Acid Rain:

Current and Projected Status of Coldwater Fish Communities in the Southeastern US in the Context of Continued Acid Deposition

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Executive Summary

Abstract

By analyzing comprehensive stream chemistry data from brook trout streams across Virginia, this report predicts the consequences of reductions in acid deposition for the health of trout stream ecosystems. Many of Virginia's brook trout streams are part of acid-sensitive ecosystems in Appalachian forests. Despite the reductions in acid-causing air pollution required by the 1990 Amendments to the Clean Air Act, these streams continue to be threatened by acid deposition. Currently only about 50 percent of the 304 Virginia trout streams covered in this report are "not acidic," compared to an estimated 82 percent of pre-industrial, forested watersheds in Virginia. Approximately 6 percent are "chronically acidic" and unable to support brook trout or other fish species. The results of this analysis suggest that a 70 percent reduction in acid deposition from 1991 levels will be necessary to retain about 50 percent of Virginia's brook trout streams in the "not acidic" condition. At lesser reductions in acid deposition, a large number of Virginia's trout streams – up to 35 percent if no further reductions in deposition levels are accomplished — will become "chronically acidic" and will no longer support wild trout populations in the year 2041.

Background

The 1990 Amendments to the Clean Air Act provide for significant reductions in emissions of sulfur dioxide (SO_2) and some reductions in emissions of nitrogen oxides (NO_x), the pollutants that are responsible for acid deposition. Many scientists and resource managers, including EPA, have questioned whether these reductions will be sufficient to protect sensitive ecosystems, while others have questioned whether every region of the country will receive the full benefit of these national cuts (EPA 1995).

The research detailed in this report examines one set of sensitive ecosystems – headwater streams in Virginia that hold brook trout – in an attempt to determine how much deposition must be reduced to maintain their current condition. Specifically, the report uses computer modeling techniques to evaluate the degree of acidification in Virginia's brook trout streams, together with the capacity of individual streams to neutralize additional acid, in order to predict whether they will continue to support brook trout in the middle term (the year 2011) and long term (the year 2041).

The forested mountain watersheds that provide habitat for brook trout in Virginia are particularly sensitive to the effects of acidic deposition. Among forested mountain watersheds, however, there is a range of sensitivity to acidic deposition directly related to the chemistry of the soil and bedrock of the watershed. Each stream has a greater or lesser ability to neutralize acid precipitation, which can change over time as more acid is deposited on the watershed. This report uses measurement of acid neutralizing capacity ("ANC," expressed in microequivalents per liter, µeq/L) to estimate the degree of each stream's acidification and its remaining buffering capacity.

We have divided Virginia's streams into four categories:

- **Chronically Acidic:** ANC values less than 0 *µeq/L* indicate streams that are no longer able to neutralize acid deposition and cannot host populations of brook trout or any other fish species.
- **Episodically Acidic:** Streams with an ANC between *0 and 20 µeq/L* experience regular episodic acidification at levels harmful to brook trout and other aquatic species and host, at best, reduced fish populations.
- **Transitional:** Streams whose ANC values fall between *20 and 50 µeq/L* are extremely sensitive to further acidification; they may or may not host brook trout populations, depending on the frequency and magnitude of acid events and other habitat characteristics. They certainly will host fewer fish species than streams with higher ANC values.

▶ **Not Acidic:** Streams with acid neutralizing capacity (ANC) greater than 50 *µeq/L*, a level which poses no threat to brook trout (although levels as low as 50 µeq/L may still be too acidic for most other fish species). This category includes streams on limestone bedrock, which have the highest ANC values, and are at no risk of acidification.

Methods

To predict the status of Virginia's headwater brook trout streams under different acid deposition scenarios, this analysis used detailed water chemistry data from 60 Virginia trout stream sites collected each quarter from 1989 to 1992. The well-accepted "MAGIC" (Model of Acidification of Groundwater In Catchments) computer model was used to analyze this data to predict future stream chemistry, and in particular the acid/base status of those 60 streams under the chosen acid deposition scenarios. The MAGIC model uses soil chemistry and precipitation chemistry to predict stream chemistry. It can be used to estimate both the past and future acid-base status of streams and likely effects on fish communities. The MAGIC model was the principal model used by the National Acid Precipitation Assessment Program (NAPAP) to estimate the potential future damage to lakes and streams in the eastern United States, and has also been used to predict brown trout responses to acidification in Norway and Scotland.

The 60 streams were chosen from 344 brook trout streams included in a 1987 water quality survey of the state's undisturbed brook trout streams. Although no one is certain of the total number of brook trout streams in the state, estimates by the Virginia Department of Game and Inland Fisheries indicate that the 344 streams represent approximately 80 percent of the historical total. Because the goal was to evaluate the effects of deposition on relatively undisturbed streams, watersheds with significant development or other disturbances that would alter stream chemistry were not included in the 1987 survey. Based on geological data, the subset of 60 was chosen to be representative (in terms of acid sensitivity) of all the mountain brook trout streams in Virginia. The results of the analysis were then used to predict the future status of the general population of streams in the state.

About 10 percent of Virginia trout streams have carbonate (limestone) bedrock in their watersheds, and therefore they are not sensitive to acidification; these

Chart 1

Historical and Current Status of Undisturbed Forested Watersheds

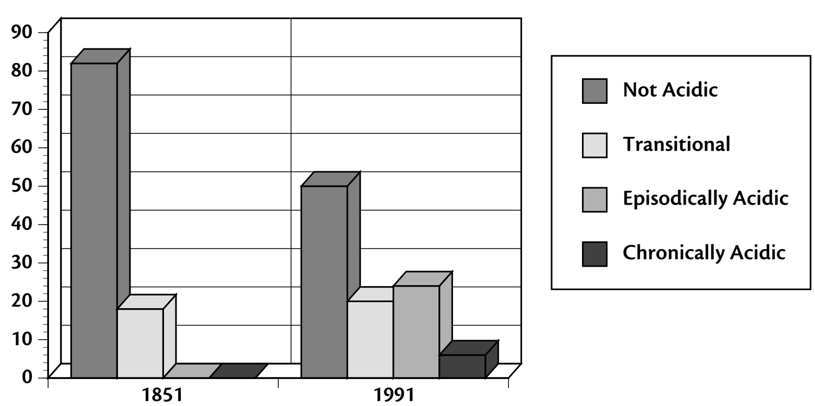
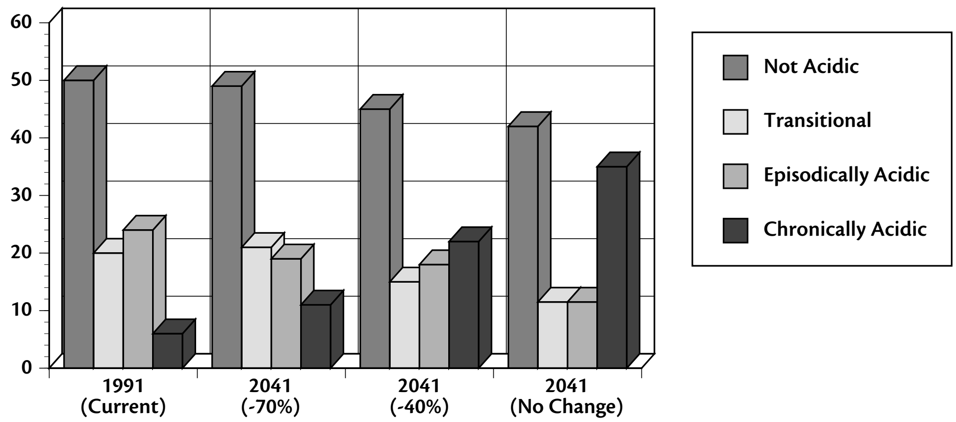


Chart 2

Effects of Future Deposition Scenarios on Subject Streams



streams were not included in this analysis. About 20 percent have substantial direct human disturbance in the watershed (housing, agriculture, etc.); streams in this category were also excluded because their stream chemistry may be affected by anthropogenic factors other than atmospheric deposition. Of the 344 streams sampled in 1987, 40 fell into one of these two causes for exclusion, and the results from the 60 streams in this analysis can therefore be applied directly to 304 streams. This represents approximately 70 percent of all the historical brook trout streams in the state, and approximately 90 percent of the population of brook trout streams without significant direct human disturbance.

The landscape/bedrock geology categories for the 60 streams in this analysis were Blue Ridge basaltic (4 streams), Blue Ridge granitic (18 streams), Blue Ridge siliciclastic (16 streams), and Valley and Ridge siliciclastic (22 streams). Basaltic, granitic, and siliciclastic (such as sandstone or shale) bedrock types represent a series of increasing acid sensitivity.

Findings

The MAGIC model was first used to evaluate the historical vs. current (as of 1991) condition of these streams. The results indicated that about 82 percent of pre-industrial forested watersheds in Virginia would be in the "not acidic" category, and the remaining 18 percent could be classified as "transitional." The assessment shows that currently only 50 percent of the population of streams on non-limestone bedrock are "not acidic." An estimated 20 percent of the streams have ANC values between 20 and 50 μeq/L, and fall into the "transitional" category. Another 24 percent experience regular episodic acidification at levels harmful to brook trout and other aquatic species. The remaining 6 percent of streams are "chronically acidic" and cannot host brook trout or any other fish species.

