SUMMARY OF GEOLOGIC FACTORS THAT MAY INFLUENCE THE SENSITIVITY OF SELECTED WATERSHEDS IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO TO ATMOSPHERIC DEPOSITION

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CONCLUSIONS

Surficial materials in the watersheds examined in Rocky Mountain National Park play the dominant role in evaluating sensitivity to acidification. Most soils in the area have formed from a parent material (overburden) of glacial or alluvial origin. The mineralogic composition of soils and overburden is dependent on parent rock type composition, susceptibility to chemical weathering, and climate.

The rock types in the area were shown to have a statistically insignificant influence on the buffering capacity of soils tested. This resulted primarily from the low clay content of the soils which in turn was dependent on composition of parent rock types, rock weathering characteristics and climatic influence on rate and degree of weathering. Mineralogically, clay content is directly proportional to the buffering capacity of a soil. In spite of lack of statistical significance between buffering and rock types in the area, biotite gneiss and schist and granite were the best regression indicators of equivalent bases. The latter was the dependent variable selected to indicate buffering characteristics of the soils.

In the absence of clays, most of the buffering capacity of soils was attributable to decomposed organic matter and soil pH. Landform types are useful in estimating the buffering capacity of surficial materials as they imply the amount of organic matter present and the thickness of soil and overburden present. Examples of two landform types implying minimum and maximum capacities are bare bedrock and wet meadows.

Concentrations of cations needed to buffer acidification in water samples exhibited good correlation with rock types in the watersheds. Chemical weathering characteristics of the rock types control the contribution of the cations to soil water, streams and lakes. This results from leaching of minerals during percolation of water through the soil and overburden and joints in bedrock. Thus the bedrock geology of the area is an important factor influencing water chemistry, while not significantly influencing the buffering capacities of the soils sampled.

The best criteria for estimating the sensitivity of study area watersheds to acidification are water cation concentrations and pH. The four watersheds studied have been ranked according to increasing sensitivity as follows:

Upper Colorado River Basin	least sensitive
East Inlet basin and Fall River basin	intermediate
Glacier Gorge basin	most sensitive

Introduction

Rocky Mountain National Park is characteristic of the alpine-subalpine ecosystem. This ecosystem will probably be undergoing changes due to deposition of wet and dry acidic substances in the near future. This study is a part of the more comprehensive "Evaluation of the Sensitivity of Selected Natural Areas in the Rocky Mountain Region to Biological Perturbations from Atmospheric Deposition (Acid Rain)," funded by the U.S. Fish and Wildlife Service and the National Park Service. The present study focuses on the geologic and geomorphic factors that might influence the sensitivity of four watersheds in Rocky Mountain National Park to acidification. This report summarizes master's thesis research conducted by Herzog (1982).

The four watersheds selected were Glacier Gorge and Fall River basins on the east side of the Continental Divide and East Inlet and Upper Colorado River basins on the west side of the Divide (Figure 1). The criteria used in selection of these watersheds were geologic control (bedrock and glacial erosion/deposition), as determined from existing information; orientation of the watersheds; climatic factors and access by foot trail.

Glacier Gorge, Fall River and East Inlet basins are underlain by Precambrian granite and metamorphic rocks, whereas the Upper Colorado River basin is predominantly underlain by Precambrian metamorphic rocks and Tertiary intrusive and extrusive rocks. Glacial till is present in all four watersheds. Studying east-west oriented drainages permits assumptions of relatively equal impact of precipitation throughout the watershed. Climatic factors suggested the selection of watersheds on both east and west sides of the Continental Divide.

