EFFECTS OF ATMOSPHERIC DEPOSITION ON WATER QUALITY IN HIGH ALPINE LAKES OF GRAND TETON NATIONAL PARK, WYOMING

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Executive Summary

This report focuses on the effects of atmospheric deposition on the water chemistry of high alpine lakes in Grand Teton National Park (GRTE). Atmospheric deposition is the primary cause of acidification in lakes and streams in the United States. Mountainous watersheds have an especially low buffering capacity for nitrogenous acidifying compounds that are common in atmospheric deposition because of their limited soil development and vegetation, short growing season, and large areas of exposed bedrock. These watersheds are also susceptible to the release of atmospheric pollutants during spring snowmelt - pollutants that accumulate in the snowpack during the winter. This inherent sensitivity to acidification, coupled with increased deposition of atmospheric pollutants due to population growth and industrialization, means that acidification of high elevation lakes and streams is a concern for resource managers, particularly in relatively unaffected wilderness areas.

Increased urbanization of the Western United States has caused a dramatic increase in atmospheric deposition of anthropogenically-produced compounds in recent years. Long term monitoring of high elevation lakes and streams in Rocky Mountain National Park, Colorado, has indicated increased levels of atmospheric deposition and increased sensitivity to acidification in Park waters (*Mast et al.,* 1990; *Baron,* 1992; *Campbell et al.,* 1995; *Baron and Campbell,* 1997; *Peterson and Sullivan,* 1998; *Campbell et al.,* 2000; *Sueker et al.,* 2000; *Williams and Tonnessen,* 2000; *Cosby and Sullivan,* 2001). Monitoring of alpine and sub-alpine lakes in Grand Teton National Park (GRTE), Wyoming, has also indicated greater sensitivity to atmospheric deposition in recent years, although the situation is not as serious as it is at the Colorado site (*Peterson and Sullivan,* 1998; *Williams and Tonnesson,* 1997). Unlike ROMO, there is no current long term monitoring effort in place for either atmospheric deposition or water quality of high elevation lakes at GRTE. The nearest NADP monitoring station is at Tower Junction in Yellowstone National Park (YELL). The only water quality data for GRTE high elevation lakes are from the 1985 Western Lake Survey (Landers et al., 1986), the 1999 resample of this survey (*Clow et al.,* 2002) and from synoptic sampling conducted by *Gulley and Parker* (1986) and *Williams and Tonnessen* (1997). Monitoring of water quality in the high elevation lakes in GRTE is essential to elucidate long-term trends and determine the range of inter-annual and seasonal variability in sensitivity to acidification from atmospheric deposition. Therefore, the objectives of this study were: 1) to determine the status and trends in water quality of 12 high elevation lakes in GRTE with respect to atmospheric deposition impacts and 2) to use the relationships between water chemistry and watershed physical characteristics to predict which lakes in GRTE are most sensitive to acidification.

Methods

Monitoring of all potentially impacted water bodies in GRTE was impractical, so it was necessary to focus monitoring efforts on only the most sensitive sites. Basin physical characteristics such as topography, geology and vegetation were used as selection criteria and as parameters in the development of a predictive model of lake

sensitivity to acidification. The purpose being that the model will provide a planning tool that can be used to focus future monitoring efforts in GRTE high elevation lakes.

Twelve lakes were sampled during the summer of 2002. Nine of the lakes are located within GRTE on the east side of the Teton divide with the remainder on the west side in the Targhee National Forest. Sampling parameters included acid neutralizing capacity (ANC), pH, conductivity, major anions and cations, dissolved organic carbon (DOC), total and particulate nitrogen, and total and particulate phosphorous. The effects of deposition on the study areas were quantified with NADP deposition data and snowpack surveys.

Modeling efforts for the 2002 study in GRTE were centered primarily on multiple linear regression analysis and SPSS discriminant analysis. Basin physical characteristics were determined using digital coverages of topography, geology, and habitat and cover type. Step-wise multiple linear regression and discriminant analysis were used to identify which variables make a significant contribution to lake sensitivity. The model was calibrated with the data collected in the summer of 2002 at GRTE. Mean concentrations of late season samples were entered into the model. Water chemistry data collected by *Clow et al.* in 1999, *Williams and Tonnessen* in 1996, and by *Landers et al.* in 1985 were used for model testing and validation.

Results

The sampled lakes had a wide range of ANC concentrations - from 37.9 μeq L^{-1} to 1488.3 μeq L^{-1} with a median of 256.5 μeq L^{-1}. Major ion concentrations and conductivity were also highly variable in the sampled lakes. Nitrate concentrations ranged from 0.1 μeq L^{-1} to 20.1 μeq L^{-1}, with a median of 7.9 μeq L^{-1}. The highest NO_3^- concentrations occurred in lakes with the lowest ANC values, with the exception of lakes underlain by limestone. Delta Lake, which is fed by Teton Glacier, had the highest NO_3^- concentration (20.1 μeq L^{-1}). Positive correlations between ANC, conductivity, Ca^{2+}, Mg^{2+}, and Na^+ - indicative of carbonate mineral weathering - were relatively strong ($p \leq$ 0.01). Both NO_3^- and Ca/Na ratios were negatively correlated to DOC concentrations.

Six of the lakes were sampled on more than one occasion as a means of detecting temporal trends and solute fluxes. Concentrations of ANC were variable with just over half of the lakes exhibiting a decrease in ANC while the other half increased. On average, Ca^{2+} and Mg^{2+} concentrations decreased, and Na^+ concentrations increased. Nitrate concentrations decreased seasonally.

There were no consistent trends in ANC concentrations among the 12 lakes for which there are data from both 1996 and 2002. Seven of the lakes showed an increase in ANC since 1996, whereas the remainder exhibited decreased ANC concentrations.

Trapper Lake is the only lake that was surveyed for more than two years. ANC in Trapper Lake has decreased by 50% since 1985, and most major cations have also decreased since 1985, particularly Ca^{2+}, which has decreased by 48%. Unlike cation trends, anion trends in Trapper Lake were variable. Since 1985, NO_3^- concentrations have increased and SO_4^{2-} concentrations have decreased.

Topographic characteristics in the Teton Range are characteristic of glacial environments. Most of the study basins were located in glacial cirques and tarns that had

high percentages of steep slopes dominated by granitic rock and young debris and very little vegetation. This is also reflected in the correlations among basin characteristics, with the strongest and most numerous correlations occurring in the granite, limestone, and young debris categories.

The data from the Tower Junction NADP station indicate an overall increase in the potential for acidification of GRTE waters by nitrogen-based compounds in atmospheric deposition. However, since GRTE does not have its own NADP station, such an inference remains tentative.

Decreased NO_3^- and SO_4^{2-} concentrations were observed in snow samples collected at Garnet Canyon and Rendezvous Mountain between 2001 and 2002. The fact that these values are lower than the 1993-2000 averages, may be due to interannual differences in precipitation which may mask trends for wet deposition in snow.

Conclusion and Recommendations

The results of the present study suggest that both mechanisms – the acid neutralizing effect of limestone bedrock, and high nitrate from talus fields – affect the basin water chemistry at sites in GRTE. However, watersheds without limestone but with a large amount of young debris have some of the lowest ANC values. In addition, the results indicate that, in watersheds without limestone, high NO_3^- increases the sensitivity to acidification; and glacier dissolution in GRTE study basins may be responsible for seasonal increases in NO_3^- concentrations in glacier-fed lakes, which in turn decreases the ANC.

It is recommended that the National Park Service conduct additional monitoring of target lakes in GRTE - especially, Delta Lake (Figure 15), Surprise Lake and Amphitheater Lake (Figure 17), and Lake Solitude and Mica Lake (Figure 18) – all of which should be sampled annually. In conjunction with seasonal monitoring of selected lakes, an investigation into the mechanism of nitrate deposition into glacially-fed lakes (namely, Delta Lake) is suggested. It is also recommended that a NADP monitoring station be installed at GRTE to better monitor the effects of atmospheric deposition within the park.

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Introduction

Sulfur dioxide (SO_x) and nitrogen oxide (NO_x) emissions from the burning of fossil fuels and from industrial processes have greatly increased the amount and acidity of atmospheric deposition in every major industrialized country since the beginning of the 20th century (*Ingersoll et al.,* 2004). The generation of electricity and powering of internal combustion engines release nitrogen oxides into the atmosphere. The use of fertilizers to boost agricultural productivity results in the emission of ammonia and ammonium compounds. These nitrogen-based atmospheric pollutants are either adsorbed to dust particles or dissolved in atmospheric water vapor. Settling of atmospheric dust particles (dry deposition) or the occurrence of rain and snow (wet deposition) serves as a transport mechanism, returning pollutants to the earth's surface. The contaminants contained in wet and dry deposition reach surface water bodies, such as lakes and streams, primarily as runoff from surrounding terrestrial areas.

Atmospheric deposition is the primary cause of acidification in lakes and streams in the United States. Mountainous watersheds have an especially low buffering capacity for nitrogen-based acidifying compounds in atmospheric deposition because of their sparse vegetation, short growing season, poor soil development, and the presence of extensive areas of exposed bedrock. In addition, atmospheric pollutants that accumulate in the winter snowpack in mountainous watersheds are released rapidly during the spring snowmelt, resulting in a large nutrient flux that quickly overwhelms the soil's limited storage capacity. Consequently, lakes and streams in mountainous areas are especially vulnerable to acidification and other water quality impacts caused by atmospheric deposition. This inherent sensitivity to acidification, coupled with increased deposition of

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atmospheric pollutants due to population growth and industrialization, means that acidification of high elevation lakes and streams is a concern for resource managers, particularly in relatively unaffected wilderness areas.

As in most other parts of the developed world, increased urbanization of the Western United States has caused a dramatic increase in deposition of anthropogenically-produced compounds in recent years. Long term monitoring of high elevation lakes and streams in Rocky Mountain National Park (ROMO), Colorado, has indicated increased levels of atmospheric deposition and increased sensitivity to acidification in Park waters (*Mast et al.,* 1990; *Baron,* 1992; *Campbell et al.,* 1995; *Baron and Campbell,* 1997; *Peterson and Sullivan,* 1998; *Campbell et al.,* 2000; *Sueker et al.,* 2000; *Williams and Tonnessen,* 2000; *Cosby and Sullivan,* 2001). Monitoring of alpine and sub-alpine lakes in Grand Teton National Park (GRTE), Wyoming, has also indicated greater sensitivity to atmospheric deposition in recent years, although the situation is not as serious as it is at the Colorado site (*Peterson and Sullivan,* 1998; *Williams and Tonnesson,* 1997). Unlike ROMO, there is no current long term monitoring effort in place for either atmospheric deposition or water quality of high elevation lakes at GRTE. The nearest NADP monitoring station is at Tower Junction in Yellowstone National Park (YELL). Deposition data from YELL is used to evaluate GRTE because both parks are exposed to the same general air masses and are not subject to any nitrogen or sulfur point sources (*Peterson and Sullivan,* 1998). The only water quality data for GRTE high elevation lakes are from the 1985 Western Lake Survey (Landers et al., 1986) and the 1999 resample of this survey (*Clow et al.,* 2002) and synoptic sampling conducted by *Gulley and Parker* (1986) and *Williams and Tonnessen* (1997).

Monitoring of water quality in the high elevation lakes in GRTE is essential in order to elucidate long-term trends and determine the range of inter-annual and seasonal variability in sensitivity to acidification from atmospheric deposition. This is consistent with one of the goals of the National Park Service's Vital Signs Monitoring Program (VSMP): the identification of trends in water quality within GRTE and other park units (National Park Service, 2001). It is also consistent with the the Antidegradation Policy and the Outstanding National Resource Waters (ONRW) designation provisions of the Clean Water Act, which provide additional protection of a state's highest-quality waters and which emphasize "…identifying specific existing or emerging water quality problems."

Monitoring of all potentially impacted water bodies in GRTE is impractical, so it is necessary to focus monitoring efforts on only the most sensitive sites. The sensitivity of aquatic systems to environmental input can be determined by the identification of factors controlling lake water chemistry. Basin physical characteristics such as topography, geology and vegetation are oftentimes vehicles for other variables that influence water chemistry more directly (Sueker et al., 2001; Kamenik et al., 2001; Clow and Sueker, 2000; Meixner et al., 2000). Using basin physical parameters to develop a predictive model of lake sensitivity to acidification will provide a planning tool that can be used to focus future monitoring efforts in GRTE high elevation lakes. Therefore, the objectives of this study were: 1) to determine the status and trends in water quality of 12 high elevation lakes in GRTE with respect to atmospheric deposition impacts and 2) to use the relationships between water chemistry and watershed physical characteristics to predict which lakes in GRTE are most sensitive to acidification.

Study Area

Grand Teton National Park (GRTE) in northwest Wyoming encompasses some of the nation's most spectacular mountain landscapes and includes approximately ninety subalpine and alpine lakes. These lakes are embedded in the cirques and glacially-formed canyons of the Teton Range, which rises approximately 2100 m above Jackson's Hole (elevation 1892 m) (*National Park Service,* 1997).   The town of Jackson Hole is located just south of GRTE, but, as a whole, the population of northwestern Wyoming is low. Although there is very little industrial development in the immediate area, there is industrial activity to the south, east, and west of the park.

The 12 lake basins surveyed in this study include two glacial moraine lakes, three alpine kettle lakes, and seven cirque lakes (Figure 1). Nine of the lakes are located within GRTE on the east side of the Teton divide with the remainder on the west side in the Targhee National Forest. The eastern front of the Teton Range - unique in the Rocky Mountains – is very steep and is the product of erosion of Precambrian crystalline rocks along the steeply dipping Teton fault. This hard crystalline rock makes up the majority of the bedrock in the Teton Range, but darker-colored metamorphic rocks such as the Mt. Moran Gneiss and lighter-colored igneous rocks such as the Mt. Owen Granite are also present (*National Park Service,* 1997). Glaciers at the heads of stream valleys formed cirque lakes, such as Lake Solitude, and these are the dominant lake type at higher elevations in the Tetons (*Meyers*, 2000). As the ice expanded, the toes of the glaciers descended toward the valley floor. Upon reaching the valley, the ice melted, forming moraine-dammed lakes such as Bradley Lake and Trapper Lake (*National Park Service,* 1997).

The geographical extent of the effects of atmospheric deposition on aquatic systems is unknown, but dilute systems may be affected by contaminants from local, regional, or global sources (*Fenn et al.,* 2003). There is very little industrial activity in the area surrounding the park, but atmospheric deposition impacts on water quality are still an issue of concern in GRTE. The primary reasons for concern are: (1) increased residential and business development in Jackson Hole; (2) increased use of prescribed burning in and around Jackson Hole; (3) proposed oil and gas development and associated activities south, east, and west of the park; (4) agricultural practices in Idaho west of the park; and (5) metropolitan and industrial development along the western slope of the Wasatch Mountains. In addition to industry and development, the number of automobiles that pass through the park each year is a concern. Park visitation was approximately 4 million individuals in 2002, an increase of almost 36% since 1983.

Monthly mean maximum temperatures at Moose, Wyoming (elevation 1960 m), range from -3.4 $^{\circ}$C in January to 26.8 $^{\circ}$C in July (Table 1). Monthly mean minimum temperatures range from $-17.2 ^{\circ}$C in January to 5.2 $^{\circ}$C in July. Average total precipitation values at Moose, Wyoming, range from 3.0 cm in July to 6.6 cm in January, and the average total annual precipitation is 53.6 cm. However, precipitation amounts in the Teton Range are much greater. The Phillips Bench SNOTEL site (elevation 2499 m), southwest of Teton Village, receives an average of 111.3 cm of precipitation annually.

Table 1. Monthly mean maximum and minimum temperatures, and precipitation at Moose, Wyoming, and monthly mean precipitation at Phillips Bench SNOTEL site. Period of Record is 1958 to 2003 at Moose and 1971 to 2000 at Phillips Bench.

	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Moose	Max. Temperature (°C)	-3.4	-0.6	3.9	9.6	16.1	21.5	26.8	26.2	20.6	13.3	3.3	-3.2	11.2
	Min. Temperature (°C)	-17.2	-15.9	-11.2	-5.4	-0.7	2.9	5.2	4.2	0.1	-5.0	-10.3	-17.1	-5.9
	Total Precipitation (cm)	6.6	5.0	4.0	3.7	4.9	4.5	3.0	3.4	3.7	3.2	5.5	6.3	53.6
	Precipitation at Phillips Bench SNOTEL (cm)	15.2	13.0	12.2	9.4	8.9	5.8	3.3	4.1	5.1	6.4	12.4	15.5	111.3

Methods

Atmospheric Deposition

The National Atmospheric Deposition Program/National Trends Network (NADP/NTN) monitors deposition across the United States (http://nadp.sws.uiuc.edu/). Grand Teton National Park (GRTE) does not have a NADP station, but there is a station at Tower Junction in Yellowstone National Park (YELL) that has been monitoring deposition since 1980. Deposition data from the YELL Tower Junction site can be used to evaluate GRTE because both parks are exposed to the same general air masses and are not subject to any nitrogen or sulfur point sources (*Peterson and Sullivan,* 1998). Therefore, data from Tower Junction were used to evaluate atmospheric deposition during this study.

Clow et al. (2002) measured snowpack chemistry in the Rocky Mountains during the winters of 1992 – 1999 and found no statistically significant differences between NO_3^- and SO_4^{2-} concentrations in snowpack and winter volume-weighted mean wet-deposition concentrations. Therefore, snowpack surveys can be used to assess winter

period wet atmospheric deposition inputs to high elevation lakes and streams in situations where NADP/NTN monitoring sites are limited or not available. Since 1993, Snowpack surveys have been conducted at Garnet Canyon and Rendezvous Mountain at GRTE in (*Ingersoll et al*., 2002; *Ingersoll et al*., 2004), and these data were used to further evaluate atmospheric deposition in the study area.