Although nitrate deposition can be an important factor in acid precipitation, recent research has demonstrated that acidification of Virginia's headwater streams is currently being driven by sulfate deposition, and this assessment considered three scenarios of future sulfate deposition:

- **Scenario 1:** Constant deposition at 1991 levels.
- **Scenario 2:** 40 percent reduction from 1991 levels.
- **Scenario 3:** 70 percent reduction from 1991 levels.

For the 40 and 70 percent scenarios, it was assumed that sulfate deposition would be reduced linearly for 20 years beginning in 1991, and that levels would remain constant for the following 30 years (through 2041). The acid neutralizing capacity of each stream was considered at two points in time, year 2011 and year 2041. The former represents the responses of the streams at the completion of the deposition reductions, and might be considered the direct effect of the assumed reduction. The later year is included to examine any delayed effects that might occur as a result of continued deposition at the reduced levels, and gives a more accurate picture of the ultimate condition of these streams.

Scenario 1: No Reduction. Although it is likely that Virginia watersheds will see some level of sulfate reductions under the Clean Air Act, it is worthwhile to look at what would happen if the current deposition levels were allowed to continue. At constant deposition rates, the number of chronically acidic streams would jump from 6 percent currently to 35 percent by the year 2041. This represents approximately 88 streams (29 percent of 304) that would become effectively dead ecologically. The number of streams in the "not acidic" category would drop from 50 percent currently to 42 percent in the year 2041.

Scenario 2: 40 percent Reduction. According to this study's results, reducing sulfate deposition by 40 percent relative to 1991 levels by 2011 would still result in too much acid for some streams in the currently "not acidic" category to neutralize, resulting in a further decrease in the percentage of streams suitable for healthy populations of brook trout, from 50 percent currently to about 45 percent in the year 2041 (Figure 3). Under a 40-percent-reduction scenario, the "chronically acidic" streams would increase from 6 percent currently, to about 22 percent in 2041 (Figure 5).

Scenario 3: 70 percent Reduction. It appears that a 70 percent reduction in acid deposition is necessary to retain about 50 percent of the streams in the "not acidic" category (Figure 3). Nevertheless, even a 70-percent reduction will allow the number of "chronically acidic" streams (Figure 5), which are not suitable for brook trout, to increase from about 6 percent of the population currently, to about 11 percent in 2041 (versus 0 percent in 1851).

Background

"Acid Rain" is a term in common use which implies the deposition of acid materials in wet precipitation (rain, snow, fog, cloud) as well as in the dry precipitation of dust and gases; scientists prefer to use "acid deposition" to describe this process, because it explicitly includes dry as well as wet deposition. Indeed, deposition of acid materials in dry form is often equal to the amount deposited in wet form. Acid deposition is responsible for the documented loss of hundreds of fish populations in Europe and North America.

Acid Deposition Effects on Fish

The effects of acid deposition on fish involve the interaction of complex processes operating at a range of different spatial scales, from atmospheric transport to cell membrane transport. Nevertheless, the interaction of these processes can be summarized in five major points.

1. ***The source of the acid: fossil fuels***
   The burning of fossil fuels releases sulfur and nitrogen oxides into the atmosphere, where they are converted to sulfuric and nitric acids. These acidic materials may be transported long distances in the atmosphere before they are deposited in wet or dry form on landscapes.

2. ***Landscapes differ in sensitivity, based on geology.***
   Whether or not acidic deposition produces negative effects on the animals living in streams and lakes depends largely on the bedrock geology of their catchments. In landscapes underlain by limestone (carbonate bedrock), which provides substantial buffering of acidity, negative effects due to acidification are neither expected nor seen in water bodies. Basaltic, granitic, and siliciclastic (such as sandstone) bedrock types represent a series of decreasing levels of buffering capacity, such that modest amounts of acidic deposition produce conspicuous negative effects in sandstone catchments. Catchments composed of multiple bedrock types naturally show intermediate degrees of sensitivity to acidification, dependent on available local buffering capacity. Since buffering capacity ultimately depends on the weathering of acid-neutralizing material from the bedrock, hard bedrock types produce less buffering capacity for streams than soft bedrock types. Mountains by their very nature are more resistant to weathering than surrounding lowlands (that's why the mountains are still there), so mountain streams and lakes are usually the most sensitive to acidification due to the lower weathering rate and buffering capacity of their catchments. In contrast, large valley streams and lakes are the recipients of upstream weathering products, and are often less sensitive to acidification as the result of their greater buffering capacity.

   If the bedrock types underlying a given landscape unit are a heterogeneous mixture in terms of their acid-neutralizing capacity, there will be different responses among the water bodies and fish communities, even under identical acidic deposition regimes.

3. ***The role of aluminum: metabolic poison***
   Aluminum is the most abundant metal on the earth's surface, and the third most abundant element. It is non-toxic and insoluble under acid-neutral conditions, but very toxic to fish and other aquatic species under acidic conditions. Unfortunately, the solubility of aluminum increases exponentially as pH falls below 5.6; its maximum toxicity occurs at about pH 5.0. The deposition of acids results in the release of aluminum from soils and its transport in solution to streams and lakes. Both the aluminum and the hydrogen ion (derived from sulfuric and nitric acids) are toxic to fish, but in most streams and lakes the aluminum is the primary lethal agent; fish can survive more acidic conditions (i.e., lower pH) in the laboratory in the absence of aluminum.

4. Site of toxic action: fish gill

The site of the toxic action of both the hydrogen ion and aluminum is the fish gill. The gill is a complex organ responsible for oxygen and carbon dioxide exchange, as well as maintaining the proper salt and water balance in the fish's body. It is this latter function which is always compromised by acid and aluminum stress; respiration is also compromised at higher concentrations of aluminum.

Freshwater fish maintain salt (sodium chloride) in their blood at concentrations similar to those in humans and most other vertebrates. The proper functioning of most body cells, and especially blood cells in this context, depends on keeping salt concentrations in body fluids within rather narrow limits. Since salt concentrations in the blood are much higher than the water in which they swim, fish constantly lose a small amount of sodium and chloride from the blood by passive diffusion across the thin skin of the gills. The lost sodium and chloride are replaced by an energy-requiring process (active transport) using biochemical "pumps" in the gill membranes which transport sodium and chloride from low concentration in the external stream water to higher concentration in the blood.

Aluminum and hydrogen ions poison the biochemical pumps which transport sodium and chloride into the body; they also weaken the junctions between gill cells, making them leak more sodium and chloride than they otherwise would. The rapid loss without replacement of sodium and chloride produces a cascade of negative physiological effects in the fish's body.

It is a common misconception that stream acidification causes acidification of fish blood, with negative effects on oxygen transport. This does not occur at the observed levels of acidification in nature which produce fish death.

5. The cause of death: circulatory collapse secondary to electrolyte imbalance

The key indicators of incipient mortality under acute acid and aluminum stress are the concentrations of sodium and chloride in the blood plasma. When either or both (sodium and/or chloride) fall more than 30% below normal, death occurs within hours.

The proximal cause of death is ionic dilution of the blood plasma. This causes blood and body fluid disturbances which ultimately kill the fish through circulatory collapse. Under normal conditions, plasma ionic (electrolyte) concentrations and body cell ionic concentrations are in equilibrium. Under acute acid stress, ions are lost more rapidly from the blood plasma than from blood and muscle cells; as a result, there is an osmotically-driven shift of water to the cells from the plasma. Blood plasma volume may drop as much as 30%; at the same time, the red cells swell due to the osmotically-driven shift of water from the plasma; the result is a doubling of blood viscosity. The heart is unable to circulate this much thicker blood at a rate sufficient to supply oxygen to body tissues, including the heart itself, so the fish dies of circulatory collapse secondary to ionic imbalance.

Acid Rain in the Southern Appalachians

The present analysis focuses on 60 trout streams on non-limestone bedrock in Virginia, and was designed to be readily extrapolated to the larger population of all such trout streams in the state. Because of the strong relationship between bedrock geology and ANC, it is reasonable to consider the results in the context of the entire population of trout streams in the Southern Appalachians. The results of the Southern Appalachian Assessment (SAMAB, 1996), plus additional relevant material from other sources, can provide such a context. The area of analysis for the Southern Appalachian Assessment (SAA) was the Southern Appalachians, including parts of seven states (Virginia, West Virginia, North Carolina, South Carolina, Georgia, Alabama, and Tennessee), 135 counties, and approximately 37 million acres.

Water Resources and Biodiversity in the Southern Appalachians

Permanent water is significant in the Southern Appalachians. The mean density of streams and river channels is more than 12 feet of length per acre of land, and river and lake surfaces are at least 1.5% of the total surface area of the SA, both regarded as high values. Waterbodies are regarded by residents as extremely important, and multiple uses include drinking water, fishing, other aquatic recreation, transportation, livestock watering, irrigation, flood control, hydroelectric power, wildlife observation, and waterfront human habitation (SAMAB, 1996).

