Lake and Bulk Sampling Chemistry, NADP, and IMPROVE Air Quality Data Analysis on the Bridger-Teton National Forest (USFS Region 4)

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Abstract

Air quality monitoring data from several programs in and around the Bridger-Teton (B-T) National Forest—National Atmospheric Deposition Program (NADP), long-term lake monitoring, long-term bulk precipitation monitoring (both snow and rain), and Interagency Monitoring of Protected Visual Environments (IMPROVE)—were analyzed in this report. Trends were analyzed using non-parametric tests and seasonality was taken into account when possible. Nitrate (NO_3^-) showed seasonal increasing trends in all sampled lake inlets, in atmospheric deposition at NADP sites and bulk sampling sites, and at two visibility sites. NADP sites showed consistent decreasing trends for both deposition and concentrations in SO_4^{2-}, Na^+, Mg^{2+}, and Cl^- and increasing trends in NH_4^+ and inorganic nitrogen deposition. Lake and bulk deposition chemistry data showed increasing trends in cations and decreasing trends in Cl^-. Bulk deposition sites showed an increasing trend in NH_4^+. Standard Visual Range (SVR) showed an increasing trend and extinction showed a decreasing trend at all IMPROVE sites analyzed. In conclusion, considerations were listed regarding current and future air quality monitoring on the B-T National Forest.

Keywords: Bridger-Teton National Forest, NADP, IMPROVE, long-term lake chemistry, bulk deposition, air quality trends, nitrogen deposition

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Cover Photo: Two of the four lakes in the Bridger-Teton NF that were sampled for this report: Black Joe Lake (foreground, lower left); and Deep Lake (upper middle); (Forest Service photo).

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Introduction

The Bridger-Teton (B-T) National Forest is the second largest National Forest in the United States (outside of Alaska), embracing over 3.4 million acres in western Wyoming including 1.2 million acres of Class I and II Wilderness areas (fig. 1). The B-T is connected to the southern end of the 20-million acre Greater Yellowstone Ecosystem. The B-T has over 1,500 lakes, 2,000+ miles of trails, seven of the largest Glaciers in the lower 48 States, many high peaks (more than 13,000 ft elevation), and an abundance and variety of flora and fauna. Increasing atmospheric emissions associated with human population, vehicles, and expansion of oil and gas development and production pose a potential to affect air quality in the B-T National Forest.

