Sensitivity of Alpine and Subalpine Lakes to Acidification from Atmospheric Deposition in Grand Teton National Park and Yellowstone National Park, Wyoming

By Leora Nanus, Donald H. Campbell, and Mark W. Williams

Prepared in cooperation with the
Grand Teton National Park,
Yellowstone National Park, and the
Greater Yellowstone Inventory and Monitoring Network

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Conversion Factors and Abbreviations

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
hectare (ha)	2.471	acre
kilogram (kg)	2.205	pound (lb)
liter (L)	0.264	gallon (gal)
millimeter per year (mm/yr)	0.0393	inches per year (in/yr)

Vertical coordinate system is referenced to the North American Vertical Datum of 1988 (NAVD 88).
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Additonal Abbreviations

kg/ha/yr	kilograms per hectare per year
μeq/L	microequivalents per liter
ANC	acid-neutralizing capacity
DEM	Digital Elevation Model
USEPA	U.S. Environmental Protection Agency
GC	Geochemical Class (geochemical ranking)
GIS	Geographical Information System
NADP	National Atmospheric Deposition Program
NWIS	National Water Information System
PRISM	Parameter-elevation Regressions on Independent Slopes Model
STORET	Data Storage and Retrieval System

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Abstract

The sensitivity of 400 lakes in Grand Teton and Yellowstone National Parks to acidification from atmospheric deposition of nitrogen and sulfur was estimated based on statistical relations between acid-neutralizing capacity concentrations and basin characteristics to aid in the design of a long-term monitoring plan for Outstanding Natural Resource Waters. Acid-neutralizing capacity concentrations that were measured at 52 lakes in Grand Teton and 23 lakes in Yellowstone during synoptic surveys were used to calibrate the statistical models. Three acid-neutralizing capacity concentration bins (bins) were selected that are within the U.S. Environmental Protection Agency criteria of sensitive to acidification; less than 50 microequivalents per liter (μeq/L) (0–50), less than 100 μeq/L (0–100), and less than 200 μeq/L (0–200). The development of discrete bins enables resource managers to have the ability to change criteria based on the focus of their study. Basin-characteristic information was derived from Geographic Information System data sets. The explanatory variables that were considered included bedrock type, basin slope, basin aspect, basin elevation, lake area, basin area, inorganic nitrogen deposition, sulfate deposition, hydrogen ion deposition, basin precipitation, soil type, and vegetation type. A logistic regression model was developed and applied to lake basins greater than 1 hectare in Grand Teton (n = 106) and Yellowstone (n = 294).

A higher percentage of lakes in Grand Teton than in Yellowstone were predicted to be sensitive to atmospheric deposition in all three bins. For Grand Teton, 7 percent of lakes had a greater than 60-percent probability of having acid-neutralizing capacity concentrations in the 0–50 bin, 36 percent of lakes had a greater than 60-percent probability of having acid-neutralizing capacity concentrations in the 0–100 bin, and 59 percent of lakes had a greater than 60-percent probability of having acid-neutralizing capacity concentrations in the 0–200 bin. The elevation of the lake outlet and the area of the basin with northeast aspects were determined to be statistically significant and were used as the explanatory variables in the multivariate logistic regression model for the 0–100 bin. For Yellowstone, results indicated that 13 percent of lakes had a greater than 60-percent probability of having acid-neutralizing capacity concentrations in the 0–100 bin, and 27 percent of lakes had a greater than 60-percent probability of having acid-neutralizing capacity concentrations in the 0–200 bin. Only the elevation of the lake outlet was determined to be statistically significant and was used as the explanatory variable for the 0–100 bin.

The lakes that exceeded 60-percent probability of having an acid-neutralizing capacity concentration in the 0–100 bin, and therefore had the greatest sensitivity to acidification from atmospheric deposition, are located at elevations greater than 2,790 meters in Grand Teton, and greater than 2,590 meters in Yellowstone.

Introduction

Atmospheric deposition of nitrogen and sulfur and the effects of climate change on water quality and quantity in high-elevation lakes are issues that are a concern for Grand Teton and Yellowstone National Parks (herein referred to as “Grand Teton” and “Yellowstone”). Physical characteristics of high-elevation basins, such as thin, rocky soils; sparse vegetation; and a short growing season in Grand Teton and Yellowstone make them susceptible to damage from atmospheric contaminants. Deposition of nitrogen to high-elevation lakes has the potential to change the nutrient status of aquatic ecosystems through nitrogen saturation, increasing vulnerability to episodic acidification from atmospheric deposition. Current (2005) atmospheric deposition rates and proposed changes in atmospheric emissions, including increasing emissions from powerplants and energy production near Grand Teton and Yellowstone, have the potential to further alter the chemistry of these aquatic ecosystems.

Previous studies have documented strong relations between acid-neutralizing capacity (ANC) concentrations and certain basin characteristics (Melack and others, 1985; Nishida and Schnoor, 1989; Hooper and others, 1990; Clow and Sueker, 2000; Rutkowski and others, 2001; and Leora Nanus and D.W. Clow, U.S. Geological Survey, written commun., 2004). ANC is the measure of the amount of acid necessary to neutralize the bicarbonate, carbonate, alumino-hydroxy complexes, and other bases in a water sample and is determined using acidimetric Gran analysis (Kanciruk and others, 1987).

Compilation of historical water-quality data that have been collected in Grand Teton (Woods and Corbin, 2003a) and Yellowstone (Woods and Corbin, 2003b) indicates that few chemical data are available for Outstanding Natural Resource Waters in Yellowstone, particularly high-elevation lakes. Gulley and Parker (1985) conducted a limnological survey of 70 small lakes and ponds in Grand Teton and determined that the lakes were very dilute and very poorly buffered, indicating that they could be extremely susceptible to acidification caused by the atmospheric deposition of contaminants. Of the 17 high-elevation lakes sampled throughout Grand Teton and Targhee National Forest in 1996, 14 had ANC concentrations less than 200 microequivalents per liter (μeq/L), within the U.S. Environmental Protection Agency (USEPA) criteria of sensitive to acidification (M.W. Williams and K.A. Tonnessen, University of Colorado and National Park Service, written commun., 1997). Corbin (2004) sampled high-elevation lakes in Grand Teton in 2002 and determined that most lakes had ANC concentrations less than 100 μeq/L.

Atmospheric deposition maps (for 1992 through 1999) of the Rocky Mountains show regions of high atmospheric deposition in the northern Rocky Mountains (Nanus and others, 2003), including parts of Wyoming and Montana. High inorganic nitrogen deposition (3.5 to 4.5 kg/ha/yr inorganic N), sulfate deposition (4.0 to 8.0 kg/ha/yr SO_4-S), and relatively high hydrogen ion deposition (0.10 to 0.25 kg/ha/yr H^+) rates are occurring in Grand Teton and Yellowstone (Nanus and others, 2003).

Surface-water monitoring is needed in Grand Teton and Yellowstone to assess current conditions of aquatic ecosystems and evaluate the long-term effects of atmospheric deposition of contaminants on these aquatic ecosystems. To address this need, the National Park Service (NPS), Greater Yellowstone Inventory and Monitoring Network is designing a long-term monitoring plan for Outstanding Natural Resource Waters in Grand Teton and Yellowstone that will focus monitoring efforts on lakes most sensitive to atmospheric deposition. Differences in environmental settings, such as topography, hydrology, geology, and vegetation types of high-elevation lake basins between Grand Teton and Yellowstone (Zelt and others, 1999), support the need for a water-quality assessment in each park. To address this need, the U.S. Geological Survey (USGS), in cooperation with the NPS, is using a scientifically based approach to identify those systems most sensitive to atmospheric deposition of contaminants. The study described in this report identifies and quantifies the extent of lakes that are sensitive to changes such as eutrophication, fertilization, and acidification from atmospheric deposition. Results from the study described in this report will be used to aid in the design of a long-term monitoring plan for Outstanding Natural Resource Waters within Grand Teton and Yellowstone.

Purpose and Scope

The purpose of this report is to identify lakes in Grand Teton and Yellowstone that are sensitive to acidification from atmospheric deposition of contaminants. This report describes the development of multivariate, logistic regression models for estimating lake sensitivity. Sensitive lakes are defined as lakes with a greater than 60-percent probability of having an ANC concentration less than 200 μeq/L, USEPA's criteria of sensitive to acidification. Using Geographical Information System (GIS) tools and spatial statistics, physical basin characteristics data, including land-surface characteristics and atmospheric factors such as precipitation and atmospheric deposition of contaminants, were derived for use as explanatory variables in the logistic regression models. The logistic regression models were calibrated using ANC concentration data. Discrete ANC concentration bins were developed for use in the logistic regression analyses to give managers the ability to vary their sensitivity criteria based on the focus of their study.

Acknowledgments

The authors thank Sue O'Ney of Grand Teton National Park, Cathie Jean of the Greater Yellowstone Inventory and Monitoring Network, and Kathy Tonnessen of the National Park Service, Rocky Mountain Cooperative Ecosystem Studies Unit for their support of this project. This report was greatly improved by colleague reviewers Kathy Tonnessen of the National Park Service and Alisa Mast of the U.S. Geological Survey. The authors also thank Ann Rodman of Yellowstone National Park for GIS data.

Description of Data Used in the Logistic Regression Models

Only previously analyzed water-quality data and previously generated GIS data were used in the logistic regression models described in this report. The GIS data were used for basin boundary delineation of lakes and quantification of physical basin characteristics.

Lake Acid-Neutralizing Capacity Data

ANC concentration data for alpine/subalpine lakes in Grand Teton and Yellowstone were compiled. Data sources include the USGS National Water Information System (NWIS), the Federal Data Storage and Retrieval System (STORET), 1996 Grand Teton data from Tonnessen and Williams (M.W. Williams and K.A. Tonnessen, University of Colorado and National Park Service, written commun., 1997), 1999 Grand Teton and Yellowstone data from the USGS (Clow and others, 2002), and 2002 Grand Teton data (Corbin, 2004). STORET data included ANC concentrations from a limnological study conducted in Grand Teton by Gulley and Parker (1985), and the USEPA

Western Lake Survey in Grand Teton and Yellowstone (Kanciruk and others, 1987; Landers and others, 1987; Silverstein and others, 1987).

Selection criteria applied to the data sets for use in the study described in this report included only data from alpine and subalpine lakes that were sampled from July through the first week of October, lakes that were greater than 1 hectare (ha) in area and less than 4 ha in area, and ANC concentration data were available. The lake-size selection criteria was used to avoid inclusion of small tarns and ponds in the data set as well as really large lakes, and is in keeping with the selection criteria used for the Western Lake Survey (Kanciruk and others, 1987; Landers and others, 1987; Silverstein and others, 1987). A total of 52 lakes in Grand Teton and 23 lakes in Yellowstone met the selection criteria.

The ANC concentration data that met the selection criteria were classified into the three ANC concentration bins (bins) that are within the USEPA's criteria of sensitive to acidification: less than 50 μeq/L (0–50), less than 100 μeq/L (0–100), and less than 200 μeq/L (0–200) (figs. 1 and 2). ANC concentrations less than 50 μeq/L would be more appropriate for evaluating chronic acidification risk, though ANC concentrations less than 100 μeq/L likely would include lakes that may have episodic acidification. Thus, for Grand Teton, ANC concentration data were classified into bins of 0–50 μeq/L, 0–100 μeq/L, and 0–200 μeq/L to calibrate logistic regression models. For Yellowstone, no lakes had ANC concentrations less than 50 μeq/L, so only bins of 0–100 μeq/L and 0–200 μeq/L were used.

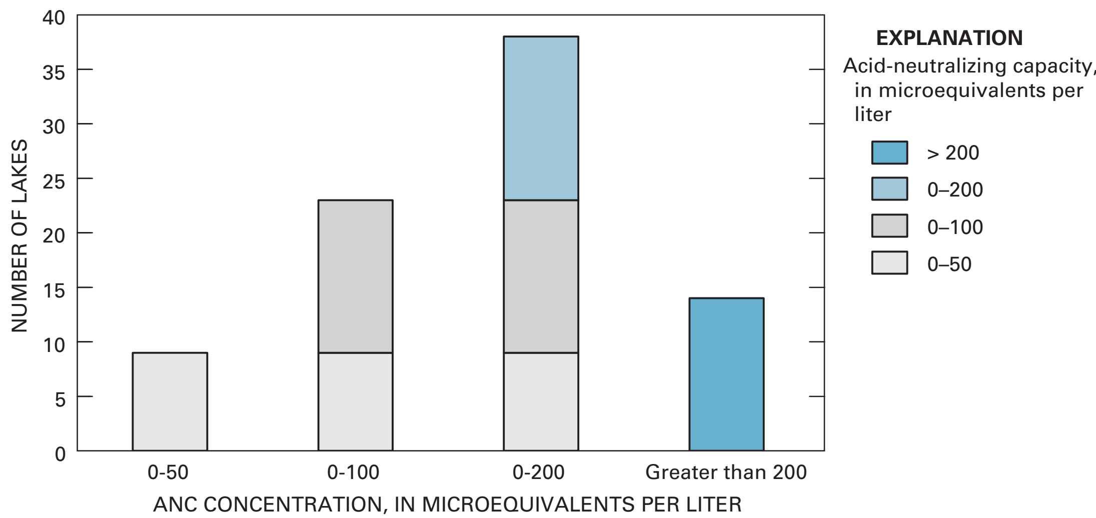


Figure 1. Frequency of lakes in acid-neutralizing capacity (ANC) concentration bins for Grand Teton National Park.

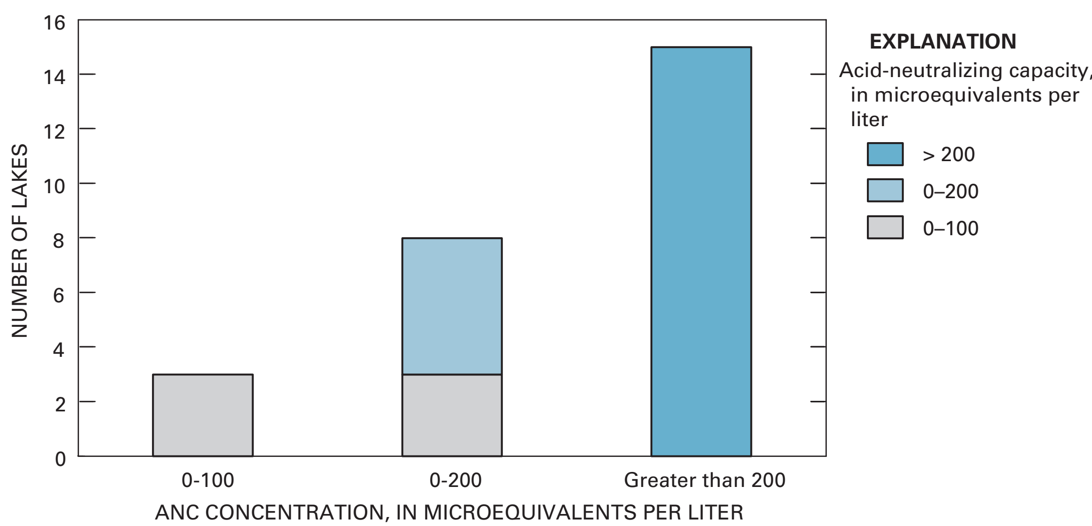


Figure 2. Frequency of lakes in acid-neutralizing capacity (ANC) concentration bins for Yellowstone National Park.

Water-quality data were examined to determine if the data sets could be combined for sites with multiple years of ANC concentration data from one data set or multiple data sets. It was determined that ANC concentrations were not variable across the ANC concentration bins either temporally or for different data sets, and that the data sets could be combined. ANC concentrations range from 18 to 1,600 μeq/L in Grand Teton and 54 to 1,621 μeq/L in Yellowstone. Water-quality data for Yellowstone Lake and Jackson Lake were not used to calibrate the regression models because of the larger size of these lakes compared to the other lakes included in the study; however, the two large lakes were included in the total lake population to which the results of the modeling were applied.

Basin Boundary Delineation

Lake coverages at a scale of 1:24,000 (U.S. Geological Survey, 2000b) were used to identify lakes with a surface area of 1–4 ha. One hundred and six lakes in Grand Teton (fig. 3 and table 6; tables 6–11 are in the appendix at the back of the report), and 294 lakes in Yellowstone (fig. 4 and table 10), had lake areas of 1–4 ha and were included in the study. By using a 10-m digital elevation model (DEM) (U.S. Geological Survey, 2000a) for Grand Teton and Yellowstone and the lake outlets, the basin boundaries for the lake watersheds were delineated in ArcGrid (Environmental Systems Research Institute, 1999). All grid cells that contribute flow to the specified lake outlet, also known as the basin pour point, were included within the basin. Basin boundary delineations were rigorously checked in GIS by overlaying the basin boundary on the DEM and hydrology coverage. Sixty-six percent of lakes in Grand Teton and 36 percent of lakes in Yellowstone that were included in the study were headwater lakes, defined as having no tributary basins entering the lake.

Physical Basin Characteristics Data

Physical basin characteristics data from a variety of data sets were quantified for each basin by using GIS tools and spatial statistics. A total of 45 (for Grand Teton; table 7) and 37 (for Yellowstone; table 8) variables of physical basin characteristics were quantified for testing as explanatory variables in the regression models. Each of the variables was considered to be a possible factor in controlling the ANC of the lake, and therefore the sensitivity of the lake to eutrophication, fertilization, and acidification from atmospheric deposition. The explanatory variables tested in the logistic regression models are defined in tables 7 (for Grand Teton) and 8 (for Yellowstone).