There is general agreement that water quality has improved in the Southern Appalachians since the adoption of the Clean Water Act in 1972; however, the rate of improvement has recently slowed since most municipal and industrial discharges now control pollution, and the remaining sources (storm water runoff, sediment contamination, acid deposition, and spills) are more difficult and expensive to control. Future water quality in some areas is likely to be challenged by population growth (SAMAB, 1996).

The Southern Appalachian Mountain zone ecosystem is widely regarded as one of the most diverse ecosystems in the temperate zone (SAMAB, 1996). Fish diversity in the Southeast region is quite high. There are about 950 freshwater fish species in North America (Jenkins and Burkhead, 1993), of which about 485 species can be found in the Southeast, and about 350 species can be found in the Southern Appalachians south of the Roanoke and New Rivers (Walsh et al., 1995). The total numbers of fish species by state in the region is impressive : 107 in Maryland, 164 in West Virginia, 199 in North Carolina, 210 in Virginia, plus the richest state freshwater fish fauna in the country, 307 in Tennessee (Jenkins and Burkhead, 1993). The absence of glaciation and a relatively warm climate, together with general latitudinal effects and abundant rainfall (35-100 inches per year), contribute to this regional diversity (Adams and Hackney, 1992). For probably the same reasons, habitat and intraspecific genetic diversity is also high (SAMAB, 1996).Thus, from a biodiversity point of view, the Southeast represents a unique national resource for aquatic animals. The SAA concluded that 70% of sampled locations show moderate to severe fish community degradation, and that about 50% of the stream miles in West Virginia and Virginia show habitat impairment.

Trout in the Southern Appalachians

Acidification is a conspicuous threat to three trout species in the region: brook trout, brown trout, and rainbow trout. Of the three, native brook trout are the most acid tolerant, brown trout introduced from Europe are intermediate in acid tolerance, and rainbow trout introduced from the western US are most sensitive. The phrase “wild trout” in this context refers to reproducing populations of any of the three.

Of the 37.4 million acres in the Southern Appalachian region, 14.6 million acres (39%) are in the range of wild trout, with up to 33,000 miles of potential wild trout streams. The distribution of trout stream mileage percentage by state is 39% in Virginia, 32% in North Carolina, 10% in Georgia, 10% in Tennessee, 7% in West Virginia, 2% in South Carolina, and 0% in Alabama. Trout are also found in a few areas outside the Southern Appalachians in the southeast, and in a few Southern Appalachian lakes. Twenty-six reservoirs greater than about 1 square mile in the Southern Appalachians contain trout; 15 are stocked, primarily with rainbow trout, and eight have incidental wild trout populations from past stocking or tributary streams. Trout may occur in three additional private reservoirs.

Of the 33,000 miles of potential wild trout streams, 24% are in Forest Service lands, 5% are in National Park Service lands, and about 70% are in private lands. About 7% are in roadless areas, and 3% are in wilderness areas. An additional 1,337 miles of stocked trout streams are outside the wild trout boundary; an unknown portion of the streams in the wild trout range are also stocked.

Trout populations are regarded by residents as one of the region’s most valuable aquatic natural resources. The status of trout populations and trout habitat is a major concern to the public in the Southern Appalachians. Sources of concern generally fall into three categories: 1) fisheries for native brook trout and introduced rainbow and brown trout; 2) “existence value” for brook trout, regarded as a beautiful and intrinsically valuable native species; and 3) the presence of trout as indicators of high water quality (SAMAB 1996).

Originally, brook trout were distributed down the spine of the Southern Appalachian Mountains through western Virginia and North Carolina, and eastern Tennessee to northwest North Carolina and northeastern Georgia, which is the southern limit of the species (MacCrimmon and Campbell 1969). Stocking programs have not greatly extended this range, despite brook trout stocking in the majority of streams in the Southern Appalachians. Rainbow and brown trout were introduced into the region in the late 19th and early 20th centuries, and continue to be stocked. Introduction of other salmonids has not been notably successful.

In the Great Smoky Mountains and neighboring areas of Tennessee, introduced rainbow trout and brown trout have been successful at lower elevations. Between 1900 and the present, brook trout have been increasingly restricted to upper stream reaches, with up to several kilometers of coexistence with rainbow trout and brown trout (Larson and Moore, 1985). In the Shenandoah National Park and adjacent areas, brown trout are rare, rainbow trout are only marginally successful, and brook trout are abundant (Mohn and Bugas, 1980). Coexistence of trout species is less common to the north.

Two putative strains of brook trout have been identified in the Southern Appalachians through modern genetic methods: a southern form and a northern form introduced through stocking; in some locations, hybrids occur (McCracken et al. 1993). Unfortunately, stocking records are poor and do not permit identification of localities where northern brook trout were introduced (Kriegler et al. 1995).

Acid Deposition in the Southern Appalachians

The Mid-Atlantic Highlands has one of the highest rates of acid deposition in the country (Herlihy et al. 1993, 1996), and the region most at risk from continued acid deposition is located along the Appalachian Mountain chain from the Adirondacks in New York to the Southern Blue Ridge in Georgia. (NAPAP 1990). The most sensitive receptors of acid deposition are aquatic ecosystems and high-elevation red spruce forests.

Mountains persist in the landscape because their bedrock is resistant to weathering, so it is not surprising that they yield streams with lower ANC than surrounding lowlands. The more base-rich valley bottoms have more buffering capacity and richer soils and are more likely to have been cleared for agriculture, whereas the poorer soils of the mountains in the Southern Appalachians are more likely to be forested. Consequently, the forested mountain streams which are the typical habitat of native trout are likely to be acid-sensitive.

The sensitivity of a landscape and its waterbodies to acid deposition is determined primarily by bedrock geology. Soils derived from quartz sandstone (siliciclastic) produce streams with little or no acid neutralizing capacity (ANC). Watersheds underlain by granite, basalt or limestone produce streams with ANC in an increasing sequence. Thus bedrock geology maps can be used to identify watersheds sensitive to acid deposition (Cosby et al.1991; Herlihy et al. 1993).

The SAA used a generalized bedrock geology map (Peper et al. 1995) suitable for regional estimates of acid deposition sensitivity, but too generalized for site-specific applications. The result was a GIS-generated map of geographic areas in the Southern Appalachians that have low, high or medium sensitivity to acid deposition; this was combined with a map of stream reaches to produce general, region-wide estimates of stream miles in each sensitivity category. The results are potentially alarming. About 27% of all trout stream miles are in Southern Appalachian areas that are moderately vulnerable to acidification, and approximately 59% of wild trout streams are in areas that are highly vulnerable to acidification.

The SAA report presents relative sensitivity, but not current acidification status, which depends in addition on the amount of acid deposition to a local watershed. Nevertheless, it is clear from other studies that acidification of streams has actually occurred. This has been demonstrated in several local areas of the Southern Appalachians.

The findings of the Fish in Sensitive Habitats Project (Bulger et al. 1995; SAMAB 1996) clearly demonstrated that both chronic and episodic acidification are occurring in Shenandoah National Park (SNP) streams. Negative biological effects in fish species richness, population density, condition factor, age, size, plus mortality of brook trout due to both chronic and episodic acidification, have all been observed. This study on the effects of acidification on fish was initiated as a result of a 14-year record of decreasing pH in some SNP streams. Data from the Great Smoky Mountains National Park (GSMNP) in Tennessee and North Carolina indicate poor buffering capacity for most of the Park's streams, and low pH in higher elevations. Significant historical decline in ANC as a result of chronic acid deposition is indicated (Kaufmann 1988, National Stream Survey). A well studied example of a damaged ecosystem is the St. Mary's River in Virginia. The fish and aquatic insect fauna of the St. Mary's were surveyed in the 1930s and again in 1988. Significant deterioration in the fauna from acidification effects were apparent in the later survey(Mohn et al., 1989).

Sulfur and Nitrogen as Acidifying Pollutants

Much of the acid deposition in the past was dominated by sulfur deposition, but recent research indicates a growing importance of nitrogen deposition as a component of acidification. 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, nitrate appears as an acidifying pollutant in streams; like sulfate, it also accelerates the depletion of base cations from soils.

In recent years the European gypsy moth, an introduced pest with few native predators, has invaded the Southern Appalachians. The caterpillars of this species can defoliate large forest areas, converting leaves into waste containing highly mobile nitrate; this can exacerbate acidification, especially episodic acidification (Webb et al., 1995). Other insect pests may produce similar effects; most VA and WVA wild trout steams are in counties that have reported hemlock woolly adelgid infestation, which may result in leaf loss and tree death.

