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## Potential for Acid Snowmelt in the Wasatch Mountains

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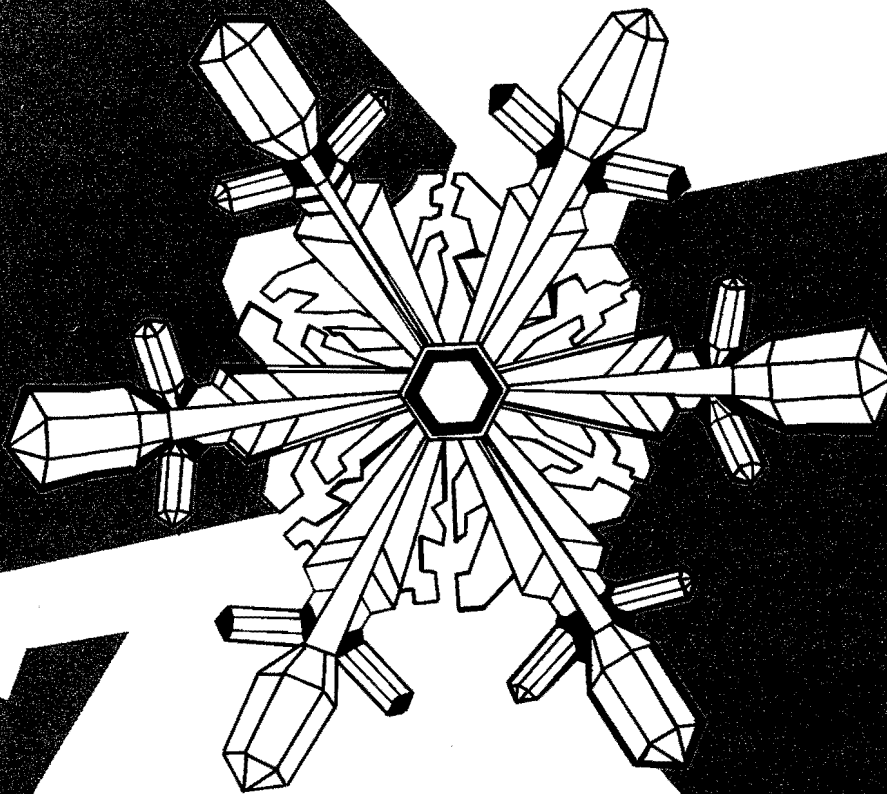
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# Potential For Acid Snowmelt In The Wasatch Mountains

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Logan, Utah 84322

November 1982

WATER QUALITY SERIES

UWRL/Q-82/06

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IN THE WASATCH MOUNTAINS

by

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## ABSTRACT

Snowmelt collected from snow cores taken from the 1982 spring snowpack in the Wasatch Mountains of northern Utah lacked mineral acidity and retained enough buffering capacity in the form of calcium and magnesium bicarbonates to titrate additional inputs of strong acid equivalent to the amount apparently already neutralized. While acid anion concentrations were higher than those found in pristine areas, they were much lower than those reported for winter precipitation in other western areas experiencing acidification of precipitation. Snowmelt pH ranged from 5.62 to 6.88 (mean = 6.17), and sulfate was relatively more important than nitrate, showing an average equivalent ratio of 3.1:1. Patterns of pH indicated decreasing pH with distance from sources of soil-derived buffering capacity in the semiarid valleys to the east. Although acid anion concentration patterns failed to point to pollution sources along the Wasatch Front, chloride concentration patterns indicated that the Salt Lake Valley airshed influenced snow chemistry in the mountains.

Snowmelt studies carried on in the laboratory and at a field site in Logan Canyon indicated that, for the alkaline snow typical of 1982, the first melt fractions had a higher pH (less acidity) than did the bulk snow. The opposite situation is typically found for acid snow. Although no acidity was present, snow pH increased by 13 percent as a result of contact with organic litter on the soil surface of a 22 m, 32 percent slope. The pH increased even more rapidly in a nearby intermittent stream (to 7.78 at the edge of the snowpack).

Difficulties in interpreting the data from the snow cores in this study include the effects of an unusually wet winter, uncharacteristically low levels of industrial activity due to economic factors, uncertainty about the relative amounts of acidity and buffering capacity reaching the sensitive Uintah Mountain watersheds to the east, and failure to distinguish between soil and acid derived sulfates. Analysis of these difficulties suggests that offsetting factors would tend to cancel effects of precipitation amount during wet-to-normal winters. The remaining factors require additional research.

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TABLE OF CONTENTS

	Page
INTRODUCTION . . . . .	1
METHODS AND MATERIALS . . . . .	3
Snow Cores . . . . .	3
Runoff Plots . . . . .	5
RESULTS . . . . .	7
Bulk Snow Core Chemistry . . . . .	7
Spatial and Temporal Patterns . . . . .	7
Some caveats . . . . .	7
Intraregional patterns . . . . .	10
Interregional comparisons . . . . .	12
Source modeling to account for snowpack chemistry . . . . .	16
Temporal trends . . . . .	18
Potential for Acid Runoff . . . . .	20
Chemistry of successive snowcore melt fractions . . . . .	20
Runoff on test plots . . . . .	22
Stream chemistry . . . . .	25
Neutralization of artificial acid precipitation . . . . .	25
CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH . . . . .	27
Conclusions . . . . .	27
Snow coring as an alternative to precipitation collection . . . . .	27
Effects of the 1981-82 winter . . . . .	28
Effects of spatial scale . . . . .	28
Effects of soil sulfates and nitrates . . . . .	28
Runoff studies . . . . .	29
Recommendations for Further Research . . . . .	29
REFERENCES . . . . .	31
APPENDIX . . . . .	35

LIST OF FIGURES

Figure	Page
1. Snowmelt collectors on Twin Creeks runoff site . . . . .	5
2. Initial pH, sulfate, nitrate, and chloride values for Wasatch Mountain snowpack during Spring, 1982 . . . . .	11
3. Dendrogram showing similarity between Wasatch Mountain snow cores as a function standardized chemical concentrations . . . . .	14
4. EC and pH in successive 1 & fractions of meltwater from Wasatch Mountain snow cores . . . . .	21
5. Ion concentrations in successive 1 & fractions of meltwater from a Twin Creeks snow core . . . . .	22
6. Representative ion concentrations in snowmelt collected in different snowpack depths above ground level at Twin Creeks field plot . . . . .	23
7. Snowmelt collector sites and changes in some ion concentrations in an ephemeral stream during snowmelt, May 9, 1982 . . . . .	26

LIST OF TABLES

Table	Page
1. Major ion chemistry of 17 snow cores from the Wasatch Mountains, taken during April 14-25, 1982 . . . . .	8
2. Minor element chemistry of 17 snow cores taken during April 14-25, 1982 . . . . .	9
3. Average spring snowpack chemistry in the Wasatch Mountains and some related data reported by other workers . . . . .	13
4. Principal components analysis of chemical concentrations in Wasatch Mountain snow cores, spring 1982 . . . . .	16
5. Geochemical ion balance for average Wasatch Mountain snowpack chemistry, Spring 1982 . . . . .	17
6. Comparison of 1969-1971 winter bulk precipitation chemistry (Hart et al. 1973) and 1959 snow core chemistry (Feth et al. 1964) with that of 1982 snow cores from similar locations . . . . .	19
7. Ion ratios between litter (0) horizon and meltwater and bulk (3 ℓ) and initial fraction (1 ℓ) snowmelt from the Twin Creek's snow core and the meltwater in the collector on the runoff plots . . . . .	24
8. Chemistry of artificial acid rain ( $10^{-4}$ N $H_2SO_4$ ) after exposure to litter and $A_1$ horizon soil in the laboratory . . . . .	25
A1. Location of snow coring sites . . . . .	35
A2. Constituent concentrations for Wasatch Mountain snow cores . . . . .	36
A3. Constituent concentrations for runoff collectors at Twin Creeks site . . . . .	37
A4. Constituent concentrations at Twin Creek sampling sites . . . . .	37



## INTRODUCTION

Acidification of precipitation in the northeastern United States, southeastern Canada, and Scandinavia is recognized as one of the most serious environmental problems in decades. Nitric and sulfuric acids, apparently discharged to the atmosphere during fossil fuel combustion, have devastated lake fisheries, reduced forest productivity, and corroded construction materials and statuary (Likens et al. 1979, Hileman 1981, 1982, Diltri 1982). More recently, acidification of precipitation in mountain areas in Utah (Hart and Parent 1974), Colorado (Lewis and Grant 1980a), Washington (Logan et al. 1982), and New Mexico (Popp et al. 1982a) has been noted, despite the absence of heavily industrialized areas immediately upwind. These findings suggest that acid precipitation may result from relatively modest local acid inputs to the atmosphere, or from metropolitan areas far upwind. The objectives of the studies reported here were to determine whether acidification of the spring snowpack has occurred in the Wasatch Mountains in northern Utah and to determine the extent to which acid snowmelt would be buffered during downslope movement toward a stream channel.

The impact of acid precipitation on water bodies is mediated by the buffering capacity of the vegetation (Hart and Parent 1974), windblown dust (Liljestrang and Morgan 1979), and soils and rocks (Kaplan et al. 1981) of the tributary watershed. For example, the acidification noted in Colorado Rockies precipitation (from an average pH of 5.43 to 4.63 during the period from 1975 to 1978) failed to increase the output of  $H^+$  from the Como Creek watershed

despite the modest amount of carbonate buffering present in the spodosols of this granitic watershed (Lewis and Grant 1979). Also, no changes in pH have occurred in the poorly buffered Cascade lakes in central Washington, despite increasing acid deposition (Logan et al. 1982), and Lewis (1982) has detected an apparent drop of only 0.22 pH units in 64 softwater Colorado Rockies lakes during the past 20-40 years. The carbonate rich limestone and dolomite bedrock of the Wasatch Mountains would consequently appear to offer adequate buffering capacity to neutralize even highly acidic precipitation.

Under circumstances where much of the runoff occurs as overland flow, however, large volumes of precipitation may enter a stream channel with only minimal soil contact. In addition to intense summer thunderstorms, such a scenario could also include rapid snowmelt or a rain-on-snow event associated with unusual winter warm front activity. Interflow through the snowpack offers no soil contact (Seip 1980, Colbeck 1981), and quickflow below the snowpack may not experience sufficient contact times with soil to neutralize any acid that was present, if melting is rapid and slopes are steep and vascularized with root channels and animal burrows. Especially on steep slopes, direct runoff from snowmelt may constitute most of the flow, offering little opportunity for neutralization of acid snowmelt by alkalinity in the soil or groundwater. In this case, stream pH would remain low until neutralized by basic materials in the streambed, or until it comingled with groundwater further downstream. Although short-term

episodes of moderate acidification undoubtedly have less serious effects on stream communities than do chronic impacts, short term decreases may

nonetheless alter community structure by affecting key species, especially those whose lifetimes are on the order of the duration of lowered pH events.

## METHODS AND MATERIALS

### Snow Cores

It was initially suspected that stationary SO<sub>2</sub> sources in the Salt Lake and Utah Lake valleys, such as the copper smelter and steel mills, would cause snowpack acidity and related variables to be higher directly to the east of these sources than they would be in the Bear River Range to the northeast. Consequently a snow core sampling network was laid out that ranged from Bear Lake Summit on US 89 in the north to Strawberry Summit on US 40 in the south. A total of 17 cores were taken from April 16 to April 25, 1982.

All snow cores were collected at least 100 m from the nearest highway to avoid contamination by road deicing treatments. In order to obtain 1.0 m long cores, high altitude sites (>1750 MSL) were chosen. Duplicate cores were taken in clearings that were as far as possible from surrounding trees and shrubs, although sampling sites were generally on the more heavily vegetated northern slopes where the snowpack was deeper than on southern exposures. The location and a brief description of each site area are presented in Table A1 of the appendix.

Snow cores were collected by driving 15 cm ID polyvinyl chloride (PVC) pipes 1.0 m into the snowpack and subsequently digging them out with a snow shovel. At sites where the snow depth was less than 1 m, the core tube was inserted into the snow diagonally or was pushed into the snowpack twice so that two short snow cores were contained in the tube, one on top of the other. The pipes had been presoaked in 6 N HCl for 12 hr and then rinsed with reagent grade water (MilleQ, Millipore Corp.) until the electrical conductivity

dropped below 1  $\mu$ S. The pipes were covered with plastic wrap (Gladwrap) secured by rubber bands during transport to avoid contamination. Following collection, pipes containing the cores were secured in a vertical position in a rack in the back of the enclosed sampling vehicle. The snow then melted through a funnel into a linear polyethylene sample bottle below. A collar covered the funnel tops surrounding the core pipes so that dust would not contaminate the sample. New bottles and funnels were precleaned in the same manner as the core tubes and kept in sealed plastic bags until needed.

Water from the melting cores was collected in three successive 1  $\ell$  fractions during the period of melting. As each 1  $\ell$  container was filled, it was capped and placed on ice for transport to the laboratory, where it was transferred to a 4°C cold room. The rate of melting and availability of space in the sampling vehicle allowed eight cores to be collected during one day, and all cores melted by approximately midnight. Within 30-40 hr of collection a 50 ml aliquot of each sample was removed for determination of EC (electrical conductivity) and pH. The remaining melt fractions then were combined for individual ion analysis. Cores 1 and 17 were exceptions: the first 1  $\ell$  melt fraction of core 1, and the combined second and third liters were analyzed separately, and the constituent concentrations volume-weighted to produce average core values. Each of the three 1  $\ell$  Core 17 melt fractions was analyzed separately, and the results similarly averaged.