Rocky Mountain National Park

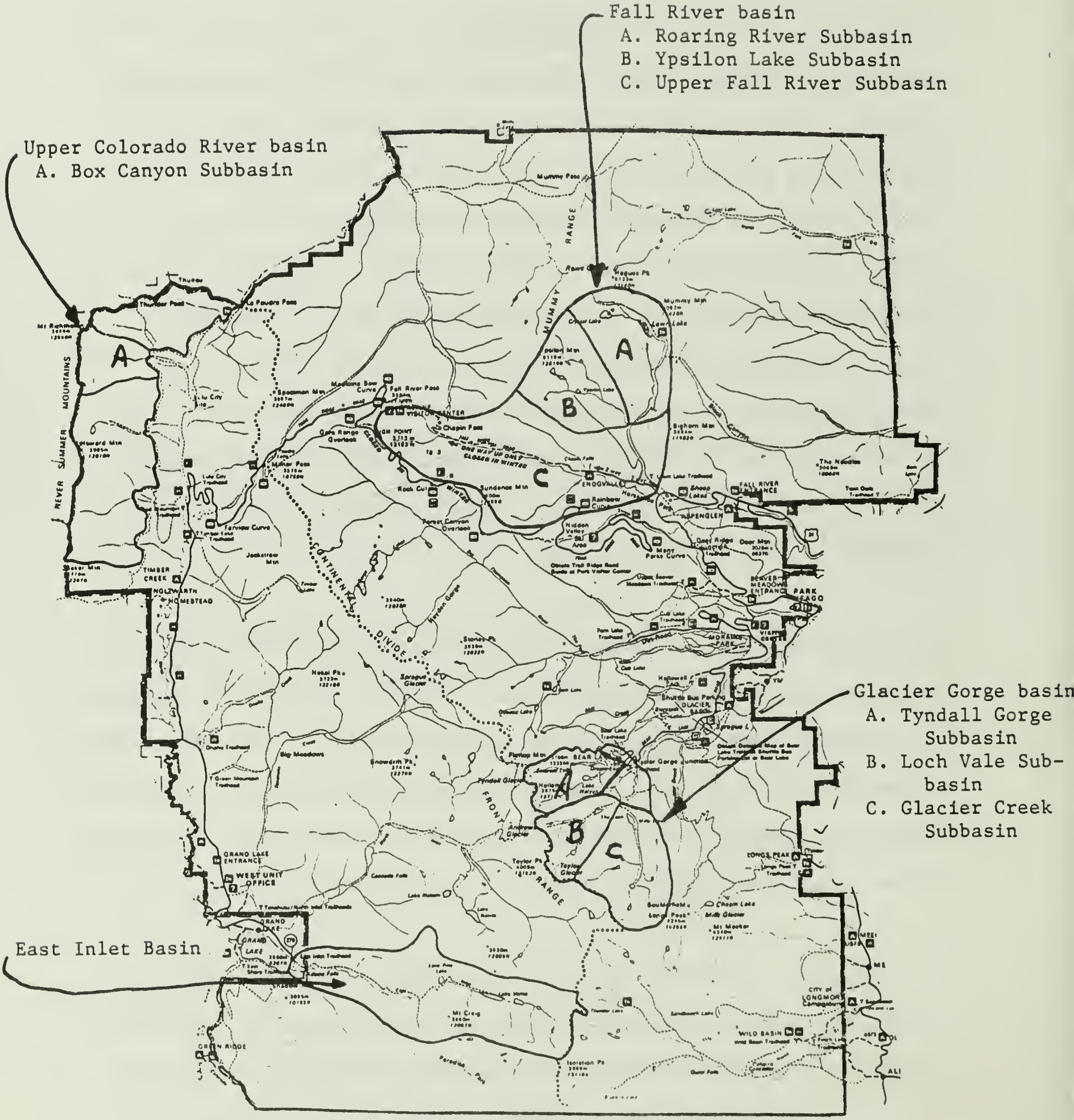

Figure 1. Location of study area, Rocky Mountain National Park, Colorado

The four watersheds are subdivided on the basis of tributary drainage as follows (Figure 1):

Glacier Gorge - Tyndall Gorge, Loch Vale, Glacier Creek subbasins

Fall River - Roaring River, Ypsilon Lake, Upper Fall River subbasins

East Inlet - not subdivided

Upper Colorado River - Box Canyon subbasin

Lithologic Units

Igneous and metamorphic rocks are present in the four watersheds and range in age from Precambrian to Tertiary; the metamorphic rocks are confined to the Precambrian. Unconsolidated materials of Quaternary age are abundant in all basins. The major bedrock units exposed in the four watersheds are (Abbott 1974; Cole 1977; O'Neill 1981):

Xqs - Biotite gneiss and schist

Xam - Amphibolite

Xgg - Quartz diorite gneiss

bc - Boulder Creek granodiorite

Ysp - Silver Plume granite

PEa, PEab, PEap - Andesite flows, breccia flows, porphyry

Ngd - Granodiorite of Mt. Richthofen Stock

Ngr - Granite of Mt. Cumulus stock

Nvr - Ash flow tuff

The mineralogical compositions of the bedrock geologic units are summarized in Table 1. Using the Goldich (1938) weathering sequence and the modal percentages of the lithologic units, a suggested weathering stability

