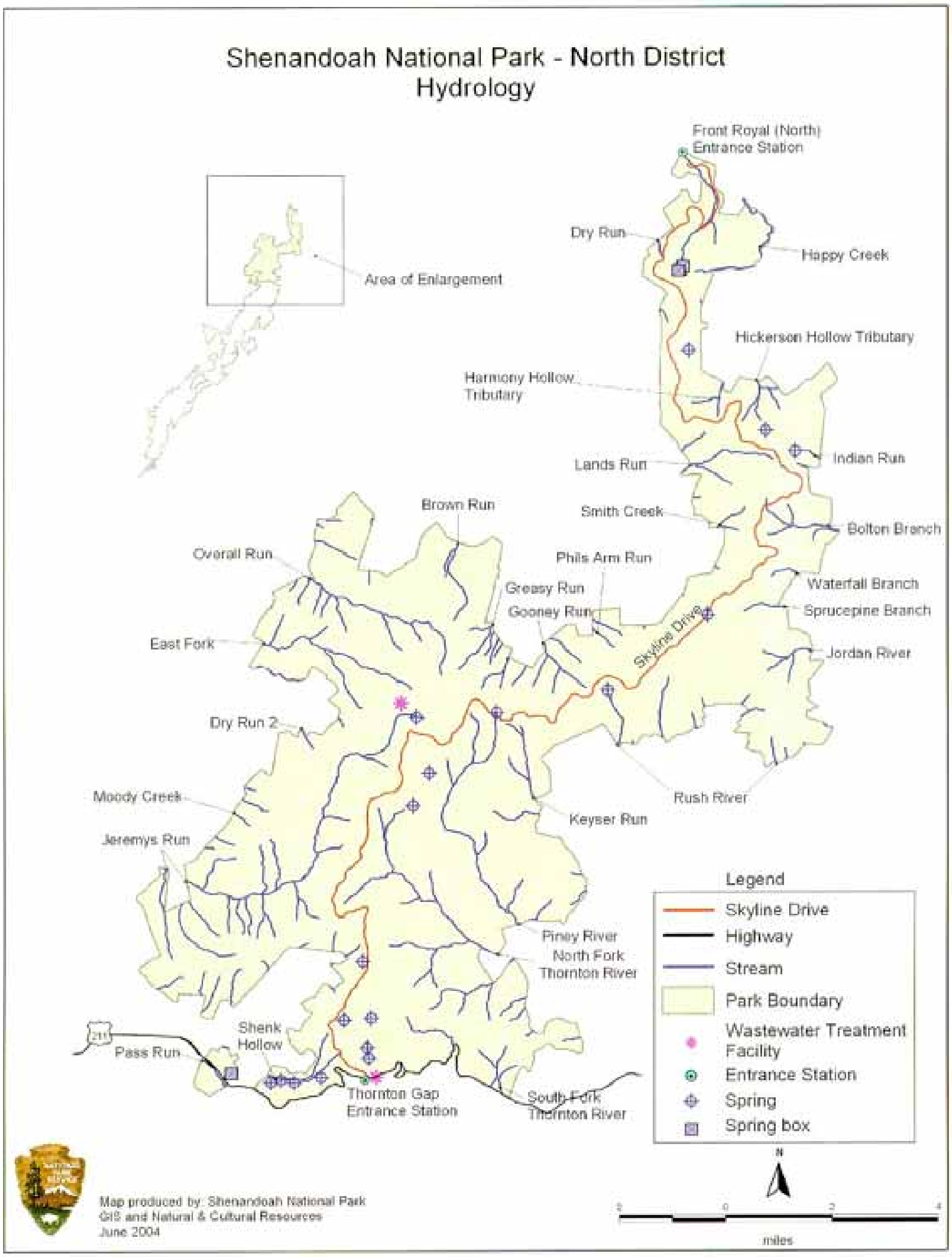


Figure 11a. Hydrology of Shenandoah National Park, North District.

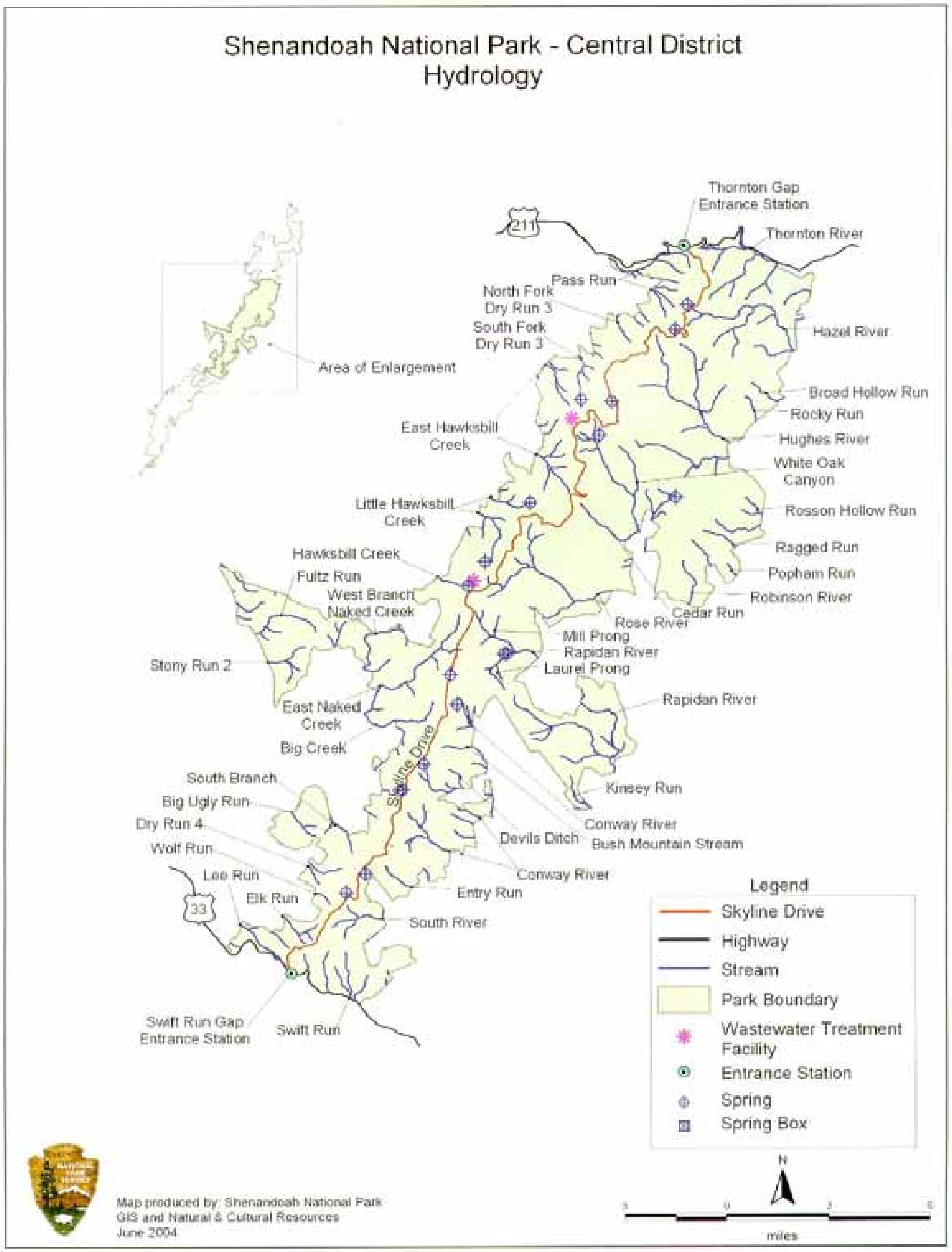


Figure 11b. Hydrology of Shenandoah National Park, Central District.

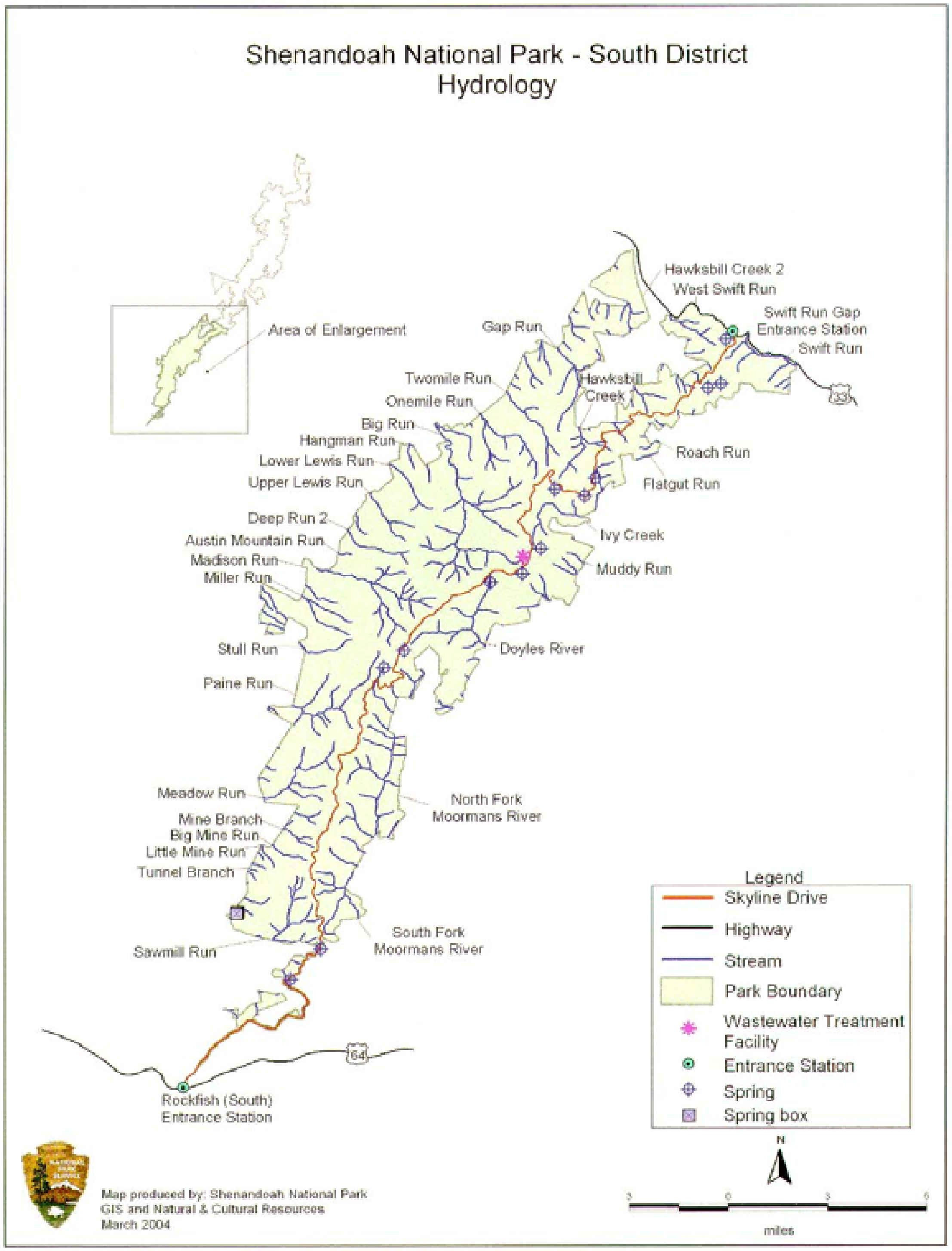


Figure 11c. Hydrology of Shenandoah National Park, South District.

during storms, biological activity in such hill slopes and zero-order basins is terrestrial.

Channels with defined banks may emanate from zero-order basins; if channels exist at the outlet of these basins they represent the headmost definable channels with temporary or ephemeral flows. Temporary channels have more or less continuous flow at least 4 or 5 months in an average year, whereas ephemeral channels flow only for several days during wet periods. Thus, temporary and ephemeral channels emanating from zero-order basins typically do not support the complete life cycles of aquatic macroinvertebrates. However, such channels are integral parts of channel networks and have distinct roles (e.g. temporary storage of organic matter).

First-order basins are the uppermost, unbranched channels with either permanent or sustained intermittent flow (more than 4 to 5 months in an average year). First-order channels may originate from the outlet of zero-order basins as springs and seeps. Second-order (one branch) or even higher order streams may be considered headwater streams, depending on the degree of coupling between hill slopes and channels. Both first and second-order channels may have intermittent reaches, depending on ground water level and the volume of sediment deposited by flowing water.

Different magnitudes and frequencies of hydrologic processes occur in headwaters and network systems. Geomorphic processes in headwaters are largely random, whereas more chronic processes related to routing of sediment, water, and wood are common in channel network systems. Such different hydrogeomorphic processes between headwater and network systems also modify biological community structure and distribution as well as recovery processes of stream biota from disturbances. Table 5 summarizes the hydrologic, geomorphic and biological processes in headwater and network systems.

The nature and degree of linkages between headwater and downstream systems are important aspects of the roles of headwater streams and routing processes of organic and inorganic matter. The degree of linkage varies spatially and temporally because of topography and mass movements. Beaver ponds, wetlands and intermittent channel reaches alter the connectivity between headwater and downstream systems. Additionally, temporal variation related to wind throw, mass movement, wildfire and land use change, as well as their respective recovery processes affect the degree of connection between headwater and downstream systems. Connectivity is important biologically for species migration, habitat, and refugia and for the flux of organic matter and nutrients.

Table 5. Characteristics of hydrologic, geomorphic, and biological processes in headwater and network systems. Modified from Gomi *et al.* (2003).

Process	Characteristic	Headwater system	Network system
Hydrology	Precipitation	Greater precipitation Greater snow accumulation	Lower snow accumulation
	Heat dynamics	Canopy closure Dependent on ground water flow	Canopy open
	Flow generation	Subsurface and ground water flow in zero-order basins and hillslopes	Saturated overland and return flows in flood plain, riparian zones tributary outflows
	Flow regime	Smaller absolute discharge volume Greater variation of unit-area peak discharge	Larger absolute discharge volume Smaller variation of unit-area peak discharge Synchronized or desynchronized outflows
	Hyporheic zone	Smaller volume	Greater lateral and vertical volume
	Stream chemistry	Soil pores, bedrock fractures, lithology Flow path in hillslopes and zero-order basin	Tributary outflows, hyporheic exchange
Geomorphology	Morphology	Higher mean altitude Steeper gradient and confined valley	Lower mean altitude Lower gradient and wider valley
	Dominant sediment movement	Episodic mass movement	Chronic bedload movement
	Channel reach type	Colluvial, cascade, step pool, bedrock	Step pool, pool riffle, ripple dune
	Roughness element	Woody debris, boulder, bed form (e.g., step)	Woody debris, log iams, bed form (e.g., bar)
Biology	Energy input	Allochthonous and lateral (from hillslope) input	Autochthonous and tributary outflows
	Organic matter	CPOM > FPOM DOC from ground water flows and leaching	CPOM < FPOM DOC from tributaries and in-stream processing
	Nutrient source	Ground water, riparian vegetation	Tributary outflows, floodplain
	Dominant functional group	Shredder	Gatherer, filterer
	Disturbance	Landslides and debris flows	Flood pulses and bedload movement

DOC, dissolved organic carbon; CPOM, course particulate organic matter; FPOM, fine particulate organic matter

Surface Water

Stream flow characteristics of SHEN streams, such as peak and low flows and rainfall to runoff ratio, are largely affected by precipitation patterns (Lynch 1987). For the latter, there is a complex relationship that is dependent on several factors including: ground water levels and soil moisture at the beginning of the year, annual precipitation amount, seasonal distribution of precipitation, form of precipitation, length of time between storm events, and intensity of individual storms. Runoff estimates were made for 49 sites in SHEN from July 1981 to July 1982 (Geber *et al.* 1988). Runoff was measured as inches in depth over a watershed basin. These estimates ranged from 10.9 inches to 39.7 inches. Higher runoff values occurred in the central section of SHEN and on the eastern side of the Blue Ridge. The lower values occurred in the southern part of the park and on the western side of the Blue Ridge. Gerbert *et al.* (1988) found only a general relationship between elevation and runoff.

Peak stream flows occur during the spring when soils are saturated, causing rainfall produced by advancing cold fronts to run off readily (Lynch 1987; Figure 12). Although soils are drier in the summer, runoff from intense thunderstorms may produce annual peak stream flow for small drainage basins. Low flows occur during June through September (Figure 12). Evapotranspiration reduces the amount of precipitation reaching the water table during these months. Consequently, ground water discharge to streams decreases through the summer because ground water is taken up by deep rooting plants.

Lynch (1987) determined the low-flow values for 11 long-term and 29 partial-record stream flow gaging stations in and around SHEN. For streams draining either crystalline or sedimentary rocks, 7Q2 low-flow values (2-year recurrence interval of the lowest average discharge for 7 consecutive days) increase as drainage areas increase (Figure 13). Also, for a given drainage area, 7Q2 low-flow values for streams draining crystalline rocks are about four times greater than low-flow values for streams draining sedimentary rocks (Figure 13). The average unit low-flow value was 0.13 to 0.032 $(ft^3/s)/mi^2$ for streams that drain crystalline and sedimentary rocks, respectively.

Variation in low-flow values is largely the result of differences in drainage basin characteristics (Lynch 1987), such as drainage area, geologic and topographic setting, regolith thickness, local climate and vegetative cover. Because vegetative cover was (circa 1980s) somewhat uniform in the park and the climatic conditions of individual basins do not vary greatly, these are of secondary importance in explaining differences in low flows. As seen in Figure 13, drainage basin size and underlying geology explain much of the observed low-flow variability.

Depth and permeability of the regolith, slope of the land surface and extent of bedrock fracturing all affect the quantity of water a basin yields during dry periods (Lynch 1987). These features, which are strongly controlled by bedrock geology, differ in SHEN. Where crystalline rocks are gently inclined, drainage areas have a thick regolith. These areas store large quantities of ground water that sustain stream flow during dry periods. Most drainage basins in crystalline rock of 1 mi^2 or more contain large areas of thick regolith.

Drainage basins that developed in sedimentary rocks in the park have relatively steep slopes and generally contain thin to nonexistent regolith (Lynch 1987). The poor development of regolith is a result of the steep slopes and the extreme resistance of bedrock to weathering. As a result, little ground water infiltrates and storage is low, accounting for the relatively low unit 7Q2 low flow values for streams draining sedimentary rocks.

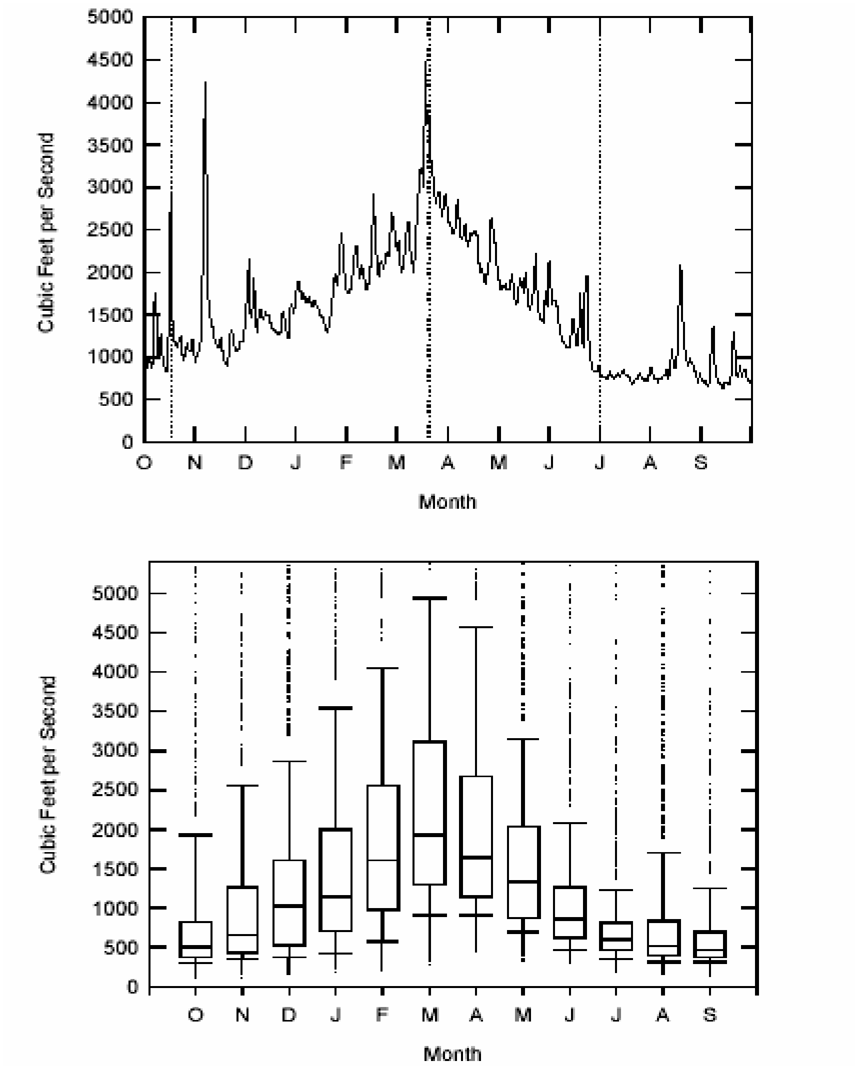


Figure 12. Representative mean annual hydrograph (top) and distribution of daily flows by month (bottom). Data are from the South Fork of the Shenandoah River at Front Royal, VA. Box and whiskers represent a five summary statistics ; bottom whisker cap is 10th percentile, bottom of box is 25th percentile, internal line is median, top of box is 75th percentile, and top whisker is 90th percentile. After NPS (2000).

Lynch (1987) conducted gain and loss discharge surveys (during base flow periods for stations from headwaters to park boundaries) for the following park streams: North Fork Moormans River, Brokenback Run, Staunton River, Paine Run and Jeremys Run. All of these streams are underlain by different geologic formations.

The North Fork Moormans River had unit flows that ranged from 0.12 to 0.17 cfs/mi^2 indicating that this stream gains water throughout its course and in quantities that are proportional to the drainage area.

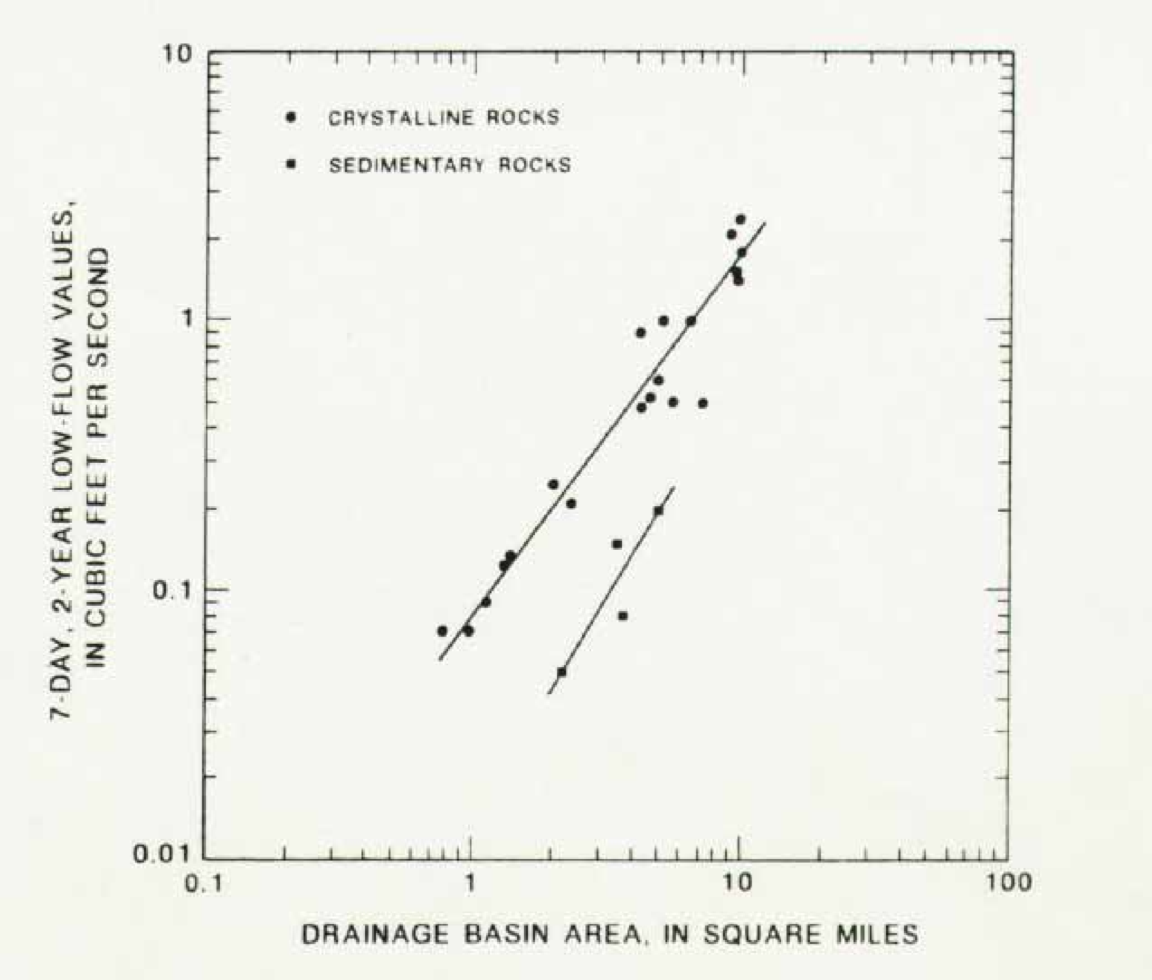


Figure 13. Relationship of low flow values for stream flow stations in and around SHEN with underlying bedrock type. After Lynch (1987).

Brokenback Run and Staunton River likewise gain water throughout their courses; however, a disproportionately large share of water comes from the headwaters. At the time of the survey, 81% of the discharge in the Staunton River came from the upper 48% of the drainage. Similarly, 47% of the discharge at Brokenback Run came from the upper 29% of the drainage. The headwater areas of these streams are characterized by gentler slopes and a thick regolith than areas farther downstream, thus providing more ground water storage for sustaining flows during dry periods. Greater unit base flows at higher elevations may be fairly common for streams draining crystalline rocks in SHEN.

Paine Run, on the other hand, had a unit discharge that was less in the upper basin than at the park boundary. Paine Run is typical of basins underlain by sedimentary rocks, where the headwater area is generally steeper than areas farther down slope, and the stream channel changes from very steep and well confined in the headwaters to a gently sloping channel coursing through valley fill in the lower reaches. In this case the steep headwater areas and associated thin regolith may not store and discharge ground water during dry periods as readily as the lower areas in the basin.

A comparison of annual discharge hydrographs (mean daily discharge) for Staunton River and Paine Run from 1992-95 supports these conclusions (Figure 14; Bulger *et al.* 1999). The 3-year discharge record for Paine Run shows it to be the flashier of the two watersheds. Conversely, base flow in Paine Run during mid to late summer was much lower than the Staunton River, indicating that Paine Run has a higher storm flow:base flow ratio than the Staunton River.

Jeremys Run represents a special hydrologic case – above 1700 feet it responded similar to Brokenback Run, but the unit flows in the lower reaches did not stabilize but continued to decline downstream reaching zero discharge at 1180 feet. During base-flow periods, most water leaving the basin moves through extensive valley fill at lower elevations. Although stream flow reappears below 1180 feet, the low unit flow suggested that the majority of the water leaving the basin was not detected.

Lynch (1987) concluded that this gain and loss study shows that significant amounts of water leaving the basins can move through alluvial deposits and valley infill areas and never be detected by measures of surface runoff. Subsurface flow through transmissive deposits may account for much of the variation in low-flow characteristics not accounted for by drainage basin size and underlying rock types.

Schupple (1983) described the geomorphology of 66 second-order drainage basins in SHEN. He looked at nine morphologic properties, such as basin area, lengths of first and second order streams, mean basin slope and mean valley side slope. There were no distinctive overall patterns in the distribution of morphometric values of drainage basins in SHEN. This lack of pattern or large-scale groupings along the north-south axis of SHEN lends support to the exclusion of latitude and large-scale climatic differences as major physical controls of basin morphology. Of the physical controls analyzed, those most directly related to the spatial patterns of basin morphometry seem to be geologic structural elements including their effect on bedrock exposure, and regionally controlled stream base level constraints.

Ground Water

Water from springs and wells are the sole source of public and staff supply for SHEN (Plummer *et al.* 2000). Many SHEN reports cite that 850 springs and seeps have been identified throughout SHEN. This number originated from DeKay (1972), which states, "…in December 1959 an inventory was made of 854

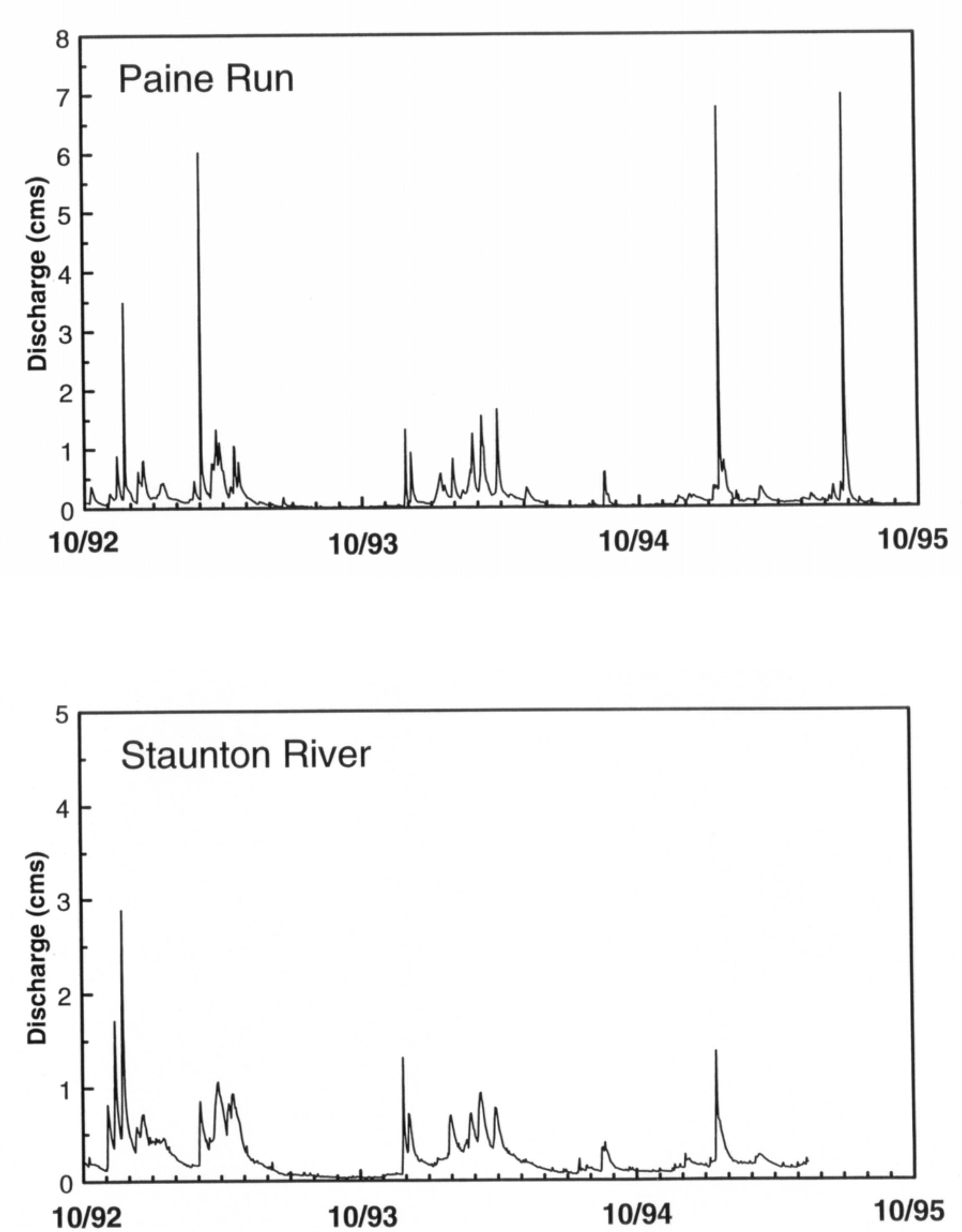


Figure 14. Three-year (1992-95) hydrograph for Paine River (top) and Staunton River (bottom). After Bulger *et al.* (1999).

known surface-water sources (personal communications, C.S. Dodge, F.V. Vest, and C.R. Montgomery 1959)”. It is unclear in the report if this number for “surface-water sources” represents just springs or both springs and creeks. We were unable to locate in park files any written documentation about that 1959 inventory.

Most of the springs in SHEN occur at elevations significantly below Park facilities, limiting their usefulness as water supplies (DeKay 1972). Little is known about these springs and seeps throughout the park, and research to date has concentrated only on ground water quality and residence times of developed springs along Skyline Drive, which includes approximately 70 springs. The important factors controlling spring flow in the park are 1) season of the year; 2) climate; and 3) characteristics of the spring's recharge area, which includes its size, regolith thickness, topography, and geology. Spring flows are typically at a minimum in late summer or early fall, which corresponds to the end of high evapotranspiration rates and low ground water recharge. Spring flows generally reach a maximum in spring, which corresponds to the end of a period of low evapotranspiration rates and ground water recharge (Lynch 1987).

In the Blue Ridge province, a thin layer of soil and weathered rock lies above the bedrock, a relatively impervious zone containing water primarily in joints, fractures, and faults. The steep terrain and thin soil covering result in rapid surface run-off and low ground water recharge (Virginia Department of Environmental Quality 2003). As a result, well yields are generally limited.

In SHEN, ground water can occur in 1) an unsaturated zone, 2) a capillary fringe, or 3) a saturated zone. The unsaturated zone lies directly beneath the land surface and is generally made up of highly weathered to partially weathered material. An unsaturated zone may be absent in SHEN beneath wetlands, streams, and areas where unfractured bedrock is exposed at the land surface (Lynch 1987). The capillary fringe is the transition zone between the unsaturated zone and the saturated zone and contains water that has moved through porous material by capillary action. The thickness of the fringe varies considerably in the Park. The valley infill areas containing boulders, gravels, and coarse sands, have a thin capillary fringe. In contrast, capillary fringe in fine-grained material (e.g., Big Meadows) may be several feet thick (Lynch 1987). Beneath the capillary fringe lies the saturated zone. In this zone water occupies all pores and voids. The imaginary surface between the capillary fringe and the saturated zone is termed the water table. The depth below land surface to the water table tends to be greatest under ridges and least under valleys. At streams and springs the water table coincides with the land surface. At Big Meadows, where the land surface is flat, the saturated zone reaches the land surface, resulting in a large wetland perched on the Blue Ridge Mountains at 3,500 feet (msl) (Lynch 1987).

Physical characteristics of the saturated zone in SHEN differ widely. Water in the regolith and fractures is captured by supply wells and sustains flow in springs and streams during periods of low precipitation. Basins in sedimentary rocks generally have a thin (<10 feet) regolith underlain by a poorly fractured, steeply inclined bedrock, which provides little ground water storage for sustaining flows during dry periods (Lynch 1987). Some of the springs that do exist in sedimentary terrain have high discharge rates during periods of precipitation, but these flows tend to decrease rapidly during times of subnormal rainfall (DeKay 1972). In contrast, basins composed of crystalline rocks contain larger quantities of ground water for sustaining flows during dry periods because regoliths are typically thicker (10 - 60 feet) and underlying bedrock tends to be more fractured and gently inclined (Lynch 1987).

In the southern and northern sections of the park, particularly in the southern section, springs are sparse. Only 18 springs in these sections have had flows measured in excess of 10 gpm (DeKay 1972). The greatest number, as well as the highest yielding and most reliable springs, are in the central section of the park where 47 springs with flows greater than 100 gpm have been identified (Lynch 1987).

Most water-bearing fractures of hydrologic significance in the park exist in the upper 300 feet of bedrock (DeKay 1972). Fractures deeper than 300 feet are sparse and tightly closed because of pressure from the overlying rocks. Shallow water-bearing fractures are not necessarily interconnected throughout SHEN. Thus, the park's ground-water system is described by Lynch (1987) as a group of isolated ground-water systems, each made up of hydraulically connected fractures and overlying regolith, and each dependent on local precipitation for its source of recharge water. Where fractures are not interconnected, the water table is not necessarily continuous or smooth but tends to be discontinuous or step like. Consequently, two wells can be in close proximity but have drastically different water levels. From 1961-1971 the Virginia Division of Mineral Resources drilled 33 borings along the mountain crest in SHEN to evaluate potential ground water sources. Twenty of these 33 borings appeared favorable for producing ground water well yields exceeding summer flows of developed springs in the area (DeKay 1972).

There has been little residential or industrial development in the Blue Ridge itself, so ground water use has been mainly for domestic needs rather than for public wells. Lynch (1987) assessed ground water withdrawals between the 1960's and 1980's and, excluding Big Meadows, found no indication of long-term effect on ground water resources in SHEN. The lower slopes of the mountains are the most favorable areas for ground water accumulation. Springs are common and often used for private water supplies (Virginia Department of Environmental Quality 2003). Big Meadows, Skyland, and Lewis Mountain campgrounds were each located near a reliable spring.

Bedrock in the Big Meadows area consists of metamorphosed basalt flows of the Catoctin Formation. The ground water system in the area consists of highly weathered bedrock (regolith approximately 70 feet thick) with primary permeability (flow between grains and pebbles), which is underlain by fractured bedrock with secondary permeability (flow through fractures and openings) (Lynch 1987). The regolith acts as a large reservoir for infiltration of precipitation and provides a pathway to fractures in the underlying bedrock. A water supply well (BM-3) used in the area for several years was found to have an adverse affect on the hydroperiod of the adjacent wetland (Martin 2002). A 1983-84 USGS ground water study of ground water pumping in the Big Meadows area found declines in the water table that began earlier in the year and were larger than would occur naturally (Lynch 1987). The effects of ground water pumping were small in December through April when demand was low and precipitation was frequent. As a result of the ground water impacts, the well (BM-3) was discontinued in the mid-1980s and used only as a backup and supplemental supply until 1992 when it was closed to all uses. Additional test drilling in 1989 resulted in successfully developing three wells (BM-9, BM-14, and BM-16). The wells are located about one mile southeast of Byrd Visitor Center and west of Stony Mountain. Currently BM-14 is used as a supplemental/backup water source when flow from Lewis Spring is insufficient to meet demand in late summer. Wells BM-9 and BM-14 could be used, if needed (Martin 2002).

Potable water for the Big Meadows area is now obtained from Lewis Spring, which flows approximately 200 gpm in the winter months, decreasing to 50 gpm in the later summer (Lynch 1987). Water is collected in buried perforated pipe from Lewis Spring and transmitted to several underground vaults before it is transmitted to the pump house where it is collected in a 5000-gallon clear well. Water is pumped from the clear well to underground storage reservoirs at the top of the hill at Blackrock, near Big Meadows Lodge. There are three underground reservoirs, two 50,000-gallon reservoirs and one 100,000-gallon reservoir. Several water lines distribute water to the Visitor Center, a wayside, housing area, maintenance area, Big Meadows Lodge and a campground (Martin 2002).

Ground water from Lewis Spring and wells in Big Meadows has been age dated by the U.S. Geological Survey (Plummer *et al.* 2000). The average age of ground water discharging to springs or wells is 6 to 7 years. The relatively young age of ground water is indicative of fast ground water travel times and therefore high susceptibility to contamination from accidental spills or releases in the recharge area of the aquifer (Martin 2002). Since there was insufficient data to construct a water table contour map for the Big Meadows area, Martin (2002) provided a conservative recharge area delineation for Lewis Spring based on topographic elevation (Figure 15). Most of the potential contaminant sources are in the northern half of the recharge areas where there is a maintenance yard, campground, ranger stations, visitor center and gas station. The other potential contaminant source is the abandoned dump and ‘bone’ yard, located about one mile southeast of Lewis Spring, near Wells BM-9, BM-14, and BM-16.

Lynch (1987) studied the ground water conditions and trends (1983-84) in SHEN to provide basic data for research and to address specific water management questions. The study primarily focused on 1) the amount and variability of precipitation, surface water, and ground water in the park, and 2) short- and long-term effects of ground water withdrawals and droughts on water resources.

