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Controls of Stream Chemistry and Fish Populations in the Neversink Watershed, Catskill Mountains, New York

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The Neversink Watershed Study was initiated in 1991 to develop an understanding of the key natural processes that control water quality within the forested, 166 km^2 64 mi^2), Neversink River watershed; part of the New York City drinking water supply system, in the Catskill Mountain region of New York. The study entailed (1) hydrological investigations of water movement from the atmosphere to streams, (2) biogeochemical investigations of nitrogen and calcium, important nutrients in forest and aquatic ecosystems whose availability has been altered by acidic deposition, (3) an investigation of elevational patterns in atmospheric deposition, and (4) fisheries investigations to determine the relative importance of physical habitat and acidic deposition in controlling the abundance and diversity of fish species in the watershed. This report summarizes the results of these investigations, which have also been presented, in detail, in peer-reviewed technical articles and reports that are cited throughout the text.

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INTRODUCTION

The City of New York relies on six reservoirs in the Catskill Mountains to provide 90% of its water supply to 8 million residents. Historically, the water collected by these reservoirs has been of high quality as a result of the pristine environment throughout much of the Catskill Mountain region. Because most of the area that is drained by the reservoirs is forested, precipitation follows a hydrologic pathway through the forest canopy, the soil, and often the underlying rock, before reemerging at the surface as stream flow. In following this pathway, the water is altered by chemical and biological processes that interact in complicated ways. An understanding of these processes is essential for discerning the effects of human activities from undisturbed conditions, and reducing or eliminating uncertainty in watershed-management decisions. To ensure a high-quality supply of water in the future, the City of New York has undertaken a comprehensive watershed-analysis and protection program that includes the Neversink Watershed Study; an investigation to determine the factors that control the chemistry and fish populations in streams that flow into the reservoirs.

The Neversink Watershed

The Neversink watershed (fig.1) was chosen for this study because it drains the least developed area within the New York City water-supply system. The watershed above the Neversink Reservoir covers 166 km^2 (64 mi^2), of which 95 percent is forested. Fewer than 1000 people reside in the watershed year-round, and agricultural activities in the basin are minimal. A few man-made ponds are used for recreation, the largest of which are Lake Cole and Round Pond (fig. 1), both of which are less than 3 ha (7.4 acres) in area. The Neversink River has been renowned for more than 100 years for high-quality trout fishing.

The Catskill Mountains are underlain by flat-lying, sedimentary bedrock that is highly fractured. Bedding planes, or horizontal separations in the bedrock caused by a change in the ancient pattern of sediment deposition that formed the rock, are also a common feature of this bedrock. The rugged terrain of the Catskills is largely the result of erosion by streams and glaciers that have resulted in steep-sided valleys and flat-topped mountains.

Glacial activity that ended about 15,000 years ago also left behind a veneer of till (sand, gravel and rocks) over the mountains and valleys. Since that time, streams have transported and redeposited some of the till in sand and gravel deposits in the valley bottoms, which are referred to as alluvium.

The climate in the Neversink watershed is similar to that of other mountainous regions in the Northeast. Mean annual temperature at the Slide Mountain National Weather Service Station (fig. 1), which is 808 m above sea level, is 4.3° C (40° F), and precipitation is about 175 cm (69 in) per year, of which about 23 percent falls as snow. Elevation ranges from 480 m (1575 ft) to 1280 m (4200 ft) and hillslopes are steep (up to 40%) with deeply incised stream channels. Streamflow, therefore, increases rapidly in response to precipitation. Wetlands cover less than 5% of the total basin area. Soils are classified in the order of Inceptisols are generally 0.5 to 1 m thick and are generally well drained. The forest consists primarily of mixed northern hardwood species dominated by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*). Balsam fir (*Abies balsamea*) is common above 1,000-m elevation, and hemlock stands grow in a few areas that have poorly drained soils.

The Catskill region receives some of the highest rates of acidic deposition (acid rain) in the Northeast (Lawrence and others, 1995), and both chronic and episodic acidification of stream water has been documented in the Neversink River Basin in previous studies (Lawrence and others, 1999; Baldigo and Murdoch, 1997). Although acidic deposition is not natural, analysis of the effects of acidic deposition were included in the study because (1) it has a pronounced effect on water quality in the Neversink watershed, and (2) it is beyond local control.

Topics of Investigation

The Neversink Watershed Study entailed (1) hydrological investigations of water movement from the atmosphere to streams, (2) biogeochemical investigations of nitrogen and calcium, important nutrients in forest and aquatic ecosystems whose availability has been altered by acidic deposition, (3) an investigation of elevational patterns in atmospheric deposition, and (4) fisheries investigations to determine the relative importance of physical habitat and acidic deposition in controlling the abundance and diversity of the primary fish species in the watershed. This report summarizes the results of these investigations, which have also been presented, in detail, in peer-reviewed technical articles and reports that are cited throughout the text.

The coarse-textured soils in the Neversink watershed transmit water readily, either laterally to stream channels or downward into the underlying till and fractured bedrock. Both soil water and ground water (water that has passed below the soil) play an important role in controlling stream flow and water quality in the Neversink watershed.

Ground-Water Recharge

Most, if not all, precipitation that falls within the watershed infiltrates the soil before reaching stream channels because the decomposing leaves and branches that form the forest floor create a highly porous layer that allows water to readily move downward. Upon infiltration, water can pass downward through the soil into the underlying till and bedrock fractures to be stored in the ground-water reservoir—a process referred to as ground-water recharge. Some of the infiltrated water is retained within the soil through absorption by soil particles, which recharges the soil-water reservoir.

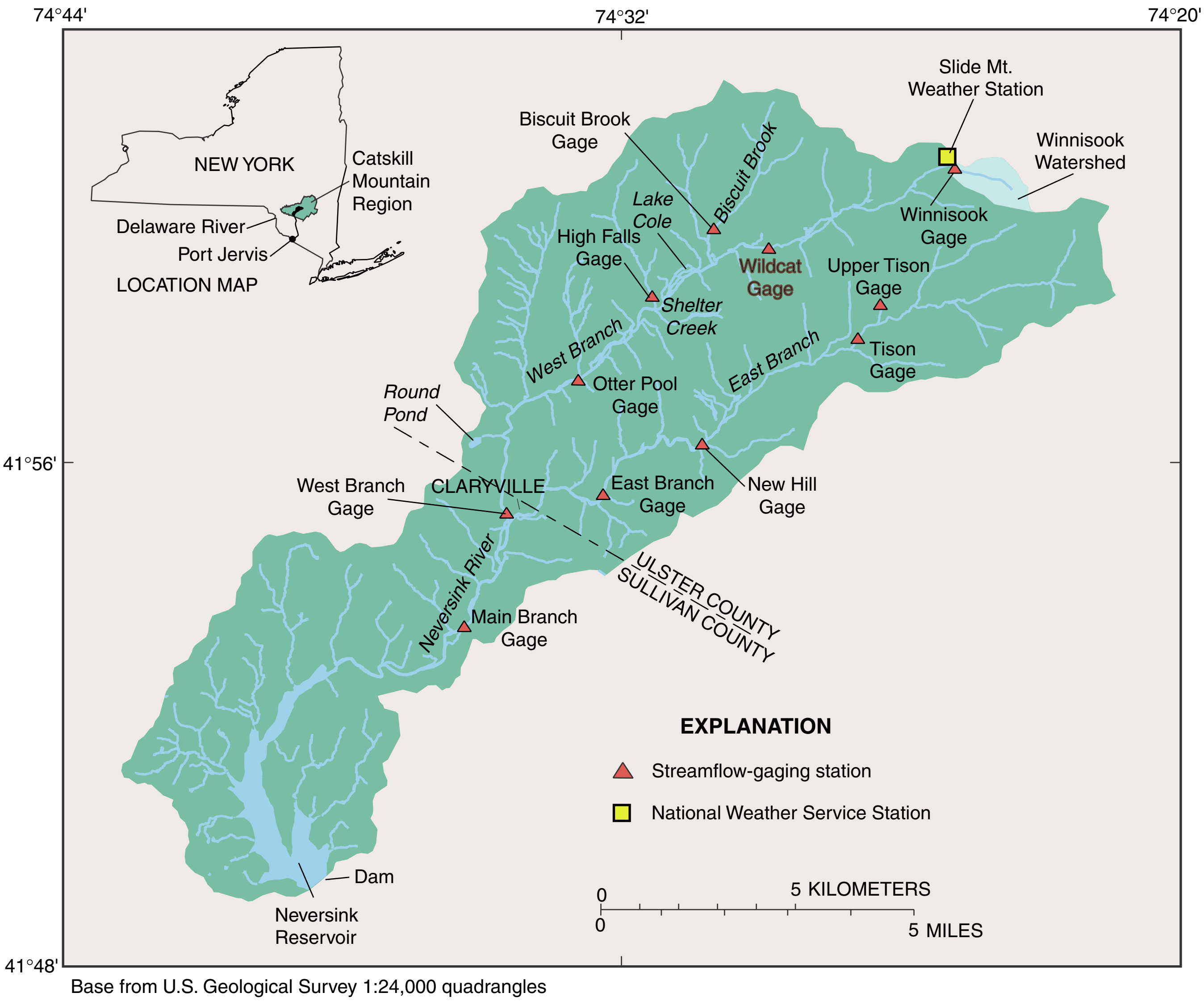


Figure 1. Locations of study watersheds and stream flow measuring stations in the Neversink River basin.

