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Relations between basin characteristics and stream water chemistry in alpine/subalpine basins in Rocky Mountain National Park, Colorado

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Abstract. Relations between stream water chemistry and topographic, vegetative, and geologic characteristics of basins were evaluated for nine alpine/subalpine basins in Rocky Mountain National Park, Colorado, to identify controlling parameters and to better understand processes governing patterns in stream water chemistry. Fractional amounts of steep slopes (≥30°), unvegetated terrain, and young surficial debris within each basin were positively correlated to each other. These terrain features, which commonly occur on steep valley side slopes underlain by talus, were negatively correlated with concentrations of base cations, silica, and alkalinity and were positively correlated with nitrate, acidity, and runoff. These relations might result from the short residence times of water 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 physical weathering rates in those areas are high. Physical weathering exposes fresh bedrock that contains interstitial calcite, which weathers relatively quickly. The fractional amounts of subalpine meadow and, to a lesser extent, old surficial debris in the basins were positively correlated to concentrations of weathering products and were negatively correlated to nitrate and acidity. These relations may reflect more opportunities for silicate weathering and nitrogen uptake in the lower-energy environments of the valley floor, where soils are finer-grained, older, and better developed and slopes are relatively flat. These results indicate that in alpine/subalpine basins, slope, vegetation (or lack thereof), and distribution and age of surficial materials are interrelated and can have major effects on stream water chemistry.

1. Introduction

Streams and lakes in high-elevation basins in the Colorado Rocky Mountains are dilute because fast hydrologic flushing rates and minimal soil development limit interaction between precipitation and geologic materials and because bedrock consists mostly of silicate minerals that weather relatively slowly. The dilute nature of surface water makes aquatic ecosystems susceptible to impacts from atmospherically deposited pollutants, such as sulfuric acid and nitrogen compounds. Atmospheric deposition of SO_4 decreased in the Colorado Rocky Mountains between the mid-1980s and the mid-1990s, but deposition of nitrogen compounds increased [*Lynch et al*., 1996]. Relatively high NO_3 concentrations have been documented throughout the year in several high-elevation streams in the northern Front Range of the Colorado Rockies, indicating that some alpine/subalpine ecosystems may be undergoing nitrogen saturation [*Campbell et al*., 1995a; *Williams et al*., 1996; *Baron and Campbell*, 1997]. However, not all basins in the area appear to be affected, despite similar nitrogen deposition across the region [*Sueker*, 1996].

Physical characteristics of drainage basins, including geology, vegetation, and basin size and relief, can strongly influence stream water chemistry and may determine how ecosystems respond to perturbations such as atmospheric deposition of pollutants or changes in climate. In some cases the effect of basin characteristics is direct; bedrock type, for example, has a direct effect on surface water chemistry because rocks of different types release solutes in different proportions when they undergo chemical weathering. In other cases the effect may be indirect; the extent and nature of surficial debris in a basin will affect flow paths and residence times of water, which, in turn, influence surface water chemistry by regulating the degree of water/rock interaction. Thus basin physical characteristics sometimes are surrogates for other variables that influence water chemistry more directly.

Relations between surface water chemistry and select basin characteristics have been investigated in a number of previous studies. Several studies documented that basins underlain predominantly by calcareous rocks tend to have surface water with higher alkalinity than basins with mostly noncalcareous rocks [*Melack et al*., 1985; *Puckett and Bricker*, 1992; *Rice and Bricker*, 1995]. The amount or thickness of glacial till in a basin also has been shown to be positively correlated to surface water alkalinity [*Newton et al*., 1987; *Peters and Driscoll*, 1987; *Turk and Campbell*, 1987; *Clow et al*., 1996]. Elevation was found to be a useful predictor of surface water alkalinity in two Colorado wilderness areas [*Turk and Adams*, 1983; *Turk and Campbell*, 1987] and in the Swiss Alps [*Drever and Zorbrist*, 1992], but it was not a good predictor in the Sierra Nevada [*Melack et al*., 1985]. *Wolock et al*. [1989] documented that topographic features influenced lake alkalinity in the northeastern United

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States; alkalinity was positively correlated with soil contact time, an index calculated from topographic information.

Each of these studies provided useful information about the influence of select basin characteristics on surface water chemistry. However, systematic analyses of relations between surface water chemistry and a broad spectrum of basin physical characteristics were generally beyond the scope of these studies. Such an endeavor would have been quite labor intensive when the previous studies were done because little map information was available in digital form. Increased availability of digital versions of topographic, vegetation, and geologic maps and geographic information system (GIS) software makes this kind of analysis more practical than in the past. Identifying basin characteristics that exert substantial control on surface water chemistry may allow development of statistical models for predicting surface water chemistry at unsampled lakes or streams. These statistical models could improve our understanding of spatial patterns in surface water chemistry and help make linkages between regional water-quality assessments and data collected at intensively studied research sites.

The purpose of this study was to evaluate relations between stream water chemistry and basin characteristics at nine alpine/subalpine basins in the Colorado Rocky Mountains. Annual volume-weighted mean (AVWM) solute concentrations in stream water were compared to digital information on basin characteristics using standard regression techniques. Specific environments that appeared to exert substantial influence on surface water chemistry were identified in the basins. Interpretations about the chemical characteristics of water in these environments were compared to data from synoptic surveys of water chemistry in two of the basins to determine if the interpretations and synoptic data were consistent. The feasibility of using information on basin characteristics to predict surface water chemistry at unsampled lakes and streams in the area was evaluated using data from this study and data collected during several previous water-quality synoptic surveys in the same area.

2. Description of Study Area

The nine study basins are in Rocky Mountain National Park (RMNP) about 100 km northwest of Denver, Colorado (Figure 1). This mountainous area is part of the Colorado Front Range, a north-south trending massif that is the easternmost range of the southern Rocky Mountains. The terrain in RMNP is dominated by glacial landforms, including cirques, arêtes, and u-shaped valleys. Glaciers covered most of the RMNP area during the Pinedale glaciation (late Pleistocene) [*Madole*, 1976]. The Pinedale glaciers left extensive lateral and terminal moraine deposits when they retreated 12,000 to 15,000 years ago [*Madole*, 1986]. Much smaller glacial advances occurred during the Holocene (10,000 years to the present); glacial and periglacial deposits from these advances include moraines and rock glaciers that occur above present treeline, which is at about 3350 m [*Madole*, 1976]. Extensive talus, deposited during the Holocene, accumulated below cliffs on steep slopes flanking the glacier-scoured valley bottoms (Figure 2). Small glaciers and permanent snowfields still occupy many of the east facing cirques and are maintained in part by snow blowing from the west side of the Continental Divide. Ridgetops generally were not glaciated during the Pleistocene because strong westerly winds prevented accumulation of snow there; the

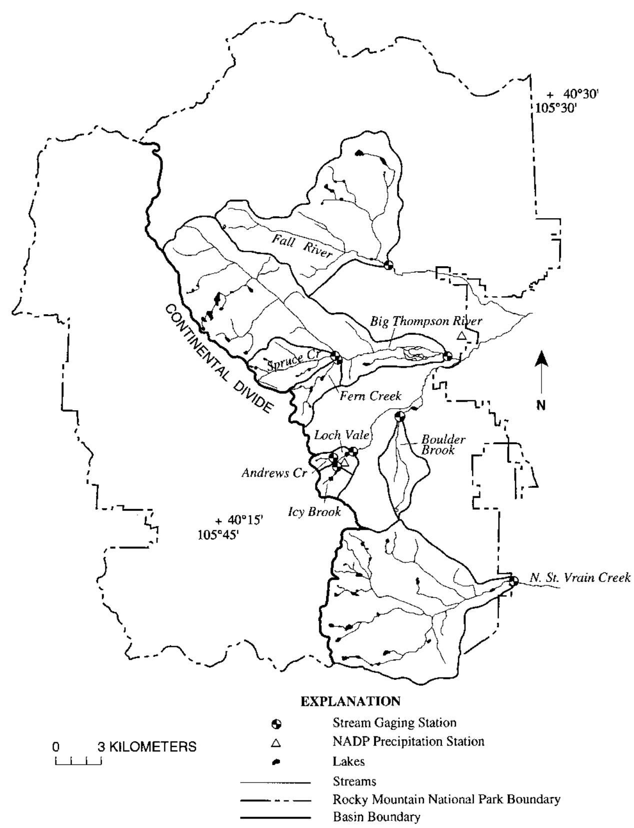

Figure 1. Location of study basins in Rocky Mountain National Park.

ridgetops are underlain mostly by colluvium that is considerably older than the surficial debris in the valleys below.

All of the study basins are in remote, roadless areas near the crest of the Continental Divide on the east side. Several of the basins are nested; Andrews Creek and Icy Brook are within the Loch Vale basin, and Spruce Creek and Fern Creek are within the Big Thompson River basin. The study basins range in size from 183 to 10,440 ha; elevations at the outlets range from 2450 to 3192 m, and elevations at the summits range from 3768 to 4345 m (Table 1). Slopes are steep; median basin slopes range from 17 to 34%.