The Future

Acidification effects, including ANC and pH decreases plus negative effects on fish, are likely to continue in the Southern Appalachians under present deposition scenarios (Elwood et al. 1991; Webb et al. 1994). The unglaciated soils of the Southern Appalachians retain more sulfate than the glaciated soils further north. This causes both a delay in acidification of streams, and delayed recovery from acidification if sulfur deposition is stopped, as the sulfur retained in soils leaches out over time. Herlihy et al. (1993) concluded that streams would continue to lose ANC as Southern Appalachian soils approach sulfur saturation, when all deposited sulfate will appear relatively rapidly in streams, versus the present condition in which a fraction of the sulfate is stored temporarily in catchment soils. Nitrate deposition exacerbates this problem.

Methods

DATA SOURCES

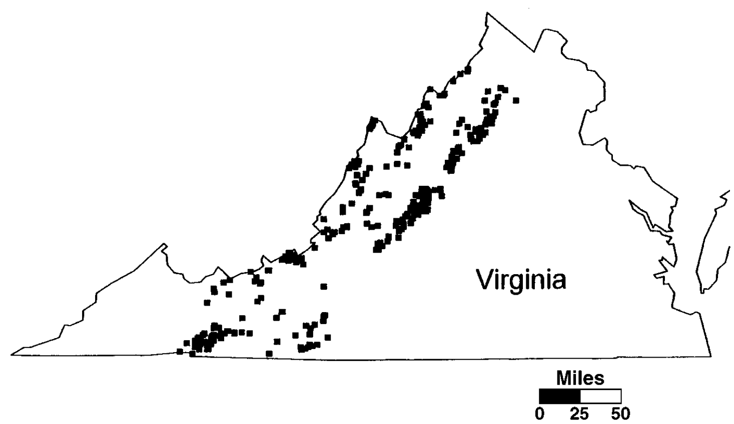
Regional Stream Sites

Regional water quality data were obtained from two closely coordinated research and monitoring programs at the University of Virginia that focus on the forested mountain watersheds of western Virginia: the Virginia Trout Stream Sensitivity Study (VTSSS) and the Shenandoah Watershed Study (SWAS).

VTSSS was established to obtain continuing information concerning the acid-base status of the mountain-headwater streams in western Virginia that support native brook trout. The VTSSS program was initiated in the spring of 1987, when stream-water samples were collected for 344, or about 80%, of the region's identified native brook trout streams (Map 1). Following the 1987 survey, a physiographically representative subset of this biologically defined stream population was selected for long-term water-quality monitoring. The VTSSS long-term monitoring program presently includes 55 streams that are sampled on a quarterly basis. Most of these streams are located on National Forest lands.

Map 1

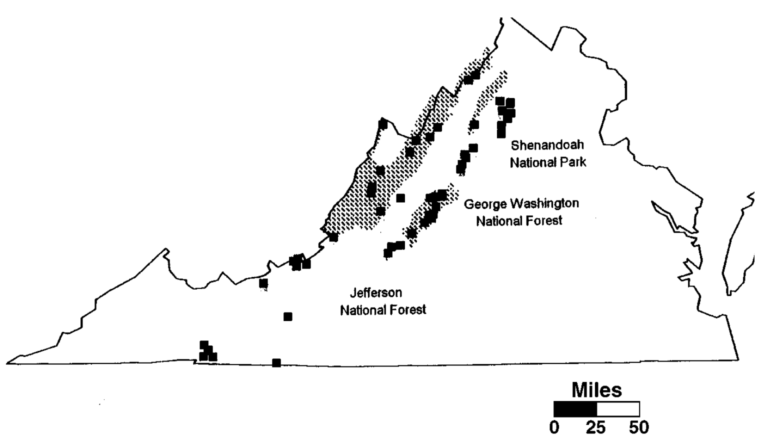
Distribution of Native Brook Trout Streams Sampled in the 1987 VTSSS Survey



SWAS was established to improve understanding of processes that determine biogeochemical conditions in the watersheds of Shenandoah National Park. The SWAS program was initiated in 1979, when weekly stream-water sampling was begun on two streams. The SWAS long-term monitoring program presently includes six streams that are sampled on a weekly basis and nine streams that are sampled on a quarterly basis (Map 2). The SWAS quarterly sampling is scheduled to coincide with VTSSS quarterly sampling. In both the VTSSS and SWAS programs,

Map 2

Distribution of Long -Term Study Streams Used for Scenario Analysis

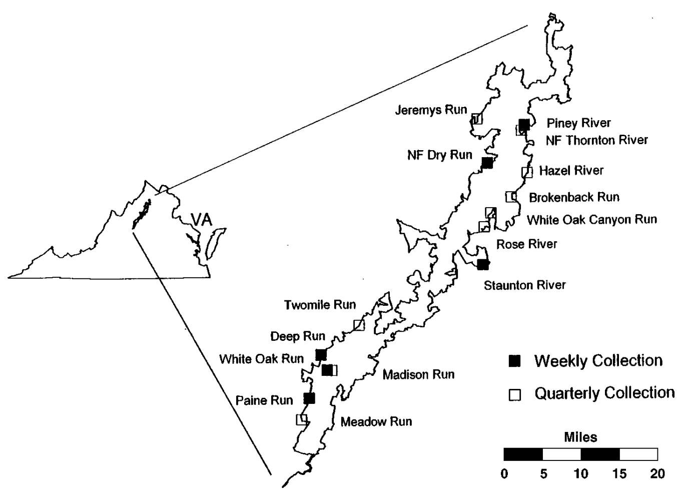


stream samples are taken during last weeks of January, April, July and October.

The water quality data used for this assessment includes quarterly data obtained by combining the VTSSS and SWAS data (the data obtained from the SWAS weekly sampling sites was sub-sampled to provide quarterly data). This resulted in 70 sites for which quarterly water quality were available for a period of five years of continuous monitoring data (the data necessary for model calibration; see discussion of MAGIC model below). Streams that have carbonate as the dominant bedrock type in their catchments were excluded, as these streams are not susceptible to acidification. Ten streams were deleted by these criteria. The remaining 60 streams selected for the study are geographically representative of the region of interest (Map 3).

Map 3

Shenandoah National Park
Stream-Water Sampling Sites



The Virginia Department of Game and Inland Fisheries has estimated that approximately 443 streams in Virginia harbor reproducing populations of brook trout. Although the exact total of native brook trout streams in Virginia is uncertain, the conclusions of this assessment (based on the sample population of 60 streams) apply to at least 70% of those streams. Approximately 10% of the total population of streams have limestone bedrock in their watersheds, and therefore are not sensitive to acidification. Another approximately 20% have substantial direct human disturbance in the watershed (housing, agriculture, etc.). The fish populations and chemistry of these streams may be affected by anthropogenic factors other than atmospheric deposition, making it impossible to reliably assess the affects of acid deposition on them. For that reason, such streams have been generally excluded from the VTSSS. The subsample of 60 streams used in this analysis can thus readily be extrapolated to a population of 304 streams, which represents approximately 70 percent of the state's historical trout streams and 90 percent of the population of brook trout streams in watersheds without substantial direct disturbance.

Water Quality Data

Samples collected for the VTSSS and SWAS programs are analyzed for sulfate, nitrate, chloride, hydrogen ion, calcium, magnesium, potassium, and sodium, ANC and pH (Table 1). Laboratory analyses are performed at the Department of Environmental Sciences of the University of Virginia. Detailed analytical and quality assurance methods and descriptions are posted at the SWAS-VTSSS website (http://wsrv.clas.virginia.edu/~swasftp).

For this project ANC is defined as the charge balance ANC: ANC = SBC – SAA, where SBC is the sum of base cation concentrations (calcium, magnesium, potassium, and sodium) and SAA is the sum of acid anion concentrations (sulfate, nitrate and chloride), with all concentrations in µeq/L.

Annual output fluxes are needed for the modeling and assessment analyses (rather than individual quarterly concentrations). Stream discharge measurements are, in turn, needed for calculation of fluxes from measured concentrations, but none of the quarterly sites has discharge data available. Thus, it was necessary to estimate quarterly stream discharge for use in calculating the annual fluxes. A number of stream gauging stations in western Virginia were selected which were geographically and elevationally representative of the quarterly catchment sites. Average quarterly stream discharges were determined for each gauging station during 1985 to 1994. The average quarterly discharges for all of the gauging stations were then further averaged to provide a single set of quarterly discharges applicable to the region. These were used for all streams in the exercise.

Landscape Classification

The forested mountain watersheds that provide habitat for brook trout in western Virginia are geochemically more sensitive to the effects of acidic deposition than other landscape categories that comprise the Southern Appalachian region (such as valley floors, agricultural lands, etc.). Among forested mountain watersheds, however, there is a still a range of sensitivity to acidic deposition, and the landscape can be further stratified by geologic category. This stratification provides the landscape classes needed to associate soil properties with each of the selected streams (a prerequisite for model calibration as described below). The assignment of each of the study streams to a landscape class also allows extrapolation of results from the study streams to the entire regional population of trout streams (using the regional weighting scheme described below).