Lake Selection and Sampling

In the summer of 2002, twelve lakes were sampled in GRTE and the Targhee National Forest, at elevations ranging from 2108 m to 3050 m and surface areas ranging from 0.9 ha to 27 ha (Figure 1 and Table 2). Lake selection was based on past sampling surveys (*Gulley and Parker,* 1986; *Landers et al.,* 1986; *Williams and Tonnessen,* 1997), basin morphometric characteristics, and accessibility.

Sampling parameters included acid neutralizing capacity (ANC), pH, conductivity, major anions and cations, dissolved organic carbon (DOC), total and particulate nitrogen, and total and particulate phosphorous. In order to obtain a well-mixed sample, samples were collected from either the center of the lake or at the outlet. Sampling dates were dependent upon accessibility and the amount of ice present on the lake surface. Generally, samples were collected from May to September at lower elevation lakes and from July to September at higher elevation lakes (Table 3). Whenever possible, both early and late season samples were collected in order to associate seasonal trends with varying water chemistry. During the *Williams and Tonnessen* survey conducted in 1996, high late-season NO_3^- concentrations were observed. Therefore, samples were collected during early and late summer to observe the

seasonal flux of nitrate and other analytes in alpine watersheds. Duplicates of all samples
- except DOC and total P, and total N - and field blanks (10%) were collected.

Table 2. Lakes Surveyed in Grand Teton National Park during the summer of 2002.

Lake Name	Elevation (m)	Surface Area (ha)	Mean Depth* (m)	Max Depth* (m)
Alaska Basin Lake	2917	0.7	-------	-------
Amphitheater Lake	2956	1.9	4.9	7
Bradley Lake	2140	27.1	13.3	34
Delta Lake	2747	2.8	1.9	8
Granite Basin Lakes	2776	3.1	-------	-------
Holly Lake	2868	3.8	3	7
Lake Solitude	2754	15.1	-------	-------
Mica Lake	2913	3.9	-------	-------
Snowdrift Lake	3050	22.2	15.2	30
Sunset Lake	2942	1.1	-------	-------
Surprise Lake	2915	0.9	3	6
Trapper Lake	2108	1.4	2.4	5

*Depth data not available for all lakes (*Gulley and Parker* 1986)

Lake water samples were collected in high-density polyethylene bottles. Heat-
etched amber glass bottles were used to collect DOC samples. All sample bottles were
treated with de-ionized water at the laboratory and were triple rinsed with sample water
on site before collection. Both filtered and unfiltered samples were taken at each site –
except for DOC (filtered only) and total phosphorous and total nitrogen (unfiltered only).
Filtered samples were collected to compare agency and laboratory protocols and to
determine the most appropriate methods for future sampling. Samples were filtered
through a 0.45 μm polycarbonate membrane at the time of collection. After the samples
were collected, they were immediately chilled and sent within 24 hours to either the
Rocky Mountain Research Station (RMRS) laboratory in Fort Collins, Colorado, or the
University of Georgia Institute of Ecology Stable Isotope Laboratory (UGIESIL) in
Atlanta, Georgia. RMRS staff conducted the analysis of anions, cations, pH,

conductivity, alkalinity, and ANC while UGIESIL staff analyzed samples for DOC, total P, and total N (Table 4). Both laboratories followed standard EPA protocols for the analysis of dilute water samples (EPA-600/4-79-020).

Table 3. Early and late season sample dates for selected GRTE lakes.

| Lake Name | No. times sampled | Seasonal Sampling Dates | | |
		Early	Mid	Late
Alaska Basin Lake	1			08/04/02
Amphitheater Lake	2		06/30/02	09/08/02
Bradley Lake	3	05/30/02	07/01/02	09/08/02
Delta Lake	1			09/08/02
Granite Basin	1			08/11/02
Holly Lake	1			08/31/02
Lake Solitude	2		07/03/02	08/31/02
Mica Lake	1			08/31/02
Snowdrift Lake	2		07/04/02	08/02/02
Sunset Lake	1			08/04/02
Surprise Lake	2		06/30/02	09/08/02
Trapper Lake	3	06/01/02	06/29/02	07/31/02

Accuracy of analyses was evaluated using certified high-purity standards traceable to the National Institute of Standards and participation in blind-audit performance tests conducted by the U.S. Geological Survey. Results of these tests rated the RMRS lab a 3.8 on a 4.0 scale. Analytical results were checked by comparing measured and predicted specific conductance and by ionic charge balance.

Modeling of Lake Water Chemistry

Mathematical models for predicting water chemistry in natural waters have been used successfully in mountain catchments (*Clow and Sueker*, 2000; *Meixner et al.,* 2000; *Wolford et al.,* 1996). Modeling efforts for the 2002 study in GRTE were centered primarily on multiple linear regression analysis and SPSS discriminant analysis.

Table 4. Laboratory protocols for samples analyzed in 2002 at GRTE.

Solute	Technique	Equipment	Laboratory
pH	Gran Analysis	PC-Titrate Autotitration system for pH and alkalinity	RMRS
ANC	Same	Same	RMRS
Conductivity	Same	PC-Titrate Conductivity Meter Model 4310 for conductivity	RMRS
Anions	Ion Chromatograph (IC) with separator column for anions (APHA 1998a) and monovalent/divalent column for cation	Anions: Waters IC with Dionex AS12 A Separator Column, Model 431 conductivity detector, Model 717 plus autosampler, Model 501 pump	RMRS
Cations	Same	Cations: Waters IC with Water IC PAK Cation M/D Column, Model 431 conductivity detector, Model 717 plus autosampler, Model 501 pump	RMRS
DOC	UV-Persulfate Infrared Detection	Shimadzu TOC-5000A Total Organic Carbon Analyzer with ASI-5000A Auto Sampler	UGIESIL
Total P	Continuous Flow Colorimetric Analysis	Technicon AutoAnalyzer	UGIESIL
Total N	Same	Same	UGIESIL

Basin Characterization

Interaction between watershed runoff and geologic materials is the primary control on the chemistry of natural waters (*Morel and Hering,* 1993). Physical weathering of geologic surfaces increases chemical weathering and is directly related to the supply of cations, silicate, sulfate, and alkalinity to surface waters. Basin physical characteristics (topography and geology) control runoff processes and pathways and, hence, the extent of interaction between water and geologic materials.

Basin physical characteristics were determined using digital coverages of topography, geology, and habitat and cover type. National Park Service staff at GRTE provided all spatial data. Categories for analysis were expressed as a percentage of the total basin surface area and were quantified using the Geographic Information System (GIS) software ArcGIS Spatial Analyst.

Geologic characteristics of each study basin were derived from a digital copy of the revised Geologic Map of Grand Teton National Park, Teton County, Wyoming, of 1992 (*Love et al.*,1992). Geology units were classified as granite, metamorphic rock, limestone, sedimentary (non-limestone), diabasic dike, old debris, young debris, or peat. Surficial debris was designated as either old (Pleistocene) or young (Holocene) because of expected differences in hydrolysis weathering (*Clow and Sueker,* 2000; *Johnson,* 1984).

The digital coverage of combined habitat and vegetation cover types was constructed from field data collected by NPS technicians in 1992 at GRTE. Classes included forest, sub-alpine meadow, tundra and un-vegetated.

Topographic characteristics were calculated using the 10-meter Digital Elevation Model (DEM) for GRTE. The GIS software ArcGIS Spatial Analyst was used to calculate basin area, median slope, median elevation, percentage of the basin with slopes ≥ 30° (steep slope), lake elevation, lake surface area, and lake area/watershed area ratios.

Model Development

A step-wise multiple linear regression method was used in the GRTE study in an attempt to associate basin characteristics with water chemistry and to identify those independent variables that exert a strong influence on the association. Discriminant analysis was also used to identify which variables make a significant contribution to the classification of lake sensitivity. Both models were run in SPSS. The data were assumed to be normally distributed and, in the case of discriminant analysis, group membership was assumed to be mutually exclusive and collectively exhaustive. However, the results

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from the linear regression model were expected to be richer because ANC is a continuous variable.

The model was calibrated with the data collected in the summer of 2002 at GRTE. Mean concentrations of late season samples were entered into the model. Parameters included ANC, pH, conductivity, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, F^-, NO_3^-, SO_4^{2-}, NH_4^+, DOC, Total P, and Total N. Water chemistry data collected by *Clow et al.* in 1999, *Williams and Tonnessen* in 1996, and by *Landers et al.* in 1985 were used for model testing and validation.

Spearman correlation matrices were used to identify the relationships between solutes and basin characteristics. After the relationships were identified, multiple linear regression was employed to obtain coefficients for model testing. Discriminant analysis was also used to identify sensitive water bodies, and ANC was the screening criteria. Categories of sensitivity were: chronic (ANC < 50µeq L^{-1}), episodic (ANC <100µeq L^{-1}), and not susceptible (ANC > 100µeq L^{-1}).

Results

Atmospheric Deposition

The 2002 annual precipitation weighted means for SO_4^{2-} and NO_3^- deposition at Tower Junction were 7.5µeq L^{-1} and 11.6µeq L^{-1}, respectively (NADP/NTN). Concentrations for both anions have increased since 2001. While NO_3^- concentrations in 2002 were the highest in 10 years, long-term data from the Tower Junction site indicate almost no change in NO_3^- deposition (Figure 2). Concentrations of SO_4^{2-} have decreased

by 30 % over this same period (Figure 3). However, NH_4^+ concentrations at Tower

Junction have doubled since the early 1990s (Figure 4).

Snowpack surveys conducted at Garnet Canyon and Rendezvous Mountain at

GRTE indicated that both nitrate and sulfate concentrations decreased from 2001 to 2002;

NO_3^- decreased from 7.0 to 5.8 µeq L^{-1}, and SO_4^{2-} decreased from 5.9 to 4.9 µeq L^{-1}

(*Ingersoll et al.,* 2002). The 2002 values were below the 1992-1999 averages for NO_3^-

and SO_4^{2-}, which were 6.89 and 7.78 µeq L^{-1}, respectively at Garnet Canyon, and 6.57

and 7.91µeq L^{-1}, respectively at Rendezvous Mountain (*Nanus et al.,* 2003).
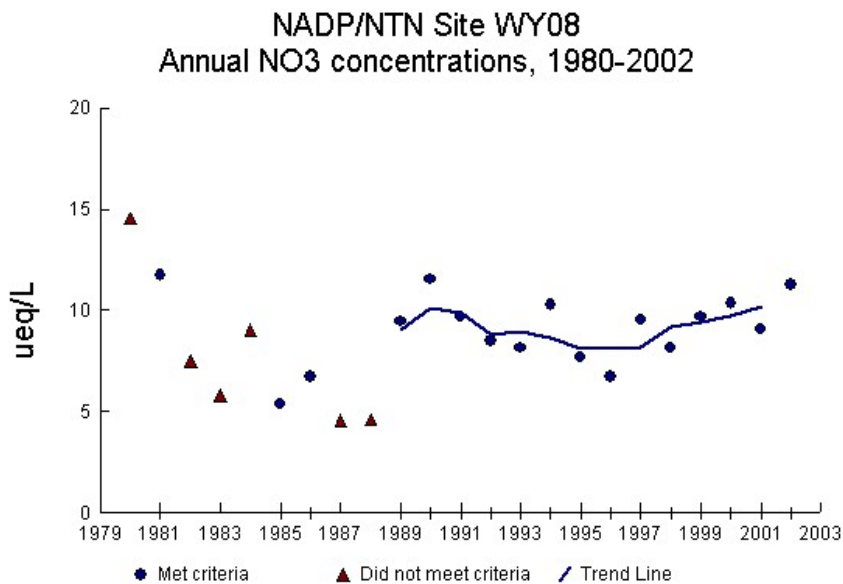
Figure 2. Trends in NO_3^- deposition at Tower Junction in YELL

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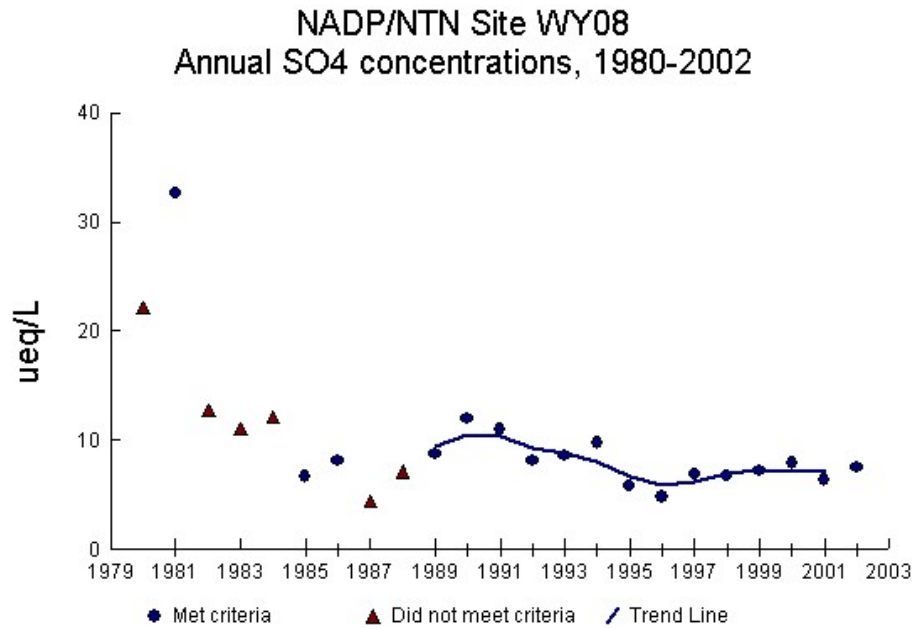
Figure 3. Trends in SO_4^{2-} deposition at Tower Junction in YELL
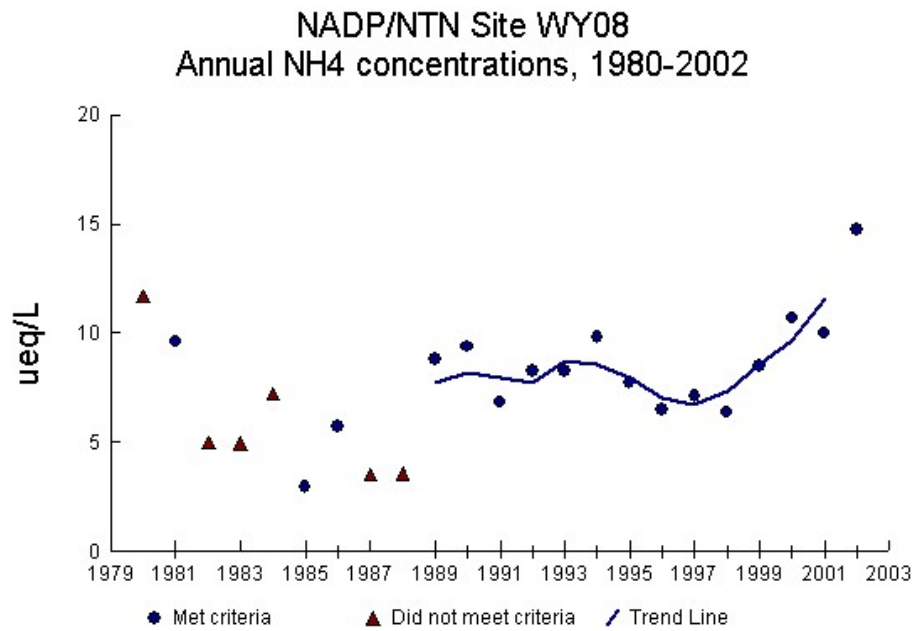
Figure 4. Trends in NH_4^+ deposition at Tower Junction in YELL

Lake Solute Concentrations

The lakes that were sampled during the summer of 2002 had a wide range of ANC concentrations (Table 5). The ANC concentrations ranged from 37.9 μeq L^{-1} to 1488.3 μeq L^{-1} with a median of 256.5 μeq L^{-1}. Surprise Lake, Amphitheater Lake, Delta Lake, and Lake Solitude had ANC concentrations below 50 μeq L^{-1}. Lakes with ANC concentrations $\leq$ 50 μeq L^{-1} are highly susceptible to acidification. Granite Basin Lake, Holly Lake, and Mica Lake had concentrations of ANC between 50 and 100 μeq L^{-1}, indicating periodic susceptibility to acidification.

Concentrations of base cations are generally low in non-acidified waters, but increase substantially in response to acidic deposition. In relatively pristine areas, the concentration of Ca^{2+}, Mg^{2+}, Na^+, and K^+ in sensitive waters will generally be less than about 50 to 100 μeq/L. Like ANC, major ion concentrations (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, NO_3^-, SO_4^{2-}) and conductivity were also highly variable in the sampled lakes (Table 5). Concentrations of Ca^{2+}, Mg^{2+}, and conductivity were the highest in Sunset Lake and the lowest in Surprise Lake. The median concentrations for Ca^{2+} and Mg^{2+} were 76.8 μeq L^{-1} and 28.9 μeq L^{-1}, respectively, and the median conductivity was 12.1μS cm^{-1}. The highest concentrations of Na^+ and K^+ were in Trapper Lake (38.8 and 26.1 μeq L^{-1}, respectively), with median values of 15.2 μeq L^{-1} for Na^+ and 9.6 μeq L^{-1} for K^+. Lake Solitude had the lowest Na^+ concentration (8.9 μeq L^{-1}), and Granite Basin Lake had the lowest K^+ concentration (3.1μeq L^{-1}).

The contribution of silicate weathering to cation concentrations in water samples is explained by Ca/Na ratios, which were calculated to allow for the effects of evapotranspiration and snowmelt contributions on concentrations of Ca^{2+} and Na^+.

Ca/Na ratios ranged from 2.4 to 34.8 μeq L^{-1}, with a median of 3.9 μeq L^-. These values are higher than what can be explained solely by silicate weathering.

