The Shenandoah Watershed Study
&
The Virginia Trout Stream Sensitivity Study

35 Years of Watershed Research and Monitoring

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SWAS-VTSSS Program
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Introduction

Acidic deposition, or “acid rain” in popular terminology, is an insidious form of pollution. Its origins can be hundreds of miles upwind from its ultimate consequences. Its effects are commonly subtle, a cumulative loss of environmental quality that occurs on time scales of decades and presents few noticeable effects in the short term. But in the long-term, the harmful effects of acidic deposition can be substantial and essentially irreversible. Such is the case in the central Appalachian Mountain region, where acidic deposition affects wild lands that have been set aside as National Forests, National Parks, and Wilderness.

Although implementation of the Clean Air Act is reducing the impact of acidic deposition on surface waters, certain areas and surface waters, including many mountain watersheds and streams in western Virginia, remain at risk.

The Shenandoah Watershed Study and the Virginia Trout Stream Sensitivity Study were established to provide increased understanding of hydrologic and biogeochemical changes in western Virginia mountain watersheds that occur in response to acidic deposition and other ecosystem stressors.

SWAS-VTSSS Program Description

Program Objectives

1) To increase understanding of factors that govern biogeochemical conditions and stressor-response relationships in forested mountain watersheds of the central Appalachian region.
2) To detect and assess hydro-biogeochemical changes occurring in these relatively undisturbed ecosystems.

Program Design

SWAS-VTSSS monitoring accounts for ecological variation among the region's forested mountain watersheds with a data-collection strategy that represents:

1) Spatial variation through the distribution of hydrochemical monitoring within a lithologic classification system.
2) Temporal variation through long-term data collection at fixed locations sampled at different frequencies.

Routine Measurements

Chemical Properties of Streams

- pH and acid neutralizing capacity
- Conductivity
- Acid anions (sulfate, nitrate, and chloride)
- Base cations (calcium, magnesium, sodium, and potassium ion)
- Silica
- Ammonium
- Dissolved organic carbon
- Monomeric aluminum fractions

Physical Properties of Streams

- Streamwater temperature
- Stream discharge

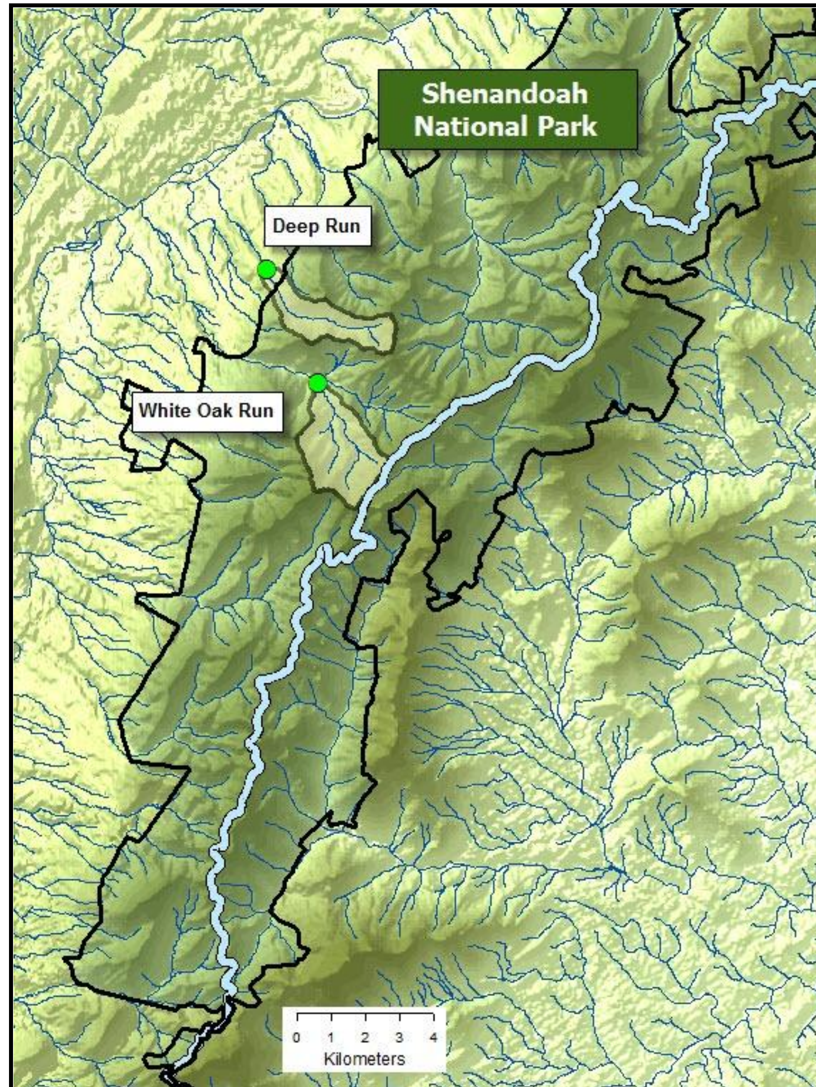
The Shenandoah Watershed Study

. . . evidence for stream acidification in western Virginia

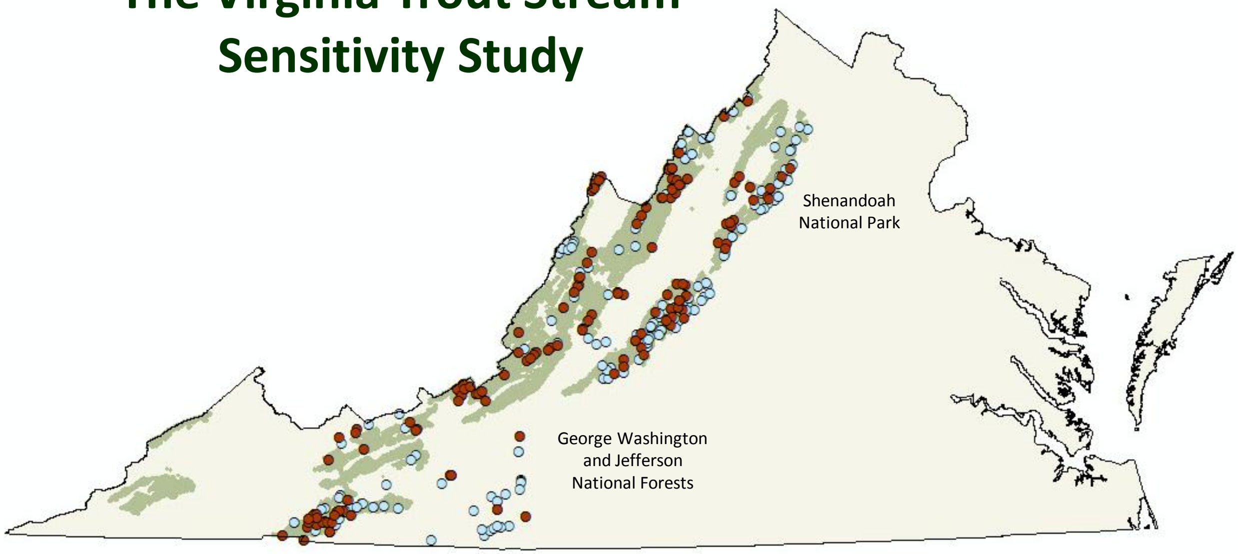
Research on stream acidification in the Virginia mountains was conducted by the Shenandoah Watershed Study (SWAS) beginning in 1979, with monitoring on two streams, White Oak Run and Deep Run in the southern part of the Shenandoah National Park.

Increasing sulfate and decreasing acid neutralizing capacity concentrations were observed in both streams in the 1980s —indicating acidification due to acidic atmospheric deposition.

The VTSSS program extended this research to streams in the broader mountain region.



The Virginia Trout Stream Sensitivity Study



The first VTSSS survey of native brook trout streams throughout western Virginia was conducted in the spring of 1987. Stream water samples were collected at 379 sites in 34 counties. The results indicated widespread sensitivity to acidification.

Approximately 50% of the streams surveyed in 1987 were identified as substantially impaired by acidification, based on acid neutralizing capacity (ANC) values of less than 50 μeq/L.

Additional surveys were conducted in 2000 and 2010. Samples were collected with the help of Trout Unlimited volunteers.

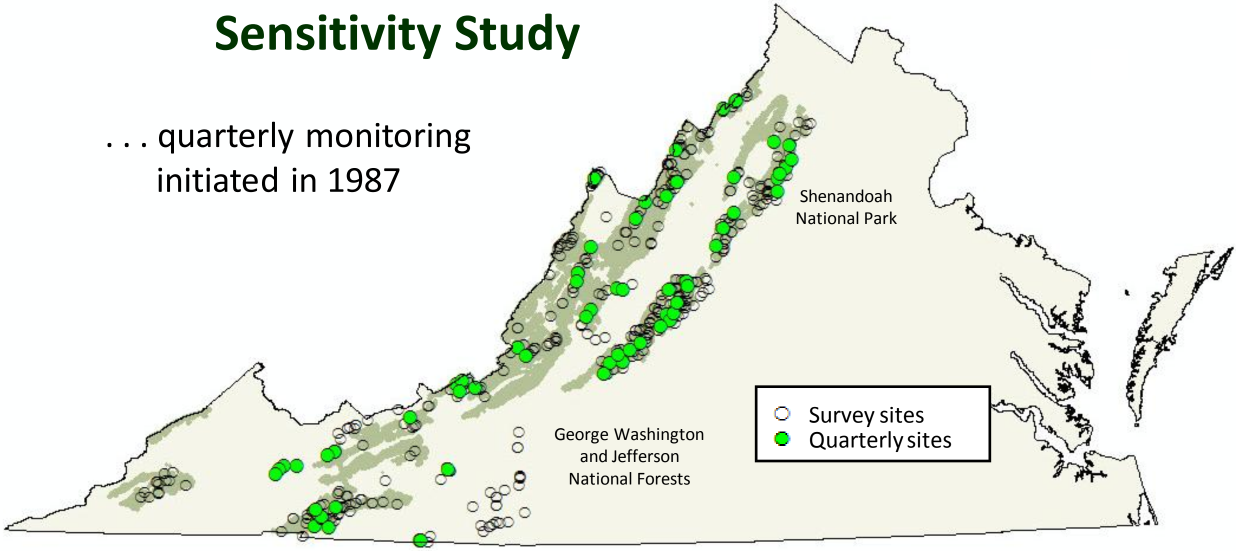
Streamwater ANC Categories for Brook Trout Status*

- **Suitable**: reproducing populations of brook trout expected where habitat suitable
- **Indeterminate, marginal, or unsuitable**: extremely sensitive to acidification, sub-lethal and/or lethal effects on brook trout possible or probable

*See slide 20 for further description of categories.