Vegetation is typical of mature alpine and subalpine ecologic communities in the Rocky Mountains. Tundra vegetation, consisting of lichen, herbaceous grasses, and low shrubs, grows on ridgetops and in the upper parts of the cirque valleys (Figure 2) [*Arthur*, 1992]. Talus deposits are mostly unvegetated, except for scattered lichen, because of the scarcity of soil. The forest generally is confined to the valley bottoms and consists primarily of subalpine fir and Engelmann spruce above 3000 m and lodgepole pine below [*Arthur*, 1992]. Subalpine meadows occur in areas of wet soils in the valley bottoms, typically at the base of talus slopes and near streams. Vegetation in the subalpine meadows consists mostly of sedge, rush, and willow.

Soils in the basins are developed on surficial debris of varying age [*Walthall*, 1985]. Young debris, which consists of Holocene glacial till, talus, and rock glacier material, has very poorly developed soils that display little horizon development. Old debris, which consists of Pleistocene glacial till and colluvium, has soils that have slight to moderate soil-horizon development. Forest soils, which occur mostly in areas with old

Table 1. Physical Characteristics of Study Basins Expressed as Fraction of Basin Area, Except for Area, Elevation, and Slope

	Topography				Vegetation Classes				Geology Classes				
Site	Basin Area, ha	Average Elevation, m	Median Slope, deg	Steep Slope*	Tundra	Unvegetated	Forest	Subalpine Meadow	Granite	Gneiss	Debris	Young Debris	Old Debris
Andrews Creek	183	3,551	33	0.56	0.24	0.75	0.01	0.00	0.04	0.63	0.29	0.19	0.10
Icy Brook	326	3,579	34	0.60	0.19	0.80	0.00	0.00	0.06	0.64	0.25	0.20	0.05
Loch Vale	661	3,555	30	0.50	0.24	0.70	0.06	0.00	0.11	0.60	0.25	0.17	0.08
Fern Creek	780	3,172	22	0.29	0.16	0.45	0.37	0.02	0.07	0.63	0.29	0.10	0.19
Boulder Brook	990	3,517	17	0.02	0.34	0.28	0.32	0.06	0.31	0.06	0.63	0.01	0.62
Spruce Creek	1,320	3,262	22	0.29	0.30	0.45	0.23	0.02	0.34	0.34	0.31	0.11	0.20
Fall River	6,280	3,364	22	0.23	0.28	0.32	0.35	0.05	0.43	0.34	0.22	0.05	0.17
North St. Vrain	8,500	3,435	17	0.15	0.18	0.36	0.42	0.04	0.34	0.15	0.49	0.10	0.39
Big Thompson	10,440	3,195	20	0.21	0.23	0.31	0.41	0.05	0.47	0.34	0.18	0.05	0.13

*Steep slope refers to the fraction of the basin having slopes ≥30°.

debris, have the most clearly defined profiles in the study basins. Bedrock consists of biotite gneiss and Silver Plume Granite, both Precambrian in age [*Braddock and Cole*, 1990]. The mineralogy and chemistry of the two units are very similar; the dominant minerals in both units include quartz, oligoclase, biotite, and microcline [*Mast*, 1992]. Trace amounts of calcite occur along some grain boundaries, fractures, and joints [*Mast et al*., 1990; *Mast*, 1992]. The main mineralogic difference between the two rock units is a greater abundance of microcline and a lesser abundance of biotite in the granite compared to the gneiss [*Mast*, 1992].

The study basins receive approximately 60 to 100 cm of precipitation annually, with about two thirds of that falling as snow between October and April [*Baron et al*., 1992; *Sueker*, 1996]. Melting of the seasonal snowpack usually is the major hydrologic event of the year, with about two thirds of the total annual runoff occurring from May through July. Evapotranspiration and sublimation have been estimated to account for approximately 40% of annual precipitation in Loch Vale [*Baron and Denning*, 1992], which has been the site of intensive process-oriented research since the early 1980s [*Baron*, 1992]. Average daily air temperature in Loch Vale ranges from approximately −6°C in January to 14°C in July.

3. Methods

Basin physical characteristics were quantified using digital topographic, vegetation, and geologic map coverages provided by the National Park Service (unpublished data, Rocky Mountain National Park, 1998). Topographic coverages were derived from digitized U.S. Geological Survey quadrangle sheets, which have a scale of 1:24,000. Information obtained from the topographic coverages included basin area, average elevation, median slope, and fraction of basin area with slopes ≥30°. Vegetation coverages were made from digitized aerial photographs. The main subunits identified on the vegetation coverages were tundra, subalpine meadow, forest, and unvegetated area. Geologic coverages were constructed from a digitized geologic map with a scale of 1:50,000 [*Braddock and Cole*, 1990]. Geologic subunits included gneiss bedrock, granite bedrock, and surficial debris (till, rock glaciers, talus, and colluvium). Surficial debris was subdivided into young (Holocene) and old (Pleistocene) because of substantial differences in the degree of soil development in the two units (see section 2).

Stream stage (water surface height) was measured every 15 min at gages installed at the outlets of each study basin. Discharge was calculated from stage using equations developed from stage and discharge measurements made over a broad range of flows using current-meter and dye-dilution techniques according to standard methods [*Rantz*, 1982].

Stream water samples were collected at the gages approximately weekly from April through August, collected biweekly in September and October, and collected once every month or two from November through March. Stream water samples were collected in high-density polyethylene bottles that had been soaked in deionized water and triple rinsed with sample water prior to collection. An aliquot of the sample was filtered through a 0.45-μm polycarbonate membrane within 24 hours of collection. A portion of the filtered sample was acidified to pH 2 using concentrated high-purity nitric acid for cation and silica analyses.

Alkalinity and pH were measured on unfiltered samples at room temperature within 1 week of collection. Alkalinity was

Characteristic	Environment				
	Tundra	Bedrock	Talus	Subalpine Meadow	Forest
Slope	moderate	very steep	steep	gentle	moderate
Vegetation	grass, herb	unvegetated	unvegetated	sedge, rush	spruce, fir, pine
Geology	colluvium	gneiss, granite	talus	Pinedale till	Pinedale till
Permeability	moderate/high	very high over surface	high	low	moderate

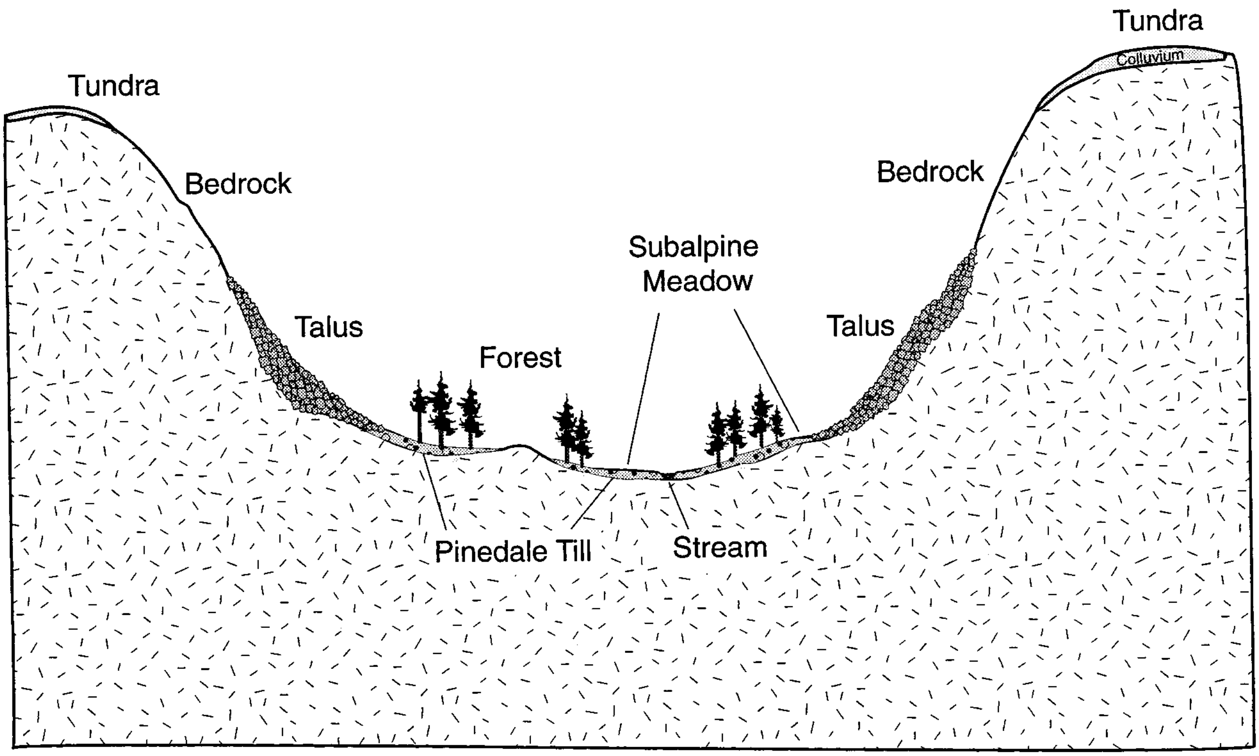

Figure 2. Schematic diagram showing common characteristics of environments in alpine/subalpine basins.

determined by Gran titration [*Gran*, 1952], and pH was measured using an electrode designed for low-ionic-strength water. Calcium, magnesium, sodium, and silica concentrations were determined by inductively coupled plasma spectroscopy on filtered, acidified samples. Sulfate, nitrate, and chloride were measured by ion chromotography on filtered, unacidified samples. Accuracy of analyses generally was better than ±5% based on repeated analyses of standard reference waters obtained from the U.S. Geological Survey, Branch of Quality Assurance [*Ludtke and Woodworth*, 1997]. Detailed discussions of discharge measurements, stream water chemistry sampling and analysis methods, and precision, accuracy, and detection limits of analyses are provided by *Campbell et al.* [1995b] and *Sueker* [1996].