Land-Surface Characteristics

Land-surface characteristics were derived from GIS data sets including a 1:24,000 lake coverage (U.S. Geological Survey, 2000b), a 10-m DEM (U.S. Geological Survey, 2000a), a 1:62,500-scale bedrock-geology coverage for Grand Teton (National Park Service, 1992), a 1:125,000-scale bedrock-geology coverage for Yellowstone (National Park Service, 1988), a 1:24,000-scale soils coverage for Grand Teton (National Park Service, 1994a), a 1:62,500-scale soils coverage for Yellowstone (National Park Service, 1997), a 1:62,500-scale vegetation coverage for Grand Teton (National Park Service, 1994b), a 10-m vegetation grid for Yellowstone (National Park Service, 1990), a 1:125,000-scale precipitation grid for Grand Teton (Spatial Climate Analysis Service, 2000), a 1:125,000-scale precipitation grid for Yellowstone (National Park Service, 1999), a 1:125,000-scale hydrogen ion-deposition grid (Nanus and others, 2003), a 1:125,000-scale inorganic nitrogen-deposition grid (Nanus and others, 2003), and a 1:125,000-scale sulfate-deposition grid (Nanus and others, 2003).

The range in elevation for Grand Teton is 1,927 to 4,185 m (fig. 5), and Yellowstone is 1,566 to 3,460 m (fig. 5). Grand Teton has a larger percentage of high-elevation terrain compared to Yellowstone (fig. 5). For each lake basin, the 10-m DEM was used to calculate mean elevation and slope and to derive other physical parameters including lake-outlet elevation, maximum elevation, basin area, lake/basin area, percentage of steep slopes (slopes > 30 degrees), and percentage of aspect (by 45-degree increments) (tables 7 and 8). Aspect of 0 degree is north, 90 degrees is east, 180 degrees is south, and 270 degrees is west.

The lithologies for Grand Teton and Yellowstone were grouped into six different geochemical classes (hereinafter referred to as "geochemical ranking") that were ranked from low to high on the basis of buffering capacity of the bedrock (Leora Nanus and D.W. Clow, U.S. Geological Survey, written commun., 2004). The geochemical rankings (GC) are as follows:

- GC 1 Class 1, Low buffering capacity: gneiss, quartzite, schist, granite;
- GC 2 Class 2, Moderate buffering capacity: andesite, dacite, diorite, phyllite;
- GC 3 Class 3, High buffering capacity: basalt, gabbro, wacke, argillite, undifferentiated volcanic rocks;
- GC 4 Class 4, Very high buffering capacity: amphibolite, hornfels, paragneiss, undifferentiated metamorphic rocks;
- GC 5 Class 5, Extremely high buffering capacity: metacarbonate, marine sedimentary rocks, marble, calcium silicate and basic intrusive rocks; and
- GC 6 Class 6, Unknown buffering capacity.

The grouped geochemical-ranking coverage is shown in fig. 6. The predominant geochemical rankings, based on the potential buffering capacity of the bedrock for Grand Teton, are GC 1, GC 3, and GC 4, and for Yellowstone they are GC 3 and GC 4. The large amount of GC 1 in Grand Teton indicates that the buffering capacity of the bedrock is lower in Grand Teton than in Yellowstone. The percentage of areal coverage

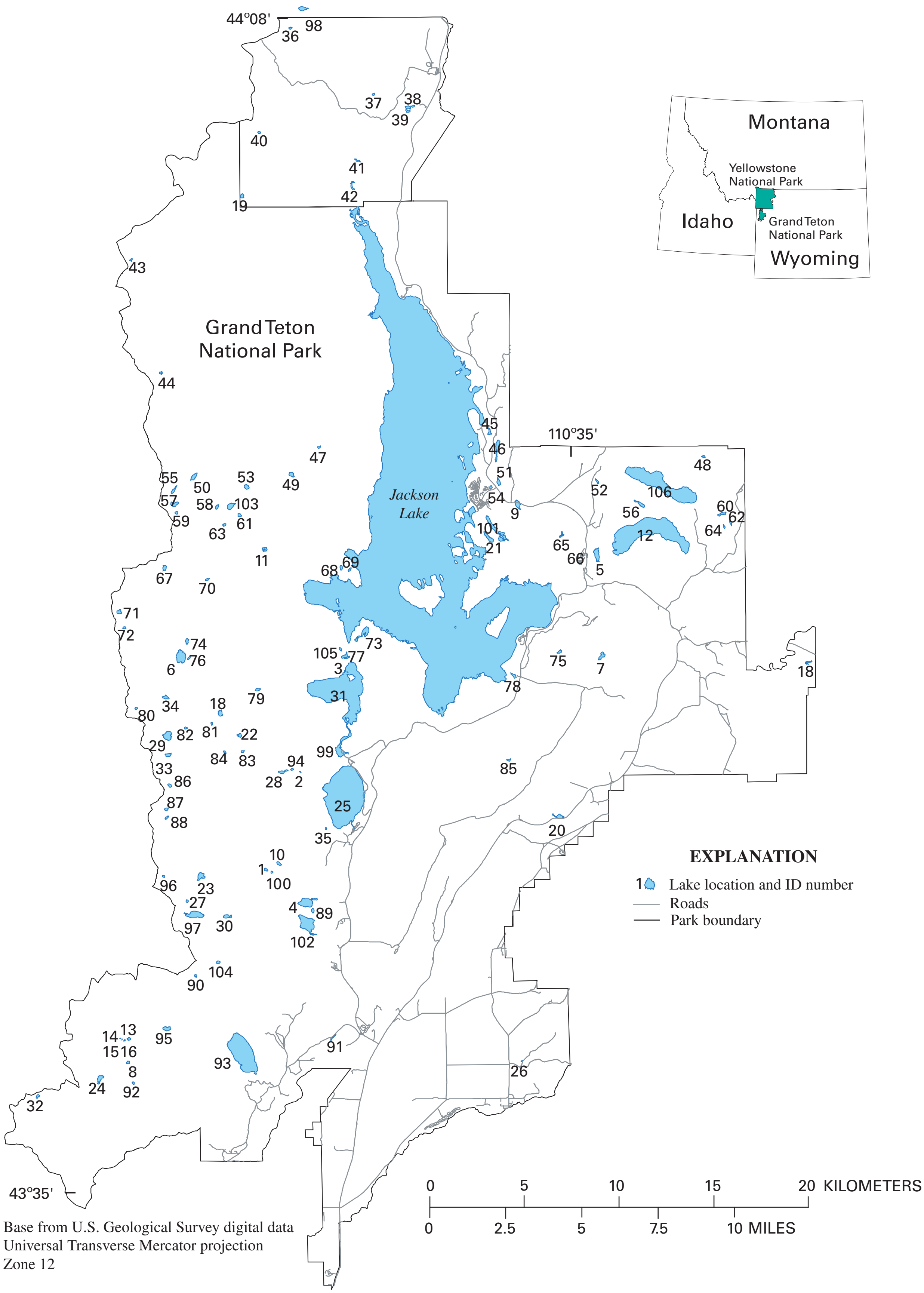


Figure 3. Location of lakes greater than 1 hectare in Grand Teton National Park.

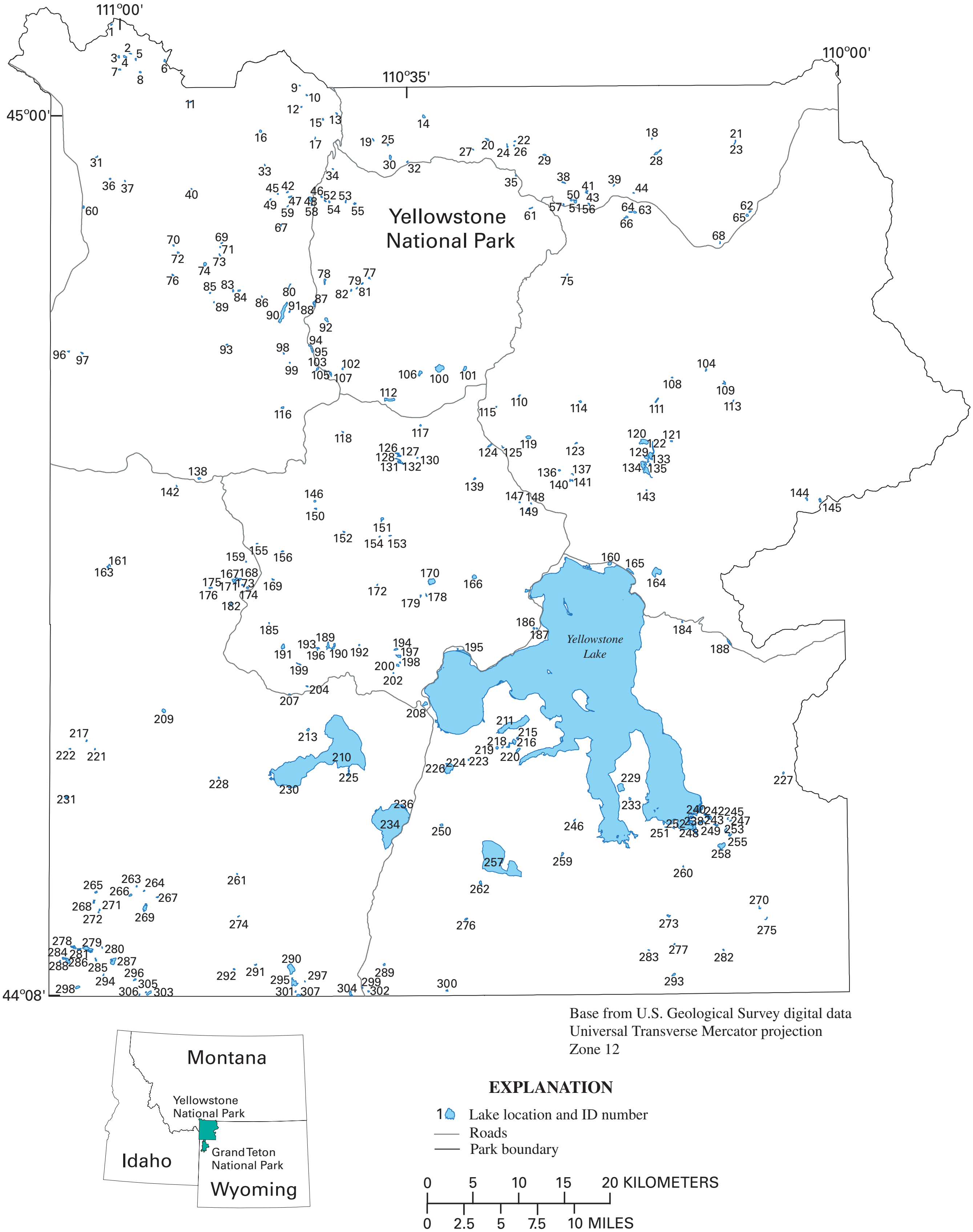


Figure 4. Location of lakes greater than 1 hectare in Yellowstone National Park.

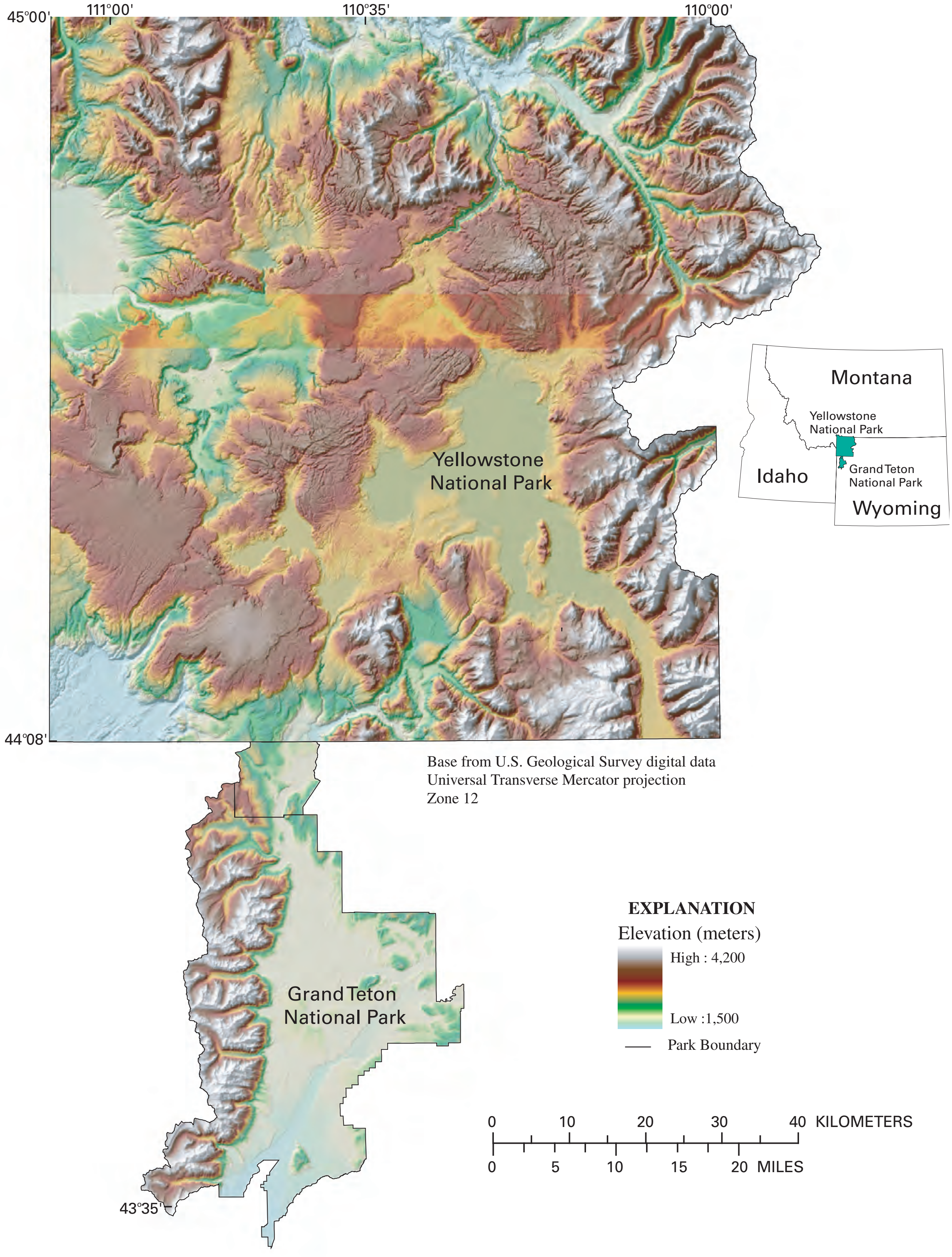


Figure 5. Elevation in Grand Teton and Yellowstone National Parks.

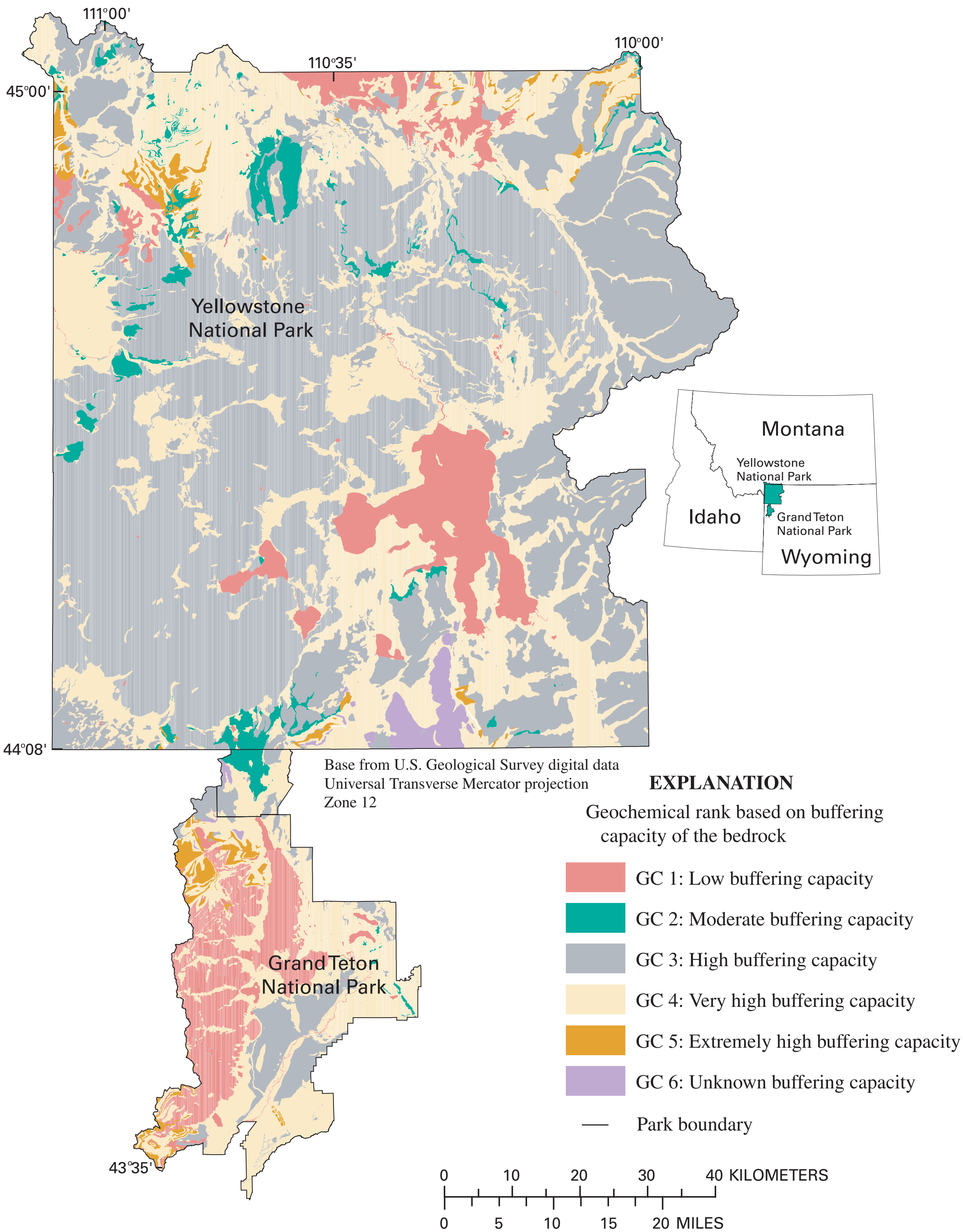


Figure 6. Geochemical rankings in Grand Teton and Yellowstone National Parks.

of the six geochemical rankings in each basin was calculated in GIS by overlaying the delineated boundaries on the geochemical-ranking coverage.