Nitrate concentrations ranged from 0.1μeq L^{-1} to 20.1μeq L^{-1}, with a median of 7.9 μeq L^{-1}. The highest NO_3^- concentrations occurred in lakes with the lowest ANC values, with the exception of Sunset Lake and Snowdrift Lake, which are located on opposite sides of the same limestone divide. Delta Lake, which is fed by Teton Glacier, had the highest NO_3^- concentration (20.1μeq L^{-1}), while the lowest NO_3^- concentrations were in Granite Basin Lake and Holly Lake (0.1μeq L^{-1}). Sulfate concentrations ranged from 7.7 μeq L^{-1} in Amphitheater Lake to 424.8 μeq L^{-1} in Sunset Lake, with a median concentration of 15.4 μeq L^{-1}.

Dissolved organic carbon (DOC) causes water to be naturally low in pH and ANC, or even to be acidic (ANC less than 0). However, DOC contributes substantially to the buffering capacity of natural waters at low pH values. Waters sensitive to acidification from acidic deposition in the West generally have DOC less than about 300 to 500 ppb (*Peterson and Sullivan*, 1998). Dissolve organic carbon concentrations ranged from 1776.0 ppb in Alaska Basin Lake to 289.0 ppb in Snowdrift Lake, with a median value of 712.0 ppb. Total P values were below detection limits (BDL) in all lakes except Alaska Basin Lake, which had a concentration of 12 ppb. Values for total N ranged from BDL in Trapper Lake to 363.0 ppb in Delta Lake, with a median of 94.0 ppb.

Correlations among solutes define lake water chemistry. Positive correlations between ANC, conductivity, Ca^{2+}, Mg^{2+}, and Na^+ were relatively strong ($p \leq 0.01$) and are indicative of carbonate mineral weathering (*Moldan and Cerny*, 1992; *Morel and*

Hering, 1993). Both NO_3^- and Ca/Na ratios were negatively correlated to DOC

concentrations (Table 6).

Quality assurance procedures of chemical analyses are detailed in Appendix B.

Ionic charge balance of each major-ion analysis was calculated by dividing the sum of

cations (hydrogen ion, calcium, magnesium, sodium, potassium, and ammonium) minus

the sum of anions (alkalinity, chloride, nitrate, and sulfate) by the total cations and anions

in solution. Ion balances calculated for the 2002 water chemistry were mostly negative

with a mean value of –4.7%, indicating an excess of measured anions over cations in

solution. One possible explanation for the negative bias of the ionic balances is that DOC

was not included in the calculation (1 mg DOC = 8 microeq charge average, *Stottlemeyer*

pers. comm.).

Table 5. Major cations, pH, conductivity, ANC, major anions, Ca/Na ratio, DOC, Total N, and Total P in sampled lakes at GRTE in 2002. Values are the mean of all samples collected. Units are in μeq L^{-1}, except for conductivity (μS/cm) and DOC, total P, and total N (ppb).

Water body	Ca	Mg	Na	K	pH	Cond	ANC	NH4	F	Cl	NO3	SO4	Ca/Na	DOC	TotP	TotN
Alaska Basin Lake	68.5	47.8	17.8	6.8	7.1	14.0	110.3	2.3	0.0	2.5	0.4	13.7	3.8	1776	12	2.0
Amphitheater Lake	38.6	12.6	14.1	5.6	6.6	7.4	49.3	1.2	0.0	3.4	5.2	7.7	2.7	1069	0	0.0
Bradley Lake	88.6	38.1	28.5	15.7	7.2	19.4	148.9	3.0	2.1	5.8	9.7	17.4	3.1	782	0	218.0
Delta Lake	50.9	16.4	12.1	13.0	6.6	9.2	42.5	0.0	0.0	5.2	20.1	12.3	4.2	642	0	363.0
Granite Basin Lake	55.2	18.5	15.1	3.1	6.7	8.7	87.7	0.0	3.6	1.7	0.1	12.8	3.7	1019	0	51.0
Holly Lake	79.4	26.5	26.7	11.1	7.0	13.3	96.7	0.8	3.9	2.9	0.1	26.8	3.0	1147	0	83.0
Lake Solitude	93.2	30.1	8.9	5.8	7.1	8.4	37.9	1.2	4.5	2.1	12.2	17.1	10.5	552	0	81.0
Mica Lake	74.2	27.6	10.5	8.1	6.9	10.8	77.9	1.7	0.0	1.8	10.0	13.7	7.1	371	0	177.0
Snowdrift Lake	514.5	206.0	15.3	16.9	7.8	75.4	676.2	0.0	2.1	3.1	13.8	54.9	33.6	289	0	183.0
Sunset Lake	1274.3	654.7	36.6	26.1	8.3	182.5	1488.3	1.6	1.7	5.0	10.5	424.8	34.8	443	0	177.0
Surprise Lake	34.5	12.0	14.5	6.0	6.6	6.8	43.0	0.9	0.0	3.8	4.4	8.2	2.4	1034	0	105.0
Trapper Lake	155.1	47.7	38.8	26.1	7.3	26.7	219.6	0.0	2.7	8.2	7.9	23.6	4.0	547	0	0.0
Median	76.8	28.9	15.2	9.6	7.0	12.1	92.2	1.1	1.9	3.2	8.8	15.4	3.9	712.0	0.0	94.0
Maximum	1274.3	654.7	38.8	26.1	8.3	182.5	1488.3	3.0	4.5	8.2	20.1	424.8	34.8	1776.0	12.0	363.0
Minimum	34.5	12.0	8.9	3.1	6.6	6.8	37.9	0.0	0.0	1.7	0.1	7.7	2.4	289.0	0.0	0.0
Range	1239.7	642.7	29.9	23.0	1.7	175.7	1450.4	3.0	4.5	6.4	20.0	417.1	32.5	1487.0	12.0	363.0
Standard Deviation	359.5	184.0	10.2	7.8	0.5	51.1	426.0	1.0	1.7	1.9	6.1	117.8	11.8	423.3	3.5	108.6

Table 6. Spearman correlation coefficients for pH, ANC, conductivity, major cations and major anions, Ca/Na ratio, Total P, Total N, and DOC.

	pH	ANC	Cond.	Ca	Mg	Na	K	NH$_4$	F	Cl	NO$_3$	SO$_4$	Ca/Na	Total P	Total N	DOC
pH																
ANC	0.98*															
Conductivity	0.96*	0.94*														
Ca	0.97*	0.91*	0.92*													
Mg	0.94*	0.94*	0.95*	0.88*												
Na	0.61†	0.70*	0.69*	0.50	0.56											
K	0.69†	0.64†	0.83*	0.71*	0.67†	0.65†										
NH$_4$	0.16	0.15	0.13	0.04	0.24	0.02	-0.03									
F	0.44	0.42	0.31	0.52	0.23	0.24	0.03	-0.27								
Cl	0.22	0.20	0.32	0.17	0.12	0.53	0.66†	-0.07	-0.15							
NO$_3$	0.31	0.16	0.34	0.41	0.31	-0.27	0.49	-0.05	-0.13	0.31						
SO$_4$	0.91*	0.89*	0.93*	0.94*	0.85*	0.64†	0.75*	0.02	0.52	0.17	0.23					
Ca/Na	0.64†	0.54	0.63†	0.73*	0.71*	-0.03	0.50	-0.05	0.13	-0.08	0.72	0.57†				
Total P	0.04	0.13	0.13	-0.13	0.31	0.13	-0.13	0.40	-0.32	-0.22	-0.31	-0.04	-0.04			
Total N	0.07	-0.01	0.19	0.16	0.10	-0.10	0.45	0.06	-0.16	0.23	0.62†	0.21	0.34	-0.31		
DOC	-0.52	-0.41	-0.47	-0.64†	-0.47	0.04	-0.55	0.18	-0.09	-0.12	-0.74*	-0.44	-0.80*	0.48	-0.44	

*Correlation is significant at the .01 level (2-tailed).

†Correlation is significant at the .05 level (2-tailed).

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Trends in Solute Concentrations

Seasonal Trends

Six of the lakes (Amphitheater Lake, Bradley Lake, Lake Solitude, Snowdrift Lake, Surprise Lake, and Trapper Lake) were sampled on more than one occasion as a means of detecting temporal trends and solute fluxes (Table 3). Concentrations of ANC decreased seasonally in Amphitheater Lake, Bradley Lake, and Surprise Lake but showed a marked increase in Lake Solitude and Trapper Lake and a slight increase in Snowdrift Lake (Table 7).

On average, Ca^{2+} and Mg^{2+} concentrations decreased – with the exception of Lake Solitude - and Na^+ concentrations increased. Nitrate concentrations decreased seasonally. Phosphate concentrations were below detection limits, and SO_4^{2-} concentrations decreased seasonally – with the exception of, once again, Lake Solitude. There was little variation in cation and anion concentrations at Surprise Lake between 1996 and 2002.

Table 7. Seasonal comparisons of pH, ANC, conductivity, major cations, and major anions for lakes sampled in GRTE in the summer of 2002.

Name	Date	pH	ANC	Cond	Ca	Mg	Na	K	NH4	F	Cl	NO3	SO4
Amphitheater Lake	06/30/02	6.47	49.3	7.4	38.573	12.59	13.049	5.576	0.61	53.46	3.357	5.225	7.704
Amphitheater Lake	09/08/02	6.606	40.3	5.8	32.385	10.697	14.05	5.371	1.22	53.32	3.103	0	6.33
Bradley Lake	05/30/02	7.192	148.9	19.4	113.273	38.099	28.491	15.704	1.497	169.21	5.754	3.097	17.406
Bradley Lake	07/01/02	7.031	108.2	15.4	86.577	28.472	21.966	13.683	0.887	119.85	4.767	9.709	16.115
Bradley Lake	09/08/02	7.027	104.6	14.4	88.573	28.472	21.053	14.886	2.994	126.66	4.118	6.451	15.387
Lake Solitude	07/03/02	6.625	37.9	8.4	47.705	13.248	8.874	4.271	0	47.3	2.031	12.241	12.763
Lake Solitude	08/31/02	7.146	107.1	13.2	93.164	30.117	14.354	5.755	1.22	121.21	2.059	1.242	17.073
Snowdrift Lake	07/04/02	7.848	658.2	75.4	514.471	205.966	14.441	16.701	0	679.27	3.131	13.757	54.925
Snowdrift Lake	08/02/02	7.846	676.2	69.8	493.713	204.32	15.311	16.932	0	661.37	2.736	12.612	53.135
Surprise Lake	06/30/02	6.546	43	6.8	34.531	11.109	13.049	5.141	0	47.14	3.78	4.435	8.203
Surprise Lake	09/08/02	6.555	41.7	6.3	33.234	12.014	14.528	5.959	0.942	53.88	3.272	0	8.12
Trapper Lake	06/01/02	7.073	170.5	23.3	128.293	39.416	36.494	24.886	0	188.51	5.387	11.66	23.632
Trapper Lake	06/29/02	7.228	176	21.7	125.2	37.276	31.579	20.512	0	183.53	3.187	7.854	20.446
Trapper Lake	07/31/02	7.324	219.6	26.7	155.14	47.727	38.756	26.088	0	235.83	8.152	4.661	22.84

Units are in $\mu eq\ L^{-1}$, except for conductivity ($\mu S/cm$) and DOC, total P, and total N (ppb).

Temporal Trends

Trends across time are useful for detecting changes in basic lake chemistry, which may be a result of climate change, natural disruption, or anthropogenic effects. There were no consistent trends in ANC concentrations among the 12 lakes for which there are data from both 1996 and 2002 (Table 8). Seven of the lakes showed an increase in ANC since 1996, whereas the remainder exhibited decreased ANC concentrations. The largest increase in ANC was Bradley Lake, where ANC increased from 102.1 to 148.9 μeq L^{-1}. The largest decline was in Mica Lake, where ANC decreased from 149.4 to 77.9 μeq L^{-1}, indicating a transition from 'not-susceptible' to 'episodic' sensitivity to acidification. Nitrate concentrations increased in all lakes except Holly and Mica Lakes.

Trapper Lake is the only lake that was surveyed for more than two years. Trapper Lake was first sampled as part of the Western Lake Survey in 1985, by *Clow et al.* in 1999, by *Williams and Tonnessen* in 1996, and as part of this study in 2002. ANC in Trapper Lake has decreased by 50% since 1985, from 441.2 μeq L^{-1} to 219.6 μeq L^{-1} (Figure 5). Most major cations have also decreased since 1985, particularly Ca^{2+}, which has decreased by 48% from 298.8 to 155.1 μeq L^{-1} (Figure 6).

Table 8. Comparison of pH, ANC, conductivity, major cations, and major anioins in GRTE lakes in 1985, 1996, 1999 and 2002 based on data from *Landers et al.*, 1985; *Williams and Tonnessen*, 1997; *Clow et al.*, 1999 and the 2002 survey.

Lake	Year	Month	pH	ANC	Cond.	Ca	Mg	Na	K	NH$_4$	F	Cl	NO$_3$	SO$_4$
Alaska Basin Lake	1996	August	6.02	89.9	9.1	51.3	31.0	15.1	5.4	≤0.5	≤0.5	3.27	≤0.5	9.52
	2002	August	7.06	110.3	14.0	68.5	47.8	17.8	6.8	2.33	≤0.5	2.45	0.42	13.72
Amphitheater Lake	1996	August	5.81	52.0	5.7	23.0	6.8	12.4	4.2	≤0.5	≤0.5	2.68	≤0.5	5.58
	2002	September	6.61	49.3	7.4	38.6	12.6	14.0	5.6	1.22	≤0.5	3.36	5.23	7.70
Bradley Lake	1996	August	6.06	102.1	11.3	71.7	23.8	21.7	14.5	≤0.5	≤0.5	5.11	6.93	11.83
	2002	September	7.19	148.9	19.4	113.3	38.1	28.5	15.7	2.99	2.1	5.75	9.71	17.41
Delta Lake	1996	August	5.89	62.6	8.0	37.3	12.2	13.3	11.4	≤0.5	≤0.5	2.74	10.77	8.72
	2002	September	6.60	42.5	9.2	50.9	16.4	12.1	13.0	≤0.5	≤0.5	5.25	20.08	12.35
Granite Basin Lake	1996	August	5.92	81.0	7.5	55.5	19.7	7.1	2.4	≤0.5	≤0.5	1.35	≤0.5	5.33
	2002	August	6.68	87.7	8.7	55.2	18.5	15.1	2.6	≤0.5	3.6	1.75	≤0.5	12.58
Holly Lake	1996	August	5.98	92.2	9.6	60.7	20.7	20.7	8.6	≤0.5	≤0.5	1.85	5.94	15.22
	2002	August	7.01	96.7	13.3	79.4	25.4	26.7	10.9	0.83	3.9	2.88	≤0.5	25.63
Lake Solitude	1996	August	6.01	106.0	10.5	79.8	28.1	11.4	4.1	≤0.5	≤0.5	1.69	3.64	12.16
	2002	July	7.15	107.1	13.2	93.2	29.2	14.2	5.0	1.22	4.527	2.06	12.24	16.78
Mica Lake	1996	August	6.11	149.4	14.6	139.1	25.3	8.9	6.2	≤0.5	≤0.5	1.41	12.60	11.30
	2002	August	6.91	77.9	10.8	69.2	23.8	10.5	7.4	1.66	≤0.5	1.81	10.11	13.55
Snowdrift Lake	1996	August	6.94	659.0	61.8	586.9	161.9	9.8	12.5	≤0.5	≤0.5	2.45	11.07	48.85
	2002	July	7.85	676.2	75.4	514.5	206.0	15.3	16.9	≤0.5	2.1	3.13	13.76	54.93
Sunset Lake	1996	August	7.30	1464.2	137.7	1388.8	613.7	16.9	16.0	0.89	≤0.5	2.99	9.14	224.59
	2002	August	8.28	1488.3	182.5	1274.3	654.7	53.8	26.1	3.49	1.7	4.99	10.47	424.81
Surprise Lake	1996	August	6.36	49.9	5.4	16.9	6.2	11.2	3.9	≤0.5	≤0.5	1.55	≤0.5	6.02
	2002	September	6.56	43.0	6.8	34.5	12.0	14.5	6.0	0.94	≤0.5	3.78	4.44	8.20
Trapper Lake	1985	September	7.85	441.2	49.3	298.8	94.0	62.6	35.6	≤0.5	3.9	8.70	2.10	38.70
	1996	August	6.32	260.6	22.6	178.7	55.6	59.0	27.6	1.28	≤0.5	14.64	2.66	21.88
	1999	October	7.5	326.7	39.3	225.0	69.9	50.9	30.6	≤0.5	≤0.5	4.8	3.5	33.1
	2002	July	7.324	219.6	26.7	155.14	47.727	38.756	26.088	≤0.5	235.83	8.152	4.661	22.84
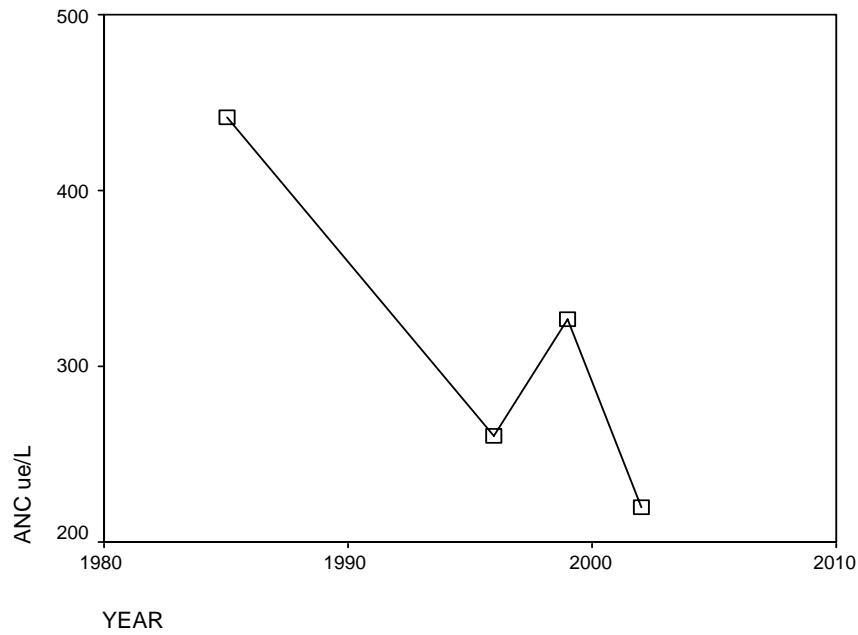
Figure 5. Acid Neutralizing Capacity (ANC) trends in Trapper Lake between 1985 and 2002 based on data from *Landers et al.*, 1985; *Williams and Tonnessen*, 1997; *Clow et al.,* 1999 and the 2002 survey.
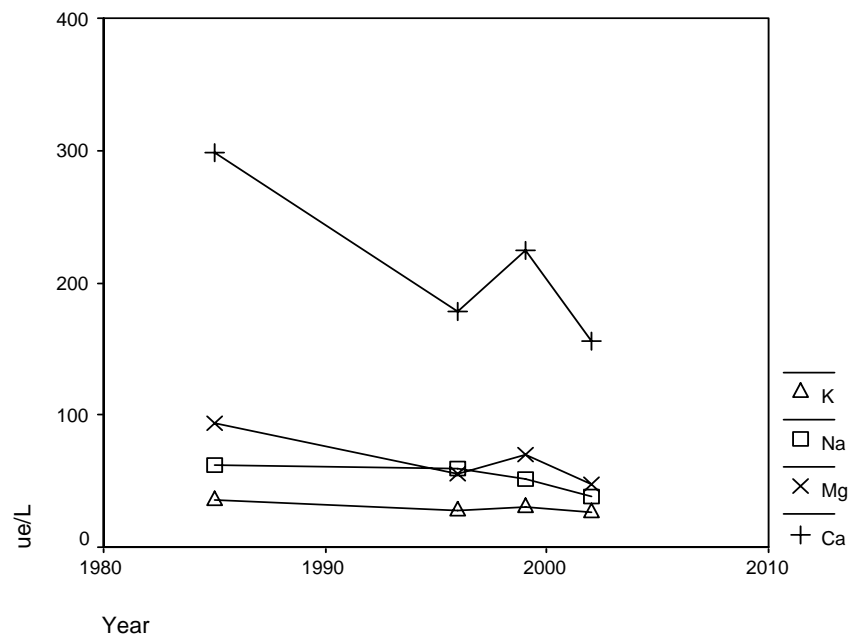
Figure 6. Cation trends in Trapper Lake between 1985 and 2002 based on data from *Landers et al.*, 1985; *Williams and Tonnessen*, 1997; *Clow et al.,* 1999 and the 2002 survey.