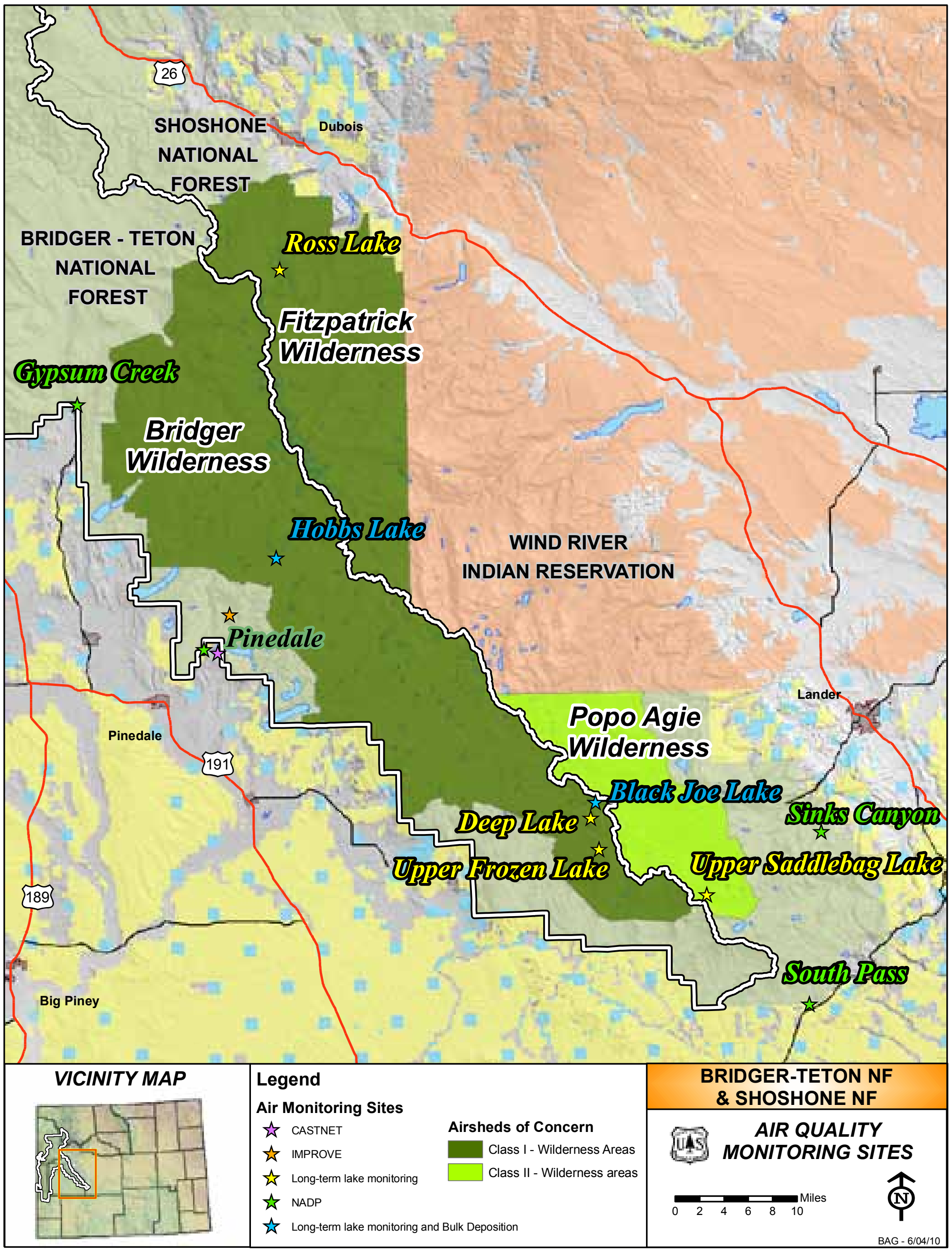

Figure 1—Bridger-Teton and Shoshone National Forests Air Quality Monitoring sites.

The Clean Air Act (http://www.epa.gov/air/caa/) requires the Forest Service to protect air quality related values (AQRVs) in Class I Wilderness Areas (those wilderness areas in existence as of August 7, 1977, that are larger than 5,000 acres). Those Wilderness areas that are not designated as Class I also have management goals identified in the 1964 Wilderness Act (http://www.wilderness.net/index.cfm?fuse=NWPS&sec=legisAct). A large piece of wilderness air protection stems from the Prevention of Significant Deterioration (PSD) provisions of The Clean Air Act. State legislation, regional haze rules, and PSD regulations determine how States conduct the air-quality regulatory process (more information can be found at: http://www.epa.gov/air/oaq_caa.html/ and http://www.epa.index.html).

In compliance with the Clean Air Act, the B-T National Forest participates in four different types of air quality monitoring programs: National Atmospheric Deposition Program (NADP) (http://nadp.sws.uiuc.edu), long-term lake monitoring, bulk deposition monitoring (wet and dry deposition), and the Interagency Monitoring of Protected Visual Environments (IMPROVE). These programs collect data on wet precipitation chemistry, lake chemistry, bulk precipitation chemistry, and visibility with the goal to monitor forest health and make practical regional haze progress to restore background conditions by 2064. The purpose of this report is to analyze existing air quality data to gain a more complete understanding of regional and local trends in air quality and to better understand possible effects to the B-T National Forest and, more specifically, the Bridger Wilderness. This report is intended to provide useful information for understanding and managing air quality in southwest Wyoming, including natural gas field exploration and development effects on air quality related resources. This report provides air quality information and associated resource information for NEPA, PSD, and document baseline for trends relative to climate change effects.

Analysis Methods

Methods for analysis followed the Data Analysis Protocol (DAP) for long-term lake monitoring (Gurrieri 2006), which was derived from the statistical, graphical, and protocol development methods of Gilbert (1987), Helsel and Hirsch (1992), and Ward and others (1990). Trends were tested using the Kruskall-Wallis test for seasonality, the Mann-Kendall, and the seasonal Mann-Kendall tests. These nonparametric tests work well with monotonic trends. They do not require normally distributed data and are much more resistant to outliers and missing data than parametric tests (Gurrieri 2006).

The null hypothesis for this analysis (H_o) is no significant trend (in lake, NADP, IMPROVE, or the bulk variables tested) observed over time. The alternative hypothesis (H_1) means that a significant increasing or decreasing trend is found over time. As suggested in the DAP, only data with eight or more observations were tested for trends (Gurrieri 2006). Figure 2 shows a flow diagram of the Data Analysis Protocol that was used to analyze trends in long-term monitoring data and to guide the data analysis found in this report.

The data and statistical analysis for this paper was generated using SAS software, Version 9.1.3 of the SAS System for Windows. (Copyright © 2009 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA.) After the data were imported into SAS, the Kruskal-Wallis test was run for each variable to see if there was a difference among seasons (seasonal data only). If seasonal differences were statistically significant at α = 0.05 level, then the seasonal Mann-Kendall test was run. If seasonal data were not statistically different, then the Mann-Kendall test was run on the annual data. The Mann-Kendall and seasonal Mann-Kendall tests report whether or not a trend exists, they do not evaluate the magnitude of the trend. The Mann-Kendall test also was used to analyze trends within individual seasons.

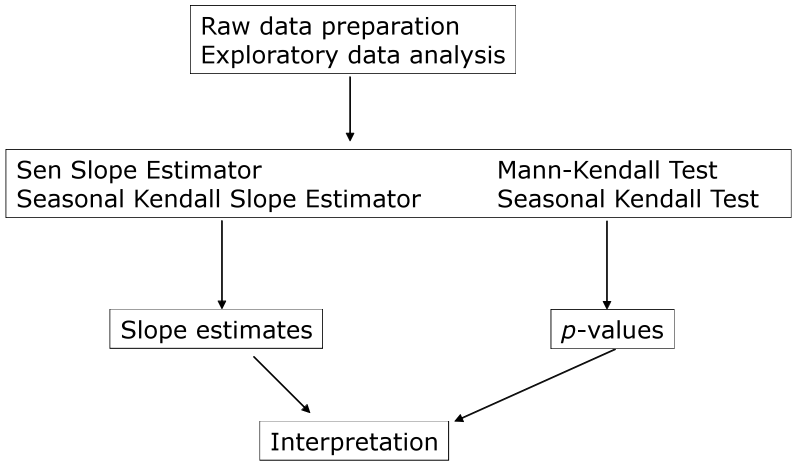

Figure 2—Flow diagram depicting temporal trend analysis protocol (Gurrieri 2006).