Solute fluxes in stream water were calculated by multiplying the solute concentration for a given sample times the volume of water passing the stream gage during the sampling period and then summing the products for all of the sampling periods during the year. Sampling periods were defined as beginning halfway in time between the current sample and the previous sample and ending halfway in time between the current sample and the next sample. Streamflow was calculated for each sampling period using 15-min-interval stage measurements and stage-discharge relations derived for each basin outlet. Annual volume-weighted mean solute concentrations were calculated for each solute by dividing the total solute flux by the total discharge for the year.

4. Results

4.1. Basin Characteristics

The topographic characteristics of most of the study basins are typical of recently glaciated alpine/subalpine terrain in the Rocky Mountains (Table 1). Average slope steepness is high in all of the study basins, but the fraction of each basin with steep slopes (defined here as ≥30°) is highly variable. Median slopes range from 17° to 34°, and the fraction of each basin with steep slopes ranges from 2 to 60%. The basins with the steepest slopes are those most strongly affected by recent glaciation. The basin with the least amount of steep slopes, Boulder Brook, appears to have been minimally affected by late Pleistocene (Pinedale) glaciation [*Madole*, 1976].

Vegetation is representative of alpine/subalpine ecosystems in the Rocky Mountains (Table 1) [*Arthur*, 1992]. Extensive

Table 2. Spearman Correlation Coefficients for Physical Characteristics of Basins

	Topography			Vegetation Classes				Geology Classes			
	Basin Area, ha	Average Elevation, m	Steep Slope	Tundra	Unvegetated	Forest	Subalpine Meadow	Granite	Gneiss	Debris	Young Debris
Average elevation	−0.63										
Steep slope	−0.79	0.47									
Tundra	0.00	0.15	−0.21								
Unvegetated	−0.79	0.54	0.95*	−0.33							
Forest	0.85†	−0.73	−0.80†	−0.32	−0.73						
Subalpine meadow	0.73	−0.51	−0.89*	0.31	−0.94*	0.66					
Granite	0.95*	−0.55	−0.70	0.20	−0.77	0.70	0.69				
Gneiss	−0.70	0.22	0.90*	−0.49	0.83†	−0.56	−0.76	−0.68			
Debris	−0.08	0.02	−0.34	0.15	−0.13	0.08	0.18	−0.24	−0.39		
Young debris	−0.72	0.57	0.92*	−0.29	0.98*	−0.72	−0.93*	−0.71	0.75	−0.11	
Old debris	0.53	−0.50	−0.83†	0.27	−0.71	0.62	0.71	0.41	−0.78	0.73	−0.70

Numbers are r values.
*Here $p \leq 0.001$.
†Here $p \leq 0.01$.

areas of each basin are unvegetated, most notably in Loch Vale and its two subbasins (Andrews Creek and Icy Brook), which are 70 to 80% unvegetated. Other vegetation classes that are important are tundra and forest, each of which occupy an average of 24% of the study basin areas. Subalpine meadows occupy relatively small portions of the basins, with amounts ranging from 0 to 6% of the basin areas.

On average, two thirds of the basin areas are classified as bedrock outcrops of gneiss or granite. An average of one third of the basin areas is covered by surficial debris. There are large differences in the relative abundance of young and old debris in the study basins. Young debris is most prevalent in Loch Vale and its two subbasins because of extensive Holocene glacial and periglacial activity, and old debris is abundant in the North St. Vrain and Boulder Brook basins.

It is possible to define specific environments within the study basins by identifying areas that have common physical characteristics. The talus environment, for example, may be recognized as areas having steep slopes, little or no vegetation, and abundant young debris. The subalpine meadow environment is characterized by gentle slopes, sedge- and rush-dominated vegetation, and wet, organic-rich soils. Five environments with common physical characteristics were recognized in the study basins: tundra, bedrock, talus, subalpine meadow, and forest (Figure 2). Some environments are most easily recognized by the type of vegetation that grows there. Hence some environments have the same names as their associated vegetation class. Recognizing environments in the study basins can be useful when interpreting spatial patterns in water chemistry within and between basins.

Some basin characteristics were highly correlated (Table 2), which may reflect the relative abundance of various environments in the study basins. Steep slopes, unvegetated terrain, and young debris were positively correlated with each other and, as noted above, are common features of the talus environment. These features were negatively correlated with the fractional amount of subalpine-meadow vegetation in the basins, which indicates that there is an inverse relation between the relative abundances of the talus and subalpine-meadow environments.

Median basin slope was highly correlated with the percentage of each basin having steep slopes (not shown, $r > 0.98$), and correlations between these variables and other variables generally were similar. For brevity, median basin slope is not discussed further.

4.2. Solute Concentrations

Stream water in the study basins is dilute because fast hydrologic flow rates and minimal soil development limit the interaction of water and geologic materials and because bedrock is mostly composed of silicate minerals that weather slowly. Annual volume-weighted mean (AVWM) alkalinities ranged from 25 to 151 μeq L^{-1}, and the median alkalinity was 62 μeq L^{-1} (Table 3). The low solute concentrations, particularly alkalinity, indicate that these ecosystems are very sensitive to acidification. Annual volume-weighted mean concentrations of NO_3 varied widely, ranging from 3 to 23 μeq L^{-1}. For comparison, AVWM NO_3 plus NH_4 in precipitation in Loch Vale in 1994 was 24 μeq L^{-1} (National Atmospheric Deposition Program/National Trends Network (NADP/NTN) Coordination Office, Illinois State Water Survey, Urbana, 1994, http://nadp.sws.uiuc.edu/) (hereinafter referred to as NADP/NTN, 1994). Annual volume-weighted mean concentrations of SO_4 in streams varied little between basins and were about twice the concentration in precipitation (NADP/NTN, 1994). Annual volume-weighted mean concentrations of weathering products (Ca, Mg, Na, K, SiO_2, and alkalinity) in streams occurred in proportions that indicate that silicate and carbonate mineral weathering reactions contribute substantial solutes to the streams. The importance of carbonate mineral weathering, which is reflected in the high Ca/Na ratios in stream water, is notable given the fact that carbonate minerals are present only in trace quantities in the granitic bedrock underlying the basins [*Mast et al*., 1990].

The pattern of correlations between runoff and solutes indicates that the degree of interaction between precipitation and soils exerts substantial influence on surface water chemistry (Table 4). Runoff was positively correlated with AVWM concentrations of H and NO_3, reflecting inputs of slightly acidic precipitation, and was negatively correlated with AVWM concentrations of weathering products. As rain or melting snow interacts with soil, the water chemistry is modified because of mineral weathering, cation exchange, and biologic processes. In undisturbed mountain ecosystems these interactions usually consume acidity and NO_3 and produce alkalinity, base cations, and silica. The observed pattern of

Table 3. Annual Runoff and Volume-Weighted Mean Concentrations in Streams

		Annual Volume-Weighted Mean Concentration										
Site	Runoff, cm	Ca	Mg	Na	K	H	Alkalinity	NO_3	SO_4	Cl	Ca/Na	SiO_2
Andrews Creek	83	51	13	16	3	0.27	25	23	25	3	3.2	30
Icy Brook	66	58	14	15	3	0.35	28	19	28	3	3.9	18
Loch Vale	62	58	16	16	4	0.30	40	15	28	4	3.6	31
Fern Creek	71	63	21	24	4	0.18	57	11	27	3	2.6	45
Boulder Brook	22	75	30	78	7	0.07	151	3	27	5	1.0	167
Spruce Creek	55	67	19	26	4	0.17	62	10	24	3	2.6	51
Fall River	27	90	42	42	9	0.10	123	6	32	7	2.1	77
North St. Vrain	45	84	28	38	5	0.14	96	8	32	5	2.2	77
Big Thompson	35	79	33	36	7	0.13	95	6	33	5	2.2	64

Units are μeq L^{-1} except for SiO_2, which is given in μmol L^{-1}.

correlations suggests that in basins with high runoff, there is less interaction between precipitation and soil than in basins with low runoff. This pattern probably reflects relatively short residence times of water in basins with high runoff [*Sueker et al*., 1999].