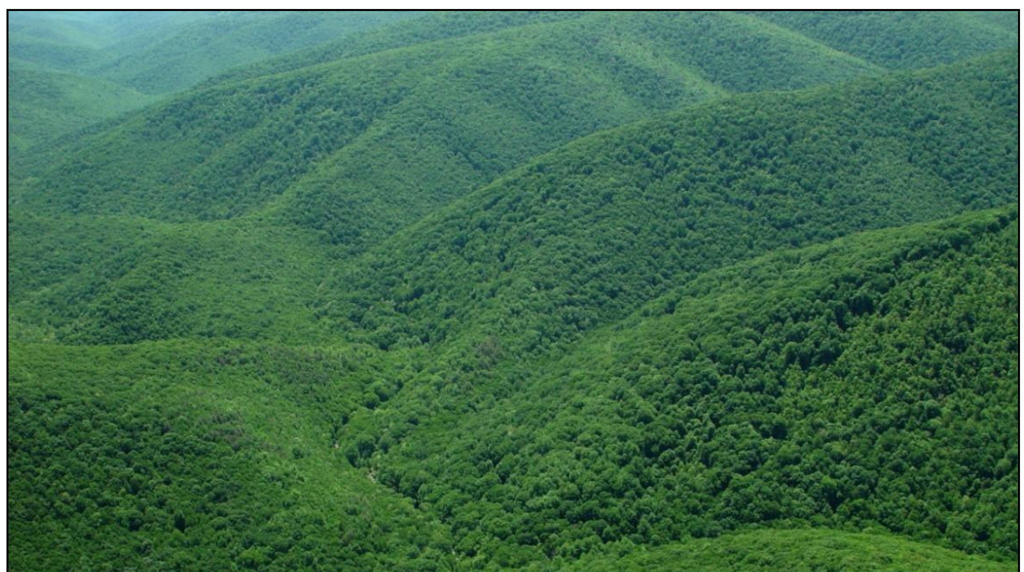
The Virginia Trout Stream Sensitivity Study

. . . quarterly monitoring initiated in 1987



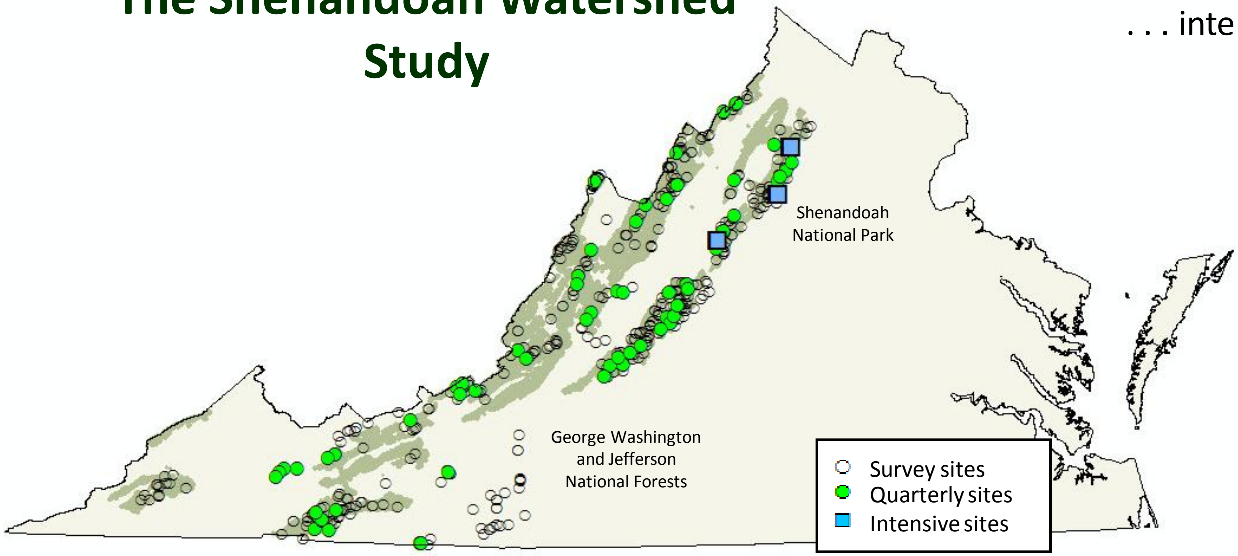
A subset of the 1987 survey streams was selected for long-term quarterly monitoring. Most of these streams are located in public conservation lands.

The quarterly sampling sites represent relatively pristine conditions and regional bedrock distribution.



The Shenandoah Watershed Study

. . . intensive monitoring initiated in 1992

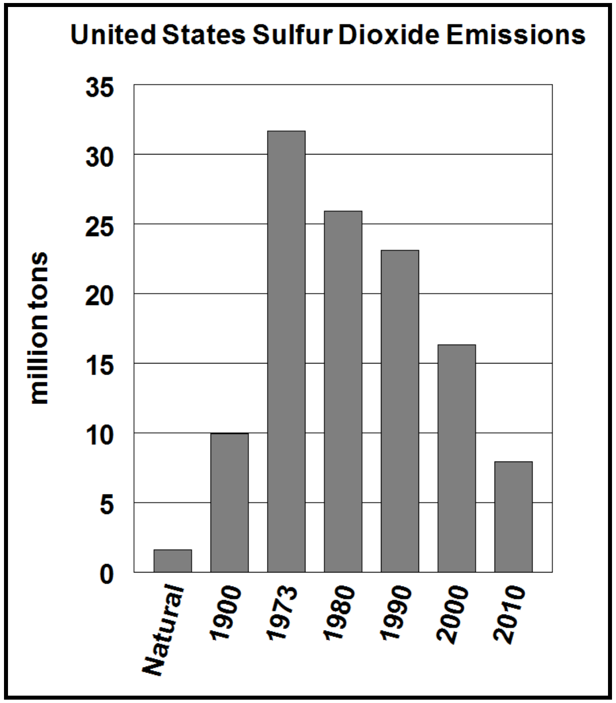


Intensive stream monitoring continues in Shenandoah National Park. Data collection on three streams includes weekly sampling, automated high-flow sampling, and continuous stream flow gauging. The three streams, Paine Run, Staunton River, and Piney River, were selected to represent the major bedrock types in the park.

U.S. emissions of sulfur dioxide have decreased but remain greater than natural levels

The main source of acidic deposition in the U.S. is emissions of acid-forming compounds, primarily sulfur dioxide and nitrogen oxide, from the burning of fossil fuels. Sulfate, derived from sulfur dioxide, has historically been the main determinant of precipitation acidity and the dominant acid anion associated with surface water acidification.

A substantial change occurred in acid-forming emissions in the past four decades, largely in response to regulatory controls, including implementation of the Acid Rain Program established by the Clean Air Act Amendments of 1990. After peaking at about 32 million tons in 1973, total U.S. sulfur dioxide emissions decreased to less than 9 million tons by 2010.

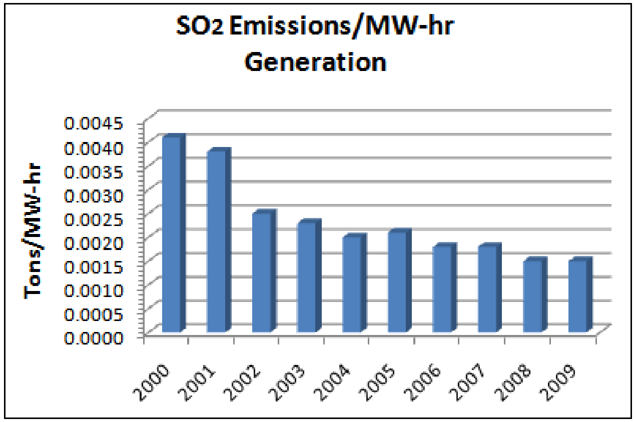


Current sulfur dioxide emissions are lower than in 1900, but are still about five times greater than estimated natural levels.

Data sources for graphic: USEPA (2000); USEPA (2011), NAPAP (1991), and Placet (1990).

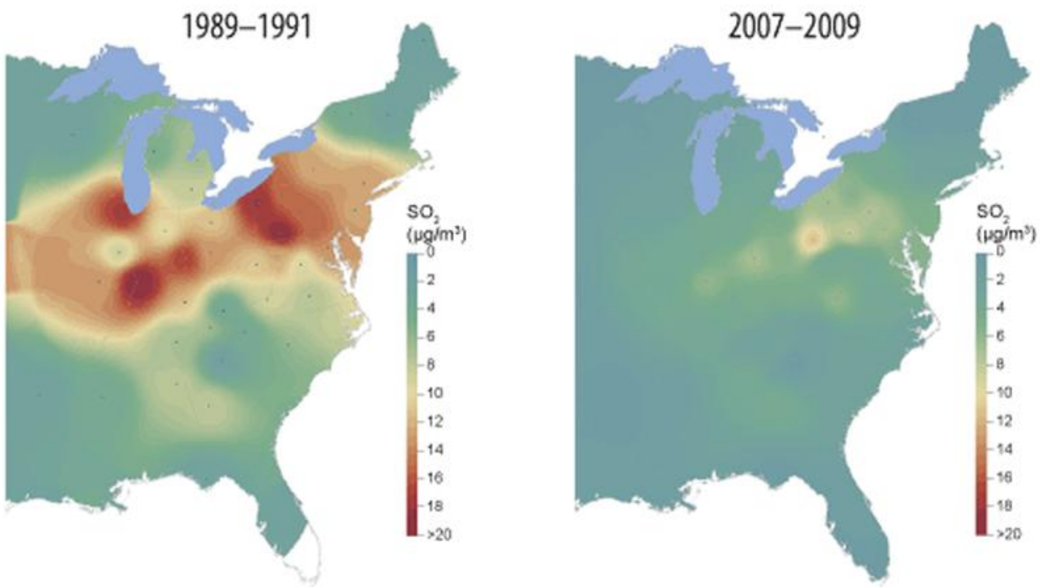
The Acid Rain Program

The Clean Air Act Amendments of 1990 established a phased approach to reducing sulfur dioxide emissions, resulting in reduced sulfur concentrations in the atmosphere, in deposition, and in surface waters. Between 1990 and 2009 sulfur dioxide emissions from U.S. coal-fired power plants declined by 64%.



For example:
Sulfur emissions declined at Dominion power plants during the period, 2000–2007, while generation increased by more than 50%. Approximately 95% of sulfur dioxide is now removed from emissions at the regional utility's largest coal-fired plant, the Mount Storm Power Station (shown in slide 8), which is upwind of western Virginia and Shenandoah National Park.