EC and pH were measured using a Corning model 130 meter equipped with a Fisher combination pH electrode, and

an Industrial Instruments model RC-16B2 conductivity bridge, respectively. Aliquots of each sample were brought to room temperature (21-22°C) before the measurements and corrected to 25°C. The pH meter was calibrated using pH 4 and 7 buffers, and the conductivity bridge with 10<sup>-4</sup> M KCl after each four samples. Observed meter drift was insignificant in both cases. Following these analyses, melt fractions were combined for the remaining analyses (except for cores 1 and 17). Samples were maintained at 4°C but were not filtered; metal subsamples were acidified with 5 percent HNO<sub>3</sub>. No subsequent analyses were performed on samples that had come in contact with the pH or EC electrodes to avoid K<sup>+</sup> or Cl<sup>-</sup> contamination. Although the sampling procedure precluded carrying blanks from the coring stage through subsequent analyses, deionized water blanks were run through all analyses.

Major ion analyses were conducted approximately 2-3 weeks following collection of the samples. While this practice may lead to somewhat higher constituent concentrations than would be present in fresh snow due to dissolution of minerals and ion exchange reactions, availability of instrument time precluded immediate analysis. Although immediate filtration has been recommended to prevent such reactions in wet-only precipitation samples (Popp et al. 1982b), the purpose of this effort was to determine meltwater chemistry, which includes effects of windblown particulates as well as the chemistry of the precipitation itself. Consequently, all analyses were run on unfiltered samples, although no visible particulates were present in any of the aliquots taken for analysis. Major cations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>++</sup>, Mg<sup>++</sup>) were determined on acidified samples using an Instrumentation Laboratory model 357 AA/AE spectrophotometer operated in emission mode. Blanks and standards were made up using 5 percent HNO<sub>3</sub> to account for matrix effects. Confidence limits ( $\alpha = 0.05$ ) based on repeated reading of 500 mg/l standards were +3  $\mu\text{g/l}$  for Na<sup>+</sup>

and K<sup>+</sup>, and +8  $\mu\text{g/l}$  for Ca<sup>++</sup> and Mg<sup>++</sup>. Separate analyses of six samples carried out two weeks apart on the four major cations showed no significant change in ion concentrations (<5%). Cadmium and lead were also run on the preserved samples on the Varian instrument using a CRA-90 carbon rod atomizer. Minimum detection limits (MDL) were 0.06 and 0.6  $\mu\text{g/l}$ , respectively. Chloride, sulfate and fluoride were run on a Dionex System 10 Ion Chromatograph at the University of Minnesota. Detection limits based on previous experiments on this instrument (Thornton et al. 1981) are 20  $\mu\text{g/l}$  with a coefficient of variation in this range of 4-5 percent.

Nitrate, nitrite, and orthophosphate were determined by AutoAnalyzer (EPA 1979) on chilled but otherwise unpreserved samples within 30-40 hr of collection. Minimum detection limits were 0.04, 0.002, and 0.004 mg/l, respectively. Ammonium-N was manually determined on fresh aliquots of each sample by the phenate method (APHA 1981); the MDL was 0.01 mg/l. TOC (total organic carbon) and TIC (total inorganic carbon) were determined by wet oxidation on an Oceanography International TOC Analyzer (MDL = 0.1 mg/l).

Mineral acidity was determined following Hendry and Brezonik (1980) by bubbling with N<sub>2</sub> (99.995% purity subsequently passed through an Alltech gas purifier) until the pH fluctuated less than 0.01 unit/minute. This procedure removes CO<sub>2</sub>, and remaining mineral acidity is determined by titration with 0.005 N NaOH to pH 7.0. However, all of the samples had a pH  $\geq$  7.0 following CO<sub>2</sub> stripping, indicating no net mineral acidity, and no titrations were performed. Alkalinity could not be determined due to insufficient volume remaining in many of the samples. Consequently, bicarbonate alkalinity was calculated following Granat (1972) based on TIC and pH values taken 2-3 weeks following sample collection. This pH value is reported as "equilibrium" pH, and was

slightly higher than the initial pH taken within 30-40 hours of collection of the samples.

#### Runoff Plots

Two sites were instrumented in Logan Canyon to investigate the possibility that interflow may concentrate acidity in some snowmelt fractions and to investigate effects of soil buffering on snowmelt runoff chemistry. One plot was located on the north slope (45°) of Hattie's Grove, in a stand of Douglas fir 200 m north of Rick's Spring. The other was on a 35° north slope in the Twin Creek drainage across US 89 from the Utah State University Forestry Camp. The latter site is covered with sagebrush and grasses and has been described in detail by Hart and Loomis (1982).

At each site, vertical wooden posts were sunk into the soil and guyed with bailing wire. PVC rain gutter cut to 92 cm lengths and capped on each end were attached to the uprights at 15 cm intervals from the ground surface with the horizontal lip at the gutter edge facing upslope. One end of the gutter was slightly elevated to allow drainage to the other end of the gutter. The latter gutter end was drilled to receive a rubber stopper, which was in turn drilled to receive a 7 mm internal diameter Nalgene tubing. The tubing ran to an enclosed steel container containing several 4 l polyethylene sample containers held on a wooden rack. The containers were not stoppered because evaporation within the steel containers would likely be negligible during the short snowmelt period in the spring. In addition to the snowpack samplers, each site had one surface litter (O) horizon sampler. This was an open PVC trough with the lip pushed into the litter at Hattie's Grove. At the Twin Creeks site, a PVC gutter was placed inside a covered galvanized steel trough (Hart and Loomis 1982) with the lip extending into the litter layer. The collector and runoff site are shown in Figure 1.

The PVC trough ends and rubber stoppers were glued with PVC cement, and following drying for 48 hr, reagent grade MilleQ water was placed in each trough. No change in pH, alkalinity or EC was noted over the following 48 hr, indicating that the troughs and cement should not affect the meltwater chemistry. The samplers were put in place following the first snow in early December. The Hattie's Grove sampler was knocked down, perhaps by deer tripping on the guy wire, sometime in February, and no snowmelt was obtained. The Twin Creek site was sampled on May 1, 1982, when approximately 30 cm of snow remained on the ground.



Figure 1. Snowmelt collectors on Twin Creeks runoff site.

## RESULTS

### Bulk Snow Core Chemistry

Ion concentrations in the combined meltwater samples from each core are shown in Table A2 in the appendix, and major and minor ion average concentrations for each station are given in Tables 1 and 2, respectively. The Twin Creeks and one Bear Lake Summit core represent the volume weighted averages of three individual melt fractions that were analyzed separately. Three of the stations (Wood Camp Hollow, Yellow Pine Campground, and Twin Creeks) represent analyses of the melt from two vertical cores taken by pushing the same core tube into the shallow snowpack twice. This procedure was assumed to give the same result as averaging values from duplicate cores taken side by side. The remainder of the values represent the average concentrations of duplicate (side by-side) cores.

Cation-anion balances were generally good within cores, the correlation coefficient ( $r^2$ ) between cation and anion concentrations being 0.90 ( $n = 17$ ,  $P < 0.001$ ). Three cores, one each from Sundance, Strawberry Summit, and Deer Valley, had imbalances exceeding 15 percent, probably due to the bicarbonate concentration, which was calculated from "equilibrium" pH and TIC. This method gave a concentration with only one significant digit for an ion that accounts for a significant fraction of the anion equivalents. Agreement between measured EC and that calculated using ion equivalent conductivities was generally quite good. Discrepancies were probably caused by small errors in hydrogen ion activity which has an extremely high equivalent conductance, and perhaps by unmeasured metallic species (e.g., Liljestr nd and Morgan 1981).

Aggregate data from cores 1-17 are also shown in Tables 1 and 2. The median values are very close to the means in most cases, suggesting that the interpretations based on mean values should not be biased because of rare high concentrations of a particular constituent. The relatively high standard deviations indicate the variability among cores. The average cation-anion balance for 17 cores ( $\mu\text{eq/l}$  values in Table 1) was in error by only 3 percent, thus suggesting that the individual ion imbalances noted above were distributed randomly about the mean.

### Spatial and Temporal Patterns

#### Some caveats

The sampling network was designed to reconnoiter the potential for acid input to streams during the snowmelt period, when meltwater constituted a substantial fraction of streamflow. Consequently, the chemistry of the snowpack itself was of greater interest than the chemistry of the original precipitation. Once on the ground the snow chemistry can be altered by dry deposition of acidic or basic particles, aerosols, and gases, by loss of dissolved constituents during partial melting, and possibly by diffusion of ions in a ripe snowpack where a continuous pathway of liquid water is available. When comparing the chemistry of different snow cores, one must therefore take into account not only patterns of atmospheric inputs from precipitation, but also input patterns of a more local nature relating to windblown soils, leaf litter, microclimatological regime, and the like. Snow cores are then an imperfect means by which to investigate spatial patterns

Table 1. Major ion chemistry of 17 snow cores from the Wasatch Mountains, taken during April 14-25, 1982. Values in upper row are in  $\mu\text{g/l}$  except pH and EC ( $\mu\text{S}$ ); values in parentheses are in  $\mu\text{eq/l}$ .

Station	pH <sub>I</sub> <sup>1</sup>	pH <sub>E</sub> <sup>2</sup>	Na	K	Ca	Mg	NH <sub>3</sub> -N	SO <sub>4</sub>	(HCO <sub>3</sub> )	Cl	EC <sup>3</sup>
Bear Lake Summit <sup>3</sup>	6.44 (0.36)	6.89 (0.13)	148 (6.4)	33 (0.8)	980 (49)	120 (10.0)	91 (6.5)	2340 (48.8)	700 (44.9)	380 (10.7)	8.3
Wood Camp Hollow	6.23 (0.59)	6.55 (0.28)	94 (4.1)	50 (1.3)	650 (32)	52 (4.2)	60 (4.3)	870 (18.1)	400 (20.1)	-	5.5
Sherwood Hills <sup>3</sup>	6.20 (0.63)	6.79 (0.16)	280 (12.2)	164 (4.2)	675 (34)	169 (13.9)	124 (8.9)	1110 (23.1)	550 (33.5)	510 (14)	8.3
Logan-Dry Canyon <sup>3</sup>	6.26 (0.55)	6.78 (0.17)	400 (17.4)	288 (7.4)	1050 (53)	118 (9.7)	127 (9.1)	2025 (42.2)	650 (39.1)	430 (12)	10.1
Sundance <sup>3</sup>	6.77 (0.17)	6.56 (0.28)	136 (5.9)	110 (2.8)	580 (29)	64 (5.3)	178 (12.7)	1080 (22.5)	400 (20.4)	360 (10)	15.7
Strawberry Summit <sup>3</sup>	6.18 (0.66)	6.40 (0.40)	344 (15.0)	192 (4.9)	685 (34)	54 (4.4)	115 (8.2)	1230 (25.6)	350 (15.5)	450 (13)	8.0
Yellow Pine Campground	5.89 (1.29)	6.80 (0.16)	336 (14.6)	368 (9.4)	420 (21)	49 (4.0)	207 (15.8)	510 (10.6)	400 (24.4)	290 (8.2)	7.5
Deer Valley <sup>3</sup>	6.40 (0.40)	6.82 (0.15)	674 (29.3)	404 (10.3)	995 (50)	111 (9.1)	86 (6.1)	1365 (28.4)	640 (40.0)	730 (21)	11.4
Snow Basin <sup>3</sup>	6.08 (0.83)	6.64 (0.23)	176 (7.7)	148 (3.8)	290 (14)	58 (4.8)	112 (8.0)	420 (8.8)	400 (22.2)	270 (7.6)	5.0
Twin Creeks	6.00 (1.00)	6.54 (0.29)	199 (8.6)	152 (3.9)	413 (21)	42 (3.5)	103 (7.4)	930 (19.4)	330 (16.7)	360 (10)	14.9
Median <sup>4</sup>	6.23	6.72	296	154	730	70	114	870	500	420	9.2
Mean <sup>4</sup> +1 SD ( $\mu\text{g/l}$ )	6.17	6.61	307+182	193+131	742+362	84+50	119+39	1092+585	492+139	426+160	10.1+4.1
Mean <sup>4</sup> +1 SD ( $\mu\text{eq/l}$ )	(0.60)	(0.22)	(13.4+7.9)	(5.0+3.4)	(37.1+18.1)	(7.0+4.2)	(8.5+2.8)	(22.7+12.2)	(26.1+7.4)	(12.0+4.5)	

<sup>1</sup>initial (after 20-30 hr)

<sup>2</sup>equilibrium (after approximately 2 weeks)

<sup>3</sup>mean values for duplicate cores

<sup>4</sup>cores 1-17

Table 2. Minor element chemistry of 17 snow cores taken during April 14-25, 1982. All values in  $\mu\text{g}/\text{l}$ .