Plummer *et al.* (2001) monitored chemical and isotopic properties of water discharging from springs and wells in SHEN to obtain information on ground water residence times. Investigated time scales included seasonal (wet season,

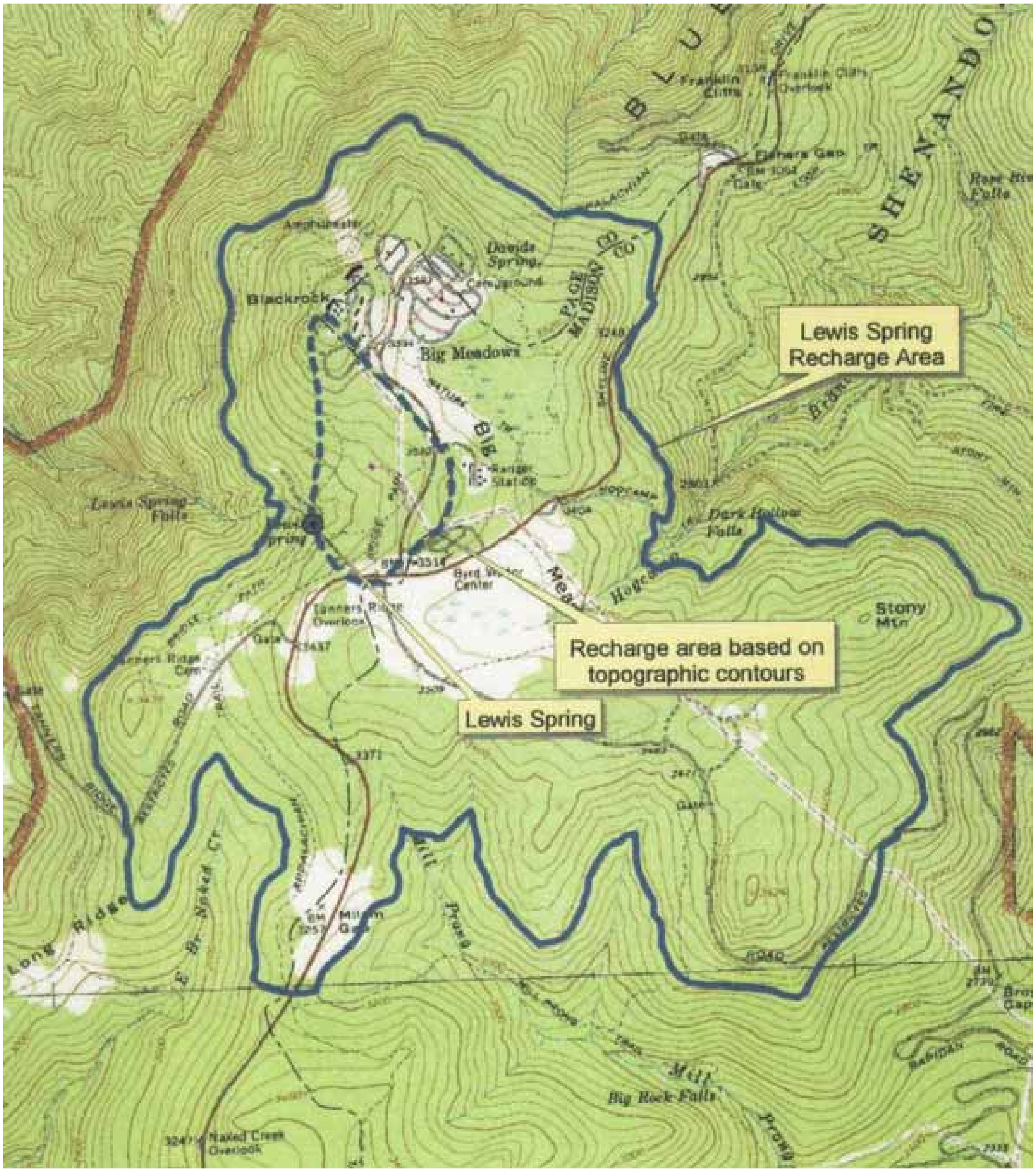


Figure 15. Delineation of area that might contribute to recharge to the flow from Lewis Spring. After Martin (2002). There are insufficient data to construct a water table contour map for the Big Meadows area. Two alternative delineations of the recharge area for Lewis Spring are shown. The smaller area (dashed line) is based on topographic contours, delineating the recharge areas of the spring as if it were a watershed. This is not a very plausible delineation as there is no basis for assuming that the groundwater divides coincide with surface water divides. The second method used to delineate the recharge area (solid line) is more conservative, overestimating the recharge area, and is based on the premise that all areas at the higher topographic elevation than the spring outlet could conceivably contribute water to the spring. For this delineation, the 3200 feet (msl) contour line was followed around the Big Meadows areas to Milam Gap on the south. There are some areas within the delineation where groundwater flows away from Lewis Spring, such as Davids Spring to the north or Hogcamp Branch to the northeast. However, delineating the area above 3200 feet msl insures that the entire recharge areas for Lewis Spring is included (Martin 2002).

Apr 1996; dry season, Aug-Sep, 1997), monthly (Mar-Sep 1999) and hourly (30-min interval, Mar 1999 – Feb 2000). Multiple environmental tracers were used to estimate the residence times of shallow ground water discharging from 35 springs and 15 wells. The ground water residence times indicate that flushing rates of mobile atmospheric constituents through ground water to streams draining the higher elevations in SHEN average less than three years in base-flow conditions.

South of SHEN, in Floyd County, Seaton (2002) found a different framework for ground water flow in the Blue Ridge Mountains. Using geophysical techniques, the shallow regolith was found to contain unsaturated areas and also localized sand and clay prone facies with water table and confined aquifer conditions residing locally. Hydraulic heads between the shallow aquifer and deeper fractured bedrock aquifer were found to vary by as much as 20 meters. Aquifer testing of the bedrock aquifer produced rapid and relatively uniform drawdowns in surrounding wells completed in the fractured bedrock aquifers. The shallow aquifers experienced minimal drawdowns indicating limited communication between the shallow and deeper bedrock aquifers. Water chemistry and age dating analyses indicated significant differences between water samples from deep and shallow aquifers. A new conceptual model for Blue Ridge aquifers was proposed based on these findings.

Through understanding the aquifer properties of the regolith and by locating the recharge areas and flow pathways within crystalline rocks, reasonable conclusions can be drawn about ground water movement in the Blue Ridge Province for water supply, contaminant transport, and watershed/wellhead protection studies (Seaton 2000).

Water Quality

Surface Water

Surface water quality information for SHEN was summarized from data retrieved from six of the U.S. Environmental Protection Agency's national databases: Storage and Retrieval (STORET) water quality database management system; River Reach File (RF3); Industrial Facilities Discharge (IFD); Drinking Water Supplies (DRINKS); Water Gages (GAGES); and Water Impoundments (DAMS) (National Park Service 2000b). The study area includes SHEN and all areas within at least 1 mile downstream of the park boundary.

The results of the retrievals for the study area from the IFD, DRINKS, GAGES, and DAMS databases located 33 industrial/municipal dischargers; ten drinking water intakes; 44 active or inactive U. S. Geological Survey (USGS) and U. S. National Weather Service water gages (including stream, well, and climate); and 22 water impoundments. As might be expected for a mountainous, top-of-the-watershed park such as SHEN there are no industrial/municipal dischargers, drinking water intakes, or water impoundments in SHEN. There are records for 13 water gages in SHEN.

Results of the STORET retrieval for the study area yielded 234,269 observations for 554 separate parameters collected by several federal agencies and the Virginia Department of Environmental Quality at 786 monitoring stations from 1930 through 1998. Most of the monitoring stations represent either one-time or intensive single-year sampling efforts by the collecting agencies. Of the 786 monitoring stations, 501 stations (representing 95,214 observations of 89 parameters) were located within the park boundary. Ninety-four percent (472) of these stations represent NPS stations from 1977-1998. Of the remaining 29 stations, seven stations represent one-time sampling by either the state in 1975 or the U.S. EPA in 1986. The U.S. Geological Survey collected water quality information from 22 stations from 1968-1992. Approximately 96 percent of the observations entered by the NPS for SHEN were collected as part of the University of Virginia's Shenandoah Watershed Study (< www.swas.evsc.virginia.edu >) from 1979 to 1998. One-hundred-ninety-one stations within the study area (134 within the park boundary) yielded longer-term records consisting of multiple observations for several water quality parameters. The stations yielding the longest-term records within the park boundary are: (a) Whiteoak Run (SHEN 0185); (b) Madison Run (SHEN 0189); (c) Paine Run (SHEN 0126); (d) Staunton River (SHEN 0333); (e) Piney River (SHEN 0620); and (f) Meadow Run (SHEN 0055). The stations yielding the longest-term records within the study area, but outside of the park boundary, are: (a) South Fork Shenandoah River at Front Royal (SHEN 0756); (b) Hawksbill Creek at the State Route 648 Bridge below Luray (SHEN 0635); (c) South River at the State Route 778 Bridge at Harriston (SHEN 0162); (d) North Fork Shenandoah River approximately 0.1 mile below the U. S. Route 340/522 Bridge (SHEN 0777); and (e) South Fork Shenandoah River near the State Route 619 Bridge at USGS gaging station (SHEN 0755).

A thorough interpretation of the water quality data summary for SHEN by the NPS (2000b) is beyond the scope of this document – it is also unnecessary. The vast majority of recent water quality information for SHEN has been analyzed and summarized by various reports and publications (e.g. Sullivan *et al.* 2003; Bulger *et al.* 1999). Therefore, for the purposes of this document, the following section provides a chronological history of water quality studies followed by a summary of their important findings.

Chronology of Water Quality Studies and Events That Affect Water Quality

1979 The Shenandoah Watershed Study (SWAS), a cooperative program of the National Park Service and the Department of Environmental Sciences at the University of Virginia, began with the establishment of water quality monitoring on two streams, White Oak Run and Deep Run. Stream water quality, discharge, and atmospheric deposition data are available on a weekly basis for these sites in SHEN for the 24-year period from 1979 to the present (the longest continuous record of stream water quality data in a national park unit). SWAS was established to understand the processes that determine biogeochemical conditions in the forested, mountain watersheds of SHEN and their responses to anthropogenic perturbations. This program documented the acid-sensitive nature of SHEN streams in the late 1970s (Hendrey *et al.* 1980). In particular, Ryan *et al.* (1989) observed decreasing trends in stream water pH and ANC consistent with acidification for these streams from 1980-87. Investigations conducted in SHEN under the SWAS program have included synoptic stream water sampling surveys, intensive watershed monitoring, and process-oriented research.

Currently data collection involves 14 primary study watersheds (Figure 16), including a combination of discharge gaging, routine quarterly (eight watersheds) and weekly (six watersheds) sampling, and high-frequency episodic, or storm flow sampling (Table 6; Galloway *et al.* 1999). Besides the 24-year continuous monitoring record for White Oak Run and Deep Run, three watersheds have weekly stream water and wet deposition data available for at least 11 years and six watersheds have weekly data available for a 6 year-period.

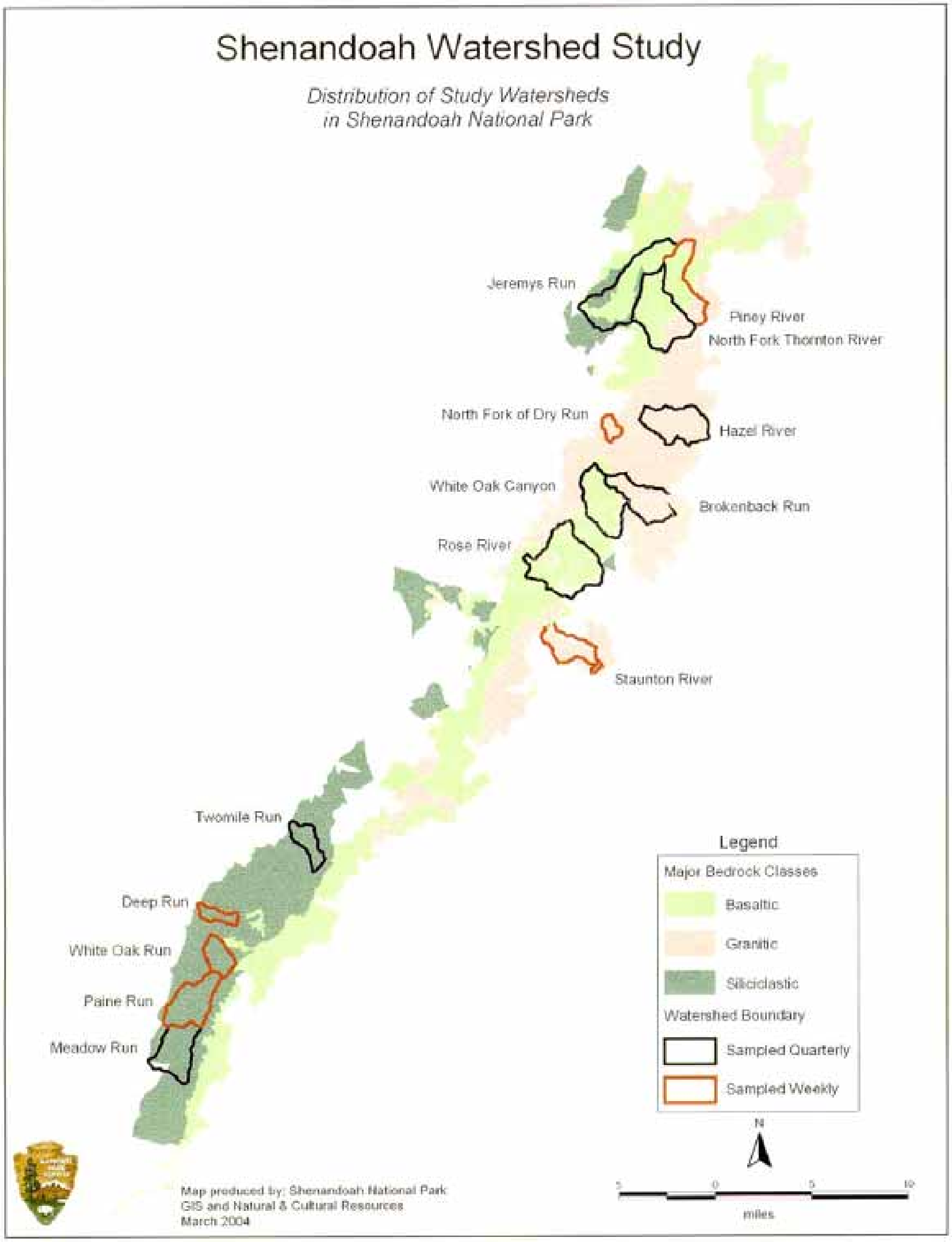
1983 Lynch and Dise (1985) completed the first parkwide water resource investigation – a synoptic stream-water survey covering 56 streams sampled six times over a 2-year (1981-82) period. As mentioned previously, Lynch and Dise noted a strong association between bedrock type and stream ANC.

1985 The Model of Acidification of Ground water in Catchments (MAGIC), a process-based model of watershed acidification, was developed and calibrated using soil and water quality data from the White Oak Run watershed in SHEN (Cosby *et al.* 1985a and b)

1986 The first significant gypsy moth defoliation occurred in SHEN. The southward progression of the moth infestation completely traversed the SHEN area and affected all of the SWAS watersheds by 1991 (Figure 17).

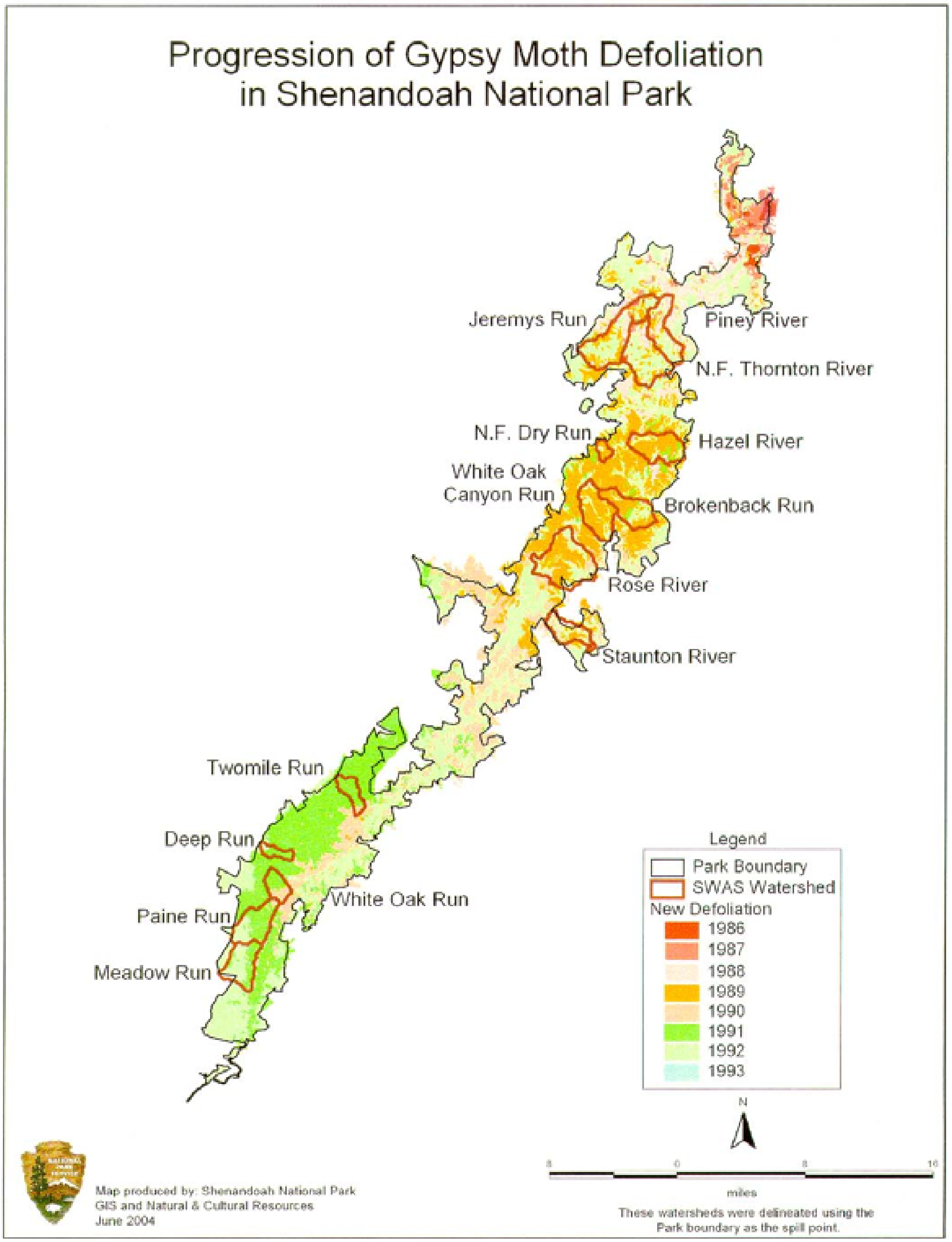
1987 The Virginia Trout Stream Sensitivity Survey (VTSSS), a cooperative venture of the U. of Virginia and a number of federal and state gencies, was established to obtain information on the acid-base status of mountain-headwater streams in western Virginia that support native brook trout. Initially, stream water quality was assessed in 344 of the state's identified native brook trout streams, including 52 sites in SHEN. This study also noted a strong correlation between geology and the ANC of streams (Webb *et al.* 1994). Much like SWAS program, these streams were stratified by geology -- 55 streams (nine in SHEN) are currently sampled on a quarterly basis.

1992 The Fish in Sensitive Habitats project (Bulger *et al.* 1999) began with the primary goals of 1) assessing the potential impact of acidification on fish populations in SHEN and 2) predicting future effects based on the observed relationships between water quality and fish responses at the individual, population and community levels (Bulger *et al.* 1995).



Map produced by: Shenandoah National Park
GIS and Natural & Cultural Resources
March 2004

Figure 16. Distribution of study watersheds for Shenandoah Watershed Study (SWAS).



Progression of Gypsy Moth Defoliation in Shenandoah National Park

Map produced by: Shenandoah National Park
GIS and Natural & Cultural Resources
June 2004

These watersheds were delineated using the Park boundary as the spill point.

Figure 17. Yearly progression of gypsy moth defoliation in Shenandoah National Park.

Table 6. Distribution of watershed data collection by bedrock geology and stream-water acid neutralization capacity (after Webb, No Date).

	Siliciclastic	**Granitic**	**Basaltic**
acid neutralization capacity	< 25 μeq/L	25 – 75 μeq/L	> 75 μeq/L
weekly stream-water sampling and analysis[1]	White Oak Run Deep Run Paine Run	NF Dry Run Staunton River	Piney River
quarterly stream-water sampling and analysis[1]	Two Mile Run Meadow Run	Hazel River Brokenback Run	Jeremys Run Rose River White Oak Canyon Run NF Thornton River
high-flow episode sampling and analysis[2]	Paine Run	Staunton River	Piney River
continuous stream-water discharge measurement	White Oak Run Paine Run	NF Dry Run Staunton River	Piney River
precipitation sampling and analysis[3]	White Oak Run	NF Dry Run	

[1] Weekly stream-water analyses include: pH, alkalinity, conductivity, calcium, magnesium, potassium, sodium, sulfate, chloride, nitrate, and silica. Quarterly stream-water analysis also includes total and organic monomeric aluminum and seston. Episode sampling includes dissolved organic carbon. [2] Episode sampling and analysis in SNP is funded through the TIME project. [3] Precipitation analyses include ammonium and all stream-water analytes except silica, aluminum fractions, dissolved organic carbon, and seston.

For this project three quarterly sites (Paine Run, Staunton River, Piney River) were upgraded to include weekly sample collection, continuous discharge, complete habitat surveys and multiple fish community surveys, high-frequency sampling during high runoff events and *in situ* bioassay studies to assess chronic and episodic lethal and sublethal effects on fish. To understand spatial variation, 232 sites were sampled in the spring of 1992 in watersheds associated with 11 SWAS quarterly sampling sites.

1993 A 3-year project on episodic acidification of three, geologically representative streams in SHEN began in this year. Episodic acidification is usually defined as the transient loss of ANC and associated depressions in pH and increases in toxic forms of dissolved aluminum in surface waters associated with rainfall and snowmelt events. Because it is primarily hydrologically controlled, it appears to be a ubiquitous process (Wigington *et al.* 1990). Episodic acidification during major hydrological events was shown to occur in SHEN. The observed patterns in ANC and major ions were similar to those noted in a large number of other studies from the Northeast.

2000 A comprehensive assessment of air quality and related values in SHEN was initiated (Sullivan *et al.* 2003). This important document provides an excellent synthesis of over 20 years of research and monitoring of acidification and its effects in SHEN streams.

2001 A study was initiated that modeled how subsurface storm flow contributes to episodic stream acidification events (Rice *et al.* 1999; Rice *et al.* in press). Subsurface flow is often a significant contributor to storm runoff in forested watersheds like SHEN that are underlain by thin permeable soils above less-permeable bedrock). The model is TOPMODEL, a water-balance model that simulates the relation between rainfall and storm flow.

Rice *et al.* (2001) proposed the development of a park-wide vulnerability map that predicts the frequency, duration and intensity of episodic acidification in SHEN streams. This study is an extension of Rice *et al.* (1999) in that the hydrologic water-balance model, TOPMODEL, will be applied to the entire park.

In 2001, the park cooperators approached the Virginia Department of Environmental Quality to request that those SHEN streams that have pH values consistently below the state water quality standard of 6.0 be listed as impaired and placed on the 303(d) list. Such a request stems from the Prevention of Significant Deterioration program of the Clean Air Act. However, under the current Shenandoah Watershed Study (SWAS) monitoring program, water samples are transported to the laboratory for pH analysis. This does not comply with criteria for data use established in 40 CFR 136 and adopted formally by the State as the preferred method for determining water quality impairment. That is, the measurement of pH in water bodies must be determined *in situ*. Therefore, no SHEN streams were 303(d)-listed in 2002. Given that the sampling window for the 2004 303(d) list closed on December 31, 2002, future samples cannot lead to a change in listing until 2006. In the meantime, Galloway and Webb (2003) were successful in obtaining funding for a 1 year-project that will obtain monthly pH data in the field from 20 (including six from SHEN) streams in western Virginia with the lowest pH values. The methods and sample size requirements will conform to the requirements established in 40 CFR 136. Additionally, these field-based pH values will be compared to the previously collected, lab-determined, pH data. The intent will be to examine differences between field and lab pH measurements and to identify factors that determine variation in the differences. It is anticipated that all of the evaluated streams will be designated ‘impaired’ and that the data will be adequate for including these streams in the next edition of the 303(d) list. Inclusion of these streams on the impaired stream list will help to insure that the problem of stream water acidification due to atmospheric deposition will receive appropriate prioritization in the Total Daily Maximum Load development process.

The entire Rapidan River watershed in SHEN was nominated in January, 2001 for designation as an Exceptional Water. That nomination was denied by the State Water Quality Control Board in October, 2001. In June, 2003 the following segments of streams in SHEN were nominated as Exceptional Waters. These stream segments include all tributaries to these waters within the park boundary. The length in miles associated with these SHEN waters is approximate.

Doyles River/Jones Falls Run – 6.9 miles
Brokenback Run – 4.3 miles
Hughes River – 3.5 miles
Rose River – 8.6 miles
Whiteoak Canyon Run – 7.2 miles
East Branch Naked Creek – 4.6 miles
East Hawksbill Creek – 4.0 miles
Jeremys Run – 15.1 miles
North Fork Thornton River – 9.1 miles
Piney River – 7.6 miles
Big Run – 20.0 miles

The comment/review period for these nominated SHEN waters ended August 25, 2003; no action has, as yet, been taken by the State Water Quality Control Board with respect to these nominated waters.

The following is a summarization of the important findings of the above studies/events:

- Synoptic sampling surveys conducted by Hendrey *et al.* (1980), Lynch and Dise (1985) and Webb (1988) identified a distribution of streams with relatively low ANC and confirmed a close association between stream-water ANC and watershed bedrock type (Figure 7; Table 7). These surveys revealed an ANC range in SHEN streams of 0 to over 200 µeq/L. Differences among watersheds in bedrock weathering rates, mineral composition, and soils are responsible for varying ANC concentrations in surface waters. Low ANC streams have values that range from 0-20 µeq/L, intermediate ANC streams have a range from 60-100, and high ANC streams range from 150-200 (Bulger *et al.* 1999).

- Atmospherically derived sulfate is the major dissolved ion in low-ANC streams associated with siliciclastic bedrock. Ryan *et al.* (1989) noted that for an 8-year period (1980-87), sulfate concentrations significantly increased at a rate of about 2 µeq/L per year in White Oak Run and Deep Run, but ANC significantly decreased at a rate of 1 µeq/L per year in Deep Run.

Table 7. Range and distribution of stream-water concentrations associated with major SHEN bedrock classes: SWAS spring 1992 synoptic survey. After Galloway *et al.* (1999).

	n	**Minimum**	**25%**	**Median**	**75%**	**Maximum**
ANC (μeq/L)						
Siliciclastic	62	-18.1	-1.0	1.2	3.7	12.8
Granitic	46	22.0	47.2	58.7	67.0	130.4
Basaltic	14	33.7	97.0	142.9	179.0	226.7
pH						
Siliciclastic	62	4.8	5.4	5.6	5.7	6.0
Granitic	46	6.0	6.7	6.8	6.8	7.1
Basaltic	14	6.6	6.9	7.1	7.2	7.3
Sum of Base Cations (μeq/L)						
Siliciclastic	62	92.1	138.1	168.2	190.4	272.1
Granitic	46	89.5	136.7	147.7	161.3	243.5
Basaltic	14	138.0	232.0	369.5	381.1	450.9
Sulfate (μeq/L)						
Siliciclastic	62	67.2	88.5	97.2	104.8	177.8
Granitic	46	13.4	30.1	36.6	42.1	96.3
Basaltic	14	12.3	36.2	62.2	97.9	164.3

Note: 25% and 75% refer to the 25th and 75th percentile values. 50% of all the values are within the interquartile range, as bounded by the 25th and 75th percentile values.

- Cosby *et al.* (1991) estimated the background sulfate concentration in low-ANC streams in the eastern U.S. to be 22 μeq/L. Based on that estimate (and 1992 SWAS survey median stream water sulfate concentrations), sulfate concentrations have apparently increased by a factor of 4.4 in streams associated with siliciclastic bedrock, 1.7 in steams associated with basaltic bedrock, and 2.8 in streams associated with granitic bedrock.

- ANCs on the west side of SHEN are significantly lower than on the east side (Lynch and Dise 1985); this reflects the distribution of bedrock geology. The proximity or orientation to upwind sources may also be a factor. ANC also increases with decreasing elevation; shorter water retention time by soil at higher elevations could be the cause.

- Cold season ANC values are generally lower than warm season ANC values for the same stream (Bulger *et al.* 1999). The lowest within-season values of ANC typically occur during high flow. Thus the lowest ANC and pH values typically occur during cold season. However, for some streams the lowest values are associated with low flows and the warm season. In this case elevated concentrations of weak acids (carbonic and organic) may tend to be associated with low-flow, warm-season conditions. In the warm season, carbonic acidity increases in the soil due to higher rates of microbial and root respiration. Organic acidity may similarly increase in soils in the warm season due to accelerated organic matter decomposition. Given reduced transport and dilution under low-flow conditions, concentrations of these soil products should increase in both soil and associated stream waters (Webb 2003).

- Analysis of hydrochemical budgets (Shaffer and Galloway 1982) for the White Oak Run and Deep Run watersheds in SHEN identified sulfate ion retention and cation exchange in soils as primary factors controlling stream water response to acidic deposition. Later analysis by Ryan *et al.* (1989) for the same watersheds indicated statistically significant trends in weekly stream water concentration consistent with acidification due to atmospheric deposition.

- Table 7 presents descriptive statistics for ANC, pH, base-cation and sulfate analyses of samples obtained in the spring 1992 survey of streams draining small sub-watersheds within the 14 primary SWAS watersheds. ANC concentrations are extremely low for streams associated with siliciclastic bedrock -- about half of the sampled streams had ANC in the chronically acidic range (<0 μeq/L) in which lethal effects on brook trout are probable. The remaining streams associated with this bedrock type had ANC in the episodically acidic range (0-20) in which sublethal or lethal effects are possible. Many streams based in granitic bedrock were in the extremely sensitive or indeterminate range. In contrast, streams associated with the basaltic bedrock type had ANC values that are well within the suitable range for brook trout.

  The pH values display a similar relationship with bedrock, with the most acidic streams associated with siliciclastic bedrock and the least acidic streams associated with basaltic. All of the streams associated with siliciclastic bedrock are in the pH range (< or equal to 6.0) identified by Baker and Christensen (1991) as too acidic for acid sensitive fish species.

  The distribution of base-cation concentrations indicates that SHEN soils have limited base-cation supplies. The base-cation concentrations in SHEN are generally less than 25 percent of the median base-cation concentration value for the general population of all regional streams sampled in the 1986 National Stream Survey (Kaufmann *et al.*, 1988; Sale *et al.*, 1988). The availability of base-cations in watershed soils is a primary determinant of stream response to acidic deposition. Percent base-saturation in the range of 10-20 percent has been cited as a threshold value for leaching of aluminum to soil and surface waters (Reuss and Johnson 1986; Cronan and chofield 1990). Median base saturation is less than 10% for SHEN soils associated with siliciclastic bedrock and less than 15% for SHEN soils associated with granitic bedrock.

Sulfate concentrations in Table 7 are consistent with previous interpretations (e.g. Galloway *et al.* 1993) that a substantial proportion of atmospherically deposited sulphur is retained in the soils of SHEN. Sulfur retention in SHEN is estimated to range from 45-65% of sulfur deposition. Sulfur deposition is relatively uniform in SHEN (Galloway *et al.* 1999); differences probably reflect variation in sulfur retention of soils associated with the different bedrock types.

- Higher stream flows result in more acidic conditions in SHEN streams, with the extreme acidic conditions occurring during storm or snowmelt runoff (Eshleman *et al.* 1999). Higher flows cause base-cation dilution that contributes to episodic acidification. The response of streams in all bedrock types is similar in that most of the lower ANC values occur at higher flows. Streams with low base flow ANC clearly experience the worst acid episodes. Pre-episode ANC is an excellent predictor of the minimum ANC during episodes, explaining 90% of the variance in minimum ANC in a linear regression model (Eshleman *et al.* 1999). An average of 75% of the discharge at peak storm flow is pre-event (old) water. Relative to the Adirondacks and Catskills, acid episodes in SHEN are less intense because the new water is less acidic (Eshleman *et al.* 1995). Only extremely acid-sensitive streams in SHEN become acidic (ANC<0) episodically.

- Increases in nitrate concentrations in SHEN streams during episodes are considered to be the result of gypsy moth defoliations and these increases contributed significantly to ANC depressions. Nitric acid flushing of a defoliated watershed's soils causes appreciable stripping of soil base cations (Bugler *et al.* 1999). No episodic data are available prior to gypsy moth defoliation, resulting in our inability to determine directly the relative contributions of nitric acid to episodic acidification during the pre-moth period. An analysis of episodic acidification of White Oak Run by Eshleman *et al.* (1996) supports the interpretation that historical episodic acidification in SHEN was intensified by gypsy moth defoliation, but this interpretation may not hold for all watersheds.

- Increases in sulfate and organic anion concentrations in SHEN streams indicate significant contributions of sulfuric and natural organic acids to episodic acidification (Bulger *et al.* 1999). This is consistent with other mid-Atlantic regions where sulfate sorption is a major control of base flow sulfate concentrations and contrasts with results from other regions of the northeast U.S. where sulfate sorption is less important (e.g. Adirondacks and Catskills; Wigington *et al.* 1993). Since the source of sulfate in SHEN is atmospheric, the contribution of sulfuric acid to episodic acidification should be interpreted as an atmospheric impact. Results from SHEN confirm that episodic acidification is partially the result of natural hydrological and biogeochemical processes, but its intensity can be dramatically affected by both atmospheric acidic inputs and forest defoliation outbreaks.

- Previous studies have shown that mobilization of dissolved aluminum during episodic acidification is a primary cause of fish mortality in streams that have low ANC under base-flow conditions (Wiggington *et al.* 1993). Streams with higher ANC during base flow are less likely to become sufficiently acidic during episodic acidification to bring aluminum into solution. In Paine Run, base-flow ANC is above 0 μeq/L and aluminum concentration is less than 20 μg/L. A high flow event in the fall of 1992 caused a depression of ANC to less than 0 and an increase in aluminum concentration to about 100 μg/L, well above the threshold for adverse effects on aquatic biota.

- Although nitrate also contributes to deposition acidity (Galloway *et al.* 1984), nitrate is typically retained in forested watersheds due to biological uptake and is thus thought to play a relatively minor role in surface-water acidification (Baker *et al.* 1990). Although a number of investigators (e.g., Stoddard and Kellogg 1993) have suggested that nitrogen saturation and release of nitrate to surface waters may be increasing in upland watersheds of eastern North America, this potential has received little attention with respect to mountain headwater streams in western Virginia. This was reasonable given that the median nitrate concentration for samples in the 1987 VTSSS survey was 0.0 μeq/L (Webb *et al.* 1989a, b) and the discharge-weighted mean concentrations for Deep Run and White Oak Run in SHEN were only 1.2 μeq/L for the period of 1980-87 (Ryan *et al.* 1989). However, the situation changed in association with the southward-advancing range of the gypsy moth. Most of western Virginia is now infested with this moth, and severe forest defoliation has occurred in many of the more northerly mountain watersheds. This infestation and defoliation has been accompanied by large increases in nitrate and changes in other ionic constituents related to the acid-base status of the monitored stream waters. Given this dramatic change, acidification of mountain headwater streams in the SHEN is no longer strictly sulfate driven.

Ground Water

Rocks in the Blue Ridge province are relatively insoluble, thus ground water is not severely mineralized, but iron content is high in some locations (Virginia Department of Environmental Quality 2003). Hopkins (1984) found the chemical quality of waters from wells and springs in the Blue Ridge immediately south of the park, along Blue Ridge Parkway, to be suitable for public supply. It is low in dissolved solids and iron, and is classified as soft (hardness < 60 mg/L). Concentrations of arsenic, cadmium, chromium, copper, lead, mercury, selenium, and zinc were below the EPA imits set for public water supplies. The igneous and metamorphic rocks in the Blue Ridge region have high natural uranium content. Water from 87 percent of wells sampled in the region exceeded the proposed national drinking-water standard of radon, which is 300 picocuries per liter (pCi/L) (U.S. Geological Survey 2001).

In 1985, Virginia established the Ground Water Protection Steering Committee, composed of representatives from nine state and one federal agency who implement programs that have the potential to impact ground water quality. The Committee developed the Ground Water Protection Strategy for Virginia in 1987. This was followed by the 1990 Supplement, which assessed the State's progress in implementing actions called for in the Ground Water Protection Strategy. The most recent document is the 1995 Supplement, which examines the State's progress from 1990 to 1995 in carrying out activities suggested in the Ground Water Protection Strategy and charts the Steering Committee's course for next five years (Virginia Department of Environmental Quality, 2004). The state of Virginia has prepared a final draft for Ground Water Quality Standards (62.1-44.15(3a) of the Code of Virginia) in 2003. The proposal provides general requirements for ground water standards based on physiographic region and anti-degradation policy for ground water in Virginia.

From 1996 -1997, the chemical and isotopic composition of water discharging from 44 springs and 32 wells in SHEN and vicinity were measured. The U.S. Geological Survey completed several synoptic samplings of selected springs and wells in the park, along with other studies of air and precipitation chemistry. The final report by Plummer *et al.* (2000) tabulates the chemical and isotopic data collected during this study. Appendix A summarizes the field parameters (water temperature, dissolved oxygen, pH, and specific conductivity), and major element composition (dissolved calcium, magnesium, sodium, potassium, chloride, sulfate, and titration alkalinity) recorded in Plummer *et al.* (2000). Appendix B summarizes concentrations of minor elements, including dissolved strontium, silica (as SiO_2), iron, nitrate (as N), and manganese. Using additional data collected in 1999, Plummer *et al.* (2001) found flushing rates of mobile atmospheric constituents through ground water to streams draining the higher elevations in SHEN average less than three years in base-flow conditions.

At Big Meadows, water quality is routinely tested at Lewis Spring to comply with standards set by the Virginia Department of Health and the National Park Service Public Health Guidelines. Monitoring includes daily checking for residual chlorine levels and monthly samples for bacteriological contaminants. Organic and inorganic chemistry are monitored at 3-5 year intervals. The Big Meadows water system has met the EPA Safe Drinking Water criteria since 1993 (Martin 2002).

The potential for contamination of water supplies in SHEN is compounded by several factors. Water discharged from several shallow, unconfined springs can be easily contaminated from surficial sources. The potential for contamination of water supplies is increased by the location of facilities in the park. Also, water pumped from wells in fractured rock is difficult to protect from contamination because recharge zones and underground flow paths are complex and currently unknown. Pumping from wells can further complicate our understanding of local ground water flow paths, since pumping can alter the natural flow paths (Plummer *et al.* 2000). Unfortunately, original developments in the 1930's at SHEN (buildings, campgrounds and other park facilities) were located near the largest springs that occur at the higher-altitudes in SHEN, which are more scenic. The shallow springs and fractured-rock aquifers in these areas are susceptible to contamination by improperly functioning waste disposal (septic) systems, or from run-off from facilities operations at the park (Plummer *et al.* 2000).

Wetland and Riparian Areas

Floodplains, riparian areas, and wetlands occur at the interface between land and water. Collectively these areas represent only a small proportion of the landscape in SHEN. However, their hydrologic and ecological importance is very significant (Naiman *et al.* 1993). Individually and collectively, these areas provide many critical functions including water supply, maintenance of water quality, flood attenuation, essential habitats for flora and fauna, and maintenance of biodiversity.

Natural riparian areas are some of the most diverse, dynamic, and complex biophysical habitats in the terrestrial environment (Naiman *et al.* 1993). The riparian area encompasses the stream channel between low and high water marks, and that portion of the terrestrial landscape above the high water mark where vegetation may be influenced by elevated water tables or flooding and by the ability of the soils to hold water (Naiman and Decamps 1997). Thus, riparian areas are ecotones between the aquatic habitat of a stream and the surrounding terrestrial habitats. Riparian zones are key systems for regulating aquatic-terrestrial linkages and they may be early indicators of environmental change (Decamps 1993). The riparian zone may be small in headwater streams. In mid-sized streams the riparian zone is larger, being represented by a distinct band of vegetation whose width is determined by long-term (>50 years) channel dynamics and the annual discharge regime.

Physically, riparian zones control mass movements of materials and channel morphology (Naiman and Decamps 1997). Material supplied to streams comes from erosion of stream banks, a process influenced by root strength and resilience, as well as from the uplands. Stream banks largely devoid of riparian vegetation are often highly unstable and subject to mass wasting that can widen channels by several tens of feet annually. Major bank erosion is 30 times more prevalent on nonvegetated banks exposed to currents as on vegetated banks (Beeson and Doyle 1995).

In addition, riparian zones provide woody debris. Woody debris piles dissipate energy, trap moving materials, and create habitat (Naiman and Decamps 1997). Depending upon size, position in the channel and geometry, woody debris can resist and redirect water currents, causing a mosaic of erosional and depositional patches in the riparian corridor (Montgomery *et al.* 1995).

Riparian forests exert strong controls on the microclimate of streams (Naiman and Decamps 1997). Stream water temperatures are highly correlated with riparian soil temperatures, and strong microclimatic gradients appear in air, soil, and surface temperatures, and in relative humidity.

Ecologically, riparian zones: 1) provide sources of nourishment—allochthonous inputs to rivers and herbivory; 2) control nonpoint sources of pollution, in particular, sediment and nutrients in agricultural watersheds; and 3) create a complex of shifting habitats with different spatio-temporal scales, through variations in flood duration and frequency and concomitant changes in water table depth and plant succession (Naiman and Decamps 1997).

Presently, nothing is known about the structure (from a vegetative compositional standpoint) or function of riparian areas of SHEN. An on-going U.S. Geological Survey study (Young *et al.* 2000) should provide SHEN with an understanding of the structure of its riparian areas via riparian zone delineation and assessment of vegetation type and condition.