Soil type for Grand Teton and Yellowstone was grouped for each individual park based on preexisting soils classifications into 17 different types for Grand Teton (table 7) and 5 different types for Yellowstone (table 8) (Ann Rodman, National Park Service, written commun., 2004).

Vegetation type was classified into low, medium, and high classes based on sensitivity to deposition of contaminants (tables 7 and 8). High sensitivity includes agricultural or unvegetated terrain such as snow, ice, rock, and water. Medium sensitivity includes forest and tundra, and low sensitivity includes subalpine meadow.

Atmospheric Factors

Atmospheric factors, including precipitation amount and atmospheric deposition rates of inorganic nitrogen, sulfate, and hydrogen ion, also were included as explanatory variables in the logistic regression models. The mean-annual precipitation variable for each basin was derived from a 30-year (1961–90) average annual precipitation grid (Parameter-elevation Regressions on Independent Slopes Model; PRISM; Spatial Climate Analysis Service, 2000). Within the study area, mean-annual precipitation, by lake basin, ranged from a low of 530 mm/yr to a high of 4,720 mm/yr.

Atmospheric deposition of hydrogen ion, inorganic nitrogen, and sulfate has the potential to alter the chemistry of aquatic ecosystems, through nitrogen saturation and episodic acidification, thus increasing the sensitivity of lakes to future acidification from atmospheric deposition in Grand Teton and Yellowstone. Mean-annual deposition of hydrogen ion, inorganic nitrogen, and sulfate were calculated for each basin. Within the study area, mean annual atmospheric deposition ranges are as follows: hydrogen ion deposition ranges from 0.03 to 0.1 kg/ha/yr hydrogen ion, 0.2 to 4.3 kg/ha/yr inorganic nitrogen, and 0.7 to 6.8 kg/ha/yr sulfate (Nanus and others, 2003). The variability in solute deposition was largely controlled by precipitation amount (Nanus and others, 2003).

Description of Logistic Regression Modeling Technique

Multivariate logistic regression for each ANC concentration bin was used to identify lakes with a high probability of sensitivity to acidic deposition. Logistic regression differs from linear regression in that the result is the probability of being above or below a threshold, rather than a predicted value (Helsel and Hirsch, 1993). The large variability in ANC concentrations in Grand Teton and Yellowstone is such that predicting the probability for a lake to be within a discrete ANC concentration bin (0–50 μeq/L, 0–100 μeq/L, and 0–200 μeq/L) is a good approach and supports the use of logistic regression over other statistical analyses.

The probability equation is:

$$\text{Logit (P)} = \frac{e^{b_o + b_x}}{1 + e^{b_o + b_x}} \qquad (1)$$

where

Logit (P) is probability that ANC concentration is within a specified ANC concentration bin;

e is natural logarithm;

b_o is constant;

and

b_x is vector of slope coefficients and explanatory variables.

Basin characteristics (45 for Grand Teton and 37 for Yellowstone) were used as explanatory variables, and ANC concentrations at 52 lakes in Grand Teton and 23 lakes in Yellowstone were used as the dependent variable to calibrate the regression models. First, all explanatory variables were tested independently using univariate logistic regression, and the explanatory variables that have significant influence (p-value ≤ 0.1) were included in an initial multivariate logistic regression analysis. Only explanatory variables that were significant (p-value ≤ 0.05) in the initial multivariate analysis were included in the final multivariate logistic regression models. The resultant multivariate logistic regression models are highly significant (p-value ≤ 0.05), compared with an intercept-only model that contains none of the explanatory variables. Once the final multivariate logistic regression models were calibrated, the resultant probability equations for each ANC concentration bin were applied to all lakes greater than 1 ha in Grand Teton and Yellowstone. Thus, the model was applied to lakes with ANC data (that were used to calibrate the models) and lakes without data to determine the probability for a lake to be in an ANC concentration bin. To enable further evaluation of the logistic regression model for each ANC concentration bin, model-based predicted probabilities were compared to measured concentrations by using the Hosmer-Lemeshow Goodness-of-Fit (Hosmer and Lemeshow, 1989). For example, Somers' D is used to determine the strength and direction of relation between pairs of variables (SAS Institute, 1990). Its values range from –1.0 (all pairs disagree) to 1.0 (all pairs agree). The c-statistic is another measure of rank correlation of ordinal variables (SAS Institute, 1990). It is justified so that it ranges from 0 (no association) to 1 (perfect association). It is a variant of Somers' D index. The wald statisitic can be used to determine significance of the coefficients (SAS Institute, 1990). The wald statistic is based on chi-square distribution and is the square of the ratio of the coefficient to its standard error.

Lakes with a high probability (greater than 60 percent) of having an ANC concentration within the predefined bins were identified as potentially sensitive. These results were subdivided further into four probability ranges: probability that the estimated ANC concentration is in a bin is equal to or greater than

90 percent; probability that the estimated ANC concentration is in a bin ranges from 80 to 90 percent; probability that the estimated ANC concentration is in a bin ranges from 70 to 80 percent; and probability that the estimated ANC concentration is in a bin ranges from 60 to 70 percent. The classification grouping described above was repeated for each ANC concentration bin: 0–50 µeq/L, 0–100 µeq/L, and 0–200 µeq/L in Grand Teton, and 0–100 µeq/L and 0–200 µeq/L in Yellowstone.

Logistic Regression Model Calibration and Application

Grand Teton National Park

In Grand Teton, 52 lakes between 1–4 ha that had available ANC concentration data for July through October were used to calibrate the logistic regression models for each ANC concentration bin. After each model was calibrated for the ANC concentration bins (0–50 µeq/L, 0–100 µeq/L, and 0–200 µeq/L), the model was applied to the 106 lakes in Grand Teton that are greater than 1 ha (fig. 3 and table 6). This section of the report describes the model calibration and application for each bin in Grand Teton. Results of the univariate and multivariate logistic regression analysis for Grand Teton are presented in tables 7 and 9.

For Grand Teton, results of the lake-sensitivity classification using multivariate logistic regression indicate that the fraction of basin that is composed of soil type 9, Leighton-Moran Wolcott association soils (p-value = 0.0035), and the percent area of the basin with steep slopes (slopes greater than 30 degrees) (p-value = 0.0276) were the only physical basin characteristics that were significant at the 95-percent confidence interval (p-value $\leq$ 0.05) using an ANC concentration bin of 0–50 µeq/L (table 9). As the area of the basin with steep slopes and the area of the basin with soil type 9 increases, the buffering capacity of the basin decreases as a result of thin soils and resistant bedrock, and the probability that ANC concentrations are in the 0–50 µeq/L bin increases. The Hosmer-Lemeshow Goodness-of-Fit, which compares the measured concentrations of the response variable to the predicted concentrations obtained from models with and without the variable in question, indicates a good model fit to the calibration data. Measured ANC concentrations were compared to predicted ANC concentrations by randomly grouping the lakes with measured ANC into 10 groups with an equal number of lakes. These random groupings of 10 percent were used to evaluate model agreement between measured and predicted ANC concentration. In Grand Teton, measured ANC concentrations of 0–50 µeq/L compared to predicted in random groupings of 10 percent, showed good agreement with a r-squared value equal to 0.66 (table 9). The c statistic, a variant of Somers' D index that measures rank correlation (SAS Institute, 1990), is equal to 0.90, indicating good association.

The following probability equation was applied to the 106 delineated basins:

$$\text{Logit (P)} = \frac{e^{(-8.624 + 9.702\ (\text{soil\_9}) + 13.761\ (\text{steep slope}))}}{1 + e^{(-8.624 + 9.702\ (\text{soil\_9}) + 13.761\ (\text{steep slope}))}} \tag{2}$$

where Logit (P) and e are defined as in equation 1.

For an ANC concentration bin of 0–100 µeq/L, results indicate that the elevation of the lake outlet (p-value = 0.0005) and the area of the basin with northeastern aspects (asp45) (p-value = 0.0272) are significant at the 95-percent confidence interval (p-value $\leq$ 0.05). As the elevation of lake outlet increases and the area of the basin with northeastern aspects decreases, the probability that ANC concentration is in the 0–100 µeq/L bin increases. High-elevation watersheds with northeastern aspects have deep, seasonal snowpacks that have high rates of runoff during snowmelt and limited water/soil interaction, limiting the potential buffering capacity of the basin. Thus, elevation of lake outlet and the area of the basin with northeastern aspects were used as explanatory variables in the multivariate logistic regression model (table 9). Measured ANC concentrations 0–100 µeq/L compared to predicted in random groupings of 10 percent in Grand Teton, showed good agreement with a r-squared value equal to 0.61 (table 9). The c statistic is equal to 0.88, indicating good association.

The following probability equation was applied to the 106 delineated basins:

$$\text{Logit (P)} = \frac{e^{(-9.455 + 0.004(\text{min\_elev}) - 8.318(\text{asp45}))}}{+ e^{(-9.455 + 0.004(\text{min\_elev}) - 8.318(\text{asp45}))}} \tag{3}$$

where Logit (P) and e are defined as in equation 1.

For an ANC concentration bin of 0–200 µeq/L, only bedrock type GC 1, with low to no buffering capacity (p-value = 0.0003), was statistically significant at the 95-percent confidence interval (p-value $\leq$ 0.05), such that as the area of the basin with GC 1 increases, the probability that ANC concentration is in the 0–200 bin increases. Thus, GC 1 was used as the explanatory variable in the model. Measured ANC concentrations 0–200 µeq/L compared to predicted in groupings of 10 percent in Grand Teton, showed very good agreement with a r-squared value equal to 0.99 (table 9). The c statistic is equal to 0.86, indicating good association.

The following probability equation was applied to the 106 delineated basins:

$$\text{Logit (P)} = \frac{e^{(-2.546 + 4.883(\text{GC 1}))}}{1 + e^{(-2.546 + 4.883(\text{GC 1}))}} \tag{4}$$

where Logit (P) and e are defined as in equation 1.

Yellowstone National Park

In Yellowstone, 23 lakes, or 8 percent of lakes greater than 1 ha, met the selection criteria, and ANC data were used to calibrate the logistic regression models. Results of the univariate and multivariate logistic regression analysis for Yellowstone are presented in tables 8 and 11. Results for Yellowstone lakes with probabilities of being within the ANC concentration bins (0–100 µeq/L and 0–200 µeq/L) are presented in table 10. Two hundred and ninety-four lakes in Yellowstone are greater than 1 ha and were included in this study (fig. 4 and table 10).

For an ANC concentration bin of 0–100 µeq/L in Yellowstone, only elevation of lake outlet (min_elev, tables 8 and 11) (p-value = 0.052) was significant at the 95-percent confidence interval, such that as elevation of lake outlet increases the probability that ANC concentration is 0–100 µeq/L increases. Thus, elevation of lake outlet was used as the explanatory variable in the final multivariate logistic regression model. The Hosmer-Lemeshow Goodness-of-Fit indicates a good model fit to the calibration data. Measured ANC concentrations 0–100 µeq/L compared to predicted ANC concentrations 0–100 µeq/L in groupings of 10 percent in Yellowstone, showed good agreement with a r-squared value equal to 0.61 (table 11). The c statistic is equal to 0.95, indicating good association. The following probability equation was applied to the 294 delineated basins.

$$\text{Logit (P)} = \frac{e^{(-40.149 + 0.005(\text{min\_elev}))}}{1 + e^{(-40.149 + 0.005(\text{min\_elev}))}} \qquad (5)$$

where Logit (P) and e are defined as in equation 1.

For an ANC concentration bin of 0–200 µeq/L, the elevation of lake outlet (p-value = 0.091) and the bedrock type with high buffering capacity (GC 3) (p-value = 0.053) were significant at the 95-percent confidence interval, such that as elevation of lake outlet increased and the amount of the basin with bedrock type GC 3 increased, the probability for an ANC concentration to be 0–200 µeq/L increases. Thus, elevation of lake outlet and bedrock type GC 3 were used as the explanatory variables in the multiple logistic regression models. Measured ANC concentrations less than 200 µeq/L compared to predicted in groupings of 10 percent in Yellowstone showed agreement with a r-squared value equal to 0.54 (table 11). The c statistic is equal to 0.78, indicating good association.

The following probability equation was applied to the 294 delineated basins with unknown lake chemistry:

$$\text{Logit (P)} = \frac{e^{(-14.901 + 0.002(\text{min\_elev}) + 3.080(\text{GC 3}))}}{1 + e^{(-14.901 + 0.002(\text{min\_elev}) + 3.080(\text{GC 3}))}} \qquad (6)$$

where Logit (P) and e are defined as in equation 1.

Sensitivity of Alpine and Subalpine Lakes to Acidification from Atmospheric Deposition

Grand Teton National Park

The probabilities associated with each basin provide an indication of the lake sensitivity to acidification from atmospheric deposition. Results for Grand Teton lakes with probabilities of being in an ANC concentration bin are presented in table 6. Results indicated that 7 percent of the lakes had a greater than 60-percent probability of having ANC concentrations 0–50 µeq/L and 0 percent of the lakes had a greater than 80-percent probability of having ANC concentrations 0–50 µeq/L (table 1). Lakes with a greater than 60-percent probability of an ANC concentration bin of 0–50 µeq/L are located in areas with steep slopes and soil type 9 in western and southwestern Grand Teton (fig. 7).

Results indicated that 36 percent of lakes had a greater than 60-percent probability of having ANC concentrations less than 100 µeq/L, and 14 percent of lakes had a greater than 80-percent probability of having ANC concentrations 0–100 µeq/L (table 2). Lakes with a greater than 60-percent probability of lake sensitivity with respect to atmospheric deposition for an ANC concentration bin of 0–100 µeq/L are shown in fig. 8. Lakes with greater than 80-percent probability that ANC concentration is less than 100 µeq/L are located in western and southwestern Grand Teton. The same lakes that are significant in Grand Teton for the 0–50 ANC bin are significant at the 0–100 ANC bin.

Table 1. Predicted number and percentage of lakes in Grand Teton National Park by probability of an acid-neutralizing capacity concentration bin of 0–50 microequivalents per liter.

[Total number of lakes used in the calculation of percentage of lakes in Grand Teton National Park is 106; µeq/L, microequivalents per liter; %, percent; ANC, acid-neutralizing capacity]

Probability of ANC concentration less than 50 µeq/L	Number of lakes	Percentage of lakes
Greater than 10%	25	24%
Greater than 20%	20	19%
Greater than 30%	14	13%
Greater than 40%	12	11%
Greater than 50%	8	8%
Greater than 60%	7	7%
Greater than 70%	5	5%
Greater than 80%	0	0%
Greater than 90%	0	0%

Results indicate that 59 percent of lakes had a greater than 60-percent probability of having ANC concentrations less than 200 μeq/L, and 46 percent of lakes had a greater than 80-percent probability of having ANC concentrations 0–200 μeq/L (table 3). Lakes with a greater than 60-percent probability of lake sensitivity with respect to atmospheric deposition for an ANC concentration bin of 0–200 μeq/L are shown in fig. 9. Lakes with an 80- to 100-percent probability that ANC concentration is less than 200 μeq/L are located throughout western and southwestern Grand Teton.

Table 2. Predicted number and percentage of lakes in Grand Teton National Park by probability of an acid-neutralizing capacity concentration bin of 0–100 microequivalents per liter.

[Total number of lakes used in the calculation of percentage of lakes in Grand Teton National Park is 106; μeq/L, microequivalents per liter; %, percent; ANC, acid-neutralizing capacity]

Probability of ANC concentration less than 100 μeq/L	Number of lakes	Percentage of lakes
Greater than 10%	81	76%
Greater than 20%	61	58%
Greater than 30%	55	52%
Greater than 40%	54	51%
Greater than 50%	44	42%
Greater than 60%	38	36%
Greater than 70%	30	28%
Greater than 80%	15	14%
Greater than 90%	6	5%

Table 3. Predicted number and percentage of lakes in Grand Teton National Park by probability of an acid-neutralizing capacity concentration bin of 0–200 microequivalents per liter.