Source: www.dom.com/about/environment/report/index.jsp

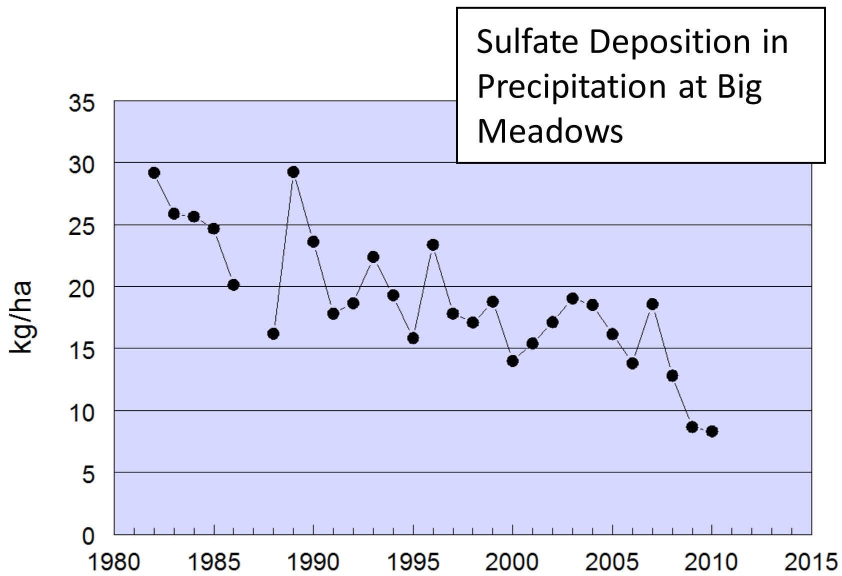


Change in annual ambient mean sulfur dioxide concentrations: comparison between 3-year means.

Source: www.epa.gov/airmarkets/progress/ARP09_3.html

Exposure to Acidic Deposition

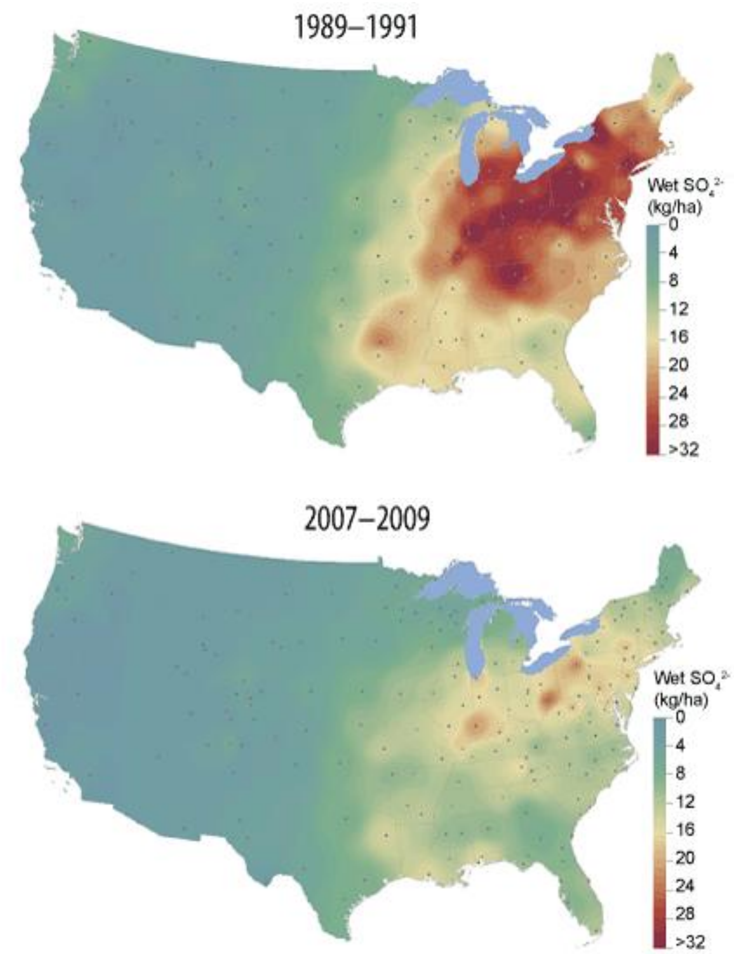
The reduction in emissions from coal-fired power plants has resulted in reduced sulfur deposition to Virginia's mountain watersheds and throughout the eastern U.S.



Sulfur deposition in precipitation at Big Meadows in Shenandoah National Park has decreased by about two-thirds from levels observed in the 1980s.

Source: nadp.sws.uiuc.edu/

Change in regional deposition of sulfate in precipitation: comparison between 3-year means



Source: nadp.sws.uiuc.edu/

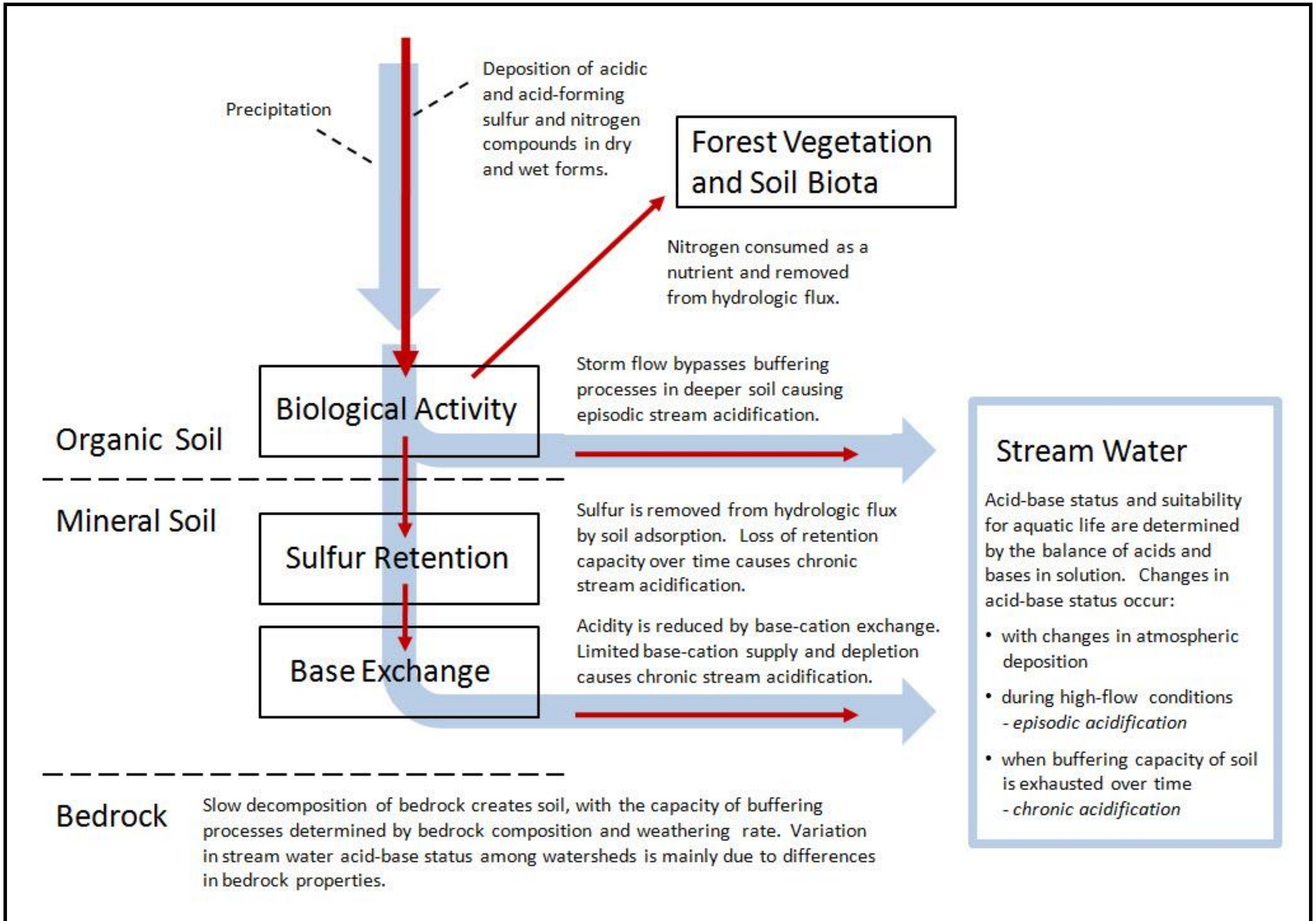
Watershed Sensitivity

Watershed response to acidic deposition may involve chronic or episodic change in the acid-base status of surface waters. The term, acid-base status, refers to the effective balance between acids and bases in solution. Surface water acidification is defined as a loss of acid-neutralization capacity (ANC). Loss of ANC related to acidic deposition occurs when concentrations of strong-acid anions associated with acidic deposition (sulfate and nitrate) increase relative to concentrations of base cations (calcium, magnesium, potassium, and sodium ions).

If surface water ANC is reduced to sufficiently low values, acidity may increase, as indicated by a depression in pH, to a range associated with adverse effects on fish and other aquatic life.

Streamwater response to acidic deposition is determined by watershed processes that affect the balance between acids and bases.

Conceptual Model

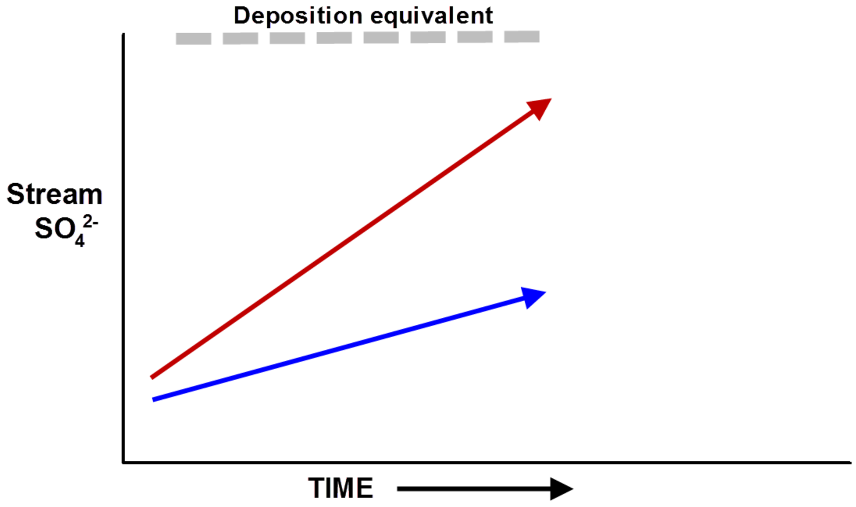


Sulfur Retention

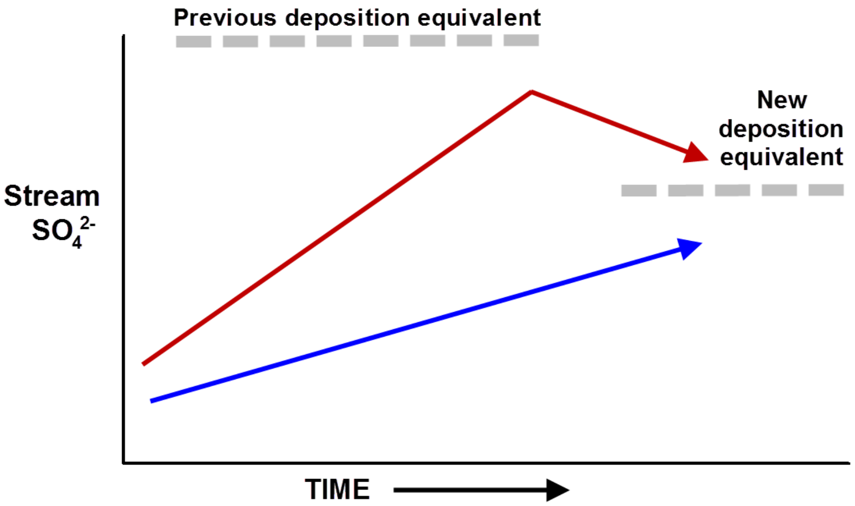
Soils in the southeastern U.S. commonly retain or adsorb sulfur, reducing or delaying the increase in streamwater sulfate concentrations associated with acidic deposition. In time, as exposure to sulfur deposition continues and the adsorption capacity of watershed soils is diminished, sulfate concentrations in streamwater increase until equilibrium with atmospheric sulfate deposition is reached. With sufficiently reduced emissions, the sulfate deposition equivalent may be reduced below streamwater sulfate concentrations, allowing sulfate concentrations in streams to decrease.