Unlike cation trends, anion trends in Trapper Lake are variable. Nitrate concentrations have increased since 1985 with most of the increase occurring after 1999 (Figure 7). Variations of Cl^- and F^- concentrations are minimal – with most F^- values falling below detection limits in 1996 and 1999. Sulfate concentrations decreased between 1985 and 1996 and increased between 1996 and 1999. On average, SO_4^{2-} concentrations have decreased since 1985 (Figure 7).
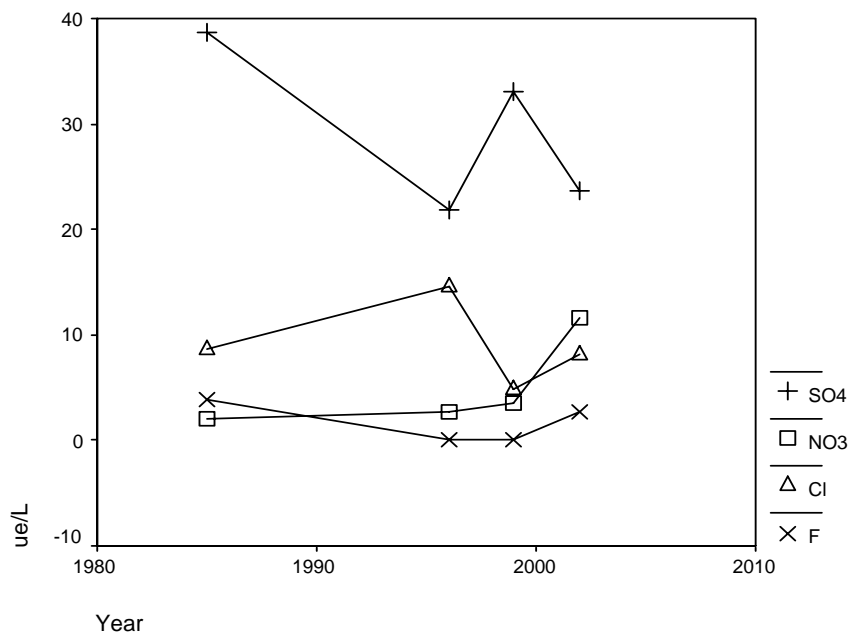
Figure 7. Anion trends in Trapper Lake between 1985 and 2002 based on data from *Landers et al*, 1985; *Williams and Tonnessen,* 1997; *Clow et al.,* 1999 and the 2002 survey.

Field-filtered vs. Laboratory-filtered Samples

Differences between field-filtered and laboratory-filtered samples were tested for independence using the Wilcoxon Signed Ranks Test and the Paired t-Test (Table 9). The Wilcoxon Signed Ranks Test showed statistically significant differences for F^- at $p \leq$ 0.05, with laboratory-filtered values higher than the field filtered values, and for pH ($p \leq$ 0.05), which was slightly higher in laboratory-filtered samples than in field-filtered

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samples. Results of the paired t-Test for these data failed to show significant differences. Since F^- concentrations have little effect on the chemistry of the sampled waterbodies, and values were below detection limits for a majority of the samples, the test results were disregarded. Discrepancies in the pH between field- and laboratory-filtered values can be attributed to processing delays and the variable nature of pH.

Table 9. P-values for Wilcoxon Signed Ranks Test and Paired t-Test for the differences between field-filtered and laboratory-filtered samples.

Solute	Wilcoxon	Paired t-test
ANC	0.345	0.232
Alk	0.586	0.908
Cond	0.042	0.123
pH	0.028	0.021
Ca	0.420	0.414
Na	0.185	0.168
Mg	0.372	0.452
K	0.507	0.705
F	0.043	0.048
Cl	0.008	0.137
NO3	0.346	0.296
SO4	0.257	0.392
NH4	0.735	0.572

Lake Water Chemistry Modeling

Basin Characterization

Topographic characteristics in the Teton Range are characteristic of glacial environments. Basin physical characteristics for lakes sampled by *Williams and Tonnessen* (1997) in 1996 and in the present survey reflect the variation in alpine and subalpine environments in GRTE (Table 10). Median slopes ranged from 16° in Alaska Basin Lake to 38° at Lake of the Crags. Percentages of slopes ≥ 30° (steep slopes) ranged from 8% at Sunset Lake to 80% in Lake of the Crags. Study lakes residing in

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basins with high percentages of steep slopes were located in glacial cirques or tarns and had surface areas ranging from 1 ha to 6 ha.

The geology of the study basins was dominated by granitic rock and young debris. Percentages of granite ranged from 0.01 (Sunset Lake) to 83.2 (Surprise Lake) and young debris comprised 6% to 60% of the study basins.

Study basins were mostly sparsely vegetated, except for Alaska Basin Lake, Granite Basin Lake, and Sunset Lake, which are located east of the divide in the Jedediah Smith Wilderness Area and have a high proportion of alpine tundra (Table 10). Bradley Lake and Trapper Lake had substantial vegetation adjacent to each shore, but the basins draining into each lake were largely unvegetated.

Most of the study basins were located in glacial cirques and tarns. This is reflected in the correlations among basin characteristics, which is typical of recently glaciated terrain (Table 11). Median slope was highly correlated with steep slope, sedimentary rock, and unvegetated terrain. Limestone was negatively correlated with steep slope and positively correlated with sedimentary rock, and old debris was negatively correlated with median elevation.

Table 10. Physical characteristics of basins sampled in 1996 and 2002. Geology and vegetation classes are expressed as a percentage of basin area.

NAME	Topography				Lake Morphology			Geology Classes								Vegetation Classes			
	Median Slope (degrees)	Median Elevation (meters)	Basin Area (ha)	% Basin w/ Slope >= 30 Degrees	Elevation	Surface Area (ha)	LA/WA	Diabasic Dike	Granite	Limestone	Metamorphic	Debris - Old	Debris - Young	Peat	Sedimentary - Non-Limestone	Forest	Sub-Alpine Meadow	Tundra	Unvegetated
Alaska Basin Lake	16.07	3019	460.81	14.65	2917	0.70	0.002		21.45	3.37	53.03		17.02	1.99	2.44	10.54	16.20	70.39	2.87
Amphitheater Lake	30.23	3122	48.14	57.99	2956	1.87	0.039		80.88				15.25			9.95			86.11
Bradley Lake	32.20	2955	1184.35	63.11	2140	27.11	0.023	0.57	35.19		21.39		24.08			20.76	3.95		72.74
Cirque Lake	24.75	3074	209.95	46.91	2928	24.93	0.119		8.01		54.05	10.60	20.08				0.04	8.02	79.85
Delta Lake	38.99	3223	430.74	77.18	2747	2.77	0.006	0.05	53.19		16.52		18.06			3.75	0.33		95.25
Granite Basin Lake	17.54	2992	147.85	14.43	2776	2.51	0.017		4.30		77.34	4.92	10.63		0.82	31.22	38.78		29.99
Holly Lake	24.50	3024	94.26	42.23	2868	2.89	0.031		40.78		43.23	0.04	12.90			8.71		34.48	53.71
Lake of the Crags	38.54	3127	201.73	80.10	2915	4.47	0.022		21.90		51.50		21.65						97.01
Lake Solitude	25.31	2969	299.82	46.02	2754	15.08	0.050		17.83		42.39		32.52		0.60			25.40	69.43
Mica Lake	29.17	3051	124.49	53.05	2913	3.85	0.031		46.61				37.02						96.82
Mink Lake	25.81	2921	96.04	48.59	2720	3.83	0.040				71.34	1.33	17.03		0.30	1.44	3.50	4.62	85.99
Rimrock Lake	30.63	3180	80.79	63.41	3022	6.46	0.080			4.54	48.02		5.87		28.27			38.90	53.08
Snowdrift Lake	24.60	3204	295.83	43.08	3050	22.18	0.075		0.01	6.67	37.40		40.68		2.31	5.44			86.43
South Leigh Lake	21.66	2908	473.15	29.61	2871	4.71	0.010	0.40	71.65		6.31	3.36	13.68	0.31	2.48	44.54	12.83		42.64
Sunset Lake	18.66	3027	22.48	7.90	2942	1.07	0.047		11.84	18.58			59.90		5.43		9.26	90.74	
Surprise Lake	27.96	3083	59.07	52.22	2915	0.94	0.016		83.23				12.64			21.41			73.93
Trapper Lake	28.69	2510	333.35	54.28	2108	1.36	0.004	2.28			69.78	11.78	14.94	0.75		49.72	24.98		24.88

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Table 11. Spearman correlation coefficients for basin physical characteristics.

	Median Slope (degrees)	Median Elevation	Basin Area (ha)	% Basin w/ Slope >= 30 Degrees	Lake Elevation	Lake Surface Area (ha)	LA/WA	Diabasic Dike	Granite	Limestone	Metamorphic	Debris - Old	Debris - Young	Peat	Sedimentary - Non-Limestone	Forest	Sub-Alpine Meadow	Tundra	Unvegetated
Median Slope																			
Median Elevation	0.23																		
Basin Area (ha)	0.20	-0.39																	
% Steep Slope	0.97*	0.15	0.36																
Lake Elevation	-0.38	0.61†	-0.59†	-0.44															
Lake Area (ha)	0.38	-0.04	0.30	0.32	-0.24														
LA/WA	-0.03	0.24	-0.46	-0.20	0.47	0.55													
Diabasic Dike	0.60†	-0.35	0.62†	0.66†	-0.76*	0.17	-0.48												
Granite	0.48	0.51	-0.26	0.45	0.13	-0.12	-0.13	-0.17											
Limestone	-0.56	0.21	-0.12	-0.60†	0.64†	-0.23	0.28	-0.33	-0.43										
Metamorphic	-0.48	-0.61†	0.52	-0.31	-0.42	0.02†	-0.37	0.20	-0.65†	-0.07									
Debris - Old	0.04	-0.72*	0.34	0.10	-0.67†	0.17	-0.36	0.61†	-0.42	-0.39	0.61†								
Debris - Young	0.11	0.20	0.04†	-0.01	0.28	0.39	0.60†	-0.06	-0.21	0.58†	-0.42	-0.46							
Peat	-0.30	-0.43	0.46	-0.10	-0.15	-0.53	-0.65†	0.29	-0.36	0.20	0.52	0.22	-0.18						
Sedimentary	-0.78*	-0.05	-0.05	-0.80*	0.48	-0.22	0.26†	-0.46	-0.58†	0.84*	0.23	-0.30	0.39	0.19					
Forest	-0.06	-0.41	0.24	0.09	-0.30	-0.33	-0.64†	0.38	-0.14	-0.31	0.49	0.67†	-0.77*	0.43	-0.24				
Meadow	-0.32	-0.53	0.38	-0.25	-0.38	-0.38	-0.58†	0.42	-0.55	0.17	0.56	0.54	-0.22	0.55	0.35	0.50			
Tundra	-0.65†	-0.20	-0.16	-0.67†	0.24	-0.32	0.11	-0.39	-0.17	0.54	0.11	-0.23	0.25	0.23	0.59†	-0.39	0.10		
Unvegetated	0.69*	0.64†	0.01	0.64†	0.08	0.52	0.25	0.01	0.53	-0.37	-0.51	-0.36	0.18	-0.52	-0.54	-0.30	-0.66†	-0.67†	

*Correlation is significant at the .01 level (2-tailed).

†Correlation is significant at the .05 level (2-tailed).

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Correlations Between Lake Chemistry and Basin Characteristics

The relationship between physical characteristics and water chemistry is complex. The type of rock present in the basin is just as important as the slope of the watershed and the amount of vegetation. The strongest and most numerous correlations were in the granite, limestone, and young debris categories (Table 12). Granite was negatively correlated ($p \leq 0.01$) with pH, ANC, conductivity, Ca^{2+}, Mg^{2+}, and SO_4^{2-}. Granite was less significantly ($p \leq 0.05$) correlated with F^- and Ca/Na ratios. Although present in only four study basins, limestone had a strong ($p \leq 0.01$) positive correlation with Mg^{2+}. Significant ($p \leq 0.05$) positive correlations also existed between limestone and pH, ANC, conductivity, SO_4^{2-}, and Ca/Na ratios. Strong ($p \leq 0.01$) positive correlations occurred between young debris and NO_3^- and Ca/Na ratios (Figure 8a). Additionally, conductivity, Ca^{2+}, Mg^{2+}, and pH (Figure 8b) were significantly correlated to young debris ($p \leq 0.05$). Chemical weathering is enhanced in study basins with young debris, which explains the relationship between young debris and major cations, NO_3^-, and pH.

Table 12. Spearman correlation coefficients for relationships between basin physical characteristics and mean lake water concentrations.

	Median Slope (degrees)	Median Elevation (meters)	Diabasic Dike	Granite	Limestone	Metamorphic	Debris - Old	Debris - Young	Sedimentary - Non-Limestone	Forest	Unvegetated
pH	-0.31	-0.42	0.16	-0.78*	0.62†	0.23	0.22	0.61†	0.53	-0.18	-0.47
ANC	-0.43	-0.45	0.11	-0.80*	0.67†	0.30	0.27	0.49	0.59†	-0.04	-0.57†
Conductivity	-0.27	-0.31	0.25	-0.71*	0.67†	0.22	0.21	0.60†	0.48	-0.18	-0.44
Ca	-0.25	-0.37	0.15	-0.77*	0.53	0.20	0.20	0.64†	0.45	-0.31	-0.37
Mg	-0.41	-0.33	0.08	-0.75*	0.76*	0.24	0.07	0.65†	0.66†	-0.23	-0.48
Na	-0.29	-0.44	0.39	-0.50	0.39	0.32	0.60†	-0.06	0.19	0.45	-0.67†
K	0.12	-0.03	0.50	-0.40	0.48	-0.09	0.18	0.53	0.10	-0.16	-0.15
NH$_4$	0.02	-0.24	-0.14	0.29	0.15	-0.37	-0.20	0.37	0.09	-0.25	-0.12
F	-0.30	-0.65†	0.09	-0.59†	-0.17	0.64†	0.59†	-0.12	0.11	0.09	-0.40
Cl	0.52†	-0.02	0.76*	0.02	0.02	-0.22	0.28	0.08	-0.33	0.25	-0.06
NO$_3$	0.47	0.36	0.25	-0.08	0.25	-0.41	-0.42	0.80*	0.07	-0.65†	0.45
SO$_4$	-0.38	-0.32	0.08	-0.69*	0.58†	0.26	0.25	0.50	0.44	-0.23	-0.45
Ca/Na	-0.17	0.06	-0.04	-0.57†	0.58†	-0.01	-0.30	0.81*	0.58†	-0.65†	-0.05

*Correlation is significant at the .01 level (2-tailed).