On average, precipitation in the Neversink watershed is evenly distributed throughout the year. Much of the winter precipitation is stored in the snowpack until snowmelt, however, which is typically greatest in March, the month in which the greatest amount of ground-water recharge also occurs (Burns and others, 1998). During the season when leaves are on the trees (late May through late September), the amount of stored water in the ground-water and soil-water reservoirs tends to decrease because uptake of soil water by forest vegetation (a process known as transpiration, which is essential for photosynthesis) generally exceeds precipitation, which prevents recharge and dries the soil (Burns and others, 1998).

Ground-Water Residence Time

Once precipitation enters the ground, it can be stored for a variable length of time before being discharged to a stream; a factor referred to as the water's subsurface-residence time. Both seasonal variations in stream flow and the chemical composition of stream water are affected by subsurface-residence time. Chemicals such as calcium and sodium, dissolve slowly from rocks and minerals, and therefore increase in concentration as subsurface-residence time increases. This process, termed mineral weathering, neutralizes the acidity of the water, thereby increasing pH and ANC (acid-neutralizing capacity).

Estimates of the subsurface-residence time measured in discharging ground water at two locations, and in stream water during base flow (between storms) in tributary watersheds of the Neversink River, ranged from about 6 months to 2 years during 1992-93 (Burns and others, 1998). These estimates (table 1) were derived from concentration measurements of ^{18}O (oxygen that is part of the water molecule, but heavier than the common form of oxygen) and ^{35}S (atoms of sulfur that are part of the sulfate ion, but heavier than the common form of sulfur) in water samples. The abundance of each of these isotopes changes through physical, chemical, and biological processes that occur as the water moves from the atmosphere through the subsurface and finally into streams. Comparison of the isotope values when the water fell as precipitation with values at the time of discharge can be used to estimate the subsurface residence time.

Relative differences in subsurface-residence time of water throughout the watershed also were estimated using data on topography and soil depth available in a geographic information system (Wolock and others, 1997). In general, subsurface-residence time of water was least at the uppermost parts of the watershed and systematically increased with decreasing elevation. Throughout the watershed, the subsurface-residence time also increased with increasing pH, ANC and the concentration of calcium.

Table 1. Estimated watershed residence time at four sites in the Neversink River Basin

Site	Residence Time ^{18}O Method (days)	Residence Time ^{35}S Method (days)
Winnisook stream	330	247-319
Winnisook spring	660	187-302
Shelter Creek tributary	375	187-302
Shelter Creek Spring	345	319-596

Discharge of Ground Water and Soil Water to Streams

Ground water in the Neversink watershed typically discharges as seeps or springs at the base of steep slopes and from rock outcrops, or discharges directly into the stream channel. Discharge of water from deep ground-water sources occurs throughout the year, and is the principal source of stream flow during the dry summer months. This water has typically moved through bedrock fractures and bedding planes (fig. 2), and generally remains below the surface for several months to more than one year. Some water moves through the matrix of the bedrock, but much slower than through the fractures and bedding planes. The discharge rate of these springs tends to vary from season to season, but does not respond to individual storms (fig. 3A; Burns and others, 1998).

During extended periods of rainfall or snowmelt, rates of recharge can exceed rates of discharge, which results in upward movement of the water table (the level below which all pore spaces and fractures are filled with water). In March or April the water table is likely to be in the soil profile, within centimeters of the surface, whereas in late summer, the water table is likely to be below the soil profile, and possibly below the till (fig. 3B, Burns and others, 1998). As the water table rises, subsurface water is able to discharge from the till and the soil, as well as from bedrock (fig. 2). When the water table rises into the soil, high stream flow is maintained between storms, and rapid increases in stream flow occur during rainstorms and snowmelt, as ephemeral streams form in channels that are dry throughout most of the year. Stream water under these conditions is a mixture of ground water and soil water that reflects a range of subsurface-residence times. During drier times of the year, heavy

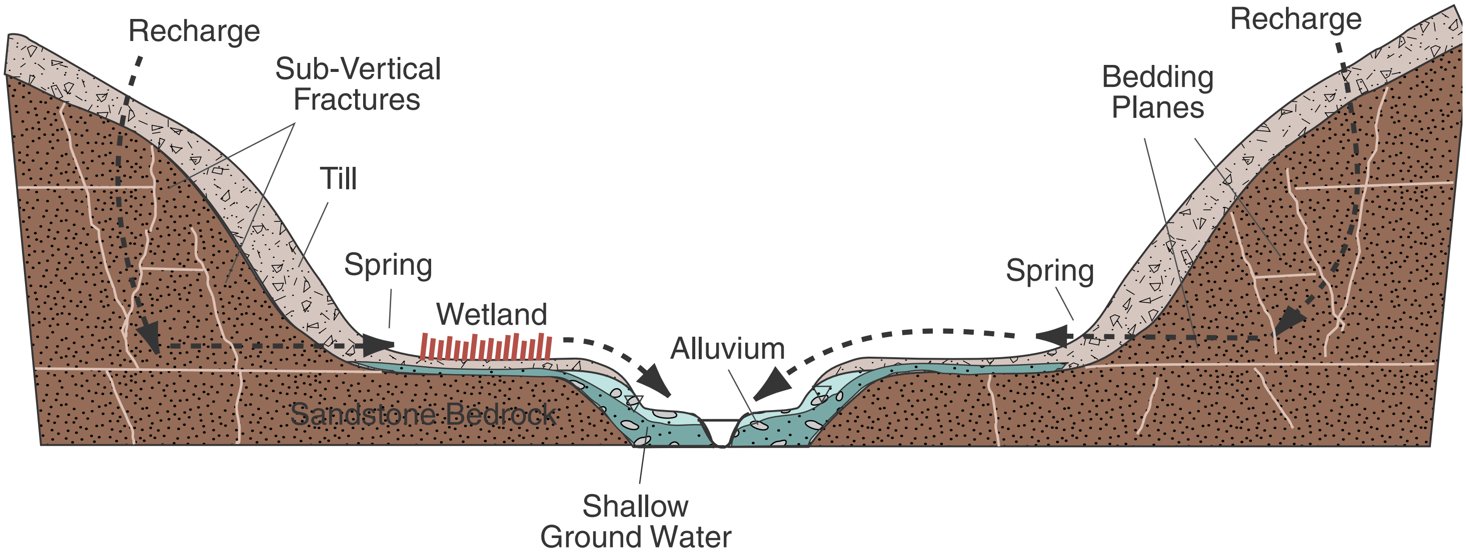


Figure 2. A conceptual model of how subsurface water moves to the stream channel.

rainstorms can also rapidly increase stream flows for short periods of time, through lateral transport of water through the soil and upper ground water reservoirs, even though the water table is deep in the till or bedrock (Brown and others, 1999). Once the rain stops, however, streamflow quickly recedes to low, pre-storm levels.

