Surface water chemistry and chemical budgets, alpine and subalpine watersheds, Fraser Experimental Forest, Colorado

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Abstract One of the primary purposes for establishing the Fraser Experimental Forest (FEF) in 1937 was to assess the long-term effect of vegetation removal on watershed hydrology. Beginning in the mid-1960s, the study was extended to include watershed chemical budgets and nutrient cycles. Annual precipitation at the FEF averages 74 cm. Two-thirds falls as snow. Annual stream-water discharge averages 36 cm. Most runoff occurs during 15 May-1 July. Snowfall and snowpack water equivalent (SWE) significantly increase with elevation and on northeast-aspect slopes. Canopy interception of snowfall exceeds 30%, and significantly reduces SWE. Ca²⁺ and SO₄²⁻ are the dominant ions in precipitation, and Ca²⁺ and HCO₃⁻ in stream water. Watershed chemical input/output budgets show strong (>95%) retention of precipitation H⁺, NH₄⁺, and NO₃⁻ input. Hydrologic variation accounts for most change in stream-water ion concentration and flux especially in subalpine catchments. Long-term study shows small clearcuts increase snowpack peak water equivalent (PWE) by 50%, the PWE load of NH₄⁺ by 106%, NO₃⁻ by 62%, and SO₄²⁻ by 14% relative to adjacent mature forested plots. Clearcuts elevate subsurface and stream-water NO₃⁻ concentration and flux relative to the control even after 10 years. Increased precipitation inputs, elevated decomposition in the organic layer, and reduced plant uptake in clearcuts likely account for the elevated inorganic N concentration and flux.

INTRODUCTION

Few long-term, watershed-level studies of chemical budgets and mineral nutrient cycles exist in the western U.S. To detect trends in budgets and processes from land disturbance and/or inputs of atmospheric contaminants requires good hydrologic data because of the effect hydrology exerts on chemical variation (Stottlemyer & Troendle, 1992).

The Fraser Experimental Forest (FEF) was established in 1937. It is located 137 km west of Denver, Colorado, contains 9700 ha, and ranges in elevation from 2665 to 3880 m (Fig. 1). A principal reason for its establishment was to examine long-term hydrologic
response to vegetation manipulation (Alexander et al., 1985; Reuss et al., 1994; Troendle et al., 1994). The hydrologic record and opportunity to manipulate vegetation in a watershed context provided the impetus to initiate studies in the mid 1960s quantifying ecosystem nutrient budgets and cycling (Stottlemyer & Ralston, 1970), and their response to land use disturbance (Reuss et al., 1994).

The objective of this paper is to briefly summarize our understanding of chemical budgets for these alpine/subalpine watershed ecosystems, the effect of canopy removal on solute quantity and quality in the snowpack, and the effect of clearcutting on solute discharge in soil and stream water. Potential watershed responses to atmospheric inputs are addressed elsewhere (see Stottlemyer, 1995, this volume).

METHODS

At the FEF, nine watersheds are gauged from early April to early November and routinely sampled for surface water chemistry. The nine consist of three undisturbed alpine, two undisturbed subalpine, and four manipulated subalpine drainages. Most
watersheds have >12 years of surface water chemistry measurements. Principal
watersheds include the coterminous Lexen (mean elevation 3250 m, area 124 ha) and
Deadhorse (3189 m, 278 ha) catchments with eastern aspects, and coterminous East
St. Louis (3286 m, 803 ha) and Fool Creek (3180 m, 297 ha) watersheds. The Fool
Creek watershed was gauged in 1940, East St. Louis, the primary control watershed,
was gauged in 1943, and Lexen and Deadhorse creeks were gauged in 1955. The
alpine portion of Fool Creek has been continuously monitored since 1985. In addition,
two small (<7 ha) gauged alpine catchments were established in 1987 in the
headwaters of the East St. Louis watershed. Six meteorological stations are within or
coterminous with the watersheds, and include Aerochem Metric wet-fall samplers at
2905 and 3400 m elevations.

The bedrock of both Lexen and Deadhorse watersheds includes some sedimentary
sandstone remnants at upper elevations over gneiss and schist bedrock. Such remnants
are absent in the Fool and East St. Louis watersheds. All watersheds were glaciated
and the streams flow over moraines at varying elevations. Soils are principally
Inceptisols with surface CEC averaging about 20 mmol·100 g⁻¹ (Retzer, 1962). Soil
pH ranges from 4.5 to 6.1. Soil base saturation averages about 10 mmol·100 g⁻¹.
Canopy vegetation along stream bottoms, northern slopes, and upper elevations
consists of old growth Engelmann spruce (Picea engelmannii) and subalpine fir (Abies
lasiocarpa). Lodgepole pine (Pinus contorta) generally dominates lower and
mid-elevation southern aspects. Alpine tundra occurs at about 3350 m (Alexander
et al., 1985). The climate of the FEF is cool, humid with long cold winters and short,
cool summers (Alexander et al., 1985). Soils remain unfrozen throughout winter
except for some exposed locations.