†Correlation is significant at the .05 level (2-tailed).
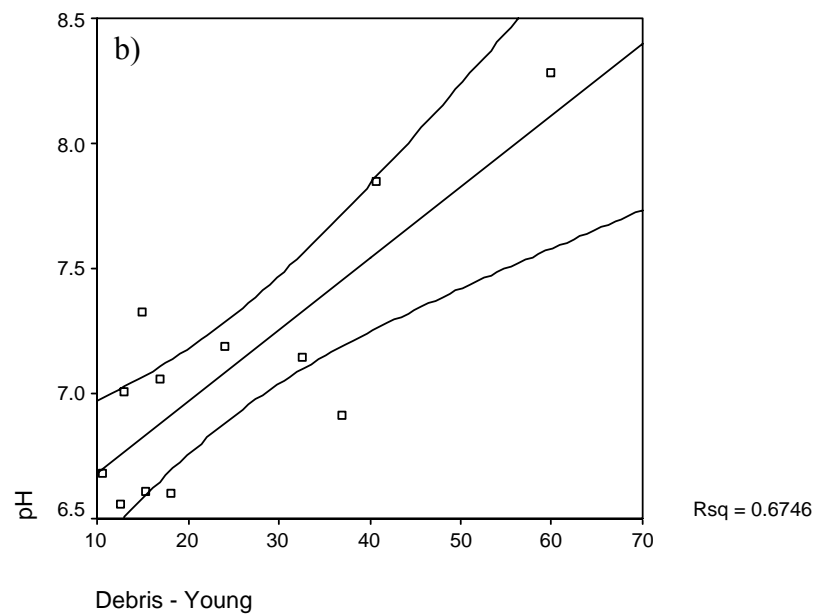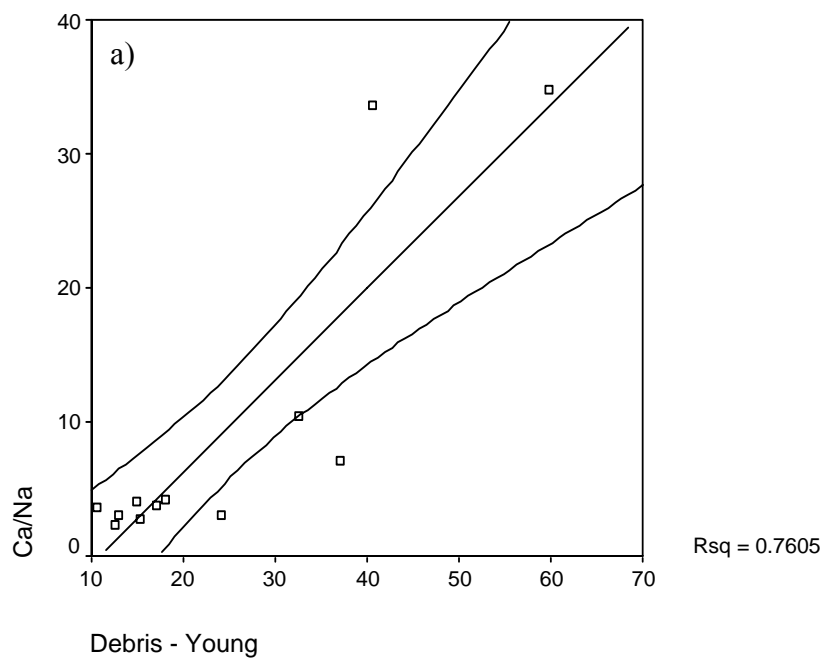
Figure 8 - Relationship between percentage of basin area with young debris and (a) mean Ca/Na ratios and (b) mean pH. Prediction lines of 95% mean confidence intervals are displayed.

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Prediction of Solute Concentrations: Multiple Linear Regression

Multiple linear regression was used to predict solute concentrations and as a method of constructing interactions among solutes and basin characteristics. The regression models were developed using data collected in 1996 by *Williams and Tonnessen* at GRTE. A total of 17 lakes were sampled. The variables for the model were selected from the physical characteristics listed in Table 10. Chloride was removed from the model because of lack of fit; and DOC, total phosphorous, and total nitrogen were removed from the model because no data were available for 1996. Likewise, a regression model is not available for NH_4^+ because a majority of the NH_4^+ values in 1996 and 2002 were below detection limits. Cirque Lake, Lake of the Crags, Mink Lake, South Leigh Lake, and Rimrock Lake had not been surveyed in 2002. Therefore, these basins served as an excellent test of the model.

The complexity of interactions between modeled parameters is illustrated in the coefficients that resulted from the step-wise multiple linear regression (Table 13). Although correlations were strong for many of the variables, the relationships were not always linear, and transformations were necessary in order to adequately fit the data. Granite and limestone served as the best predictors for solute concentrations with young debris and steep slopes playing significant roles for most solutes – especially major base cations, and pH.

Table 13. Results of multiple linear regression analysis of relationships between lake water chemistry and basin physical parameters.

Variable	Transform	Constant	Median Slope	Median Elevation	% Slope >= 30 Degrees	Limestone	Granite	Sedimentary	Metamorphic	Diabasic Dike	Young Debris	Tundra	Peat	Forest	Meadow	p-value	R^2
ANC	Log e	5.085				0.135	-1.64E-02									0.000	0.865
Cond.	Log e	2.203			1.77E-02	0.168	-1.59E-02									0.000	0.93
Ca^{2+}	Log e	4.73				0.143	-1.35E-02									0.000	0.855
Ca/Na	-	-7.491									0.686					0.000	0.737
Mg^{2+}	Log e	4.055				0.166	-2.14E-02							1.55E-02	-3.79E-02	0.000	0.974
Na^+	-	139.577		-4.05E-02		1.00E+00										0.004	0.636
K^+	-	8.13E-01			1.40E-01	1.32E+00				7.943						0.000	0.912
pH	-	7.369				6.87E-02	-1.19E-02							1.21E-02	-2.58E-02	0.000	0.967
NO_3^-	-	-16.991	7.07E-01								2.58E-01					0.001	0.737
SO_4^{2-}	Square root	3.95E+00				1.355		-1.699								0.000	0.947
F	-	8.83E-03							6.03E-02			2.41E-02	-2.40E+00			0.002	0.776

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Generally, the regression models for major cations showed good agreement between observed and predicted values (Figure 9 *b-f*). The strongest model in this group was the Mg^{2+} regression model. Limestone, granite, forest, and sub-alpine meadow were the best predictors for Mg^{2+} and accounted for 97% of the variance in concentrations. The weakest model was the Na^+ regression model (Adjusted $R^2 = 0.636$), which relied on limestone and median elevation as predictors. Limestone – by itself – would not be the best chemical predictor for basins in the GRTE study area because only four basins had limestone deposits. In this study, granite was present in every limestone basin except Rimrock Lake, which had a high percentage of metamorphic rock.

The regression model for ANC (Figure 9*a*) served as an excellent predictor for buffering capacity. Once again, limestone and granite were the predictors for the ANC model and explained 86.5% of the variance.

Anion models were not as successful as cation models. Chloride and F^- models were not available for reasons mentioned earlier – concentrations below detection limits and lack of fitness. Since neither solute is acidic, they contribute no net negative alkalinity. For this reason, the absence of Cl^- and F^- regression equations is not a concern. The regression model for NO_3^- overestimated concentrations (Figure 10*g*). This over-prediction may be caused by the incorporation of multiple seasonal samples in 2002 as opposed to one grab sample in 1996. Seasonal NO_3^- fluctuations have been observed in study lakes in GRTE, especially late season fluxes in glacier-fed lakes (discussed later). The discrepancy between years would definitely have an effect on bias within the model.

Conductivity and pH were consistently over-predicted (Figure 10*i-j*). The one

solute affected by field filtering appeared to be pH and lack of fit may be a result of poor

field or laboratory techniques. However, it seems more likely that the variations in pH

concentrations are correlated to the variations in model parameters, specifically granite

and sub-alpine meadow.
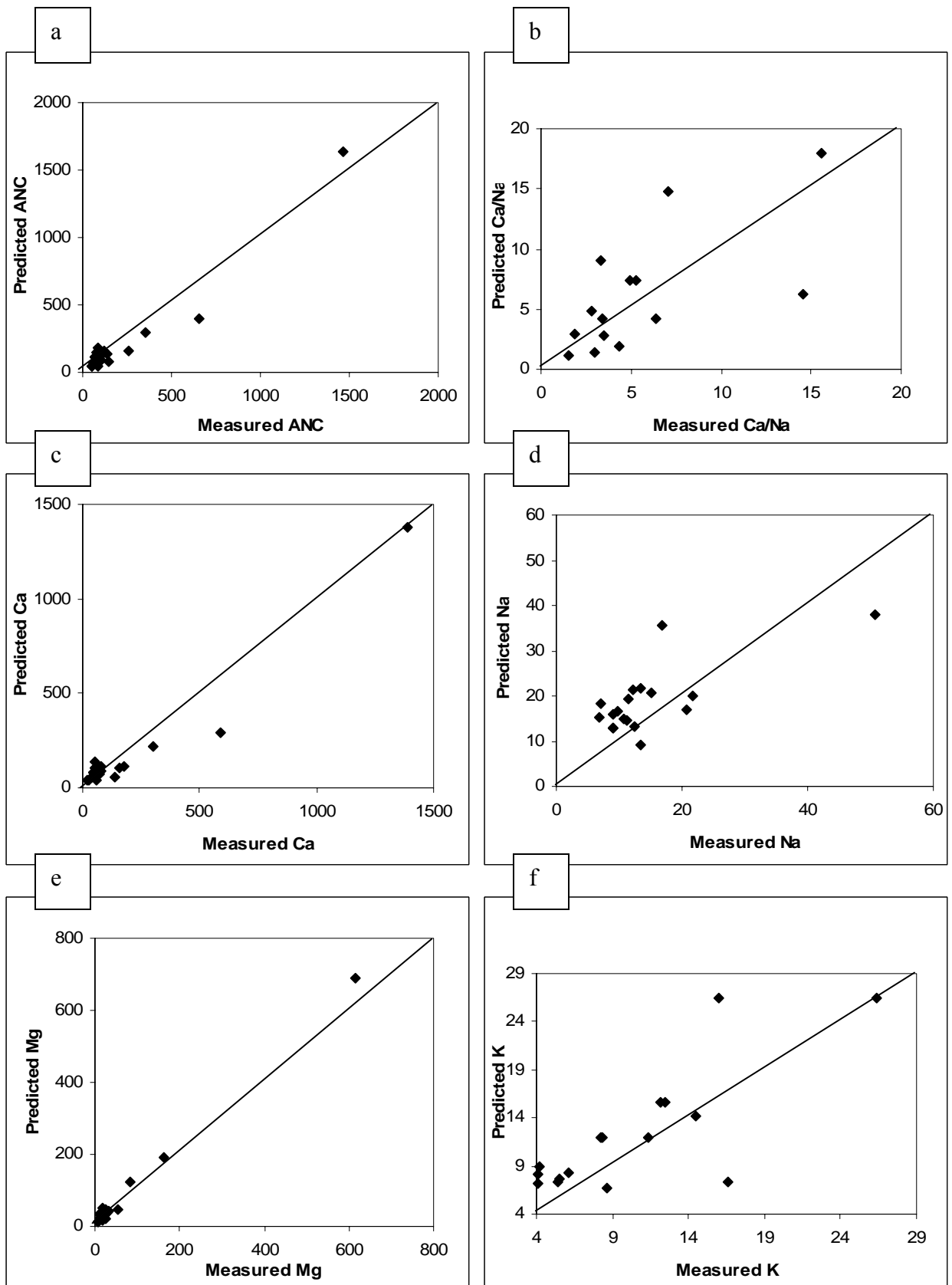
Figure 9. Relations between measured and predicted mean lake concentrations of (a) ANC, (h) Ca/NA ratios, (i) Ca^{2+}, (j)Na$^+$, (k) Mg^{2+}, and (l) K$^+$ for *Williams and Tonnessen* [1997].
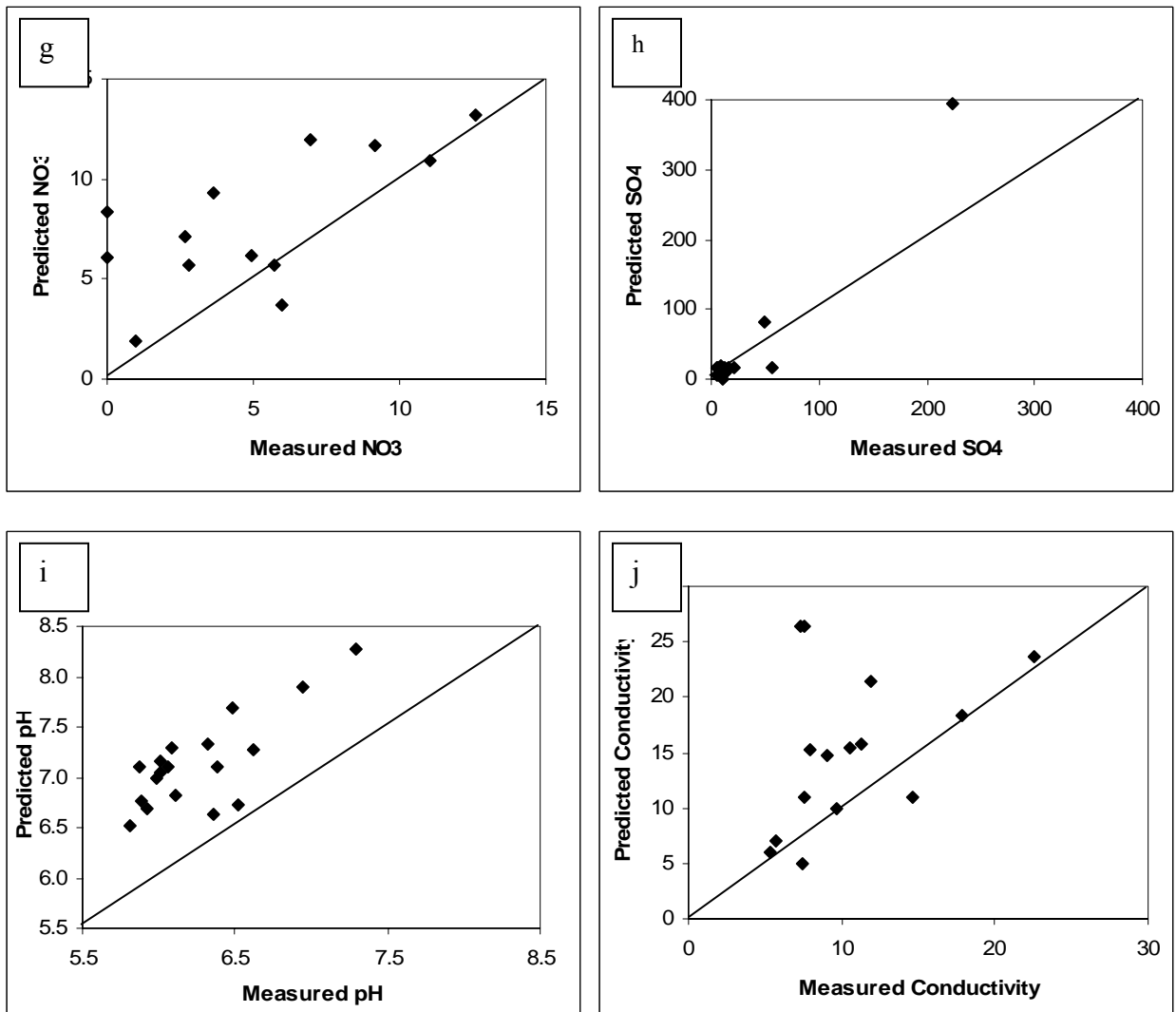
Figure 10. Relations between measured and predicted mean lake concentrations of (g) NO_3^-, (h) SO_4^{2-} ratios, (i) pH, and (j) conductivity, for Williams and Tonnessen [1997].

Discriminant Analysis

Discriminant analysis was used to identify the features responsible for splitting the data into categories of sensitivity. Categories reflected the common assumption that sensitive lakes have concentrations of ANC < 100μeq L^{-1}. Therefore, groups were coded based on their relative susceptibility to acidification: chronic (ANC < 50μeq L^{-1}),

episodic (ANC < 100μeq L^{-1}), or not susceptible (ANC >100μeqL$^{-)}$. The same data that were employed in the regression analysis were used in this categorical analysis, and granite, limestone, and young debris were the variables.

The variable that best defined group membership was granite (Figure 11). After analysis of the regression equations discussed in the previous section, it is not surprising that granite was the best variable to maximize the differences between ANC categories. On average, lakes with ANC concentrations < 50μeq L^{-1} were in basins that had total granite compositions ranging from 60% to 80%; lakes with 50μeq L^{-1}<ANC < 100μeqL^{-1} had granite deposits comprising 20% to 50% of the basin; and >100μeq L^{-1} had less than 20% granite in the basin.
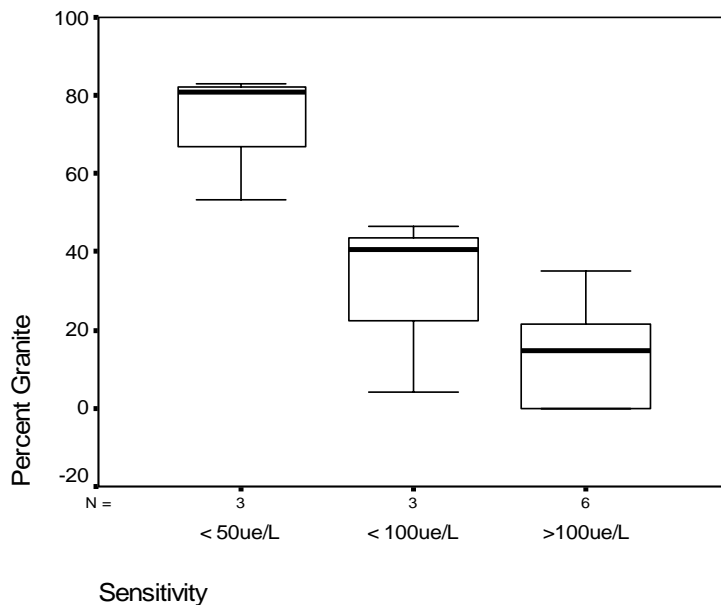
Figure 11. Boxplot of percent granite in study basins relative to acidification susceptibility.