Station	$\text{NO}_2^--\text{N}$	$\text{NO}_3^--\text{N}$	TKN	SRP	TP	TOC	Pb	Cd	$\text{F}^-$
Bear Lake Summit	<1	110	390	<4	<4	1110	1.5	<0.06	<10
Wood Camp Hollow	<1	50	290	<4	<4	<500	<0.6	<0.06	<10
Sherwood Hills	3	850	630	<4	10	<500	1.6	<0.06	<10
Logan-Dry Canyon	3	120	620	<4	10	1900	1.5	<0.06	<10
Sundance	2	130	220	<4	14	500	<0.6	<0.06	55
Strawberry Summit	2	130	230	<4	13	2500	<0.6	<0.06	16
Yellow Pine Campground	1	100	390	<4	14	700	<0.6	<0.06	<10
Deer Valley	2	130	340	<4	26	1500	1.3	0.38	<10
Snow Basin	1	60	350	4	22	5500	0.6	<0.06	16
Twin Creeks	1	80	210	5	11	2000	1.0	<0.06	13
Median	1	100	290	<4	12	800	0	0	0
Mean	1	101	372	<4	12	1040	0.5	0.02	8
	+1	+29	+160	+2	+9	+1030	+0.7	+0.09	+14

of acid inputs because of the confounding effects of local changes in the snowpack following wet deposition events.

Comparison of the data obtained during this study with data collected by other investigators for the purpose of assessing the quality and composition of Wasatch Mountain snowpack relative to geographic areas known to be experiencing acid deposition is even more difficult. Many studies rely on bulk collectors, which continuously sample both wet (snow and rain) and dry (gas and particle) deposition, but are often placed several feet off the ground, and thus may not sample some fraction of the windblown soil inputs, especially before full snow cover is established (see the section on snowmelt collectors below). Wet-only collectors remain open only during precipitation events. While time integrated wet-only samples will ultimately have a lower dissolved solid

concentration than bulk samples (e.g., Popp et al. 1982b), the relative acidity will depend on the relative importance of acid aerosol,  $\text{NO}_x$ , and  $\text{SO}_2$  deposition versus inputs of alkaline soil particles. Furthermore, the type of precipitation (snow, rain, fog, etc.) is known to affect its chemistry, as are seasonal factors for the same precipitation type (Hendry and Brezonik 1980, Raynor and Hayes 1981, Wisniewski 1982). Furthermore, changes in precipitation chemistry on an annual basis may be caused by meteorological variables such as storm paths, precipitation amount, and mixing heights, or by annual changes in industrial emissions resulting from economic or pollution control factors. It is notable that the winter of 1982 was one of the wettest on record in northern Utah, and that economic factors resulted in lower than normal activity at the copper smelter and steel mills in the Salt Lake and Provo areas, respectively.



Notwithstanding the caveats outlined above, data are only meaningful if placed in some wider context, and it is hoped that the comparisons below will serve to generate some testable hypotheses regarding the causes of spatial and temporal patterns of snowpack chemistry in the study area. However, any conclusions drawn from the comparisons must be regarded as tentative.

### Intraregional patterns

The network of sampling sites for the snow cores was designed to discern patterns of acidity or acid anion concentrations that could be related to source areas such as Salt Lake or Utah Lake Valleys. However, when the average ion concentration values at each site were plotted on a map of the study area (e.g., Figure 2), the patterns that could be discerned were not often those that were originally expected. For example, the pH isoquants in Figure 2a suggest decreasing pH from west to east, in the direction of the prevailing winter storm tracks. Two lobes of higher pH appear to impinge on the Wasatch Front from areas north and south of Great Salt Lake. This pattern could indicate a line input of acidity between Ogden and Salt Lake City, an increased input of buffering alkaline minerals from the land masses north and south of Great Salt Lake, or some combination of the two input patterns. If buffering alone accounted for the higher pH values at the westernmost sites, higher values for calcium and magnesium associated with carbonate minerals, accompanied by higher concentrations of the acid anions, nitrate and sulfate, would be expected to occur at the easternmost sites. Such patterns are not obvious for calcium or the acid anions (Figure 2b,c), although magnesium did generally decrease with decreasing pH.

It is noted that one of the Bear Lake Summit cores (#1) has been excluded from the values in Figure 2a and b. The sulfate concentration (3.24 mg/l) was much higher than the duplicate core from

the same site (#2, 1.44 mg/l), and could be excluded from the remaining sulfate values in the data set at the  $\alpha = 0.10$  confidence level using the Q-test of Dean and Dixon (1951),  $Q = 0.404$ ,  $n = 17$ . The calcium value was also unusually high, although it could not be similarly rejected. These high values may represent inclusion of a gypsum particle in the core or contamination of a sample bottle. If these values represent neutralization of  $H_2SO_4$  by  $CaCO_3$ , it seems unlikely that the calcium and sulfate values would not also be high in the duplicate core. Whatever the explanation, the initial sample pH may have been affected, although the other constituent concentrations were unremarkable. Inclusion of core #1 would result in addition of some increasing pH isopleths between Twin Creeks and Bear Lake Valley in Figure 2a, but would not alter the interpretation of Figure 2b.

The fact that Salt Lake Valley has an important effect on Wasatch Mountain snowpack chemistry is indicated by the chloride isopleths in Figure 2d. Great Salt Lake, lying to the west of the Salt Lake City and Ogden metropolitan areas, is composed of approximately 22 percent NaCl, and has the potential to act much as the ocean in coastal areas as a source of NaCl aerosols. Indeed, chloride isopleths indicate decreasing concentrations with elevation along the major highways proceeding away from the lake. Selection of the sampling sites virtually precluded trends resulting from road deicing. Sodium concentration was highly correlated with chloride concentrations in the cores, as will be discussed below. Contributions from halite in windblown soils are likely to be minimal because of the extensive snow cover during the winter of 1981-1982.

None of the remaining data showed obvious patterns, although  $NH_3-N$  concentrations were generally higher in the cores south of Salt Lake City. This may result from higher temperatures leading

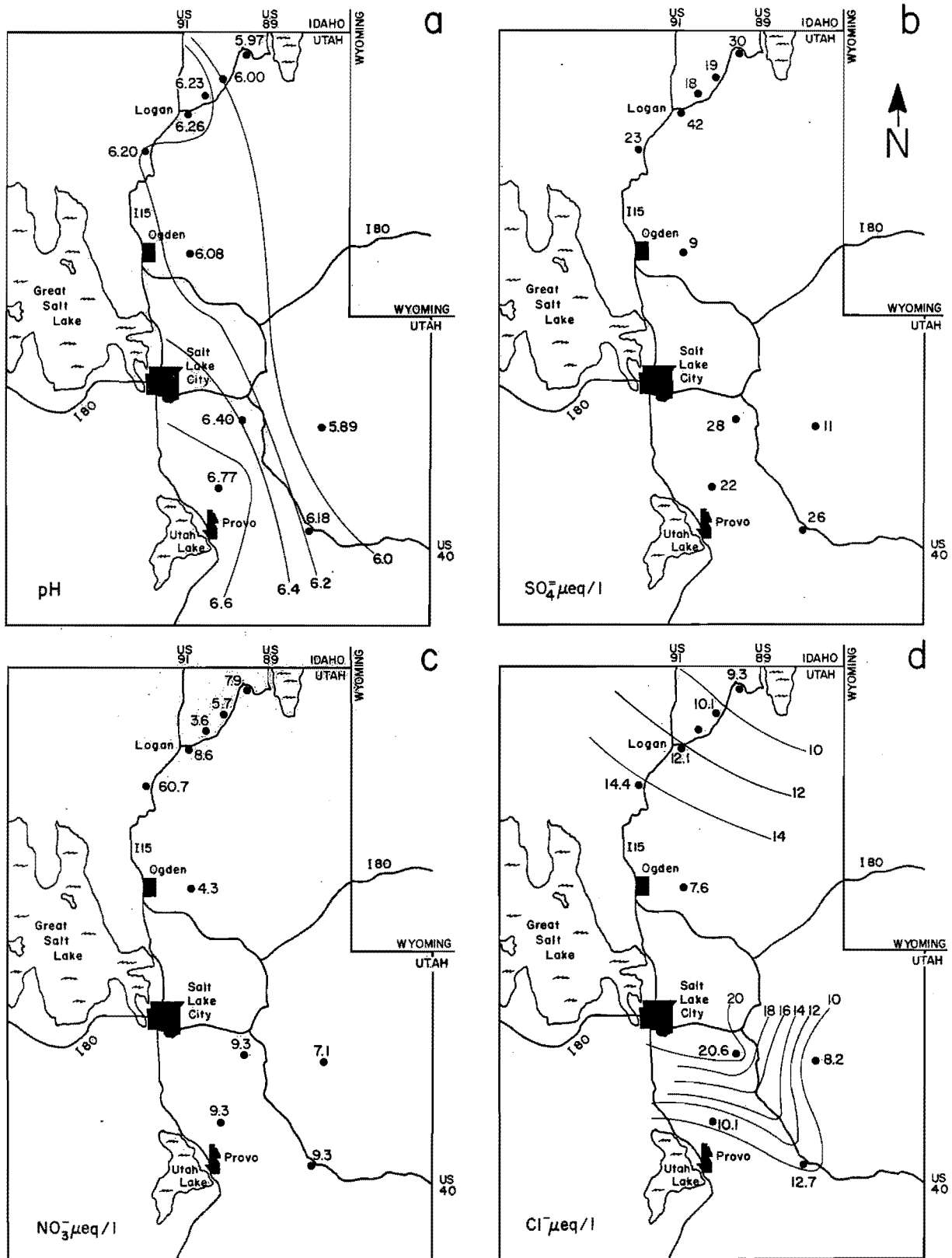


Figure 2. Initial pH, sulfate, nitrate, and chloride values for Wasatch Mountain snowpack during Spring, 1982. Core 1 has been excluded from 2a and 2b due to possible contamination.

to increased ammonia volatilization. The concentrations of all chemical species were tested for correlations with altitude, and all proved insignificant, contrary to the findings of Matveyev (1964). Nonetheless, the altitude of the sampling stations may confound spatial patterns of acid deposition through regulating the input of windblown, alkaline soils as well as thermal regime, as outlined above.

Even though individual ion concentrations may fail to reveal interpretable patterns, the interrelations among parameters may suggest sites that are receiving atmospheric deposition from common sources. It was also of interest to know whether variation in chemistry between duplicate cores was of a similar order of magnitude as the variation among sites. Q-type cluster analysis was used to gain insight into each of these patterns. Constituent concentrations in each core were standardized to the mean and one standard deviation to remove differential weights of large-valued constituents (pH was converted to  $(H^+)$ ), and clustered by mean Euclidean distance using the CLUSTAND statistical package (Marshall and Romesburg 1978). The resulting dendrogram (Figure 3) indicates that the most dissimilar groups of cores are 1) those north of Salt Lake City, 2) those from Deer Valley (due east of Salt Lake City), and 3) those taken at the three stations to the south and west. It can be seen that within a group, variability between cores often exceeds that between sampling sites. This analysis suggests the need for replacing sites with more replicate cores at the remaining sites in constant effort sampling designs.

#### Interregional comparisons

Table 3 presents the mean chemical data from the cores collected in this study with several sets of precipitation data collected by other investigators. Melt collected from a snowpack of extremely high purity from an alpine basin in the British Columbia Coastal

Mountains and snow sampled in bulk collectors on Long Island, a relatively highly impacted area downwind from New York City, provide a frame of reference in Table 3. The Big Bear data represent wet wintertime precipitation in the mountains of southern California. Although this area is described as "rural" by Liljestrang and Morgan (1981), it is just over the crest of the mountains from the Los Angeles metropolitan area. The data from Chama, New Mexico, represent annual wet-only precipitation in an unpopulated mountain area (2,380 m) southeast of Utah. This area is impacted by the Four Corners Power Plant, a major sulfate emitter. The Como Creek data represent annual bulk precipitation on the west side of the Front Range in the Colorado Rockies west of Denver. This area, although unpopulated, is apparently affected by the Denver metropolitan area airshed (see Kelly and Stedman 1980 and Lewis and Grant 1980b for an exchange of views on the source of Como Creek acidity). At least half of the precipitation included at the last three stations represents winter snowfall. However, it should be noted that the New York, New Mexico, and California data represent wet-only precipitation and therefore fail to include dry deposition of particles and gases on the collector or snow surfaces, as do bulk collectors (Como Creek), or snowpack (British Columbia and this study).

The relatively high pH and low acid anion concentrations in the Wasatch Mountain snowpack, relative to the other anthropogenically impacted sites, suggest that acid deposition during the winter is not yet a serious threat to surface water quality in the study area. However, it is important to consider the possible differences between snow cores and the other types of data found in Table 3. In northern Minnesota, Thornton et al. (1981) found that wet-only snow collections had a lower volume weighted pH than snow cores taken at the same station at the western end of their transect (4.7 versus 6.0,

Table 3. Average spring snowpack chemistry in the Wasatch Mountains and some related data reported by other workers. All values in  $\mu\text{g}/\text{l}$  except pH.