A variety of plot and watershed experiments at FEF have examined the effect of
forest manipulation on precipitation and solute inputs and their retention (Troendle
& Nellis, 1986; Stottlemyer, 1987a; Reuss et al., 1994). Fool Creek was partially
clearcut in 1955-1956 to test the effect of timber harvest on water yield. The control
or undisturbed watershed is East St. Louis. In the 1970s, two sub-basins within the
Deadhorse Creek watershed were gauged to later assess the hydrological and chemical
response to three patterns of forest removal (Troendle, 1983; Troendle & King,
1987). The control watershed is Lexen Creek. Complementary experiments were
initiated in 1980 on clearcut and vegetated plots designed to define further the effect
of forest removal on the amount and quality of soil solution and its transport
mechanisms (Troendle & Nellis, 1987; Reuss et al., 1994). Other forest response
research, at other FEF sites, has focused on change in canopy interception, deposition
of precipitation, and snowpack ion load in proximity to a clearcut (Troendle &
Meiman, 1984; Stottlemyer, 1987a; Schmidt & Troendle, 1989; Stottlemyer &
Troendle, 1994).

Details of the field and laboratory methods for these specific studies can be found
elsewhere (Troendle & Meiman, 1984; Stottlemyer, 1987a; Stottlemyer & Troendle,
1987, 1992; Troendle & King, 1987). At the FEF, stream-water samples have been
collected weekly from April to November since 1982 (weekly surface water chemistry
also exists for 1965, 1970-1971). At all sites, sampling frequency is accelerated to 2-4
times per week during snowmelt. Chemical analyses include macro ions, Al, N, P,
and DOC. Analyses are done inhouse with external quality assurance agreements with
EPA, USGS, and universities (Stottlemyer, 1987b).
RESULTS AND DISCUSSION

Precipitation

Annual precipitation over the FEF averages 74 cm, and is uniformly distributed over the year. Two-thirds falls as snow. Precipitation significantly increases with elevation (Meiman, 1987; Stottlemyer & Troendle, 1994). Due to terrestrial moisture deficits in summer, rainfall produces little stream-water discharge, but is quantitatively lost through evapotranspiration (Troendle & King, 1987). About 95% of all streamflow originates as melting snow (Troendle & Kaufmann, 1987).

The dominant cation is Ca$^{2+}$ and the dominant anion in precipitation wetfall is SO$_4^{2-}$. After 8 years of monitoring at 2905 and 3400 m elevation, we have found no significant difference in ion concentration with elevation (Stottlemyer & Troendle, 1992, 1994). Windborne dust inputs cause high variation in base cation (C$_B$) concentrations. Other studies in Colorado have found significant increases in anthropogenic ion concentration with elevation change from 1100 to 3350 m (Lewis et al., 1984). Chemical species of likely anthropogenic origin, H$^+$, NH$_4^+$, NO$_3^-$, and SO$_4^{2-}$, have low concentrations at FEF relative to other precipitation monitoring stations in the region. However, high precipitation amounts at the FEF result in total loads similar to many National Atmospheric Deposition Program (NADP) stations throughout the state (NADP, 1991). Precipitation ion load does significantly increase with elevation at FEF (Stottlemyer & Troendle, 1992, 1994) because of the strong orographic effect on precipitation amount. The most consistent are increased NO$_3^-$ and NH$_4^+$ loading with increased elevation.

Precipitation interaction with forest canopy

Canopy interception and subsequent loss of snowfall can average >30% (Troendle, 1983). The percentage intercepted is a function of aspect, vegetation type, size of precipitation events, snow density, and total winter input, and can exceed 50% on north-facing slopes due mainly to the more dense canopy (Schmidt & Gluns, 1992; Troendle et al., 1994). The intercepted snowfall is mostly sublimated and results in a significant reduction in snowpack water equivalent (SWE) relative to adjacent open areas (Schmidt & Troendle, 1989; Stottlemyer, 1987a; Stottlemyer & Troendle, 1994; Troendle et al., 1994).

The effect of forest canopy removal on snowpack solute content can therefore be very pronounced. For 8 years, snowpack peak water equivalent (PWE), ion concentration, ion loading, and the spatial distribution of ion load in the snowpack has been monitored in a 2-ha clearcut and conterminous up- and down-wind forested plots vegetated by mature spruce-fir (Stottlemyer, 1987a; Stottlemyer & Troendle, 1994). Canopy removal and attendant reduced interception increased the snowpack PWE by almost 50%, the load of NH$_4^+$ by 106%, NO$_3^-$ by 62% and SO$_4^{2-}$ by 14% relative to adjacent forested plots. In part, increased concentrations of NH$_4^+$ (46%) and NO$_3^-$ (21%) in the treated plot caused the load gain. As found in other studies (Cronan, 1980) in conifer forests, lichens are present in the mature canopy at FEF, and likely reduce inorganic N inputs beneath the canopy. The absence of canopy debris and leachates in
the open reduced snowpack H\(^+\) ion concentration and load, decreased leaching of snowpack organic debris and significantly reduced K\(^+\) concentration and loading. Other C\(_B\) showed no significant difference in concentration or loading with canopy removal.