Additionally, little is known about the number or extent of wetlands in SHEN. More importantly, it is not known if wetland areas of the park are healthy and if they are functioning properly. For example, the park GIS layer for wetlands delineates only two wetlands for the entire park – mafic wetlands in the important wetland complex in the Big Meadows area. However, National Wetland Inventory (NWI) Maps, produced by the U.S. Fish and Wildlife Service, exist in both hard copy and digital formats for the entire park. These maps are based on April 1984 aerial photography (1:58,000) and were produced in 1990 at a scale of 1:24,000. A total of 47 wetlands representing 11 wetland types are identified on these NWI maps based on the wetlands classification system of Cowardin *et al.* (1979) – the NPS standard for wetland classification. Forty-five percent of these wetlands are riverine wetlands and 40% are palustrine wetlands. Additionally, 15% are unclassified and may include wetlands such as man-modified areas, non photo-identifiable areas, and/or unintentional omissions.

Riverine wetlands are the most dominant type of wetland, primarily because of a lack of floodplain development in river/stream and tributary gorges. Riverine wetlands are located in the river channel where the water is usually flowing, and bounded on the upland side or channel bank. Palustrine wetlands include all nontidal wetlands dominated by trees, shrubs, persistent emergent vegetation and emergent mosses or lichens. This broad classification was developed to group the vegetated wetlands traditionally called by such names as marsh, swamp, bog, fen, and prairie. It also includes small, shallow, permanent or intermittent water bodies often called ponds. Palustrine wetlands may be situated shoreward of river channels; on river floodplains; in isolated catchments; or on slopes.

There are primarily three classes of palustrine wetlands in the SHEN: forested; scrub-shrub; and ponds. Forested wetlands are characterized by tall (> 20 feet), woody vegetation. Normally, they contain an overstory of trees, an understory of young trees or shrubs, and a herbaceous layer. Scrub-shrub wetlands include areas dominated by woody vegetation (< 20 feet), including young trees, tree shrubs, and trees and shrubs that are small or stunted because of environmental conditions. Scrub-shrub wetlands are often a successional stage leading to forested wetlands. The ponds are labeled as impoundments and are man-made in origin.

National Wetland Inventory maps are useful for a general understanding of the potential aerial extent and types of wetlands that are present. Though they meet current NWI minimum standards, these maps are based on high altitude photography with minimal ground-truthing (typically not more than one wetland visited per quadrangle), tend to omit smaller (< 1 acre) wetlands and wetlands with forest cover (significant for SHEN, especially since the aerial photography occurred in April after vegetation leaf-out), and the scale (1:24,000) is not adequate to detect subtle changes that may be occurring with respect to habitat boundaries or species composition changes, or delineate small wetland types, such as seeps or springs. The age of the photos could also mean that subsequent fire, drainage, beaver activity, plant growth and succession (including invasion by exotic or nuisance species) or other factors further limit the accuracy of these maps.

An additional problem with the existing NWI maps is the lack of information on plant species associations, substrates (e.g., organic vs. mineral soil), and other factors. For example, two wetlands may be classified identically on the maps as "palustrine emergent semi-permanently flooded" wetland; however, without a site visit, park staff may not know that one is a diverse habitat harboring rare species and the other is a near monoculture of cattails.

Our cursory analysis of SHEN's NWI maps shows that some of these maps are lacking in one obvious area. Riverine wetlands are grossly under-represented. The vast majority of streams and their tributaries are not delineated and when delineation occurs it is at the most downstream portion of these streams. Apparently, the photo-interpretation was conservative, i.e. only obvious water-covered stream courses were delineated. In those upper portions of watersheds with heavy forest canopy, the presence of water was not obvious and wetlands were thus not delineated, even with the presence of a stream channel. An example from another national park unit serves to illustrate the need to verify and extend NWI maps.   At New River Gorge National River an area of the gorge (and its tributaries) with existing NWI maps was re-interpreted using NPS color aerial photography and ground-truthing (Purvis *et al.* 2002). The NWI maps show 49 wetlands representing 11 wetland types. The NPS study delineated 76 wetlands representing 21 wetland types. The dominant wetland type for the NWI maps was unclassified (potential wetlands) followed by palustrine. For the National Park Service study dominant wetland types were the deciduous palustrine wetlands followed by riverine wetlands. Two things are striking: 1) the difference in total wetlands identified (76 vs 49); and 2) the difference in the riverine wetlands (32.9% by NPS vs. 3.6% by NWI). The differences are probably attributable to the ground-truthing of wetland delineations.

Acquisition of enhanced wetland inventory and characterization data is an important asset in management and protection of the park's wetland resources.

A 4-year study that began in 2000 by the U.S. Geological Survey (Young *et al.* 2000) has a special emphasis on accurately delineating and assessing vegetation in the riparian and wetland areas of SHEN. Initial location and extent of wetland areas and riparian zones will be mapped using a combination of GIS modeling from digital elevation models, assessment of existing GIS data (location of springs, seeps, and hydric soils), and analysis of infrared and radar imagery. Radar remote sensing uses microwave transmission that can penetrate forest canopies and some soil types to create images of the environment. Since microwave wavelengths used in radar imaging are particularly sensitive to absorption by water, this imagery may be effective at delineating actual wetland and riparian zone boundaries rather than using a simple buffer distance away from water features (current SHEN practice). A subset of vegetation field plots will be placed within delineated wetland and riparian zones to assess vegetation composition and to identify additional riparian and wetland associations. Wetland vegetation will be classified using the U. S. National Vegetation Classification System (USNVC) – a hierarchical classification system, defining communities by structure at broad levels and then floristically at finer levels (Grossman *et al.* 1998). The USNVC was recently adopted as a federal standard guiding vegetation mapping at federal agencies. Figure 18 shows a portion of SHEN with NWI and modeled (potential) wet areas from this project and demonstrates the potential gross underestimation of wetlands that the NWI maps represent.

Aquatic Biota

The monitoring of stream benthic macroinvertebrates has occurred since 1986 as part of the Long Term Ecological Monitoring (LTEM) Program. Seventeen core sites on 11 streams (Figure 19a, b, c) have been sampled. The sites were chosen based on a heirarchical system involving management district, geological formation/ANC, and elevation. In 1995, SHEN began to sample other sites with the goal of eventually sampling every permanent stream within park boundaries. To date, 114 sites on 55 streams have been sampled. Sampling occurs in the spring (April, May or June – originally began with sampling in spring and summer, but in 1997 reduced to only spring). Macroinvertebrates are sampled qualitatively to obtain species richness and quantitatively for statistical trend analysis. Additionally, the following physicochemical and habitat parameters are measured: discharge, temperature, dissolved oxygen, pH, conductivity, total dissolved solids, depth, width, substrate, vegetative cover and type, debris retention, and pool:riffle ratio. Voshell and Hiner (1990) described sampling techniques and LTEM protocols.

Sullivan *et al.* (2003) summarized the LTEM macroinvertebrate database for a 12-year period (1988-2000). They found the macroinvertebrate fauna to be represented by five phyla: Annelida; Arthropoda; Mollusca; Nematoda; and Platyhelminthes. Aquatic insects (Anthropoda, Class Insecta) were represented by 79 families representing nine orders (Coleoptera, Collembola, Diptera,

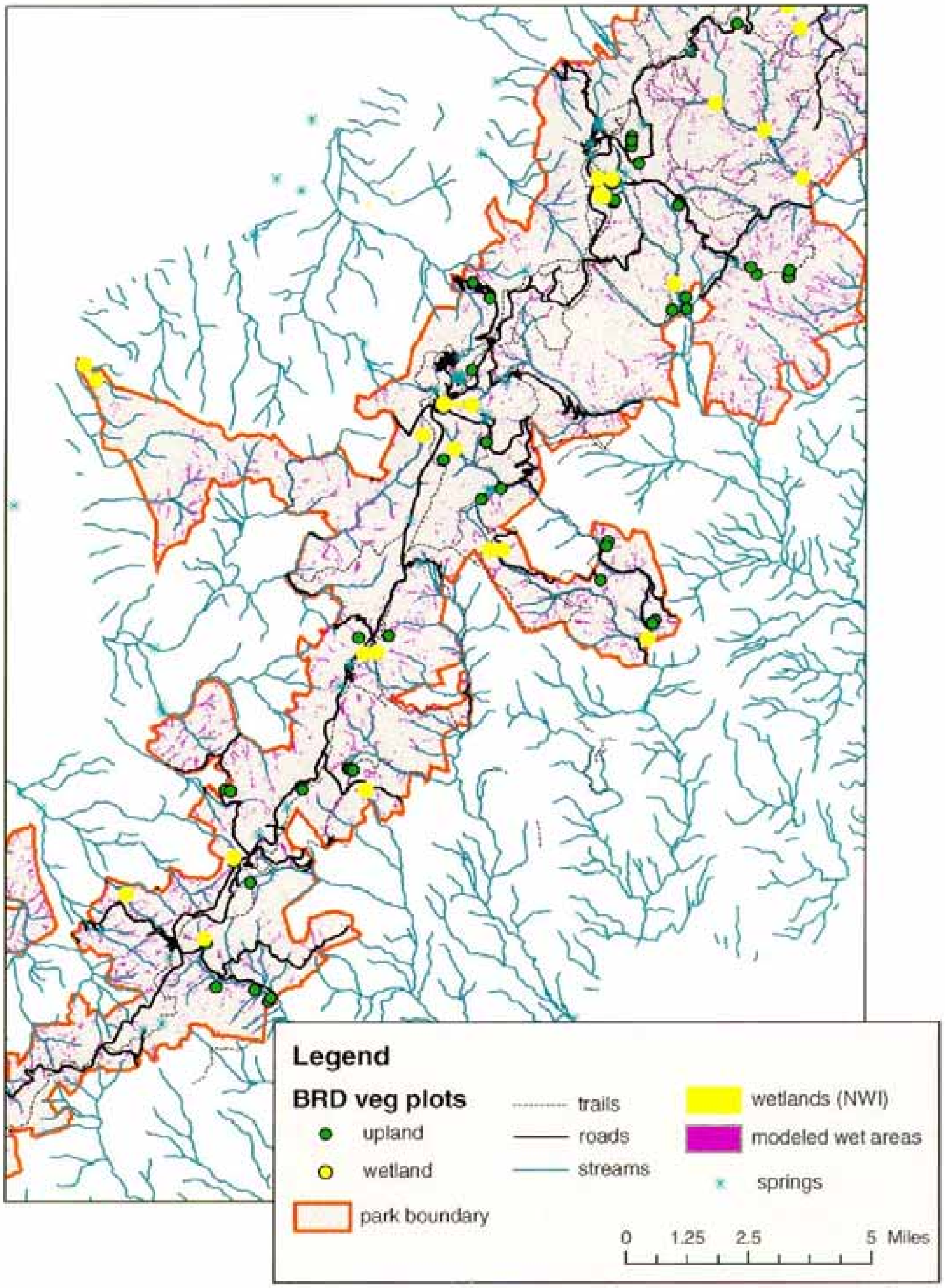


Figure 18. Modeled wet areas for a portion of Shenandoah National Park from a USGS study by Young etal (2000). Abbreviations are: BRD–Biological Resources Division; veg–vegetation; NWI–National Wetland Inventory.

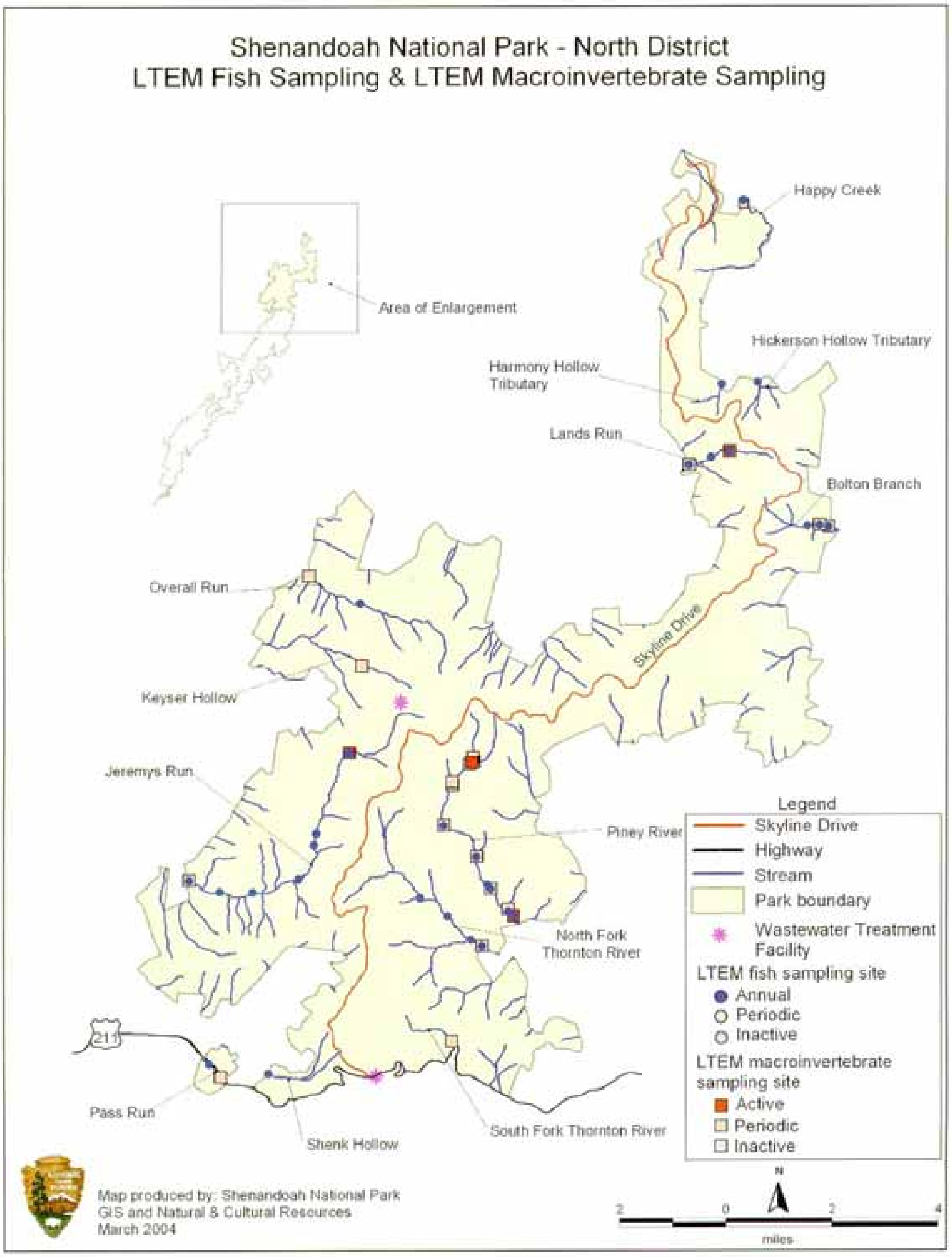


Figure 19a. LTEM fish and macroinvertebrate sampling sites in Shenandoah National Park, North District.

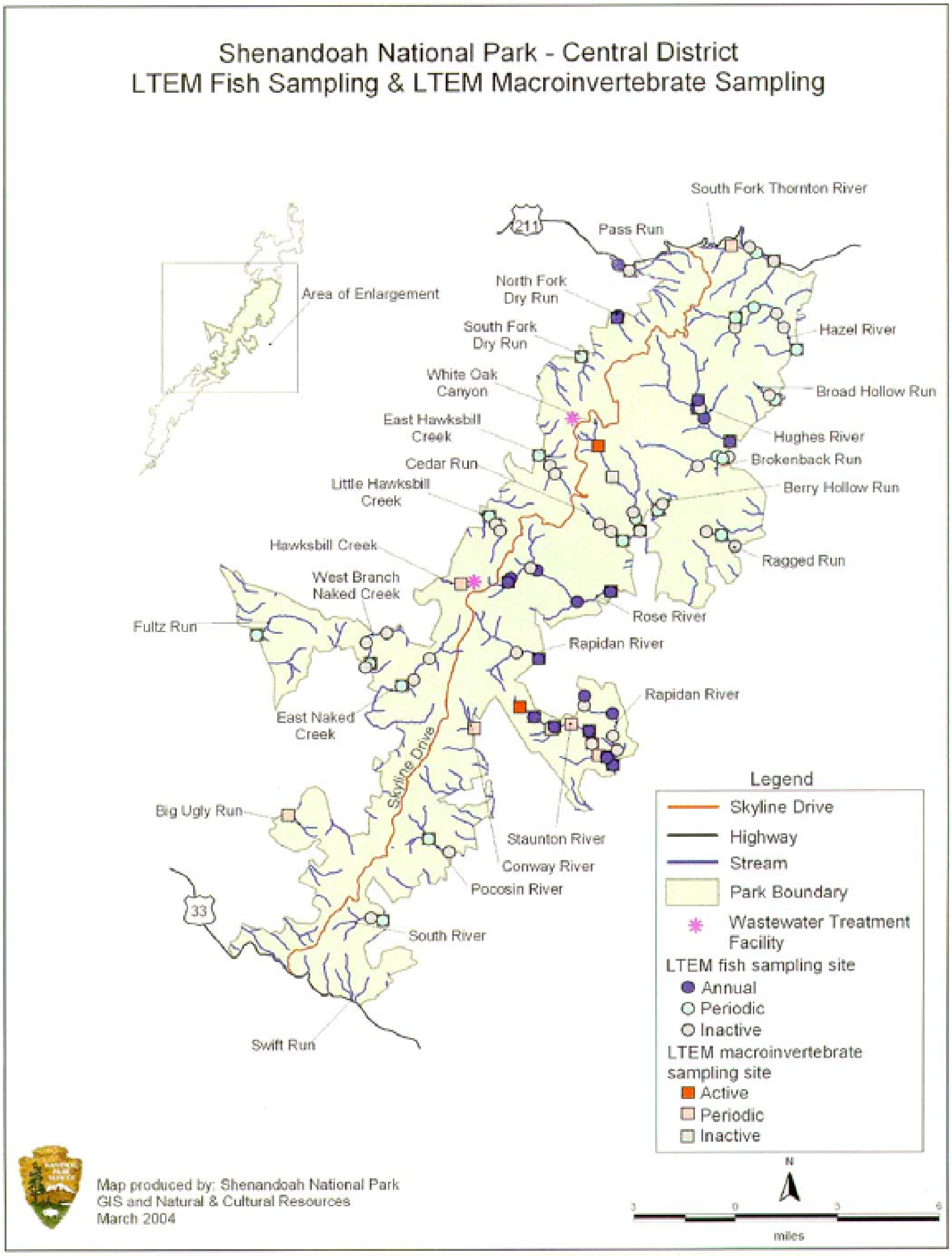


Figure 19b. LTEM fish and macroinvertebrate sampling sites in Shenandoah National Park, Central District.

71

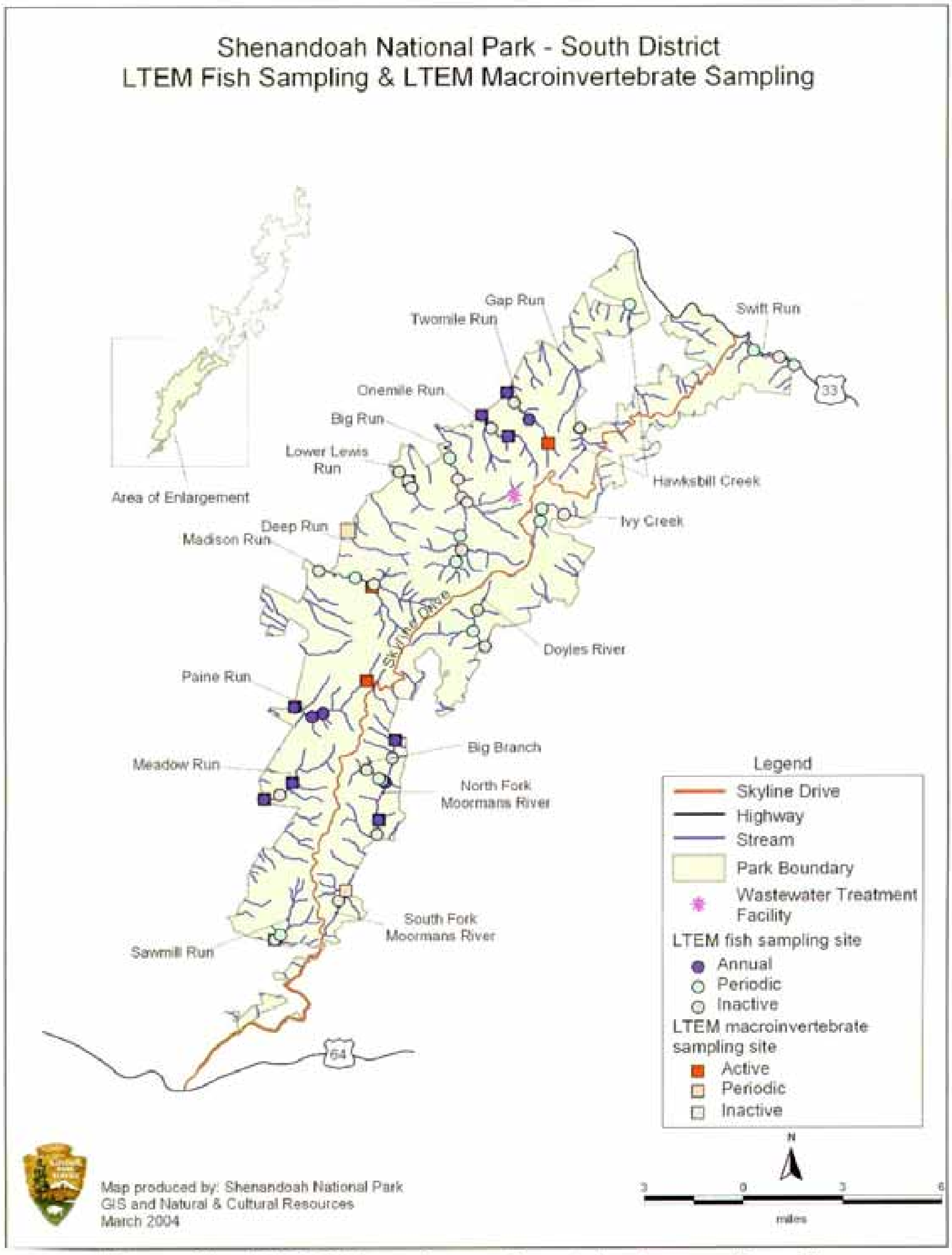


Figure 19c. LTEM fish and macroinvertebrate sampling sites in Shenandoah National Park, South District. 72

Ephemeroptera, Hemiptera, Megaloptera, Odonata, Plecoptera and Trichoptera). Not all families are present in each stream; the total number of insect families found in a given stream varies from 21 to 56.

Sullivan *et al.* (2003) further examined the quantitative relationships between macroinvertebrate communities and stream water quality in SHEN streams. They used only aquatic insect data from the LTEM database and quarterly water quality data from the 14 SWAS watersheds over a 12-year period (1988-2000). They limited the study to an investigation of mayflies (Ephemeroptera), caddisflies (Trichoptera), and stoneflies (Plecoptera) because these orders were frequently encountered and numerous. They used a combined metric called EPT (for Ephemeroptera, Plecoptera, and Trichoptera) to assess the integrity of the aquatic insect community. They found strong relationships between mean and minimum ANC and the number of families per order. The strongest relationship was with Ephemeroptera followed by Plecoptera and Trichoptera, respectively. There was little difference in the strength of the relationships between mean and minimum ANC although the latter was always slightly stronger. Similarly, the EPT index was strongly related to mean and minimum ANC. Total numbers of Ephemeroptera and Trichoptera were highly correlated with mean and minimum ANC; there was no relationship between total numbers of Plecoptera and ANC. It should be noted that while these relationships are relatively strong (based on r^2 values), the change over the range of ANC is small (based on regression slopes). For example, the change in the number of Ephemeroptera families over the range of ANC (0-300 µeq/L) is only four to six. The change is even smaller for mean ANC (four to five families). The change over this range is similar for Plecoptera and Trichoptera. The difference in macroinvertebrate families/order over a range in ANC should be compared to Figure 19 which shows a change in fish species richness from one to nine species over a much reduced range in ANC. The use of higher taxonomic levels may limit the usefulness of this relationship, especially when considering potential monitoring metrics. Perhaps the number of genera in each aquatic insect order would be a more sensitive indicator of changes in ANC.

Johnson and Snyder (No Date) examined the recovery (over 3 years) of stream macroinvertebrate assemblages after the June 27, 1995, 500+year flood on the Staunton River. Thirty inches of rain fell in approximately 16 hrs over steep terrain causing major debris flows in the lower portion of this watershed. They found that measures of benthic community structure were insensitive and inconsistent indicators of long-term responses to the flood. On the other hand, comparisons of productivity between impacted and unimpacted sites indicated that the flood and associated debris flows did have long-term effects on the benthic communities – there were clear between-site differences in production among trophic groups. They concluded that the flood/debris produced changes similar in pattern and magnitude to other anthropogenic disturbances, particularly clear-cut logging.

Voshell and Marshall (1994) studied the effects of gypsy moth defoliation on aquatic biota of headwater streams in SHEN. They sampled six streams, three defoliated and three references, for 1 year. Most indicators of water quality were unaffected by riparian defoliation in this short-term analysis; however, some changes related to defoliation were observed. In particular feeding gypsy moth larvae greatly reduced the magnitude of the autumn pulse of terrestrial organic inputs and greatly increased the amount of detritus entering defoliated streams in the spring. Defoliation showed only subtle changes in benthic macroinvertebrate community structure; however, their study did not allow observations on the condition of individuals, just survival. Finally, aquatic insect populations in defoliated streams showed increased secondary production, apparently because thermal changes accompanying defoliation allowed species to initiate a second generation after defoliation.

The experimental design of Voshell and Marshall (1994) did not allow them to address effects of long-term nitrate leaching, but the only indication of reduced alkalinity occurred in May and was ephemeral. Because nitrate leaches through the soil as nitric acid, intensive defoliation by gypsy moth larvae would be expected to have an impact on stream benthic communities similar to that of acid deposition (i.e., reduced ANC and pH).

Klemm *et al.* (2003) developed a macroinvertebrate biotic integrity index for the Mid-Atlantic highlands region as part of the Ecological Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency. They collected data from 574 stream reaches in this area, four of which were located in SHEN (North Fork Thornton River, Ragged Run, Swift Run and North Fork Moormans River). Samples were collected during late April to June, 1993-1995.

Early (pre-1950s) fisheries work in SHEN was short-term and produced variable results (McNulty-Huffman 1991), probably because ecological conditions had improved since park establishment, and were continuing to improve. SHEN subsequently asked the U.S. Fish and Wildlife Service to conduct a comprehensive survey of the trout fishery in the park. The result was the study of Lennon (1961) who surveyed 46 streams in the 1950s. He found that trout in many streams to be seriously threatened or in some cases lost because of a series of droughts from1951-1955. Later work by Sheridan (1966; 1972) in the late 1960s to early 1970s showed that most trout populations had recovered significantly.

After the above surveys, the U.S. Fish and Wildlife Service became less active in SHEN; however, the Virginia Department of Game and Inland Fisheries increased its involvement in park fisheries management. As part of a state wide trout survey, Mohn and Bugas (1980) included both habitat analysis and standing crop evaluations for six park streams and provided much needed baseline data. Generally, streams on the east slope provided the best trout habitat because invertebrate productivity, water flow, and pool formation were more consistent.

SHEN expanded its involvement in fisheries management beginning in 1982 by initiating a comprehensive fisheries monitoring program. The fisheries monitoring program at SHEN began as an effort to evaluate the status of the native brook trout – park streams offer anglers one of the greatest concentrations of nearly pure brook trout in the eastern U.S. This expansion occurred because of increasing fishing pressure, acidic deposition effects on aquatic resources, and a significant reduction in the assistance from other agencies due to budget limitations (McNulty-Huffman 1991).

In the developing years of the program, qualitative sampling techniques were used to obtain relative trout numbers and size classes and a list of other species present in 132 sites located along 46 park streams (Atkinson 2003). Smaller streams had as few as one monitoring site whereas larger streams had a total of six sites. Approximately half of the total sites were sampled each year for a 2-year sampling frequency for most streams – eight small drought prone streams were sampled every 4 years and two streams were sampled annually. Eleven years of qualitative sampling on these 46 streams were summarized in a Fisheries Management and Data Report (NPS 1994).

In 1994, the program was revised to include more quantitative sampling. The revised program includes 43 streams and 74 sites split between quantitative and qualitative components (Atkinson 2003; Figure 19a, b, c). The quantitative component included 36 sites sampled annually along 15 streams stratified across the three dominant bedrock formations. An additional five qualitative sites are also included in the annual sampling schedule. The resulting range of streams include a mix of small and large streams on the eastern and western slopes of the park, stratified from north to south in all of the 3 administrative districts. The remaining 25 streams and 34 sites are qualitatively sampled on a 5-year rotation.

From the standpoint of numbers of sites and streams, the current fisheries monitoring program differs little from the 1994 program. Presently, a total of 43 streams and 75 sites are sampled with 41 sites along 18 core streams and 34 sites along 25 optional streams. Five of the 18 core streams are monitored jointly with the Virginia Department of Game and Inland Fisheries (VDGIF). VDGIF also periodically monitors a sixth stream (Conway River) downstream from the park boundary. Park crews typically assist with the Conway River monitoring.

The field component of the fisheries monitoring program typically runs from mid-June to mid-August. In addition, the following physicochemical data are collected: flow; temperature; pH; conductivity; dissolved oxygen; and total dissolved solids. Habitat sampling includes a combination of actual measurements (width, length, depth, gradient) with visual estimates (riparian cover, stream substrates and habitat features).

Exotic brown and rainbow trout have disrupted native brook trout populations in many streams throughout the Southeast. As monitoring data began to show an increase of these species in park waters, staff began to systematically remove these fish from streams. Electrofishing runs with the primary objective of removing brown trout began in 1986. Naturalized populations of brown and rainbow trout are known from only 5 of the 50 plus recognized trout streams in the park.

A Fisheries Management Plan was finalized in 1987 with the following objectives: 1) to preserve and perpetuate the native brook trout as an integral component of the park's aquatic ecosystems; and 2) to allow for recreational fishing on those park streams that consistently produce adequate numbers of game fish for maintaining population stability. Therefore the Plan discusses a monitoring program with protocols and fishing regulations and enforcement. It also discusses the criteria for determining that a stream should be closed to fishing. Presently, there are three closed streams, Ragged Run, Dry Run, and One Mile Run. There are 22 streams open for harvest.

Roghair *et al.* (2002) studied the response of habitat and the brook trout population in the Staunton River after the June 1995 500+ year flood and debris flow event. Age-0 trout density exceeded pre-flood levels within 1 year and adult density exceeded pre-flood levels within 2.5 years. This rapid colonization was expected given that a source population existed in the Rapidan River (Staunton River flows into this river).

As far as habitat is concerned, Roghair *et al.* found that discharge was lower in 1999 (last year of study) than in 1995, but the total number of habitat units decreased and average surface area and total stream area increased. The pre-flood channel consisted of a large number of small surface area habitat units. By 1999 the channel became more typically organized and consisted of a smaller number of large surface area habitat units.

The distribution and status of the fish community in SHEN (through 2002) is shown in Table 8. A total of 33 species and one hybrid (tiger trout) are found in SHEN streams. The number of species in east side streams ranges from 1-22 with a mean of 9.6 species. For the west side streams, the number of species ranges from 1-19 with a mean of 6.8 species. The range in total number of species and the mean number of species for the three management districts are as follows: North District (range 2-20, mean 8.7), Central District (range 2-22, mean 7.2), and South District (range 1-20, mean 8.2). Brook trout is the most frequent species encountered (94%), followed by blacknose dace (92%), longnose dace (57%), rosyside dace (55%), and mottled sculpin (47%). Rare species, based on frequency of occurrence, include satinfin shiner, carp, largemouth bass, redbreast sunfish, greenside darter and johnny darter, all with only one occurrence (2%). Potomac sculpin is the next rarest species (4%).

Mitchell (1999) stated that although the general composition of the amphibian fauna of SHEN is known (Witt 1993; Table 9), the distribution of amphibians by watershed and stream has not been adequately assessed. Grant *et al.* (in manuscript), in an attempt to address stream salamander species richness and abundance in relation to environmental factors in SHEN, surveyed 49 stream sites in the early summer of 1999. Sampling was based on a stratified random design using elevation, bedrock type, and aspect. At each site they measured water temperature, specific conductance, pH, and ANC. Eleven amphibian species were identified at the 49 sites – seven salamander and four anuran

Table 8. Distribution of SHEN fishes by stream (Shenandoah National Park files).

Stream	Abundance	Bolton Branch	Happy Creek	Hickerson Hollow	Jeremy's Run	Land's Run	Overall Run	Piney River	Shenks Hollow	Thornton River, N. Fork	Berry Hollow	Broad Hollow Run	Brokenback Run	Cedar Run	Dry Run, N. Fork	Dry Run, S. Fork	East Hawksbill Creek	Fultz Run	Hannah Run	Hazel River	Hogcamp Branch	Hughes River	Little Hawksbill Creek	Naked Creek, E. Branch	Naked Creek, W. Branch	Pass Run	Pocosin Hollow Run	Ragged Run	Rapidan River	Rose River	South River	Staunton River	Swift Run	Thornton River, S. Fork	Whiteoak Canyon Run	Big Branch	Big Run	Doyles River	Eppert Hollow Run	Hawksbill Creek (Beldor)	Ivy Creek	Lower Lewis Run	Madison Run	Meadow Run	Moormans River, N. Fork	Onemile Run	Paine Run	Rocky Mt. Run	Sawmill Run	Twomile Run	# of Streams
Park District		N	N	N	N	N	N	N	N	N	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	
Drainage		R	P	P	P	P	P	R	P	R	R	R	R	R	P	P	P	P	R	R	R	R	P	P	P	P	R	R	R	R	R	R	J	R	R	J	P	J	P	P	J	P	P	P	J	P	P	P	P	P	
Side of Park		E	E	E	W	W	W	E	W	E	E	E	E	E	W	W	W	W	E	E	E	E	W	W	W	W	E	E	E	E	E	E	E	E	E	E	W	E	W	W	E	W	W	W	E	W	W	W	W	W	
# of Species		4	13	2	7	10	6	12	4	20	5	2	6	4	2	1	1	2	4	11	2	20	2	3	11	14	4	4	22	16	2	5	9	17	10	3	19	12	8	17	1	3	9	3	20	3	3	13	7	2	
Eel, American	C	◆				◆		◆		◆			◆						◆	◆		◆							◆	◆	◆	◆	◆	◆	◆			◆													16
Carp, Common	R																																				◆														1
Dace, Mountain Redbelly	U		◆							◆												◆							◆											◆					◆						6
Dace, Rosyside	A		◆		◆	◆	◆	◆		◆	◆		◆	◆						◆		◆			◆		◆	◆	◆	◆			◆	◆	◆	◆	◆	◆		◆			◆		◆			◆	◆		27
Dace, Longnose	A		◆		◆	◆	◆	◆		◆	◆			◆					◆	◆		◆			◆	◆	◆		◆	◆		◆	◆	◆	◆		◆	◆	◆	◆			◆		◆			◆	◆		28
Dace, Blacknose	A	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	45
Stoneroller, Central	U		◆			◆				◆																◆											◆	◆		◆					◆			◆			9
Fallfish	U									◆										◆									◆					◆																	4
Chub, Creek	A		◆		◆	◆	◆	◆		◆										◆		◆			◆	◆			◆	◆				◆	◆		◆	◆	◆	◆			◆		◆			◆			21
Minnow, Cutlips	U									◆												◆							◆																						3
Chub, River	C					◆	◆	◆		◆										◆		◆				◆			◆	◆				◆	◆		◆	◆					◆					◆			15
Chub, Bluehead	C		◆			◆		◆	◆	◆										◆					◆				◆					◆			◆		◆	◆					◆			◆			14
Shiner, Satinfin	R																												◆																						1
Shiner, Common	C		◆							◆										◆		◆				◆			◆	◆			◆	◆			◆	◆	◆	◆			◆		◆						15
Minnow, Bluntnose	U		◆																																		◆			◆								◆			4
Hogsucker, Northern	U																			◆						◆								◆			◆			◆					◆						6
Sucker, Torrent	C							◆		◆			◆									◆						◆	◆	◆		◆	◆	◆	◆		◆	◆							◆				◆		15
Sucker, White	C		◆			◆		◆		◆												◆			◆	◆			◆	◆			◆	◆			◆	◆		◆			◆		◆			◆			17
Madtom, Margined	U																					◆							◆																◆						3
Trout, Brook	A	◆			◆	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	46
Trout, Tiger	U																					◆								◆															◆						3
Trout, Brown	U									◆			◆									◆								◆															◆						5
Trout, Rainbow	U																					◆				◆				◆															◆						4
Sculpin, Mottled	A	◆	◆	◆	◆			◆	◆	◆	◆											◆		◆	◆	◆			◆	◆			◆	◆	◆		◆		◆	◆		◆						◆	◆		23
Sculpin, Potomac	U																								◆															◆											2
Bass, Rock	U		◆							◆												◆							◆					◆			◆			◆											7
Bass, Smallmouth	U									◆												◆			◆				◆					◆			◆			◆								◆			8
Bass, Largemouth	U																									◆																									1
Sunfish, Redbreast	U																																												◆						1
Pumpkinseed	U							◆																					◆								◆							◆	◆						5
Darter, Greenside	R																									◆																									1
Darter, Johnny	R																																												◆						1
Darter, Tesselated	U									◆												◆							◆	◆				◆	◆																6
Darter, Fantail	C		◆		◆				◆																◆	◆			◆	◆							◆	◆	◆	◆			◆		◆	◆	◆	◆	◆		17

Abundance	Description	District	Drainage	Side of Park
R=Rarely encountered	Species found at intervals of five years or greater within the park.	N=North	J=James	E=East
U=Uncommon	Species with less than ten (<10) known populations in the park.	C=Central	P=Potomac	W=West
C=Common	Species with between ten and twenty (10 to 20) known populations in the park.	S=South	R=Rappahanock	
A=Abundant	Species with greater than twenty (>20) known populations in the park.			

Table 9. The amphibian and reptile fauna of Shenandoah National Park. Modified from Witt (1993). Abbreviations as follows: **S** streams; **D** dry woods; **H** humid woods; **U** under cover (rocks, logs); **M** meadows; **R** dry, rocky areas; **B** Big Meadows Swamp; **C** common; **U** uncommon; **R** rare; **T** transient, not known to breed in park; **E** expected. Status for frogs and salamanders refers to breeding season only; **1** below 2,000 feet; **2** 2,000 to 3,000 feet; **3** above 3,000 feet; **Sp** spring; **Su** summer; **F** fall.

Species	**Habitat**	**Occurrence**	**Elevation**	**Breeding Period**
Snapping Turtle *Chelydra serpentina*	S	T	1-2	Sp
Stinkpot (Musk Turtle) *Sternothaerus odoratus*	S	T	1	Su
Spotted Turtle *Clemmys guttata*	B	U	1-2-3	Sp
Painted Turtle *Chrysemys picta*	S	T	1	Sp
Five-lined Skink *Eumeces fasciatus*	D,U,R	C	1-2-3	Sp
Northern Fence Lizard *Sceloporus undulatus hyacinthinus*	D,R	C	1-2	Sp
Northern Water Snake *Natrix sipedon*	S,H,U	U	1-2	Su
Queen Snake *Natrix septemvittata*	S,U	R	1	Su
Red-bellied Snake *Storeria occipitomaculata*	S,D,H,U	U	1-2-3	Su
Eastern Garter Snake *Thamnophis sirtalis*	S,D,H,U,M,R, B	U	1-2-3	Su
Ribbon Snake *Thamnophis sauritus*	S,H,U,M	U	1-2	Su
Ringneck Snake *Diadophis punctatus*	D,H,U,M, R,B	C	1-2-3	Su
Black Racer *Coluber constrictor*	D,H,U,M, R,B	U	1-2-3	Su
Milk Snake *Lampropeltis doliata*	D,H,U,M,B	U	1-2-3	Su
Eastern Worm Snake *Carphophis amoenus*	D,U	U	1	Su
Black Rat Snake *Elaphe obsolete*	D,H,U,M,B	C	1-2-3	Su
Eastern Hognose Snake *Heterodon platyrhinos*	D,U,H	U	1	Su
Rough Green Snake *Opheodrys aestivus*	S,H,M	U	1	Su
Smooth Green Snake *Opheodrys vernalis*	D,U,M	U	2-3	Su
Northern Copperhead *Agkistrodon contortix*	D,H,U,R	C	1-2-3	Su
Timber Rattlesnake *Crotalus horridus*	D,H,U,R	C	1-2-3	Su
Jefferson Salamander *Ambystoma Jeffersonianum*	M,B	R	3	Sp
				Breeding

Species	Habitat	Occurrence	Elevation	Period
Spotted Salamander *Ambystoma maculatum*	M,B	U	1-2-3	Sp
Red-spotted Newt *Diemictylus viridescens*	S,D,H,U	U	1-2-2	Sp
Dusky Salamander *Desmognathus fuscus*	S,U,B	C	1-2-3	Sp, Su
Virginia Seal Salamander *Desmognathus moniticola jeffersoni*	S,U,B	C	1-2-3	Sp, Su
Four-toed Salamander *Hemidtylium scutatum*	B	C	1-2-3	Sp
Spring salamander *Gyrinophilus porphyriticus*	S,U,B	U	1-2-3	Sp
Northern Red Salamander *Pseudotriton ruber ruber*	S,H,U	R	1-2	F
Two-lined Salamander *Eurycea bislineata*	S,H,U,B	C	1-2-3	F
Long-tailed Salamander *Eurycea longicauda longicauda*	S,H,U	R	1-2-3	F
American Toad *Bufo americanus*	D,H,M,R,B	C	1-2-3	Sp
Fowler's Toad *Bufo woodhousei*	D,H,M,R,B	U	1-2	Sp
Northern Cricket Frog *Acris crepitans*	S,H	U	1-2	Sp
Spring Peeper *Hyla crucifer*	S,H,B	U	1-2-3	Sp
Gray Treefrog *Hyla versicolor*	S,H,B	U	1-2-3	Sp
Upland Chorus frog *Pseudacris triseriata*	S,H,B	U	1-2-3	Sp
Bullfrog *Rana catesbelana*	S,B	R	1-2-3	Sp
Green Frog *Rana clamitans*	S,B	C	1-2-3	Sp
Leopard Frog *Rana pipien*	S	E	1	Sp
Pickerel Frog *Rana palustiris*	S,B	C	1-2-3	Sp
Wood Frog *Rana sylvatica*	S,D,H,U, M,B	U	1-2-3	Sp

species. Desmongnathine salamanders comprised 68% of the total number of salamander individuals collected. *Desmognathus monticola* was found at 40 and *D. fuscus* at 41 of the 49 sites. *Eurycea bislineata* had the highest abundance (20% of total captures) and was found at 43 of 49 sites. *Gyrinophilus porphyriticus* was found at 33 sites and had the next highest abundance. The other species of salamander were quite uncommon as were the anurans.