The Mann-Kendall and seasonal Mann-Kendall use α to quantify the probability that a trend exists. For this report the α (alpha) level for statistical significance was set at α = 0.1. A value of $\alpha = 0.1$ means there is a 10 percent possibility of falsely rejecting the null hypothesis that no trend exists (Salmi and others 2002). We set the p-value significance at 0.1 to allow a wider extent of trend detection. The Sen's slope estimator shows the magnitude not the significance of a trend. This magnitude depends on the units of measure and can be a negative or positive value depending on whether the trend is decreasing or increasing, respectively. It is important to note that a decreasing trend may represent either an improvement or degradation in environmental quality depending on the context. All graphs in this report, unless noted otherwise, illustrate statistically significant trends, but only selected significant trends are graphed (for space conserving purposes).

National Atmospheric Deposition Program (NADP)

The NADP was initiated in 1978 to monitor geographic and temporal trends in the chemical composition of wet deposition (rain and snow) with the primary purpose of acid rain benchmark monitoring. The program was prompted by scientific evidence and public concern in the 1970s that acid rain could be damaging to aquatic ecosystems throughout the United States. The program grew steadily though the early 1980s and has stabilized at about 200 sites. The NADP network data is used by a wide variety of scientists and resource managers to evaluate wet deposition to and its effects on agriculture, forests, rangelands, freshwater streams and lakes, and cultural resources. All of the NADP sites are operated according to NADP protocols (http://nadp.sws.uiuc.edu/documentation/completeness.asp). Sample buckets are exchanged each Tuesday throughout the calendar year and the samples are shipped to the Central Analytical Lab (CAL) at the Illinois State Water Survey for chemical analysis.

Both annual and seasonal NADP data were downloaded from the NADP website (http://nadp.sws.uiuc.edu) for the following five sites: Gypsum Creek (WY98), Murphy Ridge (UT08), Pinedale (WY06), Sinks Canyon (WY02), and South Pass (WY97). Figure 3 shows the locations of NADP sites for all of Wyoming including all the sites analyzed in this report. Gypsum Creek and Pinedale are both on the west side of the Wind River Range and are operated by the Forest Service (established in 1982) and BLM (established in 1984) respectively. Sinks Canyon (established 1984) and South Pass, established 1985) are located on the Washakie District of the Shoshone National Forest and operated by BLM and the Forest Service respectively. Murphy Ridge (established in 1986) is located in

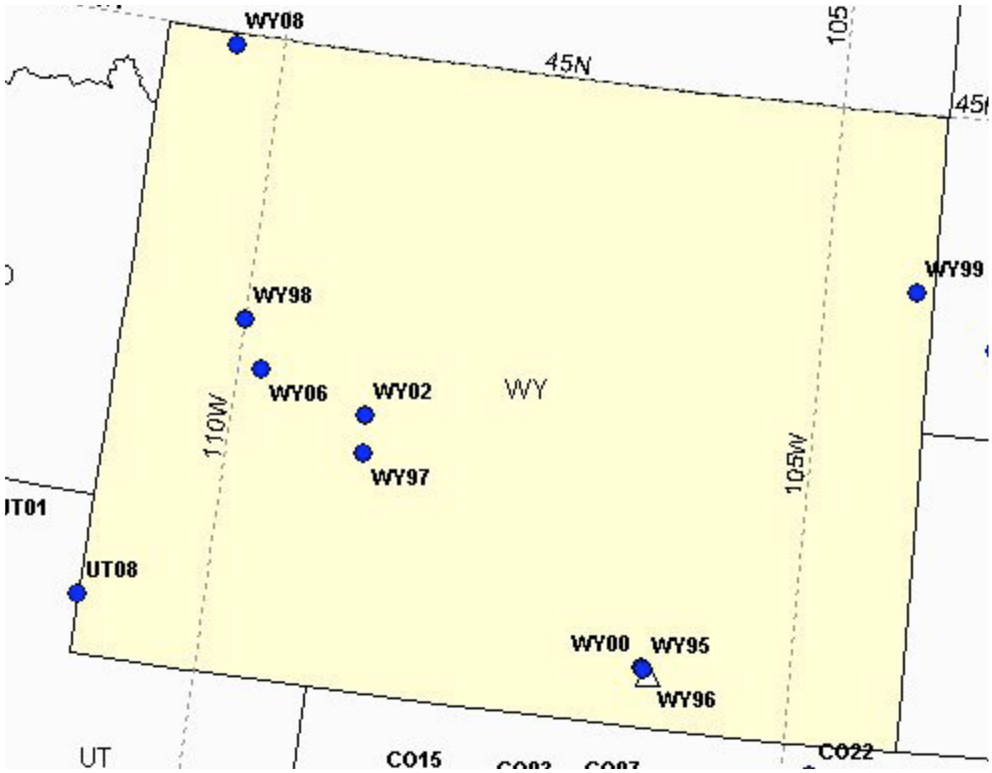

Figure 3—NADP sites in and near WY: WY08 Yellowstone NP, WY98 Gypsum Creek, WY06 Pinedale, WY02 Sinks Canyon, WY97 South Pass City, WY00 Snowy Range, WY96 Nash Fork, WY99 Newcastle, UT08 Murphy Ridge, and CO22 Pawnee.

