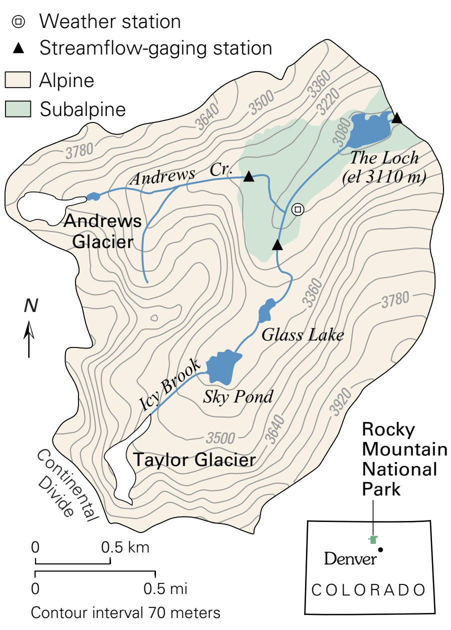
Loch Vale, Colorado

A Water, Energy, and Biogeochemical Budgets Program Site

Alpine and subalpine ecosystems are vulnerable to impacts from acidic deposition and changes in climate because they have a short growing season, and large amounts of snowmelt are released from deep seasonal snowpacks in the spring (Campbell and others, 1995). Research at the Loch Vale Watershed provides process-level information that augments synoptic and long-term monitoring of atmospheric deposition and water quality in other sensitive Rocky Mountain ecosystems. Together, these research and monitoring studies support policy decisions by other government agencies regarding natural resource management issues.

The Loch Vale Watershed drains 661 hectares of alpine and subalpine terrain in Rocky Mountain National Park, about 100 kilometers northwest of Denver, Colorado. The western boundary of the watershed is the Continental Divide; streams drain to the northeast. The basin ranges in elevation from 3,110 meters (10,200 feet) at the outlet to 4,192 meters (13,153 feet) at Taylor Peak. The two main tributaries in Loch Vale—Andrews Creek and Icy Brook—join above the Loch, which is the lowest of three lakes in the watershed. Streamflow gages are operated on Andrews Creek, Icy Brook, and at the outlet of The Loch.

The Loch Vale watershed is located in a roadless area of Rocky Mountain National Park.



Geomorphology in Loch Vale is typical of recently glaciated terrain in the southern Rockies. The lower, forested part of the watershed is a U-shaped valley overlain by poorly developed soils formed on thin, patchy till. The steep valley sidewalls are mostly unvegetated and are characterized by bedrock cliffs that are mantled with talus near the base. Small glaciers, permanent snowfields, and rock glaciers occupy cirques in the headwater areas. Tundra is found along the ridge tops. Climate in Loch Vale is characterized by long, cold winters with short growing seasons (3–4 months). Precipitation averages 123 centimeters per year (1983–97) of which about 75 percent accumulates in a seasonal snowpack from November through April. Melting of the snowpack is the major hydrologic event of the year; over 60 percent of the annual streamflow typically occurs in June and July. Average annual runoff (1992–97) from Andrews Creek and Icy Brook was 100 and 78 centimeters, respectively.

Hydrologic Processes

One of the objectives of the WEBB study has been to improve the understanding of hydrologic processes in snowmelt-dominated watersheds. Isotopic and chemical tracers were used as tools to evaluate sources and flowpaths of water in Andrews Creek during the 1994 snowmelt season (Mast and others, 1995). Bulk snowpack, snowmelt, rain, and streamwater samples were analyzed for $\delta^{18}O$ and dissolved silica. Hydrograph separation calculations based on $\delta^{18}O$ were used to estimate premelt versus snowmelt (old versus new) sources of water to the stream. Hydrograph separations based on silica indicated how precipitation was transported to the stream—through the subsurface or overland.