[Total number of lakes used in the calculation of percentage of lakes in Grand Teton National Park is 106; μeq/L, microequivalents per liter; %, percent; ANC, acid-neutralizing capacity]

Probability of ANC concentration less than 200 μeq/L	Number of lakes	Percentage of lakes
Greater than 10%	75	71%
Greater than 20%	71	67%
Greater than 30%	67	63%
Greater than 40%	64	60%
Greater than 50%	64	60%
Greater than 60%	63	59%
Greater than 70%	57	54%
Greater than 80%	49	46%
Greater than 90%	29	27%

Yellowstone National Park

Results for Yellowstone lakes with probabilities of being in an ANC concentration bin are presented in table 10. Results indicated that 13 percent of lakes had a greater than 60-percent probability of having ANC concentrations 0–100 μeq/L, and 9 percent of lakes had a greater than 80-percent probability of having ANC concentrations 0–100 μeq/L (table 4). Lakes with a greater than 60-percent probability of lake sensitivity with respect to atmospheric deposition for an ANC concentration bin of 0–100 μeq/L are shown in fig. 10. Lakes with 80- to 100-percent probability that ANC concentration is less than 100 μeq/L are located throughout eastern and northwestern Yellowstone. The exception is unnamed lake (261) in southwestern Yellowstone.

Results indicated that 27 percent of lakes had a greater than 60-percent probability of having ANC concentrations 0–200 μeq/L, and 13 percent of lakes had a greater than 80-percent probability of having ANC concentrations less than 200 μeq/L (table 5). Lakes with a greater than 60-percent probability of lake sensitivity with respect to atmospheric deposition for an ANC concentration bin of 0–200 μeq/L are shown in fig. 11. Lakes with greater than or equal to 90-percent probability that ANC concentration is 0–200 μeq/L are located throughout eastern and central Yellowstone. The exception is unnamed lake (261) in southwestern Yellowstone. Lakes with greater than 80-percent probability that ANC concentration is less than 200 μeq/L are located throughout central, southeastern, and southwestern Yellowstone.

Comparison between Grand Teton National Park and Yellowstone National Park

For comparison of results between Grand Teton and Yellowstone, an ANC concentration bin of 0–100 μeq/L was selected because it was the lowest ANC concentration bin used for the multivariate logistic regression analysis that was common to both parks. The results of the modeling in Grand Teton and Yellowstone indicate that the identification of lakes can be based on a greater than 60-percent probability of having an ANC concentration bin 0–100 μeq/L. A higher percentage of lakes in Grand Teton (36 percent) were determined to be sensitive to deposition of contaminants than in Yellowstone (13 percent) for the 0–100 μeq/L ANC bin.

For Grand Teton and Yellowstone, the elevation of the lake outlet was significantly correlated with ANC concentration such that as elevation increased, ANC concentration decreased. In Grand Teton, the area of the basin with northeast aspects also was significant. Results of this study indicate that the lakes that exceeded 60-percent probability of having an ANC concentration of less than 100 μeq/L, and therefore at risk to atmospheric deposition, are located at elevations greater than 2,790 m in Grand Teton and greater than 2,590 m in Yellowstone. Rutkowski and others (2001) used a GIS-based model to assess surface-water sensitivity to atmospheric deposition in Wilderness Areas of Nevada, Idaho, Utah, and Wyoming, and determined that elevation and bedrock geology were significant predictors of low ANC surface waters.

Table 4. Predicted number and percentage of lakes in Yellowstone National Park by probability of an acid-neutralizing capacity concentration bin of 0–100 microequivalents per liter.

[Total number of lakes used in the calculation of percentage of lakes in Yellowstone National Park is 294; μeq/L, microequivalents per liter; %, percent; ANC, acid-neutralizing capacity]

Probability of ANC concentration less than 100 μeq/L	Number of lakes	Percentage of lakes
Greater than 10%	101	34%
Greater than 20%	88	30%
Greater than 30%	73	25%
Greater than 40%	55	19%
Greater than 50%	43	15%
Greater than 60%	38	13%
Greater than 70%	29	10%
Greater than 80%	26	9%
Greater than 90%	16	5%

Table 5. Predicted number and percentage of lakes in Yellowstone National Park by probability of an acid-neutralizing capacity concentration bin of 0–200 microequivalents per liter.

[Total number of lakes used in the calculation of percentage of lakes in Yellowstone National Park is 294; μeq/L, microequivalents per liter; %, percent; ANC, acid-neutralizing capacity]

Probability of ANC concentration less than 200 μeq/L	Number of lakes	Percentage of lakes
Greater than 10%	207	70%
Greater than 20%	164	56%
Greater than 30%	132	45%
Greater than 40%	115	39%
Greater than 50%	97	33%
Greater than 60%	80	27%
Greater than 70%	60	20%
Greater than 80%	39	13%
Greater than 90%	15	5%

Atmospheric deposition of inorganic nitrogen, sulfate, and acidity was not significantly correlated with ANC concentrations, which may be because deposition is fairly similar among these sites. However, very high-risk basins include lakes where ANC concentrations are low and atmospheric deposition of contaminants is relatively high. Lakes with a greater than 60-percent probability of having an ANC concentration less than 100 μeq/L in Grand Teton and Yellowstone were within the following ranges for average annual atmospheric deposition: 0.05–0.15 kg/ha/yr hydrogen ion, 1.0–3.5 kg/ha/year inorganic nitrogen, 2–8 kg/ha/yr sulfate. Summit lake and unnamed lake (261) in southwestern Yellowstone were located in an area with deposition of 2–2.5 kg/ha/year inorganic nitrogen.

The uncertainty associated with the combined use of GIS modeling and multivariate logistic regression is difficult to quantify. The best available NPS GIS data for Grand Teton and Yellowstone were used in this study; however, finer resolution GIS data, not currently (2005) available, may improve the model. Differences in the resolution of the geology and soils GIS data between Grand Teton and Yellowstone may have influenced the comparison results. Additionally, the physical geology, including the presence of major geologic contacts or faults within each lakes basin influences ANC concentration to an unknown degree and was not included as a variable in this study. Environmental variables other than those included in this study also may contribute to variability in some lake ANC concentrations and can be difficult to quantify; these variables could include recreational use, fire, and thermal activity.

The GIS and logistic regression modeling approach described in this report can be used as a cost-effective tool to help resource managers identify lakes likely to be sensitive to atmospheric deposition of contaminants and develop long-term monitoring programs. The sensitivity for both Grand Teton and Yellowstone lakes indicate a need for long-term monitoring, to identify seasonal variability and episodic acidification. In the future, it may be prudent to use the probability estimates to identify one to two alpine lakes in each park with a lake area of 1–4 ha that could be monitored by collecting samples each season for a minimum of 5 years. These intensive monitoring sites also could include climate stations for precipitation sample collection. The combination of intensive lake-chemistry and precipitation-chemistry data at one to two alpine lakes in each park would allow resource managers to observe short-term and long-term variability in inorganic nitrogen and sulfate deposition. Additionally, three to four lakes could be sampled once annually for at least 10 years to monitor long-term change. These could include lakes with the highest probability for ANC concentrations less than 50 μeq/L in Grand Teton and less than 100 μeq/L in Yellowstone, and with good spatial distribution within each park.

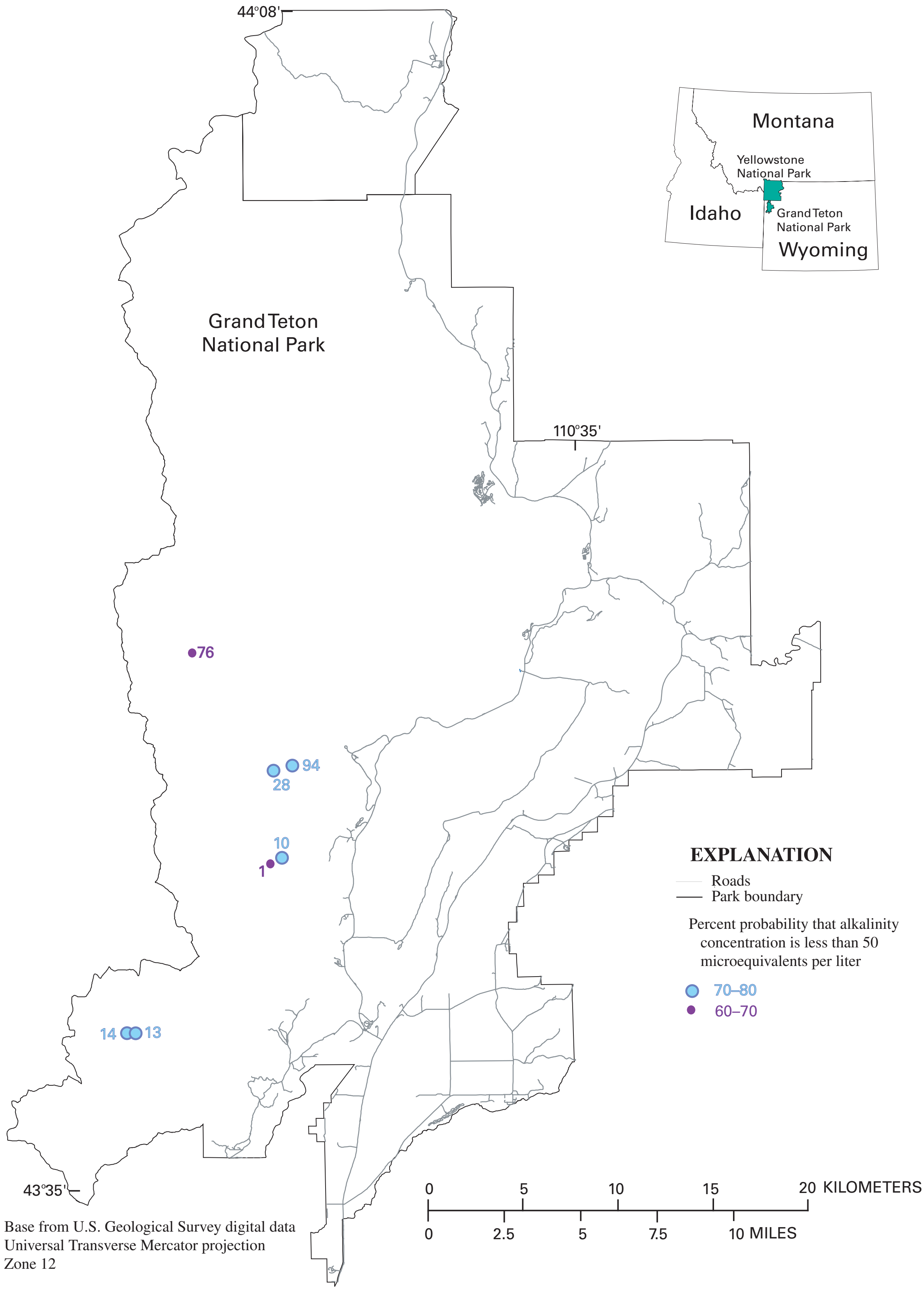


Figure 7. Probability greater than 60 percent of lake sensitivity in Grand Teton National Park to atmospheric deposition using an acid-neutralizing capacity concentration bin of 0–50 microequivalents per liter.

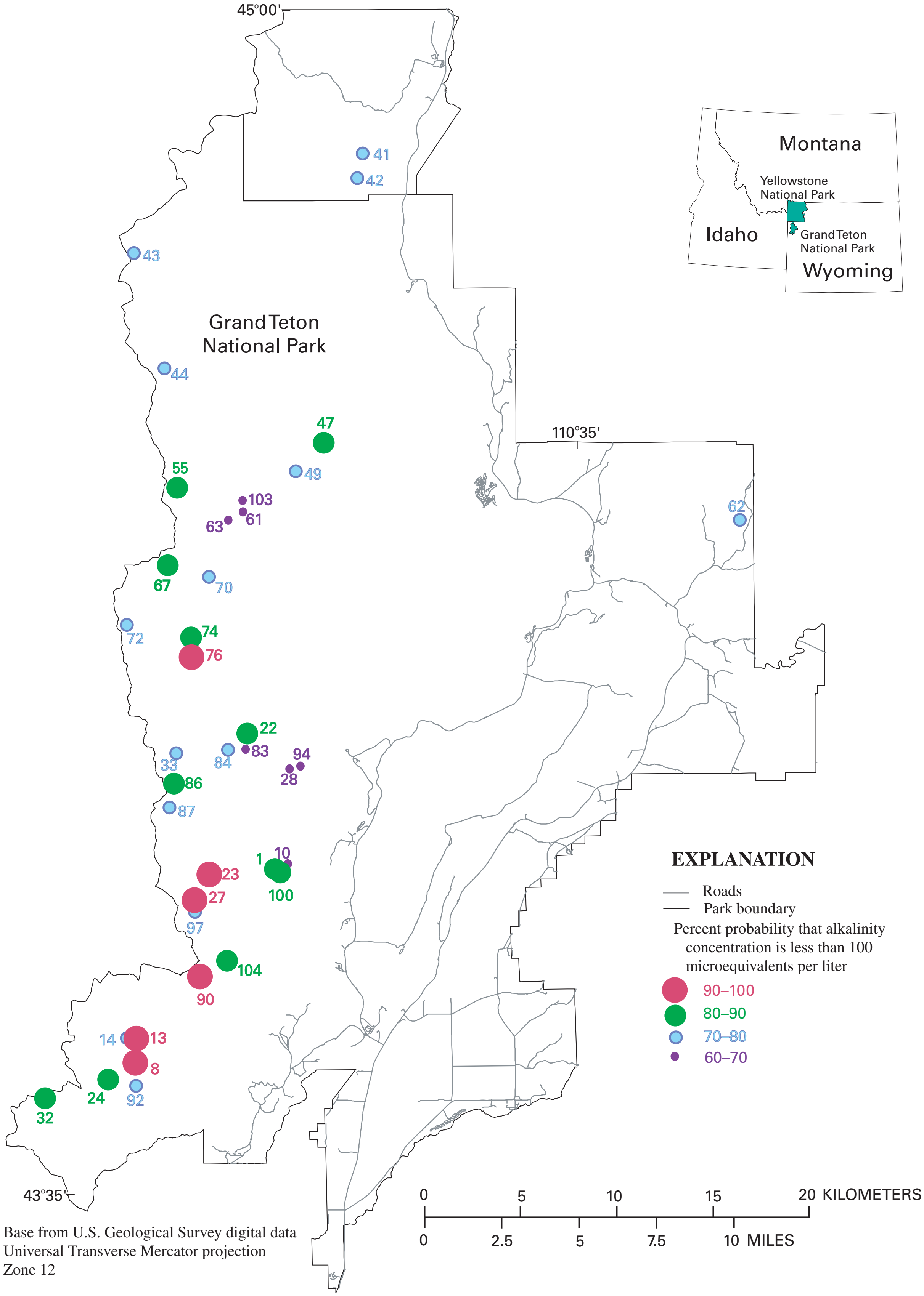
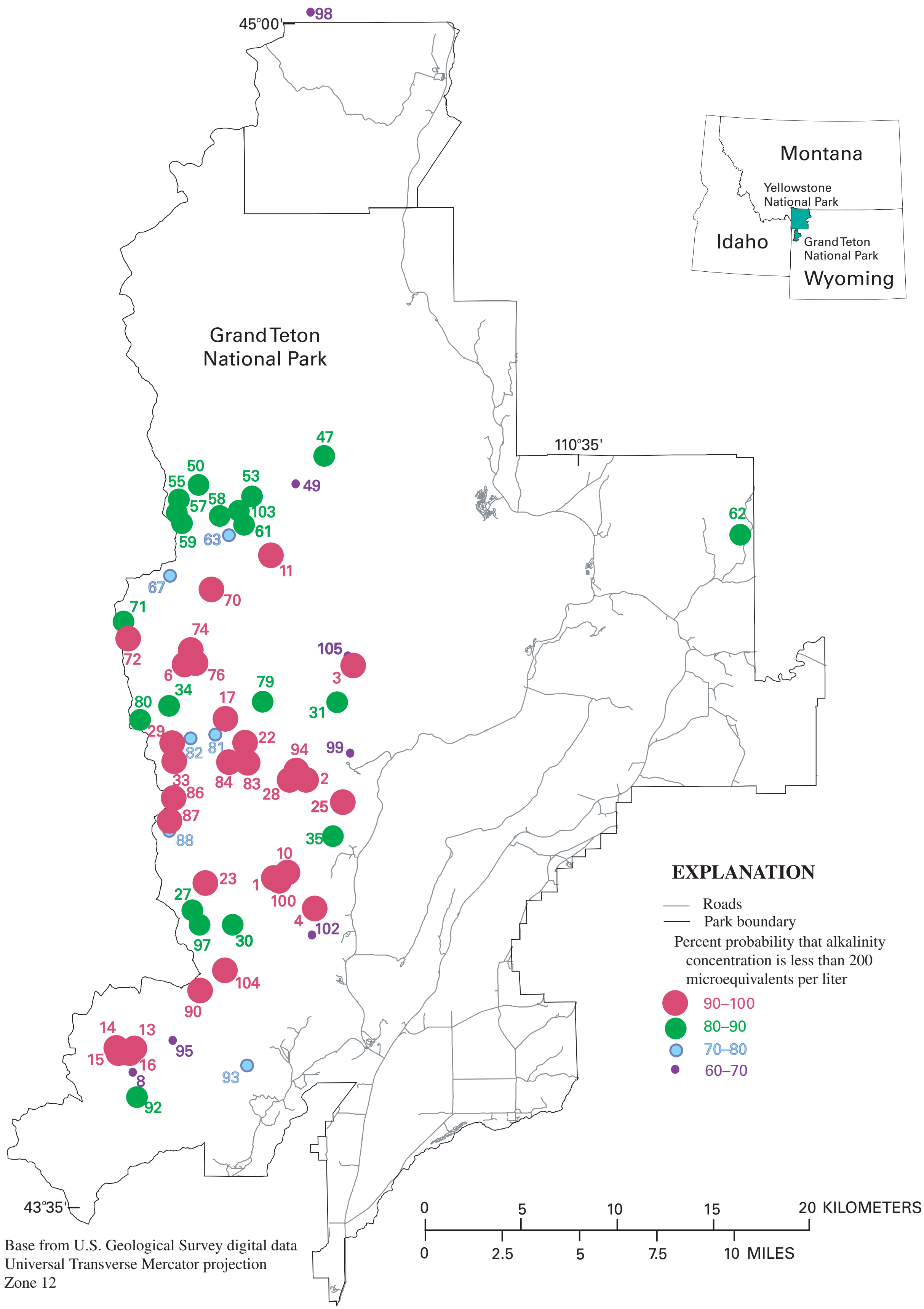


Figure 8. Probability greater than 60 percent of lake sensitivity in Grand Teton National Park to atmospheric deposition using an acid-neutralizing capacity concentration bin of 0–100 microequivalents per liter.