Utah on the border of Wyoming and operated by the British Petroleum-Amoco Production Company. The elevation of the five NADP sites that were analyzed range from 2,146 m at Murphy Ridge to 2,524 m at South Pass; none of the sites are in designated wilderness areas.

NADP data were analyzed for trends in annual concentrations (μeq/L) and deposition (kg/ha) and for trends within each season. For the seasonal data, winter includes January, February, and March; spring includes April, May, and June; summer includes July, August, and September; and fall includes October, November, and December. These seasons are the same as seasons 1 to 4 in the IMPROVE data discussed later in this report. Trends are reported in order of annual and seasonal concentrations followed by annual and seasonal deposition. The full period of record available at the time of analysis was used to analyze each site and was site dependent with beginning data between 1982 and 1987 and the latest data available between 2006 and 2008.

NADP Concentration Trends

Each site was analyzed for trends in volume weighted mean (VWM) concentrations (μeq/L), lab specific conductance (Lcond)(μS/cm), Ca^{2+}, Cl^-, K^+, Mg^{2+}, Na^+, NH_4^+, NO_3^-, lab H^+ (LH), and SO_4^{2-}. Annual trends are shown in table 1. Lab H^+ at Murphy Ridge and Na^- at Sinks Canyon did not show an overall difference among seasons (table 1). Trends for each season are shown in tables 2 through 6. Annual precipitation (cm) at NADP sites are shown for the years 1982 to 2008 for the purpose of general background information (fig. 4). Selected annual concentration trends are shown in figures 5 to 8.

Table 1—NADP: VWM concentrations, Mann-Kendall test for annual trends at five NADP sites: ss represents the Sen's slope estimate (the negative sign represents a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1. Seasonality was taken into account when appropriate.

Variable (μeq/L/yr)	Gypsum Creek WY98		Murphy Ridge UT08		Pinedale WY06		Sinks Canyon WY02		South Pass WY97	
	ss	p	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.033	0.239	-0.172	0.162	-0.05	0.164	0	0.99	0.112	0.132
Mg^{2+}	-0.033	**<0.001**	-0.082	**0.004**	-0.046	**<0.001**	-0.033	**0.012**	-0.014	0.121
K^{+}	-0.001	0.691	-0.008	0.192	0	0.343	0.002	0.477	0.007	**0.092**
Na^{+}	-0.104	**<0.001**	-0.221	**<0.001**	-0.145	**<0.001**	-0.098	**0.005**	-0.075	**<0.001**
NH_4^{+}	0.177	**<0.001**	0.257	**0.009**	0.166	**0.002**	0.187	**<0.001**	0.146	**0.005**
NO_3^{-}	0.031	0.523	0.049	0.678	0.11	0.182	0.007	0.901	0.103	**0.082**
SO_4^{2-}	-0.177	**<0.001**	-0.423	**<0.001**	-0.262	**<0.001**	-0.261	**<0.001**	-0.22	**<0.001**
Cl^{-}	-<0.001	**<0.001**	-0.187	**<0.001**	-0.102	**<0.001**	-0.061	**<0.001**	-0.074	**<0.001**
LH	-0.047	0.283	-0.179	**0.071**	0.023	0.965	-0.075	**0.011**	-0.123	**0.009**
Lcond	-0.041	**0.027**	-0.166	**<0.001**	-0.029	**0.075**	-0.05	**0.003**	-0.019	0.299

Table 2—NADP: VWM concentrations, Mann-Kendall outputs for seasonal trends, Gypsum Creek **(WY 98)**: ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (μeq/L)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.040	**0.037**	-0.066	0.710	-0.166	0.509	0.073	0.382
Mg^{2+}	-0.034	**<0.001**	-0.049	0.253	-0.060	0.119	-0.009	0.595
K^{+}	-0.009	**0.003**	0.003	0.747	0.006	0.771	0.010	0.113
Na^{+}	-0.119	**0.003**	-0.073	0.137	-0.087	**0.032**	-0.116	**0.009**
NH_4^{+}	0.024	0.456	0.166	**0.039**	0.623	**0.008**	0.333	**<0.001**
NO_3^{-}	-0.020	0.710	0.044	0.637	0.118	0.711	0.087	0.413
SO_4^{2-}	-0.187	**<0.001**	-0.222	0.172	-0.190	0.139	-0.111	0.267
Cl^{-}	-0.111	**<0.001**	-0.098	**0.002**	-0.141	**0.010**	-0.078	**0.003**
LH	-0.010	0.901	-0.055	0.442	-0.092	0.355	-0.051	0.792
Lcond	-0.072	**0.003**	-0.045	0.333	-0.027	0.853	-0.006	0.874