Loch Vale basin, looking upstream from the Loch outlet

THE WEBB PROGRAM

The Water, Energy, and Biogeochemical Budgets (WEBB) Program was started in 1991 at five small watersheds in the United States to examine water, energy, and biogeochemical fluxes and to determine the effects of atmospheric deposition, climatic variables, and human influences on watershed processes.

The five sites are at Loch Vale, Colorado; Luquillo Experimental Forest, Puerto Rico; Panola Mountain, Georgia; Sleepers River, Vermont; and Trout Lake, Wisconsin. These sites are supported, in part, by other programs in the USGS, other Federal and State Agencies, and Universities.

U.S. Department of the Interior
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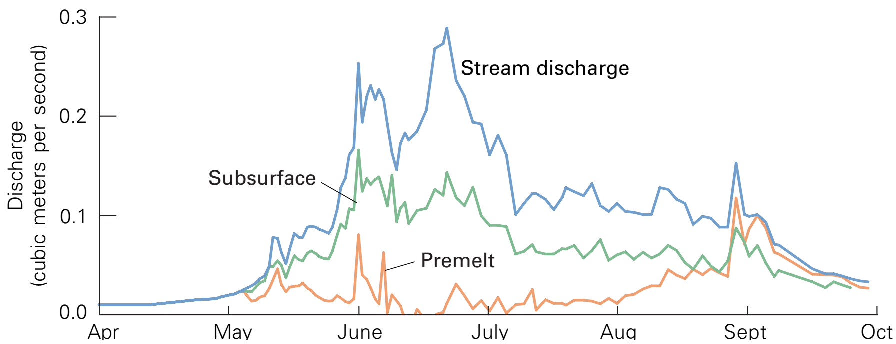


Premelt component of streamflow from hydrograph separations using $\delta^{18}O$ measurements; subsurface contribution to streamflow from hydrograph separations using silica; and total stream discharge.

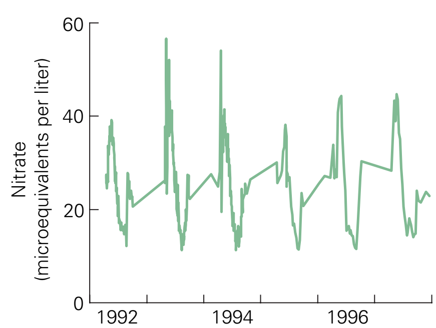
Calculations based on $\delta^{18}O$ indicate that premelt water was a significant component of streamflow only at the beginning of the melt cycle, accounting for 33 percent of flow before June 1 but only 17 percent of flow for the entire season. This suggests that streamflow at the beginning of melt is derived primarily from premelt water that is displaced into the stream by infiltrating snowmelt. As melt continued, premelt water was eventually flushed from soils and shallow subsurface reservoirs. Afterwards streamflow was almost entirely generated by recent snowmelt. The apparent increase in the premelt component in late summer probably is an artifact of the model and represents recharge of subsurface reservoirs by isotopically heavy summer rains.

Most streamflow is derived from melting snow, although much of it passes through soil before entering the stream.

Calculations based on silica indicate that flow through the subsurface accounted for more than 75 percent of streamflow during the initial stages of snowmelt and about 45 percent during the peak-flow period (overland flow accounted for the rest). This result indicates that even at peak discharge, as much as half of snowmelt moves through soil and shallow subsurface reservoirs before discharging into the stream.

Nitrogen Deposition and Cycling

Atmospheric deposition of two forms of nitrogen—nitrate and ammonium—is higher in the Front Range of Colorado than in many other parts of the Rocky Mountains, although it is moderate compared to other regions, such as northern Europe and the northeastern United States. Elevated nitrogen deposition can result from atmospheric emissions of nitrogen compounds from many human activities, such as agriculture (crop or livestock production) and fossil-fuel combustion (automobiles, electric power generation, or industrial operations). In most undisturbed watersheds, nitrogen is used to meet nutrient requirements of the ecosystem, and little nitrogen is exported in streamflow. In the Front Range, however, nitrogen in atmospheric deposition exceeds nutrient requirements. Consequently, there is export of nitrate in streams even during the growing season when biological demand for nitrogen is greatest. Excess stream-water nitrogen can result in changes in natural biogeochemical cycling that lead to acidification or eutrophication of lakes and streams, diminished ecosystem health, and changes in terrestrial or aquatic species composition.