The landscape classes used here are based on an analysis of stream water quality in relation to watershed geology. The geographic area covered includes the Blue Ridge Mountains and the Ridge and Valley Physiographic Provinces of western Virginia. Within these provinces there are a number of distinct bedrock types that can be used to classify the streams based on the dominant bedrock type within their catchments. Previous analyses by Lynch and Dise (1985) and Webb et al. (1994) have established that a close relationship exists between stream water quality and bedrock type for catchments in the mountains of Virginia. In particular, Webb et al. (1994), identified six geological classes that served to account for spatial variation in ANC among the VTSSS and SWAS quarterly sampling sites (Figure 3). The six classes described by Webb et al. (1994) were reduced to four classes for this project. Streams in the carbonate class were not included in this analysis. An additional simplification was achieved by defining a single siliciclastic class for the Valley and Ridge Provinces which includes both the "siliciclastic" and "minor carbonate" classes (the minor carbonate catchments are actually predominantly siliciclastic with minor carbonate inclusions).

The landscape classes adopted for this study and the number of selected stream sites within each of the classes are thus: Blue Ridge siliciclastic (16 streams); Blue Ridge granitic (18 streams); Blue Ridge basaltic (4 streams); and Valley and Ridge siliciclastic (22 streams).

Atmospheric Deposition

Atmospheric deposition used for this assessment was the total deposition flux of the major ions to each catchment. Total deposition consists of three components:

Total deposition = wet deposition + dry deposition + cloud/fog deposition.

Wet deposition is the flux of ions occurring in precipitation. Dry deposition results from particulate and gaseous fluxes. Cloud and fog inputs are also important at all sites.

Wet deposition of ions and precipitation volume were estimated for watersheds associated with each of the 60 streams using the model of Grimm and Lynch (1997). Regional precipitation and wet deposition data were interpolated to provide estimates for each of the 60 study sites. Weighted least-squares regression techniques were used to account for the influence of topography and elevation on precipitation. The solutes included in these wet deposition estimates were sulfate, nitrate, chloride, hydrogen ion, calcium, ammonium, magnesium, potassium, and sodium.

Wet deposition measurements are available at the University of Virginia for two sites in the study area, White Oak Run and North Fork Dry Run, both in the Shenandoah National Park. The wet deposition estimates for these sites extrapolated from the Grimm and Lynch (1997) model agree well with the observed wet deposition for sulfate, nitrate and ammonium ions (ratio of measured to estimated wet deposition = 1.0 for sulfate, 1.0 for nitrate and 0.8 for ammonium ions), justifying the application of the extrapolated wet deposition estimates to the 60 streams in this study.

There are no observations of dry deposition or cloud/fog deposition for any stream included in this study. Estimates of dry deposition fluxes and cloud/fog deposition fluxes of sulfate and nitrate have, however, been published for two sites in the Shenandoah National Park. Dry deposition has been estimated for Big Meadows, VA, a part of the National Dry Deposition Network (NDDN) established in 1986. The network currently operates as a component of the Clean Air Status and Trends Network (CASTNet). Clarke et al. (1997) describe the 50 station CASTNet dry deposition network and give estimates of dry deposition for the year 1991. Estimates of annual cloud/fog deposition fluxes are available for North Fork Dry Run for the years 1986-1987 as part of the output of the Mountain Cloud Chemistry Project (MCCP; Vong et al., 1991). The period of time covered by the MCCP data does not directly overlap the period included in this study (1989-1992), but it is sufficiently close in time that the data can be reliably used.

The dry deposition and cloud/fog deposition fluxes measured at these two sites are assumed to be approximately the same at the White Oak Run and North Fork Dry Run sites, where wet deposition was measured. This assumption allows calculation of total deposition for those two sites. The ratio of estimated total deposition to the observed wet deposition was then calculated for sulfate, nitrate and ammonium ions. These ratios (called the dry deposition factor) were then used for all 60 streams in this study to calculate total deposition of sulfate, nitrate and ammonium ions from the estimated wet deposition data. The dry deposition factors used were: 2.0 for sulfate, 2.5 for nitrate and 2.5 for ammonium. The values of these factors are consistent with published values used in previous studies in this region (Cosby et al., 1985b).

Deposition History

The modelling requires a temporal sequence of anthropogenic deposition. The pattern of historical deposition and the total loading of acidic deposition determine how the model simulates responses to future changes in loading.

Such long-term, continuous historical deposition data do not exist. The approach adopted for this project was to use historical emissions as a surrogate for deposition. The emissions for each year in the historical period are normalized to emissions in the reference year (the year for which observed data are available). This produces a sequence of scalar numbers (scale factors) that have a value of 1.0 for the reference year. Values of the scale factor for other years are (by definition) the fractions of reference year emissions that occurred in that year (e.g., if emissions in 1950 were 86% of what they were in the reference year, then the scale factor for 1950 is 0.86).

Using this scaled sequence of emissions, historical deposition was estimated by multiplying the total deposition measured (or estimated) for the 1991 (the reference year in this project) by the emissions scale factor for any year in the past to obtain deposition at that year in the past. An implicit assumption is that the relationship between emissions and deposition is unchanged over time. Thus, if emissions in 1950 were 86% of the emissions in the reference year, then deposition in 1950 is assumed to be 86% of deposition in the reference year.

A key assumption in this procedure is that the "source" area for the emissions used to scale deposition at a site can be correctly identified. Emissions data for both SO_2 and NO_x are available on a state-by-state basis back to the turn of the century. In NAPAP, yearly emissions from all states comprising an EPA administrative region were added together to produce a "regional" emissions history. All sites for modelling that were situated within a particular EPA region used that regional emissions history. That approach was adopted for this project, and deposition histories for the streams were scaled using the scaled sequence of SO_2 and NO_x emissions in the EPA mid-Atlantic region.

Soil properties

Soil data for use in the model application were available for a total of 18 sample sites located in five forested mountain watersheds in western Virginia. Soil data for four of the watersheds were obtained in 1986 and 1987 through the Direct-Delayed Response Program (DDRP), a component of the National Acid Precipitation Assessment Program. The methods of soil sampling and analysis used for the DDRP are described in Church et al. (1992). Soil data for the additional watershed were obtained through the SWAS program using methods closely comparable to those of the DDRP.

The soil sample sites were assigned to each of the geologically defined landscape classes. The number of soil sample sites available for each class were: Blue Ridge siliciclastic (9); Blue Ridge granitic (3); Blue Ridge basaltic (3); and Valley and Ridge siliciclastic (3).

The soils data for the individual soil horizons at each sampling site were aggregated based on horizon, depth, and bulk density to obtain single vertically aggregated values for each site. The soil parameters used in the model included soil depth, bulk density, pH, cation-exchange capacity, and exchangeable bases on the soil (calcium, magnesium, potassium, and sodium).

THE MAGIC MODEL

The potential effects of sulfur deposition on surface water quality have been well-studied throughout the United States, particularly within EPA's Aquatic Effects Research Program (AERP), a component of the National Acid Precipitation Assessment Program (NAPAP). Major findings were summarized in a series of State of Science and Technology Reports (e.g., Sullivan 1990, Baker et al. 1990) and the final NAPAP policy report, the 1990 Integrated Assessment (NAPAP 1991). The major tools available for evaluating the potential response of aquatic resources to changes in atmospheric deposition of sulfur are mathematical models. One of the prominent models developed to estimate acidification of lakes and streams is MAGIC (Model of Acidification of Groundwater In Catchments, Cosby et al., 1985a-c). MAGIC was the principal model used by the National Acid Precipitation Assessment Program (NAPAP) to estimate future damage to lakes and streams in the eastern United States (NAPAP 1991, Thornton et al. 1990). The validity of the model has been confirmed by comparison with estimates of lake acidification inferred from paleolimnological reconstructions of historical lake changes in pH (Sullivan et al. 1991, 1996) and with the results of several catchment-scale experimental acidification and de-acidification experiments (e.g., Cosby et al. 1995, 1996).

Model Description

MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on surface water chemistry. The model simulates soil solution chemistry and surface water chemistry to predict the monthly and annual average concentrations of the major ions in these waters. MAGIC consists of: 1) a section in which the concentrations of major ions are assumed to be governed by simultaneous reactions involving sulfate adsorption, cation exchange, dissolution-precipitation-speciation of aluminum and dissolution-speciation of inorganic carbon; and 2) a mass balance section in which the flux of major ions to and from the soil is assumed to be controlled by atmospheric inputs, chemical weathering, net uptake and loss in biomass and losses to runoff. At the heart of MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change of surface water acidity thus depend both on flux factors and the inherent characteristics of the affected soils.

Cation exchange is modeled using equilibrium (Gaines-Thomas) equations with selectivity coefficients for each base cation and aluminum. Sulfate adsorption (the attachment of sulfate ions to soil particles) is represented by a Langmuir isotherm. Aluminum dissolution and precipitation are assumed to be controlled by equilibrium with a solid phase of aluminum trihydroxide. Aluminum speciation is calculated by considering hydrolysis reactions as well as complexation with sulfate and fluoride. Effects of carbon dioxide on pH and on the speciation of inorganic carbon are computed from equilibrium equations. Organic acids are represented in the model as tri-protic analogues. First-order rates are used for retention (uptake) of nitrate and ammonium in the catchment. Weathering rates are assumed to be constant. A set of mass balance equations for base cations and strong acid anions are included. Given a description of the historical deposition at a site, the model equations are solved numerically to give long-term reconstructions of surface water chemistry (for complete details of the model see Cosby et al., 1985 a-c, 1989).