Parameter	British Columbia, Canada <sup>1</sup>	Long Island, New York <sup>2</sup>	Big Bear, California <sup>3</sup>	Chama, New Mexico <sup>4</sup>	Como Creek, Colorado <sup>5</sup>	Wasatch Mountains Utah
pH	5.20	4.54	5.42	4.8	4.77	6.17
Sodium	25	1150	97	700	304	307
Potassium	17	-	17	700	247	193
Calcium	35	-	186	800	611	742
Magnesium	20	-	91	200	70	84
NH <sub>3</sub> -N	7	196	105	-	192	119
NO <sub>3</sub> <sup>-</sup> +NO <sub>2</sub> <sup>-</sup> -N	25	670	238	300	273	101
Sulfate	-	2400	312	2600	1450	1092
Bicarbonate	-	-	-	-	2620	1592
Chloride	200	1846	185	1000	-	426
SO <sub>4</sub> <sup>=</sup> /NO <sub>3</sub> <sup>-</sup> ratio (equivalents)	-	1.0	0.4	2.5	1.5	3.1

<sup>1</sup>Zeman and Slaymaker (1975); snowmelt, May-June 1973

<sup>2</sup>Raynor and Hayes (1981, 1982); wet-only (snow) collectors, June 1976-June 1979

<sup>3</sup>Liljestr nd and Morgan (1981); 2 bulk collectors, May 1975-April 1978

<sup>4</sup>Popp et al. (1982a); 1 wet-only collector, 1979-1981

<sup>5</sup>Lewis and Grant (1979); 1 wet-only collector, January-March 1979

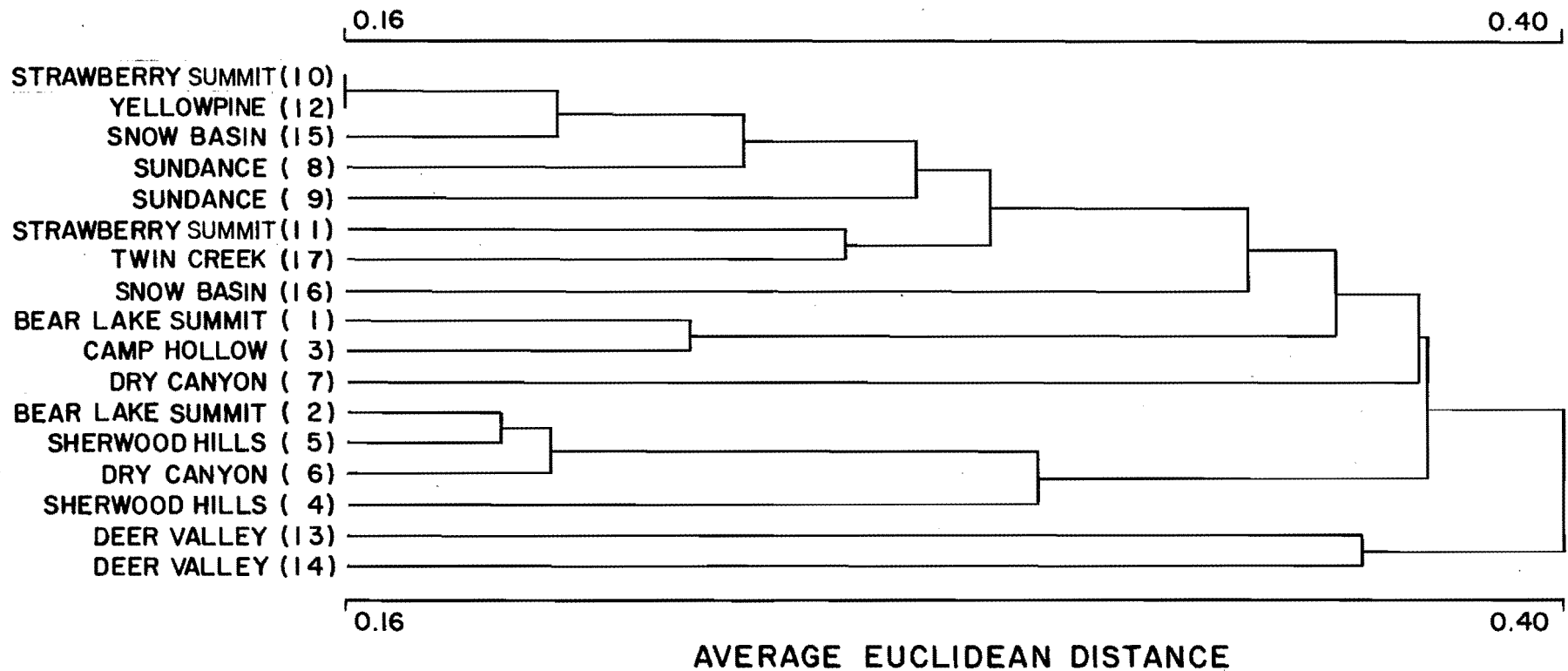


Figure 3. Dendrogram showing similarity between Wasatch Mountain snow cores as a function standardized chemical concentrations. Cophenetic correlation = 0.804.

respectively), where the ratio of windblown soils to acid deposition was relatively low. Popp et al. (1982a) have also demonstrated that the pH of snow in bulk collectors increased with time when exposed to windblown dust in the mountains of New Mexico. Consequently, the initial pH values observed in the snow cores from this study are almost certainly higher than would have been observed in wet-only collectors. The fact that the pH of the unfiltered samples increased between 1-2 days and 2-3 weeks after collection (initial versus equilibrium pH in Table 1) indicates that acid-base equilibrium may take weeks at cold (4°C) temperatures. This line of reasoning also suggests that major cation concentrations (e.g., Ca<sup>++</sup> and Mg<sup>++</sup>) in this study overestimate the true concentrations in snowfall and would probably also be higher than samples taken from bulk precipitation collectors. The importance of the discrepancy between ion concentrations measured by the technique used in this study and the actual ion concentrations in snowfall or snowmelt will be discussed below.

For the same reasons that snowfall pH and alkaline earth cations may be overestimated in the snow core meltwater, the acid anion concentrations also must overestimate the true snowfall values. Deposition of SO<sub>2</sub>, NO<sub>x</sub>, or acid aerosols resulted in lowering the pH of snow cores relative to wet-only precipitation at the eastern end of the Minnesota transect studied by Thornton et al. (1981), where anthropogenic inputs of acids exceeded the buffering capacity of windblown soils. Also, exposure of the snowpack to aeolian gypsum or other soils derived sources of sulfate or nitrate would elevate the concentration of these ions relative to fresh snowfall. A significant gypsum stratum is present in the Great Salt Lake Desert, and this stratum is exposed south of Great Salt Lake (Bingham 1980). However, there is no evidence for higher sulfate concentrations at the southern sampling sites (Figure 2b),

which would be expected if gypsiferous sulfate were superimposed on an acid sulfate source.

Assuming that the bulk of the sulfate and nitrate are derived from their respective acids rather than soil sources, the sulfate to nitrate ratio suggests the relatively greater importance of SO<sub>2</sub> than NO<sub>x</sub> in contributing acid to the snowpack. This is in contradistinction to reports that the principal source of acidity is NO<sub>x</sub> in western watersheds (Lewis and Grant 1980a, Liljestrand and Morgan 1981, McColl 1981, Leonard et al. 1981). Apparently acid deposition in most western studies results from the heavy traffic patterns in San Francisco, Los Angeles, and Denver, whereas the much less densely populated Wasatch Front produces significantly lower inputs of NO<sub>x</sub>. Although Utah and Idaho sulfur emissions are among the lowest in the nation (Nieman, in Hileman 1982), the valleys along the Wasatch Front do contain copper smelting and steel industries, as well as the normal complement of coal-fired power plants associated with industry and population centers in the West. Although it is probable that these industries are responsible for the relatively high SO<sub>4</sub><sup>=</sup>:NO<sub>3</sub><sup>-</sup> ratio in the Wasatch snowpack, the concentrations of both anions are low relative to the Four Corners (Chama) or eastern seaboard locations.

One final note of caution is appropriate in comparing the Wasatch snowpack data with the other values in Table 3. The Chama and Como Creek data include rainfall as well as snowfall. Popp et al. (1982b) found winter precipitation (mostly snowfall) to have a higher pH and SO<sub>4</sub><sup>=</sup>:NO<sub>3</sub><sup>-</sup> ratio than summer precipitation at two sites in New Mexico. Also, although the pH of snow events was lower than that of rain events in the Minnesota study, the opposite is true of precipitation at other locations (Raynor and Hayes 1981, Pack 1982). However, it is likely that even any qualitative gener-

alization regarding the comparative chemistry of rain and snowfall is fraught with factors that covary with precipitation type (e.g., wind direction, source area) and may be more important than the relative efficiency of rain versus snow scavenging processes.

Source modeling to account for snowpack chemistry

In an initial attempt investigate possible common sources of ions in the snow cores, principal components analysis (PCA) was applied to the chemical data. Principal components can be thought of as representing factors that contribute to ions or groups of ions that covary among the samples. PCA was applied to snow cores 1-17 by using the FACTOR subroutine of SPSS (Kim 1975) with varimax rotation of the principal components. The first five PC's had eigenvalues greater than 1.0 and accounted for 89.2 percent of the variability in the data set (Table 4).

The first PC corresponds to a common source of Na<sup>+</sup>, K<sup>+</sup>, and Cl<sup>-</sup>, probably from Great Salt Lake rather than road salt (Figure 2d). The second PC represents a source of Ca<sup>++</sup> and SO<sub>4</sub><sup>=</sup>, with a rather high association with lead. The remaining three PC's represent NH<sub>4</sub><sup>+</sup> coupled slightly with NO<sub>3</sub><sup>-</sup>, initial pH, and alkalinity, respectively. Initial pH in PC 4 does not correlate highly with other ions, and is seen to be slightly inversely related to the acid anions, SO<sub>4</sub><sup>=</sup> and NO<sub>3</sub><sup>-</sup>. Linear stepwise regression of all chemical variables against initial H<sup>+</sup> activity (I<sub>pH</sub>) indicated the strongest association with low sulfate and high calcium concentrations. This analysis suggests common occurrences of alkali earth chlorides and of calcium with sulfate but little unneutralized strong acid deposition. Although this model is consistent with gypsum deposition, a high correlation between calcium and sulfate would also result from scavenging of acid sulfates on calcium

and magnesium carbonates in the atmosphere. In the latter scenario, the calcium/magnesium deposition pattern would, to a large extent, control wet sulfate deposition, and to a lesser extent, SO<sub>2</sub> and NO<sub>x</sub> deposition on the snowpack.

If one were to hypothesize mineral acid sources for sulfate and nitrate, a conceptual geochemical model (e.g.,

Table 4. Principal components analysis of chemical concentrations in Wasatch Mountain snow cores, spring 1982.

Constituent	PC 1 30.7% <sup>1</sup>	PC 2 21.9%	PC 3 17.7%	PC 4 9.9%	PC 5 9.0%
IH <sup>2</sup>	0.01	-0.29	0.08	0.93	-0.09
NH <sub>4</sub> <sup>+</sup>	-0.23	-0.19	0.93	0.10	0.10
Ca	0.27	0.90	0.12	-0.16	0.19
Na	0.93	0.12	-0.15	0.01	0.16
K	0.87	0.01	0.09	0.23	0.12
Pb	-0.05	0.45	-0.36	-0.07	-0.15
NO <sub>3</sub> <sup>-</sup>	0.42	0.25	0.51	-0.40	0.32
TKN	0.20	0.15	-0.15	0.21	0.01
SO <sub>4</sub> <sup>=</sup>	0.03	0.92	-0.06	-0.21	0.16
Cl <sup>-</sup>	0.89	0.20	-0.18	-0.25	-0.01
ALK	0.11	0.25	0.13	0.10	0.94
TP	0.40	-0.23	-0.03	-0.03	-0.12
TOC	0.18	0.18	-0.10	0.07	0.11

<sup>1</sup>Percent of model variability accounted for by PC

<sup>2</sup>Initial (20-30 hr) H<sup>+</sup> activity

Liljestrand and Morgan 1981) is useful. Such a model is presented in Table 5 for the average snowpack chemistries in the bottom row of Tables 2 and 3. Contributions from Great Salt Lake aerosols were subtracted (1) following the method of Granat (1972) for seawater and using the chemical ratios of Whitehead and Feth (1961) and Sturm (1980). This model assumes no differential efficiency in transportation of the various ions from the lake to the aerosol, and constant lake water composition over time; the latter assumption is not exactly correct for Great Salt Lake (Sturm 1980). Also, chloride, rather than sodium was used as an indicator of NaCl contribution, for reasons given below.

The next step was to correct for the neutralization of mineral acidity (2). Carbonate alkalinity was assumed to be associated with calcium and magnesium carbonates in their empirical stoichiometric ratios in the snow samples following for correction for

Mg<sup>++</sup> inputs from Great Salt Lake. For simplicity, all HNO<sub>3</sub> was assumed to be neutralized by atmospheric ammonia (3) and the remaining ammonia to react with H<sub>2</sub>SO<sub>4</sub> (4) to form NH<sub>3</sub>NO<sub>3</sub> and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, respectively. The remaining calcium and magnesium carbonates were assumed to result from the reaction of their respective carbonates with H<sub>2</sub>SO<sub>4</sub> and the 0.2 meq/l remaining hydrogen ion to be associated with H<sub>2</sub>SO<sub>4</sub> (5). This leaves 4.2 μeq/l of SO<sub>4</sub>, and 7.0 μeq/l of alkali metal cations, a discrepancy amounting to only 3 percent of the initial ion equivalent concentration. The mean E<sub>pH</sub> (6.61) of the samples is close to the equilibrium pH (6.64) predicted if carbonates were controlling the pH in an open system at the sample storage temperature (4-5°C).