The Amphibian Research and Monitoring Initiative (ARMI) of the U.S. Geological Survey has been monitoring populations of streamside salamanders at nine streams (Jeremys Run, Piney River, North Fork Thornton, Dry Run, Rose River, Staunton River, Two Mile Run, Paine Run, Meadow Run) in SHEN since 1998 (http://www.mp2-pwrc.usgs.gov/nearmi/sites/; Jung *et al.* 2000). Under the ARMI program, SHEN is an apex site where intensive amphibian research and monitoring is being conducted. The objectives of ARMI's streamside salamander inventory and monitoring project in SHEN are: 1) conduct transect and quadrat sampling of streamside salamanders; 2) determine detection rates and population estimates along transects; and 3) establish a long-term streamside salamander monitoring program in SHEN. With regard to the former, Jung *et al.* (2000) evaluated four survey techniques (electroshocking; leaf litter bag; 1m^2 quadrats; 50 m transect) for stream salamanders. Generally speaking, the 50 X 1m transects yielded the highest species richness (Figure 20). The ARMI program also monitors all known vernal pools in the park. To date, five vernal pools (Big Meadows, Hog Camp Swamp, Swamp Island, Rocky Creek and Pond Ridge) show a species richness that ranges from one to four with *Rana sylvatica* present in all five vernal pools.

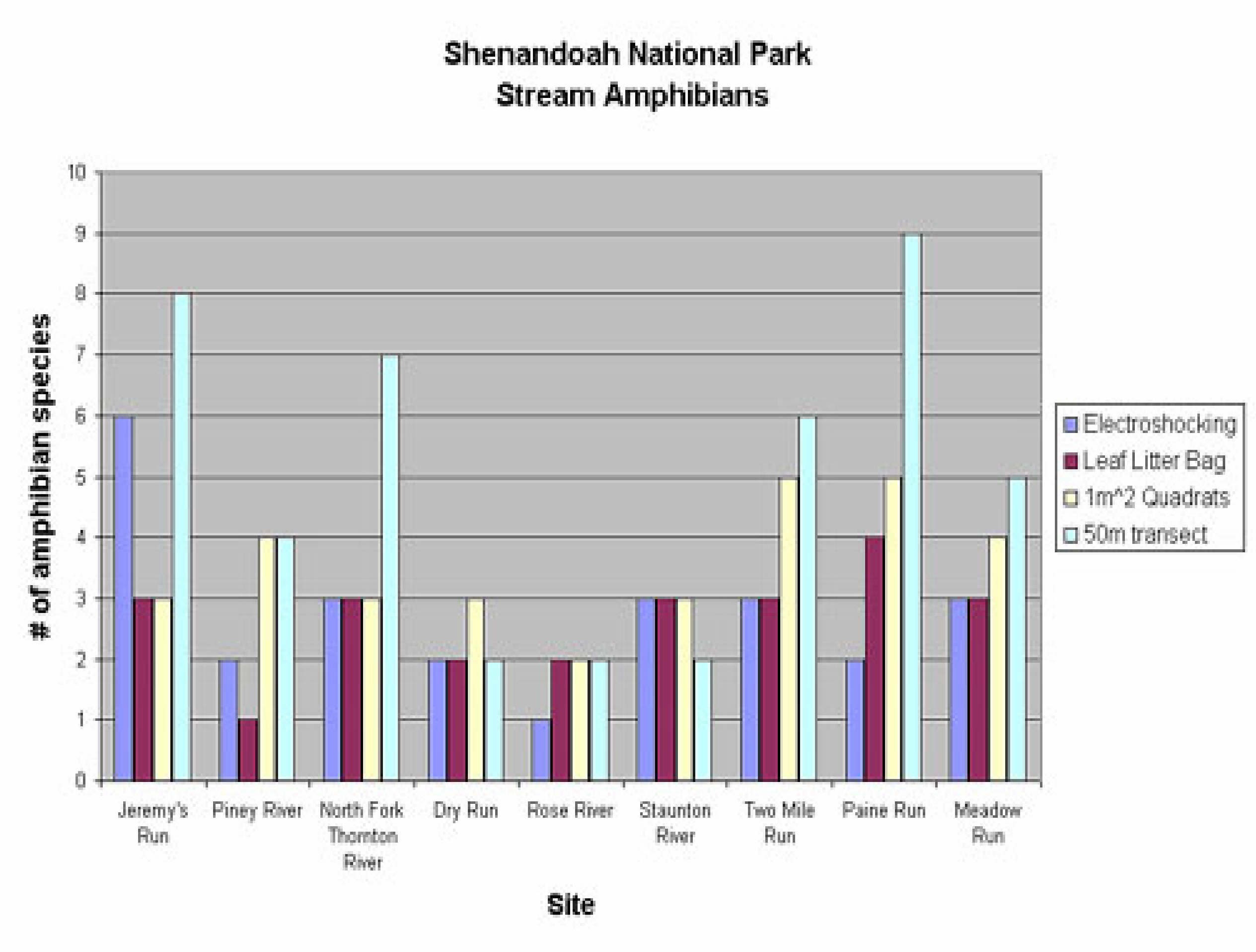


Figure 20. The number of amphibian species collected using four sampling techniques in Shenandoah National Park. After Jung *et al.* (2000).

Effects of Acidic Deposition on Aquatic Biota

Feldman and Conner (1992) conducted a study in 1985 to determine whether the macroinvertebrate community structure of streams varies in relation to ANC levels. Because mayflies are sensitive to low pH levels, they examined the structure of mayflies in six streams receiving acid deposition. Three of the streams had low ANC (<50 μeq/L) and a mean pH of 5.84. The other three streams had higher ANC (150-300 μeq/L) and a mean pH of 7.10.

Twenty-four mayfly species were found in the six streams. Seven of these species were not found in the streams with low ANC. In addition a significantly lower abundance of mayflies was found in the low ANC streams. The results indicated that greater abundance and richness of mayfly species are found in streams with higher ANC.

Smith and Voshell (1994) analyzed LTEM benthic macroinvertebrate data collected in the first 6 years (1986-1992) of the program. They found that benthic communities in low alkalinity streams were different from those of other streams in SHEN. This difference, however, was based only on sites being stratified by bedrock geology type; no environmental data were available to link to the benthic community data. They suggested that a future study be conducted when the LTEM database had matured to the point of including environmental data.

Building on the suggestion by Smith and Voshell (1994), Moeykins and Voshell (2002) conducted the first comprehensive analyses of the entire LTEM database on macroinvertebrates and related biological, physical and chemical measurements. Their analysis was based on interpretation of 10 physicochemical parameters measured at 89 sites in SHEN (28 low-ANC and 61-higher-ANC sites) for which macroinvertebrate data were available. They selected 12 metrics representing six broad categories of benthic community ecological condition (Table 10). Metric values were used in subsequent statistical analyses.

Results of the study by Moeykins and Voshell (2002) included: 1) normal ANC sites in SHEN are comparable to the best sites in the Blue Ridge physiographic province; and 2) atmospheric deposition in low-ANC streams causes the only change in ecological condition in SHEN streams. Other disturbances, such as fire, flood, and recreation do not appear to have had noticeable long-term effects on the streams.

The recent study by Kauffman *et al.* (1999) on macroinvertebrate community changes in the proximate St. Mary's River is noteworthy. They compared the macroinvertebrate data over a 60-year time frame beginning in 1935. The changes in the St. Mary's River benthic community are consistent with stream water acidification. Whereas 29-32 taxa were documented in the 1930s, no more than 22 taxa were observed in the 1990s. Acid-sensitive taxa have generally declined in abundance and some may have been extirpated. In contrast, certain acid-tolerant taxa have increased in abundance apparently due to a competitive release from the loss of acid-sensitive taxa. Furthermore, the total abundance of

Table 10. Metrics and expected response to increasing perturbation in streams in the Blue Ridge Mountain ecoregion. After Moeykins and Smith (2002).

Measure Category	Metric	Definition	Expected Response to Perturbation
Richness	Number of taxa	The total number of taxa in the macroinvertebrate assemblage	Decrease
Richness	Number of EPT	Total number of taxa in the orders Ephemeroptera (E, mayflies), Plecoptera (P, stoneflies), and Trichoptera (T, caddisflies)	Decrease
Composition	% EPT	Relative abundance of insects in the orders Ephemeroptera, Plecoptera, and Trichoptera	Decrease
Composition	% Ephemeroptera	Relative abundance of Ephemeroptera	Decrease
Composition	% Hydropsychidae/ Trichoptera	Percent abundance of insects in the family Hydropsychidae divided by the total number of caddisflies	Increase
Composition	% *Leuctra/* Plecoptera	Percent abundance of the low pH tolerant stonefly *Leuctra* divided by the total number of stoneflies	Increase
Balance	% 5 dominant taxa	Relative abundance of the 5 most abundant taxa	Increase
Tolerance	HBI (modified Hilsenhoff Biotic Index)	Weighted sum of total taxa by pollution tolerance values	Increase
Tolerance	% Intolerant organisms	Percent abundance of macroinvertebrates with tolerance values of 0, 1, 2, or 3	Decrease
Trophic	% Scrapers	Relative abundance of the functional feeding group containing scrapers	Decrease
Trophic	% Shredders	Relative abundance of the functional feeding group containing shredders	Decrease
Habit	% Haptobenthos	Relative abundance of macroinvertebrates requiring clean, firm, course substrates (crawlers and clingers)	Decrease

mayflies and caddisflies has decreased and the abundance of stoneflies has increased over this time period. This appears consistent with other studies of these taxa in acidified waters (Peterson and Van Eeckhautz 1992; Baker *et al.* 1990; Kimmel and Murphy 1985).

Consistent with this study of the St. Mary's River, currently acidified SHEN streams may have hosted more diverse macroinvertebrate communities in pre-industrial times. Given the relatively rapid recovery time of stream invertebrate communities from disturbance, more productive and diverse communities might be among the first positive results of lower acid deposition. On the other hand, if stream water ANC declines further, we can expect macroinvertebrate diversity to decrease.

Bulger *et al.* (1999) documented for the first time the effects of stream acidification on fish for streams in SHEN. They observed effects at three ecological levels of organization: individual; population; and community.

1) Individual – In a laboratory stream both brook trout and blacknose dace avoided acid pulses (pH 5.1) by sheltering in a pH-neutral

microhabitat refuge. Both species exhibited an adaptive response to sublethal pH depressions. Because some tributaries have higher ANC than the main stem, they could act as refugia from acidic episodes. Bulger *et al.* suggested that future research sample fish movements in and out of pH neutral refugia before, during and after episodic acidification, the identification of all alkaline microhabitats accessible to fish populations and incorporating additional factors into laboratory-based avoidance experiments.

In mortality bioassays using early life stages of brook trout, there was clear evidence of high mortality rates associated with acid events (abrupt decreases in ANC and pH, together with increases in toxic aluminum concentrations) in the most acid-sensitive streams. In bioassays using brook trout eggs differential mortality could only be attributed to ANC differences – higher survival rates in high- versus low-ANC streams. Differences in mortality during storm flow events suggested that episodic acidification may be the principal mode of acidification impact on fish populations in SHEN's low-ANC streams. Since 29% of SHEN's watersheds are underlain by siliciclastic bedrock, a substantial portion of the park may experience toxic episodes.

2) Population – Brook trout density increased significantly with increasing ANC and pH. Statistical analysis indicated that no combination of habitat parameters explained the variance in trout density across streams, whereas water chemistry and habitat did. In contrast, blacknose dace densities appear to be limited more by biotic interactions (competition/predation) in streams with high species richness; where fewer species are present, blacknose dace densities appear limited by acidification stress.

   Mean weight of brook trout from higher ANC streams were similar and fish from these streams were heavier than trout from acid-sensitive streams. However, condition factors (a length/weight relationship) for brook trout in high ANC and low ANC streams were similar –fish in these streams had lower condition factors than in the intermediate ANC stream. For the low ANC stream trout, the combination of lowest condition factors and mean weights suggested that poor water quality may be affecting trout growth.

   For blacknose dace the heaviest fish with the highest condition factors were in the high- and intermediate-ANC streams, but density and biomass were only intermediate or low among these streams. The low-ANC stream consistently had the most fish, highest standing stocks, lowest average weights and lowest condition factors. The inverse relationship between mean density and mean condition factor suggested that the condition of blacknose dace was density-dependent.

The above results do not link known differences in ANC directly to population-level performance of brook trout and blacknose dace. Bulger *et al.* (1999) suggested linking resource availability with temporal variation in water quality, e.g., examination of the availability and caloric content of food organisms could be linked to changes in growth, condition and survival of fish in acidic waters.

3) Community -- Acidification has been shown to reduce species richness by eliminating sensitive species from fish communities. Since SHEN contains streams with low ANC and receives substantial acid deposition, the fish species richness of at least some of its streams may have been lowered by acidification. However, the fish community records at SHEN are too recent (begun in the 1980s) to demonstrate loss of species from streams. Nevertheless, there is a strong relationship between the number of fish species in streams now and their acid-base status, such that streams with low ANC host fewer species (Figure 21). This relationship suggests that if stream ANC is lowered in SHEN, species could disappear from SHEN streams. The blacknose dace in Meadow Run is now only rarely seen.

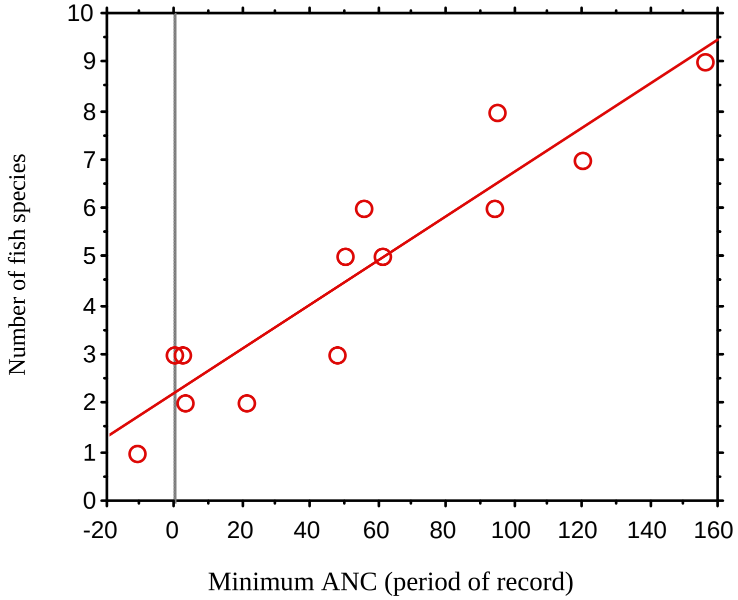


Figure 21**.** Relationship between minimum ANC and fish species richness for 13 streams in Shenandoah National Park. Modified from Bulger *et al.* (1999).

Amphibians (frogs, toads, salamanders) are recognized as sensitive indicators of environmental change for the following reasons: 1) they posses permeable skin, gills and eggs that allow the uptake of chemicals; 2) most have a complex life cycle that involves inhabiting aquatic environments as larvae and terrestrial environments as adults; 3) many hibernate or live in soils that expose them to toxic chemicals; and 4) they function as both prey and predators in aquatic and terrestrial food webs (Dunson *et al.* 1992). Increasingly, amphibians are listed as protected or sensitive species under federal and state laws.

Amphibians in the Mid-Atlantic region have not yet experienced the dramatic declines that have occurred elsewhere. However, amphibians have suffered population declines from acid precipitation and from habitat loss and alteration in this region (Freda and Dunson 1985; Freda *et al.* 1991). Mitchell (1999), using a suite of standardized sampling techniques (Mitchell 1998) inventoried the amphibian fauna over a 4-year period from Paine Run, Staunton River, and Piney River, which represented a gradient from low ANC, to moderate ANC, to high ANC, respectively. Paine Run with lowest ANC and pH values of the three streams had the highest species richness (15) of amphibians. In contrast, the Piney River with the highest ANC and pH values had the lowest amphibian species richness (8). In Paine Run, the low pH values were apparently within the tolerance limits of salamander species because early life history stages were observed indicating reproducing populations. The presence of eggs, tadpoles and metamorphs of frog species suggests that these frog species also tolerated acid levels in Paine Run. Given the indirect relationship of amphibian species richness versus ANC/pH, there appeared to be little detrimental affect from acid deposition and the lack of buffering capacity.

Grant *et al.* (in manuscript) observed a few patterns of stream salamander species assemblages in SHEN at primarily first stream order mountain stream sites. Salamanders such as *G. porphyriticus* and *E. bislineata* with extended larval stages (2 years or more) are exposed to acidic stream water for longer periods during development than desmognathine salamanders (9-month larval stage; Petranka 1998). They found shorter *E. bislineata* larvae and *G. porhyriticus* adults in siliciclastic and granitic bedrock (low and medium ANC, respectively) compared with basaltic bedrock (high ANC) suggesting that chronic stream acidification may be affecting growth or survival. Additionally, data suggested that *Desmognathus* spp. abundance may be affected by stream acidification. These relationships suggest a stream salamander response to the acid-base status of streams in SHEN. On the other hand, the lack of a consistent pattern in the distribution and abundance of adult salamanders may indicate that stream salamanders in SHEN are not strongly affected by historic or current watershed acidification. However, the relationships observed by Grant *et al.* suggest avenues of further research. More study is needed to test directly the potential effects of watershed acidification on stream salamander populations.

Rare, Threatened and Endangered Species

In 1989 the Shenandoah Salamander (*Plethodon shenandoah*) was federally listed as an endangered species. The entire geographic range of this small woodland salamander is limited to three general population isolates along north and west facing talus slopes above 2000 feet on Hawksbill, Stony Man and Pinnacles in the park's Central District.

The northern pine snake (*Pituophis melanoleucas*), corn snake (*Elaphe guttata*), eastern king snake (*Lampropeltis getulus*), and four-toed salamander

(*Hemidactylium scutatum*) are rare to nonexistent within the park at this time. There are no recent SHEN records (last 30 years) of either pine snakes or four-toed salamanders and both are likely now extirpated from the park. Corn snakes and eastern kingsnakes are both early successional stage species that have declined within the park as the forest landscape matured.

There are also a few scattered reports, including one within the past 5 years, of wood turtles (*Clemmys insculpta*) from the park's North District. This species remains unconfirmed within the park. Wood turtles are a state listed threatened species within Virginia.

There are 17 wetland/riparian plants that are considered rare in SHEN. None of these is federally listed; however, *Carex polymorpha* (variable sedge) is listed as a state endangered species. *Aster radula* (rough-leaved aster), *Ca. leptonervia* (finely-nerved sedge), and *Conioselinum chinense* (hemlock parsley) are considered likely to occur in SHEN, but their presense has not been confirmed. *Mimulus moschatus* (muskflower) was present historically in SHEN but it has not been found recently.

NATURAL RESOURCE MANAGEMENT STAFFING

The organization of the natural resource management function within the Division of Natural and Cultural Resources at SHEN is presented in Figure 22. This current organization is the result of a re-organization that occurred in 2003

From the standpoint of water resources management, in Fiscal Year 2003 0.6 FTE and $71,500 (to University of Virginia for SWAS) were allocated from SHEN base funds. From the Inventory and Monitoring base funds, $194,000 were allocated for the monitoring of fish and macroinvertebrates. This dollar figure represents 2.0 FTE plus expenditures. In Fiscal Year 2004, approximately $144,600 will be allocated to water resources management from SHEN base funds. This figure represents 1.2 FTE plus $71,500 to the SWAS program. An additional $182,000, representing 2.0 FTE will be allocated for fish and macroinvertebrate monitoring from the Inventory and Monitoring base funds.

Meeting the current natural resource objectives requires funding and human resources that greatly exceed SHEN's current Natural Resources program. Cooperative agreements and partnerships have helped to alleviate some of the inadequate support towards natural resource management. Many of the park projects that directly or indirectly relate to water resources have been summarized in the preceding sections of this report.

WATER RESOURCE ISSUES AND RECOMMENDATIONS

The National Park Service Water Resources Division and Shenandoah National Park personnel held a water resources scoping workshop in Harrisonburg, VA on November 14, 2002. A total of 20 individuals, representing a mix of state and

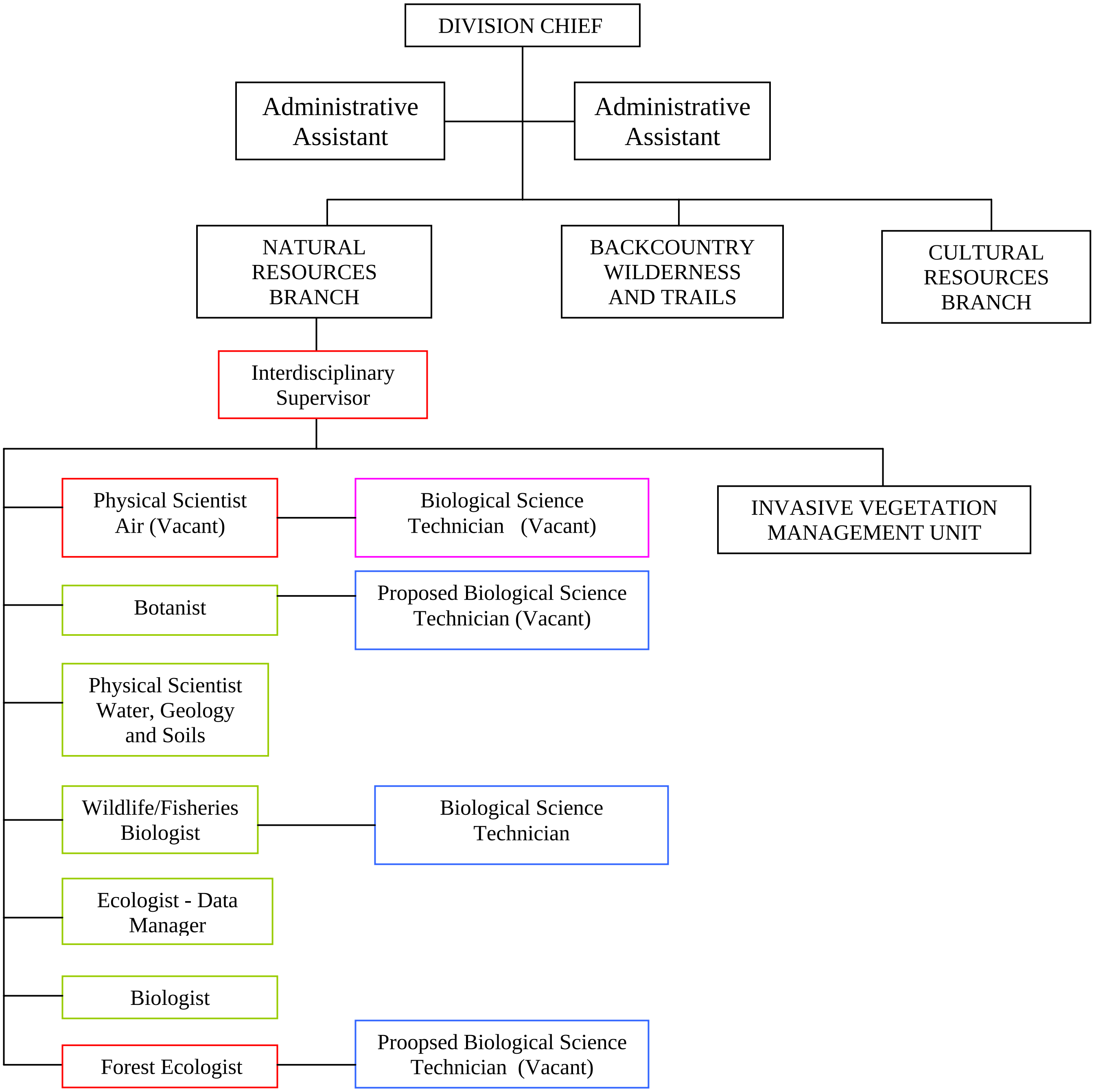


Figure 22. Diagram of the organization of natural resources management, including water resources, at Shenandoah National Park. Colors refer to grade level – Red = GS-12; Green = GS-11; Blue = GS-07; and Purple = GS-06.

federal agencies, academic institutions, and environmental organizations, attended this workshop. Invitations to attend this workshop were sent to the following organizations: National Park Service – Northeast Regional Office; U. S. Geological Survey; U.S. Environmental Protection Agency; U.S. Fish and Wildlife Service; Virginia Department of Environmental Quality; Virginia Department of Game and Inland Fisheries; University of Virginia; Virginia Polytechnic and State University; University of Maryland; James Madison University; Trout Unlimited; Friends of the Shenandoah River; and Friends of the North Fork of the Shenandoah River.

The purpose of this workshop was to familiarize the Water Resources Division with the water resources of the park and to identify and prioritize water resource issues and management concerns. Subsequent discussions were held with other federal and state personnel, as well as other water resource professionals in order to further define/refine potential water resource issues.

A total of 31 water resource issues were identified at the scoping workshop, subsequently consolidated, and prioritized (via workshop attendee votes) into six high priority issues (see Appendix C). These six issues have undergone some additional consolidation and transformation during the development of this scoping report. The six water resource issues are presented below in descending order of priority.

Inventory and Classify Wetland Attributes

Basic wetland inventory maps prepared by the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI) program are available for SHEN. However, these maps grossly under-represent riverine wetlands. Apparently, the upper reaches of stream courses were not photo-interpreted as stream channels because of the forested canopy over these streams. Additionally, many known wet areas, such as springs, are not delineated on the maps; seeps are not even represented. Given the likelihood of many more potential wet areas, including springs and seeps, especially at the junctions of valley bottoms with their side slopes, it would appear SHEN needs to inventory and classify those remaining wet areas. This is more than apparent in the potential wet areas that were modeled in the on-going study of Young et al. (2000) (see Figure 18).

The lack of comprehensive and high-quality wetland inventory maps for SHEN can have important impacts on management and protection of the park's resources. For example:

- ➢ Park staff cannot properly protect important wetland resources if they do not know of their existence. For instance, recreational traffic along trails, formal or informal, may be affecting wetland resources. Impacts cannot be fully evaluated and mitigated unless the potentially affected wet areas are identified and characterized.
- ➢ Existing threats, particularly invasion of exotic plant species, may go unnoticed. It is important to not let localized exotic plant 'hotspots' explode into massive (and perhaps irreversible) invasions.

- An enhanced inventory that locates and characterizes wetland habitats would focus other park research, resource management, and interpretation efforts.

The study by Young *et al.* (2000) is currently limited to a portion of the Central District. However, the modeling of potential wet areas in this study provides an excellent beginning to a parkwide wetland inventory. Besides providing a map of potential wet areas, this study's approach would also classify wet areas based on vegetation type. Given the potential number of wet areas parkwide (see Figure 18), this classification allows the park to field verify a subset of wetland 'vegetation types'. SHEN should work with the U.S. Geological Survey in the future to model potential wet areas for the remainder of the Central District and the other districts.

Once wet areas have been delineated, their physicochemical and biological characterizations are important to establish baseline conditions. This would provide the basis for any future wetland monitoring program. Such a characterization would depend on management needs and availability of resources. We offer the following for consideration in deciding on the appropriate level of characterization:

- Level 1 surveys are designed to identify and characterize spring resources, delineate the distribution of important species and salient aspects of their habitat and to determine unique resource challenges.

- Level II surveys qualitatively sample riparian and aquatic communities to determine community structure, and quantitatively sample salient physicochemical elements to identify aquifer affinities.

- Level III surveys quantitatively sample additional physicochemical elements to determine aquifer dynamics. Quantitatively sample riparian and aquatic communities and habitats to determine spatial and temporal variation in environmental and biotic characteristics and to quantitatively determine biotic and abiotic interactions.

With regard to the Young *et al.* (2000) study, we offer a note of caution to SHEN. This study is using vegetation field plots to classify potential wetland vegetation according to the U.S. National Vegetation Classification System (USNVC). This classification system was recently adopted as the Federal standard guiding primarily terrestrial vegetation mapping at federal agencies. It is a hierarchical classification system defining vegetation communities by structure at broad levels then floristically at finer levels. However, the NPS standard for wetland classification (Procedural Manual #77-1: Wetland Protection) is the Cowardin *et al.* (1979) system of the U.S. Fish and Wildlife Service – a system that looks at much more (e.g., hydrology) than just vegetation in classifying wetlands. Therefore, field verification of potential wet areas identified under the Young *et al.* methodology should be by a field crew knowledgeable in the Cowardin system. At the same time the field crews could ground truth the under-represented riverine wetlands and extend the riverine classifications with SHEN.

Springs and seeps are relatively small aquatic and riparian systems that are maintained by ground water flowing onto the land surface through natural processes (Hynes 1970). They are classified as wetlands under the Cowardin *et al.* (1979) system; springs are also considered a special form of lotic system (Hynes 1970). They occur where water reaches the earth's surface through fault zones and rock cracks that occur when water creates a passage by dissolving rock. Spring hydrology is influenced by the characteristics of regional and local geology and how water moves through an aquifer. The size of an aquifer depends on regional and local geology and climate.

Springs and seeps occur in many sizes. Seeps are small springs that support small amounts of riparian vegetation that is adapted to drier conditions, and they often dry up on a regular basis. Springs may also be small but they have larger aquatic habitats, dry less frequently, and generally support larger riparian zones with species that rely on moist soils. Springs are frequently categorized by the morphology of their source. Limnocrenes are sources where water flows from large deep pools, helocrences are marshy and bog-like, and rheocrenes flow into a confined channel (Hynes 1970).

Springs and seeps are distinctive aquatic habitats – each may be a unique combination of physical and chemical conditions (Hynes 1970). When compared to streams their flow and temperature are more constant over an annual cycle and they have a more integral connection with ground water. They can be cold, warm or hot. Dissolved oxygen concentrations are frequently very low in hot springs and high in cooler springs. At spring sources, dissolved oxygen concentrations are frequently low and increase downstream with exposure to the atmosphere (Hynes 1970). Conductivity may also range from very low to very high in some harsher environments. Odum (1971) calls a spring the aquatic ecologist's natural constant temperature laboratory because of the relative constancy of the chemical composition, velocity of water and temperature.

Though their biotic communities are usually less diverse than stream ecosystems, springs are often habitat for endemic species because they are benign habitats that have served as refugia during periods of climatic variability (Minckley 1963). Geological and hydrogeological settings are also important factors that regulate the structure of aquatic communities in springs.

Within a spring system, environmental variation is typically lowest near the source where environments are comparatively stable and it is greatest downstream (Deacon and Minckley 1974). As a result, the composition of source and downstream communities is usually different, and species that occupy the source usually prefer habitats that are unique to this area and they are frequently absent from downstream habitats.

Previous studies of springs in SHEN were limited in number and scope (Dekay 1972; Plummer *et al.* 2001). Dekay (1972) analyzed 30 springs for public water supplies. From the standpoint of permanency of flow, 18 occurred on basalt bedrock, 10 on granitic and two on siliciclastic. This difference appeared to be a function of differences in the residuum depth among the bedrock types.

Plummer *et al.* (2001) found that shallow ground water, which is associated with springs and seeps, is relatively young in age (0-3 years) compared to well water from fractured rock (up to 25 years). Additionally, there were transient responses in temperature and conductivity in spring discharge within several hours of large precipitation events. This suggests that water from the study springs is closely associated with recent infiltration of precipitation into shallow residuum, therefore making them vulnerable to contamination.

The park and SWAS program personnel recently collaborated on a PMIS project statement that proposes an inventory and characterization of the known springs in SHEN. This study would extend the work of Dekay (1972) and Plummer *et al.* (2001) by suggesting that for springs over shallow residuum, water quality should be similar to streams draining watersheds associated with the same bedrock type. Thus, the relationships between water quality and bedrock for springs should correspond to the relationship observed between water quality and bedrock type for park streams (Lynch and Dise 1985). For springs derived from older ground water from rock fractures, water quality will probably differ from the relationships observed for streams and springs associated with residuum.   Thus, water quality may provide a basis for discriminating between spring water sources.

The significance of correspondence between spring and stream water composition in the park is that spring waters in many areas of the park may be subject to the same effects of acidic deposition as streams. Because acidic deposition is largely mediated by contact with soils and other surficial materials, the acid-base status of springs that are associated with shallow residuum may have been altered by historic acidic deposition and may be a response to changing acidic deposition levels. Springs associated with deeper bedrock may not be responsive to acidic deposition.

The intent of the spring inventory study is to inventory and characterize, over a 2-year period, the physical, chemical and biological aspects of the known springs (70-100) throughout the park, and use that information to group (via cluster analysis) similar springs such that there will provide an informed basis for the design of a long-term monitoring program. This study is an excellent beginning towards an understanding of the ecology of known spring areas in SHEN and the use of multivariate statistics to partition the inherent heterogeneity of spring areas into groupings is appropriate – especially for establishing a long-term monitoring program with limited resources. However, the discrepancy between the number of known springs and the unsubstantiated 850 known surface-water sources cited by DeKay (1972) is too large to ignore – and as Figure 18 suggests, the number of potential spring/seep areas may exceed this number. Given that springs/seeps are distinct aquatic habitats often with individual uniqueness and that they may be experiencing loss of biodiversity from acidic deposition, it would appear important that SHEN attempt as complete an inventory as possible for springs/seeps. This is not to say that SHEN should not establish some spring monitoring program after the proposed 2-year known spring inventory. But information obtained from a continued inventory of spring/seeps may further refine the initial spring groups as well as determine new groups. That is, the more that SHEN knows about its population of springs/seeps, the more it will know about the range of spring/seep conditions. A long-term monitoring program will then be able to better account for the variation in responses to changing environmental conditions.

Given the potential number of springs/seeps (≥ 850), the task is quite daunting especially from a field-based search and identification procedure. More practicable is for the spring/seep inventory task to take its lead from the ongoing wetlands inventory and identification study (Young *et al.* 2000; see page 73). In this case, the methodology, a combination of GIS data, GIS digital elevation modeling and infrared and radar imagery, provides potential wet areas. These potential wet areas can be prioritized for the likelihood of spring/seep presence and then field verified. Once spring/seep locations have been determined, any of the three levels of characterization, discussed above for wetlands, can be used to obtain baseline conditions.

With regard to establishment of a long-term monitoring program for springs/seeps, we offer the following for consideration. A realistic and as yet largely unappreciated monitoring tool would be biomonitoring of the organisms living in natural ground water outflows. Because the fauna of springs live there permanently, integrating the effects of geology, vegetation, and climate in space and time, they can potentially provide an additional and especially accurate index of ground water quality and the history of individual aquifers. Such assessment integrates the effects of contamination. In this sense the biological study of springs could provide a very effective tool for the management and quality control of ground water resources.

Re-Evaluate Existing Water-Based Monitoring Programs

SHEN recently (winter of 2003) initiated a review of its long-term ecological monitoring program (LTEM). Participants (park staff, cooperators, stakeholders) at a workshop agreed to begin with a fresh conceptual design planning effort for monitoring that would build on past work. Such a planning effort would include objective setting, development of conceptual ecological models, articulation of ecosystem stressors, preparation of criteria that would be used for selection of program components/indicators/attributes, and finally documentation of the selection of those components. Once the conceptual design effort is complete, programmatic changes could occur (discontinue some programs, start new program components, etc.). Generally speaking, an integrated approach to review and revision of the park’s air, water and aquatic biota monitoring program goals and objective should benefit the understanding of aquatic ecosystem status and trends, relevancy to park management, and overall monitoring program efficiency.

From our perspective, it is prudent for SHEN to conduct a review of its LTEM program at this time. The only other SHEN LTEM review was conducted in 1996 by the Washington Office of the NPS (U.S. Geological Survey 1996a). It appears that the conclusions from that review were never disseminated to park staff in 1996; current park staff became aware of this review only recently. Additionally, much has transpired within the SWAS program since 1996 (e.g., Bulger *et al.* 1999; Sullivan *et al.* 2003b).

An extensive review of the water resources component of the LTEM program is beyond the scope of this report. However, we offer the following observations, suggestions, and/or recommendations for consideration during the LTEM review period. The majority of these offer no new revelations and many are probably self-evident. What is important is that these observations are codified in this NPS Water Resources Division document.

- From our perspective the SWAS program through the University of Virginia has been and continues to be an effective ‘partnership’ for SHEN. Over the years, the design of the SWAS program evolved to reflect increased understanding of biogeochemical processes in SHEN watersheds. The current program appears to seek a balance between efficient use of available funding and effective detection and understanding of change. Any erosion of funding will inevitably compromise the effectiveness of the program. Table 11 provides a breakdown of the annual costs of the SWAS program over a 10-year period (1993-2002). The long-term commitment of University of Virginia investigators and the efforts by the NPS and others to obtain funding for these investigators have made the association work.

  An in depth look at Table 11 demonstrates just how effective the SWAS program has been in cobbling together funding from three sources (SHEN, Other NPS, and University of Virginia). The cost commitment by SHEN has been fairly stable with the exception of 1997 – excluding 1997, funds from SHEN ranged from 20.14 to 28.88% of the total amount available to SWAS. Also noteworthy is that the SHEN/University of Virginia partnership that is SWAS has been successful in obtaining ‘Other NPS’ funding, although that funding has dropped off since 1997. Perhaps in response to the drop in ‘Other NPS’ funding, the University has been successful in obtaining additional funding from non-NPS sources, especially since 1998. Previous to 1998, non-NPS sources were essentially non-existent.

  The average proportion of funds provided to SWAS from the three sources over the time period was 26.33% from SHEN; 34.89% from Other NPS; and 38.77% from the University of Virginia. However, from 1997-2002 these proportions changed substantially: 25.18% from SHEN; 10.9% from Other NPS; and 55.29% from the University of Virginia. Given the erosion of SHEN’s proportion (coupled with the erosion due to inflation), the drop-off of Other NPS funds, and the lack of any guarantee for further non-NPS

Table 11. Breakdown of annual costs associated with maintaining the Shenandoah Watershed Study. Data provided by Rick Webb of the University of Virginia.

YEAR	SHEN[1]	IN-KIND	OTHER NPS	OTHER	SUM	SHEN %	IN-KIND %	OTHER NPS %	OTHER %
1993	41097	12955	144366	0	198418	20.71	6.53	72.76	0.00
1994	43265	13656	144366	0	201287	21.49	6.78	71.72	0.00
1995	46897	15253	144366	0	206516	22.71	7.39	69.91	0.00
1996	58916	21948	158695	0	239559	24.59	9.16	66.24	0.00
1997	98470	26810	14329	20923	160532	61.34	16.70	8.93	13.03
1998	74910	16061	14329	179669	284969	26.29	5.64	5.03	63.05
1999	77155	16061	0	289809	383025	20.14	4.19	0.00	75.66
2000	81156	16894	35103	147885	281038	28.88	6.01	12.49	52.62
2001	77155	16061	120115	110900	324231	23.80	4.95	37.05	34.20
2002	77155	15924	120115	74845	288039	26.79	5.53	0.00	25.98
TOTAL	676176	171623	895784	824031	2567614				
AVERAGE						26.33	6.68	34.89	32.09

SHEN = SWAS Program base funding from SHEN
IN-KIND = Waived U. of Virginia Overhead (25.5 to 43% over the 1993-2002 period)
OTHER NPS = NRPP projects
OTHER = EPA, USGS, Va Dept of Forestry

[1] Information provided by the park (S. Spitzer, pers. comm.) for five of the years does not match these figures. However, the above figures maintain the relative difference between years.

funding, the SWAS program could be at a crossroads in maintaining a sustainable program. Furthermore, SHEN is facing more budgetary constraints that could further erode its proportion. All of this runs counter to our recommendation that SHEN increase its annual contribution to the SWAS program. Our recommendation is based on: 1) the success and productivity of the partnership between SHEN and the University of Virginia; and 2) the need (discussed below and for other issues) for SHEN to change the spatio-temporal monitoring framework of SWAS, increase the use of biological indicators, and add water quality parameters to the suite of parameters already monitored.