NITROGEN TRANSFORMATIONS AND MOVEMENT

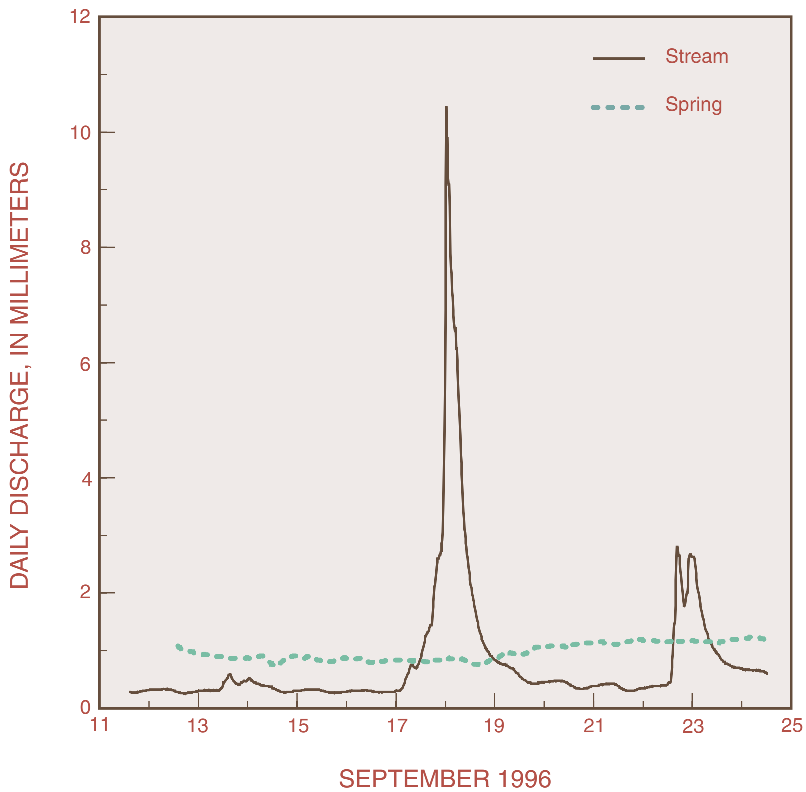
Nitrogen is the nutrient that is generally most limiting to plant growth and, therefore, is used extensively for crop fertilization. An essential component of proteins, nitrogen is also found in high concentrations in both animal and human waste. For these reasons, agriculture and development often result in elevated levels of nitrogen in ground water and surface water, where it may promote algal growth and associated eutrophication, particularly in coastal waters.

Nitrate, one of the most common forms of nitrogen, has a U.S. Environmental Protection Agency recommended health standard of 10 mg/L. Concentrations above this level can cause methemoglobemia (blue-baby disease), a blood disorder in infants.

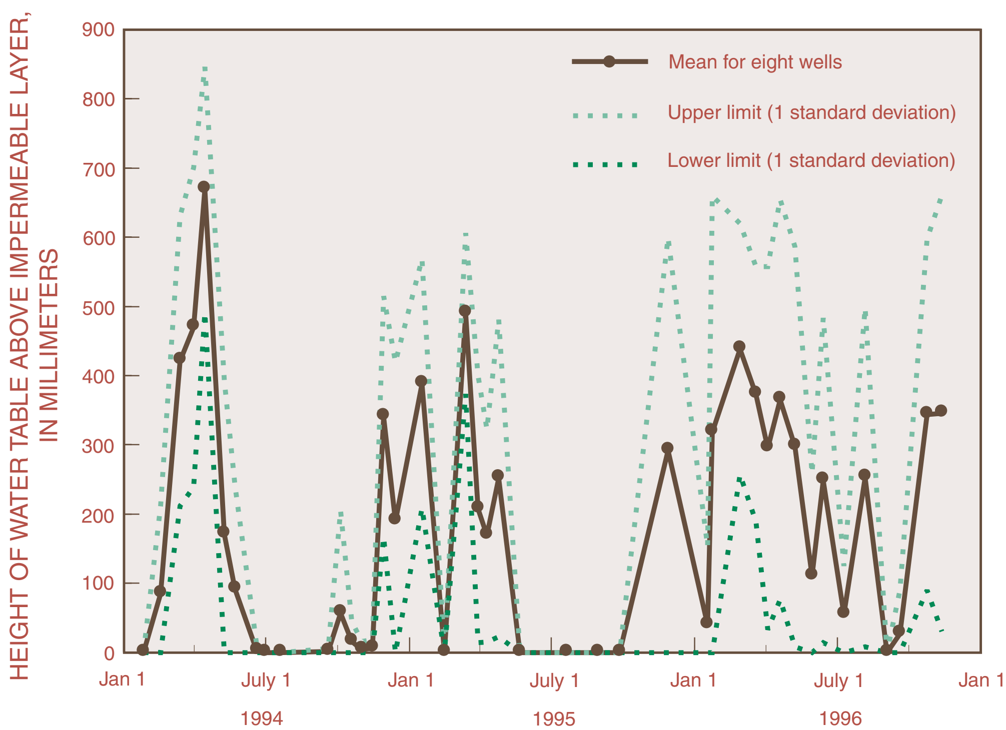
Because the Neversink watershed is sparsely populated, and has almost no agriculture, inputs of nitrogen occur through (1) natural fixation of gaseous nitrogen in the atmosphere by plants, and (2) atmospheric deposition of pollutants (acid rain). Nitrogen fixation can be performed only by a small number of specialized plant species, therefore, natural inputs of nitrogen to ecosystems tend to be low, and the growth of non-nitrogen fixing plants tends to be limited in the absence of nitrogen from fertilization or pollution. In these types of ecosystems, the high plant demand for nitrogen results in little or no nitrogen reaching surface waters.

In the northeastern U.S., high levels of atmospheric deposition for several decades has led to elevated concentrations of nitrogen in surface water and ground water (mostly as nitrate and to a lesser extent, as organic nitrogen). Rates of atmospheric nitrogen deposition in the Neversink watershed are among the highest in the northeastern U.S.—about 10-20 kg N/ha/yr from wet and dry deposited forms. This nitrogen is deposited from the atmosphere mainly in the form of nitric acid, and ammonium and nitrate salts.

If nitrogen availability exceeds plant demand in forest soils (a condition termed nitrogen saturation), the microbial process termed nitrification is stimulated. Through this process, nitric acid is produced, which can (1) acidify soils and surface waters, (2) affect the availability and movement of other chemicals in the soil that can be either toxic or beneficial, and (3) adversely effect aquatic life. The following sections describe the transformations and transport (referred to as cycling) of nitrogen that has been atmospherically deposited in the Neversink watershed.



A. STREAM AND SPRING DISCHARGE, SEPTEMBER 1996



B. WATER-TABLE HEIGHT AT EIGHT WELLS, 1994-96

Figure 3. Ground water measurements: (a) discharge of a Neversink River tributary and a nearby spring during a 53 mm and a 26mm rain storm. (b) mean height of water table above the impermeable layer (±1 standard error), based on eight wells in a tributary watershed of the Neversink River basin.

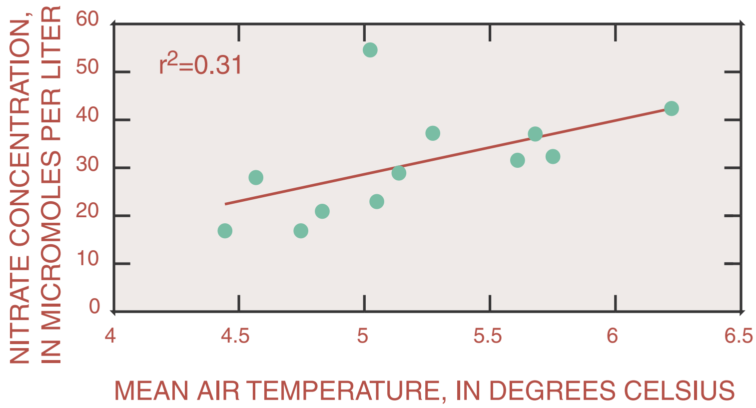


FIGURE 4. Relations between stream nitrate concentrations and air temperature at Biscuit Brook for water year 1984-85.

Retention and Release of Soil Nitrogen

Although the primary form of nitrogen deposited from the atmosphere is in the form of nitrate (from nitric acid or ammonium nitrate salt), as is most of the nitrogen in stream water, analysis of the isotopic composition of nitrate in precipitation, soil water, and stream water, showed that most of this nutrient in soil water and stream water has cycled through the biota at least once and been released again by microbial processes (Burns and Kendall, in review). This conversion can be identified through isotope analysis because root or microbial uptake of deposited nitrogen changes the isotopic composition; a change that can be identified by the comparison of nitrate in precipitation with nitrate found in stream water and soils. Microbial processes can convert nitrogen from organic matter to ammonium (called nitrogen mineralization), and from ammonium to nitrate (called nitrification). Because nitrate is the form of nitrogen that is most easily transported by water from the soil to the stream, these microbial processes play an important role in controlling the release of nitrogen to surface waters.