The residual alkali sulfates could have several explanations. It is unlikely that they represent unaltered mineral inputs from the deserts, where alkali sulfates are apparently not abundant (Bingham 1980). Also, no major

Table 5. Geochemical ion balance for average Wasatch Mountain snowpack chemistry, Spring 1982.

Process	Ion Concentration (μeq/l)									
	H <sup>+</sup>	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>++</sup>	Mg <sup>++</sup>	NH <sub>4</sub> <sup>+</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
Initial snow concentration	0.2	13.4	5.0	37.1	7.0	8.5	26.1	22.7	12.0	7.1
Source of Ions										
(1) Great Salt Lake	0.2	2.4	4.7	37.1	6.6	8.5	26.1	21.7	0.0	7.1
(2) Ca <sub>0.8</sub> Mg <sub>0.18</sub> CO <sub>3</sub>	-	-	-	15.7	1.0	-	0.0	-	-	-
(3) HNO <sub>3</sub> +NH <sub>3</sub> →NH <sub>4</sub> NO <sub>3</sub>	-	-	-	-	-	1.4	-	-	-	0.0
(4) H <sub>2</sub> SO <sub>4</sub> +NH <sub>3</sub> →NH <sub>4</sub> SO <sub>4</sub>	-	-	-	-	-	0.1	-	20.3	-	-
(5) H <sub>2</sub> SO <sub>4</sub> +Ca <sub>0.8</sub> Mg <sub>0.2</sub> CO <sub>3</sub> → Ca <sub>0.8</sub> Mg <sub>0.2</sub> SO <sub>4</sub> +H <sub>2</sub> O+CO <sub>2</sub>	0.0	-	-	0.0	0.0	-	-	4.2	-	-
Unaccounted for	0.0	2.3	4.7	0.0	0.0	0.0	0.0	4.2	0.0	0.0



Salt Lake Valley sulfur sources use soda ash scrubbers, and  $\text{Na}^+:\text{SO}_4^{2-}$  equivalent ratios are quite low (0.04) in the proximal plume of the copper smelter (Eatough et al. 1982). A more likely explanation is that the sodium and potassium ions resulted from ion exchange reactions with aeolian sodic clays deposited on the snow surface from the desertic valleys to the west (J. Jurinak, Utah State University, College of Agriculture, personal communication). These soils are easily eroded, and also would readily exchange  $\text{Na}^+$  or  $\text{K}^+$  with  $\text{Ca}^{++}$  in the meltwater. If this is the case, then these ions also represent neutralized acid deposition. This analysis would indicate that 21.7  $\mu\text{eq}$  of  $\text{H}_2\text{SO}_4$  and 7.1  $\mu\text{eq}$  of  $\text{HNO}_3$  have been neutralized by 28.8  $\mu\text{eq}$  of ammonia and carbonates, compared with an approximately equal equivalent concentration of unused buffering capacity (30.9  $\mu\text{eq}/\text{l}$ ).

If the hypothetical geochemical model in Table 5 is correct, certain differences in snowpack chemistry could be predicted to occur in a "normal" water year. Decreasing areal extent and duration of snow cover should make more alkaline soil minerals available for aeolian transport to snowpack surfaces. On the other hand, if Great Salt Lake aerosol is relatively unaffected by snow cover, the sodium concentration should be a function of dilution with snowpack water equivalent and effective distance from the lake (e.g., Figure 2d). The calcium to sodium ratio would thus be expected to increase, as would the concentration of all ions except  $\text{H}^+$ , whose concentration would depend on the bicarbonate concentration for a similar input of strong mineral acid to 1982. A concomitant increase in  $\text{H}_2\text{SO}_4$  would increase the sulfate: sodium ratio over 1982. All of these assumptions assume similar mesoscale meteorological conditions with respect to Great Salt Lake aerosol transport. The 1982 major winter storms were approximately equally distributed between the northwest and southwest quadrants.

Unfortunately, the hypothetical geochemical model cannot rule out the possibility that some or all of the sulfate came from gypsum. Confirmation of the ultimate source of sulfates may ultimately be possible by calculating anion/aluminum ratios (Thornton et al. 1981) or by employing stable sulfur isotope ratios (Nriagu and Harvey 1978) which may differ between gypsum and sulfate from  $\text{SO}_2$ . Even if all of the sulfate and nitrate came from acid emissions, however, the sources were insufficiently strong during 1982 to titrate the alkalinity deposited on or with the snowfall during the winter of 1982.

#### Temporal trends

While few historical data for precipitation or snowpack chemistry exist, two relevant studies have been performed in the study area. A set of snow cores was taken near Bear Lake Summit by an SCS field crew in December 1959 and analyzed by Feth et al. (1964), and winter bulk precipitation collections were taken by Hart et al. (1973) in Logan Canyon and Blacksmith Fork during the winters of 1969-1971. Again, one is forced to deal with data that are not exactly comparable. Collection and specific analytical methods differ, sites are not in exact juxtaposition, and meteorological conditions are undoubtedly different. Comparisons should be made with extreme caution and the data are presented here in order to concatenate data that may otherwise escape notice.

The January-March data for the Hart study are compared with the Logan dry canyon cores, and several snow cores from the Feth study with the corresponding cores from this study in Table 6. The pH was considerably higher in the 1982 cores than in all but the Strawberry Summit snow cores. Initial (Logan) or equilibrium (Bear Lake Summit) pH was used, depending on the length of time between sample collection and analysis in the previous study. No

Table 6. Comparison of 1969-1971 winter bulk precipitation chemistry (Hart et al. 1973) and 1959 snow core chemistry (Feth et al. 1964) with that of 1982 snow cores from similar locations. All values in mg/l except pH and EC ( $\mu$ S).

Constituent	Logan Canyon		Bear Lake Summit		Snow Basin		Strawberry Summit	
	1969-71 unweighted bulk precipitation	1982 snow cores	1959	1982	1959	1982	1959	1982
pH	5.5	6.11	6.5	6.92	-	6.62	7.2	6.42
Na <sup>+</sup>	0.2	0.2	0.3	0.1	0.5	0.2	0.4	0.3
K <sup>+</sup>	0.8	0.2	0.2	0.0	-	0.1	-	0.2
Ca <sup>++</sup>	0.6	0.7	1.2	1.0	-	0.3	4.0	0.7
Mg <sup>++</sup>	0.1	0.1	0.2	0.1	-	0.0	-	0.0
TP	0.06	0.01	-	0.0	-	0.02	-	0.01
NO <sub>3</sub> -N	0.05	0.08	0.23	0.11	-	0.06	-	0.13
SO <sub>4</sub>	-	1.3	1.0	1.4 <sup>3</sup>	-	0.4	-	1.2
Cl <sup>-</sup>	-	0.4	1.1	0.4	0.2	0.3	5.0	0.5
EC	132	10	10	8	42	5	39	8

1 pH<sub>I</sub>  
 2 pH<sub>E</sub>  
 3 core #2 only

other trends are apparent in the data, except for generally higher sodium values in the 1959 cores than in those collected during this study. The high potassium value, attributed by Hart et al. (1973) to aeolian soil from agricultural operations, may well be due to KCl contamination from the electrode used to measure the pH of these small samples before the other analyses were done. Also, the Hart et al. (1973) EC values are also surprisingly high for precipitation samples. This may be the result of failing to volume weight the mean values. For reasons discussed previously, the generally higher concentrations in the 1982 cores may result from dry fallout not collected by the bulk samplers.

The Bear Lake Summit cores taken during this study contained lower con-

centrations of all constituents except sulfate than the 1959 cores. The concentrations of the constituents other than calcium and sulfate occur in ratios of 0.35-0.5, perhaps suggesting dilution. The winter of 1959-1960 was drier than normal while the winter of 1981-1982 was one of the wettest on record. The high calcium and sulfate values at Bear Lake Summit are remarkable, and may suggest enrichment since 1959, inasmuch as most of the sites in the 1982 study had sulfate concentrations greater than 1 mg/l. It may be significant, however, that the 1959 cores were taken earlier in the winter. In conclusion, differences in collection and analytical methodologies superimposed on natural sources of variation preclude establishing long term trends in acidification of winter snowpack in the Northern Wasatch Mountains.

## Potential for Acid Runoff

### Chemistry of successive snowcore melt fractions

The bulk chemistry of a snow column does not accurately represent the worst case water quality conditions during spring snowmelt. Because dissolved ions disrupt the low free energy inherent in ice crystal formation, they tend to concentrate in the liquid phase during melting, elevating ion concentrations in the first melt. This concentration of acidity and other dissolved ions has been demonstrated by Seip (1980) for an acidic snowpack and the resulting streamflow in field plots in Norway.

Figure 4a demonstrates this phenomenon for ionic concentrations, as measured by electrical conductivity, for the Wasatch snow cores. In all cases EC declined between the first and second liter of water collected as the cores melted, and in most cores, again in the third. However, similar trends in pH were less consistent (Figure 4b), but samples with higher initial pH ( $>6.2$ ) tended to show decreasing pH in the later, rather than earlier, melt fractions. Overall for pH, the ratio of ( $H^+$ ) in the initial liter of melt to the core average was less than, but not significantly different than, 1 ( $\bar{x} = 0.88$ ,  $n = 17$ ,  $\alpha = 0.90$ ); the highest ratio observed was 1.4. Such a pattern of higher EC and higher pH in the initial melt fractions would be expected in geochemically alkaline, rather than acid snow, because the concentration of alkalinity would exceed that of mineral acidity in the earlier melt fractions.

The three melt fractions from Core 17, taken at the Twin Creeks runoff

sites, were analyzed separately. The results demonstrate the changes in snowpack chemistry occurring during snowmelt. Meltwater chemistry profiles for  $Na^+$ ,  $Ca^{++}$ ,  $H^+$ ,  $SO_4^{=}$ , and  $NO_3^-$  are shown in Figure 5. The large decreases in major constituents and the smaller sequential decrease in nitrate is juxtaposed against the indifferent behavior of  $H^+$  activity and alkalinity. Other ions showed similar trends to  $Na^+$  and  $Ca^{++}$  concentrations. Heavy metal concentrations were low and showed no trends.

This study indicates that, as would be expected, alkaline snow concentrates alkalinity, rather than acidity, in the initial melt fractions. However, it should be noted that the cores melted from the sides inward, thus integrating the vertical inhomogeneities in snowpack chemistry. Actual snowpacks typically melt from the top and bottom. If acid deposition was more intense early in the season and was not titrated by higher inputs of windblown alkaline minerals due to greater exposure of source areas before snowcover was well established, then pH in the first meltwater fraction could be somewhat lower. Also, the cores taken one atop the other add a confounding element because of possible vertical peculiarities in the distribution of dust and detritus. Although cores were generally free of such debris, it tended to be deposited in the final melt fraction, where present. Such litter could alter the pH of the stored sample through titration (Table 8), which may be confused with lower initial  $H^+$  activity. Nonetheless, many of these same reactions may occur during snowmelt in the field, where residence times may be long during ripening of the snowpack.