- Perhaps the biggest reason for the cost-effectiveness of the SWAS program is that the monitoring framework substantially partitions the inherent spatial and temporal variability existing among SHEN watersheds. The ability to successfully and meaningfully partition ecosystem variability is an important first step in the development of any monitoring framework. The SHEN stratification is based on differences in the watershed properties that determine biogeochemical conditions and stressor-response relationships. The successful SWAS strategy of distributing hydrochemical monitoring efforts within the context of a lithologic classification system has gained acceptance as a model for watershed monitoring in other park units and national forests. Temporal variability is captured by collecting water quality data at varying frequencies within each bedrock class. The SWAS monitoring framework should continue to be the basis of long-term monitoring of water quality at SHEN. However, the SWAS watersheds make up only a fraction of the total number of watersheds in SHEN (Figure 10). This begs the question of what about the status and trend of water quality in the streams of other watersheds? Given current funding constraints, it would not appear possible to extend the SWAS program to streams in other watersheds. A solution may lie with the existing LTEM fish and aquatic macroinvertebrate monitoring programs. These programs currently measure physicochemical water quality and habitat parameters, and often sample streams that are not part of their programs (Figure 19a, b, c). We would suggest the development of a periodic sampling program (possibly couched in a rotating design) of streams that are not part of these LTEM programs. The primary purpose of such sampling should be to confirm the park-wide applicability of stream water status determined through the more intensive and regular data collection obtained for the representative SWAS watersheds.

- The focus of the SWAS monitoring program continues to be the collection of water quality data from the lower reaches (i.e., lower elevations) of watersheds. This is undoubtedly a function of accessibility. However, the LTEM review (U.S. Geological Survey 1996a) recommended water quality sampling at headwater, middle, and lower stream reaches. This recommendation is rooted in the observation that acids deposited on the landscape can be partially neutralized by the time they reach lower elevations.

  We agree with the spirit and intent of this LTEM review recommendation, but given the reality of eroding budgets, it would not appear sustainable. From our perspective, a more sustainable design would hinge on water quality sampling at headwater and lower stream reaches in the SWAS watersheds. In the long term, we do not feel that the added information from middle reach locations would be cost efficient for the SWAS program. There would also appear to be little that park management could gain. The continued sampling at lower reaches would preserve the continuity of the long-term data set.

  Since most of SHEN's streams are zero to first order and the park's annual average snowpack is relatively low, headwater springs and seeps are the best sampling location at higher elevations in the SWAS watersheds. However, such a headwater sampling program would be constrained by site access. Currently, the SWAS program includes sites that can be accessed with generally short hikes. The hiking distances that would be involved in conducting a routine headwater sampling program would limit both the number of sites that could be sampled and the type of instrumentaion (e.g., discharge gages and automatic samplers) that could be installed and maintained. Another issue is the intermittent nature of surface flow at the higher reaches of most SHEN streams.

Given the funding and logistical constraints to routine monitoring of headwater areas, it may, alternatively, be necessary to conduct periodic, spatially intensive surveys of SWAS watersheds similar to those comprehensive surveys of multiple SWAS watersheds conducted in the 1990s, such as the Fish in Sensitive Habitats project (Bulger *et al.* 1999). Such surveys sampled both the upper and middle reaches of watersheds.

Currently, the SWAS program conducts weekly sampling in six watersheds and quarterly sampling in eight watersheds (Figure 16). Although the park has recently expended limited resources to provide upgrades at weekly sampling sites, it would appear prudent to consider conversion of all weekly sampling of lower reaches to quarterly sampling at headwater and lower stream reaches. Or weekly sampling could be limited to only one watershed per bedrock class. This would partially offset the additional costs associated with the sampling of headwater reaches.

It is important to consider that weekly and episodic sampling, especially in conjunction with the measurement of continuous discharge, provide information about extreme conditions and fluxes that cannot be obtained through quarterly sampling. Episodic and weekly sampling provide information on the extreme conditions that are ultimately the limiting conditions for aquatic biota. In addition, the understanding of watershed processes is dependent upon quantification of watershed fluxes, something that cannot be obtained through a less-intensive quarterly sampling program. It is actually the understanding obtained through this process-level component that has guided the development of the SWAS program’s spatially and temporally hierarchical monitoring framework design (R. Webb, U. of Virginia, 2004, pers. comm.).

Another aspect of reducing the frequency and dimensions of data collection would be loss of power to detect change in both concentrations and fluxes at individual sites.

It is our opinion that SHEN needs to develop monitoring program objectives and desired outcomes (see below) that will help in deciding the appropriate role of weekly watershed monitoring in addressing management concerns and needs. Eroding budgets will further force hard decisions regarding a total or limited reduction in watersheds that are monitored weekly. From our perspective, continued weekly sampling in SHEN to understand watershed processes and episodic acidification should be more appropriately considered in the research realm and not part of the base-funded SWAS monitoring program. Such a scenario would ensure long-term monitoring of sensitive resources and then appropriate research to fill in the knowledge gaps.

- Given the funding structure of the SWAS program and the past and present mix of specialties among park staff, there appears to be an over reliance on University of Virginia scientists for water resource stewardship at SHEN. The water monitoring program at SHEN should be a cooperative venture with the University of Virginia, where park staff are members of the monitoring/research team, intimately involved with day-to-day decisions, co-authors on journal publications and protocol development, and members of graduate student research committees. Without such involvement and direction by park staff, the program exists on 'autopilot' and park involvement is on an *ad hoc* basis. More often than not this leads to unlinked management and monitoring objectives. Interestingly, the previous LTEM program review (U.S. Geological Survey 1996a) suggested that the then weaknesses of the water monitoring program could have been prevented if the program had access to a full or part time hydrologist. For the interim, we suggest more involvement by Alan Ellsworth, NPS regional hydrologist, with the SWAS program. For the long term, the permanent addition to park staff of a dedicated water resource professional, such as a hydrologist or aquatic ecologist, is recommended.

- Any monitoring program needs to develop clear objectives. Identifying monitoring objectives has implications for the type, intensity and scale of measurements. Having a clearer idea of desired products and outputs should be an aid in the development of objectives. The eventual monitoring design should be appropriate to the objectives. Monitoring program objectives should also be clearly linked to management questions – without more specificity, the resulting monitoring program is in danger of developing data that do not respond to specific management concerns and provide information explicitly helpful to managers.

  For managers to develop a commitment to long-term monitoring, it has to be seen as answering, even if preliminarily, questions about current management issues and trends and conditions, based on the best available hypotheses about appropriate triggers of concern. In addition, a common view of the respective roles of research and monitoring is needed.

  The need to annually synthesize data and results and report them to managers, not just accumulate data, is extremely important. If monitoring objectives relate to meeting managers needs, then reporting to managers is equally as important as developing data that are responsive to managers' questions.

- Because of a lack of conformity with a Virginia Department of Environmental Quality criterion for pH data use established in 40 CFR 136, SHEN streams that are consistently below a pH value of 6.0 could not be listed as impaired on the State’s 303(d) list. (It is interesting to note that the LTEM review in 1996 called for SHEN staff to determine whether the water samples taken under the SWAS program met accepted State sampling criteria.) Because of this situation, SHEN is interested in any other recognized avenues for the assessment of impairment.

In Virginia the designation of aquatic life use for a waterbody includes the propagation, growth, and protection of a balanced, indigenous population of aquatic life which may be expected to inhabit the waters. Support of aquatic life use can be determined by the assessment of conventional parameters (e.g., pH); toxic pollutants in the water column, toxic pollutant analysis of sediments, nutrient analysis, and /or biological assessment of benthic communities (Virginia Department of Environmental Quality 2002). Benthic assessments are the prominent aquatic life use determinant in Virginia (Virginia Department of Environmental Quality 2002), and VDEQ does not consider for use in assessment any non-agency biological data other than from benthic communities.

After review and approval of monitoring and QA/QC protocols, VDEQ will consider data generated by other State and Federal monitoring programs. Presently, VDEQ has established a water quality data sharing agreement with the US Forest Service for George Washington and Jefferson national forests. The US Forest Service program has collected macroinvertebrate data from approximately 500 monitoring stations within the two national forests. Sampling for macroinvertebrates is conducted using the same collection methodology (Rapid Bioassessment Protocol II -- Pflakin *et al.* 1989) that state biologists use in VDEQ’s ambient biomonitoring program. Therefore, the raw data collected by the USFS should be highly comparable with DEQ data. The U.S. Forest Service has used the Macroinvertebrate Aggregated Index for Streams (MAIS -- Smith and Voshell 1997) to assess these raw data and make initial water quality interpretations. MAIS is a nine-metric index – these same metrics are also part of the 12-metric index used by Moeykins and Smith (2002; see Table 10).

Given SHEN’s extensive benthic macroinvertebrate monitoring program, it should seek State approval of this program and supply benthic data to the State for the assessment of impairment. Once the problem surrounding the use of SWAS pH data is resolved, either through the methodology of Galloway and Webb (2003) or through the use of a different field methodology, the combination of pH with benthic community assessments will provide a powerful tool for the determination of impairment. However, SHENs’ benthic collection methodology is quantitative (Voshell and Hiner 1990), whereas that of Rapid Bioassessment Protocol II should be considered qualitative to semi-quantitative. Therefore, the methodologies are not comparable as is the case with the U.S. Forest Service. This may be a stumbling block, but should not be a road block to State approval of SHEN’s benthic monitoring program. On the positive side, SHEN has used MAIS as an analytical tool (Demarest 2001). MAIS is quite similar in structure and function to those metrics used in Rapid Bioassessment Protocol II (Pflakin *et al.* 1989).

Restoration of Streams Impacted by Acidic Deposition

In 1999, the U.S. Forest Service began a restoration project in the St. Marys River, a nearby lotic system that has experienced the effects of acid deposition. To neutralize acidity temporarily (5-10 years), 140 tons of limestone sand were added to the river and five tributaries with the goal of improving ecosystem health and biodiversity. From 1998 to 2001 stream water quality improved (increased ANC) and macroinvertebrate and fish species richness increased.

There is a perception among park staff that the 'success' of this restoration effort may bring pressure upon SHEN to 'restore' some of its stream systems. However, this 'restoration' of the St. Marys River is an all too common ecological misstep by land management agencies concerned with only the short term. Webb (2002) succinctly states a position on this subject that SHEN should subscribe to:

> *This is not ecosystem restoration. One cannot ignore the terrestrial and aquatic linkages of the system. For most naturally functioning forested mountain watersheds the primary source of acid neutralization is the accumulated supply of exchangeable base cations in the soil. That is, variations across streams in acid base status are due in large part to variations in base-cation availability in watershed soils, which in turn is initially determined by the properties of the rocks from which the soils are derived.*
>
> *Although repeated liming of streams like the St. Marys River may improve conditions in the streams, the loss of base cations from watershed soils will continue as long as elevated acidic deposition continues. The loss of base neutralization capacity from watershed soils should properly be considered the fundamental, long-term impact of acidic deposition on watershed ecosystems. This is an impact that can only be mitigated by reducing acidic deposition.*

However, given the long-term nature of the harm caused by base cation depletion, it may be appropriate for SHEN to consider replacement of soil bases through whole watershed liming or fertilization (R. Webb, U. of Virginia, 2004, pers. comm.). Any such undertaking would be experimental and the range of potential effects is uncertain. Pilot investigations involving a broad multidisciplinary team would be required.

Impacts of Changing Chemical Composition Streams on Aquatic Biota

Over the past two decades our understanding of atmospheric pollution and its effects on the environment has gradually developed. This increased understanding is in large part the product of long-term ecological and atmospheric studies, such as those conducted at SHEN.

Combining newly acquired data with long-term datasets developed over decades at individual research sites, incremental advances have been made over the last 10 years in refining our understanding of the ecological effects of acid deposition, and the chemical and biological mechanisms through which those effects manifest themselves. However, we do not fully understand acid deposition and its impacts on surface water chemistry and biology, soils and forest ecosystems. Furthermore, physical climatic variability can complicate our ability to detect ecological changes that may result from declines in atmospheric deposition. Variations in precipitation from year to year and in relation to topography can result in uncertainty regarding deposition rates and trends. [This argues for the need to collect spatially distributed information concerning deposition, compositon, and amount.] Changes in rates of ecological processes can be affected both by climate and acid deposition. As with most complex interactions, at least as many questions remain as have been answered.

In order to evaluate the effectiveness of environmental policies and programs, a firm commitment is needed to long-term monitoring programs that helps in assessing the status and trends of ecological systems, as well as discerning when and where recovery is evident. Monitoring data allow evaluation of the effectiveness of emission controls, exploration of dose-response relationships, validation of predictive models, and understanding of watershed processes. Continued long-term monitoring of wet deposition, dry deposition, stream flow, water chemistry, soil chemistry and biological condition are essential for understanding and evaluating the response of ecological systems to acid deposition.

We have developed a record of chemical response of surface waters and watersheds to acid deposition, but we have a limited foundation to determine if long-term changes in acid deposition are leading to long-term biological responses. Our present understanding of biological trends is not based on biological data, because sustained biological monitoring rarely occurs. Instead, we must extrapolate biological effects from monitoring of chemical indicators (e.g., pH, ANC, sulfate, and nitrate) combined with an understanding of the ecological effects of chemical changes. For example, we might expect recovery of aquatic ecological systems if we detect increasing pH and decreasing inorganic aluminum concentrations. Chemical and biological interactions within the ecosystems, however, may complicate simple cause and effect relationships like these. Moving beyond such indirect analyses demands developing and refining biotic indicators for evaluating acidification and recovery of aquatic ecosystems. Therefore, including biological resources in monitoring activities is critical if we are to truly advance our understanding of ecological effects of acid deposition. Furthermore, we can evaluate the effectiveness of past and future clean air legislation only by undertaking selected biological assessments.

Scientists now recognize that complete recovery of aquatic ecosystems will not occur until the sublethal effects of acidification on aquatic organisms are minimized or eliminated. Although seldom directly fatal for large-bodied aquatic organisms, sublethal chronic effects such as impacts on the food chain, biodiversity, and overall ecosystem health are key factors in determining the long-term impact of acid deposition on aquatic life.

Presently used ecological indicators of acidification and recovery are adequate to measure aquatic responses to changes in deposition. These include chemical indicators; indicators focusing on groups or assemblages of species (i.e., multimetric indices); and indicators of sublethal effects on organisms. Chemical indicators are the only widely used indicators.

Given the ongoing review of SHEN's LTEM program, it is appropriate to consider the incorporation of biological indicators into the SWAS program. In particular the fish and aquatic macroinvertebrate monitoring programs and past studies (e.g., Bulger *et al.* 1999) offer the ability to develop indicators of sublethal effects as well as multimetric indices. We suggest a better integration of these monitoring programs with the SWAS program. A step in this direction is the analysis of relationships and trends from existing data conducted by Sullivan *et al.* (2003b). The aquatic monitoring program continues to collect extensive, quantitative data that are amenable to the use of multimetric indices. One such index (MAIS) is already in use by the park. Another could be developed from the metrics contained in Table 10. Such indices could be used to understand biological effects of both chronic and episodic acidification.

Bulger *et al.* (1999) noted that the blacknose dace is perhaps the most sensitive fish species to acidification. Given the body of information contained on this species in Bulger *et al.*, it should be possible to develop (or develop with additional research) population-level indicators of sublethal effects. Once developed, the fish monitoring program would be the appropriate avenue for data collection and analysis. Such population-level indicators for blacknose dace may not be as effective at understanding the effects of both chronic and episodic acidification; however, additional research could address their utility. The U.S. Geological Survey (1996) intimated such an approach with blacknose dace. Furthermore, it suggested the use of multi-species population-level indicators. That is, determine if several macroinvertebrate species have similar population-level responses to acidification as blacknose dace. Combining such multi-species indicators that cross structural and functional ecological 'lines' would be most useful.

In the future the assessment of biogeochemical variability of SHEN's streams from the regional perspective of acid deposition will, in all likelihood, need to be placed in the larger context of climate change. Current model projections predict that the climate of the Mid-Atlantic region will become warmer and wetter (Moore *et al.* 1997; Gleick *et al.* 2000;> http://www.epa.gov/maia/html/globwarm.html <). A warmer atmosphere would influence the occurrence and severity of acid deposition. Many chemical reactions that lead to acid deposition are affected by temperature. For example, increases in air temperature could change stream sulfate concentrations during the growing season (Moore *et al.* 1997). Increased air temperature can enhance sulfate reduction causing a decline in stream sulfate concentrations and an increase in ANC. Also, a longer growing season would increase the time period when sulfate reduction influences stream chemistry. Nitrogen concentrations could also change dramatically if nitrogen cycling is altered. In the Northeast the highest annual average nitrate concentrations and yields coincided with highest average annual air temperatures (Moore *et al.* 1997). This relationship suggests that soil microbial activity increased during warm years resulting in higher concentrations of nitrate in soil and surface waters.

Climatic projections from global circulation models for the next 100 yrs show temperature increases in the southern part of the Mid-Atlantic ranging from 3.6^{o} C in summer to 4.4^{o} C in autumn (Moore *et al.* 1997). Precipitation is expected to increase in winter and spring, but the models predict decreases in summer and fall. Overall, from a water budget perspective, there should be a shift to drier conditions because the increase in temperature will result in higher evapotranspiration rates that offset any precipitation increase. These changes in temperature and precipitation could cause the climate of the Mid-Atlantic to become less variable in terms of fewer rapid changes in weather rather than reduced extremes (Moore *et al.* 1997). Summer thunderstorms will likely increase in intensity, and the time between storms will increase. This would lead to greater variability in stream flow (especially in summer) with smaller streams experiencing more flash flooding as well as longer periods of low flow.

Less frequent but more severe summer storm events could result in increased episodic acidification. The period of dry deposition and soil microbial action between storms will increase and the wash-out of sulfate during increased runoff will result in more severe sulfate pulses during storms. Similarly, the dilution of base-cation concentrations during storm events should also increase. Therefore, increased acidity during storm events could occur under warmer, drier conditions of the future.

The potential effects of climate change on mercury toxicity and propagation through aquatic foodwebs could affect the contamination problem. Higher temperatures and metabolic rates will probably increase biomagnification and bioaccumulation rates, increasing contaminant levels in all organisms (Moore *et al.* 1997). Foodweb alterations from increased temperatures and toxicity (e.g. loss of species) may affect energy transfer to higher trophic levels and, thus, mitigate the transfer of mercury. Also, a change in food chain length may also affect biomagnification. Mercury concentrations in top predators may be greater where food chains are long similar to that observed for PCBs where top predators in short food chains have lower body burdens (Moore *et al.* 1997).

Clearly, there is a need to develop analyses, experimental designs and aquatic indicators that distinguish between climatic and anthropogenic effects (acid deposition) on SHEN's streams. Moore *et al.* (1997) suggested that reductions in the flow of headwater streams may provide an indicator or early signal of climatic warming. Such a hydrological indicator would be particularly useful for SHEN because it would be less likely to be affected by direct anthropogenic stressors than biological or chemical indicators. Additionally, it could be argued that the type of spatially and temporally distributed hydrochemical monitoring program maintained by the SWAS program provides a reasonable probability of identifying and understanding multiple and possibly unexpected causes of biogeochemical change that may affect SHEN watersheds. The effect of the gypsy moth infestation in the late 1980s and early 1990s provides a case in point. The dramatic, but transient, change in nitrogen and other constituents in SHEN streams would have been difficult to interpret properly without the long-term record and intensity of data collection provided by the SWAS program. This case is also an argument for the retention of some weekly watershed sampling as part of the base-funded SWAS program.

Inventory of Impacts on Water Quality

There has been a lot of effort toward assessing the influences atmospheric deposition has on water chemistry in SHEN, e.g. Sullivan *et al.* (2003). Equally important is an understanding of water quality impacts from the park's existing infrastructure and operations. An inventory of park structures and activities (past and present) that influence or have the potential to influence water quality in SHEN is needed – Table 12 is the beginning of such an inventory. Once identified, management and monitoring of these point and non-point pollution sources through best management practices (i.e., controlled/treated parking lot runoff, secondary petroleum tank containment, etc.), should be employed to minimize threats to the park's sensitive aquatic habitats, visitors, and potable water supplies.

In the original 1930s development and construction of SHEN, most buildings, campgrounds and other facilities were located and constructed in the higher altitudes along Skyline Drive, where the most scenic parts of the park are located (Plummer *et al.* 2000). These high-altitude locations are the top of the watershed, maximizing the influence from contamination on SHEN's aquatic environments and water supplies down gradient. Many of the perennial streams in the park contain sensitive habitat for several species, including brook trout. Obviously, surface contaminants (accidental spills, untreated runoff, etc.) and shallow subsurface contaminants (leaking underground storage tanks, septic systems, etc.) can influence surface water chemistry in local streams, but ground water in SHEN is also very susceptible to contaminants. The relatively young age of ground water recorded at higher elevations in SHEN is indicative of the fast ground water travel times, and therefore high susceptibility to contamination from accidental spills or releases in the recharge area of the aquifer (Martin 2002).

A major structure in the park that is a source for pollutants is Skyline Drive. This road traverses the entire length of the park along the crest of the Blue Ridge Mountains. Since the road is at the top of the watershed, it has the potential to

Table 12. Potential point and nonpoint source impacts on water quality in Shenandoah National Park (Dave Demarest, SHEN, pers. comm. 2003). Not included are park roads, fire roads, trails, towers, and developed areas.

RIGHTS OF WAY MAINTAINED BY NON-NPS ENTITIES

Gas Lines

- Sawmill Run
- Swift Run

Power Lines

- Loft Mountain
- Simmons Gap
- Swift Run
- Sawmill Run
- Pinnacles
- Big Meadows
- Lewis Mountain
- Panorama
- Piney River
- Mathews Arm/Elkwallow
- Dickey Ridge
- Front Royal
- Head Quarters

State Roads

- 661
- 659
- 663
- 600
- 625
- 759
- 669
- 33
- 340
- 211

NATIONAL PARK SERVICE FACILITIES AND SITES

Drain Fields (There is some discrepancy among staff as to actual number)

- Dickey Ridge
- Piney River
- Elkwallow
- Head Quarters
- Pinnacles Lab
- Pinnacles Picnic Area
- White Oak Cabin
- Lewis Mountain
- Swift Run Entrance Station

- Simmons Gap
- Waynesboro Entrance Station
- South River Picnic Area

Pit Toilets (Total number is unknown)

- Elkwallow
- Hughes River Gap
- Dundo Group Picnic Area
- South River Picnic Area

Known NPS Sanctioned Landfills

- Mathews Arm (possible DDT dump site)
- SHEN Headquarters (significant quantities of paint)
- Pinnacles
- Big Meadows (Army used Big Meadows as a troop raining ground in the 1940s)
- Baldface Mountain
- South District locations unknown

CCC-era Camp Landfills (known sites – many other sites are suspected)

- Headquarters
- Pinnacles
- Baldface Mountain
- Big Meadows
- Skyland
- Camp Rapidan and Marine Barracks

Sewage Treatment Plants (all tertiary)

- Mathews Arm – discharges to Keyser Run drainage
- Panorama – discharges to South Fork Thornton River drainage
- Skyland – discharges to Kettle Canyon drainage
- Big Meadows – discharges to Lewis Run drainage
- Loft Mountain – discharges to Eppert Hollow Run (tributary to Big Run)

Known Spills

- Headquarters – in early 1990's gasoline seeped through tile system under maintenance yard to Shenk Hollow (non-NPS property)
- Simmons Gap – in late 1990's petroleum noticed below maintenance yard
- Panorama -- in April 2002 transformer in power line next to wastewater treatment plant blew up over wetland area. (Allegheny Powers Haz Mat crew from Pennsylvania conducted 'clean up')

---

serve as a non-point source of road runoff that could affect nearly all headwater streams, ground water, and associated biota on both the west and east flanks of the Blue Ridge Mountains. With up to 1.8 million visitors per year, traffic on Skyline Drive is particularly heavy during the peak leaf-viewing season (October), when visitation increases by about 25%. As such, there may be a seasonal variation in the concentrations of road runoff constituents from vehicular traffic (Rice and Jung 2003). This issue extends to the parking lots in SHEN too.

The combustion process of vehicles and the wearing of vehicles, road surface degradation, and application of road maintenance chemicals (deicing salts) disseminate pollutants into the environment. Roads can concentrate a wide variety of pollutants that can degrade local water quality. Potential pollutants include heavy metals (Pb, Zn, Cu, Cd, Cr, Pt), mineral oil, and polycyclic aromatic hydrocarbons (PAHs). Herbicides for weed control, and all sorts of materials that can fall from trucks (e.g., salt, chemicals, and agricultural products) or car accidents can also pollute the environment (Van Bohemen and Janssen Van De Laark 2003). The main processes by which vehicles disseminate pollutants into the environment are combustion processes, the wear of vehicles (engine, tires, brakes), leaking of oil and coolants, and corrosion. Lead and PAHs are released in combustion processes, zinc is derived from tire dust (zinc is a catalyst used in the manufacture of tires), and copper is derived from the corrosion of radiators and brakes (Oostergo 1997). The quantity of pollutants is determined by traffic intensity. Water that runs off a road surface can convey some of the pollutants in a dissolved or suspended form to the surrounding environment. Most metals and almost all PAHs are bounded to the silt that is flushed off roads. The quantity of rainwater that runs off is dependent on several variables including; evaporation rate, spray and pool formation, road geometry, and type of road surface. High concentrations of pollutants in runoff are typical for the first flush after a dry period (Fritzer 1992). Road salt is applied to Skyline Drive and on major highways that traverse the park during icy conditions on an as-needed basis. The dominant type of salt applied for deicing is sodium chloride, but calcium chloride and potassium chloride may also be applied in lesser amounts (Rice and Jung 2003). Rice and Jung (2003) prepared a proposal for investigating the water quality effects of runoff from roads in SHEN. The proposal did not successfully compete for NPS funding in FY03 or FY04, but is an important project that should be revised and submitted for funding in the future.

Other sources for pollutants include SHEN’s maintenance facilities where hazardous materials are used and stored, septic systems, wastewater treatment plants, and activities such as building projects, washing operations, and visitor recreation (i.e., horseback riding). The first step in inventorying sources in SHEN that could impact water quality is to conduct an Environmental Audit on the park’s infrastructure and operations. This was completed in 1998-99 (PRIZIM 1999) as part of a Servicewide program that requires all NPS facilities to receive an environmental audit by the end of FY2002. The audit identified numerous issues that the park was quick to address. Some of the follow-up by SHEN is captured below:

1. The park was not maintaining procedures for recycling nickel cadmium batteries. In response, the park has educated staff of proper disposal procedures, recycling all batteries through available vendors.

2. Active leak was observed from a kerosene tank supply line. The tanks have since been removed and the contaminated soils properly disposed, with clean soils brought to the site and seeded.
3. Water with an oil sheen and petroleum odor was observed in the underground piping manway for an above-ground storage tank. The water was pumped from the manway and properly disposed. The source of the leak has been corrected.
4. Rusty five-gallon drums labeled as solvents were observed in a grassy area on the north side of a bone yard. The drums were removed and properly disposed.
5. The park discharged (daily) untreated wastewater from backwashing the tertiary treatment units due to an unmaintained control valve that remained opened after backwashing occurs. The valve has been replaced, preventing wastewater discharge.
6. Numerous hazardous material storage and labeling violations identified, that have since been corrected.
7. Discharge monitoring reports for the Big Meadows wastewater treatment plant indicated the park exceeded its permit limits of 28 µg/L for copper for three samples taken during the audit period (08/28/99: 78 µg/L, 03/17/99: 48 µg/L, 08/19/98: 145 µg/L). In response, equipment for the treatment plant has been upgraded.
8. Construction of a new leach field next to the visitor center did not include sediment or erosion controls. Appropriate SHEN staff has been trained on NPDES Storm Water requirements related to construction activities.
9. SHEN is monitoring efforts by a concessionaire to meet regulatory requirement for temporary closure of petroleum underground storage tanks at Elwallow Wayside, Big Meadows Wayside, and Loft Mountain.

The action of those employees who first encounter an accidental release in the park could well determine the severity of the impact(s) on human health and the environment. Therefore it is important for NPS staff to understand the basic requirements for response to hazardous substance spills. SHEN's Emergency Operations Plan (EOP), which serves as the park's Emergency Response Plan was updated in 2000. The plan provides clearly defined roles and responsibilities, procedures and resources to respond to hazardous material releases within the Park (National Park Service, 2000c). Key environmental documentation and records (MSDS sheets, UST closure reports, etc.) for SHEN have been identified and filed together for easy access. An updated Spill Prevention Control and Countermeasure Plan (SPCCP) is needed for current operations at SHEN to maintain compliance with 40 CFR 112 (EPA Regulations on Oil Pollution Prevention).

Two primary water quality concerns related to recreation trails in SHEN are: 1) accelerated sediment yields from trail erosion; and 2) bacteria contamination from horse and human sources.

Over time, many trail segments in a mountainous terrain deteriorate by natural processes and by wear from recreation traffic (Summer 1986, Tinsley and Fish 1985). The magnitude of trail deterioration is determined by characteristics of the trail, its environment, and the recreation use that the trail receives (Cole 1987). On a trail in Great Smoky Mountains National Park, Whittaker (1978) found that horse use caused more pronounced increases in trail width, trail depth, and litter loss than hiker use. In a study of impact to existing recreational trails, Wilson and Seney (1994) measured the effect of user impacts, including hiker and horse traffic, on sediment yield following simulated rainfall. In the study, sediment yield following horse use was found to be significantly greater than hiker use. This is explained by the simple fact that horses are heavier and their weight is carried on a shoe with a small weight-bearing surface, thus soil displacement is greater. The increased sediment yields from trail use, under the right conditions, can enter a waterbody and degrade water quality through increased turbidity and total dissolved solids, and degrade aquatic habitat by covering the natural substrate through increased sediment deposition. In contrast, Summer (1980) was unable to detect differences in erosion rates between trails in Rocky Mountain National Park used by hikers and those used by horses, suggesting that trail characteristics and/or environment, contribute to the cumulative outcome on trail impacts.

The trails in SHEN cross several streams and unnamed tributaries. These stream crossings are particularly sensitive to bacteria contamination from horse and human sources. At these locations, management to buffer these areas may be warranted, in order to minimize the potential of animal or human wastes entering directly or within close proximity of a waterbody.

With the extensive recreational use in SHEN such as camping, hiking, horseback riding, swimming, and fishing, visitors are often in contact with streams in the park. The U.S. Geological Survey will measure storm-flow bacteria concentrations in six streams in SHEN starting in fiscal year 2005 (Hyer 2003). The storm-flow conditions would be evaluated to provide a basic level of water-quality data to the NPS and to describe the patterns in bacteria concentrates that occur during and just after storm events. Sampling locations would be selected based on park records of recreational use, site accessibility, and presence of existing septic systems or sewage treatment plant (Hyer 2003). This study should lead into follow-up assessments, identifying point and non-point sources for bacteria contamination identified in the U.S. Geological Survey study.

Building from these inventories and studies should ultimately lead toward implementation of BMPs for structures and activities that potentially threaten water quality in the park.

Mercury Deposition

Atmospheric deposition of mercury, listed as a priority pollutant by the U. S. Environmental Protection Agency, and its subsequent contamination of aquatic ecosystems has become a problem of national and global extent. Mercury deposited into lakes and streams undergoes aqueous phase chemical reactions to form toxic methylmercury, which is of greatest concern to human health. In the U.S., mercury makes more surface waters impaired for fishing than any other toxic contaminant. Currently, most states including Virginia have mercury fish consumption advisories – such advisories were few to nonexistent 15 years ago.

Mercury is emitted into the air from anthropogenic [e.g. fossil fuel combustion – 80% of the total anthropogenic emissions can be attributed to this source (U.S. EPA 1997)] and natural (e.g. volcanic eruptions) emission processes and from re-entrainment. Re-entrained mercury originally came from both anthropogenic and natural emissions. Mercury is emitted in three forms -- elemental, oxidized, or particulate (U.S. EPA 1997).

Once airborne, mercury in its different forms can chemically react and can be transported. Elemental mercury is not very reactive and can travel great distances. Eventually mercury is deposited, through wet or dry processes, into water bodies. All three forms of mercury can be dry deposited and the rates of deposition will vary depending on the deposition surface characteristics and meteorological conditions. Mercury may deposit directly into aquatic systems, but it may also be intercepted by the surrounding forested watershed before it moves into the streams. The latter may be the dominant pathway of mercury into streams. However, despite an increased understanding of mercury in standing water, details of the mercury cycle (from source to fish) in stream ecosystems are less understood. Data are sparse for mercury in all components of stream ecosystems, including water, sediment and aquatic biota.

Once mercury is transformed into methylmercury via methylation, methylmercury enters the food chain and is bioaccumulated. Methylmercury accumulates at an ever-increasing rate as it moves up the food chain. Therefore, the threat of exposure is most severe to those animals at the top of the aquatic food chain and those animals and humans that feed on them. Elimination of methylmercury from fish tissue takes place very slowly, with tissue half-lives being on the order of months to years.

The chemistry of mercury is complex and its behavior difficult to predict in nature. Total mercury concentrations in the environment have not been found to be effective predictors of bioaccumulation in fish. Depending on physical, chemical and biological conditions at a site, mercury can remain largely tied up in sediments, released from particulate matter to other locations, or be taken up by aquatic biota where it may concentrate and become a threat to humans and other fish-eating animals (Ullrich *et al.* 2001). Although the precise factors controlling the accumulation of mercury in aquatic biota are not fully understood, it is clear that fish and other aquatic species are much more efficient in accumulating methylmercury than the inorganic forms that predominate in the environment. Thus, factors that influence the rate in which inorganic mercury is transformed to methylmercury also influence bioaccumulation as well.

Research has revealed that the problems of acid deposition and mercury deposition are linked. Levels of mercury in fish tissue tend to be higher in more acidic water (U.S. Geological Survey 2000; Lutter and Irwin 2002). Acidity in the water is the result of deposition of sulfuric and nitric acids that are chemically formed in the air from emissions of sulfur dioxide and nitrogen oxides. Similarly, the major source of these chemicals is fossil fuel combustion.

Some recent research has focused on the tendency of low-alkalinity (< 50μeq/L) waters to have a relatively high potential for acid deposition effects and increased bioaccumulation of mercury in fish (Wiener and Stokes 1990). Edible fish tissue concentrations of mercury above the US Environmental Protection Agency-recommended 0.3 µg/g wet weight value used for fish consumption advisories have been found even in relatively pristine (but low alkalinity) waters.

Alkalinity, specific conductance, pH and the concentration of calcium in waters are inversely correlated with mercury concentrations in fish (Wiener and Stokes 1990). Low-pH systems generally promote higher concentrations, mobility, and methylation of mercury (U.S. Geological Survey 1996b).

Recent studies have shown that several key environmental parameters are linked with high levels of mercury in fish (Wiener 1996). However, this is a very complex area of research that is controlled by ecosystem parameters (e.g., water chemistry, wetlands presence/absence), aqueous mercury speciation, food web structure, size, age, and growth rate of organisms, population size, etc. (Wiener 1996).

In addition to acidity, the concentration of dissolved organic carbon has a strong influence on the uptake of mercury by fish. Increasing the acidity and/or the dissolved organic carbon level enhances the mobility of mercury in the environment, thus making it more likely to enter the food chain (U.S. Geological Survey 2000).

There has been considerable confusion on the subject of methylmercury versus total mercury. Much of the mercury in sediments can be in the inorganic form, so that total and methylmercury measures in the same sediments can result in very different concentrations (Irwin *et al.* 1997).

Another point of confusion related to total mercury versus methylmercury is the notion that most inorganic mercury is “locked up in the sediments” and no longer represents a biological hazard (Irwin *et al.* 1997). Inorganic mercury in sediments is often bound to sulfides and other compounds and generally represents less of an immediate biological hazard than organic (methylated) or other more mobile forms of mercury. However, there are mechanisms (flooding, bioturbation, release of sulfide gases, bacterial action, etc.) which tend to bring this presumably “locked up” mercury to the surface or up into the water column or even the atmosphere. Once this happens, methlylation and uptake mechanisms tend to transform these relatively harmless “locked up” forms of mercury into more hazardous and more bioavailable forms.   At least part of the mercury in sediments is vertically mobile, which is a factor needing more study. Methylmercury moves from the sediments upwards into the water.

When exposed to mercury in both mediums, fish accumulate more mercury from sediments than from water (Munawar et al. 1984). Lower pH levels (indicating increased acidification) are correlated with increased mercury accumulation in fish (Wiener 1988). At low pH, there is typically a higher methylmercury production than at higher pH levels.

Streams in SHEN vary considerably in terms of pH and other important water chemistry parameters due to variation in dominant bedrock types underlying individual watersheds. All streams in SHEN have low ionic strength. Streams underlain by siliciclastic bedrock have low ANC and consequently very low pH. As a result of low pH, these streams may be the most vulnerable to mercury contamination. Streams underlain by basaltic bedrock have higher ANC and pH whereas streams underlain by granitic bedrock have intermediate values for these parameters. As a result, bedrock distribution in SHEN may reflect a gradient in watershed response to atmospheric deposition of mercury. This is the rationale behind a proposed study by Snyder *et al.* (2003). Their objectives are to determine the distribution, abundance, and variability of mercury in fish in SHEN and to assess the relationship between stream water chemistry and mercury concentrations in brook trout, the top aquatic carnivore in the park. Similarly, Bank *et al.* (*in review*) assessed the relationship between water quality and mercury concentrations in lotic salamanders of SHEN (see Table 9 for species).

The study by Snyder *et al.* (2003) is an appropriate and necessary first step in determining the extent and variability of mercury contamination in brook trout. Such information will assist the park in determining if fish consumption advisories should be posted. Furthermore, this study's results may point to the need for more fish tissue monitoring. Equally important is to see if the current understanding of the relationships between bedrock type, pH, and ANC can help explain the distribution and variability of mercury contamination. This would allow a more focused fish tissue monitoring program. However, understanding the variability of mercury concentrations in brook trout via bioaccumulation and biomagnification begs some basic questions. What are the sources and pathways of total mercury derived from atmospheric deposition to SHEN streams? What is the fate and transport of mercury in SHEN streams? These questions are similar to those questions that the SWAS program is attempting to answer with regard to acidic deposition and the biogeochemistry of forested catchments. Therefore, the understanding of mercury deposition and its fate and transport in streams would be a logical extension of the SWAS program. We suggest the addition of mercury and its co-factors (such as pH, ANC, DOC) as parameters to be monitored by the SWAS program. We would anticipate that results from this addition would aid the understanding of mercury contamination in SHEN streams much like past research has in the Northeast.

Research in the Northeast in small forested catchments (http://vmc.snr.uvm.edu/CurrentIssues/CImercury.htm; http://wwwbrr.cr.usgs.gov/projects/SW_corrosion/sleepers/) is beginning to provide some answers to these questions. Results to date suggest that up to 90% of atmospheric mercury is retained in the forest, mostly on the forest floor. It is accumulated and released from forests to streams during major hydrologic events. Stream water quality monitoring programs currently are looking at concentrations of mercury, dissolved organic carbon and several trace metals in soil and stream solutions, comparing the behavior of mercury with DOC and trace metals in these media, and using the results to identify factors that might affect the transport of dissolved mercury in an upland catchment. For example, both dissolved and particulate mercury were positively correlated with stream discharge in the Sleepers River in Vermont suggesting that most stream transport of mercury occurs during high-flow periods (Figure 23). Episodic export of particulate mercury during the highest flows appears to be the dominant mechanism of mercury movement. In addition strong correlations were found between dissolved and particulate mercury and dissolved and particulate organic carbon fractions (Figure 24). Mercury export occurs principally in discrete episodes of high flow accompanied by large releases of particulate organic carbon. Two possible explanations for these mercury-organic carbon correlations: 1) mercury in stream water represents a small fraction of incoming mercury in rain or snowmelt that avoids removal by the soil because it associates with a mobile organic carbon fraction or 2) mercury and organic carbon are flushed from a common source- the soil organic horizon by infiltrating meltwater or rising ground water. Although methylmercury *per se* is diluted with increasing flow during snowmelt (Bishop *et al.* 1995), these episodic fluxes of total mercury may be the dominant source of mercury that is ultimately methylated and assimilated in the food web in downstream waters.

Finally, to understand how to solve the problem of mercury contamination, resource managers must understand where the mercury comes from, and how it is deposited to the park landscape. Research on the fate and transport of mercury in the terrestrial and aquatic environments is critically dependent on the quantification of atmospheric inputs of mercury. In this regard the addition of wet-deposition mercury monitoring in the park in 2001 is applauded; however, a complete picture will remain unknown until the monitoring of dry-deposition mercury is technologically feasible.