Correlations among solutes reflect the dominant biogeochemical reactions that influence AVWM stream chemistry. Stream water alkalinity was positively correlated with AVWM concentrations of Na, SiO_2, and to a lesser degree, Ca, Mg, and K (Table 4). The positive correlations between alkalinity, Na, and SiO_2 are largely attributable to silicate weathering. Correlations between alkalinity and Ca, Mg, and K may be due to silicate and carbonate mineral weathering or cation exchange. Alkalinity was negatively correlated with H, NO_3, and runoff, indicating that atmospherically deposited NO_3 has a strong influence on stream water alkalinity.

Interestingly, alkalinity also was negatively correlated with the AVWM Ca/Na ratio of stream water. The negative correlation might be considered surprising because the dominant source of alkalinity and Ca in surface water in Loch Vale is carbonate mineral weathering [*Clow et al*., 1997]. Carbonate weathering tends to increase alkalinity and the Ca/Na ratio in surface water, so one might expect a positive correlation between the two chemical parameters. This seeming discrepancy indicates that although calcite weathering rates are relatively high in the talus environment, much of the alkalinity contributed by calcite weathering is either diluted by precipitation or consumed by acids in talus water (or both). The median Σcation/alkalinity ratio in talus water is about 3:1, which indicates that about two thirds of the alkalinity generated by biogeochemical processes is consumed.

4.3. Relations Between Basin Characteristics, Runoff, and Solute Concentrations

Runoff in the basins was positively correlated with the fraction of each basin having steep slopes ($\geq 30°$), unvegetated terrain, and young debris (Table 5). As noted in section 4.1, these features commonly occur in the talus environment. Low evapotranspiration rates in the talus environment, which may be due to sparseness of vegetation and lack of water near the surface, may help explain high runoff in basins with abundant talus. Basin location and aspect also may contribute to differences in runoff. Basins with high runoff tend to be those adjacent to and east of the Continental Divide; these basins receive substantial precipitation input from snow blown from the west side of the divide.

Runoff was negatively correlated with the percentage of each basin occupied by subalpine meadows (Table 5). This inverse relation might be due to relatively high rates of evapotranspiration in the subalpine meadows, where soils generally are saturated and water moves relatively slowly. Runoff was positively correlated with the fraction of each basin underlain by gneiss and was negatively correlated with the fraction underlain by granite. These correlations may be related to the prevalence of gneiss in basins with abundant steep slopes and granite in basins with relatively flat slopes.

Patterns in correlations between specific groups of solutes and groups of landscape characteristics provide insight into

Table 4. Spearman Correlation Coefficients for Annual Volume-Weighted Mean Concentrations in Streams

	Runoff	Ca	Mg	Na	K	H	Alkalinity	NO_3	SO_4	Cl	Ca/Na
Ca	−0.83*										
Mg	−0.85*	0.93†									
Na	−0.88*	0.87*	0.87*								
K	−0.91†	0.92†	0.98†	0.91†							
H	0.87*	−0.83*	−0.88*	−0.98†	−0.91†						
Alk.	−0.93†	0.90†	0.90†	0.97†	0.92†	−0.93†					
NO_3	0.95†	−0.87*	−0.93†	−0.94†	−0.94†	0.95†	−0.97†				
SO_4	−0.46	0.59	0.59	0.28	0.56	−0.27	0.36	−0.40			
Cl	−0.86*	0.85*	0.85*	0.80*	0.92†	−0.77	0.82*	−0.80*	0.72		
Ca/Na	0.87*	−0.83*	−0.88*	−0.98†	−0.91†	1.00†	−0.93†	0.95†	−0.27	−0.77	
SiO_2	−0.89†	0.88*	0.86*	0.99†	0.90†	−0.95†	0.98†	−0.95†	0.31	0.80*	−0.95†

Numbers are *r* values.
*Here $p \leq 0.01$.
†Here $p \leq 0.001$.

Table 5. Spearman Correlation Coefficients for Relations Between Physical Characteristics of Basins and Annual Volume-Weighted Mean Stream Water Concentrations

	Topography			Vegetation Classes				Geology Classes				
	Basin Area, ha	Average Elevation, m	Steep Slope	Tundra	Unvegetated	Forest	Subalpine Meadow	Granite	Gneiss	Debris	Young Debris	Old Debris
Runoff	−0.73	0.20	0.83*	−0.48	0.88*	−0.48	−0.84*	−0.80*	0.85*	−0.05	0.83*	−0.55
Ca	0.92†	−0.52	−0.83*	0.12	−0.83*	0.80*	0.81*	0.90†	−0.75	−0.02	−0.81*	0.60
Mg	0.85*	−0.58	−0.83*	0.15	−0.91†	0.77	0.89†	0.85*	−0.66	−0.13	−0.92†	0.53
Na	0.74	−0.44	−0.94†	0.41	−0.94†	0.68	0.93†	0.71	−0.89†	0.29	−0.93†	0.81*
K	0.81*	−0.46	−0.85*	0.29	−0.93†	0.70	0.86*	0.85*	−0.76	−0.11	−0.93†	0.54
H	−0.73	0.50	0.91†	−0.45	0.96†	−0.65	−0.96†	−0.73	0.85*	−0.18	0.95†	−0.75
Alkalinity	0.77	−0.40	−0.93†	0.35	−0.93†	0.67	0.91†	0.75	−0.87*	0.25	−0.92†	0.77
NO_3	−0.80*	0.47	0.92†	−0.36	0.98†	−0.67	−0.94†	−0.81*	0.83*	−0.13	0.95†	−0.70
SO_4	0.60	−0.08	−0.35	−0.38	−0.38	0.53	0.34	0.58	−0.21	−0.56	−0.35	−0.16
Cl	0.70	−0.14	−0.75	0.23	−0.78	0.59	0.72	0.74	−0.72	−0.20	−0.76	0.35
Ca/Na	−0.73	0.50	0.91†	−0.45	0.96†	−0.65	−0.96†	−0.73	0.85*	−0.18	0.95†	−0.75
SiO_2	0.76	−0.43	−0.97†	0.36	−0.94†	0.71	0.90†	0.73	−0.92†	0.32	−0.92†	0.83*

Numbers are r values.
*Here $p \leq 0.01$.
†Here $p \leq 0.001$.

how different environments influence surface water chemistry. Annual volume-weighted mean concentrations of base cations, SiO_2, and alkalinity (Figure 3a) were negatively correlated with steep slopes, unvegetated terrain, and young debris (common characteristics of the talus environment) and were positively correlated with subalpine meadow vegetation (Table 5). Conversely, H and NO_3 (Figure 3b) were positively correlated with steep slopes, unvegetated terrain, and young debris and were negatively correlated with subalpine meadow vegetation (Table 5). These correlations indicate that the talus and subalpine meadow environments have important, but opposite, effects on surface water chemistry in the alpine/subalpine ecosystem. Basins with abundant talus tend to have streams that contain relatively high concentrations of NO_3 and H and low concentrations of weathering products; basins with abundant subalpine meadow vegetation tend to have streams with low concentrations of NO_3 and H and higher concentrations of weathering products.

There were strong positive correlations between AVWM Ca/Na ratios in stream water and the fraction of basin areas having steep slopes (Figure 3c), unvegetated terrain, and young debris (Table 5). These relations indicate that carbonate mineral weathering is particularly important in the talus environment, probably because of the abundance of fresh rock surfaces there. Bedrock in the study basins contains trace amounts of interstitial calcite, which weathers relatively quickly compared to the silicate minerals in the rock. Calcite can become depleted from rock surfaces over time, but high rates of physical weathering in the talus environment periodically cause fresh rock surfaces to be exposed [*Mast*, 1992]. In addition, the young debris that is prevalent in the talus has been exposed to weathering for a relatively short time compared to old debris (<4 kyr compared to >12 kyr). Silicate weathering contributes a relatively high proportion of weathering products to stream water in basins with abundant old debris, probably because much of the calcite present near the surfaces of rocks in old debris has weathered away. This is reflected in the positive correlations between old debris and AVWM concentrations of Na and SiO_2 in stream water.