Nitrate export in Andrews Creek peaks during snowmelt, as nitrogen is released from both soil and the snowpack. Peak nitrate concentrations sometimes exceed 50 microequivalents per liter (μeq/L). Biological demand for nitrogen causes nitrate concentrations in the stream to fall to a minimum of around 10 μeq/L during summer before rising to 20–30 μeq/L during fall and winter.

For water years 1992–97, annual nitrogen export from two tributary streams in the Loch Vale Watershed was not directly related to annual nitrogen deposition, indicating that ecosystem biogeochemical processes (nitrogen-cycling) controlled the release of nitrogen (Campbell and others, 2000). There was a positive relation between annual nitrogen retention and annual nitrogen deposition, indicating that parts of the ecosystem are nitrogen-limited. However, a large percentage of these watersheds are covered by bare rock and talus deposits that have little capacity for nitrogen assimilation and large potential for mineralization and nitrification. Even in the areas with sparse vegetation and soil, the nitrate in streams and ground water has an isotopic signature ($\delta^{15}N$ and $\delta^{18}O$) that is distinct from that of nitrate in atmospheric deposition, as expected when nitrogen from deposition is cycled through biological processes (Kendall and others, 1995). Because of the importance of biological processes, climatic factors also play a role in controlling export of atmospherically deposited nitrogen from alpine/subalpine watersheds.

N-cycling in plants and soils, as well as direct flushing of nitrogen from atmospheric deposition, controls watershed export of N.

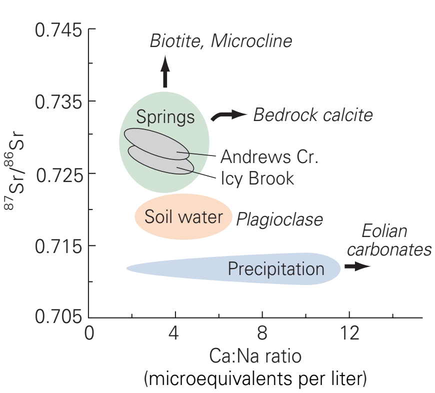
Sources of Alkalinity and Base Cations

Geochemical processes, including mineral weathering, cation exchange, and adsorption/desorption, are major sources of solutes to stream water in alpine/subalpine environments. Of these processes, mineral weathering is the main long-term source of alkalinity, silica, and base cations, and also is an important sink for CO_2 in the atmosphere. The amount of alkalinity produced or CO_2 consumed by mineral weathering depends on the types of minerals involved. Weathering of carbonate minerals generally produces more alkalinity and consumes less CO_2 than weathering of silicate minerals.

Isotopes of Sr have been used in Loch Vale to identify mineral weathering reactions and to evaluate sources of Ca in natural water. The Sr-isotope technique takes advantage of the fact that Sr substitutes for Ca in mineral lattices, and each type of mineral tends to have a different $^{87}Sr/^{86}Sr$ ratio. When different types of minerals weather, they release Sr with a unique $^{87}Sr/^{86}Sr$ ratio, imparting a signature on the interacting water. Results indicate that about one-quarter of the annual flux of calcium in surface water in Loch Vale was derived from silicate weathering, one-half came from weathering of bedrock calcite, and the remaining one-quarter was from eolian carbonates (Clow and others, 1997).

> About one-quarter of the calcium in streams is derived from silicate minerals, one-half is from bedrock calcite, and the remainder is from eolian calcite.