Magic has been used to reconstruct the history of acidification and to simulate the future trends on a regional basis and in a large number of individual catchments in both North America and Europe (Lepisto et al., 1988; Whitehead et al., 1988; Cosby et al., 1989, 1990, 1996; Hornberger et al., 1989; Jenkins et al., 1990a-c; Wright et al, 1990, 1994; Norton et al., 1992).

Implementation

Atmospheric deposition and net uptake-release fluxes for the base cations and strong acid anions are required as inputs to the model. These inputs are generally assumed to be uniform over the catchment. Atmospheric fluxes are calculated from concentrations of the ions in precipitation and the rainfall volume into the catchment. The atmospheric fluxes of the ions must be corrected for dry deposition of gas, particulates and aerosols and for inputs in cloud/fog water. The volume of streamflow in the catchment must also be provided to the model. In general, the model is implemented using average hydrologic conditions and meteorological conditions in annual or seasonal simulations, i.e., mean annual or mean monthly deposition, precipitation and streamflow are used to drive the model. The model is not designed to provide temporal resolution greater than monthly. Values for soil and streamwater temperature, partial pressure of carbon dioxide in the soil, and streamwater and organic acid concentrations in soilwater and streamwater must also be provided.

As implemented in this project, the model is a two-compartment representation of a catchment. Atmospheric deposition enters the soil compartment and the equilibrium equations are used to calculate soil water chemistry. The water is then routed to the stream compartment, and the appropriate equilibrium equations are reapplied to calculate streamwater chemistry.

Once initial conditions (initial values of variables in the equilibrium equations) have been established, the equilibrium equations are solved for soil water and streamwater concentrations of the remaining variables. These concentrations are used to calculate the streamwater output fluxes of the model for the first time step. The mass balance equations are (numerically) integrated over the time step, providing new values for the total amounts of base cations and strong acid anions in the system. These in turn are used to calculate new values of the remaining variables, new streamwater fluxes, and so forth. The output from MAGIC is thus a time-trace for all major chemical constituents for the period of time chosen for the integration. Details of the numerical integration and a computer code for implementing the model are given by Cosby et al. [1984a].

Calibration Procedure

The aggregated nature of the model requires that it be calibrated to observed data from a system before it can be used to examine potential system response. Calibration is achieved by setting the values of certain parameters within the model which can be directly measured or observed in the system of interest (called "fixed" parameters). The model is then run (using observed atmospheric and hydrologic inputs), and the output (stream water and soil chemical variables, called "criterion" variables) are compared to observed values of these variables. If the observed and simulated values differ, the values of another set of parameters in the model (called "optimized" parameters) are adjusted to improve the fit. After a number of iterations, the simulated-minus-observed values of the criterion variables usually converge to zero (within some specified tolerance). The model is then considered calibrated. If new assumptions (or values) for any of the fixed variables or inputs to the model are subsequently adopted, the model must be re-calibrated by re-adjusting the optimized parameters until the simulated-minus-observed values of the criterion variables again fall within the specified tolerance.

The calibration procedure requires that soils, stream, and atmospheric deposition data be available for each stream. There are, however, no measurements of either soil properties or atmospheric deposition at each of the selected streams. The requisite data has been estimated for each site (see above) by: a) using model extrapolations of measurements for deposition; and b) assigning soil properties based on landscape classification of the stream. These estimates of the fixed parameters and deposition inputs are subject to uncertainties, therefore a "fuzzy" optimization procedure was implemented for calibrating the model. The fuzzy optimization procedure consisted of multiple calibrations of each catchment using random values of the fixed parameters drawn from the observed possible range of values, and random values of deposition from the range of model estimates. Each of the multiple calibrations began with (1) a random selection of values of fixed parameters and deposition, and (2) a random selection of the starting values of the adjustable parameters. The adjustable parameters are then optimized using the Rosenbrock (1960) algorithm to achieve a minimum error fit to the target variables. This procedure is undertaken ten times for each stream. The final calibrated model is represented by the ensemble of parameter values and variable values of the successful calibrations.

Calibrations are based on volume-weighted, mean annual fluxes for a given period of observation. The length of the period of observation used is not arbitrary. Model output will be more reliable if the annual flux estimates used in calibration are based on a number of years rather than just one year. There is a lot of year-to-year variability in atmospheric deposition and catchment runoff. Averaging over a number of years reduces the likelihood that an "outlier" year (very dry, etc.) is the primary data on which model forecasts are based. On the other hand, averaging over too long a period may remove important trends in the data that need to be simulated by the model. For the study here, the model was calibrated using 5 years of data (1989-1992 calendar years) to provide the volume weighted annual flux estimates for both deposition and runoff.

All 60 streams included in this project were successfully calibrated. Ten calibrations were attempted and at least 5 successful calibrations were achieved for each stream. Eight or more successful calibrations were obtained for 52 of the streams. For each stream, all successful calibration parameter sets were used for hindcast and forecast simulations. For example, if a given stream had 10 successful calibrations, the parameter sets for each of those calibrations were used in the model to reconstruct the historical changes in stream water quality (based on the assumed historical deposition pattern) and to forecast the future changes in water quality (based on four assumed future deposition scenarios, see below). There are, thus, for this example, 10 values for each water quality variable in every year of the historical reconstruction, and 10 values of each variable for each year of each of the future deposition scenarios.

The results discussed below are based on the median values of the simulated water quality variables for each stream for any given year. The use of median values for each stream assures that the simulated responses are neither over- or underestimates, but approximate the most likely behavior of each stream (given the assumptions inherent in the model and the data used to constrain and calibrate the model).

Regional Weighting Scheme

Estimates of the regional responses to changing deposition on water quality in trout streams in Virginia require a procedure whereby the responses derived for the 60 streams in this study can be scaled-up to represent the responses of the entire population of trout streams in Virginia. The 60 streams successfully calibrated are a subset of the 344 streams sampled in the 1987 Virginia Trout Stream Sensitivity Study. As discussed fully above, the results from these 60 streams can be applied to a population of 304 out of the original 344 streams. The results do not apply to streams that have significant amounts of limestone bedrock in their catchments and thus are not susceptible to acidification (an estimate 10 percent of all historical brook trout streams in Virginia), or that have substantial direct human disturbance in their catchments, such as houses or agriculture (an estimated 20 percent of the all Virginia trout streams). The regional population of interest for this study, therefore, comprises the 304 trout streams in Virginia that potentially can be (or have been) affected by changes in acidic deposition and for which the primary human disturbance is acidic deposition.

Regional estimates of stream responses were, therefore, derived using a weighting scheme based on: a) the number of calibrated streams in each of the bedrock classes used to stratify the data for this project; and b) the total number of VTSSS streams in each of these bedrock classes. For instance, 103 of the VTSSS streams occur on granitic bedrock while in this project 18 of those streams were calibrated and used for hindcasts and forecasts. A weight of 5.7 (= 103/18) is applied to the results of each of the 18 streams when statistical summaries are produced. The weights for streams in the other bedrock classes are: basaltic 6.25 (= 25/4); Blue Ridge siliciclastic 4.3 (= 69/16); Valley and Ridge siliciclastic 4.86 (= 107/22). Using this scheme, the results presented below in terms of percentages of streams thus refer to percentages of the entire regional population of 304 streams (not to percentages of the 60 streams actually calibrated).

Results

Forecast Scenarios

Three scenarios of future acidic deposition were considered in this study: constant deposition at 1991 levels and two levels of reduced deposition (40% and 70% reductions from 1991 levels). The scenarios are based only on changes in sulfate deposition; all other ions in deposition for each stream are assumed to remain constant into the future at 1991 levels. For each scenario, simulations were run for fifty years into the future (1991 - 2041). For the two scenarios assuming reduced deposition, the sulfate deposition reductions were implemented linearly over 20 years (1991 - 2011), with constant sulfate deposition at the reduced level assumed for the final 30 years of simulation (2011 - 2041).

Output from the future simulations are examined at two times, the years 2011 and 2041. The former represents the responses of the streams immediately at the completion of the deposition reduction and might be considered the "direct" effect of the assumed reduction. The latter year is included to examine any "delayed" effects that might occur as a result of continued deposition at the reduced levels.

Stream Classification

Results are presented as percentages of streams in four classes defined by the average annual (volume-weighted) mean value of stream ANC. The ANC ranges of the four classes were chosen because they represent thresholds for responses of fish (individuals and populations) to acidic conditions in streams (Table 1 and below).