TABLE 1

Major bedrock units: (⟵) Composition and relative susceptibility to chemical weathering

	Lithologic Units								
Minerals (by %)	Ngr	Ysp	bc	Nvr	Ngd	Xgg	Xqs	PEa,PEab, PEap	Xam
Quartz	35	27	31	High	10	30-65	37	None	7-10
Microcline	60	38	26	High	32	7-40	11	Minor	
Orthoclase							3	Minor	
Plagioclase	4	24	25	Minor	40	10-30	22	High	20-40
Plagioclase type*		Olig.	And.		And.		Olig.	And.	Labr.
Biotite	1	7	15	Minor	18	15-35	18	High	7-20
Hornblende									20-60
Magnetite		2							5-30
Cordierite							6		
Accessory		2	2						
	Least Weatherable---------------------------------Most Weatherable								

* olig. = Oligoclase
And. = Andesine
Labr. = Labradorite

classification is shown on Table 1. The susceptibility to chemical weathering increases to the right. The classification is essentially based on the relative modal percentages of the mafic minerals, hornblende and biotite, and plagioclase, as these minerals are more susceptible to chemical weathering (Goldich 1938). Some attention has been given to the physical stability of the rock, i.e., schistosity in the biotite gneiss and schist (Xqs). The location of the ash flow tuff (Nvr) in the classification is questionable because of possible influence on weathering of the moderately high temperature of formation and the glassy matrix.

Methods of Study and Sampling Procedures

Soil samples were collected by excavating soil pits by hand to a maximum depth of 50 cm. Three hundred to seven hundred g samples of each soil horizon exposed were collected and described. These samples were assumed to be representative of the soils encountered in the different landform types in the study area. Representative hand specimens of rock types were collected and identified. Rock-type names conformed to those used in the Park by Abbott (1974), Cole (1977), O'Neill (1981) and Braddock (unpublished). Five hundred ml water samples were collected by McCarley at the inlet, outlet and center of the lakes encountered and at every 500 ft of elevation and below the confluences of streams.

Parent materials of the soils were determined by geologic reconnaissance of the area adjacent to each soil sample and by binocular microscope examination of the 2 to 4 mm fraction of each soil sample. Glacial till is the parent material for most of the soil samples analyzed, and is derived from the geologic units upvalley. Therefore, the composition of the 2 to 4 mm fraction of the soil samples is representative of both the glacial till parent material and parent rock. The areal extent of mapped geologic units, surficial and bedrock, in each basin was determined using a planimetric digitizer and geologic maps. Weathering characteristics of the various bedrock and surficial materials were studied because they directly affect the type and amount of soil present.

Landform types (Table 2) are helpful in determining the parent material of the soils developed, the thickness of overburden and the existing vegetation. They convey surface features and materials that combined with associated vegetation characterize mappable areas (Herzog 1982). This information can be obtained by analysis of aerial photographs. Stream gradients for all rivers and streams studied were determined with a linear digitizer.

Seismic refraction surveys were conducted at seven sites to determine the thickness and types of surficial materials overlying bedrock. A Nimbus ES-125 single channel signal enhancement seismograph was used. The surveys were made in coniferous forests on moraine veneer, wet meadows and dry meadows. The seismic velocities obtained permitted grouping of geologic materials at the seven sites into four categories: soil, alluvial deposits, glacial till, and bedrock (Table 3). Numerous factors influenced these values. They include thickness of organic material, water content, clay content, percentage of boulders, lithologic makeup of glacial till and type and degree of weathering and/or jointing of bedrock.

TABLE 2

Representative landform types observed in research area.

Surface features and/or materials	Associated vegetative cover
Exposed bedrock	Open canopy - coniferous forest
Talus slope	Open canopy - coniferous forest and meadow
Unglaciated regolith	Closed canopy - coniferous forest
Moraine - ground	Aspen forest
lateral	Sagebrush
end	
Moraine veneer	
Wet meadow	
Dry meadow	
Wet tundra	
Dry tundra	

TABLE 3

Seismic Refraction Data Summary

Profile #	Soil Velocity Thickness	Glacial or Alluvial* Velocity Thickness	Bedrock Velocity	Landform Type
1	396 m/s - 0.7 m	1699 m/s - 5.5 m	2417 m/s	Moraine veneer
2	215 m/s - 1.4 m	1390 m/s - 6.2 m	3135 m/s	Dry meadow
3	224 m/s - 0.8 m	1117 m/s - 3.8 m	2391 m/s	Wet meadow
4	374 m/s - 1.9 m	None present	3941 m/s	Moraine veneer
5	None present	955 m/s - 3.2 m	3758 m/s	Wet meadow
6	326 m/s - 1.5 m	1594 m/s - 5.3 m	3208 m/s	Moraine veneer
7	318 m/s - 1.7 m	None present	2989 m/s	Moraine veneer

*Unconsolidated parent material underlying soil.