Streamwater concentrations of sulfate increase or decrease depending on the relative sulfate deposition equivalent. The graphics depict changing streamwater sulfate concentrations for two watersheds, one with strong sulfate retention (blue arrow) and one with weak sulfate retention (red arrow).

Before emission reductions



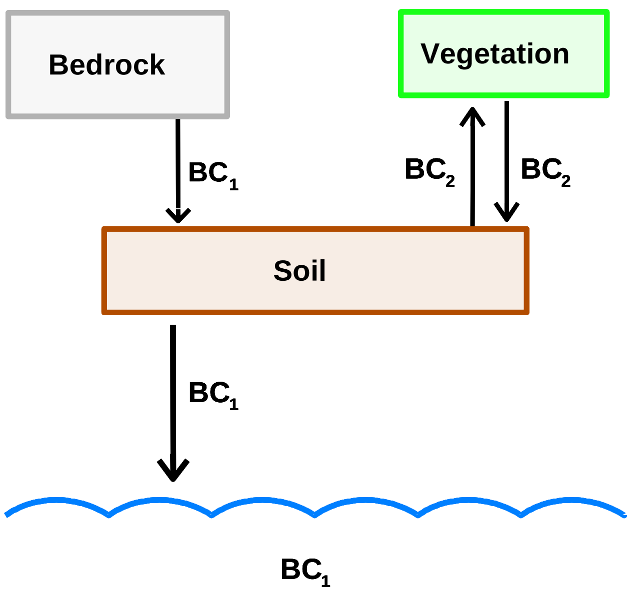
After emission reductions



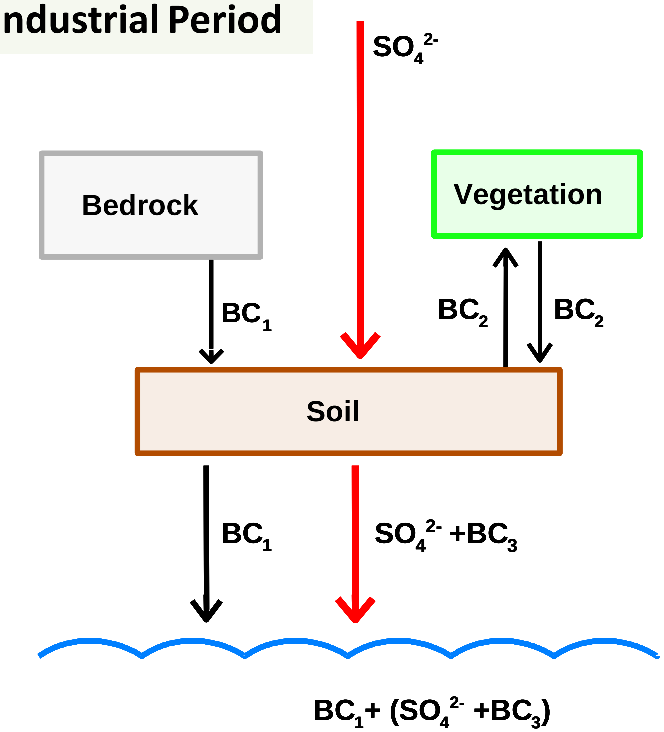
Base-Cation Exchange

Although base-cation exchange in watershed soil reduces direct surface water acidification, it may also deplete the base-cation supply in the soil, resulting in long-term soil acidification and delayed recovery of surface waters following reductions in acidic deposition. In the pre-industrial, pre-acidification period, the rate of base-cation export in a stream (BC_1) was mainly determined by the rate of base-cation release from bedrock. Base-cation uptake from the soil by mature forests (BC_2) was effectively recycled. In the post-industrial, acidification period, additional base cations (BC_3) are leached from the soil to balance the flux of sulfate. The capacity of soil to increase the export of base cations to maintain the balance of acids and bases and prevent the loss of ANC in surface water is ultimately determined by the composition and weathering properties of watershed bedrock.

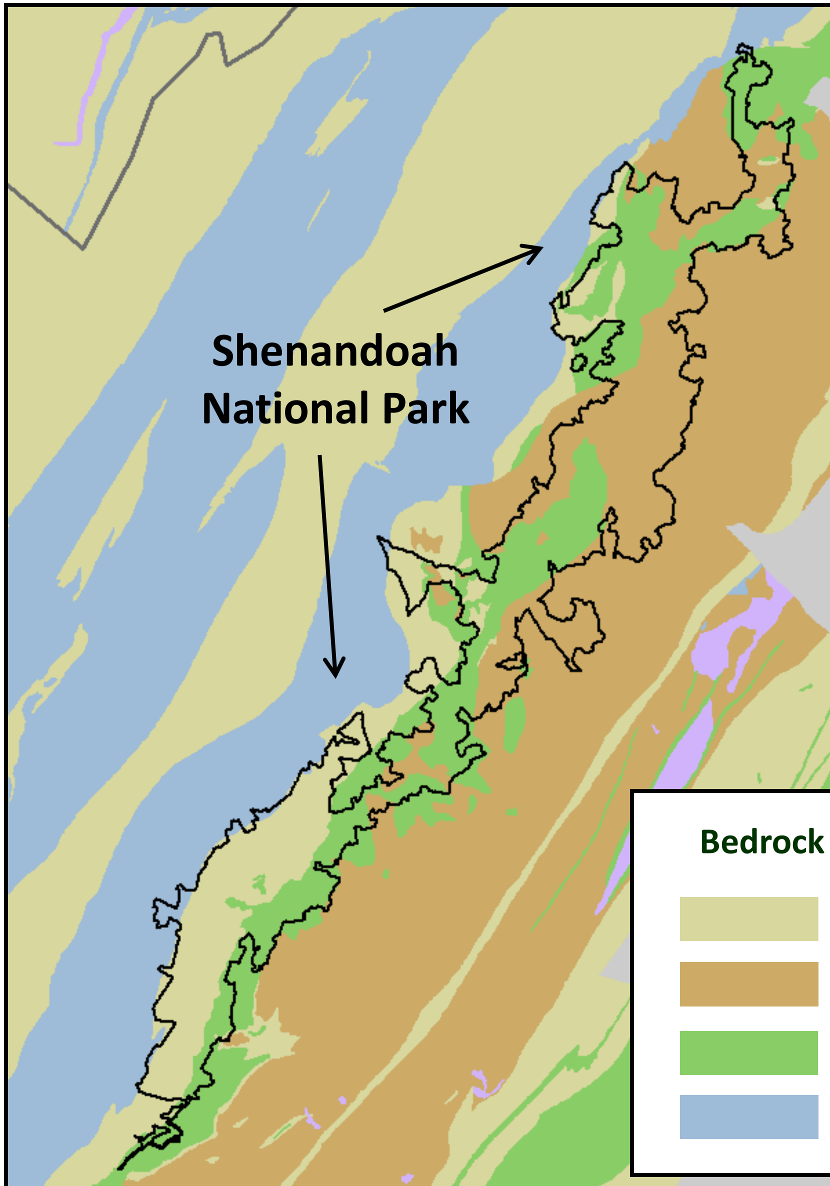
Pre-Industrial Period



Post-Industrial Period



Watershed Bedrock Classification



Bedrock differences account for much of the variation in watershed response to acidification and other ecosystem properties in the western Virginia mountains. Bedrock classification provides a basis for regional extrapolation of observations made for individual watersheds and streams.

For example, the 3 major bedrock classes in Shenandoah National Park differ with respect to base-cation content and weathering rate. Siliciclastic bedrock is base-poor compared to mafic bedrock, and felsic bedrock is intermediate. This gradient is reflected in soil properties, streamwater acid-base status, and in the richness of aquatic life.

Siliciclastic watersheds
- median soil base saturation ~10%
- streamwater ANC <0 to 50 μeq/L
- 1-3 fish species

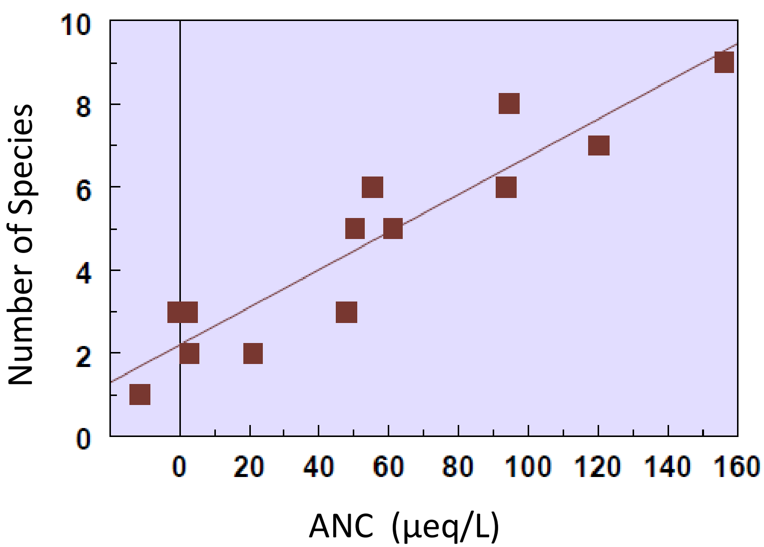
Felsic watersheds
- median soil base saturation ~15%
- streamwater ANC 40 to 100 μeq/L
- 3-6 fish species

Basaltic watersheds
- median soil base saturation >40%
- streamwater ANC >100 μeq/L
- 5-10 fish species

For more information on bedrock determination of acid-base status, see Sullivan, et al. (2007).

Biological Response

Fish species richness is strongly dependent on the acid-base status of streamwater. Streams with low ANC host fewer species. This suggests that the more-sensitive fish species disappeared in the past as streams acidified.



Relationship between number of fish species and minimum ANC recorded in Shenandoah National Park streams (from Bulger et al., 1999).