Table 3—NADP: VWM concentrations, Mann-Kendall outputs for seasonal trends, Murphy Ridge **(UT08)**: ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (μeq/L)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.109	0.352	-0.364	0.342	-0.160	0.756	-0.112	0.612
Mg^{2+}	-0.073	**0.075**	-0.131	0.107	-0.082	0.271	-0.060	0.258
K^{+}	-0.029	**0.037**	-0.009	0.509	0.006	0.821	0.000	0.955
Na^{+}	-0.577	**0.002**	-0.171	0.205	-0.149	**0.090**	-0.157	**0.012**
NH_4^{+}	0.044	0.843	0.234	0.291	0.796	**0.055**	0.409	**0.048**
NO_3^{-}	0.108	0.652	-0.069	0.526	0.178	0.592	0.109	0.612
SO_4^{2-}	-0.411	**0.009**	-0.447	**0.065**	-0.333	0.128	-0.463	**0.024**
Cl^{-}	-0.456	**<0.001**	-0.219	**0.028**	-0.157	**0.045**	-0.110	**0.024**
LH	0.006	0.955	-0.098	0.383	-0.060	0.612	-0.270	**0.015**
Lcond	-0.216	**0.021**	-0.172	0.146	-0.070	0.367	-0.191	**0.037**

Table 4—NADP: VWM concentrations, Mann-Kendall outputs for seasonal trends, Pinedale (WY06): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (µeq/L)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.150	**0.010**	-0.141	0.478	0.075	0.791	0.102	0.843
Mg^{2+}	-0.059	**<0.001**	-0.055	0.103	-0.062	0.225	-0.025	0.151
K^+	-0.013	**0.001**	0.003	0.544	0.016	0.440	0.002	0.860
Na^+	-0.328	**0**	-0.144	**0.070**	-0.072	0.186	-0.122	**<0.001**
NH_4^+	0.00	0.659	0.222	**0.052**	0.680	**0.004**	0.246	**0.071**
NO_3^-	0.011	0.724	0.054	0.707	0.325	0.234	0.251	0.146
SO_4^{2-}	-0.296	**<0.001**	-0.336	**0.033**	-0.290	0.134	-0.121	0.234
Cl^-	-0.173	**<0.001**	-0.085	**0.033**	-0.078	0.186	-0.064	**0.023**
LH	0.261	**0.009**	-0.050	0.440	-0.214	**0.064**	0.035	1.000
Lcond	-0.043	**0.098**	-0.038	0.338	-0.074	0.355	0.023	1.000

Table 5—NADP: VWM concentrations, Mann-Kendall outputs for seasonal trends, Sinks Canyon (WY02): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1. Na^+ trends are shown even though there was no overall significance between seasons.

Variable (µeq/L)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.066	0.243	0.315	**0.045**	-0.263	0.244	0.075	0.710
Mg^{2+}	-0.042	**0.005**	0.018	0.518	-0.098	**0.078**	-0.036	0.297
K^+	-0.005	0.128	0.007	**0.061**	-0.005	0.673	0.005	0.129
Na^+	-0.117	**0.002**	-0.033	0.309	-0.098	**0.018**	-0.069	**0.059**
NH_4^+	0.042	0.568	0.226	**0.031**	0.319	**0.097**	0.306	**0.001**
NO_3^-	-0.097	0.254	-0.005	0.882	-0.004	0.980	0.191	0.102
SO_4^{2-}	-0.197	**0.004**	-0.248	**0.012**	-0.535	**0.024**	-0.253	**0.074**
Cl^-	-0.078	**<0.001**	-0.035	**0.063**	-0.101	**0.009**	-0.052	**0.009**
LH	0.006	0.980	-0.128	**0.009**	-0.173	0.157	-0.069	0.286
Lcond	-0.069	**0.015**	-0.044	**0.078**	-0.110	0.244	-0.027	0.568

Table 6—NADP: VWM concentrations, Mann-Kendall outputs for seasonal trends, South Pass (WY97): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (µeq/L)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.125	**0.057**	0.252	**0.009**	0.024	0.874	0.349	**0.045**
Mg^{2+}	-0.041	**0.002**	0.016	0.411	-0.037	0.195	0.015	0.711
K^+	-0.002	0.299	0.013	**0.059**	0.011	0.369	0.011	0.130
Na^+	-0.196	**<0.001**	0.008	0.804	-0.126	**0.048**	-0.053	**0.039**
NH_4^+	0.021	0.916	0.194	**0.087**	0.433	**0.054**	0.203	**0.045**
NO_3^-	-0.023	0.369	0.138	0.165	0.146	0.413	0.188	**0.035**
SO_4^{2-}	-0.269	**0.001**	-0.239	0.130	-0.254	0.187	-0.062	0.597
Cl^-	-0.131	**0**	-0.038	0.233	-0.093	**0.008**	-0.035	**0.077**
LH	0.056	0.916	-0.183	**0.011**	-0.184	0.316	-0.113	0.170
Lcond	-0.067	0.107	-0.009	0.691	-0.044	0.635	0.024	0.673