The relative importance of mineral weathering reactions differs according to landscape because of differences in the mineralogic and hydrologic characteristics of those landscapes. These differences in weathering reactions are exemplified in a plot of $^{87}Sr/^{86}Sr$ against Ca/Na ratios. Low $^{87}Sr/^{86}Sr$ and high Ca/Na ratios in precipitation and bedrock runoff indicate that these water types are strongly influenced by dissolution of eolian carbonates. Soil water has a somewhat higher $^{87}Sr/^{86}Sr$ and lower Ca/Na ratio, indicating that it is influenced more by weathering of silicate minerals than carbonates. Stream and spring water have even higher $^{87}Sr/^{86}Sr$ ratios, indicating that they are influenced by weathering of biotite, microcline, and bedrock calcite.

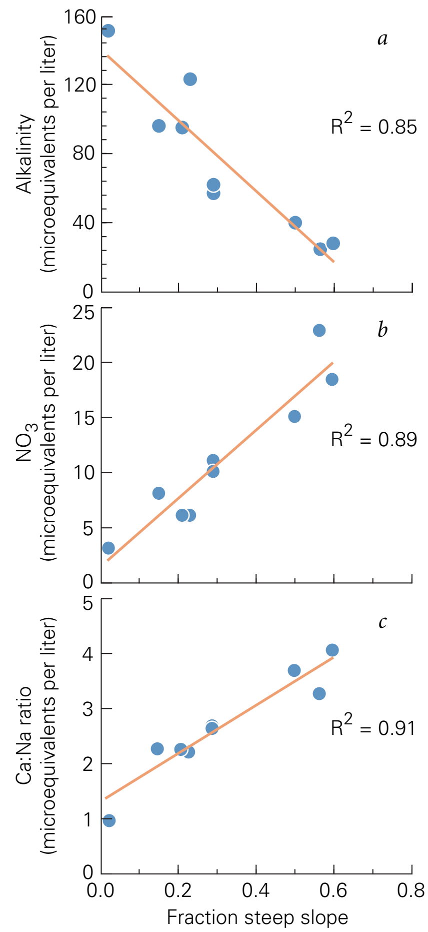


Relation between $^{87}Sr/^{86}Sr$ and Ca/Na for various water types in Loch Vale.

Basin Characteristics and Stream-Water Chemistry

Relations between stream-water chemistry and topographic, vegetative, and geologic characteristics of basins were evaluated for nine alpine/subalpine watersheds in Rocky Mountain National Park (Clow and Sueker, 2000) to improve the understanding of processes regulating stream-water chemistry and solute fluxes in alpine/subalpine watersheds.

Fractional amounts of steep slopes (>30˚), unvegetated terrain, and young geologic deposits within each watershed were positively correlated to each other. These terrain features, which commonly are found on steep valley sidewalls that are covered by talus, were inversely correlated with concentrations of base cations, silica, and alkalinity in steam water and were positively correlated with nitrate, pH, and runoff. These relations probably are due to the short residence times and limited soil development in the talus environment, which limit chemical weathering and nitrogen uptake. Steep, unvegetated terrains also tend to promote high Ca/Na ratios in stream water, probably because high physical weathering rates in those areas expose fresh bedrock that contains interstitial calcite, which weathers relatively quickly. The fractional amounts of subalpine meadow and old geologic debris in the watersheds were positively correlated to concentrations of Ca, Na, and alkalinity, and inversely correlated to nitrate and pH. This may reflect more opportunities for silicate weathering and nitrogen uptake in the lower-energy environments of the valley floor, where soils are better developed than those on the steep valley walls and where slopes are relatively flat.