"Not Acidic": ANC greater than 50 µeq/L

Streams in this classification have an average annual ANC which poses little threat to brook trout and little likelihood of storm-induced acid episodes lethal to brook trout. ANC in these streams typically remains above zero in all seasons and flow regimes. As a result, reproducing brook trout populations are expected if the stream has otherwise suitable habitat. It should be noted, however, that streams with ANC as low as 50 µeq/L are likely to host fewer fish species relative to streams with ANC above 200µeq/L, because most fish species are less tolerant of low pH than brook trout. ANC values below 200µeq/L are regarded as "sensitive" to acidification for general ecological purposes

Table 1

Acid Neutralizing Capacity (ANC) categories for brook trout response
(based on volume weighted annual average alkalinity)

µeq/L	Classification	Biological Response
■ >50	"not acidic"	reproducing brook trout populations expected where habitat is suitable
■ 20-50	"transitional"	extremely sensitive to acidification; brook trout response variable
■ 0-20	"episodically acidic"	sub-lethal and/or lethal effects on brook trout likely
■ <0	"chronically acidic"	lethal effects on brook trout likely

(Altshuller and Lindhurst, 1984; Winger et al., 1987; Knapp et al., 1988). This study drew the line for "healthy" streams much lower, in part to be conservative and in part because brook trout are a relatively acid tolerant species. It is important to remember that many streams in this category, although capable of sustaining healthy brook trout populations, are in other respects potentially damaged ecosystems.

"Transitional": ANC 20 to 50 μeq/L

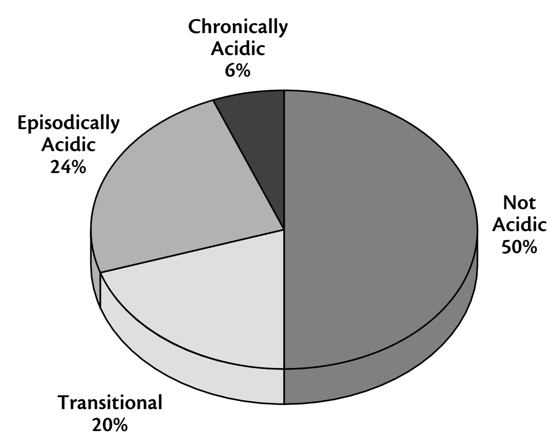
This is a problematic category for prediction of acid deposition effects. Brook trout populations can be healthy if other habitat characteristics are favorable or poor in marginal habitats. Streams in this classification have an average annual ANC which renders them "extremely sensitive" to acidification (Gibson et al., 1983; Schindler, 1988), because any further reduction in ANC can produce conspicuous negative effects. In this range of average annual ANC, streams may or may not experience lethal episodic acidification during storms. The occurrence of episodic acidity depends on a number of hydrologic and physical/chemical characteristics that cannot be readily predicted (such as the ratio of storm- to baseflow, which is a function of the geomorphology of the catchment and storm severity, and the occurrence of springs or minor alkaline tributaries that can buffer storm events at these levels of annual ANC). The status of brook trout populations is also difficult to predict. In general, membership in this category can be regarded as transient, as a stream moves from "not acidic" to the next category "episodically acidic" during acidification (or in the other direction during recovery from acidification).

"Episodically Acidic": ANC 0 to 20 μeq/L

Streams in this classification have an average annual ANC that makes acid episodes likely (Hyer et al., 1995), albeit at different frequencies of occurrence from stream to stream. Streams in this category have lost sensitive species, and display a reduced species richness. Examples of species lost might include longnose dace, mottled sculpin, northern hog sucker, central stoneroller, river chub, and rosyside dace (Heard et al., in press; Bulger et al., 1995; Bulger et. al, SNP:FISH Final Report). There are measurable sub-lethal stresses on individuals, including low body weight and condition factor (in blacknose dace, Dennis et al., 1995; Dennis and Bulger, 1995; and brook trout, Bulger et al., SNP:FISH final report), or lower population density (in brook trout, Bulger et al., SNP:FISH final report) of more acid-tolerant species in streams in this category (Bulger et al., 1995). Lost year classes of brook trout also become more likely at this ANC level. Streams in this category can have baseflow chemistry tolerable to brook trout fry, but acidic episodes lethal to brook trout fry (MacAvoy and Bulger, 1995).

Figure 1

Percentage of Streams in Alkalinity Classes of Interest
Observed, 1991

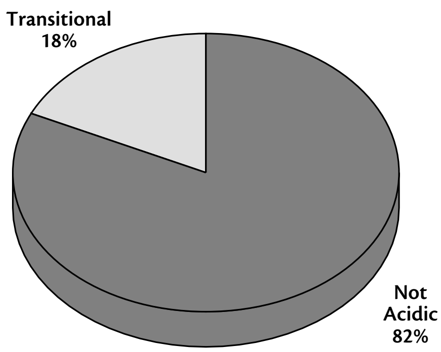


"Chronically Acidic": ANC less than 0 μeq/L

Streams in this classification have an average annual ANC less than 0 ueq/L. In order for a forested, headwater stream in the mountains of Virginia to have an annual average ANC less than 0 ueq/L, it must have a negative ANC for most of the year, not just during storm events. As a result, the biological communities of streams in this category are severely affected. Loss of even acid-tolerant species occurs in these streams, and species richness is very low. Conditions lethal due to acid stress are common. Such streams cannot support healthy brook trout populations.

Figure 2

Percentage of Streams in Alkalinity Classes of Interest Simulated, 1851



Current and historical conditions

Based on the observed volume weighted annual average alkalinities for 1991, there are a significant number of trout streams in western Virginia that currently have moderate to severe problems with acidity (Figure 1). Only 50% of the streams are currently “not acidic” and thus have water quality that poses no threat to brook trout. Approximately one-third (30%) of all trout streams in Virginia are currently either episodically or chronically acidic. Of that 30%, 24% experience episodic acidification and 6% have become chronically acidic. In addition to the 30% reliably assumed to have problems of some severity, there are an additional 20% of the streams (transitional streams, Figure 1) that may also be experiencing difficulties.

An estimate of how much of this current condition is attributable to the effects of industrially-generated acidic deposition can be made by examining the hindcast conditions of the streams. Based on the model simulations, 82% of these streams would have been “not acidic” prior to the onset of acidic deposition (Figure 2). The 18% of streams for which the hindcast is indeterminate probably were suitable for trout, because there would have been no source of strong acid during storms, and thus no possibility of episodic acidification in these marginal streams. The hindcast simulations produced no streams with chronic or episodic acidification problems.

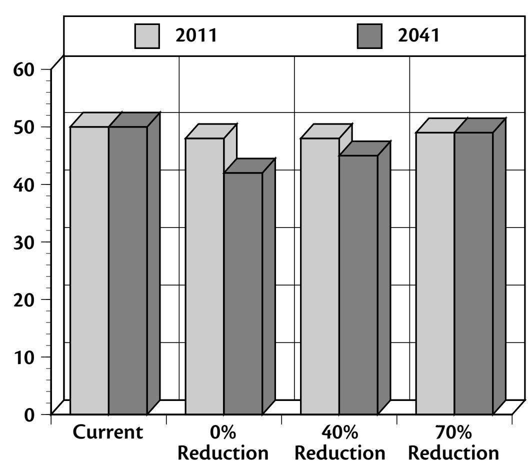
These results (based on model reconstructions) suggest, therefore, that acidic deposition is responsible for damage to brook trout populations in approximately one-third of all trout streams on non-limestone bedrock in western Virginia (at least 100 streams). In addition, the model results suggests that only approximately half of all trout streams on non-limestone bedrock in western Virginia can currently be safely assumed to produce minimal acid effects on brook trout.

Responses of streams to future deposition reductions

In considering the forecast responses of streams to the future deposition scenarios and given the current af-

Figure 3

Response to Deposit Reduction: Percentage of “not-acidic” headwater streams in western Virginia (Average annual alkalinity > 50 μeq/L)



fected condition of the streams, two important questions can be identified: 1) will the number of "episodically acidic" plus "chronically acidic" (average annual ANC < 20 μeq/L) streams decrease if acid deposition is reduced, and 2) will the number of "not acidic" (average annual ANC > 50 μeq/L) streams increase if acidic deposition is reduced?

Streams that are "not acidic" (ANC > 50μeq/L)
None of the scenarios produces large changes in the number of suitable ("not acidic") trout streams in the short-term (20 years) (Figure 3, Year 2011). However, a small number of streams will be lost from the suitable category over the next 20 years even with a 40% reduction.

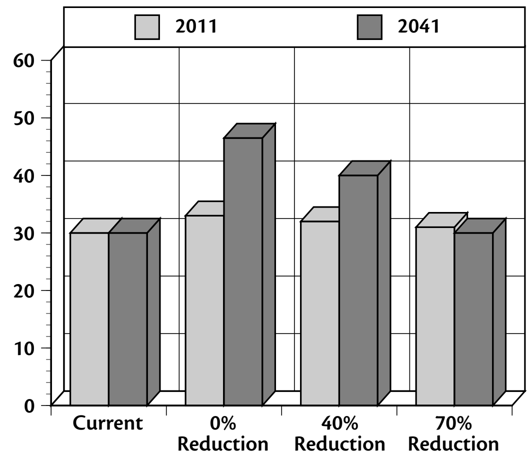
The long-term (50 years) responses indicate that the percentage of "not acidic" streams will decrease in the future (Figure 3, Year 2041), from 82% in 1851, to 50% now, to 49% following a 70% reduction, to 45% following a 40% reduction, and to 42% assuming constant deposition at 1991 levels. This response is delayed due to leaching of accumulated sulfate in soils, with concomitant loss of base cation buffering. As the soil's ability to buffer the acidic deposition declines, the average annual ANC of some streams will fall below the 50 ueq/L criterion for suitable trout water.