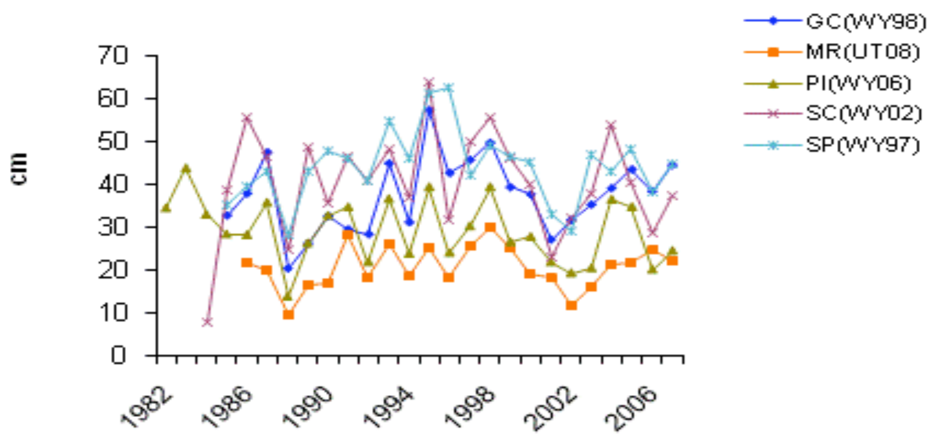

Figure 4—Annual precipitation in centimeters from 1982 to 2007 at Gypsum Creek (GC), Murphy Ridge (MR), Pinedale (PI), Sinks Canyon (SC),and South Pass (SP).

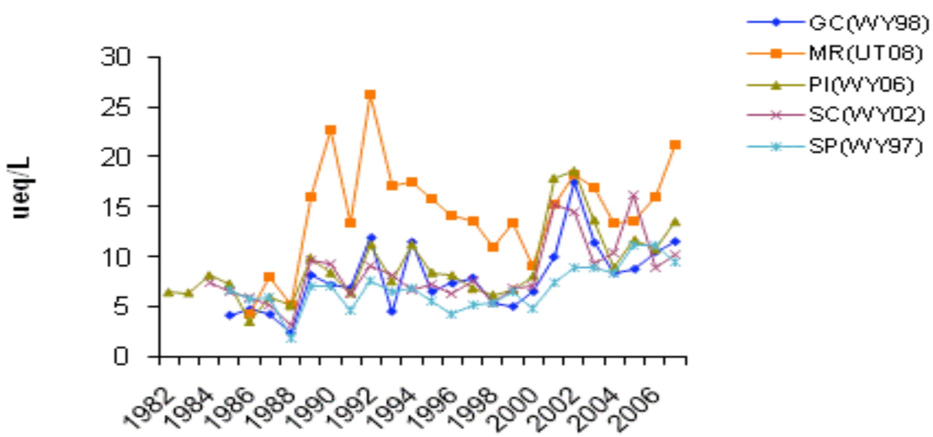

Figure 5—Annual NH_4^+ concentration (μeq/L) trends from 1982 to 2007 at Gypsum Creek (GC), Murphy Ridge (MR), Pinedale (PI), Sinks Canyon (SC),and South Pass (SP).

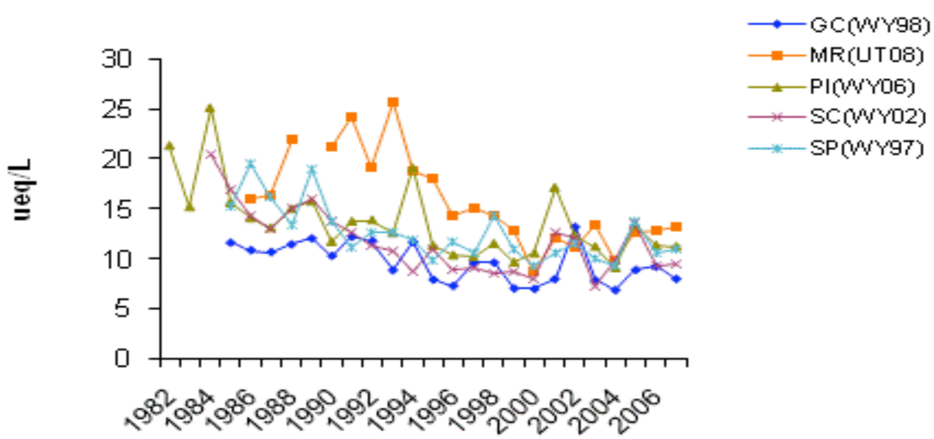

Figure 6—Annual SO_4^{2-} concentration (μeq/L) trends from 1982 to 2007 at Gypsum Creek (GC), Murphy Ridge (MR), Pinedale (PI), Sinks Canyon (SC),and South Pass (SP).