Species commonly present in streams with low ANC

Brook Trout (Salvelinus fontinalis)

Blacknose Dace (Rhinichthys atratulus)

Fantail Darter (Etheostoma flabellare)

Mottled Sculpin (Cottus bairdi)

Species commonly present in streams with high ANC

Rosyside Dace (Clinostomus funduloides)

Torrent Sucker (Thoburnia rhothocea)

Longnose Dace (Rhinichthys cataractae)

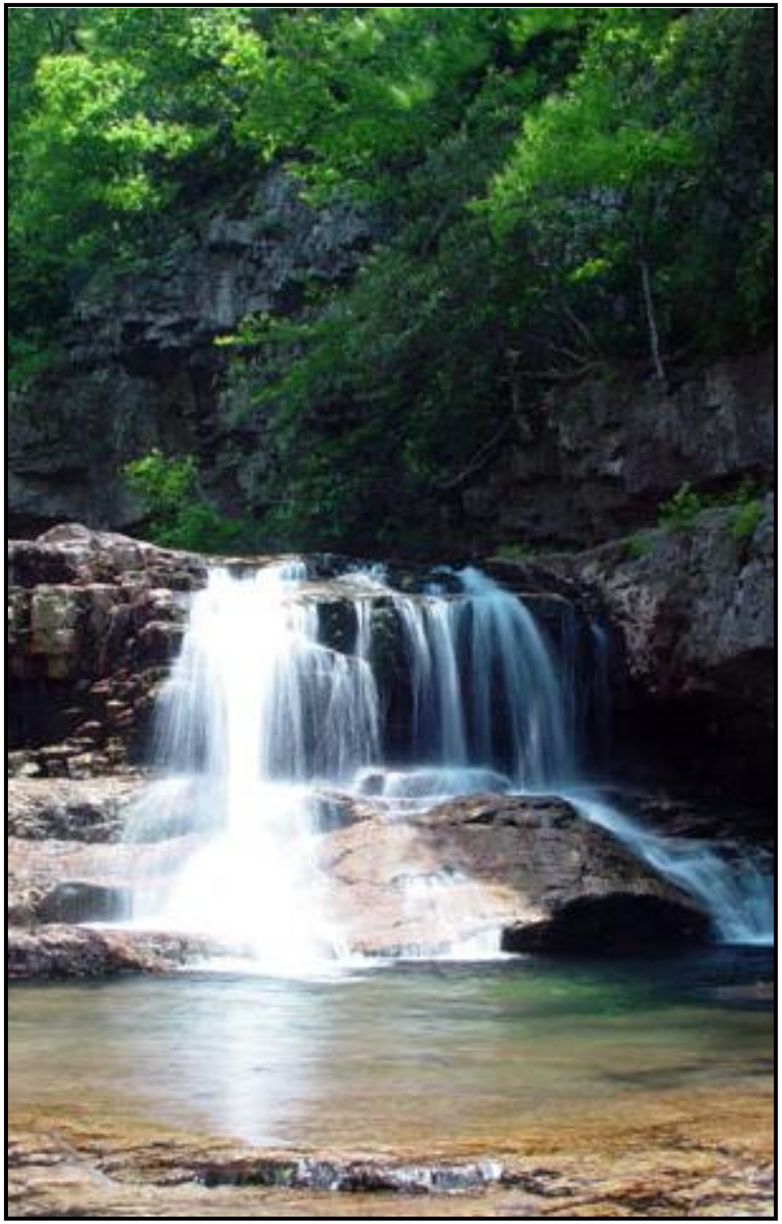
Creek Chub (Semotilus atromaculatus)

Images from EFISH (http://www.fw.vt.edu/efish)

Saint Marys River Case Study

Saint Marys River, which drains the Saint Marys Wilderness in the George Washington National Forest, is among the most well known and well studied of the streams in the central Appalachian region that have been affected by acidic deposition. In 1999, the USDA Forest Service and various cooperators began a limestone mitigation project in response to both the evidence of existing impact and the risk of further impact. The first treatment involved the addition of limestone sand (140 tons) by helicopter delivery to the main stem and major tributaries. Streamwater quality improved following treatment, but the effects were temporary. Treatment was thus repeated with additional limestone (230 tons) in 2005 and again in 2013.

The water chemistry and biological data collected for the Saint Marys River prior to and following the limestone treatments provide an opportunity to examine the relationship between stream acidification and the status of stream fauna.



The falls of Saint Marys River.

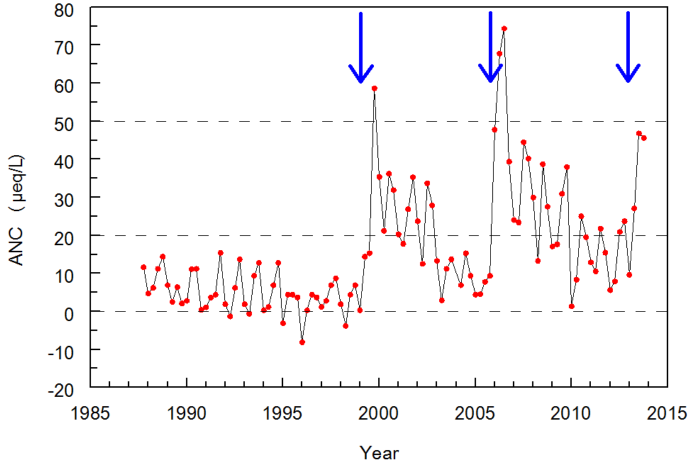
Watershed Response to Acidic Deposition

Saint Marys River Case Study

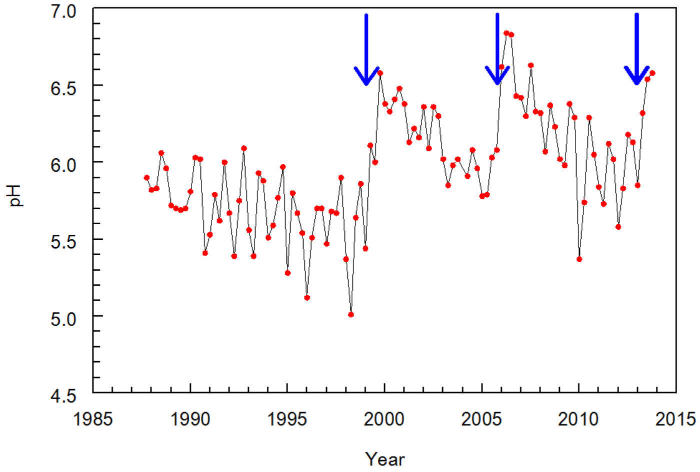
A long period of decline in streamwater ANC and pH was reversed after limestone treatment in 1999. This was followed by a multiyear decline with values returning to near pre-treatment levels. The second treatment in 2005 also produced improvement that was followed by a decline. A third treatment in 2013 has again produced an improvement. The apparent pattern of response, in which limestone treatment needs to be repeated every 4-5 years, approximates expectations prior to the treatment project.

The Saint Marys River watershed is dominated by siliciclastic bedrock.

Saint Marys River – Acid Neutralizing Capacity



Saint Marys River – pH



ANC and pH values for VTSSS quarterly samples collected near the downstream Wilderness boundary. Limestone was added upstream in 1999, 2005, and 2013 (blue arrows). ANC values are shown in relation to brook trout suitability categories (see slide 20).

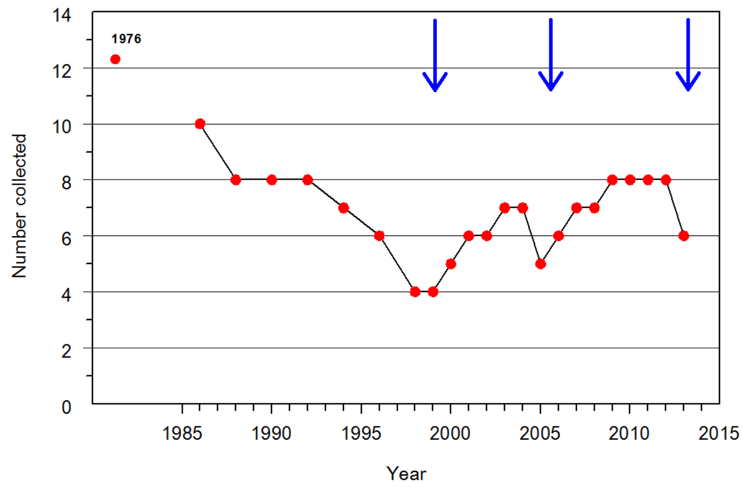
Biological Response: Case Study

The responses of aquatic fauna to limestone treatment in Saint Marys River generally followed the same pattern as streamwater ANC and pH. A long period of decline in species and taxa richness was reversed following the first treatment, followed by a multiyear decline with values returning to near pre-treatment levels. The second treatment also produced improvement that was again followed by a multiyear decline.

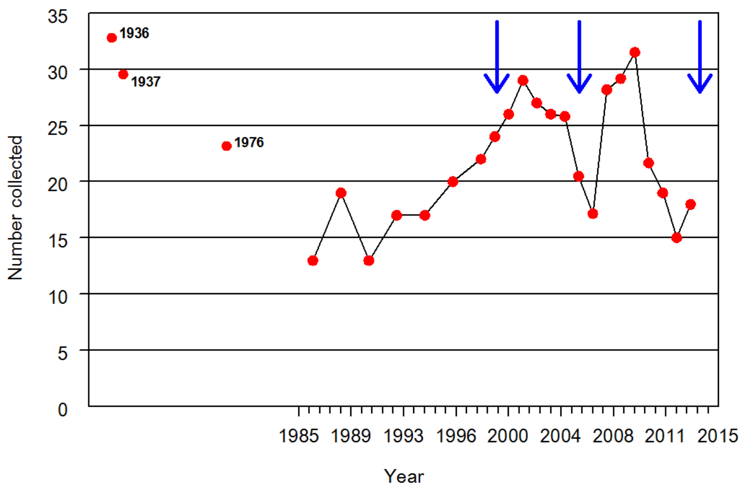
Although limestone treatment provides an option for sustaining aquatic life in acidified streams such as Saint Marys River, limestone treatment is only a partial solution to the ecosystem harm associated with acidic deposition. The neutralizing effect of limestone treatment is temporary and does not extend to watershed soil or to components of the aquatic system that are upstream of the limestone application.

For more information, see Downing (2011).

Saint Marys River – Fish Species Collected



Saint Marys River – Invertebrate Taxa Collected



Invertebrate taxa and fish species collected in Saint Marys River, showing historic decline and response to limestone treatment (blue arrows). The numbers collected are the combined totals for multiple sampling sites. The data were provided by the Virginia Department of Game and Inland Fisheries and the USDA Forest Service.

Model Analysis

Evaluating Deposition Scenarios

The MAGIC (*Model of Acidification of Groundwater in Catchments*) computer model was developed in the 1980s using information obtained for the White Oak Run watershed in Shenandoah National Park (see slide 4). The MAGIC model, which uses soil and precipitation chemistry to predict stream chemistry, has since been widely used to predict the future acid-base status of lakes and streams given alternate future acidic-deposition scenarios.