It is interesting that debris, which is the sum of young and old debris, was not a useful predictor of solute concentrations

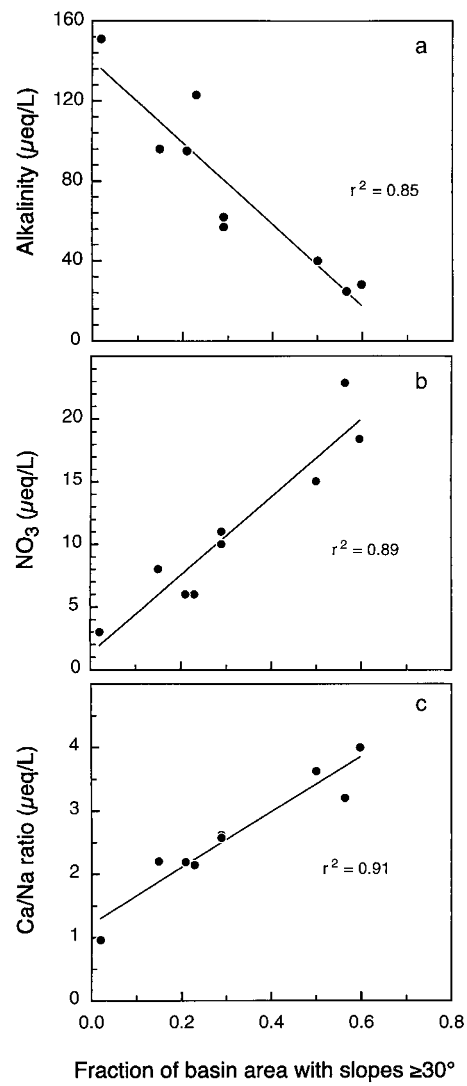

Figure 3. Relations between fraction of basin area with slopes ≥30° and annual volume-weighted mean concentrations of (a) alkalinity, (b) NO_3, and (c) Ca/Na ratios in stream water.

Table 6. Median Concentrations of Solutes in Water in Tundra, Talus, Forest, and Subalpine Meadow Environments and in Stream Water During Loch Vale Synoptic Studies

	SC	pH	Ca	Mg	Na	K	NH_4	Alkalinity	NO_3	SO_4	Cl	Ca/Na	SiO_2
Wet deposition	9	4.9	6	1	2	<1	10	na	14	12	2	3.2	na
Tundra	15	6.7	74	23	29	6	<1	43	29	41	6	2.5	56
Talus	24	6.8	129	35	32	7	2	72	43	74	7	4.1	54
Stream transect	10	6.4	51	13	14	3	2	23	24	31	3	4.1	19
Forest	9	6.0	40	17	19	4	1	24	<1	16	6	2.1	77
Subalpine meadow	24	6.7	127	33	81	7	<1	315	<1	9	8	1.7	237

Wet deposition concentrations are 1994 annual volume-weighted means. SC is specific conductance. Units are μeq L^{-1} except for SC, which is given in μS cm^{-1}, and SiO_2, which is given in μmol L^{-1}.

in the study basins. Several previous studies in other parts of the United States had identified the extent or thickness of debris as a good predictor of lake alkalinity [*Newton et al.*, 1987; *Peters and Driscoll*, 1987; *Turk and Campbell*, 1987]. Results from the present study indicate that sometimes it is necessary to differentiate between types or ages of surficial material in order to make accurate predictions of solute concentrations based on geologic characteristics.

The strong relations identified in this study between surface water chemistry and topographic characteristics are consistent with results reported by *Wolock et al*. [1989], who applied the variable source area model TOPMODEL to 145 catchments in the northeastern United States. *Wolock et al*. [1989] determined that lake alkalinity was positively correlated with an index of soil contact time, which was calculated from catchment topographic features. Results from the present study indicate that it may be useful to apply TOPMODEL to catchments in the Colorado Rockies.

5. Discussion

5.1. Spatial Patterns in Solute Chemistry Within Basins

Variations in stream water chemistry among the study basins reflect differences in hydrology and in the rates and types of geochemical and biologic reactions occurring in the basins. Results of this study indicate that it is possible to relate variations in stream water chemistry to differences in physical characteristics of basins and by inference to differences in the relative abundance of various environments in the basins. Each environment has common physical characteristics, which cause that environment to influence surface water chemistry in specific ways. In the talus environment, for example, steep slopes and high permeability lead to short residence times and limited opportunities for water/rock interaction. High rates of physical weathering in the talus produce an abundance of fresh rock surfaces and promote carbonate mineral weathering relative to silicate mineral weathering. Thus water draining the talus tends to be dilute and have high Ca/Na ratios. Other environments influence water moving through them in different ways because of differences in flow paths, residence times of water, and rates and types of biogeochemical reactions operating in them. Further insight into processes occurring within specific environments can be gained by evaluating patterns in water chemistry within and among environments.

Several synoptic surveys of water chemistry have been conducted in Loch Vale during middle to late summer to investigate spatial patterns in water chemistry within the basin. Data collected from the tundra environment in Loch Vale indicate that surface water chemistry in the tundra is strongly influenced by atmospheric deposition, evapotranspiration (ET), mineral weathering, and nutrient cycling processes (Table 6). Concentrations of Cl in tundra water are 2 to 3 times greater than those in precipitation; although dry deposition may contribute some Cl, much of the difference probably is due to ET. Evapotranspiration would affect other solutes in a similar manner and must be accounted for when evaluating the effects of other processes on water composition. Concentrations of weathering products in tundra water are substantially higher than those in precipitation (after accounting for ET), indicating that mineral weathering has a strong influence on tundra-water chemistry. Dry deposition of particulates may contribute Ca, Mg, and SO_4 to the tundra environment [*Clow and Mast*, 1995] and might help explain the high concentrations of SO_4 in tundra water. Relatively low Ca/Na ratios in tundra water probably are due to depletion of carbonate minerals in the old soils that have developed in the tundra environment (Table 6).

The importance of nutrient cycling in the tundra environment is indicated by spatial patterns in NO_3 concentrations. In a suite of water samples collected from the tundra, samples obtained just below snowfields had NO_3 concentrations that averaged 5 μeq L^{-1}, and samples collected farther downslope had NO_3 concentrations that averaged 43 μeq L^{-1}. The increase in NO_3 concentrations indicates that nitrogen assimilation in the tundra soils was minimal and that mineralization and nitrification were important. An increase in Cl concentrations from 4 μeq L^{-1} near the snowfields to 8 μeq L^{-1} downslope indicates that ET could account for only a small portion of the increase in NO_3. Previous research in Loch Vale and at Niwot Ridge, an alpine/subalpine area 20 km to the south, has indicated that the tundra and talus environments in the Colorado Front Range may be undergoing nitrogen saturation [*Campbell et al*., 1995b; *Williams et al*., 1996]. High NO_3 concentrations in the tundra synoptic samples from Loch Vale (Table 6), which were collected during the growing season, are consistent with symptoms of nitrogen saturation [*Stoddard*, 1994].

Despite the strong influence of soil processes on water flowing through the tundra environment and the relatively large fraction of the basins characterized as tundra, it appears that tundra has little effect on surface water chemistry at the outlets of the study basins. This is indicated by the lack of correlation between AVWM solute concentrations and the percentage of each basin characterized as tundra. The lack of effect at the outlets probably is due to a hydrologic disconnect between tundra and surface water lower in the basins. Recharge of tundra soils is minimal because high winds during the winter prevent accumulation of snow along the ridgetops, and ET during the summer removes much of the rain that falls on the

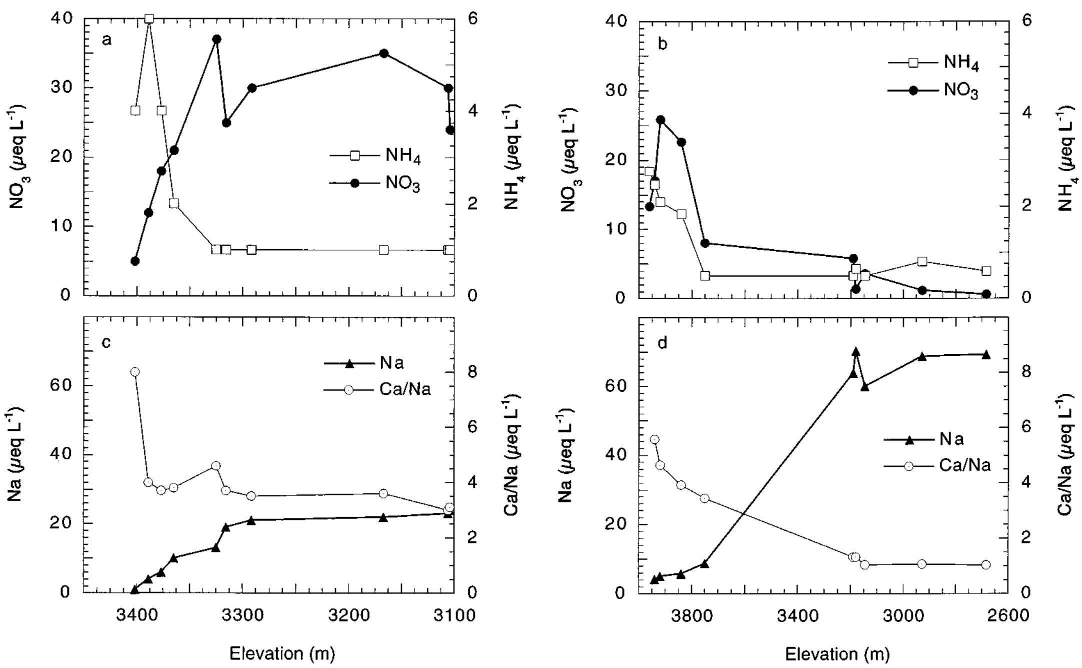

Figure 4. Variations in concentrations of (a) NO_3 and NH_4 in Loch Vale, (b) NO_3 and NH_4 in Boulder Brook, (c) Na and Ca/Na in Loch Vale, and (d) Na and Ca/Na in Boulder Brook with elevation.

tundra. Although solute concentrations in tundra water can be high, the amount of water and fluxes of solutes leaving the tundra environment are low.