Atmospheric deposition is an important source of the nitrogen that cycles through the Neversink watershed, but average nitrate concentrations in stream water in any given year are not related to the amount of atmospheric nitrogen deposition that year. Instead, average annual concentrations in Biscuit Brook (a tributary of the Neversink River) increase as the average annual air temperature increases (fig. 4; Murdoch and others, 1998). Warmer temperatures stimulate microbial activity, which leads to increased rates of mineralization and nitrification, and greater loss of nitrate from soil to streams. A buildup of nitrogen in the soil from several decades of acidic deposition has apparently shifted the control of nitrogen retention from root uptake to microbial assimilation once nitrogen availability exceeded the nutrient demands of the trees. Uptake of nitrogen by roots results in long-term storage in trees, but the short lifespan of microbes results in frequent release of organic nitrogen as microbes die, which subsequently can be mineralized, nitrified and transported to streams.

Nitrate concentrations were also found to decrease in the upstream direction in the Winnisook watershed, a headwater tributary of the upper West Branch Neversink River (fig. 1), despite increased atmospheric deposition of nitrogen at upper elevations of this watershed (Lawrence and others, 2000). Increased levels of nitrogen deposition at high elevations would be expected to result in higher stream concentrations of nitrate at upper elevations than lower elevations. The opposite relationship was observed, however, because organic matter in the soil, derived from leaves and needles, accumulates at a greater rate at upper elevations where cooler temperatures slows decomposition rates. Nitrogen incorporated in the organic matter cannot be released to stream water without first being decomposed.

Although other studies in Europe and North America have shown that long-term atmospheric deposition of nitrogen is directly related to elevated nitrate concentrations in surface waters, results of the Neversink watershed investigations indicate that assessment of the effects of atmospheric deposition on stream-water chemistry requires consideration of natural biological processes in the soil, and the manner in which physical factors such as climate affect the rates of these biological processes.

Role of Ground-Water Seeps

The deep ground water flow system discussed earlier strongly affects the concentrations of nitrate in stream water during the summer. As conditions become progressively drier over the summer, stream flow consists of a greater proportion of deep ground water. Subsurface-residence times and monthly hydrologic budgets indicate that much of this deep ground water was recharged during early spring and late fall, when nitrogen was not actively taken up by forest vegetation (Burns and others, 1998). The concentration of nitrate in soil water is greater during these recharge periods than during the summer growing season (fig. 5a).

Therefore, groundwater with relatively high nitrate concentrations discharges from these seeps to nearby streams throughout the summer (fig. 5b; Burns and others, 1998).

Role of Wetlands

The Neversink watershed contains no large wetlands, however, small, riparian (stream-side) wetlands with dense growths of herbaceous plants and mosses are formed in the vicinity of ground-water discharges (Hall, 1997). Surface water that passes through these wetlands undergoes significant decreases in nitrate concentrations during spring, summer, and fall (Burns and others, 1998) through uptake by the herbaceous vegetation and denitrification (conversion of nitrate to gaseous nitrogen by bacteria in the oxygen-poor sediments of the wetlands; Ashby and others, 1998). These wetlands appear to play a particularly important role in limiting the amount of nitrogen that enters streams during the growing season.

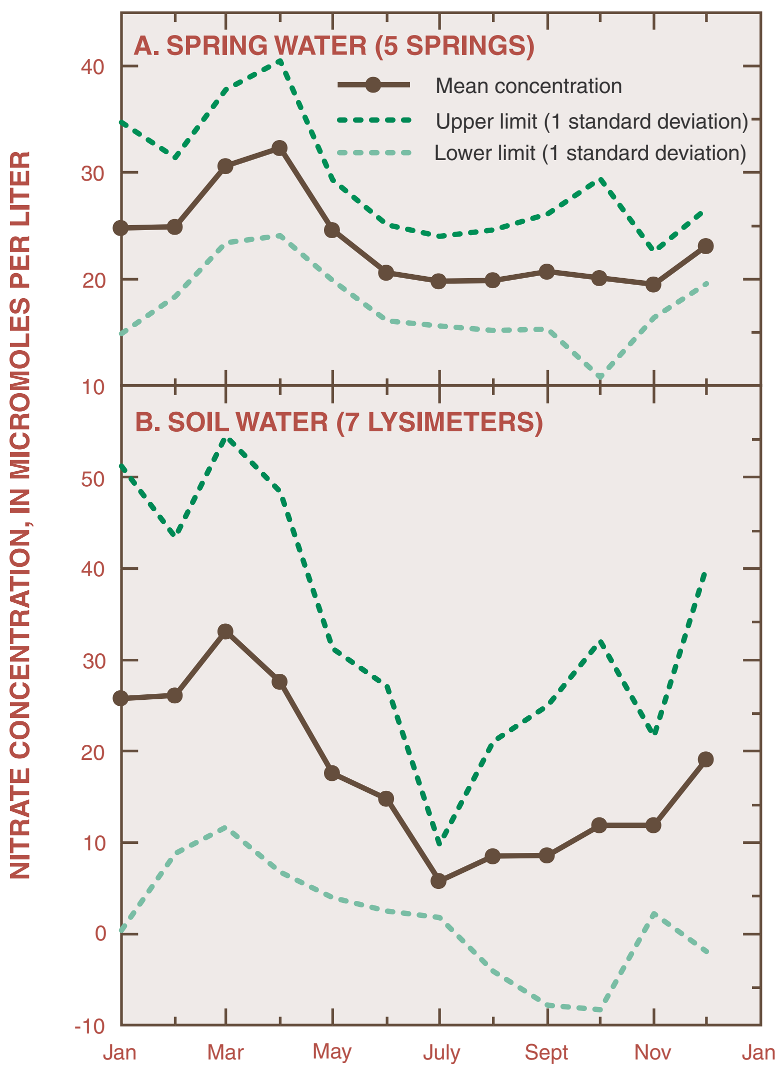


Figure 5. Mean nitrate concentration from (a) five springs and (b) seven C horizon lysimeters in a tributary watershed of the Neversink River basin.

Role of Stream Processes

Once nitrate enters the stream, concentrations can be lowered through processes that are similar to those in riparian wetlands (Burns, 1998). Monitoring of all inputs and losses of nitrate in two stream-reaches of the Neversink River during four, 48-hour periods of baseflow in April, June, July, and September of 1992, showed a net loss of nitrate (when compared to more conservatively transported constituents such as chloride and sulfate) during each sampling interval in both reaches (fig. 6). Nitrate concentrations in stream water of these reaches also varied over the course of each day—concentrations were highest in the early morning before sunrise and were lowest in the late afternoon, when photosynthesis rates and plant uptake rates were probably highest. Analysis of stream sediments at three locations in these reaches revealed that mixing with upwelling ground water did not result in a loss of nitrate, except at one downstream location, where nitrate was completely removed by denitrification as stream water mixed with ground water that tends to be oxygen-poor. In general, plant uptake and denitrification in the Neversink River is important in reaches with slow-moving water and fine-grained sediments, but less effective in reaches with turbulent, fast-moving water—the type of stream reach that is most common in the Neversink watershed.

Depletion of Soil Calcium

Acid rain has been suspected to cause calcium depletion in forest soils since the 1970's, but little evidence of this process was available until the 1990's. Results of the Neversink Watershed Study significantly contributed to these advances by establishing clear linkages among acidic deposition, loss of calcium in the soil, and acidification of stream water.

Calcium Transformations and Movement in Forested Watersheds

Calcium, the most abundant acid neutralizing cation (or base cation) in forest soil, is an essential nutrient for tree growth, and is used in the formation of wood and in the maintenance of cell walls, the primary structure of plant tissue. Trees obtain calcium from the soil, but to be taken up by roots, the calcium (a positively charged ion) must first be dissolved in soil water. Exchangeable calcium, calcium adsorbed to negatively charged surfaces of soil particles, can be readily dissolved, and therefore is the primary source of calcium available to roots.