Results

The results for soils reveal that seismic velocities travel more slowly in softer or more organic-rich soils. Sites 2 and 3 were in meadows with no relief and abundant organics and their soils produced the lowest seismic velocities. Generally, all soils had velocities corresponding to moist, loamy or silty soils reported by Redpath (1973), indicating low clay content. The glacial till velocities correspond to values obtained by Redpath (1973) for dry glacial moraine deposits in the Sierra Nevada of California. These deposits have low clay content similar to those encountered in the project area. Most bedrock velocities were low indicating a fairly large degree of weathering and/or jointing and implies good interaction of bedrock with ground water.

Seismic profiling revealed the thickness of the soils to be in the range of 0 to 1.9 m; the alluvial materials, 3.0 to 3.7 m; and the glacial till, 0 to 7 m (Table 3). These values are for materials in the center of the stream valleys and decrease up the side slopes. Although these values are not thick by comparison with non-alpine surficial materials, they could be quite adequate for buffering of acid precipitation if sufficient clay and organic material exist. Stream gradients are generally indicative of the landform type and are easily obtainable from topographic maps. The steepness of gradient generally is indirectly proportional to the thickness of both glacial and alluvial overburden in the terrain encountered. Examination of air photos permits refinements of thickness estimates as bedrock exposures which are masked by map contour interval may be identified.

Soil chemistry parameters, cation exchange capacity and percent base saturation, provided by Dr. Wm. McFee of Purdue University, were used to obtain the equivalent bases value for each soil sample. Percent of decomposed organic matter, from wet chromic acid titration, and pH of the soils were used in regression analyses to determine their correlation with soil buffering capacity. Water chemistry parameters, cation concentrations and pH levels, provided by McCarley of the University of Virginia, were used to quantify the effects of the occurrence of different geologic units, the presence of wet meadows and the thickness of overburden on the downstream water quality. These water chemistry parameters were also used to make estimates of the sensitivity to acidification of each watershed.

Soil Buffering Capacity

A measure of the buffering capacity of soils is its equivalent bases values. The factors that might influence this value are thought to be the pH, the percent decomposed organic matter, the percent of clay, the clay mineralogy, the geologic parent material (or the percentage of rock types in glacially derived soils), the landform type associated with the soil and the elevation. In this study, the clay mineralogy and the percent of the clay were not determined.

All of the above factors (variables) can be quantified with the exception of the landform type. These variables were analyzed by multiple regression analysis programs, BMDPIR and 9R (BMDP 1981) with equivalent bases as the dependent variable and pH, percent decomposed organic matter, percentage of each rock type, and elevation as the independent variables. Since landform type could not be quantified, separate regression analyses for soil samples from each major landform type were thought to be the proper approach. However, moraine veneer of Pinedale age was the only landform type with a sufficient data set.

Rock types discernable in the 2 to 4 mm gravel fraction were Silver Plume granite (Ysp), biotite gneiss and schist (Xqs), amphibolite (Xam), andesite porphyry (PEap), granodiorite of Mt. Richthofen Stock (Ngd), and ash flow tuff (Nvr). The number of observations for amphibolite (Xam) were small and were rejected as insignificant. All observations for ash flow tuff (Nvr) were either 0% or 99%. This variable was only used in Regression 1 (Table 4). Table 5 lists the range of values and means for all independent and dependent variables. This shows that granite is the most abundant rock type and andesite is the least abundant. Values of pH ranged from 4.2 to 6.3 and equivalent bases from 0.2 to 57.6.

In regression analysis 1 (Table 4), all independent variables were utilized. As would be expected, they together provide the highest coefficient of determination, R^2, value of all combinations of fewer variables. Data for this analysis (Appendix B, Herzog, 1982) show that pH and % organic matter combined to be the major contributors to the R^2 value. Regression analyses 2-5 (Table 4) show no significant correlation between rock type and soil buffering capacity. Although of no statistical significance, gneiss and schist (Xqs) and granite (Ysp) in the samples contributed most to the R^2 values obtained (Appendix B, Herzog, 1982).