Water chemistry in the talus environment is similar to that in the tundra environment with a few important exceptions (Table 6). Results of *t* test analyses on the synoptic samples indicated no significant differences in solute concentrations at $p < 0.05$, except for alkalinity, Ca, and SO_4 concentrations and Ca/Na ratios, which were higher in the talus water samples than in the tundra water samples. The higher alkalinity, Ca concentrations, and Ca/Na ratios probably reflect greater inputs from carbonate mineral weathering due to the presence of fresh mineral surfaces in the talus. Relatively high SO_4 concentrations in the talus water might be due to weathering of pyrite, which may be present in trace quantities in the bedrock. Like calcite, pyrite weathers relatively rapidly and can become depleted from rock surfaces over time. Thus the presence of fresh rock surfaces in the talus might help explain the relatively high concentrations of SO_4 in water draining the talus. An alternative explanation for the high alkalinity, Ca, SO_4, and Ca/Na values of talus water is that dry deposition rates of carbonate and $CaSO_4$ particulates may be relatively high in the talus environment [*Clow and Mast*, 1995]. The surfaces of talus deposits are highly porous, consisting mostly of large boulders with abundant void spaces that can be efficient traps for particulate matter.

The synoptic water samples from the talus environment had relatively high concentrations of NO_3, which indicates that mineralization and nitrification processes in the tundra are important and that microbiota in the talus are not nitrogen-limited (Table 6). This hypothesis is supported by water chemistry data collected along stream transects in Loch Vale and Boulder Brook during early September (Figure 4). Samples collected in Loch Vale just below snowfields, where streamflow begins (3402 m), had NO_3 concentrations of about 5 μeq L^{-1} and NH_4 concentrations of about 4 μeq L^{-1} (Figure 4a). The stream descends rapidly across talus at first, increasing in size because of inputs from meltwater percolating through the immature, poorly sorted sand, gravel, and cobbles that compose the talus soils. Within 100 m of elevation loss, NO_3 concentrations increased to 37 μeq L^{-1}, and NH_4 concentrations declined to <1 μeq L^{-1}. These concentrations persisted as the stream flowed downstream through small wetlands, forest, and several lakes to the Loch Vale outlet, which was the lowest elevation sampling point. These spatial trends in nitrogen compounds support the hypothesis that mineralization and nitrification processes in the talus soils can have a substantial effect on stream water chemistry in alpine/subalpine basins.

In Boulder Brook, patterns in NO_3 and NH_4 concentrations near the headwaters were similar to those in Loch Vale (Figure 4b). However, NO_3 concentrations did not plateau at lower elevations; instead, they continued to decline with elevation after leaving talus soils and were <1 μeq L^{-1} at the Boulder Brook gage. The spatial pattern in nitrogen compounds along the stream transect in Boulder Brook could be related to the presence of abundant talus deposits above 3600 m and older, better developed forest soils lower in the basin. These data indicate that in Boulder Brook, nitrogen assimilation in the forest soils is effective at reducing NO_3 concentrations in stream water. In Loch Vale, nitrogen is not assimilated as effectively, perhaps because old debris and forest occur only in discontinuous patches at low elevations.

Spatial patterns in Ca/Na ratios in samples collected along the stream transects support the hypothesis that geochemical reactions in old and young debris exert different influences on stream water chemistry. In Loch Vale the stream sample collected nearest the snowfield had a Ca/Na ratio of 8, and Ca/Na ratios declined to 4 within 25 m of elevation loss (Figure 4c).

Table 7. Coefficients of Multiple-Linear Regression Models for Streams at Basin Outlets

Solute	Constant	Basin Area	Steep Slope	Unvegetated	Young Debris	Old Debris	p Value	r^2
Ca	66.69	0.004					0.015	0.60
Mg	19.19	0.002					0.024	0.54
Na	51.37				−193.1	43.81	0.002	0.87
K	9.39				−33.0		0.001	0.83
H	−0.02			0.24			0.000	0.95
Alk.	138.33		−189.8			34.65	0.002	0.92
NO_3	−8.59		55.1			14.11	0.000	0.97
SO_4	12.73	0.002		29.49			0.003	0.86
Cl	6.31				−16.1		0.008	0.65
Ca/Na	1.72				8.8	−1.63	0.001	0.90
SiO_2	63.59				−244.9	157.89	0.000	0.92

The Ca/Na ratios continued to decline gradually with elevation, reaching a value of 3 at the Loch outlet. In Boulder Brook the pattern of decreasing Ca/Na ratios with elevation was even more pronounced (Figure 4d). These results indicate that carbonate mineral weathering has a strong influence on stream water chemistry in the upper reaches of the basins, where talus is most prevalent. Its influence diminishes downstream, probably because carbonate minerals have been depleted from the old debris that is present lower in the basins.

The stream transect data indicate that silicate mineral weathering is relatively important in areas with old debris. This is indicated by inverse relations between elevation and concentrations of Na, SiO_2, and alkalinity in Boulder Brook and Loch Vale (see Figures 4c and 4d for trends in Na) and by strong positive correlations between concentrations of Na, SiO_2, and alkalinity in the stream transect samples from Boulder Brook ($r > 0.99$) and Loch Vale ($r > 0.88$).

Water chemistry in the forest environment was evaluated using data from suction soil lysimeters installed in the Loch Vale forest. Forest soil-water samples had relatively low Ca/Na ratios compared to tundra and talus water samples (Table 6). Calcite is depleted from forest soils because they are relatively old and because relatively warm temperatures and high concentrations of organic acids in forest soils promote chemical weathering. The relatively warm temperatures in the forest soils may also promote nutrient cycling; concentrations of NO_3 were seldom above 1 μeq L^{-1} in the forest soil-water samples, even during snowmelt, indicating that the forest environment contributes little nitrogen to the stream (Table 6).

In the subalpine meadow environment, anaerobic conditions exist in most of the soils throughout the year, strongly influencing the types and rates of geochemical and biologic reactions occurring there. Concentrations of SO_4 were very low in most subalpine meadow soil-water samples (Table 6), and in some cases, samples smelled of H_2S gas, indicating that sulfate reduction was occurring in the meadow soils. Concentrations of NO_3 also were quite low in the meadow soil water, probably because of denitrification in the meadow soils. The denitrification process is important because it releases alkalinity to solution, which is reflected in high alkalinity concentrations in the meadow soil water. Ratios of weathering products in meadow soil solutions indicate that silicate mineral weathering was especially important in the subalpine-meadow environment; for example, the Ca/Na ratio in meadow soil water was lower than in any other environment in Loch Vale. Concentrations of Na and SiO_2 were very high, indicating that plagioclase weathering was particularly important in the subalpine meadow soils.

Despite the relative paucity of the subalpine meadow environment in the study basins it appears to have a substantial impact on surface water chemistry based on its strong correlation with AVWM concentrations of many solutes in this study (Table 5). This may be explained in part by the proximity of subalpine meadows to surface water bodies in the basins, which provide a good hydrologic connection between the two environments.

5.2. Predicting Solute Concentrations

Streams and lakes in national parks and class I wilderness areas receive special protection under the Federal Clean Air Act, which prohibits degradation of aquatic resources attributable to atmospheric deposition in those areas. Federal land managers must evaluate the potential for degradation when considering approval of permits for new emissions sources, such as coal or gas-fired power plants. Regional assessments of the chemical status of lakes and streams and their sensitivity to atmospherically deposited pollutants can be valuable pieces of information for resource managers when evaluating permit applications. Regional assessments generally involve collecting water chemistry information at a subset of lakes or streams within a region; sampling all surface water bodies would be impractical. To improve the quality of the assessments, it would be useful to be able to accurately predict surface water chemistry for unsampled lakes or streams based on data gathered from the subset of lakes or streams that were sampled.