**Snowpack and solute content**

Snowpack PWE averages about 38 cm on the FEF, but is quite variable in time and space. For example, from 1966 to the present the mean PWE for the Lexen Creek watershed has varied from a high of > 60 cm in 1971 to a low of 17 cm in 1981, and can increase by 25% per 300 m increase in elevation. Aspect is also a major factor. At a given elevation, the PWE on a south aspect slope is much reduced from that on the opposing slope (Troendle *et al.*, 1994). Higher snowpack evaporation accounts for two thirds of the difference and greater late winter melting for one-third. Winter thaws reduce the snowpack ion concentration and content on south aspect slopes before peak snowmelt begins (Stottlemyer & Troendle, 1994).

Snowpack ion concentration, in contrast to wet fall, generally increases with elevation. Reduced mid-winter thawing of the snowpack at higher elevations accounts for some of the increase. NH\(_4^+\) and NO\(_3^-\) are the most consistent (Stottlemyer & Troendle, 1994). Most ion concentrations are also significantly higher on northeast aspects. Snowpack NH\(_4^+\) and NO\(_3^-\) load is generally highest in the alpine or at the alpine/subalpine ecotone. Here peak snowpack N content can be > 1 kg inorganic N ha\(^{-1}\). With snowmelt, alpine soil water NO\(_3^-\) concentration is generally greater than at lower elevations, but there are no correlations between weekly snowpack ion loss and soil water chemistry or soil water and stream-water chemistry.

**Effect of vegetation removal on soil water chemistry**

A decade of study on the effects of clearcutting on subsurface flow processes and chemical export shows NO\(_3^-\) concentration and flux at the base of a 200-m slope still elevated relative to the control (Troendle & Nellis, 1987; Reuss *et al.*, 1994). NO\(_3^-\) was the most responsive ion following harvest, and NO\(_3^-\) flux increases offset declines in HCO\(_3^-\) flux that were also observed.

**Stream-water and solute discharge**

Annual stream-water discharge averages about 36 cm or 48% of inputs (Alexander *et al.*, 1985). Most of this runoff occurs during 15 May-1 July, following snowmelt. Stream water is moderately well buffered except for alpine catchments (Stottlemyer & Ralston, 1970; Stottlemyer & Troendle, 1987, 1992, 1994). Stream-water chemical content significantly varies among watersheds as a function of geologic substrate (Stottlemyer & Ralston, 1970; Stottlemyer & Troendle, 1987). Differences in stream-water quality are most pronounced for Ca\(^{2+}\) and HCO\(_3^-\) which are elevated in Lexen and Deadhorse creeks, where residual sandstone lenses exist. Surface water chemistry, in general, is representative of most alpine/subalpine catchments in the Central Rocky Mountains.
Input/output chemical budgets for all subalpine watersheds show strong retention for most atmospheric contaminant inputs (Stottlemyer & Troendle, 1987, 1994). Greater than 98% of H\(^+\), 95% of NH\(_4\)\(^+\), and 97% of NO\(_3\)\(^-\) inputs are retained in subalpine watersheds. The alpine catchment with the longest record (Fool Creek alpine) shows similar retention patterns. SO\(_4\)\(^2-\) output exceeds inputs by about 15% suggesting some combination of geologic weathering, dry deposition inputs, and/or low ecosystem retention. For those streams with highest ion concentration, the output of Ca\(^2+\), Mg\(^2+\), Na\(^+\), and K\(^+\) is, respectively, 16, 23, 2, and 1.2 times input. Since 1981, no significant trends in surface water chemistry have been found.

At the mouth of subalpine watersheds, temporal trajectories of discharge and ion concentration indicate that the patterns of nutrient flux are controlled mainly by the magnitude of stream-water discharge, and temporal differences in the relative contributions of snowmelt and soil water (Stottlemyer & Troendle, 1992). In subalpine catchments, there is a strong correlation between snowmelt rate and retention time and subsequent stream-water chemistry. The ion concentration in baseflow is primarily that of resident soil water. As snowmelt increases, both flowpath and retention time change altering soil exchange opportunities, and result in changing stream-water chemistry from that aligned with soil water to one aligned with precipitation. Such change has not been as apparent in alpine catchments. Large diurnal variation in the ratio of meltwater to soil water may be the cause. Generally, ions with high snowpack concentration relative to soil water concentration show much less decline in concentration with increasing stream-water discharge.

Forest disturbance appears to have long-term effects on stream-water ionic export and concentration. In sub-basins of the Deadhorse watershed, removal of one-third the canopy resulted in annual runoff increases of >30% with recovery to pretreatment levels in about 70 years (Stottlemyer, 1987a; Troendle & King, 1987). Stream ion concentrations generally increased during disturbance with K\(^+\) and NO\(_3\)\(^-\) increasing the most (1.7 and 2.3 times control concentration, respectively). Post-treatment NO\(_3\)\(^-\) concentrations and output were even higher suggesting input from increased decomposition. Seven years after treatment, NO\(_3\)\(^-\) flux remained >5 times that of pretreatment level and the current control watershed level (Stottlemyer, 1987a).

REFERENCES