The lack of variance of the chemistry of the rock units, except andesite (PEap), the widespread occurrence of migmatite (a unit consisting of a mixture of granite and metamorphic rocks), and the low clay content of the soils, most likely explain the extremely poor correlation between rock types and

TABLE 4

Regression Analyses Results

No.*	Independent Variables	No. of Cases	Coefficient of Determination R^2	Comments
1	pH, % organic matter, % Ysp, %Xqs, % PEAP, % NGD, % NVR, elevation	41	0.678	Total sample: pH, % OM best predictors
2	% Ysp, % Xqs, % PEAP, % NGD	36	0.016	Determine correlation of rock types only, % Xqs, % Ysp best predictors
3	% Ysp, % Xqs, % PEAP, % NGD	70	0.208	Only used cases with NGD present, % Xqs best predictor
4	% Ysp, % Xqs	26	0.032	Only used cases with Ysp, Xqs present, % Xqs = % Ysp as predictors
5	% Ysp, Xqs, % PEAP, % NGD	21	0.028	Late Pinedale moraine veneer landform samples, % PEap and % Xqs best predictors

*Regression analysis number

TABLE 5

Dependent and Independent Variables

a) Rock type and organic matter occurrence in soil samples by percent.

Material	Mean	Low	High	No. of observations
Ysp - Granite	50	0	99	32
Xqs - Gneiss and schist	17	0	26	32
Ngd - Granodiorite	15	0	89	10
Nvr - Ash flow tuff	13	0	99	6
PEap - Andesite	4	0	68	5
Organic matter	5.3	0.3	28.5	41

b) Ranges and means of pH, elevation and equivalent bases.

Item	Mean	Low	High	No. of observations
pH	5.3	4.2	6.3	41
Elevation	3143 m	2610 m	3645 m	41
Equiv. bases	7.2	0.2	57.6	41

equivalent bases. Most of the buffering capacity of the soils studied seems to be directly related to decomposed organic matter and increasing pH rather than clay.

The buffering capacities of surficial materials in different landform regions are dependent on the amount of organic matter and the thickness of the deposit. Landform types encountered in the study area are listed according to increasing buffering capacity: scoured rock, talus slopes and rock glaciers, tundra regions, Pinedale moraine veneer regions, ground moraine, lateral moraine, wet meadows. These landform types can be determined by examination of aerial photographs. Stream gradients can also be used to estimate, on a very large scale, the landform type in a glaciated alpine region and its associated overburden type and thickness (Table 6).

Influence on Water Chemistry

The factors that influence inorganic downstream water chemistry are the incoming precipitation, the dry deposition, the geologic composition of the watershed, the landform type (especially the areal extent of wet meadows), and the thickness of overburden. The incoming precipitation and the dry deposition were not studied. The geologic parameters are most important in influencing inorganic water chemistry. The areal extent of wet meadows are next in importance followed by overburden thickness.

The underlying geologic units affect the concentrations of cations (Ca, Mg, Na, K) in the water. Rock units that are more weatherable (Table 1) contribute a larger number of cations to the streams and lakes. The pH of the water is also affected by the geology. There appears to be a direct relationship between the mean pH of the subbasins and the mean concentrations of Ca, Na and Mg (Table 7). Potassium (K) concentrations are affected by its being a plant nutrient and its tendancy to be adsorbed by clay minerals, and were not used in this study.

TABLE 6

Stream Gradient Implications

Underlying Material	Stream Gradients		
	Rank	Mean	Standard Deviation
Rock, talus, rock glacier and associated moraine veneer	High ↓	720 m/km (1470 ft/in)	270 m/km (550 ft/in)
Moraine veneer, ground moraine		302 m/km (617 ft/in)	110 m/km (224 ft/in)
Alluvial deposits (wet meadows) associated with other materials	Low ↓	204 m/km (417 ft/in)	133 m/km (272 ft/in)
Alluvial deposits (wet meadows) alone below treeline		84 m/km (171 ft/in)	49 m/km (101 ft/mi)