The strong relations identified in this study between groups of solutes and groups of basin characteristics suggest that it might be possible to predict surface water chemistry using basin characteristics. Predictive models of this sort may involve simple- or multiple-linear regression of basin characteristics on water chemistry, using either AVWM concentrations or stream chemistry pertaining to a specific time of year. These kinds of models have important limitations, largely because they do not simulate watershed processes. In addition, variations in stream water chemistry due to flow or time of year are not accounted for, which limits the ability to extrapolate relations temporally. The major advantage of regression models is that the required information can be obtained from topographic, geologic, or vegetation maps or from remotely sensed data. This makes regression modeling a potentially powerful tool for regional-scale assessments.

The feasibility of using GIS map information to predict

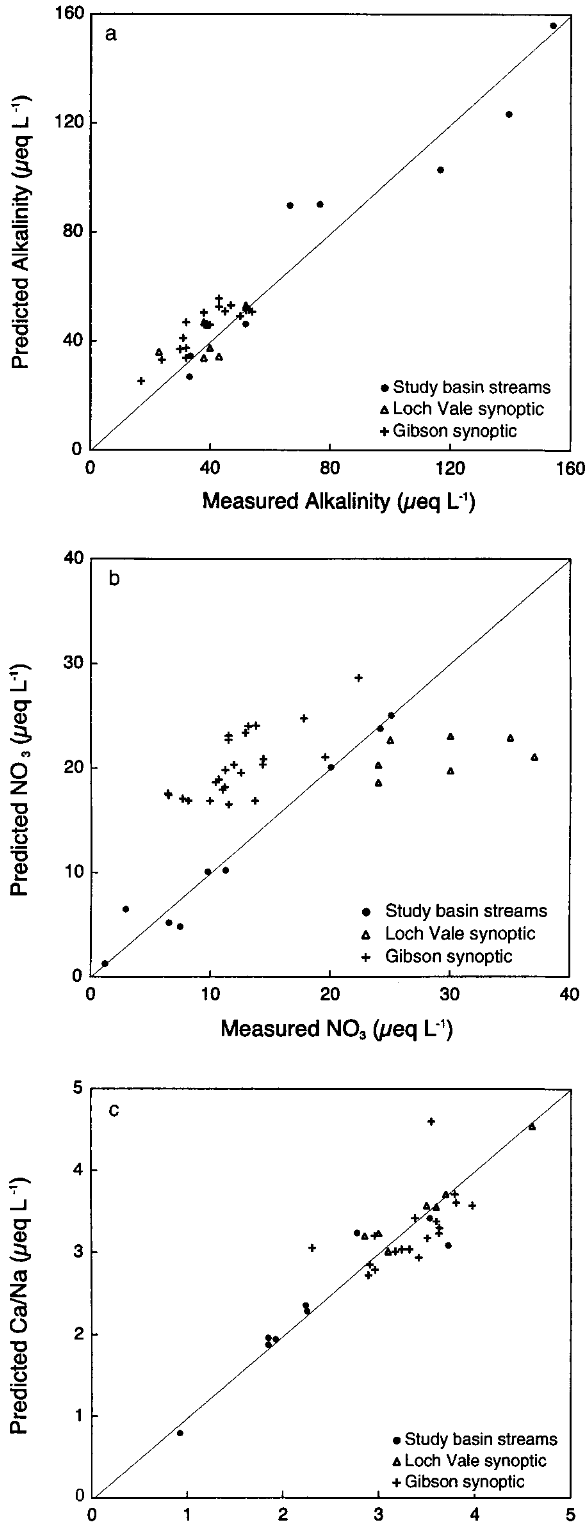

Figure 5. Relations between measured and predicted base flow concentrations of (a) alkalinity, (b) NO_3, and (c) Ca/Na ratios for streams in study basins, Loch Vale stream synoptic survey, and *Gibson et al.* [1983] synoptic survey.

surface water chemistry during base flow conditions was evaluated using stepwise multiple-linear regression. Variables were chosen from those listed in Table 1. The variable explaining the most variance was selected first, and independent variables were added in stepwise fashion if they explained a significant amount of variance ($p \leq 0.1$). Average stream water concentrations for late September/early October of 1994 were used to calibrate the models. As an example, one of the regression equations is provided below:

$$\text{predicted alkalinity} = 138.3 - 189.8(\text{steep slope}) + 34.7(\text{old debris}).$$

Basin area was the best predictor for Ca, Mg, and SO_4 concentrations, accounting for 54 to 86% of the variance (r^2) in those solutes (Table 7). Alkalinity and NO_3 concentrations were predicted using the fraction of basin area having steep slopes and old debris, which together accounted for 92 and 97%, respectively, of the variance in those solutes. Other solutes were modeled using the fraction of basin area underlain by young or old debris or a combination of the two; variances explained ranged from 83 to 95%, except for Cl ($r^2 = 0.65$). The signs of the coefficients for the variables in the models indicate whether correlations were positive or negative (Table 7); results generally were consistent with those shown in Table 5.

The regression models for alkalinity, NO_3, and Ca/Na ratios developed using the nine study basins were tested by applying the models to two independent data sets, including the 1991 Loch Vale stream synoptic survey discussed previously and a synoptic stream and lake survey conducted in RMNP in 1982 [*Gibson et al.*, 1983]. Model results are provided in Figures 5a–5c, which show generally good agreement between measured and predicted values. The most notable discrepancy was for NO_3; concentrations of NO_3 were underestimated for the 1991 Loch Vale synoptic samples and were overestimated for the 1982 synoptic samples [*Gibson et al.*, 1983]. The biases might be attributable to differences in hydrologic conditions during the 1991 and 1982 synoptic studies compared to the fall of 1994. Although flow was not measured during either of the synoptic studies, it might be possible to improve these types of models by incorporating a flow variable, which could account for variations in concentration attributable to changes in discharge.

The regression models for stream alkalinity, NO_3, and Ca/Na ratios (Table 7) were further tested by applying them to lakes sampled in RMNP as part of the 1985 Western Lake Survey (WLS) [*Landers et al.*, 1987]. Results of the model predictions are not shown, but performance generally was poor; the amount of variance in alkalinity, NO_3, and Ca/Na ratios explained by the models ranged from 19 to 35%. Differences in surface water type, lake versus stream, may account for some of the lack of fit, although that effect appears to be relatively minor based on *t* test analyses of inflow, midlake, and outflow data from the 1982 synoptic survey. The *t* test analyses indicated no significant differences in major solute chemistry between outflow and midlake samples, but alkalinity concentrations were an average of 4.5 μeq L^{-1} lower in samples collected at lake inlets than in samples collected at midlake or outlet locations.

Another possible explanation for the poor model performance is that the WLS lakes are at higher elevations and generally have substantially smaller basin sizes than the streams that were the focus of this study. The average elevation of WLS lakes in RMNP was 3305 m and average basin size was 331 ha, compared to an average elevation of 2765 m at the stream gages and an average stream basin size of 3276 ha. Thus the WLS lakes may represent a different class of surface water that is more dilute and more influenced by local variations in geology and vegetation than the streams in this study. Relatively poor model performance also was noted for high-elevation streams and lakes compared to low-elevation streams and lakes when the models were applied to the 1982 synoptic data set [*Gibson et al*., 1983].

6. Conclusions

This study documented strong relations between surface water chemistry and topographic, vegetative, and geologic characteristics of alpine/subalpine basins in Rocky Mountain National Park. Basins having abundant steep slopes, unvegetated terrain, and young debris tended to have high runoff, high concentrations of NO_3 and H, high Ca/Na ratios, and low concentrations of weathering products (base cations, SiO_2, and alkalinity). Steep slopes, unvegetated terrain, and young debris are common characteristics of the talus environment, suggesting that the talus environment has a substantial influence on surface water chemistry. Basins with relatively large amounts of subalpine meadow vegetation, and to a lesser extent old debris, tended to have opposite patterns in water chemistry.

The differences in water chemistry are largely attributable to differences in hydrology and in the rates and types of biogeochemical reactions occurring in the talus and subalpine meadow environments. Short hydrologic residence times and poor soil development limit water/rock interaction in the talus environment, but residence times in subalpine meadow soils and old debris are much longer. Nitrification and N mineralization in the talus environment contribute to high NO_3 concentrations in talus waters, which appear to have a substantial influence on stream water chemistry. Physical weathering in the talus promotes carbonate mineral weathering by exposing fresh rock surfaces; these reactions are important because they neutralize substantial amounts of acidity generated by the nitrogen reactions in the talus. Denitrification and silicate mineral weathering affect water chemistry in the subalpine meadow environment. Subalpine meadows have a surprisingly large influence on stream water chemistry given the small areas covered by this environment. This may be due to good hydrologic connection between subalpine meadows and surface water bodies.