Base from U.S. Geological Survey digital data
Universal Transverse Mercator projection
Zone 12

Figure 9. Probability greater than 60 percent of lake sensitivity in Grand Teton National Park to atmospheric deposition using an acid-neutralizing capacity concentration bin of 0–200 microequivalents per liter.

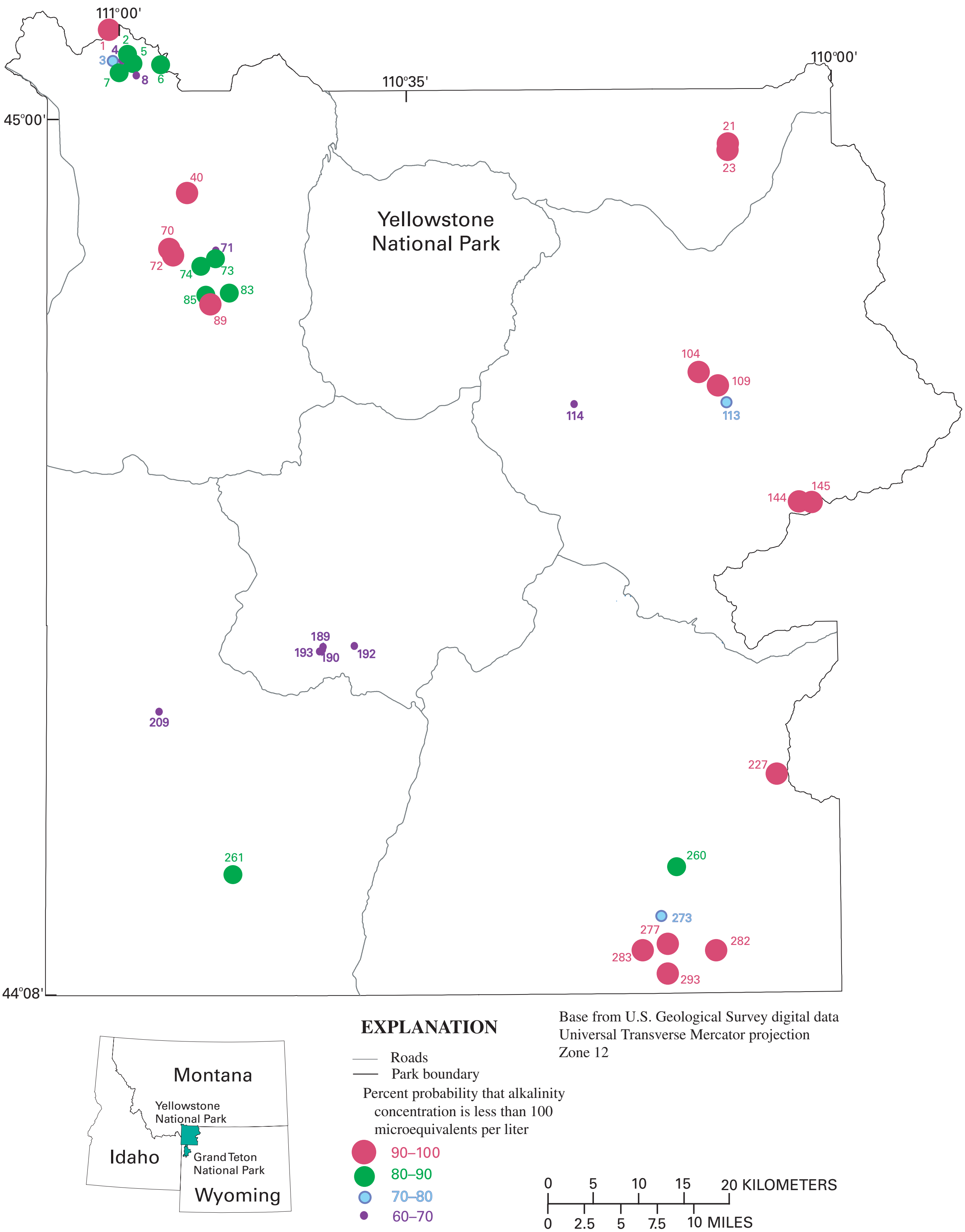


Figure 10. Probability greater than 60 percent of lake sensitivity in Yellowstone National Park to atmospheric deposition using an acid-neutralizing capacity concentration bin of 0–100 microequivalents per liter.

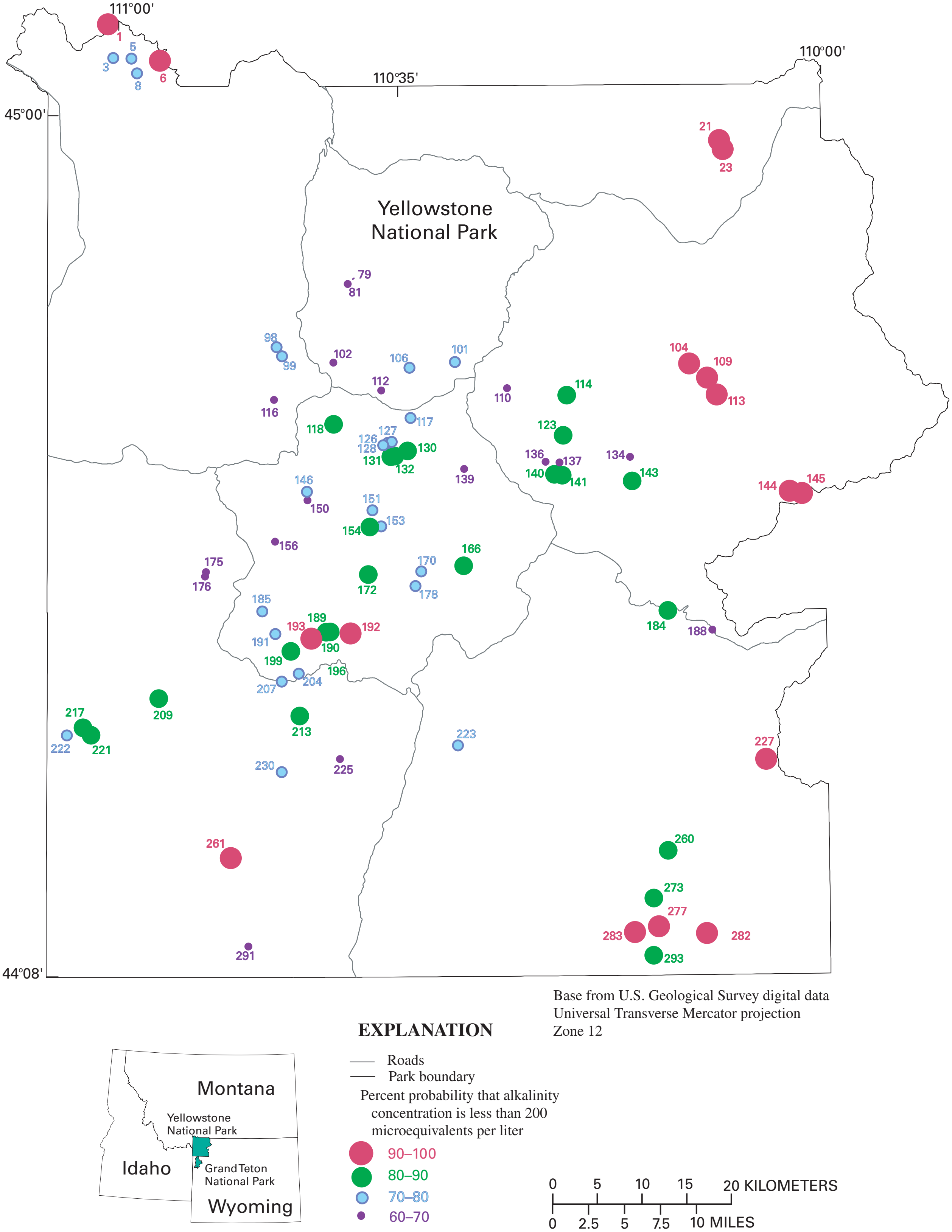


Figure 11. Probability greater than 60 percent of lake sensitivity in Yellowstone National Park to atmospheric deposition using an acid-neutralizing capacity concentration bin of 0–200 microequivalents per liter.

Summary

The sensitivity of lakes in Grand Teton and Yellowstone National Parks to atmospheric deposition of contaminants was estimated based on statistical relations between ANC concentrations and basin characteristics. This study combined the use of Geographic Information System (GIS) modeling and multivariate logistic regression using the best available GIS and water-quality data for alpine/subalpine lakes in Grand Teton and Yellowstone National Parks. The result is the identification of a subset of lakes with a high probability of having low ANC concentrations and thus greater sensitivity to atmospheric deposition of nitrate, sulfate, and hydrogen ion.

Relations between ANC concentrations and basin characteristics were explored. ANC concentrations that were measured at 52 lakes in Grand Teton and 23 lakes in Yellowstone during synoptic surveys were used to calibrate the statistical models. Basin characteristics were derived from GIS including topography, geology, vegetation, and soils. Multivariate logistic regression models were developed, and the resultant probability equations for ANC concentrations less than 50, 100, and 200 microequivalents per liter were applied to lake basins greater than 1 hectare in Grand Teton (106 lakes) and Yellowstone (294 lakes). A higher percentage of lakes in Grand Teton (36 percent) than in Yellowstone (13 percent) were predicted to be sensitive to atmospheric deposition. The lakes that exceeded 60-percent probability of having an ANC concentration less than 100 μeq/L and, therefore, had the greatest sensitivity to atmospheric deposition of contaminants, are located at elevations greater than 2,790 meters (m) in Grand Teton, and greater than 2,590 m in Yellowstone.

The GIS and logistic regression modeling approach can be used as a cost-effective tool to help resource managers identify lakes likely to be sensitive to atmospheric deposition of contaminants and develop long-term monitoring programs within the parks.

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Appendix

Table 6. Lakes greater than 1 hectare in Grand Teton National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–50, 0–100, and 0–200 microequivalents per liter.

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 3 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability		
						0–50 μeq/L	0–100 μeq/L	0–200 μeq/L
1	Amphitheater Lake	43.72	–110.78	2,956	1.87	64.69%	82.06%	91.19%
2	Arrowhead Lake	43.77	–110.75	2,790	0.23	51.95%	13.30%	91.19%
3	Bearpaw Lake	43.82	–110.73	2,088	4.59	12.01%	10.63%	76.17%
4	Bradley Lake	43.71	–110.75	2,141	27.11	27.89%	7.05%	85.95%
5	Christian Pond	43.87	–110.56	2,084	12.66	0.02%	5.16%	25.27%
6	Cirque Lake	43.83	–110.83	2,929	24.93	4.13%	43.72%	91.19%
7	Cow Lake	43.82	–110.56	2,083	6.43	0.02%	11.08%	7.48%
8	Coyote Lake	43.63	–110.87	3,110	1.62	4.81%	93.51%	63.92%
9	Cygnet Pond	43.9	–110.61	2,084	7.59	0.02%	16.91%	7.57%
10	Delta Lake	43.73	–110.77	2,748	2.77	72.59%	62.60%	91.18%
11	Dudley Lake	43.88	–110.78	2,512	3.83	41.86%	6.30%	91.00%
12	Emma Matilda Lake	43.88	–110.53	2,095	359.25	0.02%	1.23%	24.15%
13	Forget Me Not Lakes	43.65	–110.87	2,921	1.62	3.81%	72.66%	91.06%
14	Forget Me Not Lakes	43.65	–110.87	2,964	0.12	74.62%	91.92%	91.19%
15	Forget Me Not Lakes	43.64	–110.87	2,967	0.1	74.62%	41.84%	91.19%
16	Forget Me Not Lakes	43.64	–110.87	2,950	0.37	3.10%	23.91%	84.16%
17	Grizzly Bear Lake	43.8	–110.81	2,810	5.18	4.14%	48.93%	91.19%
18	Halfmoon Lake	43.82	–110.42	2,064	2.12	0.02%	0.66%	7.80%
19	Hechtman Lake	44.04	–110.79	2,394	3.02	44.95%	44.46%	7.27%
20	Hedrick Pond	43.75	–110.59	2,047	6.37	0.02%	11.32%	7.51%
21	Heron Pond	43.88	–110.63	2,065	8.72	0.02%	10.14%	7.70%
22	Holly Lake	43.79	–110.79	2,868	2.89	7.72%	84.00%	91.19%
23	Iceflow Lake	43.72	–110.82	3,247	9.39	20.97%	92.41%	90.87%
24	Indian Lake	43.63	–110.88	2,988	7.38	1.55%	87.54%	51.23%
25	Jenny Lake	43.76	–110.73	2,067	489.58	6.12%	4.89%	67.44%
26	Kelly Warm Spring	43.63	–110.61	2,037	0.26	0.02%	13.93%	7.27%
27	Kit Lake	43.71	–110.83	3,145	1.26	1.19%	95.92%	79.82%
28	Lake of the Crags	43.77	–110.77	2,916	4.47	78.93%	68.58%	91.19%
29	Lake Solitude	43.79	–110.84	2,755	15.08	18.47%	55.89%	90.00%
30	Lake Taminah	43.7	–110.8	2,761	5.46	16.94%	52.80%	88.41%
31	Leigh Lake	43.81	–110.73	2,094	413.49	6.30%	5.13%	67.55%
32	Marion Lake	43.62	–110.92	2,812	2.11	2.64%	83.93%	7.51%
33	Mica Lake	43.78	–110.84	2,913	3.85	7.77%	72.55%	91.19%
34	Mink Lake	43.81	–110.84	2,715	3.83	14.67%	6.56%	72.41%
35	Moose Pond	43.74	–110.74	2,065	0.61	10.92%	17.37%	80.56%
36	Noname-1	44.12	–110.76	2,310	1.13	0.02%	37.49%	7.27%
37	Noname-2	44.09	–110.7	2,100	1.09	0.02%	23.35%	7.27%
38	Noname-3	44.09	–110.68	2,070	4.63	0.02%	5.19%	7.27%
39	Noname-4	44.08	–110.68	2,070	1.88	0.02%	9.58%	7.27%
40	Noname-5	44.07	–110.78	2,459	1.29	0.15%	22.88%	7.27%
41	Noname-6	44.06	–110.71	2,067	1.69	0.11%	76.16%	7.27%
42	Noname-7	44.05	–110.72	2,067	3.28	0.03%	76.16%	7.27%
43	Noname-8	44.01	–110.86	2,581	1.13	0.02%	76.16%	7.27%