FURTHER RECOMMENDATIONS

The conceptual understanding of stream connectivity expressed by the River Continuum Concept and other paradigms emphasized that downstream biological communities are a function of upstream processes (Pringle 1997). The converse, to what extent are upstream communities a function of downstream processes, has not been a focus. Pringle (1997) explored the process of the transmission of disturbance upstream, i.e., how alterations of streams and rivers in their lower reaches (e.g., outside park boundaries) can produce legacies in upstream reaches on levels from genes to ecosystems. Park staff should be aware of downstream, outside of the park, land use changes whose aquatic-based impacts could transmit upstream into the park.

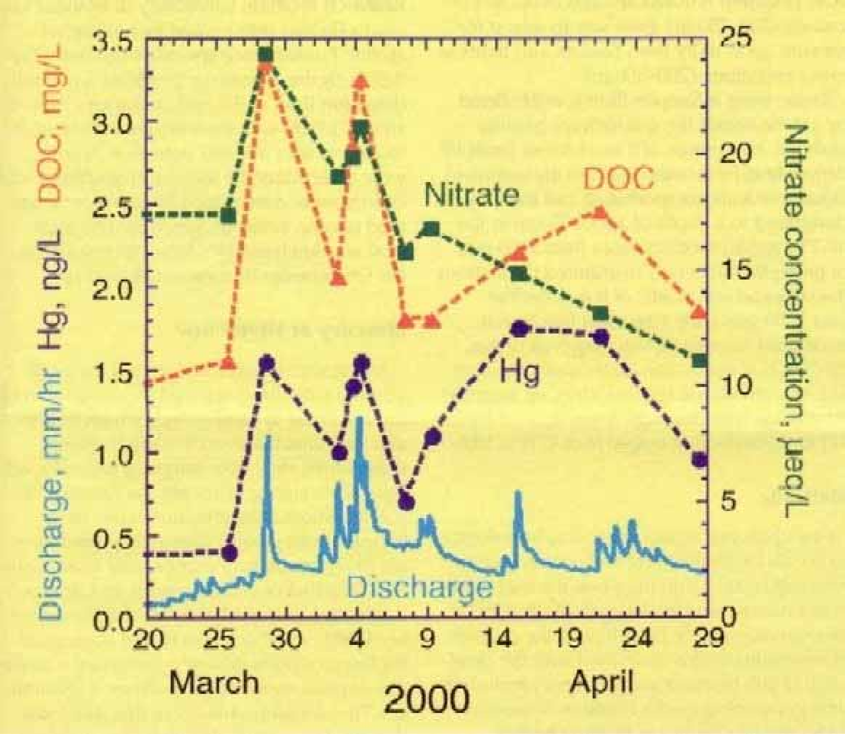


Figure 23. Relationship of mercury (Hg), dissolved organic carbon (DOC), and nitrate with discharge during the snowmelt period in the Sleepers River, Vermont (http://wwwbrr.cr.usgs.gov/projects/SW_corrosion/sleepers/).

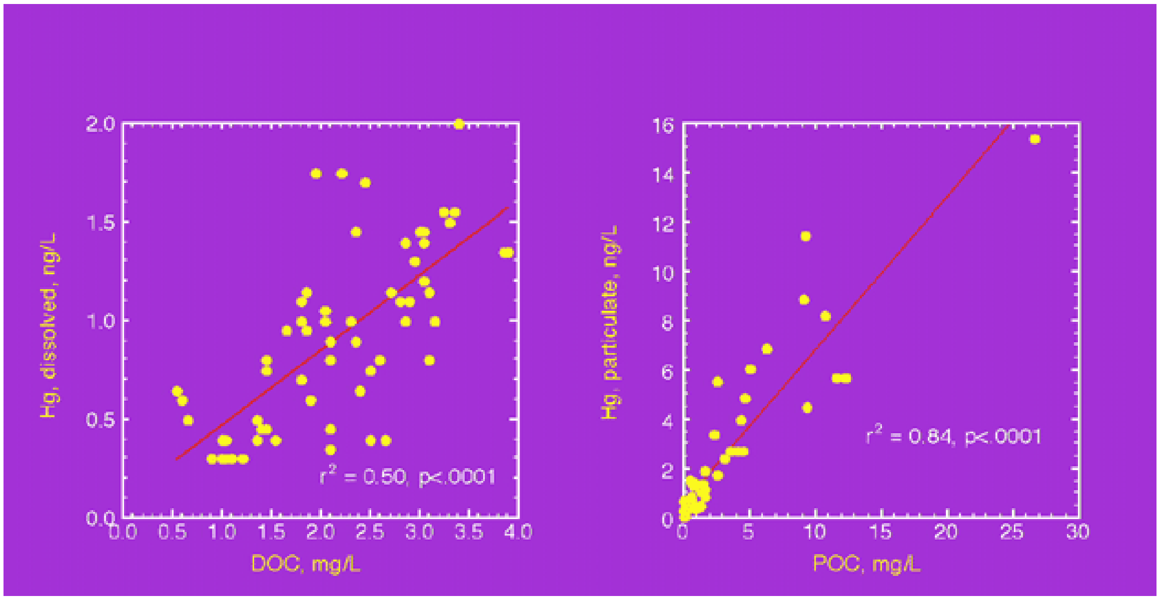


Figure 24. Relationships of the dissolved and particulate factions of mercury (Hg) and organic carbon [D(dissolved)OC and P(particulate)OC] in the Sleepers River, Vermont (http://wwwbrr.cr.usgs.gov/projects/SW_corrosion/sleepers/).

As stream systems become increasingly fragmented by human impacts, upstream populations of aquatic biota are subject to reduced genetic flow and variation. Decreases in intraspecific genetic variation are inconspicuous and thus easily overlooked. Degraded downstream areas can potentially act as population sinks for native riverine species and alternately, as sources of exotic species or facultative riverine species.

Dams are obvious examples of human activities that block migration of aquatic organisms. Effects of other types of selective environmental filters are much less obvious and they may or may not be associated with dams; they include flood frequency, drought frequency, pollution level, thermal stress, and hydrologic modifications such as headward erosion or headcutting.

When major fauna of an ecosystem are excluded from upper portions of a watershed as a result of downstream human activities, a cascade of ecosystem-level effects may occur, particularly when the extirpated species was an important food source, predator, host species, or habitat modifier.

One reason for the lack of knowledge of effects of downstream hydrologic modifications on upstream conditions is the lag time between cause and effect: for example, channel erosion is greater during floods, and changes resulting from gravel mining and channelization usually appear following seasonal floods and are often wrongly attributed to local erosion from natural causes.

The upstream effects of ground water exploitation in lower stream drainages also have been largely overlooked. The increasing exploitation of ground water reserves for municipal, industrial, and agricultural use is having profound effects on riverine ecosystems, as ground water tables are lowered.

An understanding of how disturbances are transmitted upstream, their associated lag times, and resulting upstream legacies have important management implications. The concept of downstream-upstream linkages should be incorporated into management plans to protect stream ecosystems.

On genetic and species levels, it is important to locate and protect systems that are acting as source populations for native fishes. Naturally isolated populations of fishes in upstream reaches should be identified, genetically analyzed and monitored. Despite the presence of apparently healthy populations in upstream areas, we should not assume that we have a natural situation (e.g., degraded downstream areas may be acting as a potential sink for native species or as a source of exotics species).

CONSIDERATIONS FOR FUTURE ACTION

Water Resource Scoping Reports provide NPS management with a better understanding of a park's water resources and the curent issues it faces. These reports typically summarize existing hydrological information, identify and analyze major water resource issues, and determine if further development of the water-related issues, including recommended actions (project statements), is warranted. For Shennadoah National Park, the number of water-related issues is low with a medium level of complexity, overall. Given this assessment and the following factors, we suggest that this WRSR meets the needs of current park management: 1) the existence of a longstanding, cooperative, water monitoring/research program between the park and the University of Virginia that has the ability to deal with the complexity of several of the issues; 2) the park is active with other cooperators and has already anticipated and developed recommended actions for several of the issues; and 3) the park has a well established long-term ecological monitoring program for aquatic biota. Below, we provide recommendations, based on the above issues analyses, that may serve as appropriate stimuli for future action. The park is encouraged to seek technical assistance from the NPS Water Resources Division in the development of these recommendations.

Inventory and Classify Wetland Attributes

1) SHEN should inventory, classify, and characterize wet areas. The modeling of potential wet areas in SHEN by the U.S. Geological Survey (Young *et al.* 2000) provides an excellent beginning to a parkwide wetland inventory. SHEN should work with the U.S. Geological Survey in the future to model potential wet areas for the remainder of the park.
2) SHEN should attempt as complete an inventory and characterization as possible for springs/seeps. Given the potential number of springs/seeps (≥ 850), the methodology of Young *et al.* (2000) allows the delineation of potential we areas. These wet areas can be prioritized for the likelihood of spring/seep presence and then field verified.
3) The biological study of springs/seeps could provide a very effective tool for the management and quality control of ground water resources.

Re-evaluate Existing Water-Based Monitoring Programs

SHEN recently (2003) initiated a review of its long-term ecological monitoring program (LTEM). An extensive review of the water resources component of the LTEM program is beyond the scope of this report. However, we offer the following observations, suggestions, and/or recommendations for consideration during the LTEM review period.

1) The SWAS program has been and continues to be an effective ‘partnership’ for SHEN. The current program appears to seek a balance between efficient use of available funding and effective detection and understanding of change. This balance is threatened by NPS budget erosion.
2) SWAS watersheds make up only a fraction of the total number of watersheds in SHEN. This begs the question of what about the status and trend of water quality in the streams of other watersheds? Given current funding constraints, it would not appear possible to extend the SWAS program to streams in other watersheds. A solution may lie with the existing LTEM fish and aquatic macroinvertebrate monitoring programs.

3) A 1996 LTEM review recommended water quality sampling at headwater, middle, and lower stream reaches. We agree with the spirit and intent of this LTEM review recommendation, but given the reality of eroding budgets, it would not appear sustainable. We encourage the LTEM review process to consider revisions to the current spatio-temporal framework of the SWAS sampling program.
4) The water monitoring program at SHEN appears to exist on ‘autopilot’ and park involvement is on an *ad hoc* basis. More often than not this leads to unlinked management and monitoring objectives. This and other weaknesses of the water monitoring program could be prevented if the program had access to a full or part-time water resource professional.
5) Any monitoring program needs to develop clear objectives. Monitoring program objectives should be clearly linked to management questions – without more specificity, the resulting monitoring program is in danger of developing data that do not respond to specific management concerns and provide information explicitly helpful to managers. For managers to develop a commitment to long-term monitoring, it has to be seen as answering questions about current management issues and trends and conditions. In addition, a common view of the respective roles of research and monitoring is needed.
6) SHEN should annually synthesize data and results and report them to its managers, not just accumulate data. If monitoring objectives relate to meeting managers needs, then reporting to managers is equally as important as developing data that are responsive to managers’ questions.
7) Given SHEN’s extensive benthic macroinvertebrate monitoring program, it should seek State approval of this program and supply benthic data to the State for the assessment of impairment. Once the problem surrounding the use of SWAS pH data is resolved, either through the methodology of Galloway and Webb (2003) or through the use of a different field methodology, the combination of pH with benthic community assessments would provide a powerful tool for the determination of impairment.

Impacts of Changing Chemical Composition of Streams on Aquatic Biota

1) It appears appropriate for the SWAS program to consider the incorporation of biological indicators. In particular the fish and aquatic macroinvertebrate LTEM programs and past studies offer the ability to develop indicators of sublethal effects as well as multimetric indices.
2) In the future the assessment of biogeochemical variability of SHEN’s streams from the regional perspective of acid deposition will, in all likelihood, need to be placed in the larger context of climate change. There is a need to develop analyses, experimental designs and aquatic ecological indicators that distinguish between climatic and anthropogenic effects (acid deposition) in SHEN’s streams.

Inventory of Impacts on Water Quality

There has been a lot of effort towards assessing the influences that acidic deposition has on water chemistry in SHEN. Equally important is an understanding of water quality impacts from the park's existing infrastructure and operations. Because development in SHEN is at the headwaters of watersheds, the park should be concerned about contamination of both surface and ground waters via such pollution avenues as accidental spills, nonpoint source runoff, and septic leachate. Additionally, erosion/runoff from recreation trails is a source of sediment yield to streams, as well as bacterial contamination via horse/human use.

Mercury Deposition

The U.S. Geological Survey study (Snyder *et al.* 2003) is an appropriate and necessary first step in determining the extent and variability of mercury contamination in the aquatic community. However, there appears to be a need to understand the sources and pathways of total mercury derived from the atmosphere and the fate and transport of mercury in SHEN streams. These information needs are similar to those that the SWAS program is attempting to determine with regard to acidic deposition and the biogeochemistry of forested catchments. The understanding of mercury deposition and its fate and transport in streams would be a logical extension of the SWAS program. We suggest the addition of mercury and dissolved organic carbon (a co-factor) as parameters to be monitored by the SWAS program.

LITERATURE CITED

Atkinson, J. 2003. Fisheries monitoring protocol. National Park Service, Shenandoah National Park, Luray, VA.

Bailey, C.M. 1999. Physiographic Map of Virginia. The College of William and Mary. Williamsburg, Virginia. http//www.wm.edu/geology/virginia/phys_regions.html

Baker, J., D. Bernard, S. Christensen, M. Sale, J. Freda, K. Heltcher, D. Marmorek, L. Rowe, P. Scanlon, G. Suter, W. Warren-Hicks, and P. Welbourn. 1990. Biological effects of changes in surface water acid-base chemistry. SOS/T Report 13. Acid Precipitation Assessment Program, Washington, DC.

Baker, J. and S. Christensen. 1991. Effects of acidification on biological comunities. Pages 83-106 *in* D. Charles, ed. Acidic deposition and aquatic ecosytems. Springer-Verlag, New York.

Bank, M., C. Loftin, T. Haines, and R. Jung. *in review*. Effects of watershed heterogeneity on mercury bioavailability in lotic salamanders. Ecology.

Bishop, K., Y.-H. Lee, C. Pettersson, and B. Allard. 1995. Methylmercury output from the Svartberget catchment in northern Sweden during spring flood. Water, Air, and Soil Pollution 80:445-454.

Beeson, C. and P. Doyle. 1995. Comparison of bank erosion and vegetated and nonvegetated channel beds. Water Res. Bull. 31:983-990.

Binkley, D., D. Valentine, C. Wells, and U. Valentine. 1989. An empirical model of the factors contributing to 20-year decrease in soil pH in an old-field plantation of loblolly pine. Biogeochemistry 8:39-54.

Bricker, O. and K. Rice. 1989. Acidic deposition to streams – a geology-based method predicts their sensitivity. Environ. Sci. Tech. 23:379-385.

Bulger, A., C. Dolloff, B. Crosby, K. Eshelman, J. Webb, and J. Galloway. 1995. The “Shenandoah National Park: fish in sensitive habitats” (SNP:FISH) Project. An integrated assessment of fish community responses to stream acidification. Water, Air and Soil Pollution 85:309-314.

Bulger, A. B. Crosby, C. Dooloff, K. Eshleman, J. Webb, and J. Galloway. 1999. The Shenandoah National Park: fish in sensitive habitats (SNP:FISH) Project Final Report. An integrated assessment of fish community responses to stream acidification. Shenandoah National Park, Luray, Va.

Carter, J.B. 1961. Soil survey of Rappahannock County, Virginia. USDA Soil Conservation Service. 85 pp.

Cole, D.N. 1987. Research on soil and vegetation in wilderness: A state-of-knowledge review. *In* R.C. Lucas (comp.), Proceedings National Wilderness Research Conference: Issues, State-of-Knowledge, Future Directions. General Technical Report INT-220. USDA Forest Service. Ogden, UT. pp. 135-177.

Cosby, B., P. Ryan, J. Webb, G. Hornberger, and J. Galloway. 1991. Mountains of West Virginia. Pages 297-318 *in* D. Charles, ed. Acidic deposition and aquatic ecosystems. Regional Case Studies. Springer-Verlag, New York.

Cosby, B., R. Wright, G. Hornberger, and J. Galloway. 1985a. Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. Water Resour. Res. 21:51-63.

Cosby, B., R. Wright, G. Hornberger, and J. Galloway. 1985b. Modelling the effects of acid deposition: estimation of long-term water quality responses in a small forested catchment. Water Resour. Res. 21:1591-1601.

Cowardin, L., V. Carte, F. Golet, and E. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. FWS/OBS 79/31. Washington, DC.

Cronan, C.S. and C.L. Schofield. 1990. Relationships between aqueous aluminum and acidic deposition in forested watersheds of North America and northern Europe. Environ. Sci. Tech. 24:1100-1105.

Deacon, J. and W. Minckley. 1974. Desert fishes. Pages 385-487 *in* Desert Biology, Vol II. Academic Press, New York.

Decamps, H. 1993. River margins and environmental change. Ecol. Appl. 3:441-445.

DeKay, R.H. 1972. Development of ground-water supplies in Shenandoah National Park, Virginia. Mineral Resources Report 10, Virginia Division of Mineral Resources. 158 pp.

Demarest, D. 2001. Aquatic macroinvertebrates and stream sampling health. Spring Issue of Shenandoah National Park Resource Management Newsletter. Shenandoah National Park, Luray, VA.

Driscoll, C. and many others. 2003. Nitrogen pollution iln the northeastern United States: sources, effects, and management options. BioScience 53:357-390.

Dunson, W., R. Wyman, and E. Corbett. 1992. A symposium on amphibian declines and habitat acidification. J. Herpetology 26:349-352.

Elder, J.H. and D.E. Pettry. 1975. Soil Survey of Madison County, Virginia. U.S.D.A. Soil Conservation Survey. 143 pp.

Eshleman, K., L. Eshleman, L. Miller-Marshall, and J. Webb. 1995. Long-term changes in episodic acidification of streams in Shenandoah National Park, Virginia (USA). Water, Air, and Soil Pollution 85:517-522.

Eshleman, K., R. Morgan II, J. Webb, F. Deviney, and J. Galloway. 1998. Temporal patterns of nitrogen leakage from mid-Appalachian forested watersheds: role of insect defoliation. Water Resour. Res. 34:2005-2016.

Eshleman, K., J. Moody, K. Hyer, and F. Deviney. 1999. Episodic acidification of streams in Shenandoah National Park, Virginia. Final Report to U.S. Dept. of the Interior, National Park Service, Mid-Atlantic Region (Philadelphia, PA) and Air Resources Division (Denver, CO).

Feldman, R. and E. Conner. 1992. The relationship between pH and community structure of invertebrates in streams of the Shenandoah National Park. Virginia, U.S.A. Freshw. Biol. 27:261-276.

Fievet, C., M. Allen, and J. Webb. 2003. Documentation of landuse and disturbance history in fourteen intensively studied watersheds in Shenandoah National Park, Virginia. Shenandoah Watershed Study, Department of Environmental Sciences, U. of Virginia, Charlottesville, VA.

Freda, J. and W. Dunson. 1985. The effect of acid precipitation on amphibian breeding in temporary ponds in Pennsylvania. U.S. Fish and Wildlife

Service, Eastern Energy and Land Use Team, Biological Report 80(40.22).

Freda, J., W. Sadinski, and W. Dunson. 1991. Long term monitoring of amphibian populations with respect to the effects of acid deposition. Water, Soil and Air Pollution 55:445-462.

Fritzer, H. 1992. Gewässerbelastung durch Strassen abflüsse [Water Pollution by Runoff]. Strassenforschung v. 406.

Galloway, J. and many others. 2003. The nitrogen cascade. BioScience 53:341-356.

Galloway, J. and J. Webb. 2003. Identification of native brook trout streams that are impaired by acidification. Research Proposal, Department of Environmental Sciences, U. of Virginia, Charlottesvill, VA.

Galloway, J., R. Deviney, and J. Webb. 1999. Shenandoah Watershed Study Data Assessment: 1980-1993. Project Final Report. Shenandoah National Park, Luray, VA.

Galloway, J., S. Norton, and M. Church. 1993. Freshwater acidification from atmospheric deposition of sulfuric acid: a conceptual model. Environ. Sci. Tech. 17:541A-454A.

Galloway, J., G. Likens, and M. Hawley, 1984. Acid precipitation: natural versus anthropogenic components. Science 226:829-831.

Gathright, T.M. 1976. Geology of the Shenandoah National Park, Virginia. Virginia Division of Mineral Resources, Bulletin 86. Charlottesville, VA. 93 pp.

Gebert, W., D. Graczyk, and W. Krug. 1988. Runoff for selected sites in Shenandoah National Park, Virginia, July 18, 1981, through July 17, 1982. U.S. Geological Survey Open-File Report 88-98.

Gleick, P. and many others. 2000. Water: the potential consequences of climate variability and change for water resources of the United States. The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change. For the U.S. Global Change Research Program. U.S. Geological Survey, Washington, D.C.

Gomi, T., R. Sidle, and J. Richardson. 2003. Understanding processes and downstream linkages of headwater systems. BioScience 52:905-916.

Grant, E., R. Jung, and K. Rice. i*n manuscript*. Stream salamander species richness and abundance in relation to environmental factors in

Shenandoah National Park, Virginia: a stratified random survey. U.S. Geological Survey, Patuxent Wildlife Research Center, Laurel, MD.

Grossman, D. and many others. 1998. Terrestrial vegetation of the United States, Volume I: The national vegetation classification system: development, status, and applications. The Nature Conservancy, Arlington, VA.

Hendrey, G., and many others. 1980. Geological and hydrochemical sensitivity of the eastern United States to acid precipitation. EPA-600/3-80-024, U.S. Environmental Protection Agency, Washington, DC.

Hockman, J.R., J.C. McKinney, T.R. Burruss, D. Jones, R.E. Modesitt, L.G. Manhart, and W.R. Waite. 1979. Soil survey of Augusta County, Virginia. U.S.D.A. Soil Conservation Service. 249 pp.

Hopkins, H.T. 1984. Ground-Water Availability Along the Blue Ridge Parkway, Virginia. U.S. Geological Survey. Water-Resources Investigations Report 84-4168. 154 pp.

Husar, R., T. Sullivan, and D. Charles. 1991. Historical trends in atmospheric sulfur deposition and methods for assessing long-term goals in surface water chemistry. *In,* D. Charles, ed., Acid Depostion and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag, New York.

Hyer, K.E. 2003. The Effects of Storm Events on the Bacteria Concentrations in the Streams of Shenandoah National Park, Virginia. Proposal to the National Park Service. U.S. Geological Survey – Water Resources Division. Richmond, VA. 6 pp.

Hynes, H. 1970. The ecology of running waters. Liverpool Univ. Press, Liverpool, UK.

Irwin, R., M. VanMouwerik, L. Stevens, M. Seese, and W. Basham. 1997. Environmental contaminants encyclopedia. National Park Service, Water Resources Division, Fort Collins, CO. http://www.nature.nps.gov/wrd

Johnson, Z. and C. Snyder. No date. Recovery of aquatic macroinvertebrate communities following a 500+ year flood event in Shenandoah Naitonal Park. U.S. Geological Survey, Leetown Science Center, Aquatic Ecology Laboratory, Kearneysville, WV.

Jung, R., S. Droege, J. Sauer, and R. Landy. 2000. Evaluation of terrestrial and stream salamander monitoring techniques at Shenandoah National Park. Environ. Monitoring and Assessment 63:65-79.

Kauffman, J., l. Mohn, and P. Bugas. 1999. Effects of acidification on benthic fauna in St. Marys River, Augusta County, Va. Banisteria 13:183-190.

Kaufmann, R. and many others. 1988. Chemical characteristics of streams in the mid-Atlantic and southeastern United States. Volume I: Population descriptions and physicochemical relationships. EPA/600/3-88/021a. U.S. Environmental Protection Agency, Washington, DC.

Kimmel, W. and D. Murphy. 1985. Macroinvertebrate community structure and detritus processing rates in two southern Pennsylvania streams acidified by atmospheric deposition. Hydrobiologia 124:97-102.

Klemm, D. and many others. 2003. Development and evaluation of a macroinvertebrate biotic integrity index (MBII) for regionally assessing mid-Atlantic Highlands streams. Environ. Management 31:656- 669.

Lambert, D. 1989. The undying past of Shenandoah National Park. Roberts Rinehart, Inc. Publishers. Boulder, CO.

Lennon, R. 1961. The trout fishery in Shenandoah National Park. Special Scientific Report, Fisheries No. 395. U.S. Department of Interior, Fish and Wildlife Service.

Lynch, D.D. and N.B. Dise. 1985. Sensitivity of Stream Basins in Shenandoah National Park to Acid Deposition. U.S. Geol. Surv. Water-Resources Investigations Report 85-4115. Prepared in cooperation with University of Virginia Department of Environmental Sciences. U.S. Geological Survey. Richmond. VA.

Lynch, D.D. 1987. Hydrologic Conditions and Trends in Shenandoah National Park, Virginia, 1983-84. U. S. Geological Survey. Water-Resources Investigations Report 87-4131. Richmond, VA. 115 pp.

Lutter, R. and E. Irwin. 2002. Mercury in the Environment. Environment 44:25-40.

Malanson, G. 1993. Riparian landscapes. Cambridge Univ. Press, Cambridge, UK.

Martin, L. 2002. Drinking Water Source Protection Plan, Big Meadows Area, Shenandoah National Park. NPS-Water Resources Division. Ft. Collins, CO. 17 pp.

McNulty-Huffman, C. 1991. A review of natural resource monitoring at Shenandoah National Park between 1978 and 1988. M.S. thesis, Slippery Rock University, Slippery Rock, PA.

Meyer, J. and many others. 2003. Where rivers are born: the scientific imperative for defending small streams and wetlands. American Rivers and Sierra Club, joint sponsors. http://www.amrivers.org/docs/WhereRiversAreBorn1.pdf.

Minckley, W. 1963. The ecology of a spring stream, Doe Run, Meade County, Kentucky. Wildlife Monographs 11:1-124.

Mitchell, J. 1998. Guide to inventory and monitoring of streamside salamanders in Shenandoah National Park, Viriginia. Final Report to the Legacy Resource Management Program, U.S. Department of Defense, Washington, DC.

Mitchell, J. 1999. Amphibian diversity in three montane streams with different levels of acidity, Shenandoah National Park, Virginia. Banisteria 14:28-35.

Moeykins, M. and J. Voshell. 2002. Studies of benthic macroinvertebrates for the Shenandoah National Park long-term ecological monitoring system: statistical analysis of LTEMS aquatic dataset from 1986 to 2000 on water chemistry, habitat and macroinvertebrates. Report to Shenandoah National Park, Luray, VA.

Mohn, L. and P. Bugas. 1979. Final report, Virginia trout stream and environmental inventory, January 1, 1976- December 31, 1979. Dingell-Johnson Report F-32. Virginia Commission of Game and Inland Fisheries, Richmond, VA.

Moore, M. and many others. 1997. Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. Hydrological Processes 11:925-947.

Montgomery, D., J. Buffington, and G. Pess. 1995. Pool spacing in forest channels. Water Resour. Res. 21:1097-1105.

Munawar, M., R.L. Thomas, H. Shear, P. McKee and A. Murdoch. 1984. An overview of sediment-associated contaminants and their bioassessment. Can. J. Fish. Aquatic Sci. Tec. Rept. 1253:1-136.

Naiman, R., J. Magnuson, D. McKnight, and J. Stanford. 1995. The freshwater imperative. Island Press, Washington, DC.

Naiman, R., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecol. Appl. 3:209-212.

Naiman, R. and H. Decamps. 1997. The ecology of interfaces: riparian zones. Ann. Rev. Ecol. Syst. 28:621-658.

NAPAP. 1991. 1990 integreated assessment report. National Acid Precipitation Assessment Program, Washington, DC.

NAPAP. 1993. 1992 report to Congress. National Acid Precipitation Assessment Program, Washington, DC.

NAPAP. 1998. NAPAP biennial report to Congress: an integrated assessment. National Acid Precipitation Assessment Program, Silver Spring, MD.

National Climate and Data Center. 2003. NCDC TD 9641 Clim 81 1961-1990 Normals. <http://www.worldclimate.com/cgi-bin/data.pl?ref =NW078+1300+ 445096C, 1302+445096C, 1304+445096C, 2300+445096C> <http://www.worldclimate.com/cgi-bin/data.pl?ref=N38W078+1300+440720C, 1302+440720C, 1304+440720C, 2300+440720C>.

National Park Service. 1998. Resource management plan. Shenandoah National Park. Luray, VA.

National Park Service. 1994. Fisheries management and data report. Shenandoah National Park, Luray, VA.

National Park Service. 2000a. Strategic plan. Shenandoah National Park, Luray, VA.

National Park Service. 2000b. Baseline water quality data inventory and analysis: Shenandoah National Park. Tech. Rept. NPS/NRWRD/NRTR-2000/64. Water Resources Division, Fort Collins, CO.

National Park Service. 2000c. Emergency operations plan. Shenandoah National Park, Luray, VA.

Odum, E. 1971. Fundamentals of ecology. 3rd edition. W.B. Saunders, Toronto, Canada.

Oostergo. H. 1997. Milieudata, Emissies van metalen en PAK door wegverkeer [Emission of metals and PACs by road traffic] By order of the Ministry of VROM, Hague.

Peterson, R. and L. Van Eeckhaute. 1992. Distribution of Ephemeroptera, Plecoptera, and Trichoptera of maritime catchments differing in pH. Freshw. Biol. 27:65-78.

Petranka, J. 1998. Salamanders of the United States and Canada. Smithsonian Institution Press, Washington, DC.

Pflakin, J., M. Barbour, K. Porter, S. Gross, and R. Hughes. 1989. Rapid bioassessment protocols for use in streams anad rivers: benthic macroinvertebrates and fish. EPA/444/4-89-001, U.S. Environmental Protection Agency, Office of Water, Assessment and Watershed Protection Division, Washington, DC.

Plummer, L.N. and others. 2000. Chemical and isotopic composition of water from springs, wells, and streams in parts of Shenandoah National Park, Virginia and vicinity, 1995-1999. USGS Open-file report 00-373. 70 pp.

Plummer, L.N., E. Busenberg, J.K. Bohlke, D.L. Nelms, R.L. Michel, and P. Schlosser. 2001. Ground water residence times in Shenandoah National

Park, Blue Ridge Mountains, Virginia, USA - a multi-tracer approach. Chemical Geology 179:93-111.

Pringle, C. 1997. Exploring how disturbance is transmitted upstream: going against the flow. J. N. Am. Benthol. Soc. 16:425-438.

PRIZIM. 1999. Shenandoah National Park environmental audit. Under contract to National Park Service, Shenandoah National Park, Luray, VA.

Purvis, J., M. Mathis, T. Messinger, J. Wiley, and D. Vana-Miller. 2002. Water resources management plan for New River Gorge National River, Gauley River National Recreation Area, and Bluestone National Scenic River, West Virginia. New River Gorge National River, Glen Jean, WV.

Reed, J.C., Jr. and J.T. Hack. (no date). Resume of the Geology of the Blue Ridge, Shenandoah National Park, Virginia. U.S. Geological Survey. 6 pp.

Reuss, J.O., and D.W. Johnson. 1986. Acid deposition and the acidification of soil and water. Springer-Verlag, NewYork.

Rice, K., J. Raffensperger, and R. Webb. 1999. Hydrological and geochemical controls on episodic acidification of streams in Shenandoah National Park, Virginia--Development and testing of a predictive model [abs.]: Virginia Water Research Symposium, November 15, 1999, Richmond, VA.

Rice, K., G. Hornberger, and J. Webb. 2001. Development of a park-wide geology-and topography-based map of vulnerability to episodic acidification of streams in Shenandoah National Park Virginia. Research Proposal. U.S. Geological Survey, Charlottesville, VA.

Rice, K., J. Chanat, G. Hornberger, and J. Webb. *In press*. Interpretation of concentration-discharge patterns in acid-neutralizing capacity during stormflow in three small, forested catchments in Shenandoah National Park, Virginia. U.S. Geological Survey, Charlottesville, VA.

Rice, K., W. Maben, and J. Webb. 2001. Water-quality data of soil water from three watersheds, Shenandoah National Park, Virginia, 1999-2000. U. S. Geological Survey Open File Report 01.236.

Rice, K.C and R.E. Jung. 2003. Selected constituent concentrations in road runoff and effects on water quality and biota in Shenadoah National Park, Virginia. Unpublished research proposal, U.S. Geological Survey. Charlottesville, VA. 6 pp.

Roghair, C. C. Dolloff, and M. Underwood. 2002. Response of a brook trout population and instream habitat to a catastrophic flood and debris flow. Trans. Am. Fish. Soc. 131:718-730.

Ryan, P. G. Hornberger, B. Cosby, J. Galloway, J. Webb, and E. Rastetter. 1989. Changes in the chemical compostion of stream water in two catchments in the Shenandoah National Park, Virginia, in response to atmospheric deposition of sulfur. Water Resources Research 25:2091-2099.

Sale, M. and many others. 1988. Chemical characteristics of streams in the Mid-Atlantic and southeastern United States. Volume III: Streams sampled, descriptive statistics, and compendium of physical and chemical data. EPA/600/3-88/021b, U.S. Environmental Protection Agency, Washington, DC.

Seaton, W.J. 2000. Aquifer Characterization in the Blue Ridge Physiographic Province using Resistivity Profiling and Borehole Geophysics. (abstract) Department of Geological Sciences, Virginia Tech. Blacksburg, VA. 2 pp.

Seaton, W.J. 2002. Aquifer characterization in the Blue Ridge Physiographic Province. PhD dissertation (abstract). Virginia Polytechnic Institute and State University. Blacksburg, VA.

Shaffer, P. and J. Galloway. 1982. Acid precipitation: the impact on two headwater streams in Shenandoah National Park, Virginia. International Symposium on Hydrometerology, American Water Resources Association.

Sheridan, J. 1966. Summary report, fishery management program, Shenandoah National Park. U.S. Department of the Interior, Fish and Wildlife Service.

Sheridan, J. 1972. Annual project report --- 1972, Fishery Management Program, Shenandoah National Park. Bureau of Sport Fisheries and Wildlife.

Smith, E. and J. Voshell. 1994. Analyzing long-term ecological monitoring data to determine benthic macroinvertebrate community responses to stream acidification in Shenandoah National Park. National Park Service, Shenandoah National Park, Luray, Virginia.

Smith, E. and J. Voshell. 1997. Studies of benthic macroinvertebrates and fish in streams within EPA Region 3 for development of biological indicators or ecological condition; Part I, Benthic Macroinvertebrates. Report to U. S. Environmental Protection Agency, Philadelphia, PA.

Snyder, C., J. Webb, J. Atkinson, and S. Spitzer. 2003. Effects of stream water chemistry on mercury concentration in brook trout in Shenandoah National Park. Research Proposal, U.S.Geological Survey, Leetown Science Center, Kearneysville, WV.

Stoddard, J. and J. Kellogg. 1993. Trends and patterns in lake acidification in the state of Vermont: evidence from the long-term monitoring project. Water, Air, and Soil Pollution 67:301-317.

Sullivan, T.J., B.J. Cosby, J.R. Webb, K.U. Snyder, A.T. Herlihy, A.J. Bulger, E.H. Gilbert, and D. Moore. 2003a. Assessment of the effects of acidic deposition on aquatic resources in the Southern Appalachian Mountains. Report prepared for the Southern Appalachian Mountains Initiative (SAMI). E&S Environmental Chemistry, Inc., Corvallis, OR. (available at: http://www.esenvironmental .com/sami_ download.htm).

Sullivan, T.J., B.J. Cosby, A.J. Bulger, J.R. Webb, J.A. Laurence, E.H. Lee, W.E. Hogsett, R.L. Dennis, K. Savig, H. Wayne, M. Scruggs, J. Ray, D. Miller, C. Gordon, J.S. Kern. 2003b. Assessment of Air Quality and Related Values in Shenandoah National Park. Report by E&S Environmental Chemistry, Inc. Corvallis, OR and submitted to Shenandoah National Park, Luray, VA.

Summer, R.M. 1980. Impacts of horse traffic on trails on Rocky Mountain National Park. Jour. of Soil and Water Conservation 35:85-87.

Summer, R.M. 1986, Geomorphic impacts of horse traffic on montane landforms. Journal of Soil and Water Conservation. 41:126-128.

Teetor, A. 1988. Identification and mapping of vegetation communities in Shenandoah National Park, Virginia. Research/Resources Management Report MAR—34. U.S. Department of the Interior, National Park Service, Philadelphia, PA.

Tinsley, B.E., and E.B. Fish. 1985. Evaluation of trail erosion in Guadeloupe Mountains National Park, Texas. Landscape Planning. 12:29-47.

Ullrich, S., T. Tanton, and S. Abdrashitova. 2001. Mercury in the aquatic environment: A review of factors affecting methylation. Critical Reviews in Environmental Science and Technology 31:241-293.

U.S. Department of Agriculture. 1979. General soil map of Virginia. U.S.D.A., Soil Conservation Service. Lanham, MD.

USEPA. 1997. Mercury study report to Congress. http://www.epa.gov/oar/mercury.html.

USEPA . 2000. National air pollutant emmission trends, 1900-1998. EPA 454/R-00-002, U.S. Environmental Protection Agency, Washington, DC.

U.S. Geological Survey. 1996a. Review of long-term monitoring program at Shenandoah National Park. Shenandoah National Park, Luray, VA.

U.S. Geological Survey. 1996b. Summary document for the USGS Workshop on mercury cycling in the environment. Golden, CO, July 7-9, 1996. U.S. Geological Survey, Water Resources Division, Office of Water Quality. Reston, Virginia, October, 1996.

U.S. Geological Survey. 2000. < www.usgs.gov/themes/factsheet/146-00/ >.

U.S. Geological Survey. 2001. Radon in Blue Ridge Ground Water Among Highest in Nation. http://www.usgs.gov/public/press/public_affairs/press_release/pr1469m.html .

USGAO. 2000. Acid Rain: emissions trends and effects in the eastern United States. GAO/RCED-00-47, U.S. General Accounting Office, Washington, DC.

Van Bohemen, H.D. and W.H. Janssen Van De Laak. 2003. The influence of road infrastructure and traffic on soil, water, and air quality. Environmental Management 31:50-68.

Virginia Department of Environmental Quality. 2002. Water quality assessment guidance manual for 2002. Richmond, VA.

Virginia Department of Environmental Quality. 2004. Mission and History of Ground Water Protection Steering Committee. http://www.deq.state.va.us/gwpsc/mission.html

Voshell, J. and S. Hiner. 1990. Shenandoah National Park long-term ecological monitoring system: Section III, Aquatic component user manual *in* United States Department of Interior, Shenandoah National Park long-term ecological monitoring system users manual. Shenandoah National Park, Luray, VA.

Voshell, J. and B. Marshell. 1994. Effects of gypsy moth defoliation on the aquatic biota of headwater streamsin Shenandoah National Park. National Park Service, Shenandoah National Park, Luray, VA.

Webb, J. 2002. Effects of acidic deposition on aquatic resources of the central Appalachian Mountain region. Department of Environmental Sciences, U. of Virginia, Charlottesville, VA.

Webb, J. 1988. Retention of atmospheric sulfate by catchments in Shenandoah National Park, Virginia. M.S. thesis. Department of Environmental Sciences, University of Virginia, Charlottesville, VA.

Webb, J., B. Crosby, J. Galloway and G. Hornberger. 1989a. Acidification of native brook trout streams in Virginia. Water Resour. Res. 25:1367-1377.

Webb, J., and many others. 1989b. Acidic deposition and the status of Virginia's wild trout resource. Symposium Proceedings Wild Trout IV: 228-233. U.S. Fish and Wildlife Service, Washington, DC.

Webb, R. n*o date*. Availability of hydro-biogeochemical data for watersheds in Shenandoah National Park. Department of Environmental Sciences, U. of Virginia, Charlottesville, VA.

Whittaker, P.L. 1978. Comparison of surface impact by hiking and horseback riding in the Great Smoky Mountains National Park. Management Report 24, USDI National Park Service, Southeast Region, Atlanta, GA. 32 pp.

Wiener, J. 1988. Lake acidification increases mercury accumulation by fish. U.S. Fish and Wildlife Service Research Information Bulletin No. 88-63. National Fisheries Contaminant Research Center, Field Research Station, LaCrosse, WI.

Wiener, J. 1996. Mercury in fish and aquatic food webs. Paper presented at a July 9, 1996, USGS Meeting "Mercury Cycling in the Environment." U.S. Geology Survey, Office of Water Quality, Denver, CO. Abstract available from USGS, Denver, CO. Highlights available in: Summary Document for the USGS Workshop on Mercury Cycling in the Environment Golden, Colorado, July 7-9, 1996 U.S. Geological Survey, Water Resources DivisionOffice of Water Quality. Reston, Virginia October, 1996.

Wiener, J. and P. Stokes. 1990. Enhanced bioaccumulation of mercury, cadmium, and lead in low - alkalinity waters; an emerging regional environmental problem. Environmental Toxicology and Chemistry 9:821-823.

Wigington, P. T. Davies, M. Tranter, and K. Eshleman. 1990. Episodic acidification of surface waters due to acidic deposition. State of Science and Technology Report No. 12, National Acid Precipation Assessment Program, Washington, DC.

Wigington, P. and many others. 1993. Episodic acidification of streams in the northeastern United States: Chemical and biological results of the Episodic Response Project. EPA/600/R-93/190, U.S. Environmental Protection Agency, Washington, DC.

Wilson, J.P. and J.P. Seney. 1994. Erosional impacts of hikers, horses, motorcycles, and off-road bicycles on mountain trails in Montana. Mountain Research and Development. 14:77-88.