Discussion

Atmospheric Deposition at Grand Teton National Park

Air quality in the Rocky Mountains and northern Great Plains region is considerably better than in most other areas of the continental United States. This is primarily due to the absence of high levels of fossil fuel combustion associated with metropolitan areas and because atmospheric conditions are not highly conducive to the formation and accumulation of ozone (*Peterson and Sullivan,* 1998). However, the rapidly increasing population of the region, with the resultant increase in industrial and agricultural activity, means that deteriorating air quality and consequent atmospheric deposition impacts are an ongoing concern.

The NADP monitoring station at Tower Junction in Yellowstone National Park supplied the deposition data for the GRTE study area. The observed long-term decline in SO_4^{2-} concentrations at Tower Junction is consistent with a region-wide decline in SO_4 in atmospheric deposition (*Clow et al.,* 2003). The decline is probably due to increased regulation of emissions from coal-fired power plants and a decline in the number of metal smelters in the region.

In contrast, nitrogen deposition has increased over most of the western United States since the 1980s (*Fenn et al.,* 2003). The primary sources are transportation, agriculture, and industry. The highest N-deposition rates are likely to be downwind from major urban areas, but high deposition rates may also occur downwind from agricultural sources (*Tonnessen et al.,* 2003). The absence of a trend in NO_3^- deposition at the Tower Junction site suggests that regional air quality impacts due to vehicular emissions have remained relatively similar over the last 10 years. The large increase in NH_4^+ observed at

the Tower Junction site is probably due to a regional increase in the use of ammonium-based fertilizers on agricultural soils. Taken in combination, the data from Tower Junction indicate an overall increase in the potential for acidification of GRTE waters by nitrogen-based compounds in atmospheric deposition. However, since GRTE does not have its own NADP station, such an inference remains tentative. A similar lack of NADP stations has hampered efforts to monitor atmospheric deposition status and trends in high-elevation watersheds throughout the western U.S. (*Nanus et al.,* 2003).

The increased sensitivity of high elevation watersheds to acidification is accentuated by the inputs of wet deposition as snow. The decrease in NO_3^- and SO_4^{2-} concentrations observed at Garnet Canyon and Rendezvous Mountain between 2001 and 2002, and the fact that these values are lower than the 1993-2000 averages, may be due to interannual differences in precipitation. The 2002 snowfall season in the Teton Range was much drier than in previous years, and snow depths were below the 1993-2000 average (*Ingersoll et al.,* 2004). Likewise, precipitation from rain decreased from the previous year and was part of a general decline since 1999 (*WRCC,* 2002). Interannual differences in precipitation may mask trends for wet deposition in snow.

Water Chemistry of High Elevation Lakes in Grand Teton National Park

The ability of a landscape to neutralize acidity is reflected in the chemistry of that landscapes waterbodies (*Stumm and Schnoor,* 1985). Chemical weathering – especially in abraded areas - can largely account for lake chemistry (*Stauffer,* 1990), and is the major acid neutralizing process in most mountain ecosystems. Weathering results in the neutralization of H^+ and the production of soluble base cations, aluminum and silica (H_4SiO_4). Weathering also buffers surface waters (*Johnson,* 1984) and supplies nutrient cations to the soil (*Likens et al.,* 1977). Chemical weathering rates are temperature and moisture dependent, so climate is a primary control. In the cool, dry climate typical of high elevation watersheds in semi-arid western North America, weathering rates are relatively low. Consequently, ion concentrations in lakes and streams are very low, and vulnerability to acidification is high. However, differences in basin geologic, topographic and vegetation characteristics can result in variability among high elevation watersheds in their relative sensitivity to acidification (*Clow and Sueker,* 2000; *Turk and Campbell,* 1987). For example, acid-reactive sinks in the form of sedimentary materials increase the reactivity of alpine systems (*Johnson,* 1984). The results of the present study indicate that two factors – the bedrock geology and the amount of young debris – are important controls on lake water chemistry and sensitivity to acidification. In addition, the presence of a glacier within the watershed appears to affect lake water chemistry by providing an additional source of solutes or by adding complexity to the flow path of catchment water.

Effect of Bedrock Geology

Carbonate rock dissolution is responsible for the bulk of the alkalinity in North American waters, with the remainder originating from calcium and magnesium silicates and alumino-silicates (*Johnson,* 1984). Limestone is present in parts of the GRTE study area, and lakes with limestone bedrock appear to have sufficient buffering capacity as a result of carbonate weathering. The three basins with limestone bedrock, Snowdrift Lake (Figure 12 and 13), Sunset Lake, and Alaska Basin Lake, had ANC values of 676.2, 1488.3, and 110.3μeq L^{-1}, respectively, for a mean of 758.3 μeq L^{-1}. In contrast, lakes without limestone bedrock had ANC values ranging from 42.5 to 219.6 μeq L^{-1} with a mean of 89.3 μeq L^{-1}. The highest ANC value in a basin without limestone was in Trapper Lake, which also had much higher Ca^{2+} and Mg^{2+} concentrations than any other non-limestone basin. The source of the increased Ca^{2+} and Mg^{2+} in Trapper Lake is unknown, but it may be due to a localized occurrence of limestone or other calcareous bedrock material not shown on the geological maps used for this study.

Effect of Young Debris

Physical weathering increases chemical weathering rates by increasing the surface area available for chemical reactions between bedrock material and percolating water. In glaciated landscapes, the grinding action of the glacier creates rock debris that is more chemically reactive than the bedrock from which it is derived. Freeze-thaw weathering of bedrock outcrops creates talus slopes that are similarly more reactive, which is particularly effective in mountain environments with large areas of exposed bedrock and strong seasonal temperature differences. Many of the basins included in this study

contain young (Holocene) debris created by a combination of glacial activity and physical weathering (Table 10).

The increased weathering associated with the presence of rock debris can either help or hinder a waterbody's buffering capacity, depending on the bedrock characteristics. For example, in a 1985 study of GRTE lakes, *Gulley and Parker* (1986) noted that the only significant difference in solute chemistry among survey lakes was the elevated Mg^{2+} in Schoolroom Lake. Schoolroom Lake is located below Schoolroom Glacier, which is situated on limestone bedrock. Glacial abrasion of the limestone bedrock apparently contributed to the buffering capacity of Schoolroom Lake. However, NO_3^- concentrations in talus contributed to NO_3^- in stream water in the Green Lakes Valley of the Colorado Front Range (*Williams et al.,* 1997). Talus slopes contain areas of sand, clay, and organic material that sometimes support patches of tundra-like vegetation, which may affect the N cycle. *Williams et al.* hypothesized that the increased surface area of talus, and the increased residence time of water flowing through talus fields, results in increased NO_3^- concentrations in surface waters. Similar conclusions were made in the Andrews Creek watershed in 2002 (*Sickman et al.,* 2003). In situations where talus occupies a significant proportion of a watershed, N-enrichment may be a greater problem for water quality than acidification from atmospheric deposition.

The results of the present study suggest that both mechanisms – the acid neutralizing effect of limestone bedrock, and high nitrate from talus fields – affect the basin water chemistry at sites in GRTE. The three basins with limestone bedrock (Alaska Basin, Snowdrift, and Sunset Lakes) also have high proportions of young debris, and ANC values are relatively high, suggesting that a similar mechanism to that proposed by

Gulley and Parker (1986) for Schoolroom Lake is also controlling the ANC in these lakes. However, watersheds without limestone but with a large amount of young debris, such as Lake Solitude and Mica Lake, have some of the lowest ANC values. Snowpack studies have shown that the neutralizing effect of Ca^{2+} is sometimes overcome by increases in NO_3^- and SO_4^{2-} (*Mast et al.,* 2001), which is illustrated by lower pH values (*Turk et al.,* 2001). The results of the present study indicate that, in watersheds without limestone, high NO_3^- increases the sensitivity to acidification.

Past studies have shown that Ca/Na ratios increase with increasing physical disturbance and reach a maximum in glaciated areas (*Henrikson,* 1980; *Stauffer,* 1990). In GRTE, the highest Ca/Na ratios were recorded at Snowdrift and Sunset Lakes (59 and 82, respectively). Although both basins had large percentages of young debris – Sunset Lake with 60% and Snowdrift Lake with 40% - they also resided in areas underlain by limestone. The relationship between Ca/Na ratios and juvenility observed in other areas did not apply in glacier-fed lakes in granitic basins. For example, Mica Lake had a Ca/Na ratio of approximately 16 and was 37% young debris (comparable to Snowdrift Lake) but lacked limestone deposits (47% granite, instead). These results suggest that Ca/Na ratios in GRTE lakes are more dependent on bedrock geology than on the presence of juvenile terrane with large amounts of young debris.

Figure 12. The Wall – primarily limestone - west of Snowdrift Lake as seen from Avalanche Divide

Figure 13. Snowdrift Lake as seen from Avalanche Divide

Effect of Glaciers

Glacier dissolution in GRTE study basins may be responsible for seasonal

increases in NO_3^- concentrations in glacier-fed lakes (Figure 14), which in turn decreases

the ANC. Delta Lake (Figure 15 and 16) – a glacier-fed lake – had a mean Ca^{2+}

concentration of $50.9 \mu eqL^{-1}$ but NO_3^- and SO_4^{2-} concentrations were high (20.1 µeq L^{-1}

and 12.3 µeq L^{-1}, respectively), resulting in an ANC value of 42.5 µeq L^{-1}. In contrast,

Alaska Basin Lake had a mean Ca^{2+} concentration of $68.5 \mu eq\ L^{-1}$, a mean NO_3^-

concentration of 0.4 µeq L^{-1}, and a mean SO_4^{2-} concentration of 13.7 µeq L^{-1}. The ANC

value for this lake was 110.3 µeq L^{-1}.
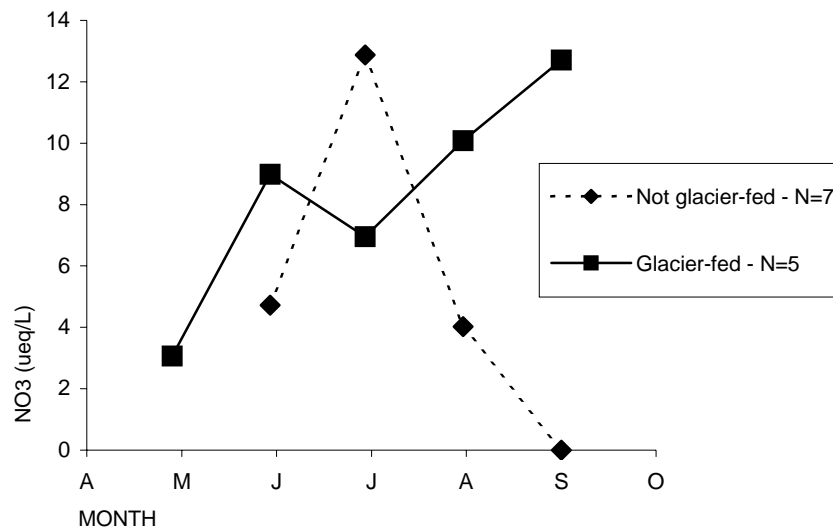
Figure 14. Relations between glacier-fed lakes and seasonal mean NO_3^- concentrations.

Research on subglacial hydrological systems is limited. Current studies have

shown that chemical processes in glacial environments are not inhibited by limited soils

and vegetation and low temperatures as was originally thought, but are enhanced by the

increased physical weathering in glacial areas (*Brown*, 2002). The contributions of

snowmelt and icemelt to the chemical composition of surface waters in glacially-fed

systems is directly related to the routing of these waters along different flowpaths

(*Tranter et al.,* 1997; *Mitchell et al.,* 2001). Studies conducted at the base of Haut

Glacier d' Arolla in Switzerland suggested that high NO_3^- concentrations in boreholes

were representative of snowmelt waters draining through a subglacial hydrologic system – a delayed flow. Therefore, the chemistry of waters draining through alpine glaciers is dependent on flow path and the long-term storage of snowpack (*Tranter et al.,* 1997).

Figure 15. Delta Lake

Figure 16. The toe and glacial moraine of Teton Glacier just above Delta Lake

Long Term Trends in Lake Water Chemistry

A lack of historical data from most GRTE lakes precluded detailed analysis of temporal trends. However, data from Trapper Lake, the only lake included in three different surveys over the last 20 years indicated a decline in ANC. Differences in solute concentrations could be attributed to changes in atmospheric deposition or differences in precipitation prior to or during sampling. The peaks in solute concentrations apparent during the 1999 survey were probably due to increased rainfall during the sample period (*Clow et al.,* 2003).

Predicting Lake Water Chemistry Based on Watershed Characteristics

The effects of watershed characteristics, such as topography, geology and vegetation, on solute concentrations have been widely studied during the past decade. *Clow and Sueker* (2000) found that the percentage of steep slopes ($\geq 30°$), unvegetated terrain, and young surficial debris were positively correlated to each other. These same features were negatively correlated with concentrations of base cations, silica, and alkalinity and were positively correlated with NO_3^-, acidity, and runoff. In the Mt Zirkel Wilderness Area, Colorado, alkalinity concentrations were correlated with elevation (*Turk and Campbell,* 1987).

Mathematical models for predicting water chemistry in natural waters have been used successfully in mountain catchments. An example is MAGIC (Model of acidification of groundwater in catchments), which was applied to two catchments in GRTE - Surprise and Amphitheater Lakes (Figure 17 and 18) – where the effects of future increases of S and N were estimated over a 50-year projection interval (*Cosby and Sullivan,* 2001). In this study, sensitivities of GRTE study lakes were not deemed as critical as that of lakes in the Sierra Nevada, but they were still considered susceptible to acidification. In other studies, lake altitude was found to be a good predictor of lake alkalinity (*Turk and Adams,* 1983; *Turk and Campbell,* 1987), but in GRTE altitude had very little impact on buffering capacity.

Modeling efforts for the 2002 study in GRTE were centered primarily on multiple linear regression analysis and discriminant analysis. Results of the multiple linear regression models for study lakes were variable, but, on average, showed good agreement with earlier sample data. Granite and limestone served as the best predictors for solute

concentrations with young debris and steep slopes playing significant roles for most

solutes – especially major base cations, and pH.

Figure 17. Surprise Lake

Figure 18. Amphitheater Lake

Calcite weathering was important in many basins in GRTE, which is reflected in the inclusion of limestone as a parameter in many of the regression models. However, the models that only relied on limestone as a predictive parameter were skewed, because very few basins had large limestone deposits. A portion of the overestimation of Ca/Na ratios can probably be attributed to the delicate balance between Ca^{2+}, NO_3^-, and young debris in lakes within GRTE.

Limitations of the models resulting from this study reside in the lack of landscape variability within the GRTE study area. For example, concentrations of base cations for Rimrock Lake were consistently overestimated. The major difference between this basin and the others in the study area was the presence of a large deposit of non-limestone sedimentary rock (28% of total basin area).

In the discriminant analysis, the variable that best defined group membership was granite. Typically, lakes with ANC concentrations < 100 µeq L^{-1} resided in basins that had total granite compositions ranging from 20% to 80%. When the categories were applied to basins sampled in 1996, the analysis held true to the categorization. South Leigh Lake had an ANC concentration of 83.2 µeq L^{-1} and was underlain with granite deposits totaling approximately 72% of the entire basin. Likewise, Lake of the Crags had an ANC of 67 µeq L^{-1} and resided in a basin of 22% granite. Therefore, the results of the discriminate analysis support the regression analysis results in that granite appears to be a suitable predictor for ANC concentrations in GRTE.

Conclusions and Recommendations

Twelve lakes in GRTE, Wyoming, were sampled for major anions and cations, ANC, alkalinity, conductivity, pH, DOC, total P, and total N in order to determine their sensitivity to acidification, and to understand the relationship between basin characteristics and lake water chemistry. The results indicate that many of the high elevation lakes in GRTE are sensitive to acidification, with half of the lakes having ANC concentrations < 100 µeq L^{-1}. Lakes in basins with granitic and/or metamorphic bedrock are the most sensitive to acidification, particularly when the basin contains a high proportion of young debris. Examples include Lake Solitude and Mica Lake (Figure 19). Lakes with basins that are at least partially underlain by limestone bedrock, such as Alaska Basin, Snowdrift and Sunset Lakes, are the least sensitive to acidification, regardless of the presence of young debris. Seasonal melt from remnant glaciers feeding several of the lakes in GRTE may increase sensitivity to acidification by increasing the

nitrogen flux in the late summer. Nutrient enrichment may also play a larger role in water quality than acidification due to increased N deposition. A lack of historical data from most GRTE lakes precluded detailed analysis of temporal trends. However, data from Trapper Lake, the only lake included in three different surveys over the last 20 years indicated a consistent decline in ANC.

Figure 19. Mica Lake (left) and Lake Solitude (right) as seen from Paintbrush Divide

It is recommended that the National Park Service conduct additional monitoring of target lakes in GRTE - specifically, Delta Lake (Figure 15), Surprise Lake and Amphitheater Lake (Figure 17 and 18), and Lake Solitude and Mica Lake (Figure 19) – all of which should be sampled annually. In conjunction with seasonal monitoring of selected lakes, an investigation into the mechanism or source of N and P in glacially fed

lakes (e.g. Delta and Mica Lakes) is suggested. It is also recommended that a NADP monitoring station be installed at GRTE to better monitor the effects of atmospheric deposition within the Park.