TABLE 7

Ranking of Basins and Subbasins by Cation Concentrations and pH of Water Samples

Calcium		Magnesium	
Box Canyon	6.06 mg/l	Box Canyon	1.33 mg/l
Upper Colorado	5.33 mg/l	Upper Colorado	0.96 mg/l
Fall River	2.11 mg/l	Fall River	0.80 mg/l
East Inlet	1.7 mg/l	Roaring River	0.25 mg/l
Roaring River	1.34 mg/l	East Inlet	0.21 mg/l
Tyndall Gorge	1.08 mg/l	Tyndall Gorge	0.16 mg/l
Glacier Creek	1.03 mg/l	Ypsilon Lake	0.15 mg/l
Loch Vale	0.80 mg/l	Loch Vale	0.14 mg/l
Ypsilon Lake	0.78 mg/l	Glacier Creek	0.14 mg/l

Sodium		Potassium	
Box Canyon	1.87 mg/l	Box Canyon	0.36 mg/l
Upper Colorado	0.90 mg/l	Upper Colorado	0.32 mg/l
Fall River	0.89 mg/l	Fall River	0.28 mg/l
Roaring River	0.62 mg/l	Ypsilon Lake	0.15 mg/l
East Inlet	0.61 mg/l	Roaring River	0.14 mg/l
Ypsilon Lake	0.41 mg/l	Tyndall Gorge	0.14 mg/l
Glacier Creek	0.41 mg/l	Glacier Creek	0.14 mg/l
Tyndall Gorge	0.39 mg/l	East Inlet	0.10 mg/l
Loch Vale	0.30 mg/l	Loch Vale	0.09 mg/l

pH	
Box Canyon	7.69
Upper Colorado	7.56
Fall River	7.06
East Inlet	6.86
Roaring River	6.83
Ypsilon Lake	6.52
Tyndall Gorge	6.51
Glacier Creek	6.49
Loch Vale	6.44

Wet meadow regions have a large amount of organic material that can form organic acids. These organic acids promote weathering of the bedrock and surficial materials releasing cations into solution. The organic material also contributes cations to the water by decomposition. These processes lead to higher cation concentrations and correspondingly higher pH values.

Overburden thickness is the least important parameter influencing cation concentrations and pH levels. Generally, residence time of water with minerals and organic matter, in surficial materials, increases with overburden thickness. The granular nature of the overburden implies high porosity and permeability allowing water to percolate through its entire thickness.

Sensitivity of Watersheds

The criteria used in determining the sensitivity to acidification of the basins and subbasins studied were cation concentrations (Ca, Mg, Na), pH levels, soil buffering capacity, occurrence of wet meadow regions, thickness of overburden and lake environs.

Water cation concentrations and pH levels seem to be the best criteria in determining the sensitivity to acidification of basins and subbasins. They reflect the underlying geologic units, the abundance of wet meadows, the thickness of overburden and are indicative of processes occurring throughout the entire basin. Soil chemical parameters are only applicable to that one sample, though extrapolation to larger areas is fundamental to field sampling. Values of pH above 6.0 show good direct correlation with alkalinity values (Figure 2). Alkalinity values are used as an indicator of the

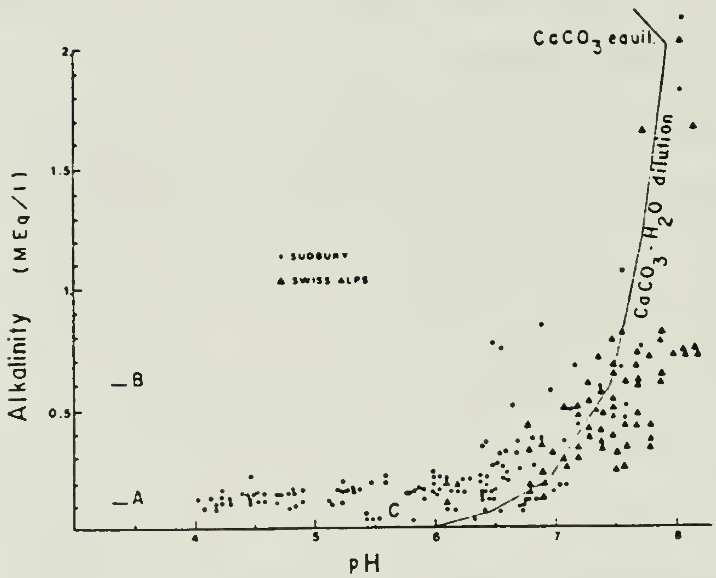

Figure 2. PH-alkalinity relationship for lakes in the Canadian Shield and Swiss Alps. The solid line represents the dilution of water equilibrated with $CaCO_3$ at 2 meq/l carbonate alkalinity. A and B represent pH boundary values for alumino silicate control whereas C represents the alkalinity pH obtained from $FeOOH-H_2O-CO_2$ (atm) equilibrium. From Kramer (1976).

sensitivity to acidification of a watershed (Oden 1976). All mean pH levels were above 6.0, thereby supporting the use of pH levels or cation (Ca, Mg, Na) concentrations as a measure of sensitivity to acidification.