Some calcium is also deposited onto forests in dust and precipitation or is returned to the soil through decomposing leaves and branches that form the forest floor. Most of the calcium in soil, however, is bound within the mineral structure of rocks within the underlying mineral soil, which makes it unavailable for roots and prevents it from being leached into surface waters. Weathering, the physical and chemical breakdown of rocks, gradually releases calcium to soil water; a process that neutralizes acidity and increases the pH of soil water and the surface waters into which it flows. Acid deposition can greatly increase the rate of leaching,

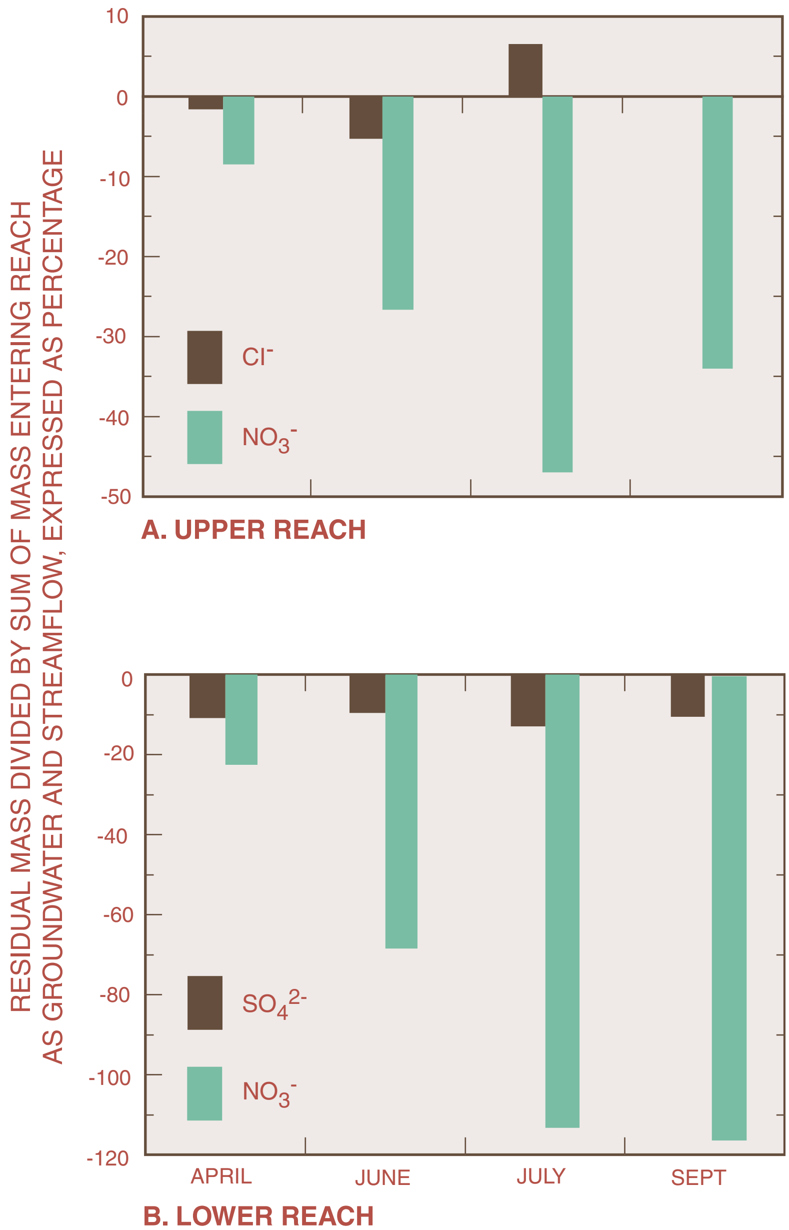


Figure 6. Mass balances for (a) nitrate and chloride in an upstream study reach, and (b) nitrate and sulfate in a downstream study reach during four sampling periods, expressed as the residual of the stream reach mass balance divided by the sum of the mass that entered each reach from ground-water and tributary flow. Negative values indicate a mass loss of the constituent through the reach; positive values indicate a mass gain of the constitiuent through the reach. Chloride was included because it tends to be unreactive in stream water, and therefore can serve as a meaurement check . A large net loss or gain of chloride would indicate that inputs or losses of water along the study reach were not measured

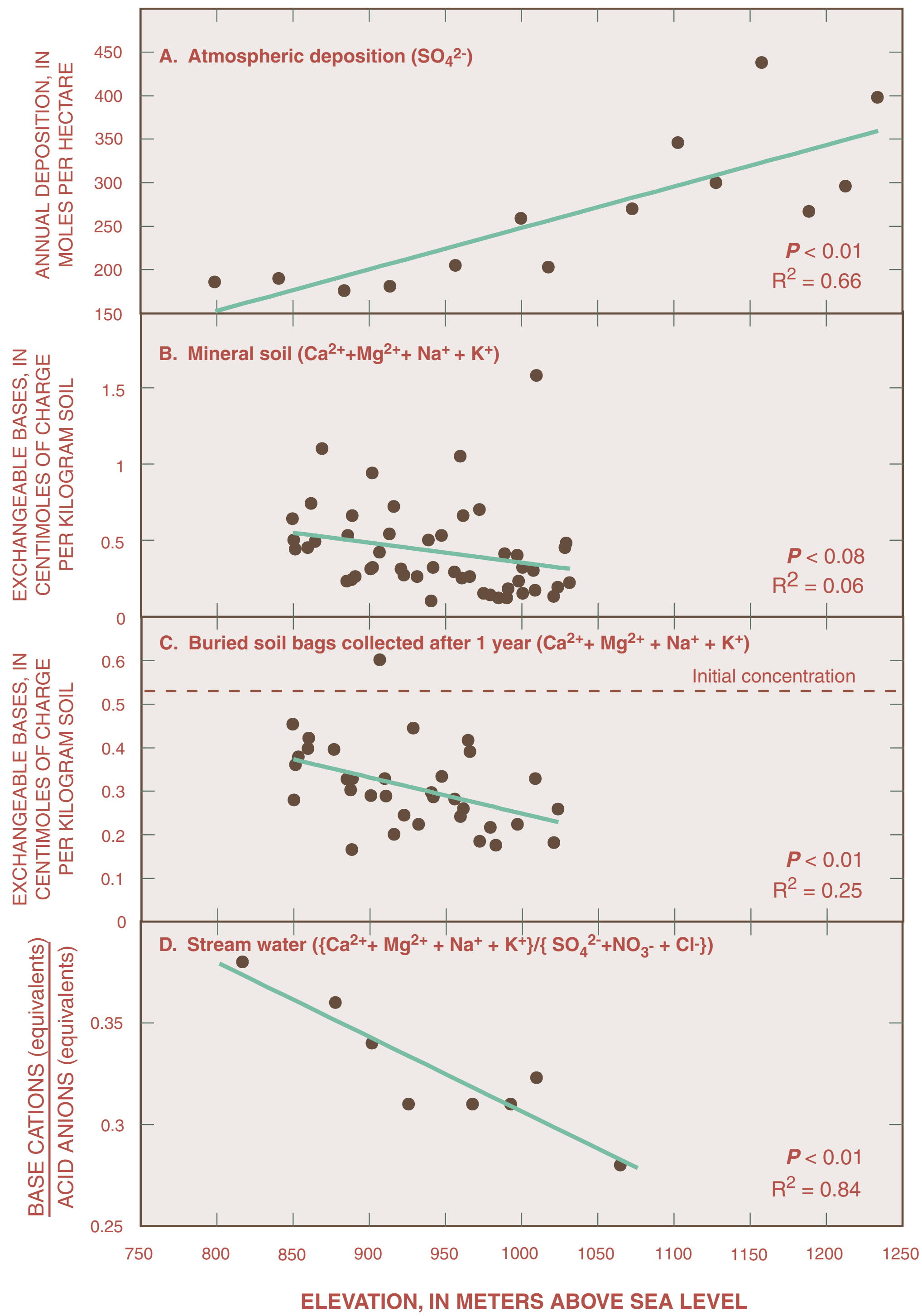


Figure 7. Elevational gradients for selected chemical constituents in Winnisook watershed; (a) annual mean atmospheric sulfate deposition; (b) exchangeable base cation concentrations in mineral soil samples; (c) exchangeable base cation concentrations in initially uniform mineral soil samples that were placed in mesh bags and leached in the mineral soil profile for one year; (d) ratio of base-cation concentrations to acid-anion concentrations from the samples collected on dates when the highest 20% of flow occurred.

and possibly deplete the exchangeable calcium reserves in the soil, however, if the leaching rate exceeds the rate at which calcium is released through weathering. Calcium leached out of the soil into surface waters is an essential nutrient for aquatic plants and animals. Therefore, an insufficient supply of calcium in the soil can adversely affect aquatic ecosystems.

Depletion of Soil Calcium In Relation to Stream Recovery from Acid Deposition

Rates of acid deposition in the Northeast have been declining since the 1970's, but most of the acidified surface waters in the region have unexpectedly shown little or no corresponding increase in pH or ANC. This lack of response has been attributed to decreases in concentrations of calcium in streamwater, a trend that is related to changes in the availability of calcium in the soil. Before the Neversink Watershed Study, however, little evidence had been obtained to link acidic deposition to changes in soil chemistry.

An elevational gradient of acidic deposition in Winnisook watershed provided a unique opportunity to evaluate the effects of varying amounts of acidic deposition on concentrations of calcium (and other base cations) in soil and stream water (Lawrence and others, 1999). Results showed that rates of atmospheric deposition of sulfuric acid increased from the lowest elevations to the highest elevations (Lovett and others, 1999), whereas the concentrations of exchangeable base cations in soil showed a reversed trend with increasing elevation (fig. 7).

