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Atmospheric Deposition Effects on Water Quality in High-Elevation Lakes of the Teton Range, Wyoming, U.S.A.

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This report focuses on the effects of atmospheric deposition on the water chemistry of high-alpine lakes in Grand Teton National Park, Wyoming. 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 subalpine lakes in Grand Teton 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 (Williams and Tonnessen 1997; Peterson and Sullivan 1998). Unlike Rocky Mountain, currently there is no long-term monitoring effort in place for either atmospheric deposition or water quality of high-elevation lakes at Grand Teton. The nearest National Atmospheric Deposition (NADP) monitoring station is at Tower Junction in Yellowstone National Park. The only water quality data for Grand Teton 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 Grand Teton is essential to elucidate long-term trends and determine the range of interannual 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 Grand Teton with respect to atmospheric deposition impacts, and (2) to use the relationships between water chemistry and watershed physical characteristics to predict which lakes in Grand Teton are most sensitive to acidification.

Methods

Monitoring of all potentially impacted water bodies in Grand Teton 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 model will provide a planning tool that can be used to focus future monitoring efforts in Grand Teton high-elevation lakes.

Twelve lakes were sampled during the summer of 2002. Nine of the lakes are located within the national park 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 Grand Teton 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. Stepwise 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 Grand Teton. 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 $\mu eq\ L^{-1}$ to 1488.3 $\mu eq\ L^{-1}$, with a median of 256.5 $\mu eq\ L^{-1}$. Major ion concentrations and conductivity were also highly variable in the sampled lakes. Nitrate concentrations ranged from 0.1 $\mu eq\ L^{-1}$ to 20.1 $\mu eq\ L^{-1}$, with a median of 7.9 $\mu eq\ L^{-1}$. 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 $\mu eq\ L^{-1}$). 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 (Figure 1), 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.

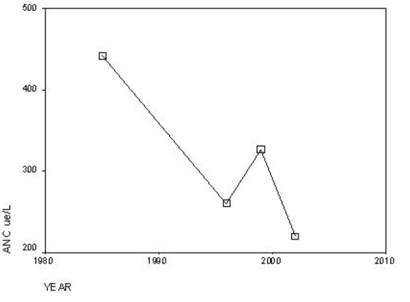

Figure 1. Acid neutralizing capacity (ANC) trends in Trapper Lake between 1985 and 2002. Based on data from Landers et al. 1985, Williams and Tonnessen 1997, Clow et al. 1999, and the 2002 survey.

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.

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 Grand Teton. A total of 17 lakes were sampled.

The complexity of interactions between modeled parameters is illustrated in the coefficients that resulted from the stepwise multiple linear regression. 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.

Generally, the regression models for major cations showed good agreement between observed and predicted values (Figure 2b–f). The strongest model in this group was the Mg^{2+} regression model. Limestone, granite, forest, and subalpine 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 Grand Teton study area because only four 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 2a) 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.

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 <100 μeq L^{-1}. Therefore, groups were coded based on their relative susceptibility to acidification: chronic (ANC < 50 μeq L^{-1}), episodic (ANC < 100 μeq L^{-1}), or not susceptible (ANC >100 μeqL$^{-)}$. 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 3). 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 < 50 μeq L^{-1} were in basins that had total granite compositions ranging from 60% to 80%, lakes with concentrations of 50–100 μeq L^{-1} had granite deposits comprising 20% to 50% of the basin, and lakes with concentrations >100 μeq L^{-1} had less than 20% granite in the basin (Figure 3).

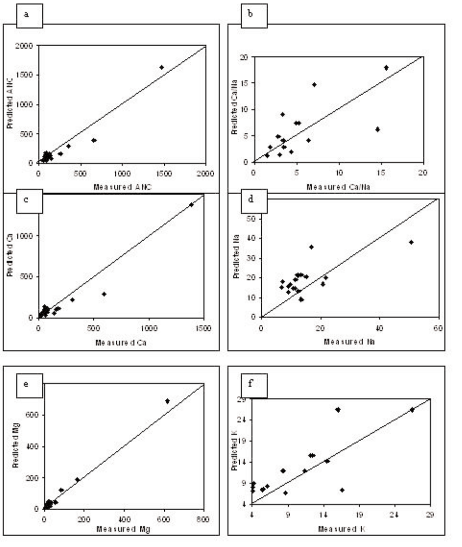

Figure 2. Relations between measured and predicted mean lake concentrations of (a) ANC, (b) Ca/NA ratios, (c) Ca^{2+}, (d) Na^{+}, (e) Mg^{2+}, and (f) K^{+} for Williams and Tonnessen (1997).

The data from the Tower Junction NADP station indicate an overall increase in the potential for acidification of Grand Teton waters by nitrogen-based compounds in atmospheric deposition. However, since Grand Teton 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.

Discussion

The ability of a landscape to neutralize acidity is reflected in the chemistry of its 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.

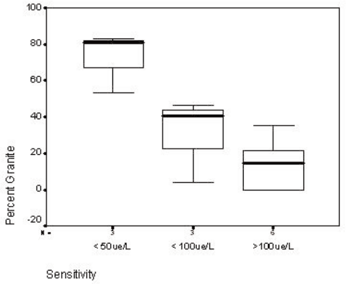

Figure 3. Boxplot of percent granite in study basins relative to acidification susceptibility.

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 Grand Teton National Park 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, Sunset Lake, and Alaska Basin Lake, had ANC values of 676.2, 1488.3, and 110.3 μeq 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 increased weathering associated with the presence of rock debris can either help or hinder a water body's buffering capacity, depending on the bedrock characteristics. For example, in a 1985 study of Grand Teton 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 that 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.

Glacier dissolution in Grand Teton study basins may be responsible for seasonal increases in NO_3^- concentrations in glacier-fed lakes (Figure 4), which in turn decreases the ANC. Delta Lake—a glacier-fed lake—had a mean Ca^{2+} concentration of 50.9 μeqL^{-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 μeq 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}.

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).

Conclusion and recommendations

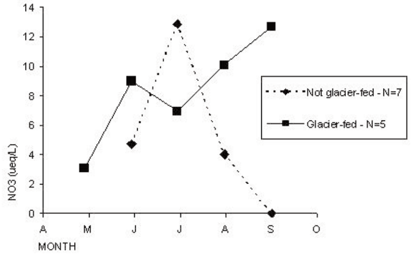

Figure 4. Relations between glacier-fed lakes and seasonal mean NO_3^- concentrations.

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 Grand Teton. 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 Grand Teton 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 Grand Teton—especially Delta Lake, Surprise Lake, Amphitheater Lake, Lake Solitude, and Mica Lake—all of which should be sampled annually. In conjunction with seasonal monitoring of selected lakes, an investigation into the mechanism of nitrate deposition into glacier-fed lakes (namely, Delta Lake) is suggested. It is also recommended that a NADP monitoring station be installed at Grand Teton to better monitor the effects of atmospheric deposition within the park.

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