One application of the MAGIC model used data collected in the 1987 VTSSS survey and subsequent quarterly monitoring (see slides 5 and 6) to determine the reduction in acidic deposition needed to prevent further damage to brook trout streams in Virginia. The results, briefly summarized here, were published in a 1998 Trout Unlimited report, *Acid Rain: Current and Projected Status of Coldwater Fish Communities in the Southeastern US in the Context of Continued Acid Deposition.*

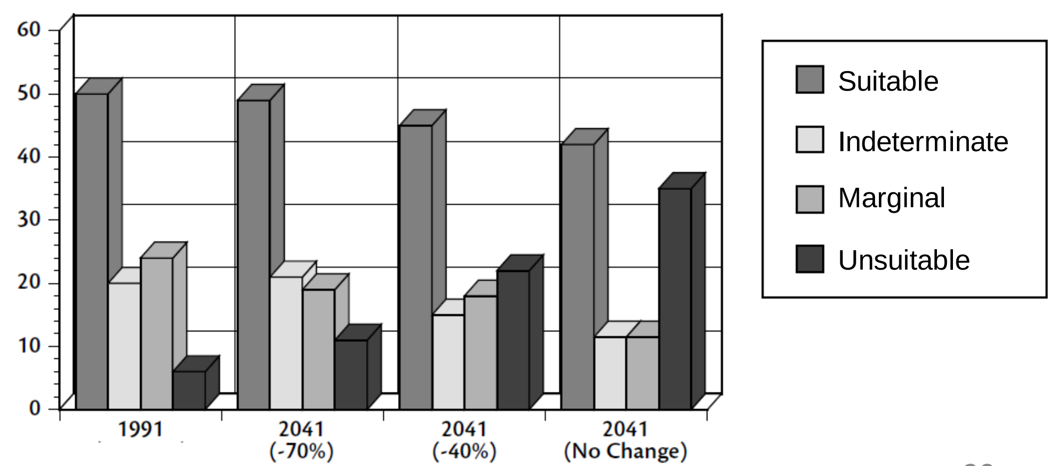
For more information, see Bulger, et al. (1998).

Streamwater ANC Categories for Brook Trout Status

Category	ANC Range µeq/L	Brook Trout Status
Suitable	>50	Reproducing populations expected
Indeterminate	20-50	Sensitive / response variable
Marginal	0-20	Sub-lethal / lethal effects possible
Unsuitable	<0	Lethal effects probable

Model forecasts indicated that a 70% reduction in deposition from 1991 levels is needed to retain about 50% of the streams in the "suitable" category in 2041. Even with a 70% reduction there would still be an increase in the number of "unsuitable" streams.

Effects of Future Deposition Reductions on VTSSS Study Streams



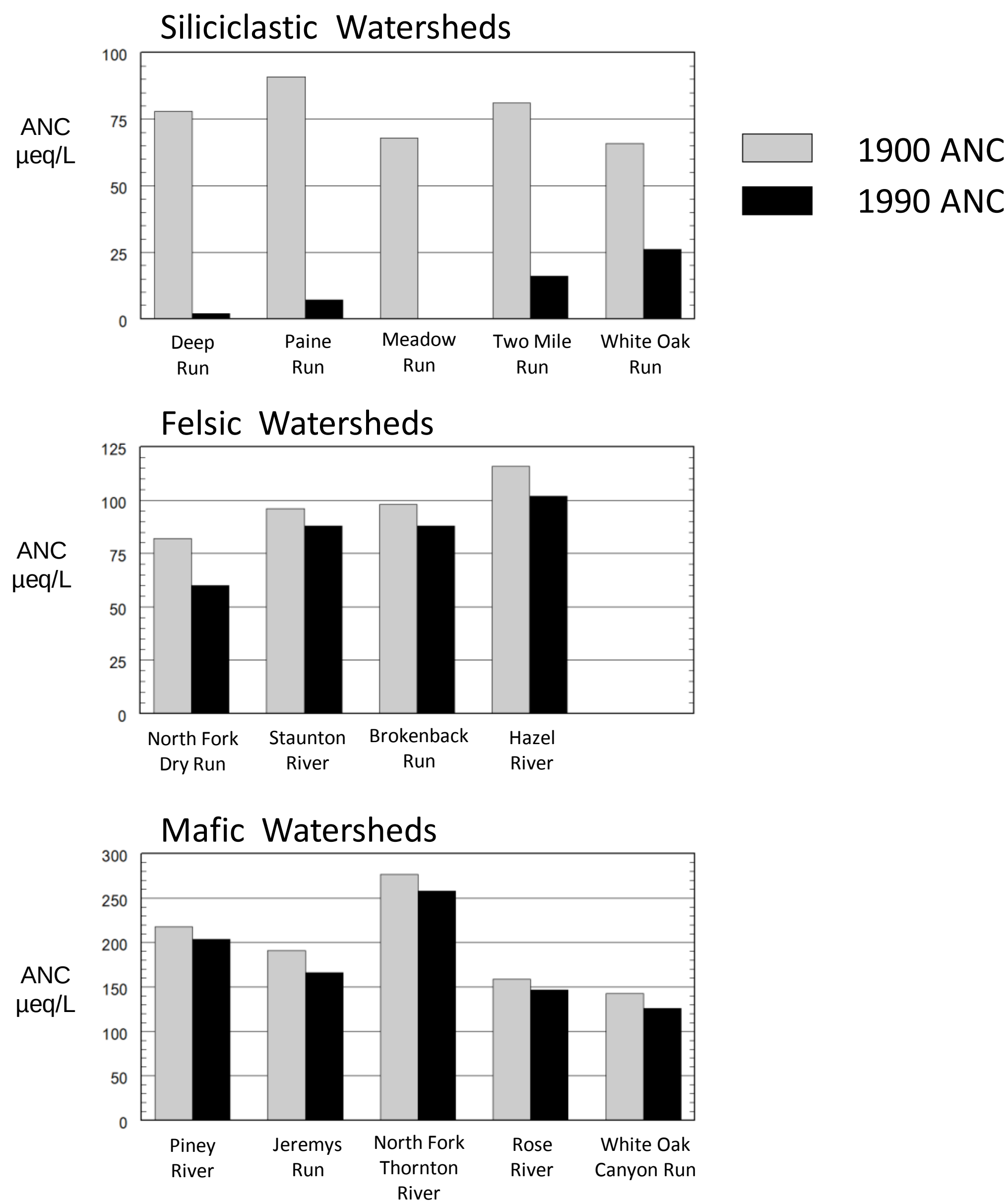
Historic ANC Loss in Shenandoah National Park Streams

Estimating Past Acidification

The MAGIC model has been applied to estimate the loss of ANC in streams due to past acidic deposition.

Model hindcasts indicate that streamwater ANC in 1900 was greater than 50 μeq/L in all of the quarterly sample streams in Shenandoah National Park (n = 14). The watersheds underlain by base-poor siliciclastic rock experienced the greatest ANC losses. For these streams, ANC has been reduced to levels associated with harm to brook trout and other aquatic life.

For more information, see Sullivan, et al. (2008).



Model Analysis

Estimating Critical Loads

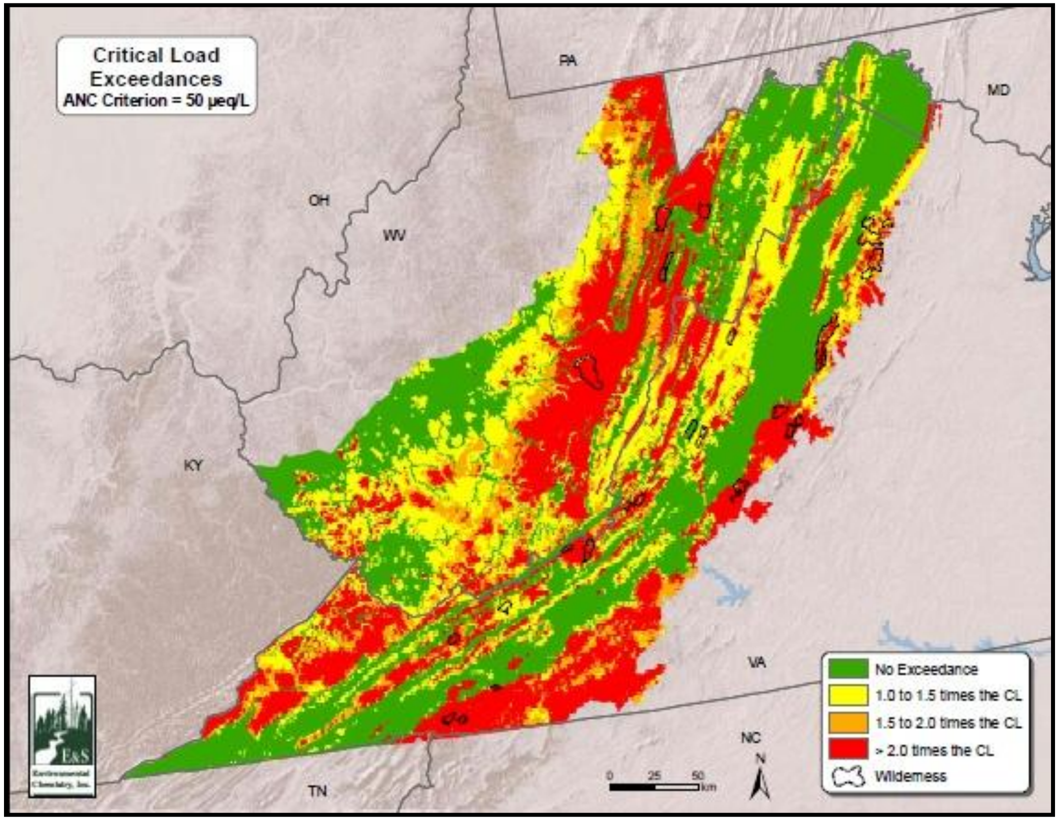
The MAGIC model has been applied to estimate critical loads for acidic deposition. A critical load, in this context, is the maximum level of acidic deposition that can be sustained without harmful effects to aquatic life.

Sullivan et al. (2010) conducted a critical loads analysis focused on the status of streams in the Virginia and West Virginia mountains. Average annual acidic deposition for the 2000-2004 period was compared with the estimated maximum deposition level that watersheds can sustain consistent with long-term attainment of streamwater ANC objectives.

For many of the modeled watersheds, the realization of a steady-state condition, in which the key acid-base properties of soils (e.g., base cation saturation and sulfate adsorption status) are stable, was projected to require hundreds of years.

For more information, see Sullivan, et al. (2010).