Witt, W. 1993. Annotated checklist of the amphibians and reptiles of Shenandoah National Park, Virginia. Catesbeiana 13:26-35.

Young, J., D. Morton, and D. Walton. 2000. Assessment of vegetation communities in relation to ecological units within Shenandoah National Park. Project Plan, No. 2077, U.S.Geological Survey, Aquatic Ecology Laboratory, Leetown Science Center, Leetown, WV.

APPENDIX A
(data from U.S. Geological Survey 2000)

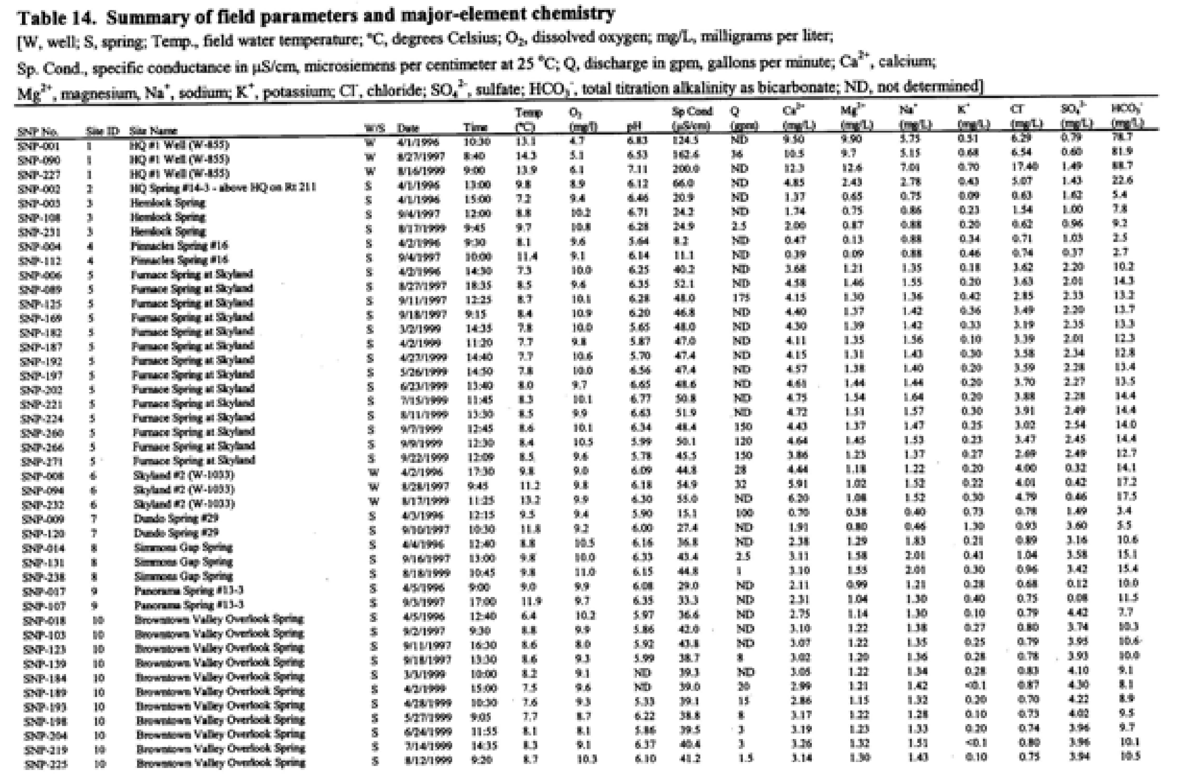


Table 14. Summary of field parameters and major-element chemistry

[W, well; S, spring; Temp., field water temperature; °C, degrees Celsius; O_2, dissolved oxygen; mg/L, milligrams per liter; Sp. Cond., specific conductance in µS/cm, microsiemens per centimeter at 25 °C; Q, discharge in gpm, gallons per minute; Ca^{2+}, calcium; Mg^{2+}, magnesium, Na^{+}, sodium; K^{+}, potassium; Cl^{-}, chloride; SO_4^{2-}, sulfate; HCO_3^{-}, total titration alkalinity as bicarbonate; ND, not determined]

SNP No.	Site ID	Site Name	W/S	Date	Time	Temp (°C)	O_2 (mg/l)	pH	Sp Cond (µS/cm)	Q (gpm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)
SNP-001	1	HQ #1 Well (W-855)	W	4/1/1996	10:30	13.1	4.7	6.83	124.5	ND	9.50	9.90	5.75	0.51	6.29	0.79	78.7
SNP-090	1	HQ #1 Well (W-855)	W	8/27/1997	8:40	14.3	5.1	6.53	162.6	36	10.5	9.7	5.15	0.68	6.54	0.60	81.9
SNP-227	1	HQ #1 Well (W-855)	W	8/16/1999	9:00	13.9	6.1	7.11	200.0	ND	12.3	12.6	7.01	0.70	17.40	1.49	88.7
SNP-002	2	HQ Spring #14-3 - above HQ on Rt 211	S	4/1/1996	13:00	9.8	8.9	6.12	66.0	ND	4.85	2.43	2.78	0.43	5.07	1.43	22.6
SNP-003	3	Hemlock Spring	S	4/1/1996	15:00	7.2	9.4	6.46	20.9	ND	1.37	0.65	0.75	0.09	0.63	1.62	5.4
SNP-108	3	Hemlock Spring	S	9/4/1997	12:00	8.8	10.2	6.71	24.2	ND	1.74	0.75	0.86	0.23	1.54	1.00	7.8
SNP-231	3	Hemlock Spring	S	8/17/1999	9:45	9.7	10.8	6.28	24.9	2.5	2.00	0.87	0.88	0.20	0.62	0.96	9.2
SNP-004	4	Pinnacles Spring #16	S	4/2/1996	9:30	8.1	9.6	5.64	8.2	ND	0.47	0.13	0.88	0.34	0.71	1.03	2.5
SNP-112	4	Pinnacles Spring #16	S	9/4/1997	10:00	11.4	9.1	6.14	11.1	ND	0.39	0.09	0.88	0.46	0.74	0.37	2.7
SNP-006	5	Furnace Spring at Skyland	S	4/2/1996	14:30	7.5	10.0	6.25	40.2	ND	3.68	1.21	1.35	0.18	3.62	2.20	10.2
SNP-089	5	Furnace Spring at Skyland	S	8/27/1997	18:35	8.5	9.6	6.35	52.1	ND	4.58	1.46	1.55	0.20	3.63	2.01	14.3
SNP-125	5	Furnace Spring at Skyland	S	9/11/1997	12:25	8.7	10.1	6.28	48.0	175	4.15	1.30	1.36	0.42	2.85	2.33	13.2
SNP-169	5	Furnace Spring at Skyland	S	9/18/1997	9:15	8.4	10.9	6.20	46.8	ND	4.40	1.37	1.42	0.36	3.49	2.20	13.7
SNP-182	5	Furnace Spring at Skyland	S	3/2/1999	14:35	7.8	10.0	5.65	48.0	ND	4.30	1.39	1.42	0.33	3.19	2.35	13.3
SNP-187	5	Furnace Spring at Skyland	S	4/2/1999	11:20	7.7	9.8	5.87	47.0	ND	4.11	1.35	1.56	0.10	3.39	2.01	12.3
SNP-192	5	Furnace Spring at Skyland	S	4/27/1999	14:40	7.7	10.6	5.70	47.4	ND	4.15	1.31	1.43	0.30	3.58	2.34	12.8
SNP-197	5	Furnace Spring at Skyland	S	5/26/1999	14:50	7.8	10.0	6.56	47.4	ND	4.57	1.38	1.40	0.20	3.59	2.28	13.4
SNP-202	5	Furnace Spring at Skyland	S	6/23/1999	13:40	8.0	9.7	6.65	48.6	ND	4.61	1.44	1.44	0.20	3.70	2.27	13.5
SNP-221	5	Furnace Spring at Skyland	S	7/15/1999	11:45	8.3	10.1	6.77	50.8	ND	4.75	1.54	1.64	0.20	3.88	2.28	14.4
SNP-224	5	Furnace Spring at Skyland	S	8/11/1999	13:30	8.5	9.9	6.63	51.9	ND	4.72	1.51	1.57	0.30	3.91	2.49	14.4
SNP-260	5	Furnace Spring at Skyland	S	9/7/1999	12:45	8.6	10.1	6.34	48.4	150	4.43	1.37	1.47	0.25	3.02	2.54	14.0
SNP-266	5	Furnace Spring at Skyland	S	9/9/1999	12:30	8.4	10.5	5.99	50.1	120	4.64	1.45	1.53	0.23	3.47	2.45	14.4
SNP-271	5	Furnace Spring at Skyland	S	9/22/1999	12:09	8.5	9.6	5.78	45.5	150	3.86	1.23	1.37	0.27	2.69	2.49	12.7
SNP-008	6	Skyland #2 (W-1033)	W	4/2/1996	17:30	9.8	9.0	6.09	44.8	28	4.44	1.18	1.22	0.20	4.00	0.32	14.1
SNP-094	6	Skyland #2 (W-1033)	W	8/28/1997	9:45	11.2	9.8	6.18	54.9	32	5.91	1.02	1.52	0.22	4.01	0.42	17.2
SNP-232	6	Skyland #2 (W-1033)	W	8/17/1999	11:25	13.2	9.9	6.30	55.0	ND	6.20	1.08	1.52	0.30	4.79	0.46	17.5
SNP-009	7	Dundo Spring #29	S	4/3/1996	12:15	9.5	9.4	5.90	15.1	100	0.70	0.38	0.40	0.73	0.78	1.49	3.4
SNP-120	7	Dundo Spring #29	S	9/10/1997	10:30	11.8	9.2	6.00	27.4	ND	1.91	0.80	0.46	1.30	0.93	3.60	5.5
SNP-014	8	Simmons Gap Spring	S	4/4/1996	12:40	8.8	10.5	6.16	36.8	ND	2.38	1.29	1.83	0.21	0.89	3.16	10.6
SNP-131	8	Simmons Gap Spring	S	9/16/1997	13:00	9.8	10.0	6.33	43.4	2.5	3.11	1.58	2.01	0.41	1.04	3.58	15.1
SNP-238	8	Simmons Gap Spring	S	8/18/1999	10:45	9.8	11.0	6.15	44.8	1	3.10	1.55	2.01	0.30	0.96	3.42	15.4
SNP-017	9	Panorama Spring #13-3	S	4/5/1996	9:00	9.0	9.9	6.08	29.0	ND	2.11	0.99	1.21	0.28	0.68	0.12	10.0
SNP-107	9	Panorama Spring #13-3	S	9/3/1997	17:00	11.9	9.7	6.35	33.3	ND	2.31	1.04	1.30	0.40	0.75	0.08	11.5
SNP-018	10	Browntown Valley Overlook Spring	S	4/5/1996	12:40	6.4	10.2	5.97	36.6	ND	2.75	1.14	1.30	0.10	0.79	4.42	7.7
SNP-103	10	Browntown Valley Overlook Spring	S	9/2/1997	9:30	8.8	9.9	5.86	42.0	ND	3.10	1.22	1.38	0.27	0.80	3.74	10.3
SNP-123	10	Browntown Valley Overlook Spring	S	9/11/1997	16:30	8.6	8.0	5.92	43.8	ND	3.07	1.22	1.35	0.25	0.79	3.95	10.6
SNP-139	10	Browntown Valley Overlook Spring	S	9/18/1997	13:30	8.6	9.3	5.99	38.7	8	3.02	1.20	1.36	0.28	0.78	3.93	10.0
SNP-184	10	Browntown Valley Overlook Spring	S	3/3/1999	10:00	8.2	9.1	ND	39.3	ND	3.05	1.22	1.34	0.28	0.83	4.10	9.1
SNP-189	10	Browntown Valley Overlook Spring	S	4/2/1999	15:00	7.5	9.6	ND	39.0	20	2.99	1.21	1.42	<0.1	0.87	4.30	8.1
SNP-193	10	Browntown Valley Overlook Spring	S	4/28/1999	10:30	7.6	9.3	5.33	39.1	15	2.86	1.15	1.32	0.20	0.70	4.22	8.9
SNP-198	10	Browntown Valley Overlook Spring	S	5/27/1999	9:05	7.7	8.7	6.22	38.8	8	3.17	1.22	1.28	0.10	0.73	4.02	9.5
SNP-204	10	Browntown Valley Overlook Spring	S	6/24/1999	11:55	8.1	8.1	5.86	39.5	3	3.19	1.23	1.33	0.20	0.74	3.96	9.7
SNP-219	10	Browntown Valley Overlook Spring	S	7/14/1999	14:35	8.3	9.1	6.37	40.4	3	3.26	1.32	1.51	<0.1	0.80	3.96	10.1
SNP-225	10	Browntown Valley Overlook Spring	S	8/12/1999	9:20	8.7	10.3	6.10	41.2	1.5	3.14	1.30	1.43	0.10	0.75	3.94	10.5

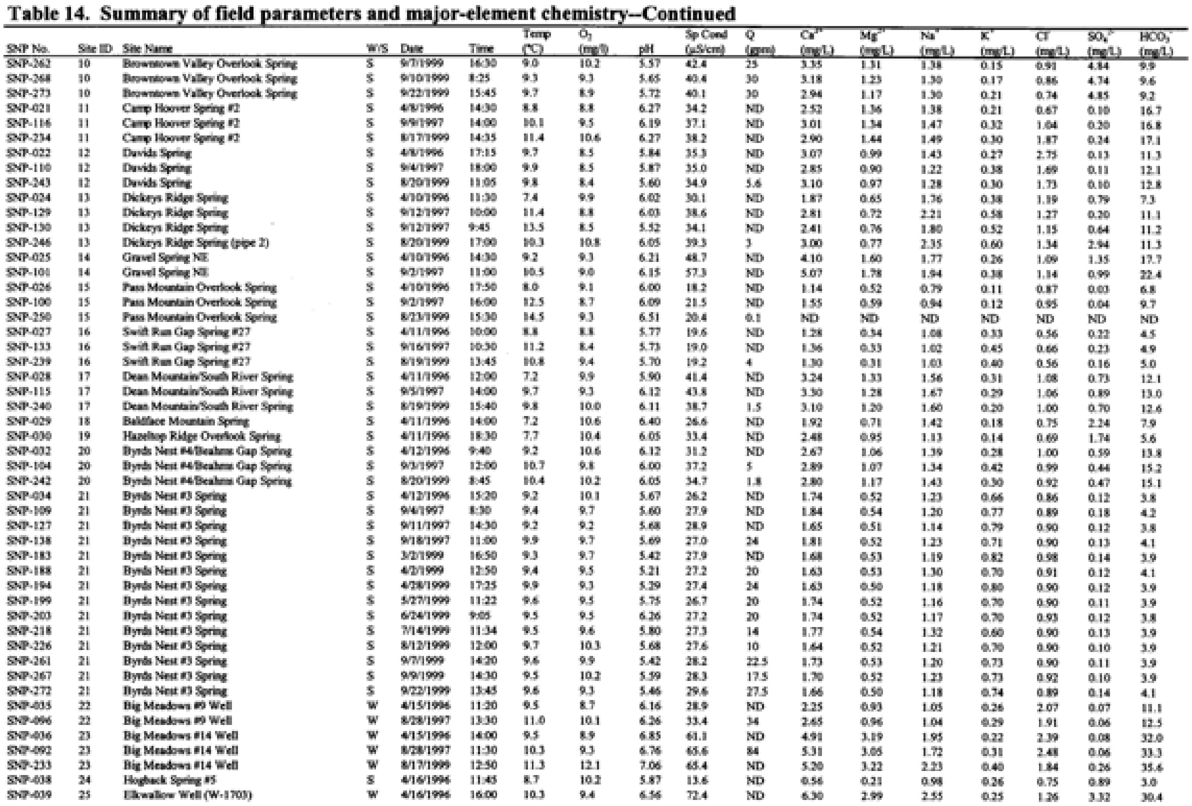


Table 14. Summary of field parameters and major-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Temp (°C)	O_2 (mg/l)	pH	Sp Cond (µS/cm)	Q (gpm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)
SNP-262	10	Browntown Valley Overlook Spring	S	9/7/1999	16:30	9.0	10.2	5.57	42.4	25	3.35	1.31	1.38	0.15	0.91	4.84	9.9
SNP-268	10	Browntown Valley Overlook Spring	S	9/10/1999	8:25	9.3	9.3	5.65	40.4	30	3.18	1.23	1.30	0.17	0.86	4.74	9.6
SNP-273	10	Browntown Valley Overlook Spring	S	9/22/1999	15:45	9.7	8.9	5.72	40.1	30	2.94	1.17	1.30	0.21	0.74	4.85	9.2
SNP-021	11	Camp Hoover Spring #2	S	4/8/1996	14:30	8.8	8.8	6.27	34.2	ND	2.52	1.36	1.38	0.21	0.67	0.10	16.7
SNP-116	11	Camp Hoover Spring #2	S	9/9/1997	14:00	10.1	9.5	6.19	37.1	ND	3.01	1.34	1.47	0.32	1.04	0.20	16.8
SNP-234	11	Camp Hoover Spring #2	S	8/17/1999	14:35	11.4	10.6	6.27	38.2	ND	2.90	1.44	1.49	0.30	1.87	0.24	17.1
SNP-022	12	Davids Spring	S	4/8/1996	17:15	9.7	8.5	5.84	35.3	ND	3.07	0.99	1.43	0.27	2.75	0.13	11.3
SNP-110	12	Davids Spring	S	9/4/1997	18:00	9.9	8.5	5.87	35.0	ND	2.85	0.90	1.22	0.38	1.69	0.11	12.1
SNP-243	12	Davids Spring	S	8/20/1999	11:05	9.8	8.4	5.60	34.9	5.6	3.10	0.97	1.28	0.30	1.73	0.10	12.8
SNP-024	13	Dickeys Ridge Spring	S	4/10/1996	11:30	7.4	9.9	6.02	30.1	ND	1.87	0.65	1.76	0.38	1.19	0.79	7.3
SNP-129	13	Dickeys Ridge Spring	S	9/12/1997	10:00	11.4	8.8	6.03	38.6	ND	2.81	0.72	2.21	0.58	1.27	0.20	11.1
SNP-130	13	Dickeys Ridge Spring	S	9/12/1997	9:45	13.5	8.5	5.52	34.1	ND	2.41	0.76	1.80	0.52	1.15	0.64	11.2
SNP-246	13	Dickeys Ridge Spring (pipe 2)	S	8/20/1999	17:00	10.3	10.8	6.05	39.3	3	3.00	0.77	2.35	0.60	1.34	2.94	11.3
SNP-025	14	Gravel Spring NE	S	4/10/1996	14:30	9.2	9.3	6.21	48.7	ND	4.10	1.60	1.77	0.26	1.09	1.35	17.7
SNP-101	14	Gravel Spring NE	S	9/2/1997	11:00	10.5	9.0	6.15	57.3	ND	5.07	1.78	1.94	0.38	1.14	0.99	22.4
SNP-026	15	Pass Mountain Overlook Spring	S	4/10/1996	17:50	8.0	9.1	6.00	18.2	ND	1.14	0.52	0.79	0.11	0.87	0.03	6.8
SNP-100	15	Pass Mountain Overlook Spring	S	9/2/1997	16:00	12.5	8.7	6.09	21.5	ND	1.55	0.59	0.94	0.12	0.95	0.04	9.7
SNP-250	15	Pass Mountain Overlook Spring	S	8/23/1999	15:30	14.5	9.3	6.51	20.4	0.1	ND	ND	ND	ND	ND	ND	ND
SNP-027	16	Swift Run Gap Spring #27	S	4/11/1996	10:00	8.8	8.8	5.77	19.6	ND	1.28	0.34	1.08	0.33	0.56	0.22	4.5
SNP-133	16	Swift Run Gap Spring #27	S	9/16/1997	10:30	11.2	8.4	5.73	19.0	ND	1.36	0.33	1.02	0.45	0.66	0.23	4.9
SNP-239	16	Swift Run Gap Spring #27	S	8/19/1999	13:45	10.8	9.4	5.70	19.2	4	1.30	0.31	1.03	0.40	0.56	0.16	5.0
SNP-028	17	Dean Mountain/South River Spring	S	4/11/1996	12:00	7.2	9.9	5.90	41.4	ND	3.24	1.33	1.56	0.31	1.08	0.73	12.1
SNP-115	17	Dean Mountain/South River Spring	S	9/5/1997	14:00	9.7	9.3	6.12	43.8	ND	3.30	1.28	1.67	0.29	1.06	0.89	13.0
SNP-240	17	Dean Mountain/South River Spring	S	8/19/1999	15:40	9.8	10.0	6.11	38.7	1.5	3.10	1.20	1.60	0.20	1.00	0.70	12.6
SNP-029	18	Baldface Mountain Spring	S	4/11/1996	14:00	7.2	10.6	6.40	26.6	ND	1.92	0.71	1.42	0.18	0.75	2.24	7.9
SNP-030	19	Hazeltop Ridge Overlook Spring	S	4/11/1996	18:30	7.7	10.4	6.05	33.4	ND	2.48	0.95	1.13	0.14	0.69	1.74	5.6
SNP-032	20	Byrds Nest #4/Beahms Gap Spring	S	4/12/1996	9:40	9.2	10.6	6.12	31.2	ND	2.67	1.06	1.39	0.28	1.00	0.59	13.8
SNP-104	20	Byrds Nest #4/Beahms Gap Spring	S	9/3/1997	12:00	10.7	9.8	6.00	37.2	5	2.89	1.07	1.34	0.42	0.99	0.44	15.2
SNP-242	20	Byrds Nest #4/Beahms Gap Spring	S	8/20/1999	8:45	10.4	10.2	6.05	34.7	1.8	2.80	1.17	1.43	0.30	0.92	0.47	15.1
SNP-034	21	Byrds Nest #3 Spring	S	4/12/1996	15:20	9.2	10.1	5.67	26.2	ND	1.74	0.52	1.23	0.66	0.86	0.12	3.8
SNP-109	21	Byrds Nest #3 Spring	S	9/4/1997	8:30	9.4	9.7	5.60	27.9	ND	1.84	0.54	1.20	0.77	0.89	0.18	4.2
SNP-127	21	Byrds Nest #3 Spring	S	9/11/1997	14:30	9.2	9.2	5.68	28.9	ND	1.65	0.51	1.14	0.79	0.90	0.12	3.8
SNP-138	21	Byrds Nest #3 Spring	S	9/18/1997	11:00	9.9	9.7	5.69	27.0	24	1.81	0.52	1.23	0.71	0.90	0.13	4.1
SNP-183	21	Byrds Nest #3 Spring	S	3/2/1999	16:50	9.3	9.7	5.42	27.9	ND	1.68	0.53	1.19	0.82	0.98	0.14	3.9
SNP-188	21	Byrds Nest #3 Spring	S	4/2/1999	12:50	9.4	9.5	5.21	27.2	20	1.63	0.53	1.30	0.70	0.91	0.12	4.1
SNP-194	21	Byrds Nest #3 Spring	S	4/28/1999	17:25	9.9	9.3	5.29	27.4	24	1.63	0.50	1.18	0.80	0.90	0.12	3.9
SNP-199	21	Byrds Nest #3 Spring	S	5/27/1999	11:22	9.6	9.5	5.75	26.7	20	1.74	0.52	1.16	0.70	0.90	0.11	3.9
SNP-203	21	Byrds Nest #3 Spring	S	6/24/1999	9:05	9.5	9.5	6.26	27.2	20	1.74	0.52	1.17	0.70	0.93	0.12	3.8
SNP-218	21	Byrds Nest #3 Spring	S	7/14/1999	11:34	9.5	9.6	5.80	27.3	14	1.77	0.54	1.32	0.60	0.90	0.13	3.9
SNP-226	21	Byrds Nest #3 Spring	S	8/12/1999	12:00	9.7	10.3	5.68	27.6	10	1.64	0.52	1.21	0.70	0.90	0.10	3.9
SNP-261	21	Byrds Nest #3 Spring	S	9/7/1999	14:20	9.6	9.9	5.42	28.2	22.5	1.73	0.53	1.20	0.73	0.90	0.11	3.9
SNP-267	21	Byrds Nest #3 Spring	S	9/9/1999	14:30	9.5	10.2	5.59	28.3	17.5	1.70	0.52	1.23	0.73	0.92	0.10	3.9
SNP-272	21	Byrds Nest #3 Spring	S	9/22/1999	13:45	9.6	9.3	5.46	29.6	27.5	1.66	0.50	1.18	0.74	0.89	0.14	4.1
SNP-035	22	Big Meadows #9 Well	W	4/15/1996	11:20	9.5	8.7	6.16	28.9	ND	2.25	0.93	1.05	0.26	2.07	0.07	11.1
SNP-096	22	Big Meadows #9 Well	W	8/28/1997	13:30	11.0	10.1	6.26	33.4	34	2.65	0.96	1.04	0.29	1.91	0.06	12.5
SNP-036	23	Big Meadows #14 Well	W	4/15/1996	14:00	9.5	8.9	6.85	61.1	ND	4.91	3.19	1.95	0.22	2.39	0.08	32.0
SNP-092	23	Big Meadows #14 Well	W	8/28/1997	11:30	10.3	9.3	6.76	65.6	84	5.31	3.05	1.72	0.31	2.48	0.06	33.3
SNP-233	23	Big Meadows #14 Well	W	8/17/1999	12:50	11.3	12.1	7.06	65.4	ND	5.20	3.22	2.23	0.40	1.84	0.26	35.6
SNP-038	24	Hogback Spring #5	S	4/16/1996	11:45	8.7	10.2	5.87	13.6	ND	0.56	0.21	0.98	0.26	0.75	0.89	3.0
SNP-039	25	Elkwallow Well (W-1703)	W	4/16/1996	16:00	10.3	9.4	6.56	72.4	ND	6.30	2.99	2.55	0.25	1.26	3.32	30.4

Table 14. Summary of field parameters and major-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Temp (°C)	O_2 (mg/l)	pH	Sp Cond (µS/cm)	Q (gpm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)
SNP-086	25	Elkwallow Well (W-1703)	W	8/26/1997	18:30	10.9	9.7	6.40	85.9	10	7.20	3.17	2.40	0.25	1.27	3.58	34.1
SNP-228	25	Elkwallow Well (W-1703)	W	8/16/1999	11:45	11.4	9.1	6.62	89.2	ND	8.00	3.70	2.61	0.30	1.15	3.36	41.0
SNP-041	26	Hightop Hut Spring	S	4/17/1996	15:15	9.9	8.8	6.06	56.1	ND	4.77	1.75	2.46	0.21	0.78	2.09	18.6
SNP-132	26	Hightop Hut Spring	S	9/16/1997	15:45	10.2	8.5	6.23	66.6	ND	6.29	2.15	2.69	0.28	0.97	1.53	25.7
SNP-043	27	Pass Mountain Hut Spring	S	4/18/1996	9:15	8.6	8.2	5.77	29.6	ND	2.05	0.96	1.20	0.20	0.97	0.05	8.3
SNP-105	27	Pass Mountain Hut Spring	S	9/3/1997	14:10	11.3	9.2	6.08	35.4	ND	2.11	0.89	1.09	0.26	0.91	0.05	8.6
SNP-048	31	Dickeys Ridge Well (W-1346)	W	4/19/1996	14:40	12.9	5.9	8.31	134.1	ND	17.30	4.17	4.19	0.31	1.41	2.87	73.6
SNP-084	31	Dickeys Ridge Well (W-1346)	W	8/26/1997	10:50	13.4	6.7	8.18	144.1	ND	18.00	3.99	3.62	0.43	1.30	2.78	78.7
SNP-230	31	Dickeys Ridge Well (W-1346)	W	8/16/1999	16:15	14.2	7.4	8.18	138.1	ND	17.20	3.97	3.58	0.30	0.98	0.12	77.3
SNP-050	33	Domestic well #1	W	4/24/1996	9:50	13.2	5.4	7.10	534.0	ND	75.9	29.4	2.36	1.24	5.18	7.78	359.0
SNP-051	34	Domestic well #2	W	4/24/1996	14:55	14.8	5.2	7.17	530.0	ND	66.5	32.9	4.99	0.74	17.6	16.7	301.0
SNP-052	35	White Oak Cabin Spring	S	4/25/1996	10:35	8.9	9.7	6.13	36.9	ND	3.34	1.10	1.23	0.14	3.44	2.23	8.5
SNP-111	35	White Oak Cabin Spring	S	9/4/1997	15:55	13.7	8.8	6.81	36.6	ND	3.07	0.98	1.09	0.28	2.47	1.98	8.8
SNP-053	36	Big Meadows #1 Well (W-1701)	W	4/25/1996	16:30	9.6	8.1	6.21	34.5	ND	2.83	1.46	1.27	0.22	0.79	0.09	16.9
SNP-083	36	Big Meadows #1 Well (W-1701)	W	9/17/1997	16:30	10.2	8.1	6.20	35.2	4.5	3.01	1.43	1.20	0.16	0.85	0.04	17.5
SNP-037	37	HQ #2 Well (W-851)	W	4/16/1996	9:45	13.1	1.9	6.12	156.4	ND	12.1	8.6	5.40	1.97	7.71	3.84	79.3
SNP-087	37	HQ #2 Well (W-851)	W	8/27/1997	10:30	16.3	4.3	6.01	164.2	710	12.5	8.2	4.82	1.71	4.24	3.11	80.5
SNP-007	38	Skyland #5	W	4/2/1996	16:00	8.3	9.2	6.34	57.2	ND	6.12	1.60	1.31	0.11	1.61	1.33	25.4
SNP-088	38	Skyland #5	W	8/27/1997	17:10	9.6	8.6	5.85	75.4	16	7.32	2.11	1.43	0.25	1.91	1.80	33.7
SNP-005	39	Pinnacles Well (W-3288)	W	4/2/1996	12:00	9.4	8.8	5.71	47.3	ND	3.78	1.08	1.62	0.52	0.94	0.16	7.2
SNP-091	39	Pinnacles Well (W-3288)	W	8/27/1997	12:45	10.1	9.1	5.78	51.1	715	3.75	1.00	1.38	0.55	0.91	0.15	7.0
SNP-019	40	Mathews Arm Spring Range View Cabin	S	4/5/1996	14:35	7.9	10.0	6.05	52.6	30	4.48	1.83	1.55	0.46	0.97	0.87	14.5
SNP-102	40	Mathews Arm Spring Range View Cabin	S	9/2/1997	15:30	12.5	8.3	6.03	51.1	ND	4.12	1.71	1.63	0.44	1.10	0.38	15.1
SNP-031	41	Lewis Mountain Spring #25-2	S	4/11/1996	16:30	8.0	7.5	6.07	19.2	ND	1.15	0.31	1.05	0.27	1.46	2.66	2.7
SNP-114	41	Lewis Mountain Spring #25-2	S	9/5/1997	11:00	10.1	8.8	6.38	23.1	ND	1.59	0.35	1.18	0.43	2.18	2.11	3.6
SNP-054	42	Old Rag Shelter Spring	S	4/26/1996	14:30	9.9	9.8	5.92	27.0	ND	1.87	0.51	1.90	0.57	1.16	2.35	7.2
SNP-118	42	Old Rag Shelter Spring	S	9/9/1997	18:00	15.2	5.8	8.70	29.2	ND	1.75	0.52	1.78	0.73	1.13	1.89	8.8
SNP-015	43	Loft Mountain Overlook Spring	S	4/4/1996	15:30	8.3	10.3	6.02	65.5	ND	4.85	2.32	2.74	0.29	0.69	6.99	14.4
SNP-121	43	Loft Mountain Overlook Spring	S	9/10/1997	17:00	13.7	6.8	6.02	81.9	ND	6.51	2.65	2.98	0.54	1.21	6.73	24.2
SNP-016	44	Loft Mountain Spring	S	4/4/1996	17:30	9.0	10.0	6.14	50.1	ND	4.21	1.53	1.80	0.29	0.91	0.88	11.3
SNP-122	44	Loft Mountain Spring	S	9/10/1997	15:00	11.1	9.2	5.85	51.4	3.3	4.25	1.44	1.41	0.54	0.91	3.46	11.7
SNP-013	45	Simmons Gap Well (W-1704)	W	4/4/1996	9:30	12.0	6.6	7.34	119.5	25	7.67	6.68	6.02	0.35	2.01	3.15	57.7
SNP-099	45	Simmons Gap Well (W-1704)	W	8/29/1997	10:00	12.1	8.0	7.13	129.1	26	8.55	6.40	5.63	0.47	2.02	2.67	60.9
SNP-137	46	Yeager's Spring (Luray)	S	9/17/1997	13:10	14.4	5.6	7.28	273.0	ND	38.3	8.9	3.83	2.45	5.63	10.09	149.3
SNP-248	46	Yeager's Spring (Luray)	S	8/23/1999	11:20	12.8	5.6	7.56	319.6	2900	42.3	10.8	4.28	2.10	7.69	11.07	171.0
SNP-042	47	Lewis Mountain Well (W-1072)	W	4/17/1996	18:20	9.6	9.3	5.72	24.3	ND	1.53	0.57	0.77	0.59	0.76	3.88	4.7
SNP-095	47	Lewis Mountain Well (W-1072)	W	8/28/1997	15:45	10.7	12.0	6.30	45.8	10	3.91	1.56	1.22	0.64	0.97	2.97	18.3
SNP-140	47	Lewis Mountain Well (W-1072)	W	9/19/1997	9:30	9.9	9.7	5.94	28.4	15	2.29	0.82	0.87	0.75	0.90	3.39	8.3
SNP-170	48	Bear Lithia Spring	S	9/8/1997	17:15	12.2	ND	ND	186.3	ND	20.4	10.0	1.44	1.72	1.60	3.28	113.7
SNP-255	48	Bear Lithia Spring	S	9/2/1999	10:20	12.1	7.4	7.94	193.6	ND	20.6	10.6	1.23	1.60	1.67	3.12	116.2
SNP-046	49	Mathews Arm Well (W-856)	W	4/19/1996	10:40	10.8	8.1	6.39	79.9	ND	5.95	4.25	3.09	0.31	1.28	1.54	39.9
SNP-085	49	Mathews Arm Well (W-856)	W	8/26/1997	15:05	10.8	8.5	6.35	86.0	28	6.30	4.06	2.66	0.48	1.24	1.65	42.0
SNP-229	49	Mathews Arm Well (W-856)	W	8/16/1999	13:10	13.0	9.1	6.37	80.0	ND	5.90	3.96	2.92	0.40	1.45	1.68	40.7
SNP-011	50	Loft Mountain Well #1 (W-715)	W	4/3/1996	15:45	10.6	7.8	7.18	63.6	ND	5.41	2.22	3.50	0.32	0.83	0.68	30.7
SNP-098	50	Loft Mountain Well #1 (W-715)	W	8/29/1997	14:00	10.9	8.6	6.82	70.8	168	6.29	2.23	3.39	0.45	0.91	0.61	33.9
SNP-235	50	Loft Mountain Well #1 (W-715)	W	8/17/1999	18:15	11.8	9.5	7.14	68.1	ND	6.10	2.27	3.32	0.40	0.90	0.64	34.7
SNP-010	51	Loft Mountain Well #2 (W-754)	W	4/3/1996	14:30	10.7	9.5	6.49	34.9	ND	3.14	0.75	1.01	0.49	0.82	2.61	12.1
SNP-097	51	Loft Mountain Well #2 (W-754)	W	8/29/1997	12:30	10.6	11.6	6.30	51.3	ND	5.13	1.11	1.58	0.67	0.86	4.05	19.0
SNP-236	51	Loft Mountain Well #2 (W-754)	W	8/18/1999	8:35	11.4	9.9	7.47	74.4	ND	8.90	1.36	2.97	0.60	0.79	3.46	36.4
SNP-012	52	Ivy Creek Shelter Spring	S	4/3/1996	18:00	8.7	9.6	6.27	50.4	ND	3.66	1.58	2.10	0.18	0.84	4.66	10.0

Table 14. Summary of field parameters and major-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Temp (°C)	O_2 (mg/l)	pH	Sp Cond (µS/cm)	Q (gpm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)
SNP-119	52	Ivy Creek Shelter Spring	S	9/10/1997	12:00	9.2	9.9	5.97	65.2	ND	5.37	2.15	2.29	0.27	0.87	3.84	13.8
SNP-237	52	Ivy Creek Shelter Spring	S	8/18/1999	10:20	9.2	10.2	5.70	58.9	2	4.50	1.88	2.39	0.20	0.74	3.48	13.7
SNP-113	53	Lewis Mountain Spring #25	S	9/5/1997	9:30	9.5	9.8	5.98	24.9	8	1.65	0.37	1.29	0.33	2.07	2.14	4.0
SNP-241	53	Lewis Mountain Spring #25	S	8/19/1999	18:05	9.7	10.4	5.93	24.4	6	1.70	0.37	1.30	0.30	1.92	2.37	4.4
SNP-033	54	Elkwallow Spring #8	S	4/12/1996	12:30	9.3	9.4	6.01	48.7	ND	4.15	1.35	2.47	0.40	0.99	3.13	14.0
SNP-106	54	Elkwallow Spring #8	S	9/3/1997	9:00	9.8	8.3	5.78	54.7	ND	4.27	1.38	2.22	0.39	1.12	2.22	15.4
SNP-244	54	Elkwallow Spring #8	S	8/20/1999	13:50	10.1	9.7	5.69	53.5	6	4.40	1.44	2.35	0.40	1.11	2.25	15.7
SNP-136	55	Hite Spring (Luray)	S	9/17/1997	11:40	13.0	6.1	7.66	238.5	ND	28.4	11.4	4.54	2.59	6.06	16.26	132.0
SNP-247	55	Hite Spring (Luray)	S	8/23/1999	8:56	13.2	7.7	8.00	274.1	ND	28.4	12.4	4.90	2.40	7.17	17.32	134.7
SNP-040	56	HQ Spring #14-1	S	4/17/1996	9:15	8.1	10.2	6.43	74.7	ND	5.23	3.60	3.43	0.28	1.19	5.55	35.2
SNP-117	56	HQ Spring #14-1	S	9/9/1997	9:10	14.1	9.5	7.20	98.1	6	7.94	3.76	3.58	0.51	7.83	0.43	39.4
SNP-249	56	HQ Spring #14-1	S	8/23/1999	14:10	16.0	9.5	6.81	105.2	7.2	8.40	4.22	4.25	0.60	12.15	0.54	37.9
SNP-023	57	Indian Run Shelter Spring	S	4/9/1996	13:00	9.0	9.8	5.86	33.5	ND	2.18	0.74	1.95	0.71	1.03	0.48	8.9
SNP-128	57	Indian Run Shelter Spring	S	9/12/1997	13:30	9.7	9.5	5.78	34.0	ND	2.40	0.74	1.87	0.82	1.22	0.54	10.4
SNP-251	57	Indian Run Shelter Spring	S	8/23/1999	18:15	10.5	10.0	5.68	35.6	1	2.60	0.78	1.89	0.80	1.14	0.49	9.8
SNP-252	58	Town of Elkton Spring	S	9/1/1999	10:25	13.5	8.0	7.66	214.6	30	22.9	12.1	0.86	2.40	1.24	1.62	135.2
SNP-253	59	Town of Elkton well	W	9/1/1999	11:15	14.3	7.2	7.66	288.0	ND	41.2	9.6	1.84	1.50	5.55	3.63	158.6
SNP-254	60	Town of Grottoes #2	W	9/1/1999	15:00	13.9	8.9	8.10	215.2	ND	26.2	10.2	0.64	2.30	1.05	5.78	130.3
SNP-256	61	Blue Ridge School #5	W	9/2/1999	12:30	16.7	4.6	7.14	232.9	ND	30.5	2.5	14.90	0.90	4.25	5.25	131.8
SNP-257	62	Town of Washington #3	W	9/2/1999	15:45	14.7	0.2	7.23	159.3	ND	18.2	3.6	6.95	3.50	4.39	6.71	85.2
SNP-263	63	Mountain side Market	W	9/8/1999	9:00	17.3	2.4	6.98	116.5	ND	10.4	3.5	5.75	1.50	2.07	3.30	61.1
SNP-134	64	Hudson Spring (Luray)	S	9/17/1997	9:45	14.2	7.2	7.33	294.4	ND	44.2	9.5	3.30	2.56	5.29	5.55	173.6
SNP-180	64	Hudson Spring (Luray)	S	3/2/1999	10:10	14.1	6.8	7.54	292.2	ND	43.6	9.7	3.63	2.64	4.99	5.43	173.0
SNP-185	64	Hudson Spring (Luray)	S	4/2/1999	8:40	14.2	6.5	7.50	293.8	ND	41.3	9.3	3.34	2.70	6.27	4.97	173.7
SNP-190	64	Hudson Spring (Luray)	S	4/27/1999	9:40	14.2	6.9	7.40	292.6	ND	42.3	9.4	3.34	2.60	5.61	5.92	174.6
SNP-195	64	Hudson Spring (Luray)	S	5/26/1999	10:00	14.3	6.9	7.85	288.4	ND	41.7	9.4	3.27	2.50	5.60	5.89	172.6
SNP-200	64	Hudson Spring (Luray)	S	6/23/1999	9:30	14.2	6.8	7.84	290.7	ND	42.7	9.6	3.36	2.60	5.61	5.89	172.7
SNP-217	64	Hudson Spring (Luray)	S	7/14/1999	9:30	14.2	6.8	8.14	292.7	ND	42.0	9.9	3.71	2.70	5.60	5.83	173.3
SNP-222	64	Hudson Spring (Luray)	S	8/11/1999	9:15	14.2	6.7	7.78	294.8	ND	41.5	9.5	3.49	2.50	5.16	5.64	173.0
SNP-258	64	Hudson Spring (Luray)	S	9/7/1999	9:30	14.2	6.9	7.51	299.4	ND	41.6	9.5	3.37	2.50	5.71	5.95	173.6
SNP-264	64	Hudson Spring (Luray)	S	9/9/1999	9:05	14.2	7.0	7.49	299.1	ND	41.6	9.5	3.43	2.50	5.78	5.71	174.0
SNP-269	64	Hudson Spring (Luray)	S	9/22/1999	9:00	14.1	6.6	7.27	305.1	ND	42.0	9.6	3.54	2.64	5.83	5.89	175.6
SNP-020	65	Lewis Spring	S	4/8/1996	10:30	8.5	9.9	5.95	33.7	ND	2.64	1.11	1.20	0.21	3.80	0.27	8.1
SNP-093	65	Lewis Spring	S	8/28/1997	17:05	9.5	10.1	5.76	39.1	ND	2.86	1.21	1.23	0.36	2.75	0.24	9.7
SNP-124	65	Lewis Spring	S	9/11/1997	9:35	9.6	8.9	5.74	40.9	ND	3.00	1.24	1.24	0.39	2.69	0.29	9.9
SNP-126	65	Lewis Spring	S	9/11/1997	10:50	9.8	10.0	ND	41.6	ND	3.07	1.27	1.28	0.33	2.72	0.27	10.3
SNP-135	65	Lewis Spring	S	9/17/1997	16:00	9.6	9.9	5.87	36.5	ND	2.87	1.21	1.23	0.35	2.73	0.22	9.9
SNP-181	65	Lewis Spring	S	3/2/1999	12:30	9.0	9.6	5.95	36.9	ND	2.78	1.19	1.19	0.42	2.51	0.29	9.2
SNP-186	65	Lewis Spring	S	4/2/1999	10:10	8.9	9.9	5.52	36.6	ND	2.75	1.20	1.33	0.10	2.54	0.30	8.7
SNP-191	65	Lewis Spring	S	4/27/1999	15:00	9.2	9.8	5.17	37.1	ND	2.80	1.19	1.18	0.40	2.76	0.27	9.5
SNP-196	65	Lewis Spring	S	5/26/1999	12:55	9.0	10.2	5.73	37.0	ND	3.02	1.22	1.17	0.20	3.15	0.27	9.7
SNP-201	65	Lewis Spring	S	6/23/1999	11:50	9.1	9.8	6.30	37.3	ND	3.04	1.22	1.23	0.30	2.83	0.30	9.8
SNP-220	65	Lewis Spring	S	7/15/1999	9:25	9.2	9.7	6.86	38.2	ND	3.05	1.30	1.37	0.20	2.82	0.29	9.9
SNP-223	65	Lewis Spring	S	8/11/1999	11:35	9.4	10.4	6.27	38.7	ND	2.89	1.25	1.26	0.30	2.72	0.27	10.0
SNP-259	65	Lewis Spring	S	9/7/1999	11:00	9.6	10.8	5.56	39.2	150	3.08	1.27	1.26	0.29	2.70	0.38	9.6
SNP-265	65	Lewis Spring	S	9/9/1999	10:40	9.6	10.1	5.58	38.7	150	3.06	1.27	1.23	0.28	2.67	0.48	9.8
SNP-270	65	Lewis Spring	S	9/22/1999	10:40	9.6	9.9	5.43	39.5	165	2.83	1.20	1.22	0.31	2.57	0.48	9.4
VR-01	66	Town of Stanley # 3	W	7/6/1999	12:30	15.3	7.7	7.80	241.0	25	26.5	14.8	0.75	1.68	0.89	0.52	159.6
VR-02	67	Town of Shenandoah # 5	W	7/6/1999	16:15	13.4	7.4	7.50	343.0	150	42.4	17.5	1.27	2.62	2.02	2.00	219.9
VR-03	68	Waynesboro Jefferson Rd # 1	W	7/7/1999	10:35	13.2	6.9	7.80	132.0	800	14.6	7.5	1.26	1.27	2.05	3.39	77.2