Table 6. Lakes greater than 1 hectare in Grand Teton National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–50, 0–100, and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 3 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability		
						0–50 μeq/L	0–100 μeq/L	0–200 μeq/L
44	Noname-9	43.96	–110.84	2,797	1.15	0.15%	76.16%	31.21%
45	Noname-10	43.93	–110.63	2,072	3.27	0.02%	6.52%	11.57%
46	Noname-11	43.93	–110.62	2,108	10.76	0.02%	19.10%	9.92%
47	Noname-12	43.93	–110.74	2,969	1.26	5.70%	80.67%	87.75%
48	Noname-13	43.92	–110.49	2,231	1.34	0.02%	11.87%	9.05%
49	Noname-14	43.91	–110.76	2,932	4.57	1.78%	73.69%	64.83%
50	Noname-15	43.91	–110.82	2,758	6.21	0.64%	52.35%	87.11%
51	Noname-16	43.91	–110.62	2,097	4.42	0.02%	13.21%	17.62%
52	Noname-17	43.91	–110.56	2,127	1.71	0.09%	11.75%	8.44%
53	Noname-18	43.91	–110.79	3,059	4.25	2.29%	82.96%	83.86%
54	Noname-19	43.91	–110.63	2,084	1.31	0.02%	5.80%	8.14%
55	Noname-20	43.91	–110.83	2,908	3.56	1.07%	56.45%	87.07%
56	Noname-21	43.9	–110.53	2,124	5.9	0.02%	10.09%	7.88%
57	Noname-22	43.9	–110.83	2,967	6.44	2.15%	45.55%	89.28%
58	Noname-23	43.9	–110.81	2,915	2.53	1.34%	46.89%	87.03%
59	Noname-24	43.9	–110.83	3,067	1.38	1.25%	57.20%	91.19%
60	Noname-25	43.89	–110.48	2,104	3.74	0.02%	12.36%	8.56%
61	Noname-26	43.89	–110.79	2,794	2.36	3.88%	61.01%	82.56%
62	Noname-27	43.89	–110.47	2,961	1.41	1.52%	77.85%	88.86%
63	Noname-28	43.89	–110.8	2,988	1.41	3.03%	65.44%	71.06%
64	Noname-29	43.89	–110.48	2,157	1.02	0.02%	25.60%	7.51%
65	Noname-30	43.88	–110.58	2,086	1.93	0.02%	1.23%	7.27%
66	Noname-31	43.87	–110.57	2,085	1.04	0.02%	16.18%	7.27%
67	Noname-32	43.87	–110.84	2,919	3.91	5.69%	89.15%	73.08%
68	Noname-33	43.87	–110.73	2,078	2.35	0.02%	16.41%	9.37%
69	Noname-34	43.87	–110.72	2,072	1.48	0.02%	3.55%	10.63%
70	Noname-35	43.86	–110.81	2,942	1.75	8.08%	74.41%	90.08%
71	Noname-36	43.85	–110.87	2,958	3.86	0.13%	10.51%	89.19%
72	Noname-37	43.84	–110.87	2,988	1.36	2.32%	65.60%	91.19%
73	Noname-38	43.84	–110.71	2,066	15.52	0.02%	4.35%	20.88%
74	Noname-39	43.84	–110.83	2,814	3.19	10.05%	79.79%	90.79%
75	Noname-40	43.83	–110.58	2,120	2.29	0.02%	23.50%	7.27%
76	Noname-41	43.83	–110.82	3,011	1.26	63.42%	93.21%	91.19%
77	Noname-42	43.83	–110.72	2,087	1.85	0.02%	16.69%	9.90%
78	Noname-43	43.82	–110.61	2,098	3.21	0.02%	26.09%	8.08%
79	Noname-44	43.81	–110.78	2,376	2.45	30.98%	19.41%	77.24%
80	Noname-45	43.8	–110.86	2,929	1.19	4.13%	43.72%	91.19%
81	Noname-46	43.8	–110.81	2,097	1.04	26.08%	4.83%	91.19%
82	Noname-47	43.79	–110.83	2,898	1.18	7.99%	56.17%	67.96%
83	Noname-48	43.78	–110.79	2,799	1.26	5.35%	67.67%	90.51%
84	Noname-49	43.78	–110.8	2,967	1.04	4.72%	79.11%	91.19%
85	Noname-50	43.78	–110.62	2,035	1.45	0.02%	11.63%	7.27%
86	Noname-51	43.77	–110.84	3,060	2.28	9.20%	80.11%	91.19%

Table 6. Lakes greater than 1 hectare in Grand Teton National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–50, 0–100, and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; µeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 3 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability		
						0–50 µeq/L	0–100 µeq/L	0–200 µeq/L
87	Noname-52	43.76	–110.84	2,929	2.03	2.35%	75.75%	91.07%
88	Noname-53	43.75	–110.84	2,918	1.59	3.68%	43.64%	87.67%
89	Noname-54	43.71	–110.74	2,143	2.48	0.02%	1.83%	37.08%
90	Noname-55	43.68	–110.82	3,118	1.14	1.27%	93.50%	91.19%
91	Noname-56	43.65	–110.73	1,962	1.14	0.02%	13.67%	7.27%
92	Noname-57	43.63	–110.86	3,066	1.05	20.68%	76.16%	82.05%
93	Phelps Lake	43.64	–110.79	2,023	184.72	5.57%	7.28%	63.02%
94	Ramshead Lake	43.77	–110.76	2,894	1.05	77.97%	68.93%	91.19%
95	Rimrock Lake	43.65	–110.84	3,023	6.46	26.50%	47.22%	80.10%
96	Schoolroom Lake	43.72	–110.84	3,067	0.94	1.23%	44.69%	26.34%
97	Snowdrift Lake	43.7	–110.82	3,051	22.18	2.88%	77.73%	85.41%
98	South Boundary Lake	44.13	–110.75	2,248	6.65	0.02%	1.62%	91.19%
99	String Lake	43.78	–110.73	2,094	29.55	4.51%	5.52%	63.60%
100	Surprise Lake	43.72	–110.77	2,906	0.94	41.78%	85.18%	91.19%
101	Swan Lake	43.88	–110.63	2,062	26.24	0.02%	10.97%	7.78%
102	Taggart Lake	43.7	–110.75	2,104	46.33	31.18%	6.59%	85.34%
103	Talus Lake	43.9	–110.8	2,947	8.52	1.15%	69.18%	86.00%
104	Timberline Lake	43.68	–110.81	3,141	2.03	47.94%	88.39%	91.19%
105	Trapper Lake	43.83	–110.73	2,107	1.36	23.99%	10.18%	77.37%
106	Two Ocean Lake	43.91	–110.53	2,102	238.72	0.02%	7.92%	11.65%

Table 7. Results of univariate logistic regression analyses for Grand Teton National Park at acid-neutralizing capacity concentration bins of 0–50, 0–100, and 0–200 microequivalents per liter and explanatory variable definitions and units.

[µeq/L, microequivalents per liter; ha, hectare; m^2, meters squared; sed., sedimentary rocks; kg/ha/yr, kilograms per hectare per year; N, nitrogen; SO_4, sulfate; S, sulfur; mm/yr, millimeters per year]

Variable	*p*-value			Definition and units
	0–50 µeq/L	0–100 µeq/L	0–200 µeq/L	
lkarea	0.246	0.12	0.304	Area of lake (ha*10,000 or m^2)
lkperim	0.139	0.071	0.107	Perimeter of lake (ha*10,000 or m^2)
wsarea	0.219	0.063	0.103	Area of basin area (ha*10,000 or m^2)
lk_wsare	0.532	0.965	0.249	Lake area/basin Area
lake_per	0.206	0.604	0.076	Lake area/perimeter of lake
head	0.551	0.33	0.686	Headwater lake yes(1) or no(0)
GC 1	0.153	0.011	0	Fraction of basin that is gneiss, quartzite, schist, or granite
GC 2	0.986	0.986	0.981	Fraction of basin that is andesite, dacite, diorite, or phyllite
GC 3	0.628	0.457	0.318	Fraction of basin that is basalt, gabbro, wacke, argillite, or volcanics
GC 4	0.222	0.019	0.003	Fraction of basin that is amphibolite, hornfels, paragneiss, metamorphics
GC 5	0.756	0.685	0.273	Fraction of basin that is metacarbonate, marine sed., marble, calcium silicate and basic intrusive rocks
max_slp	0.475	0.356	0.039	Maximum slope of watershed
mean_slp	0.115	0.085	0.004	Mean slope of basin
min_elev	0.051	0.001	0.005	Lake outlet elevation
max_elev	0.158	0.172	0.008	Maximum elevation of basin
meanelev	0.069	0.008	0.001	Mean elevation of basin
stpslpe	0.076	0.095	0.006	Fraction of slopes greater than 30 degrees
asp45	0.06	0.047	0.944	Fraction of basin with aspect 0–45 degrees
asp4590	0.752	0.888	0.083	Fraction of basin with aspect 45–90 degrees
asp90135	0.792	0.778	0.381	Fraction of basin with aspect 90–135 degrees
asp135180	0.287	0.641	0.56	Fraction of basin with aspect 135–180 degrees
asp180225	0.848	0.238	0.813	Fraction of basin with aspect 180–225 degrees
asp225270	0.343	0.62	0.229	Fraction of basin with aspects of 225–270 degrees
asp270315	0.614	0.254	0.844	Fraction of basin with aspect 270–315 degrees
asp315360	0.297	0.375	0.277	Fraction of basin with aspect 315–360 degrees
med_veg	0.496	0.013	0.008	Fraction of basin that is forest or tundra
low_veg	0.821	0.067	0.149	Fraction of basin that is subalpine meadow
high_veg	0.687	0.132	0.031	Fraction of basin that is agriculture or unvegetated (snow, rock, ice, water)
mean_n	0.75	0.30	0.03	Mean annual inorganic N deposition in basin (kg/ha/yr inorganic N)
mean_so4	0.497	0.158	0.028	Mean annual sulfate deposition in basin (kg/ha/yr SO_4-S)
mean_h	0.876	0.491	0.047	Mean annual hydrogen ion deposition in basin (kg/ha/yr H^+)
mean_ppt	0.371	0.049	0.003	Mean annual precipitation of basin (mm/yr)
soil_1	0.697	0.027	0.006	Fraction of basin that is rock outcrop/rubble land/water
soil_2	0.951	0.927	0.925	Fraction of basin that is of gravelly loam
soil_3	0.916	0.912	0.903	Fraction of basin that is loam other than gravelly loam
soil_5	0.973	0.959	0.959	Fraction of basin that is Buffork-Adel Association
soil_6	0.969	0.954	0.961	Fraction of basin that is Buffork-Tongue_River-Clayburn
soil_7	0.879	0.875	0.203	Fraction of basin that is Cryaquolis-Cryofibrists-Comp.
soil_9	0.06	0.374	0.189	Fraction of basin that is Leighton-Moran_Wolcott_association
soil_10	0.97	0.97	0.957	Fraction of basin that is Perceton-Bufork_association
soil_12	0.649	0.121	0.059	Fraction of basin that is Taglake_Sebud association
soil_14	0.986	0.986	0.981	Fraction of basin that is Tineman Association
soil_15	0.967	0.948	0.958	Fraction of basin that is Youga_tineman Association
soil_16	0.986	0.986	0.981	Fraction of basin that is Uhl_rockman Association
soil_17	0.958	0.937	0.157	Fraction of basin that is Unknown Soils

Table 8. Results of univariate logistic regression analyses for Yellowstone National Park at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter and explanatory variable definitions and units.

[µeq/L, microequivalents per liter; ha, hectare; m^2, meters squared; kg/ha/yr, kilograms per hectare per year; N, nitrogen, SO_4, sulfate, S, sulfur, mm/yr, millimeters per year]

Variable	*p*-value		Definition and units
	0–100 µeq/L	0–200 µeq/L	
lkarea	0.867	0.589	Area of lake (ha*10,000 or m^2)
lkperim	0.637	0.423	Perimeter of lake (ha*10,000 or m^2)
wsarea	0.394	0.322	Area of basin area (ha*10,000 or m^2)
lk_wsare	0.695	0.132	Lake area/basin area
lake_per	0.911	0.611	Lake area/perimeter of lake
head	0.950	0.187	Headwater lake yes(1) or no(0)
GC 1	0.708	0.580	Fraction of basin that is gneiss, quartzite, schist, or granite
GC 2	0.649	0.479	Fraction of basin that is andesite, dacite, diorite, or phyllite
GC 3	0.456	0.072	Fraction of basin that is basalt, gabbro, wacke, argillite, or volcanics
GC 4	0.377	0.305	Fraction of basin that is amphibolite, hornfels, paragneiss, or metamorphics
GC 6	0.922	0.914	Fraction of basin that is unknown buffering capacity of bedrock
mx_slp	0.061	0.156	Maximum slope of watershed
mean_slp	0.309	0.619	Mean slope of basin
min_elev	0.052	0.134	Lake outlet elevation
max_elev	0.515	0.689	Maximum elevation of basin
meanelev	0.093	0.368	Mean elevation of basin
stpslpe	0.279	0.520	Fraction of slopes greater than 30 degrees
asp45	0.445	0.680	Fraction of basin with aspect 0–45 degrees
asp4590	0.432	0.551	Fraction of basin with aspect 45–90 degrees
asp90135	0.497	0.817	Fraction of basin with aspect 90–135 degrees
asp135180	0.967	0.574	Fraction of basin with aspect 135–180 degrees
asp180225	0.297	0.247	Fraction of basin with aspect 180–225 degrees
asp225270	0.202	0.172	Fraction of basin with aspects of 225–270 degrees
asp270315	0.877	0.394	Fraction of basin with aspect 270–315 degrees
asp315360	0.495	0.167	Fraction of basin with aspect 315–360 degrees
med_veg	0.507	0.461	Fraction of basin that is forest or tundra
low_veg	0.620	0.255	Fraction of basin that is subalpine meadow
high_veg	0.872	0.855	Fraction of basin that is agriculture or unvegetated (snow, rock, water)
mean_no3	0.950	0.267	Mean annual inorganic N deposition in basin (kg/ha/yr inorganic N)
mean_so4	0.882	0.959	Mean annual sulfate deposition in basin (kg/ha/yr SO_4-S)
mean_h	0.953	0.485	Mean annual acid deposition in basin (kg/ha/yr H^+)
mean_ppt	0.661	0.843	Mean annual precipitation of basin (mm/yr)
soil_1	0.278	0.074	Fraction of basin that is inceptisols
soil_2	0.684	0.176	Fraction of basin that is mollisols
soil_3	0.688	0.533	Fraction of basin that is thermal
soil_4	0.587	0.361	Fraction of basin that is bedrock
soil_5	0.878	0.810	Fraction of basin that is water

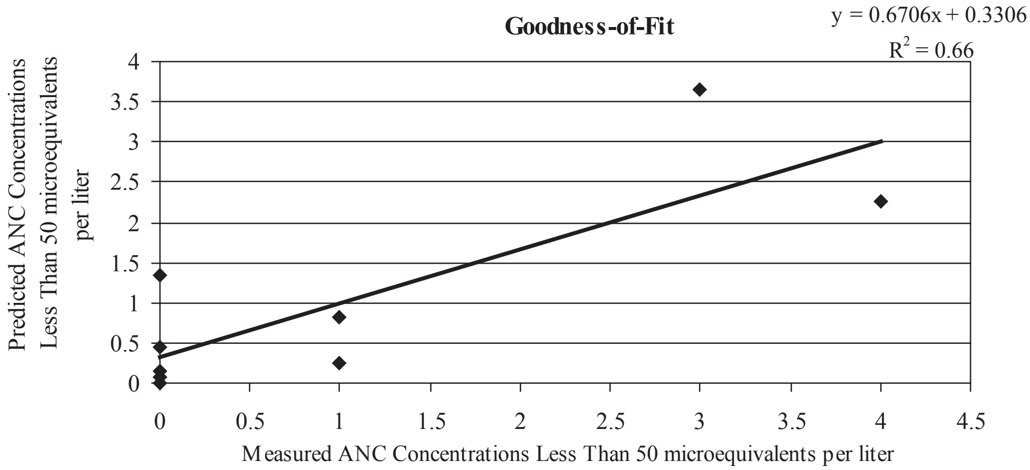
Table 9. Results of multivariate logistic regression analyses for Grand Teton National Park.

(*A*) Acid-neutralizing capacity (ANC) concentration bin of 0–50 microequivalents per liter (µeq/L).

[µeq/L, microequivalents per liter; (n), total number of lakes; (1), lakes in ANC bin 0–50 µeq/L; (0), lakes with ANC > 50 µeq/L; soil_9, fraction that is leighton-moran_wolcott_association; stpslpe, fraction of slopes > 30 degrees]

$$\text{Logit (P)} = \frac{e^{(-8.624 + 9.702(\text{soil\_9}) + 13.761(\text{stpslpe}))}}{1 + e^{(-8.624 + 9.702(\text{soil\_9}) + 13.761(\text{stpslpe}))}}$$

variable	(1)	(0)	(n)	Likelihood ratio *p*-value	score *p*-value	parameter estimate	standard error	wald chi-square	*p*-value	Somers' D	c statistic
intercept						–8.624	2.871	9.022	0.0027		
soil_9	9	43	52	0.0001	0.0018	9.702	3.320	8.538	0.0035	0.80	0.90
stpslpe						13.761	5.158	7.116	0.0276		



(*B*) Acid-neutralizing capacity (ANC) concentration bin of 0–100 microequivalents per liter.