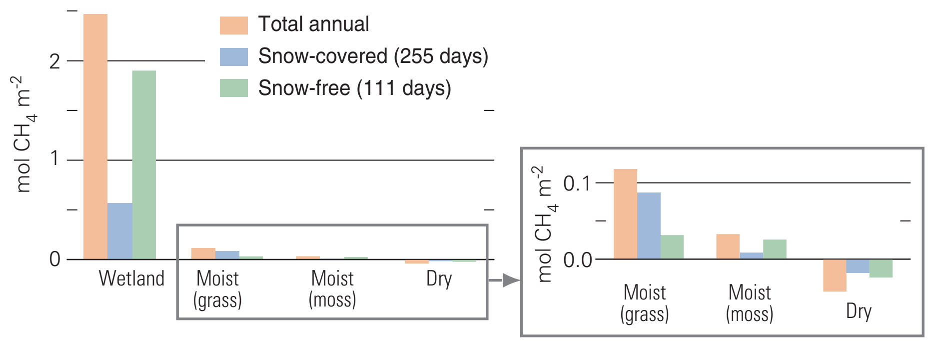
Relationships between fraction of steep slopes (>30˚) and concentrations of (a) alkalinity, (b) NO_3, and (c) Ca/Na ratios in stream water.

Carbon Gas Exchange

Carbon dioxide (CO_2) and methane (CH_4) are gases produced by soil microbial organisms during decomposition of organic materials. Microbes that produce CO_2 are found in aerobic soils that typically have low moisture content, whereas CH_4 producers live in anaerobic soils that are saturated. CH_4 also is consumed by microbes that live in aerobic soils. The rates of CO_2 and CH_4 exchange between soils and the atmosphere were measured along a moisture gradient that included a wetland with standing water, soils on the wetland perimeter with intermediate moisture content, and dry soils. These different areas are representative of some of the soil and vegetation types found in the Loch Vale Watershed. The goals of the study were (1) to estimate CO_2 and CH_4 exchange on an annual scale, (2) to determine the importance of exchange during snow-covered periods, and (3) determine the influence of environmental factors, such as soil temperature and moisture, on CO_2 and CH_4 exchange rates.

On an annual basis, the wetland and moist soils emitted CH_4 and the dry soils consumed CH_4. Exchange during

Annual, snow-covered, and snow-free period methane exchange from four soil types. Fluxes are expressed as moles of methane per square meter of land surface. Positive values are CH_4 emission from the soil to the atmosphere and negative values are fluxes from the atmosphere to the soils.



snow-covered periods was significant, accounting for 25 to 73 percent of the total annual CH_4 exchange (Wickland and others, 1999). Microbial activity continues through the winter because the deep snowpack provides insulation from cold air temperatures and prevents the soil from freezing (Mast and others, 1998). The spatial pattern of CH_4 exchange was related to soil-moisture content during snow-covered and snow-free periods. CO_2 emissions exhibited an opposite spatial pattern; CO_2 emissions increased as soil moisture decreased. CO_2 emissions during snow-covered periods accounted for 8 percent, 12 percent, and 23 percent of annual emissions from wetland, moist, and dry soils, respectively (Mast and others, 1998).

> CO_2 and CH_4 fluxes in winter are a substantial part of the annual carbon gas budget in seasonally snow-covered basins.

—D.W. Clow, D.H. Campbell, M.A. Mast, R.G. Striegl, K.P. Wickland, and G.P. Ingersoll

SUMMARY

- The response of high-elevation ecosystems to perturbations such as climatic extremes and atmospheric deposition is dependent on landscape characteristics such as topography, geology and vegetation.
- Most streamflow is derived from melting snow, although much of it is transported along shallow soil and groundwater flowpaths before entering the stream.
- Soil and vegetation are sparse in alpine landscapes, but they are important in controlling the seasonal pattern and chemical composition of streamflow.
- Soil microbial activity continues during the winter months under deep snowpacks and is important in controlling cycling of carbon and nitrogen.
- Naturally occurring isotopic and chemical tracers have proven useful for determining sources of water and solutes in remote areas where conventional hydrologic measurements are impractical.

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COLLABORATORS

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Collaborators include the National Weather Service, National Center for Atmospheric Research, University of Colorado, Colorado State University, University of Arizona, University of Wyoming, University of California, University of British Columbia, University of Southern Mississippi, and E&S Consulting.

For more information about the Loch Vale WEBB study visit:

http://co.water.usgs.gov/lochvale/

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