APPENDIX A - Solute chemistry for samples analyzed at the Rocky Mountain Research Station, Fort Collins, Colorado

Field Filtered?	Sample Name	Sample Date	pH	ANC	Cond.	H	Ca	Mg	Na	K	NH4	F	Cl	NO3	SO4	Alkalinity
False	Alaska Basin Lake #1 JEDS2-1-1	08/04/02	6.975	110.3	14	0.106	67.315	46.492	17.834	6.701	1.608	121.94	2.454	0.355	13.596	121.94
True	Alaska Basin Lake #1 JEDS2-1-1	08/04/02	6.975	110.3	14	0.106	67.116	46.986	17.704	6.42	2.328	121.77	2.313	0.419	13.721	121.77
False	Alaska Basin Lake #1 JEDS2-1--2	08/04/02	7.06	108.2	13.7	0.087	68.463	47.809	17.704	6.829	2.218	124.5	2.398	0.371	13.534	124.5
True	Alaska Basin Lake #1 JEDS2-1--2	08/04/02	7.06	108.2	13.7	0.087	67.016	47.069	17.834	6.752	1.663	122.37	2.257	0.387	13.658	122.37
False	Amphitheater Lake GRTE4-1-1	06/30/02	6.444	49.3	7.3	0.36	38.124	11.603	13.006	5.576	0.499	52.48	3.075	5.129	7.62	52.48
True	Amphitheater Lake GRTE4-1-1	06/30/02	6.47	47.7	7.4	0.339	36.876	12.014	12.701	5.371	0.61	50.68	3.357	5.225	7.704	50.68
False	Amphitheater Lake GRTE4-1-2	06/30/02	6.439	47.3	7.3	0.364	37.974	11.603	12.788	5.192	0.499	51.88	2.99	5.129	7.558	51.88
True	Amphitheater Lake GRTE4-1-2	06/30/02	6.466	43.4	7.2	0.342	38.573	12.59	13.049	5.09	0.61	53.46	3.046	5.193	7.6	53.46
False	Amphitheater Lake GRTE4-2-1	09/08/02	6.606	40.3	5.8	0.248	32.385	10.368	13.267	5.167	0	52.12	3.075	0	5.996	52.12
True	Amphitheater Lake GRTE4-2-1	09/08/02	6.606	40.3	5.8	0.248	32.236	10.697	13.615	5.167	0.887	52.78	2.877	0	6.059	52.78
False	Amphitheater Lake GRTE4-2-2	09/08/02	6.565	36.9	5.8	0.272	32.385	10.533	14.05	5.371	0	53.32	3.103	0	5.913	53.32
True	Amphitheater Lake GRTE4-2-2	09/08/02	6.565	36.9	5.8	0.272	32.236	10.533	13.354	4.987	1.22	51.82	2.962	0	6.33	51.82
False	Bradley Lake GRTE1-2	05/30/02	7.153	147	18.7	0.07	113.024	38.099	27.708	15.423	1.497	168	5.754	3.097	17.406	168
False	Bradley Lake GRTE1-1	05/30/02	7.192	148.9	19.4	0.064	113.273	37.77	28.491	15.704	0	169.21	5.698	3.032	17.302	169.21
True	Bradley Lake GRTE1-2-1	07/01/02	7.031	108.2	15.3	0.093	84.431	27.978	21.879	13.377	0	117.55	4.654	9.515	15.949	117.55
False	Bradley Lake GRTE1-2-2	07/01/02	7	106.7	15.1	0.1	85.828	27.895	21.749	13.453	0	119.32	4.682	8.935	15.99	119.32
True	Bradley Lake GRTE1-2-2	07/01/02	6.99	104	14.8	0.102	84.581	27.978	21.966	13.479	0	117.41	4.767	9.709	16.115	117.41
False	Bradley Lake GRTE1-2-1	07/01/02	7.019	105.9	15.4	0.096	86.577	28.472	21.227	13.683	0.887	119.85	4.626	9.515	15.97	119.85
False	Bradley Lake GRTE1-3-1	09/08/02	7.027	102.5	14.4	0.094	85.978	26.661	20.357	14.4	2.994	121.62	4.118	6.419	15.241	121.62
True	Bradley Lake GRTE1-3-1	09/08/02	7.027	102.5	14.4	0.094	88.573	28.472	21.053	14.246	0	126.66	4.034	6.306	15.345	126.66
False	Bradley Lake GRTE1-3-2	09/08/02	7.002	104.6	14.2	0.1	86.028	26.99	20.835	14.886	2.827	122.93	4.118	6.451	15.241	122.93
True	Bradley Lake GRTE1-3-2	09/08/02	7.002	104.6	14.2	0.1	86.577	26.497	20.879	14.323	0	122.44	4.062	6.387	15.387	122.44
False	Delta Lake GRTE999-1-1	09/08/02	6.571	42.5	9.2	0.269	49.9	14.647	12.092	13.044	0	52.19	5.246	19.918	12.326	52.19
True	Delta Lake GRTE999-1-1	09/08/02	6.571	42.5	9.2	0.269	50.898	16.128	12.136	13.018	0	55.98	5.021	18.837	12.347	55.98
False	Delta Lake GRTE999-1-2	09/08/02	6.599	38.6	9.2	0.252	50.948	16.375	12.136	12.66	0	54.63	5.105	20.079	12.305	54.63
True	Delta Lake GRTE999-1-2	09/08/02	6.599	38.6	9.2	0.252	49.8	15.635	12.049	12.916	0	56.04	5.021	17.224	12.118	56.04
False	Granite Basin #1 JEDS3-1-1	08/11/02	6.674	86.9	8.7	0.212	51.647	18.515	15.05	2.609	0	73.5	1.749	0	12.576	73.5
True	Granite Basin #1 JEDS3-1-1	08/11/02	6.674	86.9	8.7	0.212	44.162	15.635	14.441	3.095	0	63.17	1.439	0	12.722	63.17
False	Granite Basin #1 JEDS3-1-2	08/11/02	6.682	87.7	8.2	0.208	55.19	15.305	15.094	2.507	0	73.88	1.664	0	12.555	73.88
True	Granite Basin #1 JEDS3-1-2	08/11/02	6.682	87.7	8.2	0.208	43.862	16.046	14.572	2.66	0	62.86	1.41	0.065	12.805	62.86
False	Holly Lake GRTE14-1-1	08/31/02	6.97	89.8	13.2	0.107	79.441	23.287	26.708	10.921	0	111.85	2.877	0	25.63	111.85
True	Holly Lake GRTE14-1-1	08/31/02	6.97	89.8	13.2	0.107	78.892	26.497	25.838	11.126	0	114.99	2.172	0	25.193	114.99
False	Holly Lake GRTE14-1-2	08/31/02	7.006	96.7	13.3	0.099	79.042	25.427	25.925	10.921	0.832	113.15	2.539	0	25.63	113.15
True	Holly Lake GRTE14-1-2	08/31/02	7.006	96.7	13.3	0.099	74.651	25.427	25.446	11.049	0	107.44	2.285	0.097	26.755	107.44
True	Lake Solitude GRTE8-1-1-FF	07/03/02	6.625	37.9	8.4	0.237	47.206	13.084	8.221	3.811	0	46.03	1.551	11.999	12.742	46.03
False	Lake Solitude GRTE8-1-1-U	07/03/02	6.606	34.8	8.2	0.248	46.357	13.166	8.221	3.837	0	44.97	1.664	12.241	12.701	44.97
True	Lake Solitude GRTE8-1-2-FF	07/03/02	6.618	34	8.1	0.241	46.058	13.166	8.047	3.811	0	45.22	1.58	11.87	12.409	45.22
False	Lake Solitude GRTE8-1-2-U	07/03/02	6.61	33.6	8	0.245	47.705	13.248	8.874	4.271	0	47.3	2.031	11.999	12.763	47.3

Field Filtered?	Sample Name	Sample Date	pH	ANC	Cond.	H	Ca	Mg	Na	K	NH4	F	Cl	NO3	SO4	Alkalinity
False	Lake Solitude GRTE15-1-1	08/31/02	7.146	107.1	13.1	0.071	93.164	29.212	14.05	4.808	1.22	121.21	2.059	1.242	16.719	121.21
True	Lake Solitude GRTE15-1-1	08/31/02	7.146	107.1	13.1	0.071	89.671	30.117	14.354	5.755	0	120.6	1.777	0.693	16.823	120.6
False	Lake Solitude GRTE15-1-2	08/31/02	7.119	103.2	13.2	0.076	91.766	28.307	14.18	4.987	0.832	119.24	1.974	1.242	16.782	119.24
True	Lake Solitude GRTE15-1-2	08/31/02	7.119	103.2	13.2	0.076	89.022	28.636	13.832	5.55	0	117.43	1.749	0.79	17.073	117.43
False	Mica Lake GRTE16-1-1	08/31/02	6.888	75.4	10.6	0.129	68.463	23.781	10.483	7.443	1.331	84.74	1.805	10.112	13.513	84.74
True	Mica Lake GRTE16-1-1	08/31/02	6.888	75.4	10.6	0.129	65.469	23.617	10.135	8.082	0	82.07	1.41	10.144	13.679	82.07
False	Mica Lake GRTE16-1-2	08/31/02	6.91	77.9	10.8	0.123	69.212	23.699	10.178	7.213	1.663	85.03	1.721	9.999	13.554	85.03
True	Mica Lake GRTE16-1-2	08/31/02	6.91	77.9	10.8	0.123	74.202	27.649	10.396	7.801	0	94.89	1.495	10.048	13.617	94.89
False	Snowdrift Lake GRTE13-1-1-U	07/04/02	7.792	650.6	71.9	0.016	514.471	205.966	14.093	15.857	0	679.27	2.651	13.709	54.759	679.27
True	Snowdrift Lake GRTE13-1-1-FF	07/04/02	7.824	658.2	73	0.015	510.13	205.225	14.224	16.011	0	674.25	2.849	13.692	54.8	674.25
False	Snowdrift Lake GRTE13-1-2-U	07/04/02	7.808	656.2	73.3	0.016	504.79	204.649	14.311	16.011	0	668.57	2.651	13.757	54.78	668.57
True	Snowdrift Lake GRTE13-1-2-FF	07/04/02	7.848	652.9	75.4	0.014	506.138	205.39	14.441	16.701	0	670.87	3.131	13.741	54.925	670.87
False	Snowdrift Lake GRTE13-2-1	08/02/02	7.839	629.7	68.8	0.014	493.613	203.909	14.485	16.804	0	660.98	2.736	12.225	52.864	660.98
True	Snowdrift Lake GRTE13-2-1	08/02/02	7.839	629.7	68.8	0.014	493.713	203.25	14.006	16.701	0	660.18	2.398	12.338	52.76	660.18
False	Snowdrift Lake GRTE13-2-2	08/02/02	7.846	676.2	69.8	0.014	493.513	204.32	14.876	16.676	0	661.37	2.454	12.612	52.947	661.37
True	Snowdrift Lake GRTE13-2-2	08/02/02	7.846	676.2	69.8	0.014	493.114	202.921	15.311	16.932	0	660.34	2.454	12.354	53.135	660.34
False	Sunset Lake JEDS1-1-1	08/04/02	8.277	1476.7	181.7	0.005	1266.218	653.446	35.016	26.114	0	1543.21	4.062	10.467	423.059	1543.21
True	Sunset Lake JEDS1-1-1	08/04/02	8.277	1476.7	181.7	0.005	1271.806	652.211	34.798	25.525	1.497	1545.08	4.146	10.306	424.808	1545.08
False	Sunset Lake JEDS1-1-2	08/04/02	8.279	1488.3	182.5	0.005	1273.453	654.68	35.277	25.883	1.552	1551.68	4.964	10.386	422.267	1551.68
True	Sunset Lake JEDS1-1-2	08/04/02	8.279	1488.3	182.5	0.005	1274.251	653.528	36.581	25.321	0	1550.42	4.146	10.306	424.808	1550.42
False	Surprise Lake GRTE3-1-1	06/30/02	6.465	40.7	6.8	0.343	34.182	10.451	13.049	5.141	0	47.14	3.3	4.242	8.141	47.14
True	Surprise Lake GRTE3-1-1	06/30/02	6.536	41	6.8	0.291	34.232	11.109	12.701	4.246	0	47.07	3.018	4.161	8.037	47.07
False	Surprise Lake GRTE3-1-2	06/30/02	6.495	43	6.8	0.32	34.481	10.944	12.745	4.783	0	46.73	3.78	4.242	8.203	46.73
True	Surprise Lake GRTE3-1-2	06/30/02	6.546	41.2	6.7	0.284	34.531	10.78	12.701	4.399	0	47.07	2.99	4.435	7.912	47.07
False	Surprise Lake GRTE3-2-1	09/08/02	6.555	36.3	6.3	0.279	31.687	10.944	14.528	5.959	0	51.73	3.272	0	8.12	51.73
True	Surprise Lake GRTE3-2-1	09/08/02	6.555	36.3	6.3	0.279	33.234	12.014	14.485	5.448	0	53.88	3.244	0	8.058	53.88
False	Surprise Lake GRTE3-2-2	09/08/02	6.521	41.7	5.9	0.301	32.385	11.191	13.876	5.525	0.942	51.76	3.244	0	7.974	51.76
True	Surprise Lake GRTE3-2-2	09/08/02	6.521	41.7	5.9	0.301	32.685	11.52	14.485	5.422	0	52.8	3.272	0	8.037	52.8
False	Trapper Lake GRTE2-1	06/01/02	7.073	170.5	22.6	0.085	128.293	39.416	36.494	24.886	0	188.51	5.387	11.564	23.632	188.51
False	Trapper Lake GRTE2-2	06/01/02	7.047	167	23.3	0.09	127.395	39.169	36.321	24.016	0	186.35	5.303	11.66	23.59	186.35
False	Trapper Lake GRTE2-2-1	06/29/02	7.172	166.9	20.9	0.067	123.902	36.947	31.579	20.461	0	181.6	3.187	7.677	20.425	181.6
True	Trapper Lake GRTE2-2-1	06/29/02	7.228	166.4	21.1	0.059	125.2	37.276	31.536	20.512	0	183.53	3.159	7.806	20.03	183.53
False	Trapper Lake GRTE2-2-2	06/29/02	7.12	164.8	21	0.076	121.307	37.194	31.188	20.129	0	178.87	3.131	7.37	20.446	178.87
True	Trapper Lake GRTE2-2-2	06/29/02	7.221	176	21.7	0.06	123.453	36.536	31.318	20.308	0	180.18	3.159	7.854	20.425	180.18
False	Trapper Lake GRTE2-3-2	07/31/02	7.316	216.8	26.2	0.048	155.14	47.727	38.756	26.088	0	232.35	8.152	4.532	22.674	232.35
True	Trapper Lake GRTE2-3-2	07/31/02	7.316	216.8	26.2	0.048	153.792	46.986	38.104	25.756	0	234.19	3.385	4.226	22.84	234.19
False	Trapper Lake GRTE2-3-1	07/31/02	7.324	219.6	26.7	0.047	154.84	47.562	38.321	25.858	0	235.83	3.413	4.661	22.674	235.83
True	Trapper Lake GRTE2-3-1	07/31/02	7.324	219.6	26.7	0.047	154.291	47.398	37.886	25.909	0	234.74	3.441	4.564	22.736	234.74

APPENDIX B - Quality assurance tests for solute chemistry analyzed at the RMRS, Fort Collins, Colorado