[µeq/L, microequivalents per liter; (n), total number of lakes; (1), lakes in ANC bin 0–100 µeq/L; (0), lakes with ANC > 100 µeq/L; min_elev; lake outlet elevation; asp45, fraction of basin with aspect 0–45 degrees]

$$\text{Logit (P)} = \frac{e^{(-9.455 + 0.004(\text{min\_elev}) - 8.318(\text{asp45}))}}{1 + e^{(-9.455 + 0.004(\text{min\_elev}) - 8.318(\text{asp45}))}}$$

variable	(1)	(0)	(n)	Likelihood ratio *p*-value	score *p*-value	parameter estimate	standard error	wald chi-square	*p*-value	Somers' D	c statistic
intercept						–9.455	3.041	9.665	0.0019		
min_elev	23	29	52	<0.0001	<0.0001	0.004	0.001	12.136	0.0005	0.76	0.88
asp45						–8.318	3.766	4.878	0.0272		

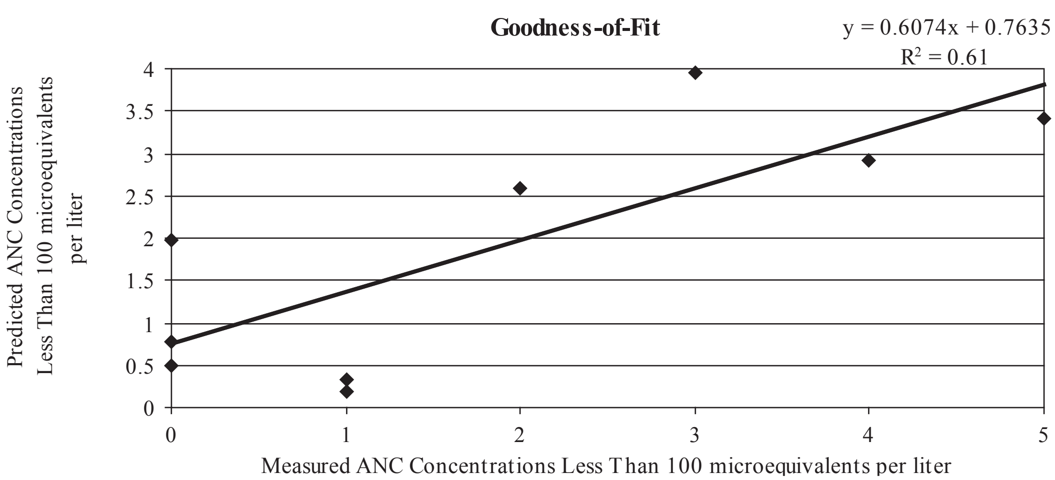


Table 9. Results of multivariate logistic regression analyses for Grand Teton National Park.—Continued

(*C*) Acid-neutralizing capacity concentration (ANC) bin of 0–200 microequivalents per liter.

[µeq/L, microequivalents per liter; (n), total number of lakes; (1), lakes in ANC bin 0–200 µeq/L; (0), lakes with ANC > 200 µeq/L; GC 1, fraction of basin that is gneiss, quartzite, schist, or granite]

$$\text{Logit (P)} = \frac{e^{(-2.546 + 4.883(\text{GC }1))}}{1 + e^{(-2.546 + 4.883(\text{GC }1))}}$$

variable	(1)	(0)	(n)	Likelihood ratio *p*-value	score *p*-value	parameter estimate	standard error	wald chi-square	*p*-value	Somers' D	c statistic
intercept	37	15	52	<0.0001	<0.0001	–2.546	1.054	5.834			
GC 1						4.883	1.344	13.189	0.0003	0.73	0.86

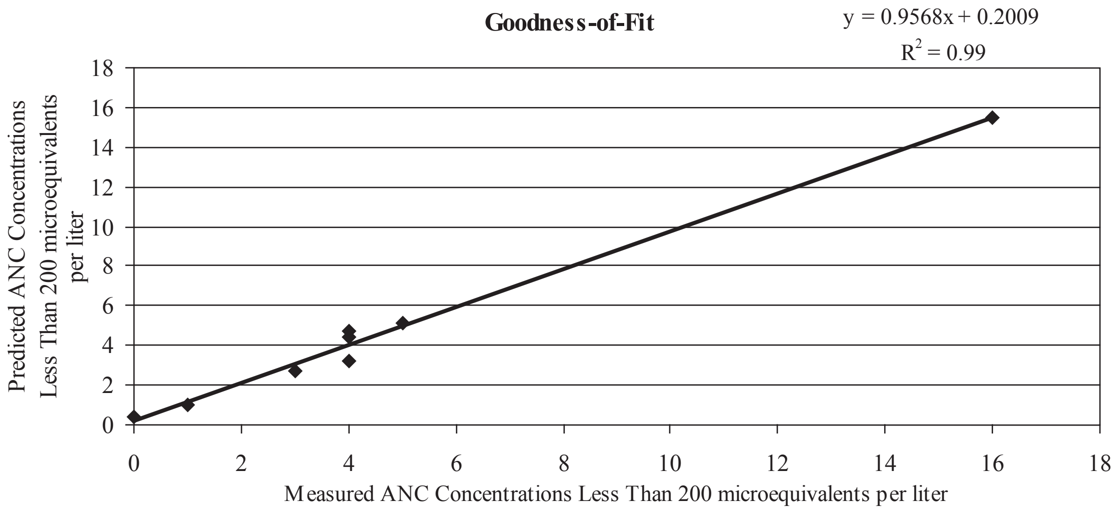


Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 μeq/L	0–200 μeq/L
1	Noname-1	45.09	–111.01	2,785	2.04	96.89%	95.95%
2	Sedge Lake	45.06	–110.98	2,699	1.42	88.94%	53.52%
3	Noname-2	45.05	–111.00	2,627	3.76	72.39%	72.40%
4	Crescent Lake	45.06	–110.99	2,614	5.96	68.21%	30.26%
5	Unnamed lake	45.05	–110.97	2,676	2.57	84.84%	73.48%
6	High Lake	45.05	–110.93	2,674	3.16	84.47%	92.84%
7	Unnamed lake	45.04	–111.00	2,655	2.68	80.34%	53.42%
8	Unnamed lake	45.04	–110.97	2,591	2.66	60.01%	69.78%
9	Noname-3	45.03	–110.75	1,662	1.03	0.00%	0.30%
10	Rainbow Lake	45.02	–110.74	1,792	1.86	0.00%	0.92%
11	Sportsman Lake	45.01	–110.9	2,349	1.89	3.26%	9.42%
12	Noname-4	45.01	–110.74	1,960	1.23	0.01%	1.67%
13	Slide Lake	45.00	–110.69	1,737	2.57	0.00%	0.60%
14	Crevice Lake	45.00	–110.57	1,687	7.57	0.00%	0.29%
15	Big Beaver Pond	44.99	–110.71	1,938	1.45	0.01%	2.51%
16	Cache Lake	44.98	–110.8.0	2,450	5.21	14.09%	15.20%
17	Noname-5	44.97	–110.72	2,255	1.17	0.77%	7.12%
18	Noname-6	44.97	–110.26	2,219	1.04	0.44%	4.92%
19	Noname-7	44.97	–110.64	2,284	1.49	1.20%	6.83%
20	Geode Lake	44.97	–110.48	1,823	4.4.0	0.00%	3.41%
21	Noname-8	44.97	–110.14	2,838	1.52	98.61%	96.91%
22	Unnamed pond	44.97	–110.45	1,797	1.24	0.00%	0.55%
23	Noname-9	44.97	–110.14	2,839	1.11	98.64%	96.94%
24	Unnamed pond	44.97	–110.46	1,773	2.22	0.00%	0.47%
25	Noname-10	44.97	–110.62	2,219	1.99	0.44%	4.92%
26	Unnamed pond	44.97	–110.45	1,779	1.2	0.00%	0.48%
27	Noname-11	44.96	–110.5.0	1,991	1.07	0.01%	5.68%
28	McBride Lake	44.96	–110.25	2,007	10.92	0.02%	1.62%
29	Unnamed pond	44.96	–110.41	2,013	3.99	0.02%	1.68%
30	Noname-12	44.96	–110.62	2,210	8.36	0.38%	9.00%
31	Noname-13	44.96	–111.03	2,225	1.64	0.48%	5.68%
32	Noname-14	44.95	–110.6	2,011	1.61	0.02%	3.88%
33	Fawn Lake	44.95	–110.79	2,373	1.34	4.66%	10.57%
34	Unnamed reservoir	44.94	–110.7	2,015	1.11	0.02%	1.86%
35	Floating Island Lake	44.94	–110.45	2,010	2.28	0.02%	2.23%
36	Unnamed pond	44.93	–111.01	2,331	2.03	2.47%	10.91%
37	Noname-15	44.93	–110.99	2,335	1.35	2.66%	17.52%
38	Junction Lake	44.93	–110.38	1,904	3.84	0.00%	1.55%
39	Unnamed pond	44.93	–110.31	1,889	1.25	0.00%	0.93%
40	Small Lake	44.92	–110.9	2,765	1.02	95.79%	49.42%
41	Unnamed pond	44.92	–110.35	1,886	2.73	0.00%	0.86%
42	Noname-16	44.92	–110.76	2,325	2.11	2.26%	8.37%

Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 μeq/L	0–200 μeq/L
43	Unnamed pond	44.92	–110.35	1,886	1.92	0.00%	0.86%
44	Noname-17	44.92	–110.28	2,102	1.38	0.07%	2.68%
45	Noname-18	44.92	–110.78	2,321	1.09	2.12%	8.21%
46	Noname-19	44.92	–110.72	2,227	2.22	0.50%	5.17%
47	Noname-20	44.92	–110.76	2,320	3.97	2.11%	8.18%
48	Swan Lake	44.91	–110.73	2,215	15.49	0.42%	4.83%
49	Hals Lake	44.91	–110.79	2,335	1.52	2.66%	8.82%
50	Ruddy Duck Pond	44.91	–110.37	2,199	3.73	0.32%	4.44%
51	Trumpter Lake	44.91	–110.36	1,862	9.01	0.00%	1.29%
52	Unnamed pond	44.91	–110.71	2,219	2.44	0.44%	4.91%
53	Unnamed pond	44.91	–110.68	2,190	2.73	0.28%	4.24%
54	Unnamed pond	44.91	–110.7	2,211	2.77	0.39%	4.73%
55	Unnamed pond	44.91	–110.67	2,199	2.65	0.32%	4.44%
56	Noname-21	44.91	–110.34	1,885	2.57	0.00%	0.85%
57	Unnamed pond	44.91	–110.38	1,893	1.66	0.00%	1.04%
58	Noname-22	44.91	–110.73	2,217	1.06	0.42%	4.86%
59	Noname-23	44.91	–110.76	2,301	1.09	1.57%	7.45%
60	Divide Lake	44.91	–111.05	2,201	3.54	0.33%	7.57%
61	Lost Lake	44.9	–110.43	2,046	2.95	0.03%	3.95%
62	Buck Lake	44.9	–110.12	2,113	2.36	0.08%	2.84%
63	Noname-24	44.9	–110.28	2,067	5.25	0.04%	2.23%
64	Noname-25	44.9	–110.29	2,074	3.41	0.05%	2.31%
65	Trout Lake	44.9	–110.12	2,119	5.25	0.09%	7.34%
66	Noname-26	44.89	–110.29	2,077	5.88	0.05%	8.09%
67	Noname-27	44.89	–110.77	2,303	1.18	1.62%	7.52%
68	Unnamed lake	44.87	–110.16	2,029	1.52	0.02%	2.66%
69	Unnamed lake	44.87	–110.85	2,567	1.67	50.73%	25.21%
70	Unnamed lake	44.87	–110.92	2,750	1.91	94.74%	47.41%
71	Unnamed lake	44.87	–110.86	2,592	1.29	60.35%	27.83%
72	Unnamed lake	44.86	–110.91	2,790	2.54	97.09%	52.70%
73	Noname-28	44.86	–110.86	2,688	1.76	87.19%	39.22%
74	Gallatin Lake	44.85	–110.88	2,688	9.92	87.24%	39.26%
75	Noname-29	44.84	–110.37	2,243	1.32	0.64%	7.15%
76	Noname-30	44.84	–110.92	2,309	1.66	1.77%	8.32%
77	Ace of Hearts Lake	44.84	–110.65	2,464	2.41	17.03%	43.47%
78	Obsidian Lake	44.83	–110.71	2,356	7.56	3.64%	49.60%
79	Noname-31	44.83	–110.66	2,468	2.16	17.86%	68.99%
80	Unnamed lake	44.83	–110.76	2,270	2.32	0.97%	27.84%
81	Noname-32	44.83	–110.67	2,473	1.17	19.08%	63.60%
82	Noname-33	44.82	–110.68	2,391	2.07	6.13%	30.05%
83	Middle Trilobite Lake	44.82	–110.84	2,674	2.97	84.53%	37.44%
84	Trilobite Lake	44.82	–110.83	2,544	4.04	41.85%	22.96%

Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; µeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 µeq/L	0–200 µeq/L
85	Echo Lake	44.82	–110.87	2,699	1.77	89.04%	40.67%
86	Noname-34	44.82	–110.8	2,384	1.44	5.48%	11.14%
87	Noname-35	44.81	–110.72	2,250	1.01	0.71%	19.34%
88	Beaver Lake	44.81	–110.73	2,251	9.65	0.72%	19.21%
89	Rosa Lake	44.81	–110.87	2,748	1.03	94.60%	47.17%
90	Grizzly Lake	44.8	–110.77	2,288	60.03	1.29%	30.31%
91	Noname-36	44.8	–110.76	2,401	1.99	7.04%	12.08%
92	Lake of the Woods	44.8	–110.71	2,362	11.06	3.97%	59.72%
93	Noname-37	44.77	–110.85	2,533	1.76	37.52%	21.88%
94	North Twin Lake	44.77	–110.73	2,301	4.3	1.57%	33.34%
95	South Twin Lake	44.77	–110.73	2,295	7.05	1.43%	36.64%
96	Noname-38	44.76	–111.07	2,008	1.1	0.02%	2.18%
97	Unnamed lake	44.76	–111.05	2,010	2.4	0.02%	2.39%
98	Noname-39	44.76	–110.77	2,418	1.23	9.00%	71.77%
99	Noname-40	44.75	–110.76	2,413	1.14	8.47%	76.21%
100	Grebe Lake	44.75	–110.55	2,445	53.13	13.25%	56.32%
101	Cascade Lake	44.75	–110.52	2,435	12.09	11.54%	69.65%
102	Noname-41	44.75	–110.69	2,341	2.46	2.92%	68.50%
103	Nymph Lake	44.75	–110.72	2,283	5.41	1.19%	39.67%
104	Noname-42	44.74	–110.18	2,711	3.05	90.68%	94.07%
105	Noname-43	44.74	–110.71	2,285	1.14	1.22%	43.82%
106	Wolf Lake	44.74	–110.58	2,438	13.59	11.99%	70.93%
107	Noname-44	44.74	–110.7	2,288	6.63	1.27%	52.29%
108	Noname-45	44.74	–110.23	2,543	1.65	41.16%	45.80%
109	Mirror Lake	44.73	–110.16	2,727	5.77	92.58%	92.53%
110	Ribbon Lake	44.72	–110.44	2,382	2.79	5.34%	67.71%
111	Wapiti Lake	44.71	–110.25	2,569	5.65	51.20%	35.68%
112	Ice Lake	44.72	–110.62	2,405	25.35	7.46%	60.47%
113	Noname-46	44.71	–110.15	2,638	1.27	75.69%	91.47%
114	Unnamed lake	44.71	–110.36	2,594	4.39	61.15%	89.46%
115	Clear Lake	44.71	–110.47	2,382	1.05	5.34%	29.41%
116	Unnamed lake	44.71	–110.77	2,299	4.68	1.53%	63.43%
117	Solfatara Lake	44.69	–110.58	2,503	2.41	27.24%	74.17%
118	Noname-47	44.68	–110.69	2,553	1.2	45.25%	87.18%
119	Wrangler Lake	44.68	–110.43	2,393	13.99	6.27%	21.32%
120	Wapiti Lake	44.67	–110.27	2,505	39.1	28.01%	19.43%
121	Noname-48	44.67	–110.23	2,528	2.64	35.64%	23.76%
122	Turn Lakes	44.66	–110.26	2,505	31.65	28.01%	22.39%
123	Noname-49	44.67	–110.36	2,489	2.68	23.29%	82.81%
124	Noname-50	44.67	–110.48	2,340	7.26	2.86%	34.18%
125	Noname-51	44.67	–110.47	2,344	1.44	3.04%	20.20%
126	Cygnet Lake #1	44.66	–110.61	2,527	2.4	35.42%	77.91%

Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 μeq/L	0–200 μeq/L
127	Cygnet Lake #2	44.66	–110.61	2,527	1.95	35.42%	77.47%
128	Cygnet Lake #3	44.66	–110.61	2,527	2.83	35.42%	77.87%
129	West Tern Lake	44.66	–110.27	2,505	13.44	28.01%	19.43%
130	Noname-52	44.66	–110.58	2,536	1.03	38.64%	86.10%
131	Cygnet Lake #4	44.66	–110.61	2,527	2.17	35.42%	79.51%
132	Cygnet Lake #5	44.66	–110.61	2,527	10.64	35.53%	80.00%
133	Unnamed lake	44.65	–110.27	2,512	2.92	30.07%	19.98%
134	White Lake	44.65	–110.27	2,509	67.59	29.08%	63.25%
135	Noname-53	44.65	–110.26	2,518	1.39	32.11%	20.51%
136	Unnamed pond	44.65	–110.39	2,490	3.04	23.37%	61.35%
137	Unnamed pond	44.64	–110.37	2,529	1.18	36.08%	65.22%
138	Harlequin Lake	44.64	–110.89	2,094	4.29	0.06%	16.91%
139	Noname-54	44.64	–110.5	2,394	3.56	6.41%	68.52%
140	Unnamed pond	44.64	–110.37	2,539	1.91	39.78%	86.29%
141	Unnamed pond	44.64	–110.37	2,542	1.87	40.81%	86.46%
142	Noname-55	44.63	–110.92	2,076	1.24	0.05%	29.61%
143	Noname-56	44.63	–110.27	2,551	1.06	44.43%	82.39%
144	Unnamed lake	44.62	–110.05	2,749	4.45	94.64%	95.12%
145	Frost Lake	44.61	–110.03	2,897	6.29	99.45%	97.74%
146	Noname-57	44.62	–110.73	2,358	3.8	3.74%	70.38%
147	Noname-58	44.61	–110.44	2,394	1.14	6.41%	11.72%
148	Noname-59	44.61	–110.43	2,399	1	6.86%	11.98%
149	Noname-60	44.61	–110.43	2,393	6.57	6.27%	11.64%
150	Noname-61	44.61	–110.73	2,301	2.7	1.57%	63.66%
151	Mary Lake	44.6	–110.63	2,510	7.34	29.57%	74.98%
152	Unnamed pond	44.59	–110.69	2,228	1.84	0.51%	24.09%
153	Noname-62	44.58	–110.62	2,530	1.4	36.30%	77.36%
154	Noname-63	44.58	–110.64	2,522	1.03	33.48%	82.31%
155	Noname-64	44.57	–110.81	2,200	1.29	0.33%	50.44%
156	Noname-65	44.57	–110.77	2,281	2.28	1.16%	61.16%
158	Noname-66	44.56	–110.38	2,357	1.52	3.71%	9.82%
159	Noname-67	44.56	–110.82	2,199	1.17	0.32%	4.44%
160	Indian Pond	44.55	–110.32	2,364	10.84	4.12%	33.78%
161	Big Bear Lake	44.55	–111.01	2,437	1.28	11.74%	49.15%
162	Noname-68	44.55	–110.35	2,358	12.08	3.72%	9.83%
163	Big Bear Lake	44.55	–111.01	2,438	1.58	11.94%	50.53%
164	Turbid Lake	44.54	–110.25	2,388	63.7	5.86%	48.40%
165	Beach Springs Lake	44.55	–110.29	2,358	15.72	3.74%	57.44%
166	Dryad Lake	44.54	–110.51	2,530	15.49	36.52%	81.47%
167	Unnamed lake	44.54	–110.83	2,202	1.76	0.34%	4.50%
168	Feather Lake	44.54	–110.83	2,201	6.67	0.33%	4.48%
169	Hot Lake	44.54	–110.78	2,244	1.64	0.65%	56.23%