Soil buffering capacities, as measured by equivalent bases, were intended to be used as a means of classifying subbasins by their sensitivity to acidification. The ranking of subbasins by this method resulted in a different order than afforded by the cation concentration or pH value method. Additionally, the regression analyses performed (Table 4) revealed essentially no correlation between rock type and equivalent bases values.

The remainder of the criteria were used in a qualitative manner to characterize the relative sensitivity of subbasins, to explain the cation concentrations observed and to support the ranking of subbasins by cation concentration and pH values.

The ranking of subbasins is (from Table 7):

Increasing Sensitivity to Acidification ↓

- Box Canyon subbasin
- Upper Colorado River basin
- Fall River subbasin
- East Inlet basin
- Roaring River subbasin
- Tyndall Gorge, Glacier Creek, Loch Vale, and Ypsilon Lake subbasins

These rankings can be extended to the four watersheds studied:

Increasing Sensitivity to Acidification ↓

- Upper Colorado River basin
- East Inlet basin and Fall River basin
- Glacier Gorge basin

Geologic control seems to be most important in this ranking scheme as the Upper Colorado River basin has a preponderance of highly weatherable rock units. These units consist of andesitic rocks (PEap, PEa, PEab) and Precambrian metamorphic rocks (Xqs, Xam, Xbh). Upper Fall River subbasin owes its sensitivity ranking to the biotite gneiss and schist (Xqs) underlying the upper reaches of the valley and the prevalence of wet meadows.

Extreme sensitivity to acidification exists in many of the lakes. These lakes are surrounded by scoured rock, talus slopes, neoglacial moraines and rock glacier deposits. Lakes with a very high sensitivity are characterized by a lack of wet meadow regions and bedrock of low weatherability. Highly sensitive lakes have wet meadows along more than 50% of their circumference, but are located in basins or subbasins that have a high overall sensitivity to acidification.

Three subbasins received a large percentage of their water from snowmelt during the summer sampling season. This water had a short residence time within the surficial materials, low cation concentrations and relatively low pH values. These are the Tyndall Gorge, Loch Vale, and Ypsilon Lake subbasins. All of these basins have relatively high percentages of metamorphic rocks (Xqs) and their streams and lakes should exhibit higher cation concentrations. If these subbasins could be sampled in the winter, higher concentrations of cations and pH levels would probably result due to the discharge being composed entirely of base flow, derived from ground water.

Recommendations for Further Study

Numerous other studies can be performed to better determine the role of geology in influencing the sensitivity to acidification of different watersheds. These are:

a) The use of clay percentages and clay mineralogy of soils in their relationship to the geologic parent materials. The data also can be used to compare to the equivalent bases values.

b) Selecting areas of study in the Rocky Mountain region with a wider range of rock types. Soil chemistry data from soil samples derived from more rock types could be used in a regression analysis of equivalent bases and rock types to identify those parent materials which ultimately contribute most to a soil's buffering capacity.

c) Extending the study area of Upper Colorado River basin below the Grand Ditch to the river, improving the data base. The sampling of water in the present study is biased, because by design of the investigating team, sampling only occurred above the Ditch. Water percolates through the glacial till that commonly exists above the Ditch and enters the Colorado River. Also, a basinwide study might reveal the influence of ash flow tuffs (Nvr) on the water quality, as Specimen Mountain is composed of these tuffs.

d) Seismic refraction profiling should be undertaken at a wide range of elevations and gradients to more accurately determine the surficial material thickness and composition in the study area.

e) Resistivity and electromagnetic methods of geophysics could be used to investigate the weathering characteristics of the different bedrock types. The information gained from this type of study would be depth and degree of weathering which are important to a study of the geologic input to water and soil chemistry.

f) A hydrologic study of the watersheds should be conducted to determine the relationships between overburden thickness, gradient of the streams, and flow patterns. Also needed would be an analysis of the percentage input of baseflow, derived from ground water, soil and surficial interflow, precipitation and snow melt to the surface water system.

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