To further investigate relations between atmospheric deposition rates and soil chemistry, a large quantity of soil was collected at a mid-elevation site in the Neversink watershed, where exchangeable base-cation concentrations were somewhat higher than in the Winnisook watershed. This soil was thoroughly mixed, placed in mesh bags, and reburied in the soil in stands of mixed northern hardwoods near the soil-sampling locations to equilibrate with the existing soil conditions for a year. This approach removed the effects of natural factors, such as spatial variations in soil mineralogy, to enable the possible effects of acidic deposition to be more clearly detected.

Analysis of the samples after one year confirmed a distinct upslope decrease in base cation concentrations (fig. 7C) and in base saturation (the base-cation concentration as a percentage of total cation exchange capacity of the soil). Detailed analysis of other factors that could cause an elevational gradient in soil acidity and leaching of base cations were found to have either minimal or undetectable effects. The elevational gradient of acidic deposition resulted in greater depletion of base cations in the soil bags at upper elevations than lower elevations; a result consistent with results obtained from analysis of the native soils.

The relation between atmospheric deposition and soil chemistry was also reflected in an elevational trend in stream-water chemistry. The ratio of base cations to acid anions in stream water decreased with increasing elevation, which indicated an uplsope increase in stream acidity (fig. 7D). A laboratory soil experiment demonstrated that this ratio in soil water was directly correlated with soil-base saturation. These results, therefore, link the

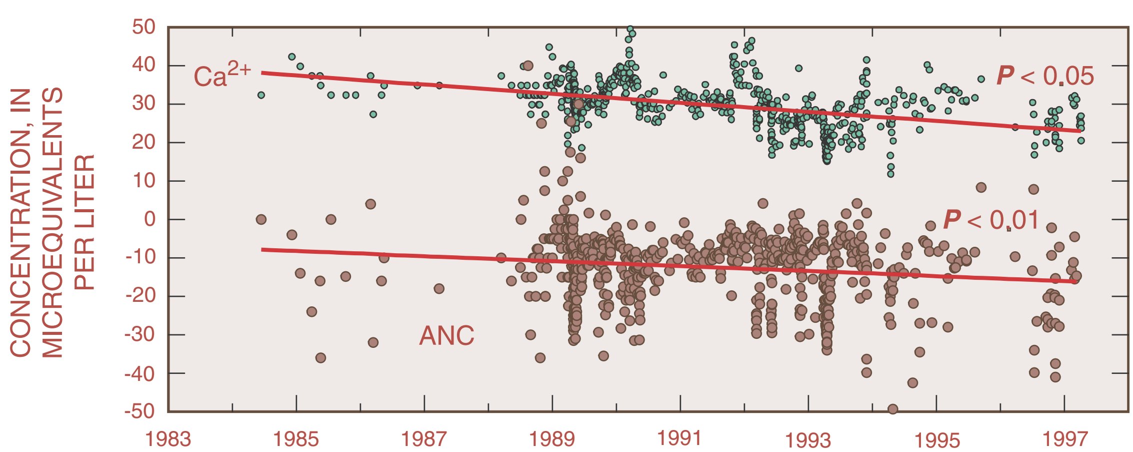


Figure 8. Calcium concentrations and acid-neutralizing capacity (ANC) of stream water in a subbasin of the Neversink River Basin.

upslope increase in atmospheric deposition to the elevational trends in calcium availability in the soil and stream-water acidification.

The relations observed in Winnisook watershed provide an explanation for why surface water acidity hasn't decreased in response to decreasing levels of acidic deposition. For the ANC of surface waters to decrease, the ratio of base cations to acid anions must increase. This ratio in soil water will not increase, however, until the base saturation increases.Therefore, a sustained recovery of surface waters will require a preceding increase in soil concentrations of available calcium. Long-term trends in concentrations of calcium and ANC in the Neversink Basin have both shown significant decreases for 1984-97 (fig.8), which indicates that soil-base saturation has decreased during this period.

ATMOSPHERIC DEPOSITION

Data from the long-term precipitation monitoring station at Biscuit Brook (data can be viewed at **http://nadp.sws.uiuc.edu/nadpdata/siteinfo.asp?id=NY68&net=NADP)** suggests that deposition of pollutants like sulfur and nitrogen are higher in the Catskills than nearly anywhere else in the Northeast. However, that single monitoring station does not tell the whole story. Atmospheric pollutants are deposited in several forms. Rain and snow are the best known, but particles, gases, and cloud droplets in the air can also deliver pollutants to forest ecosystems. Furthermore, all of these forms of deposition tend to increase with elevation in mountainous terrain. As a result, deposition levels in this mountainous watershed are even higher than the precipitation monitoring station would indicate. Research in the headwaters of the Neversink River indicates that deposition of sulfur increases by a factor of two between 750 and 1250 m elevation (fig. 7), and that most of that increase is a result of gases, particles, and cloud droplets rather than rain or snow (Lovett and others, 1999). The same pattern probably holds for the deposition of nitrogen and acidity as well. Part of the increase results from the presence of evergreen trees at the highest elevations, which effectively filter pollutants out of the air year-round. In addition, the increase in wind speed and frequency of cloud immersion also contribute to the elevational increase in atmospheric deposition. On nearby Hunter Mountain, some exposed areas such as high-elevation forest edges can receive up to four times as much deposition as the nearby lowlands (Weathers and others, 2000). Thus, there are "hot spots" of atmospheric deposition where plants, animals, and soils may be exposed to extremely high pollutant loads.

FISHERIES ASSESSMENTS

The composition of fish communities in the Neversink watershed is typical of that in upland rivers of the Northeast. Species commonly observed include brook trout, brown trout, altlantic salmon, blacknose dace, longnose dace, and slimy sculpin. Species distribution varies with (1) water quality, which is affected by acidic deposition, and (2) physical habitat factors such as channel size and stream velocity.

Effect of Stream Acidification on Fish Communities of the Neversink

Water chemistry data indicate that stream acidification within the Neversink watershed varies among reaches. Sixteen sites were grouped into four categories (minimally, moderately, strongly, and severely acidified) on the basis of mean ANC, pH, and inorganic aluminum concentrations at baseflow during a study of the relations of fish population indices to water chemistry from July 1991 through June 1994 (Baldigo and Lawrence, 2000).

The study sites differed not only in pH, ANC, and inorganic aluminum concentrations, but also in the temporal variability of these factors. Fluctuations of inorganic aluminum concentrations tended to be largest at the severely acidified sites and least at the least acidified sites. Inorganic aluminum concentrations also typically increased with increasing flows throughout the Neversink River watershed. During storms, concentrations of inorganic aluminum and pH (4.97 – 5.39) at strongly acidified sites, such as New Hill and Tisons (fig. 9) commonly exceeded the survival threshold for brook trout (inorganic aluminum = 0.200mg/L, pH = 5.0; Baldigo and Lawrence, 2000), the most acid tolerant species in the Neversink River. Concentrations of inorganic aluminum and pH appear to become toxic for varying durations at most sites in the East Branch Neversink River. Concentrations of inorganic aluminum exceeded the survival threshold for extended periods at severely acidified sites, such as Winnisook, but only rarely at the least acidic site, Main Branch and at other minimally acidified sites West Branch, Otter Pool, and Oasis Creek–2; fig. 9).