Regional Long-term Critical Load Status



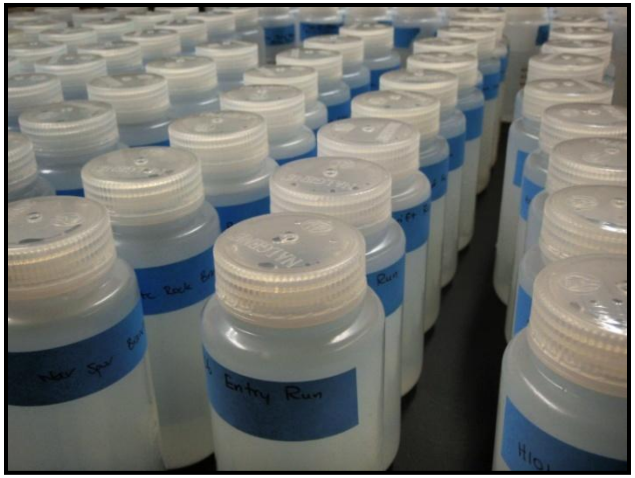
About 57% of the study area, including most of the landscape underlain by siliciclastic bedrock and most of the area designated as Wilderness, was calculated to receive acidic deposition in exceedance of the critical load value associated with preventing ANC values below 50 µeq/L.

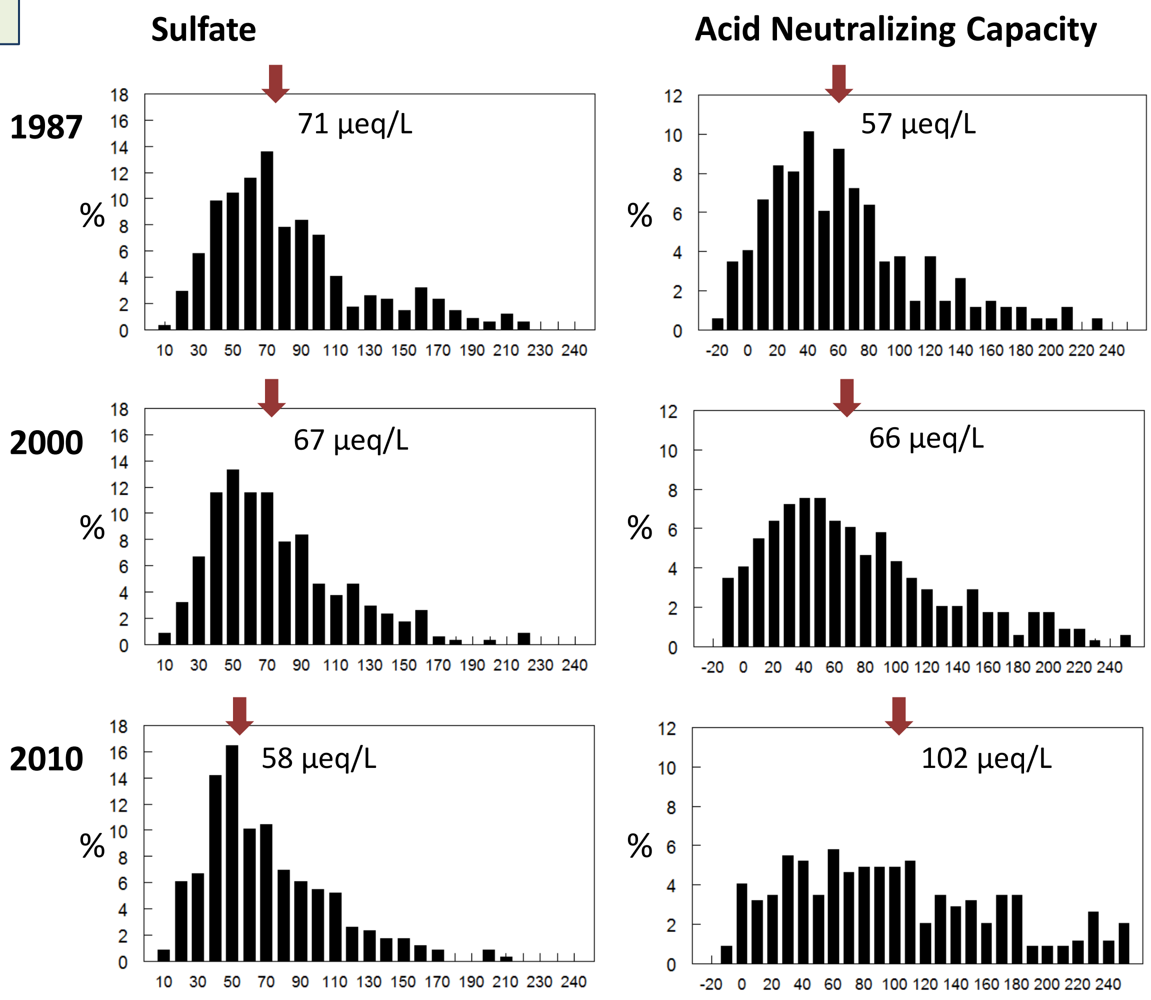
Change in Streamwater Acid-Base Status

Regional Survey Data

The 1987, 2000, and 2010 VTSSS surveys (see slide 5) have provided evidence for partial recovery from stream acidification in response to decreased sulfur emissions and deposition.

Recovery is indicated by increasing ANC and decreasing sulfate concentrations.





Median stream water sulfate decreased from 71 to 58 µeq/L between 1987 and 2010. The greatest change occurred after the 2000 survey, coincident with major sulfur emission reductions achieved by the Clean Air Act Amendments of 1990.

Median stream water ANC increased from 57 to 102 µeq/L between 1987 and 2010. Despite this evidence for recovery, ANC remained less than 50 µeq/L for a substantial percentage of the study streams.

Change in Streamwater Acid-Base Status

Regional Survey Data

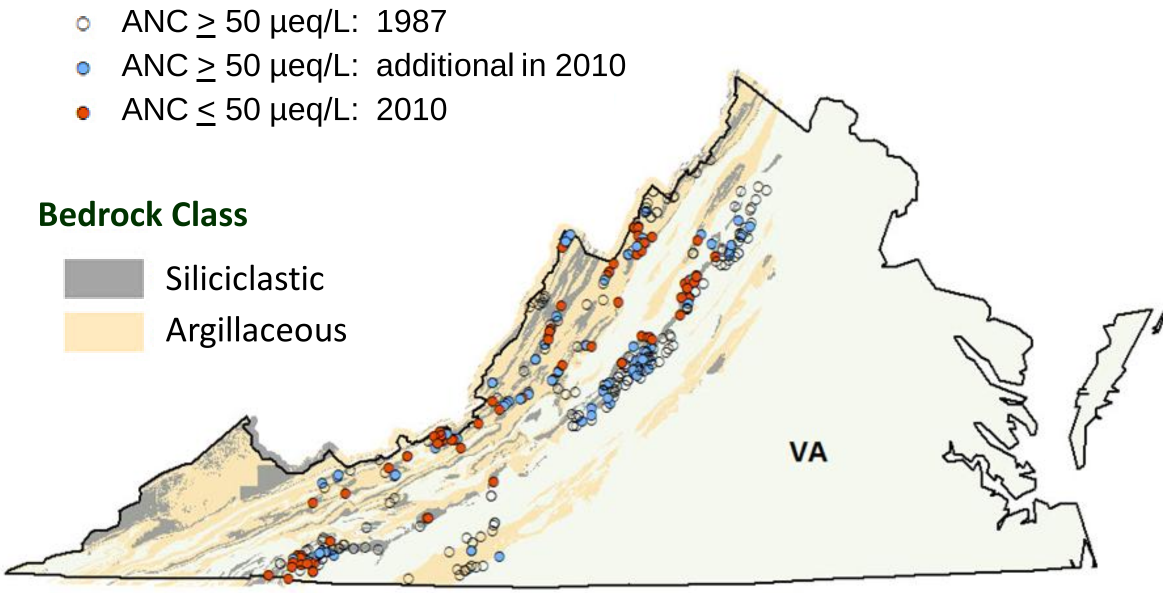
Of the 355 brook trout streams sampled in both the 1987 and 2010 VTSSS surveys:

- 46% had an ANC <50 µeq/L in 1987
- 24% had an ANC <50 µeq/L in 2010

Most (89%) of the remaining streams with ANC <50 µeq/L drain watersheds that are underlain by base-poor siliciclastic (quartzite and sandstone) or argillaceous (siltstone and shale) bedrock types.

This suggests that about one-fourth of the study stream watersheds have been subject to a level of cumulative damage by past exposure to acidic deposition that has precluded recovery in response to the recent reductions in sulfur-dioxide emissions and acidic deposition.

Change in ANC Category Between the 1987 and 2010 VTSSS Surveys



Siliciclastic and argillaceous bedrock types are prevalent in the central Appalachian mountains. It can thus be assumed that many additional streams throughout the region are also exhibiting little or no recovery in response to the recent reductions in acidic deposition.

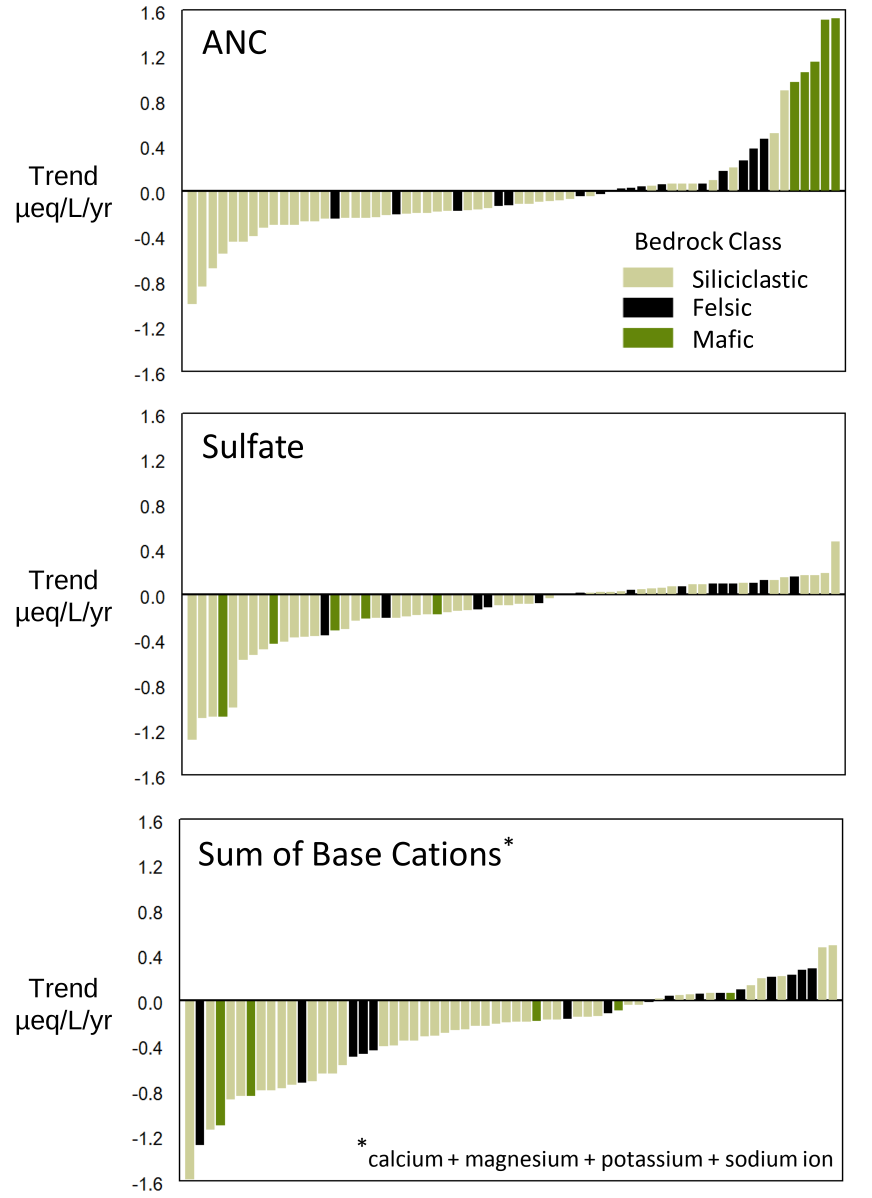
Quarterly Monitoring Data

Additional information concerning stream and watershed response to changes in acidic deposition is provided by analysis of data obtained through the VTSSS quarterly sampling program (see slide 6).