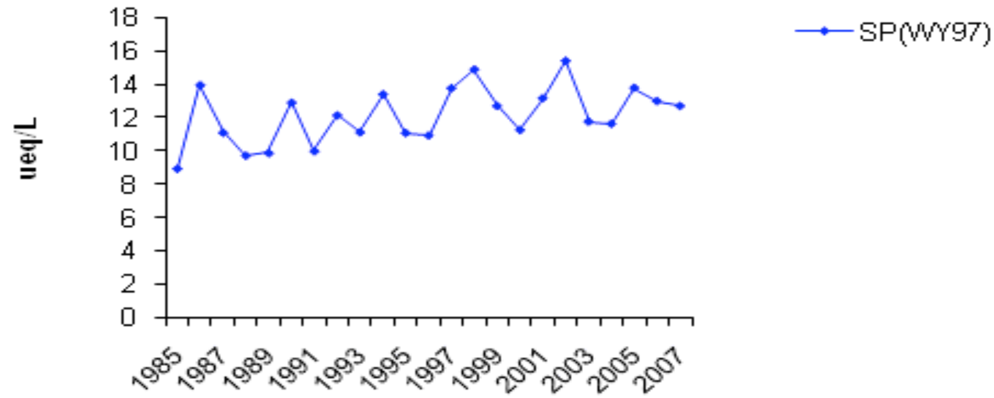

Figure 7—Annual NO_3^- concentration (μeq/L) trend at South Pass (SP) NADP site from 1985 to 2007.

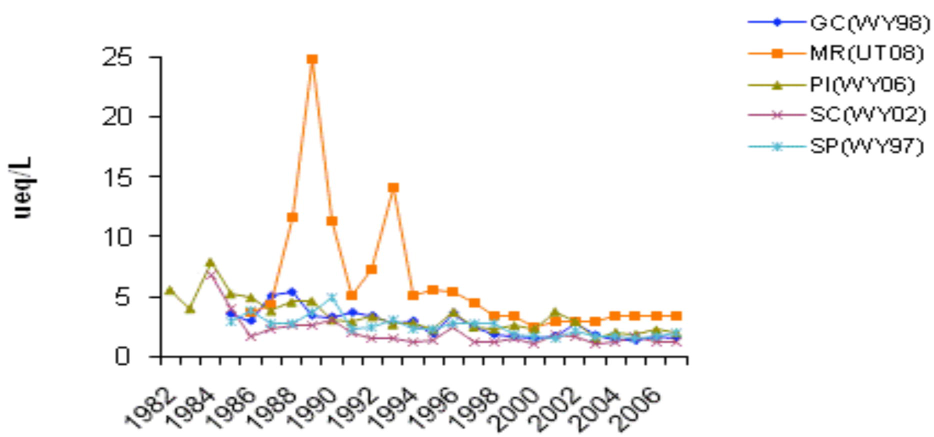

Figure 8—Annual Cl^- concentration (μeq/L) trends from 1982 to 2007 at Gypsum Creek (GC), Murphy Ridge (MR), Pinedale (PI), Sinks Canyon (SC),and South Pass (SP).

NADP Deposition Trends

Each site was analyzed for trends in deposition (kg/ha) for Ca^{2+}, Cl^{-}, K^{+}, Mg^{2+}, Na^{+}, NH_4^{+}, NO_3^{-}, total measured inorganic nitrogen (IN), and SO_4^{2-}. Annual trends (with seasonality taken into account) are shown in table 7. Trends for each season are shown in tables 8 to 12, and selected trends are shown in figures 9 through 21. The graphs focus on depicting trends in N and S.

Table 7—NADP: Deposition, Seasonal Mann-Kendall output for annual trends at five NADP sites: ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable	Gypsum Creek WY98		Murphy Ridge UT08		Pinedale WY06		Sinks Canyon WY02		South Pass WY97	
(kg/ha)	ss	p	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	0	0.651	0	0.759	-0.002	**0.002**	-<0.001	0.389	0.003	0.115
Mg^{2+}	-<0.001	**0.06**	-<0.001	**0.076**	-<0.001	**<0.001**	-<0.001	**0.002**	0	0.532
K^{+}	<0.001	**0.088**	0	0.933	-<0.001	**0.041**	0	0.583	<0.001	**0.025**
Na^{+}	-0.001	**0.001**	-0.002	**<0.001**	-0.003	**<0.001**	-0.002	**<0.001**	-0.002	**0.002**
NH_4^{+}	0.003	**<0.001**	0.001	**0.023**	0.001	**0.045**	0.003	**0.001**	0.003	**0.003**
NO_3^{-}	0.007	**0.003**	0.005	0.165	0	0.744	0.002	0.434	0.009	0.153
Cl^{-}	-0.002	**<0.001**	-0.003	**<0.001**	-0.003	**<0.001**	-0.003	**<0.001**	-0.003	**<0.001**
SO_4^{2-}	-0.003	0.115	-0.006	**0.005**	-0.01	**<0.001**	-0.011	**<0.001**	-0.011	**0.003**
IN	0.004	**<0.001**	0.003	**0.06**	0.001	0.426	0.002	**0.058**	0.004	**0.012**

Table 8—NADP: Deposition, Mann-Kendall outputs for trends, Gypsum Creek (WY 98): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable	Winter		Spring		Summer		Fall	
(kg/ha)	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	0	0.575	0	0.881	-0.001	0.771	0.002	0.411
Mg^{2+}	-<0.001	0.203	-<0.001	0.214	-<0.001	0.290	0	0.936
Cl^{-}	-0.002	**0.056**	-0.003	**0.012**	-0.004	**0.026**	-0.002	**0.059**
K^{+}	-<0.001	0.148	<0.001	0.156	<0.001	0.355	<0.001	**0.009**
Na^{+}	-<0.001	**0.059**	-<0.001	0.637	-0.002	**0.068**	-0.002	**0.030**
NH_4^{+}	0.001	**0.006**	0.003	0.135	0.011	**0.011**	0.008	**<0.001**
NO_3^{-}	0.006	**0.024**	0.002	0.710	0.008	0.398	0.017	**0.019**
IN	0.002	**0.009**	0.003	0.517	0.010	**0.047**	0.008	**0.003**
SO_4^{2-}	-0.002	0.116	-0.006	0.297	-0.003	0.492	<0.001	0.812