Differences in the severity of stream acidification appear to

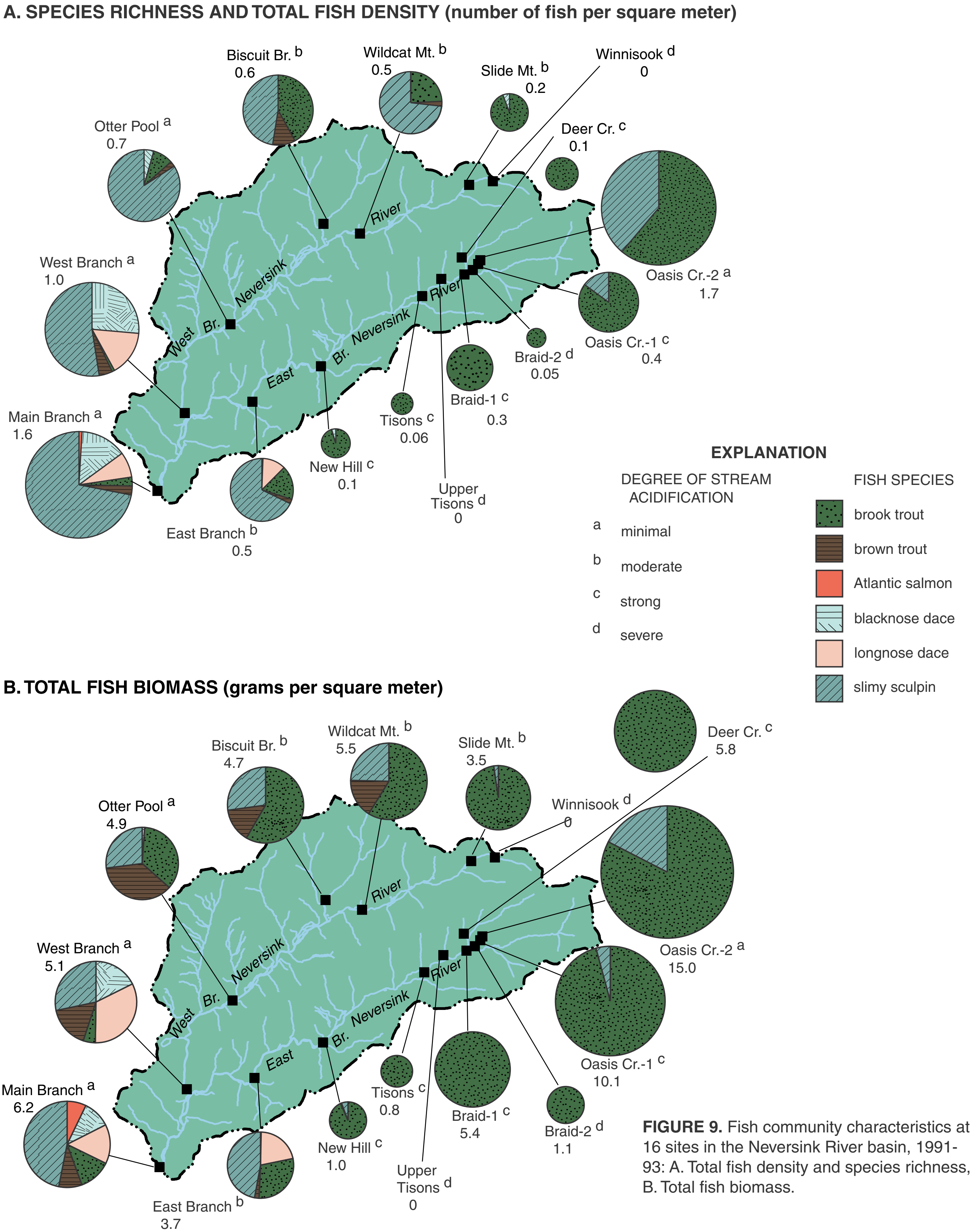


FIGURE 9. Fish community characteristics at 16 sites in the Neversink River basin, 1991-93: A. Total fish density and species richness, B. Total fish biomass.

strongly affect the distribution of fish throughout the watershed. Species richness (total number of species) and total density of fish (number of fish per m^2) were low at strongly to severely acidified sites (fig. 9). Stream habitat and changes in competition resulting from elimination of some species, however, seemed to mitigate the negative effects of acidification on the remaining fish species. Features of the habitat, rather than the degree of acidification were most strongly correlated with fish biomass (total weight of all fish). Large acid-tolerant brook trout apparently replaced smaller, and typically more numerous species such as dace and slimy sculpin at strongly acidified sites, without causing large changes in biomass. Though highly correlated with acidification factors, species richness and total density were also moderately correlated with elevation, watershed drainage area, and water temperature.

Acidification and Brook Trout Mortality

Although pH and concentrations of aluminum appear to directly affect the distribution of fish species and composition of their communities in the Neversink watershed, specific factors that control the mortality of native fish during acidification episodes have not been well characterized in previous studies. Caged, native brook trout showed increased rates of mortality in response to chronic and episodic acidification (Baldigo and Murdoch 1997). Mortality for caged, young-of-the-year brook trout became significant (>20%) when inorganic aluminum concentrations exceeded 0.200 to 0.225 mg/L for two or more days (fig. 10). This response may be attributable to the disruption of regulation of ion concentrations in blood by low pH and elevated aluminum concentrations (Baldigo and Murdoch, 1997).

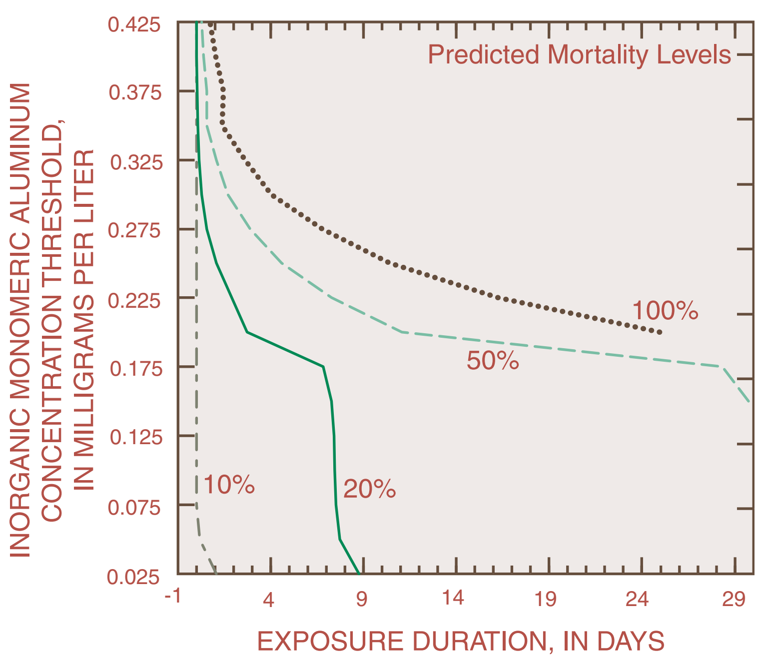


Figure 10. Estimated percent brook trout mortality as a function of exposure duration and inorganic monomeric aluminum concentration. [Modified from Baldigo and Murdoch, 1997.]

Fish mortality was greater during early spring and late fall than during other times of the year because these periods had the highest frequency of severe acidic episodes. Elevated concentrations of dissolved organic carbon in stream water during fall (after the leaves drop) increase the formation of organic-aluminum molecules that are non-toxic, and may further mitigate aluminum toxicity.

Fish Production and Soil Calcium Availability

Although stream acidification limits fish production in the Neversink watershed, several well-buffered tributary streams in the East and West Branch Neversink River provide some opportunity for reproduction. Favorable water quality, is maintained in these streams even during high flows, by the discharge of well-neutralized, ground water from deep sources. Chronically acidic streams such as that of the Winnisook watershed receive little or no inputs of ground water, and are therefore fishless. Most reaches within the Neversink watershed, however, receive sufficient amounts of ground water to prevent acidification during low flows, but become acidified during high flows when large amounts of water move through calcium-depleted soils directly into streams. Without large inputs of ground water, these streams cannot support fish during their early life-stages and provide only mediocre habitat for acid-tolerant adults. Further reductions in the diversity and densities of fish communities in the Neversink watershed are unlikely if expected decreases in atmospheric deposition of acids continue. Fish production will remain limited by chronic and episodic acidification of stream water, however, until the acid buffering ability of the soil improves.

SIGNIFICANT FINDINGS

Principle findings of the study were as follows:

1. Steep hillslopes and fractured bedrock result in discharge of groundwater with short subsurface residence times (less than a year) throughout the basin, although deep ground water tends to have sufficiently long subsurface residence times to neutralize acidic water.
2. Water discharging from soil into streams without contact with till or bedrock tends to be acidic and have elevated aluminum concentrations.
3. Riparian wetlands developed from discharging groundwater can lower nutrient concentrations before the water reaches the stream channel. However, because these wetlands tend to be small (less than an acre), they are unlikely to greatly reduce the release of nutrients to streams.
4. Once nitrate enters a stream channel, it can be taken up by algae and plants, or be converted to gaseous nitrogen through denitrification. High stream velocities and stream sediments with low organic matter content limit the effectiveness of these processes in the Neversink River, however.
5. Atmospheric deposition of nitrogen has probably increased the amount of nitrogen in the soil to a level at which it can no longer be fully retained by the forest ecosystem (nitrogen saturation), which results in the release of nitrogen to streams in the form of nitric acid.
6. Acid deposition has decreased the amount of available calcium (calcium not bound in rocks) in the soil to a level at which it cannot fully neutralize acidity in soil and stream water.
7. Acid deposition has decreased the numbers of fish and fish species in parts of the basin but has not strongly affected fish community biomass. Differences in the tolerance of fish species to acidified stream water resulted in the replacement of acid-intolerant species with acid-tolerant species in some acidified reaches of the basin.