It is clear from Figure 3 that neither the 40% nor 70% reductions in acid deposition will increase the number of suitable streams above the current 50%. In fact, the results in Figure 3 strongly suggest that a 70% reduction in deposition is needed in the long-term just to maintain the current number of streams that are currently "not acidic". Recovery of any of the 32% of streams that were lost from this category due to acidification (82% in 1851, versus 50% currently, Figures 1 and 2) is not likely unless deposition reductions in excess of 70% are achieved.

Streams that are "chronically" or "episodically acidic" (2 ANC classes)
Currently 30% of all trout streams in western Virginia are in this "combined acidic" category. Streams in this category have reduced species richness, and trout in these streams will be affected by sub-lethal and/or lethal stress. In the short-term these streams show only a moderate response to any of the deposition reduction scenarios (Figure 4, Year 2011). For 0% and 40% reductions, slight increases in the number of streams in this category are forecast for the year 2011, while the 70% reduction scenario results in no increase in streams in this category.

Figure 4

Response to Deposit Reduction: Percentage of "chronically & episodically acidic" headwater streams in western Virginia (Average annual alkalinity < 20 μeq/L)



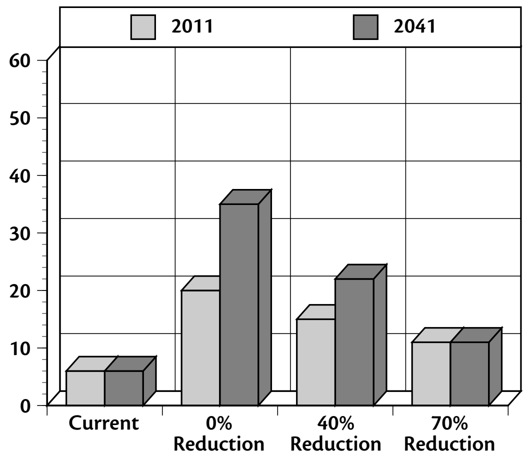
The forecast long-term responses, however, show larger changes for this "combined acidic" category (Figure 3, Year 2041). For no deposition reduction, the results suggest that an additional 17% (from 30% to 47%) of streams will join this category. This translates approximately to an additional 52 streams which will exhibit either episodic or chronic acidity with associated adverse effects on the fish in these streams. Even the 40% reduction scenario results in an increase of 10% (approximately 30 streams) in the membership of this category.

It is apparent from Figure 4 that neither the 40% nor the 70% reduction scenarios will result in a decrease in the number of streams in the chronically plus

Figure 5

Response to Deposit Reduction: Percentage of "chronically acidic" headwater streams in western Virginia

(Average annual alkalinity < 0 μeq/L)



espisodically acidic categories (i.e., there will be no recovery of lost stream resources). In fact, the results in Figure 4 strongly suggest that a 70% reduction in deposition is needed to prevent further increases in the number of streams in this category. Recovery of streams that are currently episodically or chronically acidic is not likely unless deposition reductions of greater than 70% are achieved.

Streams that are "chronically acidic" (ANC < 0 μeq/L)

Chronically acidic streams represent extreme damage due to acidification. As streams move from episodically to chronically acidic, the biological effects are more severe (e.g., loss of more species, loss of invertebrate populations that are important food sources, etc.). Practical remedial actions such as liming become more expensive and complicated as stream acidity becomes chronic, making management of these streams for fish resources problematic. Chronically acidic streams may be truly "lost" fisheries resources. It is important, therefore, to examine separately the model forecasts of numbers of streams in this category (Figure 5).

The general pattern of response is the same as for the "combined acidic" category of chronically plus episodically acidic streams. The 0% and 40% reductions result in increases in the number of streams in this severely damaged category (Figure 5). However, there are two important differences compared to the effects simulated for the "not acidic" or "combined acidic" categories.

First, there are large short-term as well as long-term changes in the percentage of chronically acidic streams. For instance, the 40% reduction scenario results in a doubling of the percentage of chronically acidic streams by 2011 (from 6% to about 13%) and an increase in the percentage of such streams to 22% by 2041. Second, the results for chronically acidic streams suggest that even a 70% reduction in deposition is not enough to hold the status quo for these streams (unlike the results for the "not acidic" and "combined acidic" categories). The number of chronically acidic streams is forecast to increase, even under the 70% reduction scenario, from 6% to 11%, and that doubling is relatively rapid, by the year 2011 (Figure 5).

As the streams in this category will be incapable of sustaining populations of brook trout and many other aquatic animals, it is worthwhile to express their numbers in absolute terms. Using the 304 streams to which the analysis applies directly as the total, assuming no reduction from 1991 levels means that an additional 88 streams will become chronically acidified (6% currently v. 35% in 2041). Assuming a 40% reduction means that an additional 48 streams (6% currently v. 22% in 2041) will become chronically acidified. Finally, even assuming a 70% reduction, an additional 15 streams will become chronically acidified (6% currently v. 11% in 2041). Due to the length of time required to restore buffering capacity, even assuming much greater future reductions most of these streams will remain acidified for the foreseeable future.

Conclusions

The present analysis deals with probable negative effects of acidification specifically on brook trout, not just at the time of the assessment, but simulated for the past and future. Figures 1 and 2 show the shift from pre-industrial ANC categories, with 82% versus 50% of streams suitable for brook trout, and 0% versus 30% of trout streams sufficiently acidic to make negative effects on brook trout likely (see Table 1 for an explanation of categories). While the present analysis focuses on brook trout, one of the most acid-tolerant fish species, it is important to remember that both brown trout and rainbow trout, as well as other ecologically important species, including many minnows, darters and aquatic insects, are less acid-tolerant than brook trout, so negative effects of acidification on these species are anticipated under conditions still tolerable for brook trout.

Projections indicate that a 70% reduction in sulfate deposition (relative to 1991 levels) is necessary to prevent the loss of more streams from the "healthy" category. Even this reduction will not increase the number of streams suitable for brook trout, and in fact will not prevent some already partially damaged streams from becoming chronically acidic, or essentially "fishless." In addition, although the analysis applies directly to streams in Virginia, it is important to note that the Southern Appalachian Assessment (1996), concluded that 59% of about 33,000 potential wild trout stream miles are in areas highly vulnerable to acidification. If these results are extrapolated to the entire 37 million-acre area of the Southern Appalachians, the potential losses to acidification are substantial, and can be measured in thousands of trout stream miles.

Glossary

Acidity is the amount of acid in a sample, usually measured on the pH scale ($-\log[H^+]$).

Acid Neutralizing Capacity (ANC) is a measure of the ability of a water sample to neutralize acid inputs (determined by titration). ANC is used as the main indicator of the acid sensitivity of a surface water to acid inputs.

Acidic refers to a water sample that has lost all ANC. Note that an ANC of 0 corresponds to a pH of about 5.3 (not pH < 7).

Acidification refers to declines in ANC or pH over time. Acidified waters had higher ANC or pH in the past. A lake or stream may have acidified, but not yet be "acidic" (see above); for example, a stream is said to have been acidified if its ANC has been lowered, even if the ANC is still above 0.

Siliciclastic is a general term referring to sedimentary or metasedimentary rocks dominated by silica (i.e., noncarbonate sedimentary rocks) such as quartzites, sandstones, phyllites, shales.

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Appendix 1: Modeled Streams by Watershed Bedrock Class

Blue Ridge Siliciclastic

Deep Run
Paine Run
Meadow Run
Kennedy Creek
Mills Creek
Saint Marys River (lower)
Otter Creek
Big Mack Creek
Two Mile Run
Saint Marys River (upper)
Chimney Branch
Bear Branch
Mine Bank Branch
Sugar Tree Branch
Saint Marys River (middle)
White Oak Run

Granitic

North Fork of Dry Run
Helton Creek
Lewis Fork
Fox Creek
Little Wilson Creek
Cornelius Creek
Fallingwater Creek
Hunting Creek
Little Cove Creek
Brokenback Run
Staunton River
Hazel River
Shoe Creek
Crabtree Creek
Meadow Creek
East Fork of Chestnut Creek

Valley and Ridge Siliciclastic

Rowland Creek
Laurel Run
Mare Run
Panther Run
Porters Creek
North Branch of Simpson Creek
Bearwallow Run
Lost Run
Shawvers Run
Pine Swamp Branch
North Fork of Stony Creek
War Spur Branch
Nobusiness Creek
Laurel Creek
Laurel Run
North River
Ramseys Draft
Little Stony Creek
Laurel Run
Morgan Run
Wolf Run
Black Run

Basaltic

Jeremys Run
Piney River
North Fork of Thornton River
Rose River