Table 14. Summary of field parameters and major-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Temp (°C)	O_2 (mg/l)	pH	Sp Cond (µS/cm)	Q (gpm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)
VR-04	69	Coyner Spring	S	7/7/1999	14:00	12.7	7.4	7.69	186.0	ND	21.8	10.4	1.19	1.81	1.71	10.3	105.4
VR-06	71	Town of Shenandoah # 2	W	7/8/1999	16:20	12.0	7.3	7.33	302.0	95	48.5	10.6	1.04	2.23	1.66	1.98	206.6
VR-07	72	Town of Shenandoah # 3	W	7/8/1999	18:20	12.3	6.3	7.41	294.0	128	39.7	15.9	0.92	2.29	1.48	2.40	203.0
VR-08	73	Town of Stanley # 6	W	7/9/1999	10:15	15.4	5.7	7.54	285.0	400	37.4	11.1	4.79	2.99	7.35	8.75	162.9
VR-09	74	Town of Stanley # 5	W	7/9/1999	13:00	14.1	7.0	7.75	249.0	32	33.9	8.6	3.84	2.71	6.64	6.08	137.4
VR-10	75	Town of Stanley # 4	W	7/9/1999	15:00	13.7	6.1	7.63	313.0	100	41.0	11.2	5.92	2.44	11.89	8.43	164.6
VR-11	76	Town of Stanley # 2	W	7/9/1999	16:45	12.9	7.4	7.68	235.0	25	29.5	12.6	0.81	2.36	0.91	0.57	157.7

Appendix B
(data from U.S. Geological Survey, 2000)

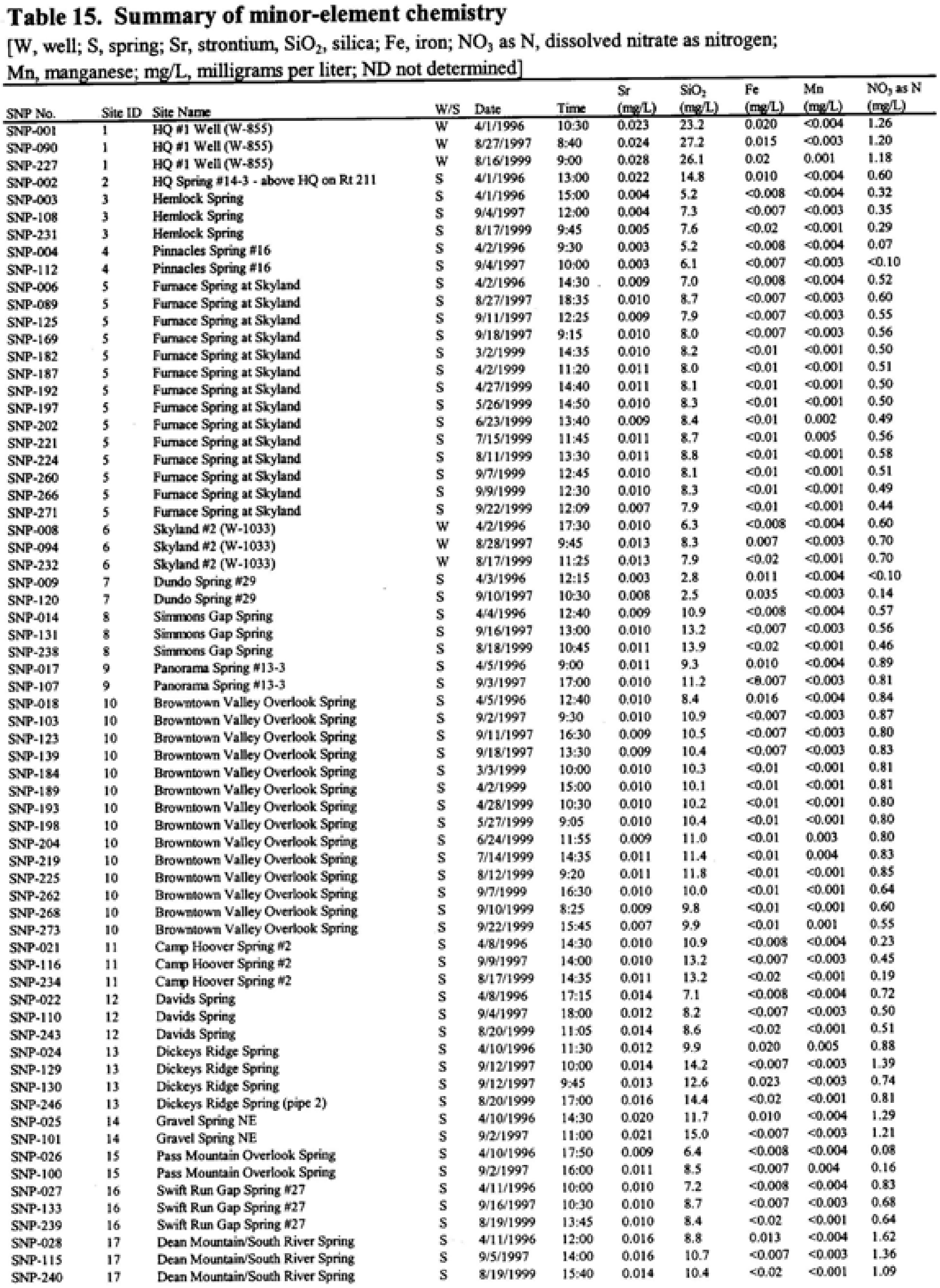


Table 15. Summary of minor-element chemistry

[W, well; S, spring; Sr, strontium, SiO_2, silica; Fe, iron; NO_3 as N, dissolved nitrate as nitrogen; Mn, manganese; mg/L, milligrams per liter; ND not determined]

SNP No.	Site ID	Site Name	W/S	Date	Time	Sr (mg/L)	SiO_2 (mg/L)	Fe (mg/L)	Mn (mg/L)	NO_3 as N (mg/L)
SNP-001	1	HQ #1 Well (W-855)	W	4/1/1996	10:30	0.023	23.2	0.020	<0.004	1.26
SNP-090	1	HQ #1 Well (W-855)	W	8/27/1997	8:40	0.024	27.2	0.015	<0.003	1.20
SNP-227	1	HQ #1 Well (W-855)	W	8/16/1999	9:00	0.028	26.1	0.02	0.001	1.18
SNP-002	2	HQ Spring #14-3 - above HQ on Rt 211	S	4/1/1996	13:00	0.022	14.8	0.010	<0.004	0.60
SNP-003	3	Hemlock Spring	S	4/1/1996	15:00	0.004	5.2	<0.008	<0.004	0.32
SNP-108	3	Hemlock Spring	S	9/4/1997	12:00	0.004	7.3	<0.007	<0.003	0.35
SNP-231	3	Hemlock Spring	S	8/17/1999	9:45	0.005	7.6	<0.02	<0.001	0.29
SNP-004	4	Pinnacles Spring #16	S	4/2/1996	9:30	0.003	5.2	<0.008	<0.004	0.07
SNP-112	4	Pinnacles Spring #16	S	9/4/1997	10:00	0.003	6.1	<0.007	<0.003	<0.10
SNP-006	5	Furnace Spring at Skyland	S	4/2/1996	14:30	0.009	7.0	<0.008	<0.004	0.52
SNP-089	5	Furnace Spring at Skyland	S	8/27/1997	18:35	0.010	8.7	<0.007	<0.003	0.60
SNP-125	5	Furnace Spring at Skyland	S	9/11/1997	12:25	0.009	7.9	<0.007	<0.003	0.55
SNP-169	5	Furnace Spring at Skyland	S	9/18/1997	9:15	0.010	8.0	<0.007	<0.003	0.56
SNP-182	5	Furnace Spring at Skyland	S	3/2/1999	14:35	0.010	8.2	<0.01	<0.001	0.50
SNP-187	5	Furnace Spring at Skyland	S	4/2/1999	11:20	0.011	8.0	<0.01	<0.001	0.51
SNP-192	5	Furnace Spring at Skyland	S	4/27/1999	14:40	0.011	8.1	<0.01	<0.001	0.50
SNP-197	5	Furnace Spring at Skyland	S	5/26/1999	14:50	0.010	8.3	<0.01	<0.001	0.50
SNP-202	5	Furnace Spring at Skyland	S	6/23/1999	13:40	0.009	8.4	<0.01	0.002	0.49
SNP-221	5	Furnace Spring at Skyland	S	7/15/1999	11:45	0.011	8.7	<0.01	0.005	0.56
SNP-224	5	Furnace Spring at Skyland	S	8/11/1999	13:30	0.011	8.8	<0.01	<0.001	0.58
SNP-260	5	Furnace Spring at Skyland	S	9/7/1999	12:45	0.010	8.1	<0.01	<0.001	0.51
SNP-266	5	Furnace Spring at Skyland	S	9/9/1999	12:30	0.010	8.3	<0.01	<0.001	0.49
SNP-271	5	Furnace Spring at Skyland	S	9/22/1999	12:09	0.007	7.9	<0.01	<0.001	0.44
SNP-008	6	Skyland #2 (W-1033)	W	4/2/1996	17:30	0.010	6.3	<0.008	<0.004	0.60
SNP-094	6	Skyland #2 (W-1033)	W	8/28/1997	9:45	0.013	8.3	0.007	<0.003	0.70
SNP-232	6	Skyland #2 (W-1033)	W	8/17/1999	11:25	0.013	7.9	<0.02	<0.001	0.70
SNP-009	7	Dundo Spring #29	S	4/3/1996	12:15	0.003	2.8	0.011	<0.004	<0.10
SNP-120	7	Dundo Spring #29	S	9/10/1997	10:30	0.008	2.5	0.035	<0.003	0.14
SNP-014	8	Simmons Gap Spring	S	4/4/1996	12:40	0.009	10.9	<0.008	<0.004	0.57
SNP-131	8	Simmons Gap Spring	S	9/16/1997	13:00	0.010	13.2	<0.007	<0.003	0.56
SNP-238	8	Simmons Gap Spring	S	8/18/1999	10:45	0.011	13.9	<0.02	<0.001	0.46
SNP-017	9	Panorama Spring #13-3	S	4/5/1996	9:00	0.011	9.3	0.010	<0.004	0.89
SNP-107	9	Panorama Spring #13-3	S	9/3/1997	17:00	0.010	11.2	<0.007	<0.003	0.81
SNP-018	10	Browntown Valley Overlook Spring	S	4/5/1996	12:40	0.010	8.4	0.016	<0.004	0.84
SNP-103	10	Browntown Valley Overlook Spring	S	9/2/1997	9:30	0.010	10.9	<0.007	<0.003	0.87
SNP-123	10	Browntown Valley Overlook Spring	S	9/11/1997	16:30	0.009	10.5	<0.007	<0.003	0.80
SNP-139	10	Browntown Valley Overlook Spring	S	9/18/1997	13:30	0.009	10.4	<0.007	<0.003	0.83
SNP-184	10	Browntown Valley Overlook Spring	S	3/3/1999	10:00	0.010	10.3	<0.01	<0.001	0.81
SNP-189	10	Browntown Valley Overlook Spring	S	4/2/1999	15:00	0.010	10.1	<0.01	<0.001	0.81
SNP-193	10	Browntown Valley Overlook Spring	S	4/28/1999	10:30	0.010	10.2	<0.01	<0.001	0.80
SNP-198	10	Browntown Valley Overlook Spring	S	5/27/1999	9:05	0.010	10.4	<0.01	<0.001	0.80
SNP-204	10	Browntown Valley Overlook Spring	S	6/24/1999	11:55	0.009	11.0	<0.01	0.003	0.80
SNP-219	10	Browntown Valley Overlook Spring	S	7/14/1999	14:35	0.011	11.4	<0.01	0.004	0.83
SNP-225	10	Browntown Valley Overlook Spring	S	8/12/1999	9:20	0.011	11.8	<0.01	<0.001	0.85
SNP-262	10	Browntown Valley Overlook Spring	S	9/7/1999	16:30	0.010	10.0	<0.01	<0.001	0.64
SNP-268	10	Browntown Valley Overlook Spring	S	9/10/1999	8:25	0.009	9.8	<0.01	<0.001	0.60
SNP-273	10	Browntown Valley Overlook Spring	S	9/22/1999	15:45	0.007	9.9	<0.01	0.001	0.55
SNP-021	11	Camp Hoover Spring #2	S	4/8/1996	14:30	0.010	10.9	<0.008	<0.004	0.23
SNP-116	11	Camp Hoover Spring #2	S	9/9/1997	14:00	0.010	13.2	<0.007	<0.003	0.45
SNP-234	11	Camp Hoover Spring #2	S	8/17/1999	14:35	0.011	13.2	<0.02	<0.001	0.19
SNP-022	12	Davids Spring	S	4/8/1996	17:15	0.014	7.1	<0.008	<0.004	0.72
SNP-110	12	Davids Spring	S	9/4/1997	18:00	0.012	8.2	<0.007	<0.003	0.50
SNP-243	12	Davids Spring	S	8/20/1999	11:05	0.014	8.6	<0.02	<0.001	0.51
SNP-024	13	Dickeys Ridge Spring	S	4/10/1996	11:30	0.012	9.9	0.020	0.005	0.88
SNP-129	13	Dickeys Ridge Spring	S	9/12/1997	10:00	0.014	14.2	<0.007	<0.003	1.39
SNP-130	13	Dickeys Ridge Spring	S	9/12/1997	9:45	0.013	12.6	0.023	<0.003	0.74
SNP-246	13	Dickeys Ridge Spring (pipe 2)	S	8/20/1999	17:00	0.016	14.4	<0.02	<0.001	0.81
SNP-025	14	Gravel Spring NE	S	4/10/1996	14:30	0.020	11.7	0.010	<0.004	1.29
SNP-101	14	Gravel Spring NE	S	9/2/1997	11:00	0.021	15.0	<0.007	<0.003	1.21
SNP-026	15	Pass Mountain Overlook Spring	S	4/10/1996	17:50	0.009	6.4	<0.008	<0.004	0.08
SNP-100	15	Pass Mountain Overlook Spring	S	9/2/1997	16:00	0.011	8.5	<0.007	0.004	0.16
SNP-027	16	Swift Run Gap Spring #27	S	4/11/1996	10:00	0.010	7.2	<0.008	<0.004	0.83
SNP-133	16	Swift Run Gap Spring #27	S	9/16/1997	10:30	0.010	8.7	<0.007	<0.003	0.68
SNP-239	16	Swift Run Gap Spring #27	S	8/19/1999	13:45	0.010	8.4	<0.02	<0.001	0.64
SNP-028	17	Dean Mountain/South River Spring	S	4/11/1996	12:00	0.016	8.8	0.013	<0.004	1.62
SNP-115	17	Dean Mountain/South River Spring	S	9/5/1997	14:00	0.016	10.7	<0.007	<0.003	1.36
SNP-240	17	Dean Mountain/South River Spring	S	8/19/1999	15:40	0.014	10.4	<0.02	<0.001	1.09

Table 15. Summary of minor-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Sr (mg/L)	SiO_2 (mg/L)	Fe (mg/L)	Mn (mg/L)	NO_3 as N (mg/L)
SNP-029	18	Baldface Mountain Spring	S	4/11/1996	14:00	0.008	8.2	<0.008	<0.004	0.35
SNP-030	19	Hazeltop Ridge Overlook Spring	S	4/11/1996	18:30	0.010	6.0	<0.008	<0.004	1.64
SNP-032	20	Byrds Nest #4/Beahms Gap Spring	S	4/12/1996	9:40	0.014	10.6	<0.008	<0.004	0.37
SNP-104	20	Byrds Nest #4/Beahms Gap Spring	S	9/3/1997	12:00	0.012	12.7	<0.007	<0.003	0.42
SNP-242	20	Byrds Nest #4/Beahms Gap Spring	S	8/20/1999	8:45	0.014	13.3	<0.02	0.001	0.41
SNP-034	21	Byrds Nest #3 Spring	S	4/12/1996	15:20	0.011	6.0	<0.008	<0.004	1.64
SNP-109	21	Byrds Nest #3 Spring	S	9/4/1997	8:30	0.012	7.0	<0.007	<0.003	1.55
SNP-127	21	Byrds Nest #3 Spring	S	9/11/1997	14:30	0.010	6.8	<0.007	<0.003	1.52
SNP-138	21	Byrds Nest #3 Spring	S	9/18/1997	11:00	0.012	7.2	<0.007	<0.003	1.55
SNP-183	21	Byrds Nest #3 Spring	S	3/2/1999	16:50	0.011	7.2	<0.01	0.007	1.47
SNP-188	21	Byrds Nest #3 Spring	S	4/2/1999	12:50	0.012	7.3	<0.01	<0.001	1.47
SNP-194	21	Byrds Nest #3 Spring	S	4/28/1999	17:25	0.012	7.4	<0.01	<0.001	1.47
SNP-199	21	Byrds Nest #3 Spring	S	5/27/1999	11:22	0.011	7.3	<0.01	<0.001	1.51
SNP-203	21	Byrds Nest #3 Spring	S	6/24/1999	9:05	0.010	7.3	<0.01	0.003	1.51
SNP-218	21	Byrds Nest #3 Spring	S	7/14/1999	11:34	0.012	7.5	<0.01	0.005	1.53
SNP-226	21	Byrds Nest #3 Spring	S	8/12/1999	12:00	0.012	7.6	<0.01	<0.001	1.54
SNP-261	21	Byrds Nest #3 Spring	S	9/7/1999	14:20	0.011	7.2	<0.01	<0.001	1.52
SNP-267	21	Byrds Nest #3 Spring	S	9/9/1999	14:30	0.011	7.2	<0.01	<0.001	1.59
SNP-272	21	Byrds Nest #3 Spring	S	9/22/1999	13:45	0.009	7.2	<0.01	0.002	1.54
SNP-035	22	Big Meadows #9 Well	W	4/15/1996	11:20	0.011	8.5	<0.008	<0.004	0.18
SNP-096	22	Big Meadows #9 Well	W	8/28/1997	13:30	0.011	11.6	<0.007	<0.003	0.28
SNP-036	23	Big Meadows #14 Well	W	4/15/1996	14:00	0.015	12.7	<0.008	<0.004	0.19
SNP-092	23	Big Meadows #14 Well	W	8/28/1997	11:30	0.014	14.5	0.014	<0.003	0.22
SNP-233	23	Big Meadows #14 Well	W	8/17/1999	12:50	0.016	15.2	<0.02	<0.001	0.19
SNP-038	24	Hogback Spring #5	S	4/16/1996	11:45	0.004	5.7	<0.008	<0.004	0.16
SNP-039	25	Elkwallow Well (W-1703)	W	4/16/1996	16:00	0.019	13.0	0.040	<0.004	1.52
SNP-086	25	Elkwallow Well (W-1703)	W	8/26/1997	18:30	0.020	15.4	0.090	0.008	1.35
SNP-228	25	Elkwallow Well (W-1703)	W	8/16/1999	11:45	0.022	16.7	<0.02	0.002	1.32
SNP-041	26	Hightop Hut Spring	S	4/17/1996	15:15	0.019	12.6	<0.008	<0.004	1.74
SNP-132	26	Hightop Hut Spring	S	9/16/1997	15:45	0.022	16.6	<0.007	<0.003	2.04
SNP-043	27	Pass Mountain Hut Spring	S	4/18/1996	9:15	0.014	7.5	0.013	0.007	1.18
SNP-105	27	Pass Mountain Hut Spring	S	9/3/1997	14:10	0.013	9.2	<0.007	<0.003	1.02
SNP-048	31	Dickeys Ridge Well (W-1346)	W	4/19/1996	14:40	0.079	16.2	0.010	<0.004	0.76
SNP-084	31	Dickeys Ridge Well (W-1346)	W	8/26/1997	10:50	0.070	17.3	0.018	<0.003	0.79
SNP-230	31	Dickeys Ridge Well (W-1346)	W	8/16/1999	16:15	0.073	17.6	<0.02	<0.001	0.45
SNP-050	33	Domestic well #1	W	4/24/1996	9:50	0.061	6.2	0.077	0.008	1.53
SNP-051	34	Domestic well #2	W	4/24/1996	14:55	0.043	6.4	0.067	0.006	9.80
SNP-052	35	White Oak Cabin Spring	S	4/25/1996	10:35	0.009	6.1	0.014	<0.005	0.56
SNP-111	35	White Oak Cabin Spring	S	9/4/1997	15:55	0.006	7.0	<0.007	<0.003	0.51
SNP-053	36	Big Meadows #1 Well (W-1701)	W	4/25/1996	16:30	0.014	10.1	0.017	0.010	0.31
SNP-083	36	Big Meadows #1 Well (W-1701)	W	9/17/1997	16:30	0.014	11.9	0.018	0.005	0.34
SNP-037	37	HQ #2 Well (W-851)	W	4/16/1996	9:45	0.029	21.5	0.287	0.011	1.09
SNP-087	37	HQ #2 Well (W-851)	W	8/27/1997	10:30	0.025	23.7	0.135	0.017	1.19
SNP-007	38	Skyland #5	W	4/2/1996	16:00	0.018	10.8	0.029	0.007	0.66
SNP-088	38	Skyland #5	W	8/27/1997	17:10	0.018	12.5	0.087	0.013	0.63
SNP-005	39	Pinnacles Well (W-3288)	W	4/2/1996	12:00	0.019	6.9	0.008	<0.004	3.64
SNP-091	39	Pinnacles Well (W-3288)	W	8/27/1997	12:45	0.018	7.8	<0.007	<0.003	3.35
SNP-019	40	Mathews Arm Spring Range View Cabin	S	4/5/1996	14:35	0.020	8.6	0.010	<0.004	2.42
SNP-102	40	Mathews Arm Spring Range View Cabin	S	9/2/1997	13:30	0.017	10.6	<0.007	<0.003	2.08
SNP-031	41	Lewis Mountain Spring #25-2	S	4/11/1996	16:30	0.007	4.4	<0.008	<0.004	0.09
SNP-114	41	Lewis Mountain Spring #25-2	S	9/5/1997	11:00	0.008	5.8	<0.007	<0.003	0.11
SNP-054	42	Old Rag Shelter Spring	S	4/26/1996	14:30	0.010	9.6	0.015	<0.005	0.28
SNP-118	42	Old Rag Shelter Spring	S	9/9/1997	18:00	0.009	11.3	<0.007	0.008	0.30
SNP-015	43	Loft Mountain Overlook Spring	S	4/4/1996	15:30	0.015	13.9	0.010	<0.004	1.95
SNP-121	43	Loft Mountain Overlook Spring	S	9/10/1997	17:00	0.017	16.9	0.030	0.004	1.83
SNP-016	44	Loft Mountain Spring	S	4/4/1996	17:30	0.013	7.4	<0.008	<0.004	2.67
SNP-122	44	Loft Mountain Spring	S	9/10/1997	15:00	0.013	7.6	0.009	0.013	1.68
SNP-013	45	Simmons Gap Well (W-1704)	W	4/4/1996	9:30	0.017	21.6	0.013	0.013	2.26
SNP-099	45	Simmons Gap Well (W-1704)	W	8/29/1997	10:00	0.016	22.2	0.011	<0.003	2.05
SNP-137	46	Yeager's Spring (Luray)	S	9/17/1997	13:10	0.234	11.0	0.033	0.005	1.56
SNP-248	46	Yeager's Spring (Luray)	S	8/23/1999	11:20	0.295	10.9	0.03	0.004	1.81
SNP-042	47	Lewis Mountain Well (W-1072)	W	4/17/1996	18:20	0.008	4.2	0.149	0.009	0.10
SNP-095	47	Lewis Mountain Well (W-1072)	W	8/28/1997	15:45	0.009	8.5	0.035	<0.003	0.13
SNP-140	47	Lewis Mountain Well (W-1072)	W	9/19/1997	9:30	0.009	5.5	0.016	<0.003	<0.10
SNP-170	48	Bear Lithia Spring	S	8/6/1997	17:15	0.046	11.1	0.014	<0.003	0.36
SNP-255	48	Bear Lithia Spring	S	9/2/1999	10:20	0.052	11.0	0.02	<0.001	0.38
SNP-046	49	Mathews Arm Well (W-856)	W	4/19/1996	10:40	0.018	17.1	0.015	<0.004	1.17
SNP-085	49	Mathews Arm Well (W-856)	W	8/26/1997	15:05	0.016	18.3	0.013	<0.003	0.74
SNP-229	49	Mathews Arm Well (W-856)	W	8/16/1999	13:10	0.017	18.5	<0.02	<0.001	0.73
SNP-011	50	Loft Mountain Well #1 (W-715)	W	4/3/1996	15:45	0.020	15.6	0.013	<0.004	0.90
SNP-098	50	Loft Mountain Well #1 (W-715)	W	8/29/1997	14:00	0.021	18.3	<0.007	<0.003	0.90

Table 15. Summary of minor-element chemistry--Continued

SNP No.	Site ID	Site Name	W/S	Date	Time	Sr (mg/L)	SiO_2 (mg/L)	Fe (mg/L)	Mn (mg/L)	NO_3 as N (mg/L)
SNP-235	50	Loft Mountain Well #1 (W-715)	W	8/17/1999	18:15	0.022	18.0	<0.02	<0.001	0.97
SNP-010	51	Loft Mountain Well #2 (W-754)	W	4/3/1996	14:30	0.014	6.5	<0.008	<0.004	0.13
SNP-097	51	Loft Mountain Well #2 (W-754)	W	8/29/1997	12:30	0.020	9.5	0.009	<0.003	0.28
SNP-236	51	Loft Mountain Well #2 (W-754)	W	8/18/1999	8:35	0.046	12.5	<0.02	<0.001	0.34
SNP-012	52	Ivy Creek Shelter Spring	S	4/3/1996	18:00	0.008	9.3	<0.008	<0.004	1.92
SNP-119	52	Ivy Creek Shelter Spring	S	9/10/1997	12:00	0.010	13.5	0.011	<0.003	2.86
SNP-237	52	Ivy Creek Shelter Spring	S	8/18/1999	10:20	0.009	13.6	<0.02	<0.001	2.44
SNP-113	53	Lewis Mountain Spring #25	S	9/5/1997	9:30	0.009	6.1	<0.007	<0.003	0.14
SNP-241	53	Lewis Mountain Spring #25	S	8/19/1999	18:05	0.009	6.0	<0.02	<0.001	0.12
SNP-033	54	Elkwallow Spring #8	S	4/12/1996	12:30	0.016	12.5	<0.008	<0.004	1.95
SNP-106	54	Elkwallow Spring #8	S	9/3/1997	9:00	0.016	14.8	<0.007	<0.003	1.56
SNP-244	54	Elkwallow Spring #8	S	8/20/1999	13:50	0.018	15.0	<0.02	<0.001	1.68
SNP-136	55	Hite Spring (Luray)	S	9/17/1997	11:40	0.331	12.4	0.025	0.004	0.86
SNP-247	55	Hite Spring (Luray)	S	8/23/1999	8:56	0.333	12.3	0.03	0.002	0.85
SNP-040	56	HQ Spring #14-1	S	4/17/1996	9:15	0.021	23.2	0.069	<0.004	0.35
SNP-117	56	HQ Spring #14-1	S	9/9/1997	9:10	0.030	26.7	<0.007	<0.003	0.47
SNP-249	56	HQ Spring #14-1	S	8/23/1999	14:10	0.034	23.6	<0.02	<0.001	0.45
SNP-023	57	Indian Run Shelter Spring	S	4/9/1996	13:00	0.015	10.9	<0.008	<0.004	1.24
SNP-128	57	Indian Run Shelter Spring	S	9/12/1997	13:30	0.014	12.5	0.009	<0.003	1.07
SNP-251	57	Indian Run Shelter Spring	S	8/23/1999	18:15	0.017	12.8	<0.02	<0.001	1.26
SNP-252	58	Town of Elkton Spring	S	9/1/1999	10:25	0.020	12.4	<0.02	<0.001	0.13
SNP-253	59	Town of Elkton well	W	9/1/1999	11:15	0.087	9.7	0.02	0.004	2.64
SNP-254	60	Town of Grottoes #2	W	9/1/1999	15:00	0.137	10.9	0.02	<0.001	0.14
SNP-256	61	Blue Ridge School #5	W	9/2/1999	12:30	0.223	27.8	0.03	0.193	0.00
SNP-257	62	Town of Washington #3	W	9/2/1999	15:45	0.067	28.0	0.22	0.113	0.00
SNP-263	63	Mountain side Market	W	9/8/1999	9:00	0.095	25.2	<0.02	<0.001	0.29
SNP-134	64	Hudson Spring (Luray)	S	9/17/1997	9:45	0.234	12.3	0.036	0.004	0.61
SNP-180	64	Hudson Spring (Luray)	S	3/2/1999	10:10	0.230	13.0	<0.01	<0.001	0.59
SNP-185	64	Hudson Spring (Luray)	S	4/2/1999	8:40	0.239	12.2	0.018	<0.001	0.60
SNP-190	64	Hudson Spring (Luray)	S	4/27/1999	9:40	0.238	12.1	<0.01	<0.001	0.61
SNP-195	64	Hudson Spring (Luray)	S	5/26/1999	10:00	0.235	12.1	0.021	<0.001	0.59
SNP-200	64	Hudson Spring (Luray)	S	6/23/1999	9:30	0.221	12.4	0.019	0.006	0.60
SNP-217	64	Hudson Spring (Luray)	S	7/14/1999	9:30	0.248	12.6	0.027	0.008	0.59
SNP-222	64	Hudson Spring (Luray)	S	8/11/1999	9:15	0.229	12.5	<0.01	<0.001	0.59
SNP-258	64	Hudson Spring (Luray)	S	9/7/1999	9:30	0.227	12.2	0.01	0.002	0.58
SNP-264	64	Hudson Spring (Luray)	S	9/9/1999	9:05	0.231	12.4	0.01	0.003	0.57
SNP-269	64	Hudson Spring (Luray)	S	9/22/1999	9:00	0.232	12.6	0.01	0.002	0.60
SNP-020	65	Lewis Spring	S	4/8/1996	10:30	0.011	6.3	<0.008	<0.004	0.52
SNP-093	65	Lewis Spring	S	8/28/1997	17:05	0.012	7.6	<0.007	<0.003	0.91
SNP-124	65	Lewis Spring	S	9/11/1997	9:35	0.012	7.6	<0.007	<0.003	1.03
SNP-126	65	Lewis Spring	S	9/11/1997	10:50	0.013	8.0	0.008	<0.003	1.04
SNP-135	65	Lewis Spring	S	9/17/1997	16:00	0.012	7.7	<0.007	<0.003	0.93
SNP-181	65	Lewis Spring	S	3/2/1999	12:30	0.012	7.4	<0.01	0.001	0.90
SNP-186	65	Lewis Spring	S	4/2/1999	10:10	0.013	7.6	<0.01	<0.001	0.97
SNP-191	65	Lewis Spring	S	4/27/1999	13:00	0.013	7.6	<0.01	<0.001	0.92
SNP-196	65	Lewis Spring	S	5/26/1999	12:55	0.012	7.7	<0.01	<0.001	0.94
SNP-201	65	Lewis Spring	S	6/23/1999	11:50	0.011	7.9	<0.01	<0.001	0.94
SNP-220	65	Lewis Spring	S	7/15/1999	9:25	0.013	8.0	<0.01	0.005	0.94
SNP-223	65	Lewis Spring	S	8/11/1999	11:35	0.013	8.1	<0.01	<0.001	0.96
SNP-259	65	Lewis Spring	S	9/7/1999	11:00	0.012	7.7	<0.01	0.000	1.09
SNP-265	65	Lewis Spring	S	9/9/1999	10:40	0.012	7.8	<0.01	0.000	1.02
SNP-270	65	Lewis Spring	S	9/22/1999	10:40	0.010	7.6	<0.01	0.003	1.09
VR-01	66	Town of Stanley # 3	W	7/6/1999	12:30	0.016	11.5	<0.02	0.001	0.05
VR-02	67	Town of Shenandoah # 5	W	7/6/1999	16:15	0.046	12.0	<0.02	0.003	0.76
VR-03	68	Wanyesboro Jefferson Rd # 1	W	7/7/1999	10:35	0.019	7.6	<0.02	0.002	0.47
VR-04	69	Coyner Spring	S	7/7/1999	14:00	0.091	9.4	<0.02	0.002	0.59
VR-06	71	Town of Shenandoah # 2	W	7/8/1999	16:20	0.116	10.2	0.03	0.003	0.22
VR-07	72	Town of Shenandoah # 3	W	7/8/1999	18:20	0.055	10.6	<0.02	0.003	0.23
VR-08	73	Town of Stanley # 6	W	7/9/1999	10:15	0.178	13.6	<0.02	0.005	0.27
VR-09	74	Town of Stanley # 5	W	7/9/1999	13:00	0.169	14.2	0.02	0.002	1.68
VR-10	75	Town of Stanley # 4	W	7/9/1999	15:00	0.108	11.5	<0.02	0.003	1.73
VR-11	76	Town of Stanley # 2	W	7/9/1999	16:45	0.016	13.0	<0.02	0.002	0.05

APPENDIX C

WATER-RELATED ISSUES IDENTIFIED IN A WATER RESOURCE ISSUES SCOPING WORKSHOP, NOVEMBER 14, 2002

List of Participants:

Gordon Olson, SHEN
Christi Gordon, SHEN
Shane Spitzer, SHEN
James Akerson, SHEN
Jim Atkinson, SHEN
Dave Demarest, SHEN
David Vana-Miller, NPS WRD
Don Weeks, NPS WRD
John Karish, NPS – Northeast Region
Carolyn Mahan, Pennsylvania State U.
Jeff Walden, Virginia Polytechnic and State U.
Greg Safford, Trout Unlimited
David Nelms, U.S. Geological Survey
Karen Rice, U.S. Geological Survey
Adrienne Averett, Virginia Polytechnic and State U.
Stephen Hiner, Virginia Polytechnic and State U.
Stephen Reeser, Virginia Dept. of Game and Inland Fisheries
Steve Wise, James Madison U.
Jim Galloway, University of Virginia
Jack Cosby, University of Virginia

<u>Surface Water</u> *(Parenthetical expression = priority ranking based on number of votes by workshop participants and the actual number of votes)*

1. Road Salt – look at conductivity of spring flows (especially along Route 211).
2. *(#2: 9 votes*) Changing chemical composition of streams.
    - Impacts on aquatic biology (chronic vs. episodic)
    - How do watershed characteristics affect distribution/organization of aquatic biology?
    - (Chemical legacy)
    - Understand dry/wet year impacts on aquatic biota.
3. (*1 vote*) Non-point source pollutants from roads and parking lots.
4. (*6 votes*) Hg in waters/biota? Should we understand dynamics of its deposition and uptake?
5. (*2 votes*) Influence of sewage treatment outflows on receiving streams.
6. Visitor safety and geologic hazards such as debris flows.
7. (*2 votes*) Road/trail sedimentation.
8. Air pollution affects
    - Global climate change
    - Understanding past landuses

    - Long-range transport
    - Local mobile sources
9. (*5 votes*) Summarizing/consolidation of data/information into something useful for park management.
10. (*#3: 8 votes*) Need to evaluate/revisit existing water quality/climate/discharge monitoring programs at SHEN (note: Klopfer website rainfall modeling (incl. SHEN)...elevation throws things off).
    - Objectives
    - Retrospective analysis
    - Water quality monitoring plan (parameter selection).
11. (*2 votes*) What are impacts of exotic species on surface waters and implications of exotic species management on SHEN surface water quality.

<u>Ground Water</u>

12. (*1 vote*) Need to consider spring monitoring.
13. (*2 votes*) Soil classification. Surficial geology (Ben Morgan).
14. (*#5: 7 votes*) Spring Inventory
    - color IR winter technique
    - physical/chemical/biological characterization
15. (*2 votes*) Evaluate need for Source Water Protection Plans.
    - Defining recharge areas of springs/wells
        - associated water quality threats
16. Evaluate current ground water monitoring.
17. Adequate spill response.
18. (*1 vote*) Evaluate long-term spring discharge and water levels in wells.
19. Landfill/septic ground water monitoring.

<u>Water Quality</u>

20. (*#4: 8 votes*) Inventory of impacts to water quality (USTs, septic, road salt, recreational use).
21. Evaluate lime treatment to surface water.
22. (*1 vote*) Better BMPs related to road/trail construction and maintenance.

<u>Atmospheric Deposition</u>

23. (*5 votes*) Sulfur/nitrogen deposition (large and local scale)
    - Water monitoring (ammonium)
24. POPs (standard list). What does SHEN have?

<u>Wetlands</u>

25. Wetlands inventory.

<u>Visitor Use</u>

26. (*1 vote*) Visitor valuation of water resources.

Floodplains/Riparian

27. Floodplain Inventory
    Visitor education
28. Riparian Inventory
    Debris flow

Aquatic Biology

29. (*1 vote*) Short-term: drought/flood
    Long-term: acidic deposition
    episodic acidification
30. Re-evaluate existing I & M biological monitoring program, especially backlog of analysis.
31. (*#1: 10 votes*) Need to complete baseline inventory of flora and fauna, especially wetlands and springs.

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-279 / August 2004 / Printed on recycled paper