Robison et al. (2013) examined trends for the quarterly sites for 1987-2011. Although sulfate concentrations declined in the majority of sites, this did not result in a general recovery of ANC. Instead, ANC declined in many streams, especially in the streams associated with base-poor siliciclastic bedrock. In contrast, ANC increased in the streams associated with base-rich mafic bedrock. The lack of recovery for watersheds with base-poor bedrock can be attributed to the decline in base cations —further evidence for cumulative damage to watershed soil by past exposure to acidic deposition.

For more information, see Robison, et al. (2013).

Ranked Trends for Quarterly Sites: 1987-2011

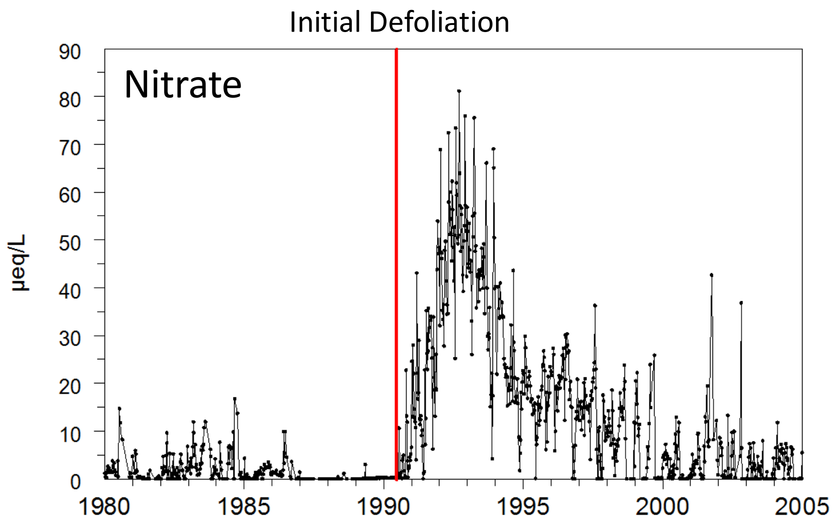


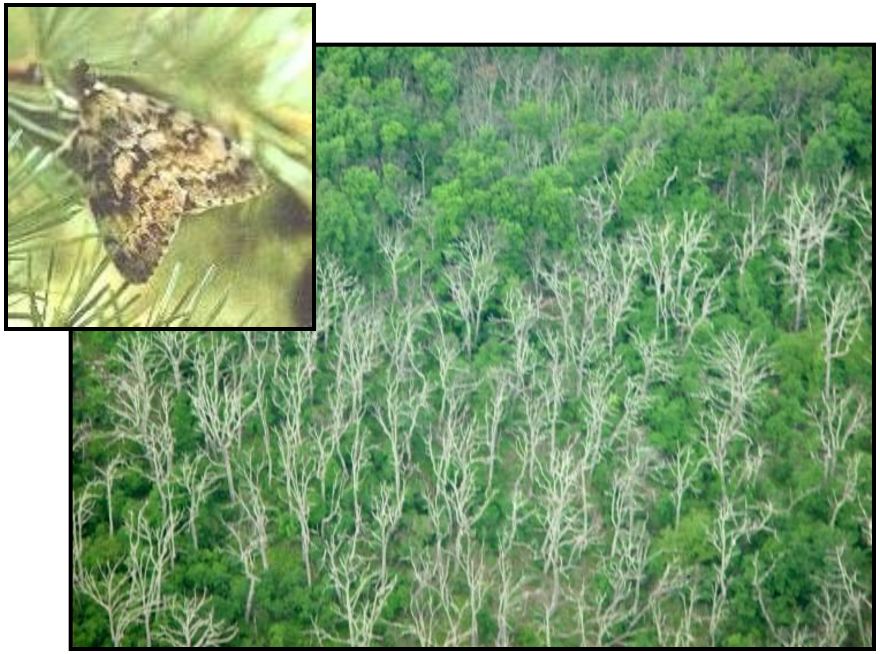
Response to Disturbance

Other factors, in addition to acidic deposition, have affected SWAS-VTSSS study streams. Among these is forest defoliation by the gypsy moth, which expanded its range southward through western Virginia in the 1980s and 1990s. A major effect of the defoliation was a transient increase in nitrate concentrations in streamwater. Although nitrate is associated with acidic deposition, nitrate concentrations in the region's mountain streams are generally low due to consumption of nitrate as a forest nutrient (see slide 7). Defoliation disrupted the cycling of nitrogen and allowed export of nitrate in streamwater. Other effects included increased concentrations of base cations and decreased concentrations of sulfate. Silica concentrations also decreased, apparently due to increased diatom production resulting from increased nitrogen in streamwater. These effects were temporary but continued for multiple years after the most-intense defoliation.

For more information, see Webb et al. (2005); Grady et al. (2007).

Nitrate Increase in White Oak Run Following Forest Defoliation



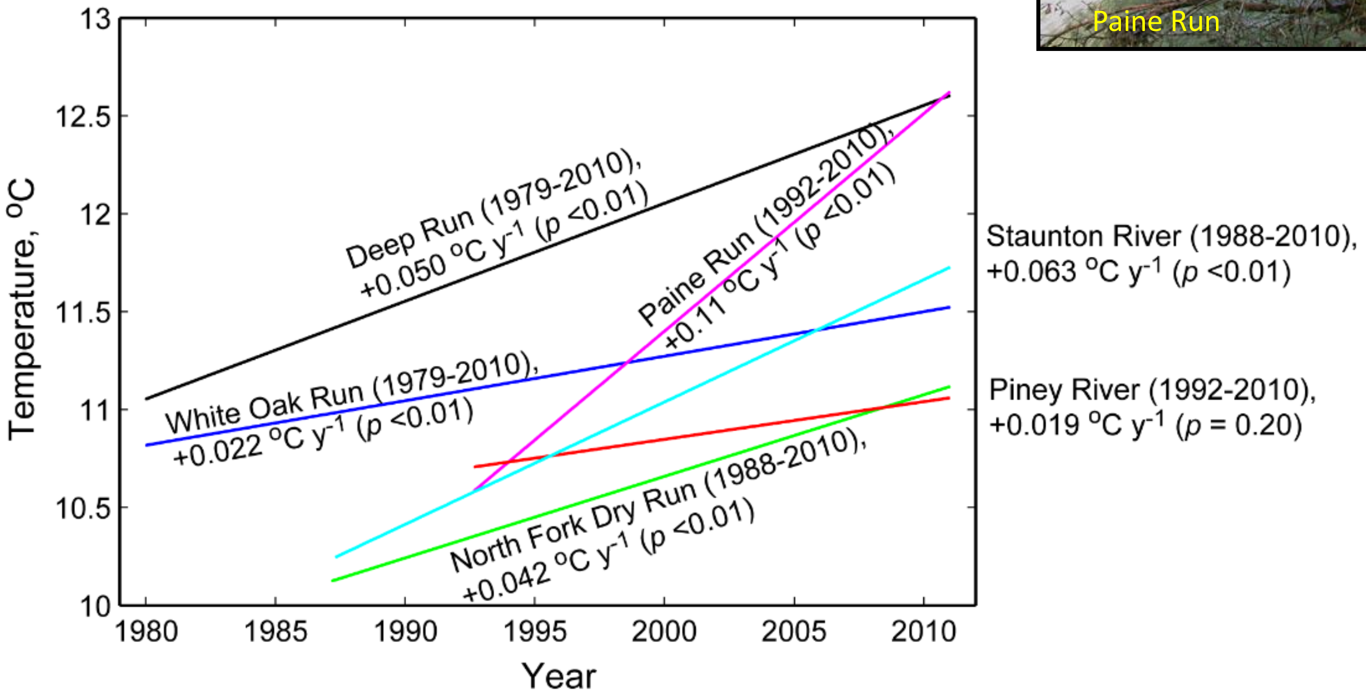


Oak mortality following defoliation

Rising Temperature

Consistent with climate change projections , streamwater temperatures have been rising in all of the streams in Shenandoah National Park that are included in the weekly data collection program maintained by the SWAS program.

If continued, the observed rate of temperature increase may result in greatly reduced habitat for brook trout and other aquatic species that require cold water.



Summary

- Sulfur dioxide from fossil-fuel burning has historically been the primary precursor of acidic deposition, and sulfate is the primary acid anion associated with stream acidification in the central Appalachian region.
- Since peaking in the 1970s, acid-forming emissions have declined substantially. Although emissions of sulfur dioxide are at the lowest level since 1900, current emissions still exceed pre-industrial levels.
- Sulfate deposition in precipitation in Shenandoah National Park has declined by about two-thirds since routine measurements began in the early 1980s.
- Streamwater response to acidic deposition is determined by watershed processes that affect the balance between acids and bases. The critical processes are sulfate retention and base-cation exchange in soil.
- Streamwater acidification is indicated by increasing sulfate and decreasing acid neutralizing capacity (ANC) concentrations. Recovery is indicated by decreasing sulfate and increasing ANC concentrations.
- Variation in watershed response to acidic deposition in the central Appalachian region is mainly determined by bedrock. Streams associated with base-poor siliciclastic bedrock (sandstone and quartzite) are the most susceptible to acidification. Siliciclastic bedrock is prevalent throughout the central Appalachian region.
- Sulfate concentrations decreased in most Virginia mountain streams in recent years. This, however, has not resulted in a general recovery of ANC, especially in streams associated with base-poor siliciclastic bedrock.
- The lack of recovery for watersheds with base-poor bedrock can be attributed to a decline in base-cations in streamwater. This is the result of cumulative damage to watershed soil by past exposure to acidic deposition.
- In addition to the adverse effects of acidic deposition, brook trout streams in western Virginia are affected by forest disturbance and increasing water temperature.

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