Field Filtered?	Sample Name	Sample Date	Sum of Anions	Sum of Cations	Total Ions	% Ion Diff.	Sum of Bases	Sum of Acids	Diff. = Alk.	ANC	Flag % Ion Diff.	% Cond. Diff.	Flag %Cond.	Theor. Cond.
False	Alaska Basin Lake #1 JEDS2-1--1	08/04/02	126.70	140.06	266.76	-5.005	138.34	16.40	121.94	110.3	OK	-5.96	OK	13.17
True	Alaska Basin Lake #1 JEDS2-1--1	08/04/02	126.75	140.66	267.41	-5.200	138.23	16.45	121.77	110.3	OK	-5.66	OK	13.21
False	Alaska Basin Lake #1 JEDS2-1--2	08/04/02	124.50	143.11	267.61	-6.953	140.80	16.30	124.50	108.2	OK	-3.44	OK	13.23
True	Alaska Basin Lake #1 JEDS2-1--2	08/04/02	124.50	140.42	264.92	-6.009	138.67	16.30	122.37	108.2	OK	-4.54	OK	13.08
False	Amphitheater Lake GRTE4-1-1	06/30/02	65.12	69.17	134.29	-3.011	68.31	15.82	52.48	49.3	OK	-3.75	OK	7.03
True	Amphitheater Lake GRTE4-1-1	06/30/02	63.99	67.91	131.90	-2.976	66.96	16.29	50.68	47.7	OK	-6.53	OK	6.92
True	Amphitheater Lake GRTE4-1-2	06/30/02	59.24	70.25	129.49	-8.506	69.30	15.84	53.46	43.4	OK	-5.43	OK	6.81
False	Amphitheater Lake GRTE4-1-2	06/30/02	62.98	68.42	131.40	-4.143	67.56	15.68	51.88	47.3	OK	-5.70	OK	6.88
True	Amphitheater Lake GRTE4-2-1	09/08/02	49.24	62.85	112.08	-12.145	61.71	8.94	52.78	40.3	OK	-0.50	OK	5.77
False	Amphitheater Lake GRTE4-2-1	09/08/02	49.37	61.43	110.81	-10.887	61.19	9.07	52.12	40.3	OK	-1.88	OK	5.69
True	Amphitheater Lake GRTE4-2-2	09/08/02	46.19	62.60	108.79	-15.084	61.11	9.29	51.82	36.9	Check	-2.62	OK	5.65
False	Amphitheater Lake GRTE4-2-2	09/08/02	45.92	62.61	108.53	-15.384	62.34	9.02	53.32	36.9	Check	-3.31	OK	5.61
False	Bradley Lake GRTE1-1	05/30/02	177.04	195.30	372.34	-4.906	195.24	26.03	169.21	148.9	OK	-4.26	OK	18.57
False	Bradley Lake GRTE1-2	05/30/02	175.36	195.82	371.18	-5.512	194.25	26.26	168.00	147	OK	-0.72	OK	18.56
True	Bradley Lake GRTE1-2-1	07/01/02	138.32	147.76	286.08	-3.300	147.66	30.12	117.55	108.2	OK	-4.14	OK	14.67
False	Bradley Lake GRTE1-2-1	07/01/02	136.01	150.94	286.95	-5.203	149.96	30.11	119.85	105.9	OK	-4.18	OK	14.76
True	Bradley Lake GRTE1-2-2	07/01/02	134.59	148.11	282.70	-4.781	148.00	30.59	117.41	104	OK	-1.76	OK	14.54
False	Bradley Lake GRTE1-2-2	07/01/02	136.31	149.03	285.33	-4.457	148.93	29.61	119.32	106.7	OK	-3.09	OK	14.63
True	Bradley Lake GRTE1-3-1	09/08/02	128.18	152.44	280.62	-8.643	152.34	25.68	126.66	102.5	OK	-0.34	OK	14.35
False	Bradley Lake GRTE1-3-1	09/08/02	128.28	150.48	278.76	-7.966	147.40	25.78	121.62	102.5	OK	-0.42	OK	14.34
True	Bradley Lake GRTE1-3-2	09/08/02	130.43	148.37	278.81	-6.434	148.28	25.83	122.44	104.6	OK	0.40	OK	14.26
False	Bradley Lake GRTE1-3-2	09/08/02	130.41	151.67	282.08	-7.536	148.74	25.81	122.93	104.6	OK	2.11	OK	14.50
True	Delta Lake GRTE999-1-1	09/08/02	78.70	92.45	171.15	-8.031	92.18	36.20	55.98	42.5	OK	3.54	OK	9.53
False	Delta Lake GRTE999-1-1	09/08/02	79.99	89.95	169.94	-5.862	89.68	37.49	52.19	42.5	OK	3.26	OK	9.50
True	Delta Lake GRTE999-1-2	09/08/02	72.96	90.65	163.61	-10.811	90.40	34.36	56.04	38.6	OK	-0.84	OK	9.12
False	Delta Lake GRTE999-1-2	09/08/02	76.09	92.37	168.46	-9.665	92.12	37.49	54.63	38.6	OK	2.54	OK	9.43
True	Granite Basin #1 JEDS3-1-1	08/11/02	101.06	77.54	178.60	13.167	77.33	14.16	63.17	86.9	OK	1.49	OK	8.83
False	Granite Basin #1 JEDS3-1-1	08/11/02	104.75	88.03	192.78	8.672	87.82	14.32	73.50	86.9	OK	7.60	OK	9.36
True	Granite Basin #1 JEDS3-1-2	08/11/02	101.97	77.35	179.31	13.729	77.14	14.28	62.86	87.686	OK	7.92	OK	8.85
False	Granite Basin #1 JEDS3-1-2	08/11/02	105.48	88.30	193.79	8.866	88.10	14.22	73.88	87.686	OK	14.82	OK	9.42
True	Holly Lake GRTE14-1-1	08/31/02	117.17	142.46	259.62	-9.743	142.35	27.37	114.99	89.8	OK	0.82	OK	13.31
False	Holly Lake GRTE14-1-1	08/31/02	122.20	140.46	262.67	-6.953	140.36	28.51	111.85	89.8	OK	0.75	OK	13.30
True	Holly Lake GRTE14-1-2	08/31/02	125.84	136.67	262.51	-4.128	136.57	29.14	107.44	96.7	OK	1.03	OK	13.44
False	Holly Lake GRTE14-1-2	08/31/02	128.76	142.24	271.01	-4.974	141.31	28.17	113.15	96.7	OK	2.81	OK	13.67
True	Lake Solitude GRTE15-1-1	08/31/02	126.39	139.97	266.36	-5.096	139.90	19.29	120.60	107.1	OK	1.20	OK	13.26
False	Lake Solitude GRTE15-1-1	08/31/02	131.65	142.52	274.17	-3.968	141.23	20.02	121.21	107.1	OK	2.75	OK	13.46
False	Lake Solitude GRTE15-1-2	08/31/02	127.57	140.15	267.72	-4.700	139.24	20.00	119.24	103.2	OK	-0.27	OK	13.16

Field Filtered?	Sample Name	Sample Date	Sum of Anions	Sum of Cations	Total Ions	% Ion Diff.	Sum of Bases	Sum of Acids	Diff. = Alk.	ANC	Flag % Ion	% Cond. Diff.	Flag %Cond.	Theor. Cond.
True	Lake Solitude GRTE15-1-2	08/31/02	122.81	137.12	259.93	-5.503	137.04	19.61	117.43	103.2	OK	-1.75	OK	12.97
True	Lake Solitude GRTE8-1-1-FF	07/03/02	64.19	72.56	136.75	-6.117	72.32	26.29	46.03	37.9	OK	-12.08	OK	7.39
False	Lake Solitude GRTE8-1-1-U	07/03/02	61.41	71.83	133.23	-7.823	71.58	26.61	44.97	34.8	OK	-11.72	OK	7.24
True	Lake Solitude GRTE8-1-2-FF	07/03/02	59.89	71.32	131.21	-8.714	71.08	25.86	45.22	34.0305	OK	-12.07	OK	7.12
False	Lake Solitude GRTE8-1-2-U	07/03/02	60.39	74.34	134.74	-10.354	74.10	26.79	47.30	33.6	OK	-8.28	OK	7.34
True	Mica Lake GRTE16-1-1	08/31/02	100.63	107.43	208.07	-3.267	107.30	25.23	82.07	75.4	OK	1.35	OK	10.74
False	Mica Lake GRTE16-1-1	08/31/02	100.83	111.63	212.46	-5.083	110.17	25.43	84.74	75.4	OK	3.70	OK	10.99
False	Mica Lake GRTE16-1-2	08/31/02	103.17	112.09	215.26	-4.141	110.30	25.27	85.03	77.9	OK	2.92	OK	11.12
True	Mica Lake GRTE16-1-2	08/31/02	103.06	120.17	223.23	-7.665	120.05	25.16	94.89	77.9	OK	6.29	OK	11.48
True	Snowdrift Lake GRTE13-1-1-FF	07/04/02	729.54	745.60	1475.15	-1.089	745.59	71.34	674.25	658.2	OK	-1.70	OK	71.76
False	Snowdrift Lake GRTE13-1-1-U	07/04/02	721.72	750.40	1472.12	-1.949	750.39	71.12	679.27	650.6	OK	-0.34	OK	71.66
True	Snowdrift Lake GRTE13-1-2-FF	07/04/02	724.70	742.68	1467.38	-1.226	742.67	71.80	670.87	652.9	OK	-5.27	OK	71.42
False	Snowdrift Lake GRTE13-1-2-U	07/04/02	727.39	739.78	1467.16	-0.844	739.76	71.19	668.57	656.2	OK	-2.65	OK	71.36
True	Snowdrift Lake GRTE13-2-1	08/02/02	697.20	727.69	1424.88	-2.140	727.67	67.50	660.18	629.7	OK	0.77	OK	69.33
False	Snowdrift Lake GRTE13-2-1	08/02/02	699.58	728.82	1428.40	-2.048	728.81	67.82	660.98	629.7	OK	0.89	OK	69.41
True	Snowdrift Lake GRTE13-2-2	08/02/02	744.14	728.29	1472.43	1.077	728.28	67.94	660.34	676.2	OK	2.33	OK	71.42
False	Snowdrift Lake GRTE13-2-2	08/02/02	745.74	729.40	1475.14	1.108	729.39	68.01	661.37	676.2	OK	2.40	OK	71.48
False	Sunset Lake JEDS1-1-1	08/04/02	1915.87	1980.80	3896.66	-1.666	1980.79	437.59	1543.21	1476.7	OK	7.54	OK	195.39
True	Sunset Lake JEDS1-1-1	08/04/02	1917.43	1985.84	3903.28	-1.753	1984.34	439.26	1545.08	1476.7	OK	7.76	OK	195.80
False	Sunset Lake JEDS1-1-2	08/04/02	1927.66	1990.85	3918.51	-1.613	1989.29	437.62	1551.68	1488.3	OK	7.64	OK	196.45
True	Sunset Lake JEDS1-1-2	08/04/02	1929.03	1989.69	3918.72	-1.548	1989.68	439.26	1550.42	1488.3	OK	7.65	OK	196.46
True	Surprise Lake GRTE3-1-1	06/30/02	56.22	62.58	118.79	-5.356	62.29	15.22	47.07	41	OK	-8.51	OK	6.22
False	Surprise Lake GRTE3-1-1	06/30/02	56.38	63.17	119.55	-5.673	62.82	15.68	47.14	40.7	OK	-7.22	OK	6.31
True	Surprise Lake GRTE3-1-2	06/30/02	56.54	62.70	119.23	-5.165	62.41	15.34	47.07	41.2	OK	-6.75	OK	6.25
False	Surprise Lake GRTE3-1-2	06/30/02	59.22	63.27	122.50	-3.305	62.95	16.22	46.73	43	OK	-5.29	OK	6.44
True	Surprise Lake GRTE3-2-1	09/08/02	47.60	65.46	113.06	-15.794	65.18	11.30	53.88	36.3	Check	-6.56	OK	5.89
False	Surprise Lake GRTE3-2-1	09/08/02	47.69	63.40	111.09	-14.137	63.12	11.39	51.73	36.3	OK	-7.90	OK	5.80
True	Surprise Lake GRTE3-2-2	09/08/02	53.01	64.41	117.42	-9.712	64.11	11.31	52.80	41.7	OK	3.01	OK	6.08
False	Surprise Lake GRTE3-2-2	09/08/02	52.92	64.22	117.14	-9.649	62.98	11.22	51.76	41.7	OK	3.19	OK	6.09
False	Trapper Lake GRTE2-1	06/01/02	213.77	229.17	442.94	-3.478	229.09	40.58	188.51	170.5	OK	-0.49	OK	22.49
False	Trapper Lake GRTE2-2	06/01/02	210.29	226.99	437.28	-3.819	226.90	40.55	186.35	167	OK	-4.69	OK	22.21
True	Trapper Lake GRTE2-2-1	06/29/02	197.39	214.58	411.98	-4.172	214.52	30.99	183.53	166.4	OK	-1.51	OK	20.78
False	Trapper Lake GRTE2-2-1	06/29/02	198.19	212.96	411.15	-3.592	212.89	31.29	181.60	166.9	OK	-0.76	OK	20.74
False	Trapper Lake GRTE2-2-2	06/29/02	195.75	209.89	405.64	-3.487	209.82	30.95	178.87	164.8	OK	-2.57	OK	20.46
True	Trapper Lake GRTE2-2-2	06/29/02	207.44	211.67	419.11	-1.011	211.61	31.44	180.18	176	OK	-2.85	OK	21.08
True	Trapper Lake GRTE2-3-1	07/31/02	247.25	264.69	511.94	-3.406	264.64	30.45	234.19	216.8	OK	-2.43	OK	25.56
True	Trapper Lake GRTE2-3-1	07/31/02	250.34	265.53	515.87	-2.945	265.48	30.74	234.74	219.6	OK	-3.54	OK	25.75
False	Trapper Lake GRTE2-3-1	07/31/02	250.35	266.63	516.98	-3.149	266.58	30.75	235.83	219.6	OK	-3.34	OK	25.81
False	Trapper Lake GRTE2-3-2	07/31/02	252.16	267.76	519.92	-3.001	267.71	35.36	232.35	216.8	OK	-0.39	OK	26.10

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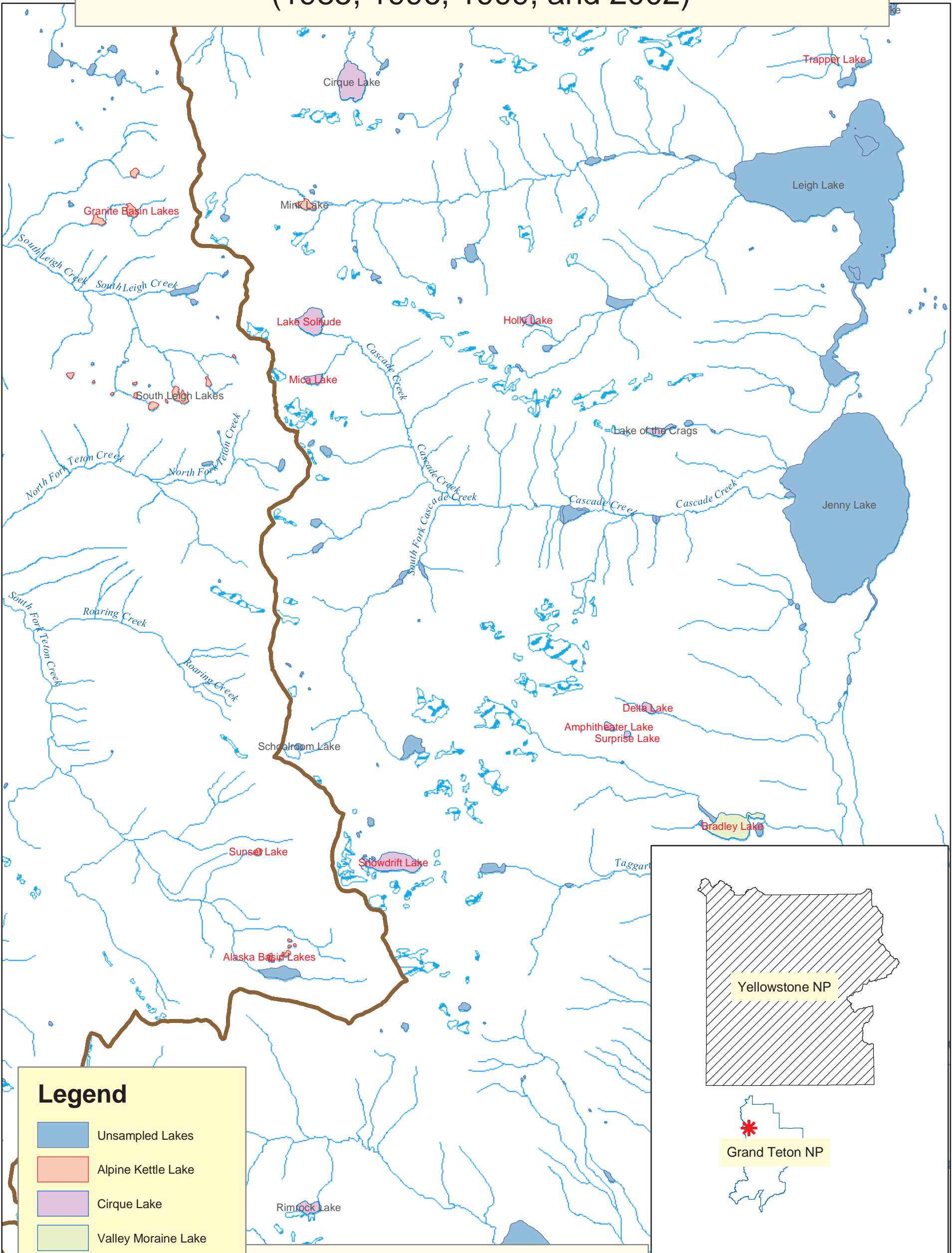
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Figure 1 - Lakes Sampled in Grand Teton National Park
## (1985, 1996, 1999, and 2002)

Trapper Lake

Cirque Lake

Leigh Lake

Mink Lake

South Leigh Creek

South Leigh Creek

Granite Basin Lakes

Lake Solitude

Holly Lake

Mica Lake

Cascade Creek

South Leigh Lakes

North Fork Teton Creek

North Fork Teton Creek

Lake of the Crags

Cascade Creek

Cascade Creek

Cascade Creek

South Fork Cascade Creek

Jenny Lake

South Fork Teton Creek

Roaring Creek

Roaring Creek

Delta Lake

Amphitheater Lake
Surprise Lake

Schoolroom Lake

Bradley Lake

Sunset Lake

Taggart

Snowdrift Lake

Alaska Basin Lakes

Legend

▮	Unsampled Lakes
▭	Alpine Kettle Lake
▮	Cirque Lake
▮	Valley Moraine Lake
▨	Glaciers and snow fields
—	Streams and rivers
▭	Park boundary

Lakes with red annotation were
sampled in 2002.

Rimrock Lake

Yellowstone NP

✳

Grand Teton NP

N
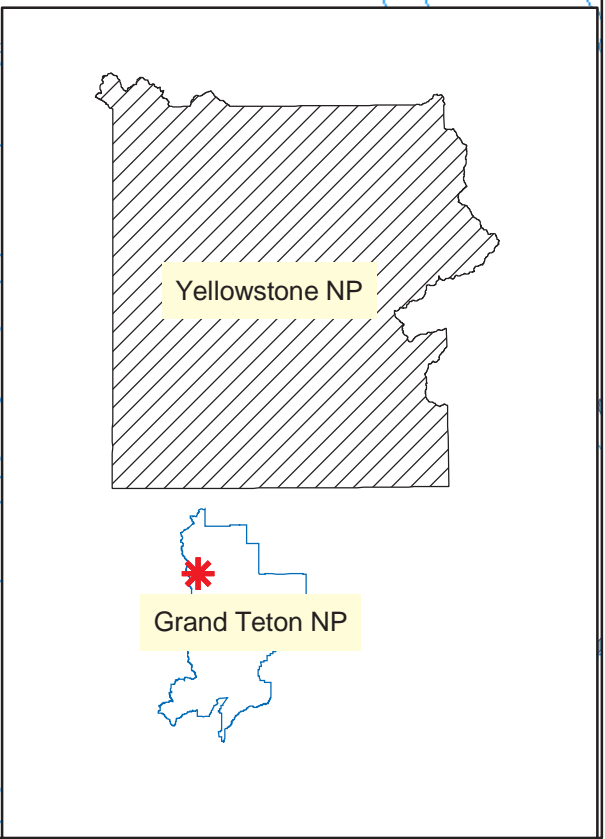
Map produced by Jennifer Ann Corbin for inclusion with:
"Effects of atmospheric deposition on high
alpine lakes in Grand Teton National Park, Wyoming"
by Jennifer Ann Corbin a M.S. thesis requirement for the
College of Forestry and Conservation at the
University of Montana, May 2004.

Miles
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