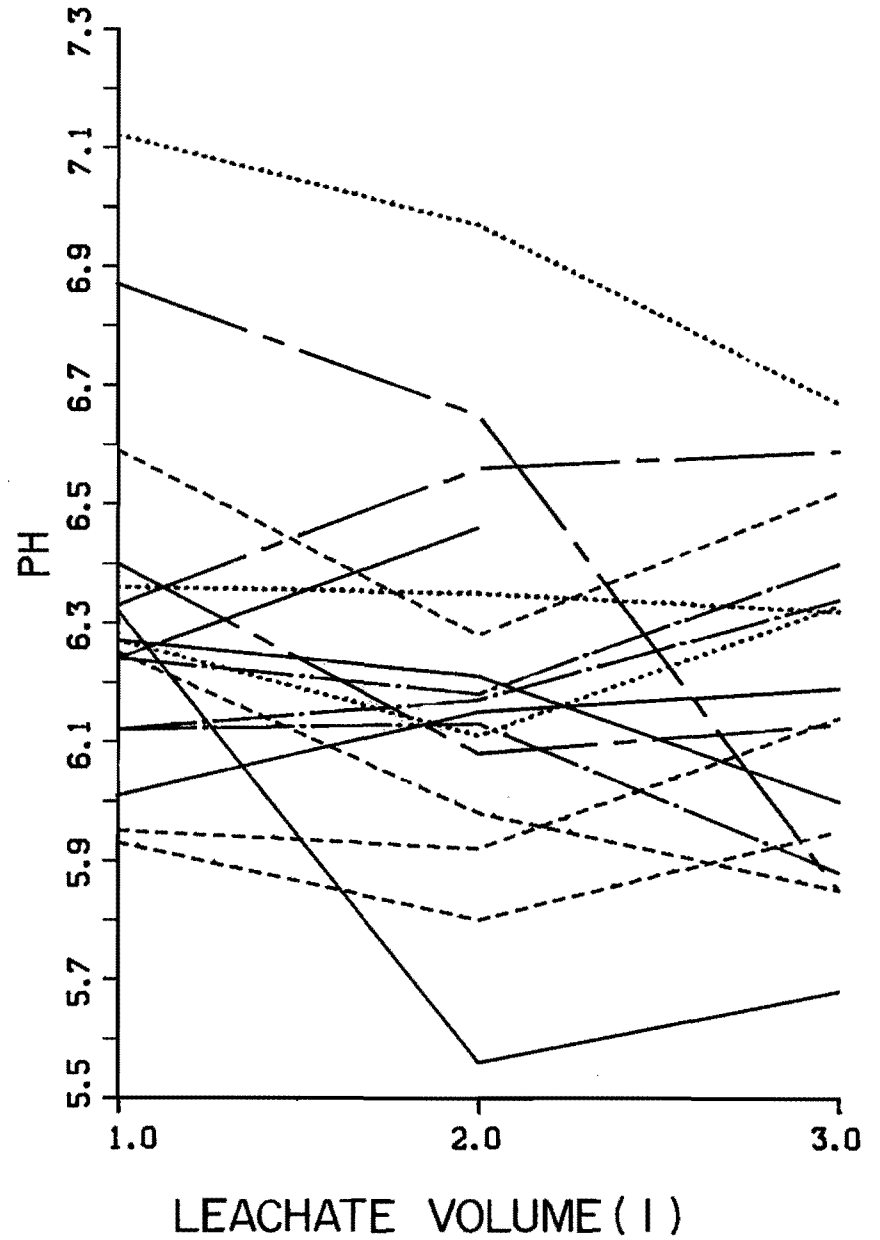
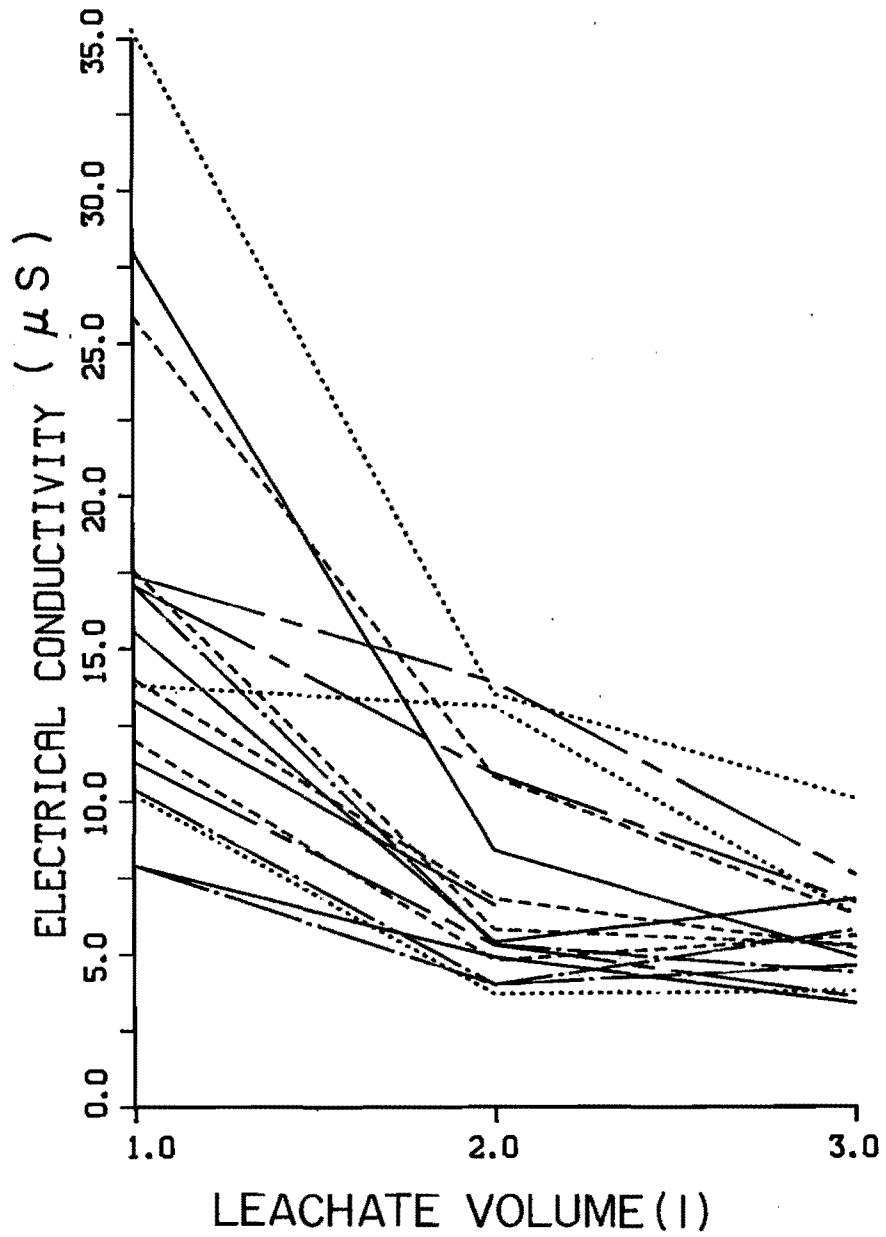


Figure 4. EC and pH in successive 1 l fractions of meltwater from Wasatch Mountain snow cores. Each line connects measurements from successive 1 l melt fractions.

### Runoff on test plots

Although two sets of runoff collectors were installed in Logan Canyon, the Hattie's Grove collectors were damaged, either by deer or vandalism, prior to snowmelt, and no data were obtained. At the other site, Twin Creeks, several of the tubing connections between the runoff troughs and the collecting bottles were pulled loose, apparently by downslope movement of the snowpack. However, the five samples collected on May 1, 1982, adequately reflect the vertical chemical profile of the sample collectors: 92 cm, 76 cm, 46 cm, and 30 cm above ground level and the trough sampling the litter (0) horizon. The complete data are given in Table A3 in the appendix, and the trends are summarized in Figure 6.

The three graphs, EC,  $\text{Na}^+/\text{K}^+$ , and total organic carbon, at the top of Figure 6, show similar trends: increasing concentrations with snowpack depth, especially in the 30 cm collector, and much lower concentrations in the litter horizon collector. These trends were repeated by most other major ions. TKN and phosphorus species showed no trends with depth, while nitrate and ammonium had their greatest concentrations in the (0) collector. Lead showed slightly elevated concentrations in the 30 cm collector, and a quite high level (45  $\mu\text{g}/\text{l}$ ) in the (0) collector. Alkalinity and  $\text{H}^+$  activity (Figure 6e) showed an inverse relationship within the snowpack, except in the litter horizon collector, where a slightly below neutral pH was accompanied by low alkalinity.

The most likely explanation for the patterns of major ion and TOC concentrations in Figure 6, is that the snow collected by the open troughs was contaminated by windblown dust and litter during periods when there was no snow cover, with increasing contamination in the collectors nearest the ground. This would explain the low ion concentrations in the 0 horizon collec-

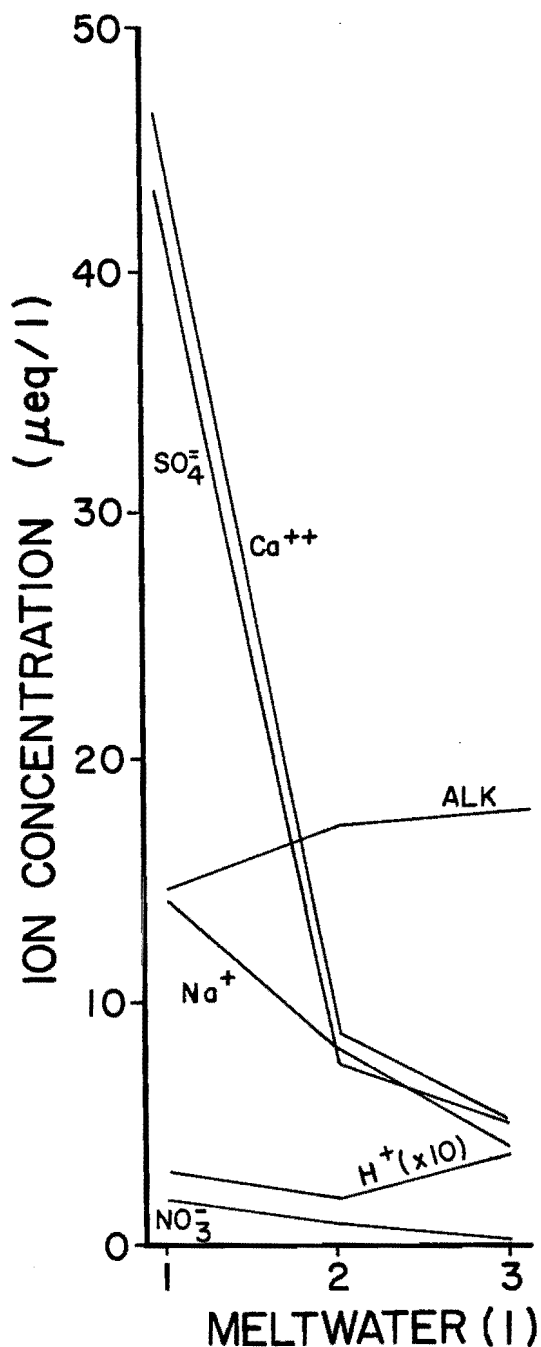


Figure 5. Ion concentrations in successive 1 & fractions of meltwater from a Twin Creeks snow core.

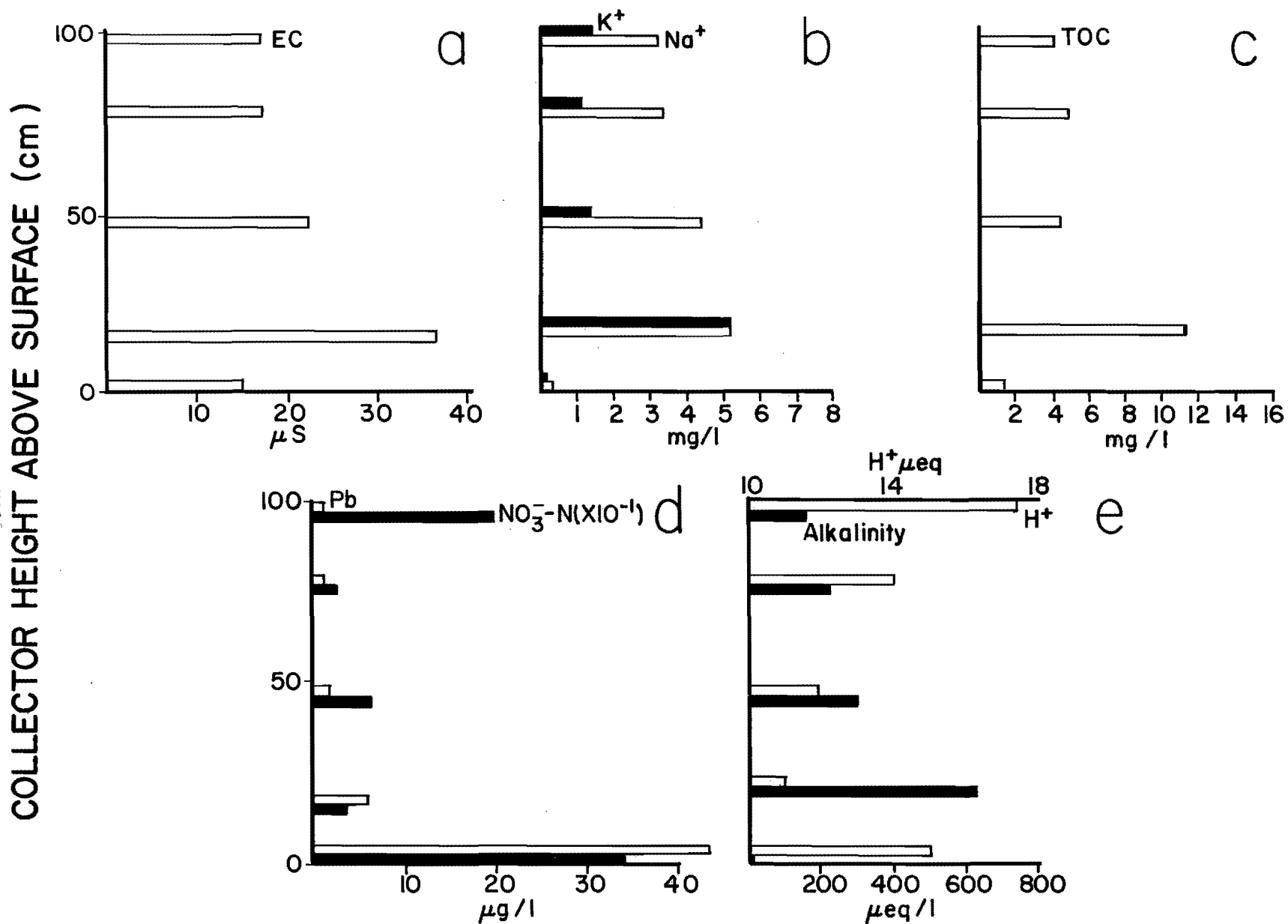


Figure 6. Representative ion concentrations in snowmelt collected in different snowpack depths above ground level at Twin Creeks field plot. The bottom bars represent the litter horizon (0) collector.

tor which was covered and thus would not have been contaminated. Otherwise it would be hard to explain why snowmelt percolating through the entire snowpack, or snowmelt occurring at the snow-soil interface, would appear to have higher concentrations of ions than flow through the litter horizon. Although the collectors were installed following the first snow, the initial shallow snow cover may have melted, at least on parts of the slope below the sites, before the permanent winter snowpack was established. The sagebrush also may have acted as a source of dust before the lowest two collectors were finally covered.