Topographic and geologic characteristics of basins were useful predictors of surface water chemistry within the study area, accounting for more than 80% of the variance in concentrations of most solutes. Application of the same multiple-linear regression equations to data from several water-quality synoptic surveys yielded mixed results. Prediction of water chemistry for basins of similar size and elevation was generally successful, but predictions for higher-elevation lakes in small, headwater cirques were not. These results indicate that although regression models can provide useful information, care should be exercised when applying models to surface water bodies in basins with substantially different characteristics than those of the calibration data set.

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References

Arthur, M., Vegetation, in *Biogeochemistry of an Alpine Ecosystem*, *Ecol. Stud*., vol. 90, edited by J. Baron, pp. 76–92, Springer-Verlag, New York, 1992.

Baron, J. (Ed.), *Biogeochemistry of a Subalpine Ecosystem*, *Ecol. Stud*., vol. 90, 247 pp., Springer-Verlag, New York, 1992.

Baron, J. S., and D. H. Campbell, Nitrogen fluxes in a high elevation Colorado Rocky Mountain basin, *Hydrol. Processes*, *11*, 783–799, 1997.

Baron, J., and A. S. Denning, Hydrologic budget estimates, in *Biogeochemistry of a Subalpine Ecosystem*, *Ecol. Stud*., vol. 90, edited by J. Baron, pp. 28–47, Springer-Verlag, New York, 1992.

Baron, J., A. S. Denning, and P. M. McLaughlin, Deposition, in *Biogeochemistry of an Alpine Ecosystem*, *Ecol. Stud*., vol. 90, edited by J. Baron, pp. 48–75, Springer-Verlag, New York, 1992.

Braddock, W. A., and J. C. Cole, Geologic map of Rocky Mountain National Park and vicinity, Colorado, *U.S. Geol. Surv. Map*, *I-1973*, 1990.

Campbell, D. H., D. W. Clow, G. I. Ingersoll, M. A. Mast, N. E. Spahr, and J. T. Turk, Nitrogen deposition and release in alpine watersheds, Loch Vale, Colorado, U.S.A., in *Biogeochemistry of Seasonally Snow-Covered Catchments*, edited by K. Tonnessen, M. W. Williams, and M. Tranter, *IAHS Publ*., *228*, 243–253, 1995a.

Campbell, D. H., D. W. Clow, G. P. Ingersoll, M. A. Mast, N. E. Spahr, and J. T. Turk, Processes controlling the chemistry of two snowmelt-dominated streams in the Rocky Mountains, *Water Resour. Res*., *31*(11), 2811–2821, 1995b.

Clow, D. W., and M. A. Mast, Composition of precipitation, bulk deposition, and runoff at a granitic bedrock catchment in the Loch Vale Watershed, Colorado, USA, in *Biogeochemistry of Seasonally Snow-Covered Catchments*, edited by K. A. Tonnessen, M. W. Williams, and M. Tranter, *IAHS Publ*., *228*, 235–242, 1995.

Clow, D. W., M. A. Mast, and D. H. Campbell, Controls on surface water chemistry in the upper Merced River basin, Yosemite National Park, California, *Hydrol. Processes*, *10*, 727–746, 1996.

Clow, D. W., M. A. Mast, T. D. Bullen, and J. T. Turk, Strontium 87/strontium 86 as a tracer of mineral weathering reactions and calcium sources in an alpine/subalpine watershed, Loch Vale, Colorado, *Water Resour. Res*., *33*(6), 1335–1351, 1997.

Drever, J. I., and J. Zorbrist, Chemical weathering of silicate rocks as a function of elevation in the southern Swiss Alps, *Geochim. Cosmochim. Acta*, *56*, 3209–3216, 1992.

Gibson, J. H., J. N. Galloway, C. Schofield, W. McFee, R. Johnson, S. McCarley, N. Dise, and D. Herzog, Rocky Mountain acidification study, *Rep. FWS/OBS-80/40.17*, 137 pp., U.S. Fish and Wildlife Serv., Washington, D. C., 1983.

Gran, G., Determination of the equivalence point in potentiometric titrations, part II, *Analyst Amsterdam*, *77*, 661–671, 1952.

Landers, D. H., et al., Population descriptions and physico-chemical relationships, in *Western Lake Survey*, *Phase I: Characteristics of Lakes in the Western United States*, vol. 1, *Rep. EPA-600/3-86/054a*, U.S. Environ. Prot. Agency, Washington, D. C., 1987.

Ludtke, A., and M. Woodworth, USGS blind sample project–Monitoring and evaluating laboratory analytical quality, *Fact Sheet FS-136-97*, 2 pp., *U.S. Geol. Surv*., Denver, Colo., 1997.

Lynch, J. A., V. C. Bowersox, and J. W. Grimm, Trends in precipitation chemistry in the United States, 1983–1994–Analysis of the effects in 1995 of phase I of the Clean Air Act Amendments of 1990, Title IV, *U.S. Geol. Surv. Open File Rep*., *96-346*, 100 pp., 1996.

Madole, R. F., Glacial geology of the Front Range, Colorado, in *Quaternary Stratigraphy of North America*, edited by W. C. Mahaney, pp. 297–318, Van Nostrand Reinhold, New York, 1976.

Madole, R. F., Lake Devlin and Pinedale glacial history, Front Range, Colorado, *Quat. Res*., *25*, 43–54, 1986.

Mast, M. A., Geochemical characteristics, in *Biogeochemistry of an Alpine Ecosystem*, *Ecol. Stud*., vol. 90, edited by J. Baron, pp. 93–107, Springer-Verlag, New York, 1992.

Mast, M. A., J. I. Drever, and J. Baron, Chemical weathering in the Loch Vale watershed, Rocky Mountain National Park, Colorado, *Water Resour. Res*., *26*(12), 2971–2978, 1990.

Melack, J. M., J. L. Stoddard, and C. A. Ochs, Major ion chemistry and sensitivity to acid precipitation of Sierra Nevada lakes, *Water Resour. Res.*, *21*(1), 27–32, 1985.
Newton, R. M., J. Weintraub, and R. April, The relationship between surface water chemistry and geology in the North Branch of the Moose River, *Biogeochemistry*, *3*, 21–35, 1987.
Peters, N. E., and C. T. Driscoll, Hydrogeologic controls of surface-water chemistry in the Adirondack region of New York State, *Biogeochemistry*, *3*, 163–180, 1987.
Puckett, L. J., and O. P. Bricker, Factors controlling the major ion chemistry of streams in the Blue Ridge and Valley and Ridge physiographic provinces of Virginia and Maryland, *Hydrol. Processes*, *6*, 79–98, 1992.
Rantz, S. E., Measurement of stage and discharge, in *Measurement and computation of streamflow*, vol. 1, *U.S. Geol. Surv. Water Supply Pap. 2175*, 631 pp., 1982.
Rice, K. C., and O. P. Bricker, Seasonal cycles of dissolved constituents in streamwater in two forested catchments in the mid-Atlantic region of the eastern USA, *J. Hydrol.*, *171*, 137–158, 1995.
Stoddard, J. L., Long-term changes in watershed retention of nitrogen–Its causes and consequences, in *Environmental Chemistry of Lakes and Reservoirs*, *Adv. Chem. Ser.*, vol. 237, edited by L. A. Baker, pp. 223–284, Am. Chem. Soc., Washington, D. C., 1994.
Sueker, J. K., Isotopic and chemical flowpath separation of streamflow during snowmelt and hydrogeologic controls of surface-water chemistry in six alpine-subalpine basins, Rocky Mountain National Park, Colorado, Ph.D. dissertation, 202 pp., Univ. of Colo., Boulder, 1996.
Sueker, J. K., J. T. Turk, and R. L. Michel, Use of cosmogenic ^{35}S for comparing ages of water from three alpine-subalpine basins in north-central Colorado, *Geomorphology*, *27*, 61–74, 1999.
Turk, J. T., and D. B. Adams, Sensitivity to acidification of lakes in the Flat Tops Wilderness Area, Colorado, *Water Resour. Res.*, *19*(2), 346–350, 1983.
Turk, J. T., and D. H. Campbell, Estimates of acidification of lakes in the Mt. Zirkel Wilderness Area, Colorado, *Water Resour. Res.*, *23*(9), 1757–1761, 1987.
Walthall, P. M., Acidic deposition and the soil environment of Loch Vale watershed in Rocky Mountain National Park, Ph.D. dissertation, 148 pp., Colo. State Univ., Fort Collins, 1985.
Williams, M. W., J. Baron, N. Caine, and R. Sommerfeld, Nitrogen saturation in the Rocky Mountains, *Environ. Sci. Technol.*, *30*, 640–646, 1996.
Wolock, D. M., G. M. Hornberger, K. J. Beven, and W. G. Campbell, The relationship of catchment topography and soil hydraulic characteristics to lake alkalinity in the northeastern United States, *Water Resour. Res.*, *25*(5), 829–837, 1989.

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