MANAGEMENT IMPLICATIONS

The characteristics of the flow path of water as it is transformed from precipitation to stream water have important implications for water quality in the Neversink Basin. Recharge of ground water often occurs in areas remote from the stream channel, but this water can discharge at the stream channel within months or less of entering the ground-water reservoir. In some cases, the discharging water passes through a small wetland before entering the stream, but in many cases it enters the stream directly. A short subsurface-residence time and limited riparian influence means that the water entering the stream will strongly reflect the characteristics of the recharge area. If this recharge area is a healthy, growing forest, nutrient concentrations will be low, but if the recharge area is affected by agriculture or a declining forest, then nutrient concentrations could be relatively high. The traditional approach of using buffer strips along the stream channel to protect water quality, therefore would have limited success in a watershed such as the Neversink. Because the geology of the Neversink River watershed is typical of the Catskill Mountains, this type of hydrologic system is likely to be common in other watersheds in the Catskill Mountain region from which New York City derives it’s water supply.

Several decades of acidic deposition have led to large amounts of available nitrogen and low amounts of available calcium in the forest soils of the basin. This condition causes low pH and elevated aluminum concentrations that often exceed toxic levels for fish, and has degraded water quality throughout much of the Neversink River. The low growth rates and population densities of fish communities present under these conditions means that the natural fishery in parts of the Neversink River probably cannot support even a moderate level of sport fishing.

Water chemistry of the Neversink River also suggests the possibility of a nutrient imbalance in the forest ecosystem. The relatively high concentrations of nitrate in Neversink stream water suggest that the soils have reached nitrogen saturation. Like nitrogen, calcium is an essential nutrient for tree growth, but has generally been considered to be in sufficient supply in forest ecosystems. Depletion of calcium coupled with nitrogen saturation, however, may have resulted in a nutrient imbalance in the Neversink forests. This condition could potentially result in a decreased tolerance of trees to stresses such as drought, air pollution, and insect infestations, which could lead to decreased forest growth and increased release of nutrients to surface waters. The long-term health of the forest is therefore an important factor in sustaining the supply of high quality drinking water.

REFERENCES CITED

Ashby, J.A., Bowden, W.B., and Murdoch, P.S., 1998, Controls on denitrification in riparian soils in headwater catchments of a hardwood forest in the Catskill Mountains, U.S.A.: Soil Biology and Biochemistry, v. 30, p. 853-864.

Baldigo, B. P., and Murdoch, P. S., 1997. Effect of stream acidification and inorganic aluminum on mortality of brook trout *(Salvelinus fontinalis)* in the Catskill Mountains, New York: Canadian Journal of Fisheries and Aquatic Sciences, v. 54, p. 603-615.

Baldigo, B. P., and Lawrence, G. B., 2000. Composition of fish communities in relation to stream acidification and habitat in the Neversink River, New York: Transactions of the American Fisheries Society, v. 129, p. 60-76.

Brown, V.A., McDonnell, J.J., Burns, D.A., and Kendall, C., 1999, The role of event water, rapid shallow flowpaths, and catchment size in summer stormflow: Journal of Hydrology, v. 217, p. 171-190.

Burns, D.A., 1998, Retention of NO_3^- in an upland stream environment: A mass balance approach: Biogeochemistry, v. 40, p. 73-96.

Burns, D.A., Murdoch, P.S., Lawrence, G.B., and Michel, R.L., 1998, The effect of groundwater springs on NO_3^- concentrations during summer in Catskill Mountain streams: Water Resources Research, v. 34, p. 1987-1996.

Burns, D.A., and Kendall, C., in review, Sources of NO_3^- in drainage water of two Catskill Mountain watersheds differentiated through analysis of ^{15}N and ^{18}O, Water Resources Research.

Hall, B.R., 1997, Environment-plant species relationships in groundwater seeps in the Catskill Mountains of New York, M.S. Thesis, State University of New York, College of Environmental Science and Forestry, Syracuse, New York, 83 p.

Lawrence, G.B., Burns, D.A., Murdoch, P.S., and others, 1995, Workplan of the Neversink Watershed Study: U.S. Geological Survey Open-File Report 94-368.

Lawrence, G.B., David, M.B., Lovett, G.M., and others, 1999, Soil calcium status and the response of stream chemistry to changing acidic deposition rates in the Catskill Mountains of New York: Ecological Applications, v. 9, p. 1059-1072.

Lawrence, G. B., Lovett, G. M., and Baevsky, Y. H., 2000, Atmospheric deposition and watershed nitrogen export along an elevational gradient in the Catskill Mountains, New York: Biogeochemistry, v. 50, p. 21-43.

Lovett, G.M., Thompson, A.W., Anderson, J.B., and Bowser, J.J., 1999, Elevational patterns of sulfur deposition at a site in the Catskill Mountains, New York, Atmospheric Environment, v. 33, p. 617-624.

Murdoch, P.S., Burns, D.A., and Lawrence, G.B., 1998, Relation of climate change to the acidification of surface waters by nitrogen deposition: Environmental Science and Technology, v. 32, p. 1642-1647.

Weathers, K.C., Lovett, G.M., Likens, G.E., and R. Lathrop, 2000, The effect of landscape features on deposition to Hunter Mountain, Catskill Mountains, New York: Ecological Applications, v. 10, p. 528-540.

Wolock, D.M., Fan, J., and Lawrence, G.B., 1997, Effects of basin size on low-flow stream chemistry and subsurface contact time in the Neversink River watershed, New York: Hydrological Processes, v. 11, p. 1273-1286.

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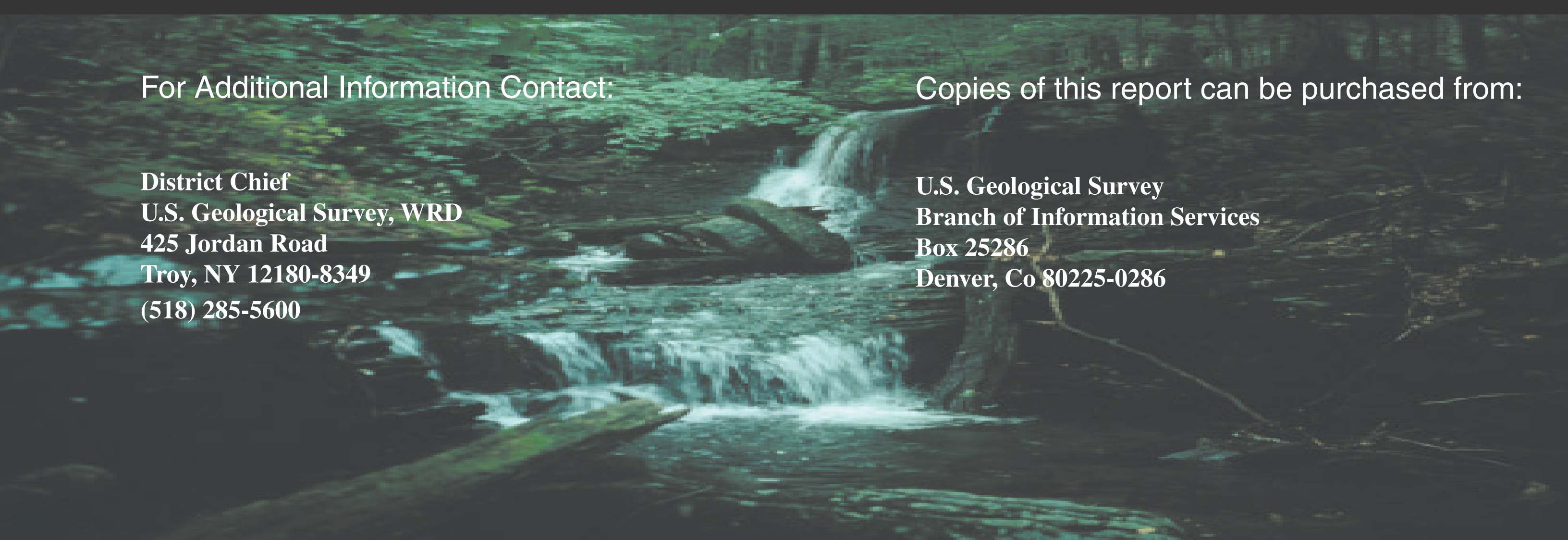

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