If this explanation is accurate, the measurements taken to represent increasing snow pH with depth may actually be the result of more alkaline dust being deposited in the lower container. The lack of pattern in the P and TKN concentrations could result from the less dense nature of the contributing particulates, or their more random occurrence than the major soil ions. The high inorganic nitrogen concentrations in the O horizon collectors, as well as the higher H<sup>+</sup> activity and low alkalinity, may have resulted from mineralization and nitrification of the litter under the snow cover. The latter may have occurred within the sample bottles as temperatures increased in the closed sampling pit exposed to the spring sunlight. The elevated lead concentration in the 30 cm collector may represent lead in soil dust, although the main highway is approximately 1 km away in a downslope direction, and snowmobiles are not allowed in the immediate vicinity. The high lead concentration in the O horizon collector may have resulted from soldered joints in the braces overhanging the PVC collection trough, although it could also have resulted from lead accumulated in the soil litter.

Because of these uncertainties regarding contamination of the above-ground collectors by windblown soil, it

is impossible to say with certainty whether snowpack interflow was different in concentration than bulk snow chemistry or whether the volume of interflow was significant. Samples from the O horizon collector, however, can be compared to the Twin Creeks snow core chemistry to determine chemical changes resulting from passage of the meltwater downslope or downward through the snowpack. Table 7 gives ion ratios between the O horizon and both bulk core and initial (1 ℓ) meltwater chemistry. Most of the ion concentrations more than doubled during the short passage downslope; in contrast, H<sup>+</sup> and sulfate decreased. The change is less pronounced but similar with respect to the initial melt fraction of the core, except that calcium also appears to decrease. Even short passages of melt-

Table 7. Ion ratios between litter (O) horizon meltwater and bulk (3 ℓ) and initial fraction (1 ℓ) snowmelt from the Twin Creek's snow core and the meltwater in the collector on the runoff plots.

Ion	O: Bulk Core	O: Initial Core
H <sup>+</sup>	0.15	0.27
Na <sup>+</sup>	2.6	1.6
K <sup>+</sup>	2.2	1.4
Ca <sup>++</sup>	1.7	0.7
NH <sub>4</sub> <sup>+</sup>	2.2	1.6
SO <sub>4</sub> <sup>=</sup>	0.5	0.6
Cl <sup>-</sup>	2.2	1.9
HCO <sub>3</sub> <sup>-</sup>	1.5	1.6
-		
NO <sub>3</sub> -N	1.6	3.1

water down vegetated slopes titrate most of what little  $H^+$  ion is present in the meltwater, as well as experiencing significant, though small, changes in meltwater chemistry.

#### Stream chemistry

The titrating effect of soils and groundwater was even more evident in an ephemeral stream near the runoff plots. The chemistry of a series of streamwater grab samples taken from the edge of the snowbank to a point 20 m above the highway crossing on May 9, 1982, is detailed in Table A4 in the appendix. Sampling sites and some representative ion concentrations are shown in Figure 7. The pH rises from 7.78 to 8.24, alkalinity from 0.4 to 1.0 meq/l, and  $Na^+$  from 0.17 to 0.22 meq/l. Nitrogen, phosphorus, and TOC values are generally higher at the downstream station, but similar and variable at the four stations at the higher elevations (Table A4). Even during peak snowmelt, additions of groundwater, or reactions with basic carbonate minerals in the stream channel apparently neutralized what little  $H^+$  was present in the 1982 spring snowpack. It is noted that these runoff studies were conducted in only a single location and should not be generalized to sites with more acidic soils without further field studies.

#### Neutralization of artificial acid precipitation

In order to test the ability of the forest litter and A horizon soil in the Wasatch Mountains to neutralize acidic precipitation, if it were to occur, samples from the Hattie's Grove runoff collector site were placed in a glass beaker and mixed with distilled water titrated to pH 4 with  $H_2SO_4$ . The soil was covered with the solution, and the beaker was sealed with plastic wrap and a rubber band and incubated at 20°C. Samples were taken daily for a week by filtering through a Buchner

funnel, and subsequently through Whatman GFC filters. The data are summarized in Table 8.

In summary, the pH rose to 7.2 ( $A_1$  horizon) to 6.9 (O horizon) during the first 24 hr of contact. Electrical conductivity increased in both samples, but more so in the litter zone. Alkalinity showed a similar trend. Most important, one day of contact raised all of the ion concentrations above to values higher than those observed in the O horizon collector at the Twin Creeks site, despite the higher  $H^+$  activity of the simulated rain. Caution should be used in interpreting experiments with artificial acid rain, which in this case did not include  $HNO_3$  or other ions.

Table 8. Chemistry of artificial acid rain ( $10^{-4}$  N  $H_2SO_4$ ) after exposure to litter and  $A_1$  horizon soil in the laboratory.

Day	pH	EC μS	Alkalinity meq/l
<u>Litter</u>			
(O) horizon			
1	6.9	248	1.2
2	6.8	338	1.4
3	6.9	312	1.8
4	6.6	449	2.5
5	6.7	488	2.9
6	6.8	534	3.5
7	6.5	624	3.4
<u><math>A_1</math> Horizon</u>			
1	7.2	170	1.8
2	6.8	146	1.2
3	7.0	145	1.1
4	7.2	235	1.1
5	7.2	320	2.7
6	7.2	231	2.3
7	7.1	248	2.4



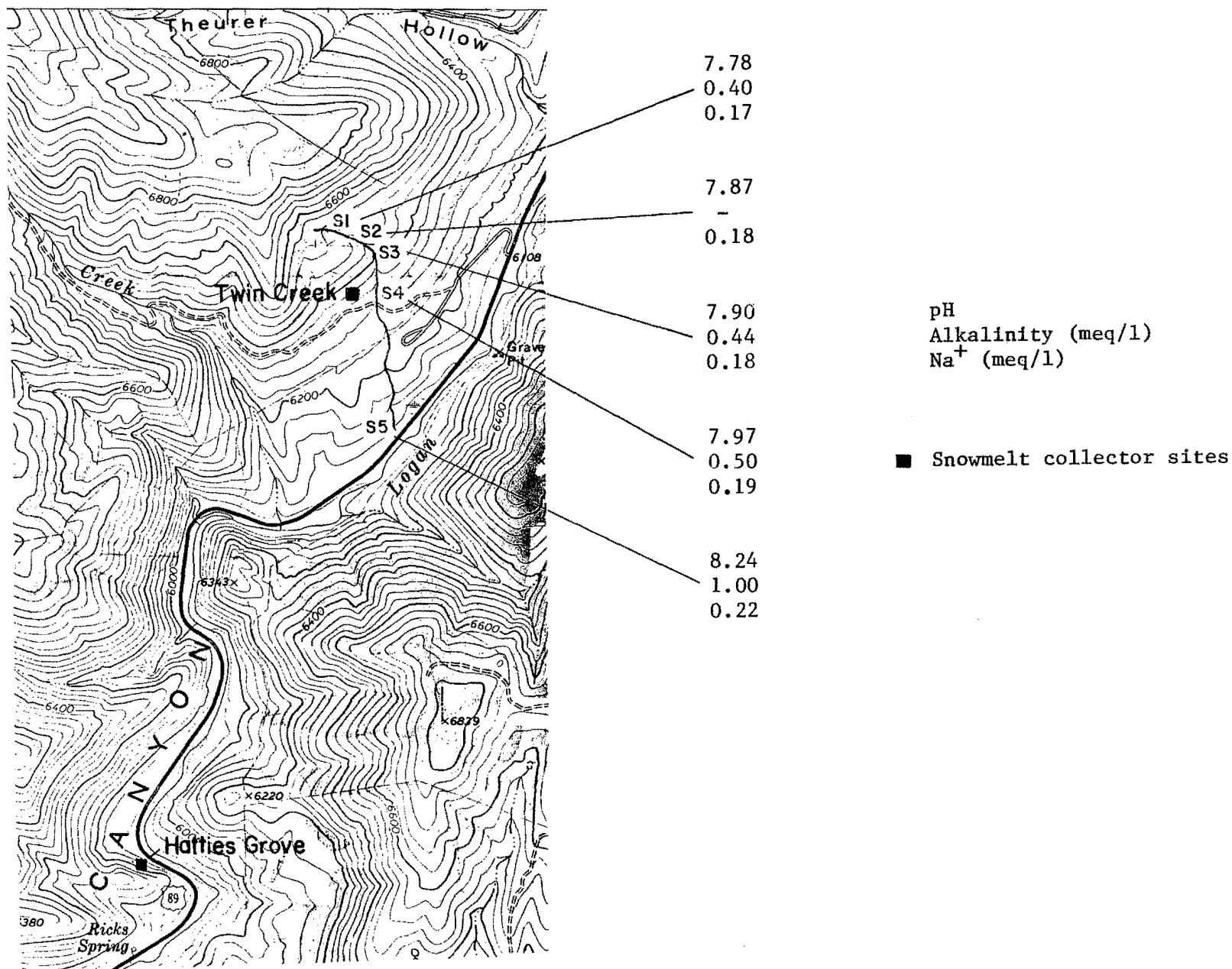


Figure 7. Snowmelt collector sites and changes in some ion concentrations in an ephemeral stream during snowmelt, May 9, 1982.

## CONCLUSIONS AND SUGGESTIONS

### FOR FURTHER RESEARCH

#### Conclusions

Snowmelt collected from snow cores taken from the 1982 spring snowpack in the Wasatch Mountains of northern Utah lacked mineral acidity and retained enough buffering capacity in the form of calcium and magnesium bicarbonates to titrate additional inputs of strong acid equivalent to the amount apparently already neutralized. While acid anion concentrations were higher than those found in pristine areas, they were much lower than those reported for winter precipitation in other western areas experiencing acidification of precipitation. Major difficulties in interpreting the chemical data from the cores result from four major factors:

1. Lack of information on site-specific relationships between wet or bulk precipitation collectors and meltwater chemistry from snow cores.

2. Sampling during an atypically wet winter with unusually low atmospheric emissions.

3. Sampling a restricted area with similar soils and bedrock.

4. Lack of information on soil sulfate and nitrate sources.

The implications of these factors with regard to the conclusions of this study prior to introducing suggestions for further research that could help resolve some of the present difficulties.

#### Snow coring as an alternative to precipitation collection

Snow coring offers an attractive alternative to precipitation collection

in western wildland watersheds for two reasons. First, access to mountain sites during the winter when most precipitation occurs is difficult and expensive, and occasionally impossible. Furthermore, snowfall is more difficult to collect in samplers in mountain locations where gusty winds drive snow horizontally, and where drifting may rapidly cover a sampler located at a convenient distance from the ground. Second, snowmelt provides the biggest danger to aquatic ecosystems in the west, because it usually constitutes the majority of water in a stream reach or lake during the melt period.

The greatest apparent difficulty in interpreting results obtained from snow cores is the rate of equilibration of atmospheric acids with soil derived bases in the meltwater. If the principal reactions occur on a time scale similar to the time taken for a volume of meltwater to reach a stream, then the initial (30-40 hr) pH values measured in this study may adequately represent the meltwater leaving a snowpack. The argument that any kind of bulk precipitation collections inadequately characterizes wet precipitation is accurate, but perhaps meaningless in the context of effects on surface waters, which receive the integrated input of the snowpack including both wet deposition and dry deposition of acidic or basic gases and aerosols. In any case more study needs to be done on the rate of neutralization and ion exchange reactions in meltwater fractions collected from snow cores, and on the effects of filtration on such reactions.

With respect to the present study, we conclude that a worst case scenario, in which all inputs of nitrate and

sulfate were from acid deposition, with only atmospheric ammonia present to act as an 'instant' buffer, the average snowmelt pH would be 4.7 (based on Tables 1 and 2), but that the initial pH value of 6.17 is more representative of snowmelt reaching a stream channel. Because the major ion concentrations in the snowmelt samples probably include dissolved carbonate minerals that would have been removed by filtration, the short-term (1-5 days) buffering capacity of carbonates in the snowmelt probably is smaller than the 43.7  $\mu\text{eq/l}$  suggested by the geochemical model. However, the presence of a maximum of only 20.3  $\mu\text{eq/l}$  of net acid anions ( $\text{SO}_4^{2-} + \text{NO}_3^- - \text{NH}_4^+$ ) suggests that the necessary buffer capacity of basic minerals deposited in the snowpack is not high. Also, although possible differences in the scavenging efficiencies of snow, rain, and snowpack surfaces for  $\text{NO}_x$  and  $\text{SO}_2$  and their products cloud comparisons somewhat, the samples collected in this study do not support the ubiquitous dominance of  $\text{NO}_x$  over  $\text{SO}_2$  suggested by precipitation collections at sites closer to very large western metropolitan areas.

#### Effects of the 1981-82 winter

There can be no doubt that the winter of 1981-82 was atypically wet in the Wasatch Mountains. However, the effect of dilution by the higher volume of snow during a wet winter may be offset to some extent by the decreased input of alkaline soil minerals owing to more widespread snow cover at lower altitudes. Also, the low level of activity of the copper and steel industries along the Wasatch Front relative to previous years may have resulted in low or acid inputs to the airshed than are normal. What little historical data are available are not readily comparable with the data in this study because of methodological differences. Continuation of snowpack sampling on an annual basis is needed in order to determine the effects of increased industrial activity and dry-to-normal winters.