Table 10 Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; µeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 µeq/L	0–200 µeq/L
170	Beach Lake	44.54	–110.57	2,483	37.05	21.55%	76.57%
171	Goose Lake	44.54	–110.84	2,201	14.28	0.33%	25.11%
172	Noname-69	44.53	–110.64	2,538	1.13	39.55%	86.25%
173	Unnamed lake	44.53	–110.83	2,197	2.31	0.31%	4.40%
174	Lower Basin Lake	44.53	–110.82	2,587	3.5	58.28%	27.24%
175	Crater Lake #4	44.53	–110.87	2,286	1.4	1.24%	61.70%
176	Unnamed lake	44.53	–110.87	2,283	1.83	1.19%	61.35%
177	Bridge Bay	44.53	–110.43	2,357	10.33	3.67%	10.55%
178	Noname-70	44.52	–110.57	2,483	2.34	21.55%	70.90%
179	Noname-71	44.52	–110.58	2,489	2.47	23.12%	41.54%
182	Gooseneck Lake	44.51	–110.84	2,234	2.29	0.55%	54.89%
184	Noname-72	44.49	–110.22	2,558	1.61	47.03%	87.45%
185	Noname-73	44.5	–110.79	2,444	1.1	12.98%	79.05%
186	Noname-74	44.49	–110.42	2,393	2.96	6.27%	11.64%
187	Noname-75	44.49	–110.42	2,376	1.4	4.90%	10.74%
188	Sylvan Lake	44.47	–110.16	2,564	11.79	49.41%	67.70%
189	Delacy Lake (West)	44.47	–110.71	2,593	13.23	60.69%	86.41%
190	Delacy Lake (East)	44.47	–110.7	2,593	10.2	60.69%	86.68%
191	Mallard Lake	44.47	–110.77	2,454	13.95	14.80%	77.29%
192	Noname-76	44.47	–110.67	2,605	1.77	64.82%	89.96%
193	Unnamed pond	44.47	–110.72	2,614	2.76	68.01%	90.39%
194	Noname-77	44.47	–110.61	2,538	5.86	39.32%	22.33%
196	Noname-78	44.47	–110.72	2,571	1.2	52.04%	88.19%
197	Chickadee Lake	44.46	–110.61	2,534	10.13	38.08%	22.02%
198	Unnamed lake	44.46	–110.61	2,547	1.56	42.67%	23.16%
199	Teal Lake	44.46	–110.75	2,568	3.19	50.96%	86.48%
200	Nuthatch Lake	44.45	–110.61	2,547	5.36	42.67%	23.16%
202	Noname-79	44.45	–110.62	2,553	1.03	45.25%	23.81%
204	Noname-80	44.43	–110.74	2,413	2.09	8.44%	72.32%
206	Noname-81	44.42	–110.45	2,357	3.91	3.67%	9.79%
207	Scaup Lake	44.43	–110.76	2,411	2.37	8.18%	72.27%
208	Noname-82	44.42	–110.57	2,373	14.66	4.72%	59.29%
209	Summit Lake	44.41	–110.94	2,605	12.33	64.82%	87.07%
210	Shoshone Lake	44.37	–110.69	2,374	2860.28	4.79%	52.06%
211	Delusion Lake	44.39	–110.45	2,383	229.83	5.46%	11.43%
212	Noname-83	44.4	–110.5	2,354	2.28	3.52%	14.15%
213	Pocket Lake	44.39	–110.74	2,486	5.85	22.28%	82.53%
214	Noname-84	44.39	–110.25	2,355	1.57	3.56%	9.69%
215	Noname-85	44.38	–110.45	2,388	2.15	5.86%	11.39%
216	Hidden Lake	44.38	–110.45	2,388	23.77	5.86%	11.39%
217	Noname-86	44.38	–111.04	2,544	1.96	41.85%	86.64%
218	Noname-87	44.37	–110.47	2,393	1.11	6.27%	11.64%

Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 μeq/L	0–200 μeq/L
219	Unnamed lake	44.37	–110.48	2,401	5.39	7.04%	12.08%
220	Unnamed lake	44.37	–110.45	2,386	11.94	5.66%	11.25%
221	Noname-88	44.37	–111.03	2,548	1.22	43.14%	86.84%
222	Noname-89	44.37	–111.06	2,396	1.31	6.56%	71.01%
223	Noname-90	44.36	–110.52	2,429	1.07	10.56%	77.69%
224	Riddle Lake	44.35	–110.54	2,412	72.18	8.25%	15.62%
225	Noname-91	44.35	–110.68	2,374	5.54	4.79%	65.58%
226	Noname-92	44.35	–110.55	2,412	1.09	8.36%	12.78%
227	Glade Lake	44.34	–110.08	2,942	3.23	99.72%	94.76%
228	Madison Lake	44.34	–110.86	2,502	1.68	27.15%	53.60%
229	Alder Lake	44.33	–110.31	2,360	48.66	3.84%	14.07%
230	Noname-93	44.33	–110.76	2,375	1.18	4.81%	69.55%
231	Buffalo Lake	44.32	–111.07	2,342	5.15	2.96%	52.48%
232	Noname-94	44.32	–110.2	2,359	1.23	3.81%	9.91%
233	Noname-95	44.32	–110.29	2,373	4.39	4.72%	20.82%
234	Lewis Lake	44.3	–110.62	2,371	1122.15	4.55%	46.42%
236	Noname-96	44.31	–110.61	2,371	7.92	4.55%	31.21%
237	Noname-97	44.31	–110.2	2,359	7.62	3.77%	9.88%
240	Noname-98	44.31	–110.19	2,359	1.76	3.77%	9.88%
241	Noname-99	44.31	–110.21	2,358	1.39	3.74%	9.85%
242	Noname-100	44.3	–110.19	2,359	5.36	3.77%	9.88%
243	Noname-101	44.3	–110.19	2,359	9.29	3.77%	25.86%
244	Noname-102	44.3	–110.21	2,358	8.91	3.72%	9.83%
245	Noname-103	44.3	–110.16	2,362	1.12	3.99%	12.33%
246	Unnamed lake	44.3	–110.37	2,458	1.85	15.73%	41.46%
247	Noname-104	44.3	–110.16	2,363	1.05	4.01%	39.88%
248	Noname-105	44.3	–110.2	2,358	7.31	3.72%	28.21%
249	Noname-106	44.29	–110.18	2,359	3.42	3.77%	9.88%
250	Aster Lake	44.3	–110.55	2,489	5.94	23.12%	18.08%
251	Noname-107	44.29	–110.24	2,368	1.08	4.37%	43.75%
252	Noname-108	44.29	–110.24	2,385	1.03	5.61%	51.75%
253	Noname-109	44.29	–110.16	2,359	2.45	3.77%	9.88%
255	Noname-110	44.29	–110.16	2,363	3.62	4.04%	10.10%
257	Heart Lake	44.27	–110.48	2,272	884.68	1.00%	19.93%
258	Trail Lake	44.27	–110.17	2,363	35.19	4.01%	37.77%
259	Outlet Lake	44.27	–110.39	2,371	5.81	4.53%	19.94%
260	Noname-111	44.25	–110.22	2,702	1.01	89.49%	82.47%
261	Noname-112	44.25	–110.83	2,670	1.14	83.77%	92.73%
263	Noname-113	44.24	–110.97	2,133	1.61	0.11%	41.43%
264	Noname-114	44.23	–110.96	2,143	1.54	0.13%	42.74%
265	Little Robinson Lake	44.23	–111.03	1,978	3.83	0.01%	4.40%
266	Lake Wyodaho	44.23	–110.98	2,067	5.34	0.04%	33.20%

Table 10. Lakes greater than 1 hectare in Yellowstone National Park, including lake-identification number, lake name, latitude, longitude, elevation of lake outlet, lake area, and associated probabilities at acid-neutralizing capacity concentration bins of 0–100 and 0–200 microequivalents per liter.—Continued

[DD, decimal degrees; Elev, elevation of lake outlet above North American Vertical Datum of 1988; m, meters; ha, hectare; μeq/L, microequivalents per liter; %, percent]

Lake number (see fig. 4 for location)	Lake name	Latitude (DD)	Longitude (DD)	Elev (m)	Lake area (ha)	Probability	
						0–100 μeq/L	0–200 μeq/L
267	Noname-115	44.23	–110.94	2,167	1.8	0.20%	46.02%
268	Noname-116	44.22	–111.03	1,977	3.74	0.01%	1.38%
269	Ranger Lake	44.21	–110.96	2,122	22.56	0.10%	24.29%
270	Noname-117	44.21	–110.12	2,382	1.53	5.36%	11.06%
271	Noname-118	44.21	–111.02	1,951	1.51	0.01%	1.21%
272	Noname-119	44.21	–111.03	1,953	1.13	0.01%	1.22%
273	Unnamed lake	44.2	–110.24	2,627	4.83	72.39%	83.98%
274	Noname-120	44.21	–110.83	2,314	1.41	1.91%	51.03%
275	Noname-121	44.2	–110.11	2,383	1.41	5.43%	11.11%
276	Basin Creek Lake	44.2	–110.52	2,252	4.29	0.73%	5.81%
277	Noname-122	44.18	–110.24	2,835	1.1	98.55%	96.87%
278	Noname-123	44.18	–111.06	1,977	10.45	0.01%	14.93%
279	Noname-124	44.17	–111.04	1,971	34.03	0.01%	9.14%
280	Noname-125	44.18	–111.02	1,960	1.05	0.01%	6.71%
281	Noname-126	44.17	–111.05	1,977	4.37	0.01%	13.29%
282	Noname-127	44.17	–110.17	2,994	1.66	99.88%	98.64%
283	Noname-128	44.17	–110.27	2,784	1.25	96.82%	95.92%
284	Noname-129	44.17	–111.07	1,977	5.66	0.01%	12.08%
285	Noname-130	44.16	–111.03	1,963	3.27	0.01%	22.13%
286	Robinson Lake	44.16	–111.07	1,977	16.9	0.01%	13.10%
287	Lilypad Lake	44.16	–111.01	1,953	26.94	0.01%	8.20%
288	Unnamed Lake	44.16	–111.08	1,974	1.2	0.01%	23.19%
289	Forest Lake	44.16	–110.63	2,262	3.58	0.85%	38.17%
290	Beula Lake	44.15	–110.76	2,256	53.01	0.78%	11.90%
291	Noname-131	44.16	–110.81	2,317	2.2	2.00%	65.57%
292	Noname-132	44.15	–110.84	2,180	2.1	0.24%	45.75%
293	Mariposa Lake	44.15	–110.24	2,729	5.67	92.80%	84.96%
294	Noname-133	44.15	–111.02	1,943	1.31	0.01%	11.09%
295	Hering Lake	44.14	–110.76	2,257	30.72	0.80%	5.98%
296	Noname-134	44.14	–110.97	1,971	3.93	0.01%	22.84%
297	Noname-135	44.14	–110.74	2,285	1	1.23%	6.87%
298	Phoneline Lake	44.14	–111.05	1,935	10.01	0.01%	12.38%
299	Unnamed lake	44.14	–110.66	2,097	1.48	0.07%	25.50%
300	Unnamed lake	44.13	–110.55	2,497	2.25	25.40%	18.72%
301	Noname-136	44.13	–110.75	2,247	1.96	0.68%	5.68%
302	Noname-137	44.13	–110.65	2,095	2.15	0.06%	3.44%
303	Winegar Lake	44.13	–110.96	1,963	11.93	0.01%	9.01%
304	Tanagar Lake	44.13	–110.68	2,124	9.59	0.10%	25.44%
305	Noname-138	44.13	–110.96	1,962	1.29	0.01%	21.99%
306	Noname-139	44.13	–110.97	1,977	1.34	0.01%	23.43%
307	South Boundary Lake	44.13	–110.75	2,247	6.68	0.68%	5.66%
308	Yellowstone Lake			2,353	34496	3.47%	18.20%

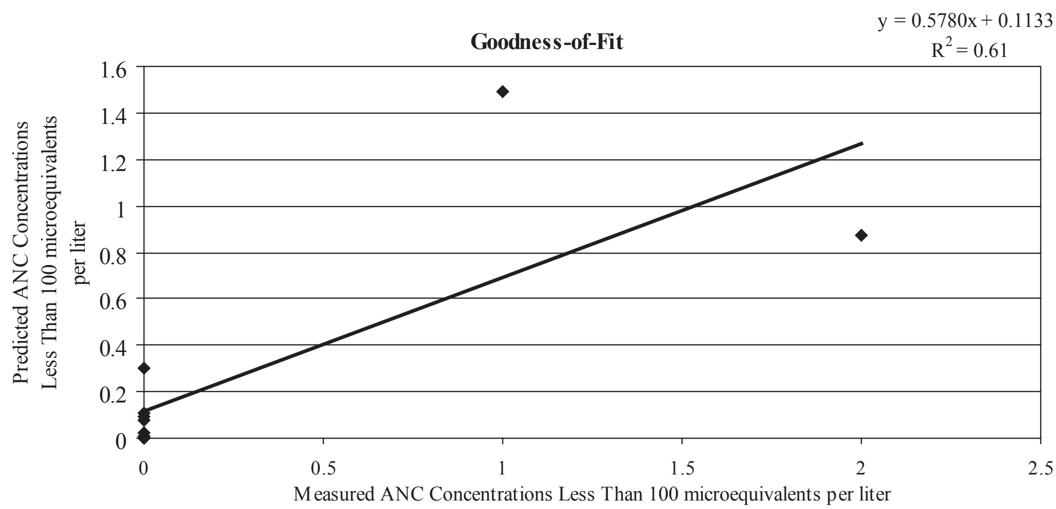
Table 11. Results of multivariate logistic regression analyses for Yellowstone National Park.

(*A*) Acid-neutralizing capacity (ANC) concentration bin of 0–100 microequivalents per liter.

[μeq/L, microequivalents per liter; (n), total number of lakes; (1), lakes in ANC bin 0–100μeq/L; (0), lakes with ANC > 100μeq/L; min_elev; lake outlet elevation]

$$\text{Logit (P)} = \frac{e^{(-40.149 + 0.005(\text{min\_elev}))}}{1 + e^{(-40.149 + 0.005(\text{min\_elev}))}}$$

variable	(1)	(0)	(n)	Likelihood ratio *p*-value	score *p*-value	parameter estimate	standard error	wald chi-square	*p*-value	Somers' D	c statistic
intercept						–40.149	20.276	3.921	0.048		
min_elev	3	20	23	0.0036	0.0110	0.005	0.003	3.764	0.052	0.90	0.95



(*B*) Acid-neutralizing capacity (ANC) concentration bin of 0–200 microequivalents per liter.

[μeq/L, microequivalents per liter; (n), total number of lakes; (1), lakes in ANC bin 0–200 μeq/L; (0), lakes with ANC > 200 μeq/L; min_elev; lake outlet elevation; GC 3, fraction of basin that is basalt, gabbro, wacke, argillite, or volcanics]

$$\text{Logit (P)} = \frac{e^{(-14.901 + 0.002(\text{min\_elev}) + 3.080(\text{GC 3}))}}{1 + e^{(-14.901 + 0.002(\text{min\_elev}) + 3.080(\text{GC 3}))}}$$

variable	(1)	(0)	(n)	Likelihood ratio *p*-value	*p*-value	parameter estimate	standard error	wald chi-square	*p*-value	Somers' D	c statistic
intercept						–14.901	7.863	3.591	0.058		
min_elev	8	15	23	0.0238	0.0383	0.002	0.001	2.862	0.091	0.56	0.78
geochem 3						3.080	1.594	3.733	0.053