#### Effects of spatial scale

The sampling sites during this study were chosen to detect spatial patterns caused by anthropogenic impacts of the Wasatch Front metropolitan area. The range of sites were limited, however, by presence of snow on the dates sampled, distance from the laboratory, and availability of access by four-wheel drive vehicle. The pattern of increasing  $\text{H}^+$  activity in samples with increasing distance from Salt Lake Valley may indicate the decreased availability of soil-derived buffering capacity. The fact that excess buffering capacity remains, even at the easternmost sites, may indicate that atmospheric acids from the Salt Lake City/Provo metropolitan area are titrated before reaching the Uintah Mountains. If true it would be significant because of the low neutralizing capacity of soils and rocks in these granitic mountains. That the Salt Lake Valley airshed is being represented in snowpack chemistry is strongly suggested by the decreasing chloride concentrations with distance from Great Salt Lake. Sampling in the Uintas and also in the mountains west of Salt Lake Valley would be helpful in understanding spatial trends.

#### Effects of soil sulfates and nitrates

The geochemical model assumes, but cannot prove, that all sulfate and nitrate derive from inputs of acidic gases and aerosols from fossil fuel combustion (or possibly lightning in the case of  $\text{NO}_3^-$ ). If this is the case the average acid concentration in the snow, before neutralization by soil minerals and ammonia, is 30  $\mu\text{eq/l}$ , with sulfate exceeding nitrate by an equivalent ratio of 3.1:1. However, Thornton et al. (1980) found significant amounts of sulfate and nitrate associated with aluminum (an indicator of soil "contamination") in their westernmost sampling site in northern Minnesota, and the possibility that some of the sulfate

derives from gypsum has already been stated. Stable isotope or metal tracer studies or mineralogical analyses may help to clarify the source of sulfate.

#### Runoff studies

The chemical characteristics of successive aliquots of meltwater collected from the melting snow cores confirmed that, in alkaline snowpacks, alkalinity tends to be concentrated in the initial melt fractions. Studies in upper Logan Canyon indicated that short contact times with A-1 and litter horizons in the soil rapidly increase the pH and alkalinity of meltwater, and this phenomenon is further perpetuated even in low order streams. Further studies at other sites are needed to confirm the generality of these observations.

#### Recommendations for Further Research

The following recommendations are designed to focus attention on the problems outlined above, and are felt to represent the highest priority items in terms of cost/benefit ratio.

1. Extend the snow coring network into the Uintah Mountains to the west, the Raft River and Tooele Mountains to the east, and at least as far south as skyline drive in the Wasatch Mountains for one, and preferably two years.

2. The above extension should probably coordinate with SCS snowcourse surveys. This would provide the only economical access to the Uintah Range, and would provide simultaneous snow depth and water content data from which to calculate areal deposition rates as well as concentrations.

3. Establish a wet-dry collector at the Logan Canyon snowmelt site, and take simultaneous snow cores with precipitation collections for comparative analyses. Also, 6-10 replicate cores should be taken at a single location in order to assess the short order variability among cores from a single site.

4. The source of sulfate ( $\text{SO}_2$  versus soils) should be studied using stable isotope studies or metal tracers that are associated with soil or stack plumes, but not both.

5. Runoff studies should be extended for an additional year, but with collector troughs being protected prior to being covered by new snow. Collectors should also be protected from wild animals and shifting snowpack.

6. Coring provides a low cost alternative to precipitation collection if water quality, rather than vegetation effects, are of chief concern.

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## APPENDIX

Table A1. Location of snow coring sites.

Core #	Lab #	Description	USGS Quad Map	Elevation (m)	Date
1	1346	Bear Lake Summit - 100 m south of	Garden City	2350	4-16-82
	1347	snow fence, crust on top, full			
2	1348	cores did not reach soil			
3	1349	Wood Camp Hollow - 40 cm of ripe	Mt Elmer	1750	4-16-82
		snow off ski trail-cores taken			
		atop one another, some detritus on			
		snow surface (removed)			
4	1350	Sherwood Hills - open clearing in	Mt Pisgah	1890	4-16-82
5	1351	aspens above lodge oil supply-full			
		cores did not reach soil - some			
		litter (removed)			
6	1351	Logan Dry Canyon - snow bank in	Logan Peak	2220	4-17-82
7	1352	aspens off trail, one short, one			
		long core			
8	1437	Sundance - north of top of ski run in	Aspen Grove	2260	4-22-82
9	1438	aspen clearing, two full cores,			
		no soil			
10	1439	Strawberry summit - 100 m S.W. of	Co-op Creek	2350	4-22-82
11	1440	road near Bullspring - 70 cm cores			
12	1441	Yellow Pine Campground - 45 cm cores	Hoyt Peak	2170	4-22-82
		taken one atop the other from Willow			
		near Beaver Creek			
13	1442	Deer Valley - 100 cm cores (no soil)	Park City E.	2320	4-23-82
14	1443	on top of Rossi Hill 100 m above road			
15	1444	Snow Basin - full cores taken at angle	Chicken Spring	1950	4-23-82
16	1445	E of X-ski trail in aspen clearing	Creek		
17	1768	Twin Creeks - single full core taken	Temple Peak		4-25-82
	1769	near runoff collectors			
	1770				



Table A2. Constituent concentrations for Wasatch Mountain snow cores.

Core	Lab	IpH	EqpH	NH4	Ca	Mg	Na	K	Cd	Pb	EC
1-1	1346	6.32	6.32	105.	4.00	0.00	284.	58.	0.00	0.70	30.1
1-2	1347	5.62	6.16	70.	0.40	0.03	174.	24.	0.00	0.00	11.9
2	1348	6.44	6.89	100.	0.98	0.12	296.	66.	0.00	1.30	8.6
3	1349	6.23	6.55	60.	0.65	0.05	94.	50.	0.00	0.00	5.5
4	1350	6.18	6.73	133.	0.46	0.15	334.	176.	0.00	1.40	7.5
5	1351	6.20	6.86	114.	0.89	0.19	224.	154.	0.00	1.80	9.1
6	1352	6.34	6.74	127.	1.12	0.17	450.	340.	0.00	1.50	10.3
7	1353	5.99	6.83	****	0.98	0.07	350.	238.	0.00	0.00	10.0
8	1437	6.88	6.55	171.	0.73	0.07	130.	112.	0.00	0.00	19.6
9	1438	6.69	6.58	184.	0.43	0.06	144.	108.	0.00	0.00	13.0
10	1439	6.26	6.33	99.	0.55	0.05	350.	226.	0.00	0.00	6.7
11	1440	6.11	6.49	131.	0.82	0.06	340.	158.	0.00	0.00	9.2
12	1441	5.89	6.80	207.	0.42	0.05	336.	368.	0.00	0.00	7.5
13	1442	6.34	6.81	79.	0.77	0.11	874.	556.	0.00	0.00	11.1
14	1443	6.48	6.83	93.	1.22	0.11	474.	252.	0.38	1.30	11.6
15	1444	6.03	6.58	113.	0.29	0.05	172.	148.	0.00	0.00	4.8
16	1445	6.14	6.72	111.	0.29	0.07	182.	148.	0.00	0.60	5.3
17-1	1468	6.25	6.53	139.	0.93	0.05	326.	240.	0.00	0.80	26.9
17-2	1469	5.98	6.72	105.	0.21	0.02	392.	156.	0.00	0.60	11.2
17-3	1470	5.85	6.43	66.	0.10	0.05	78.	60.	0.00	1.50	6.5

Core	NO2	NO3	TKN	SO4	Cl	ALK	TIC	PO4	TP	F	TOC
1-1	0.0	0.10	0.18	****	0.40	1.20	0.80	0.00	0.00	11.0	1.3
1-2	0.0	0.08	0.32	1.05	0.22	0.00	0.40	0.00	0.00	0.0	0.0
2	0.0	0.11	0.39	1.44	0.38	2.20	0.70	0.00	0.00	0.0	1.1
3	0.0	0.05	0.29	0.87	****	0.00	0.40	0.00	0.00	0.0	0.0
4	3.0	0.09	0.64	0.69	0.53	1.20	0.50	0.00	10.00	0.0	0.0
5	0.0	0.08	0.62	1.53	0.50	1.20	0.60	0.00	0.00	0.0	0.0
6	0.0	0.10	0.63	1.95	0.42	2.20	0.70	0.00	14.00	0.0	1.2
7	3.0	0.13	0.60	2.10	0.43	0.00	0.60	0.00	6.00	0.0	2.6
8	2.0	0.12	0.22	1.50	0.42	1.80	0.40	1.00	16.00	0.0	0.5
9	3.0	0.13	0.23	0.66	0.30	1.80	0.40	0.00	12.00	55.0	0.4
10	2.0	0.15	0.21	0.81	0.42	1.80	0.30	1.00	20.00	10.0	0.9
11	1.0	0.11	0.25	1.65	0.48	1.80	0.40	1.00	6.00	23.0	3.9
12	1.0	0.10	0.39	0.51	0.29	1.80	0.40	1.00	14.00	0.0	0.7
13	2.0	0.13	0.41	0.87	0.91	1.80	0.70	1.00	30.00	0.0	1.7
14	3.0	0.13	0.27	1.86	0.55	1.80	0.60	1.00	22.00	0.0	1.2
15	1.0	0.06	0.44	0.42	0.23	1.80	0.30	1.00	20.00	19.0	0.3
16	1.0	0.06	0.26	0.42	0.31	0.00	0.50	6.00	24.00	14.0	0.8
17-1	1.0	0.11	0.26	2.10	0.42	1.80	0.30	2.00	12.00	10.0	1.2
17-2	1.0	0.06	0.20	0.45	0.40	1.80	0.30	1.00	2.00	30.0	0.7
17-3	1.0	0.07	0.17	0.24	0.26	1.80	0.40	****	20.00	0.0	4.0

Table A3. Constituent concentrations for runoff collectors at Twin Creeks site.

Collector Height (cm)	Lab #	pH	NH <sub>3</sub> <sup>-</sup> -N (µg/l)	Ca <sup>++</sup> (mg/l)	Mg <sup>++</sup> (mg/l)	Na <sup>+</sup> (mg/l)	K <sup>+</sup> (mg/l)	Cd (µg/l)	Pb (µg/l)	EC (µS)
92	1450	6.76	12	1.2	0.1	1.72	0.74	<0.06	1.4	17.6
76	1448	6.85	12	1.2	0.1	1.76	0.62	<0.06	1.6	17.5
46	1449	6.93	<4	1.3	0.1	2.32	0.83	<0.06	1.5	23.4
30	1451	6.96	<4	1.8	0.1	4.75	2.64	<0.06	6.1	32.8
0	1447	6.82	222	0.7	0.1	0.52	0.34	<0.06	45.0	15.5

Collector Height (cm)	NO <sub>2</sub> <sup>-</sup> -N (µg/l)	NO <sub>3</sub> <sup>-</sup> -N (µg/l)	TKN (µg/l)	SO <sub>4</sub> <sup>=</sup> (mg/l)	Cl <sup>-</sup> (mg/l)	Alkalinity (µeq/l)	PO <sub>4</sub> -P (µg/l)	TP (µg/l)	F <sup>-</sup> (µg/l)	TOC (mg/l)
92	2	200	50	2.4	3.3	0.15	21	70	19	4.2
76	4	30	200	0.3	1.8	<0.22	6	54	-	4.8
46	3	60	70	0.7	3.0	0.29	23	56	-	4.6
30	2	30	160	0.6	2.1	0.63	14	80	-	11.5
0	12	340	220	1.3	0.8	<0.01	8	50	10	4.2

37

Table A4. Constituent concentrations at Twin Creek sampling sites.

Station #	Lab #	pH	NH <sub>3</sub> <sup>-</sup> -N (µg/l)	Ca <sup>++</sup> (mg/l)	Mg <sup>++</sup> (mg/l)	Na <sup>+</sup> (mg/l)	K <sup>+</sup> (mg/l)	Cd (µg/l)	Pb (µg/l)	EC (µS)
S-1	1474	7.78	22	4.0	1.5	4.00	4.16	<0.06	<0.6	62.3
S-2	1475	7.87	17	3.1	1.5	4.12	3.84	<0.06	<0.6	63.8
S-3	1476	7.90	16	3.5	1.5	4.25	3.83	<0.06	<0.6	62.8
S-4	1477	7.97	14	4.3	1.6	4.46	3.63	<0.06	<0.6	70.6
S-5	1478	8.24	126	8.0	2.2	5.01	3.36	<0.06	<0.6	128

Station #	NO <sub>2</sub> <sup>-</sup> -N (µg/l)	NO <sub>3</sub> <sup>-</sup> -N (µg/l)	TKN (µg/l)	SO <sub>4</sub> <sup>=</sup> (mg/l)	Cl <sup>-</sup> (mg/l)	Alkalinity (µeq/l)	PO <sub>4</sub> -P (µg/l)	TP (µg/l)	F <sup>-</sup> (µg/l)	TOC (mg/l)
S-1	6	210	200	1.43	2.6	0.40	170	212	70	3.8
S-2	6	190	220	1.38	1.9	-	160	206	-70	3.9
S-3	6	190	350	1.33	2.3	0.44	160	188	-80	4.0
S-4	5	200	1410	1.32	2.6	0.50	140	194	-80	3.9
S-5	6	580	280	1.36	3.6	1.00	150	190	-90	4.6