Table 9—NADP: Deposition, Mann-Kendall outputs for seasonal trends, Murphy Ridge (UT08): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (kg/ha)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	0	0.840	-0.002	0.561	0	0.888	0	0.977
Mg^{2+}	-<0.001	0.277	-<0.001	0.195	-<0.001	0.651	-<0.001	0.551
K^+	-<0.001	0.245	-<0.001	0.791	<0.001	0.232	0	0.955
Na^+	-0.002	**0.009**	-0.002	0.256	-0.001	0.224	-0.002	**0.010**
NH_4^+	<0.001	0.250	0	1	0.007	**0.054**	0.003	0.133
NO_3^-	0.007	**0.085**	-0.007	0.509	0.011	0.150	0.004	0.735
Cl^-	-0.003	**0.009**	-0.003	**0.076**	-0.003	0.202	-0.001	0.166
SO_4^{2-}	-0.003	0.246	-0.011	0.154	-0.007	0.158	-0.008	0.127
IN	0.002	**0.098**	-0.003	0.771	0.010	0.108	0.003	0.396

Table 10—NADP: Deposition, Mann-Kendall outputs for seasonal trends, Pinedale (WY06): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (kg/ha)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-0.002	**0.006**	-0.004	0.203	-0.004	**0.081**	0	0.773
Mg^{2+}	-<0.001	**<0.001**	-0.001	**0.035**	-0.001	**<0.001**	-<0.001	**0.072**
K^+	-<0.001	**0.008**	-<0.001	0.530	-<0.001	0.774	0	0.642
Na^+	-0.003	**<0.001**	-0.003	**0.027**	-0.003	**<0.001**	-0.002	**0.002**
NH_4^+	0	0.501	0.001	0.738	0.004	**0.093**	0.004	**0.009**
NO_3^-	<0.001	0.895	-0.007	0.326	-0.008	0.261	0.012	**0.098**
Cl^-	-0.003	**<0.001**	-0.003	**0.002**	-0.005	**<0.001**	-0.002	**0.005**
SO_4^{2-}	-0.007	**<0.001**	-0.020	**0.012**	-0.026	**<0.001**	-0.006	**0.061**
IN	0	0.548	-0.002	0.517	0.002	0.479	0.006	**0.027**

Table 11—NADP: Deposition, Mann-Kendall outputs for seasonal trends, Sinks Canyon (WY02): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (kg/ha)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	-<0.001	0.300	0.007	0.157	-0.006	**0.022**	0	0.881
Mg^{2+}	-<0.001	**0.023**	<0.001	0.804	-0.001	**0.002**	-<0.001	0.263
K^+	-<0.001	0.236	<0.001	0.106	-<0.001	0.709	<0.001	0.295
Na^+	-0.002	**0.001**	-<0.001	0.619	-0.002	**0.008**	-0.002	**0.027**
NH_4^+	0	0.347	0.006	0.180	0.004	0.187	0.006	**0.007**
NO_3^-	0	0.822	0.002	0.843	-0.006	0.413	0.015	**0.053**
Cl^-	-0.002	**<0.001**	-0.003	**0.036**	-0.004	**0.003**	-0.002	**0.003**
SO_4^{2-}	-0.006	**0.030**	-0.015	0.118	-0.023	**0.015**	-0.009	0.253
IN	0	0.615	0.004	0.471	0.002	0.691	0.007	**0.037**

Table 12— NADP: Deposition, Mann-Kendall outputs for seasonal trends, South Pass (WY97): ss represents Sen's slope estimator (the negative sign signifies a decreasing slope); p represents p-value; red numbers equal significant trends when p<0.1.

Variable (kg/ha)	Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
Ca^{2+}	0	0.458	0.011	**0.018**	-0.003	0.443	0.006	**0.026**
Mg^{2+}	-<0.001	**0.076**	<0.001	0.243	-<0.001	**0.060**	-<0.001	0.265
K^+	<0.001	0.853	<0.001	**0.013**	<0.001	0.791	<0.001	**0.072**
Na^+	-0.004	**0.007**	<0.001	0.862	-0.003	**0.008**	-<0.001	0.256
NH_4^+	0.001	0.611	0.004	**0.065**	0.004	0.153	0.004	**0.031**
NO_3^-	0.003	0.711	0.010	0.188	0	1	0.018	**0.057**
Cl^-	-0.004	**0.002**	-0.001	0.292	-0.003	**0.001**	-0.001	0.241
SO_4^{2-}	-0.012	**0.061**	-0.006	0.518	-0.020	**0.020**	-0.008	0.328
IN	0.002	0.916	0.006	**0.030**	0.003	0.354	0.008	**0.053**

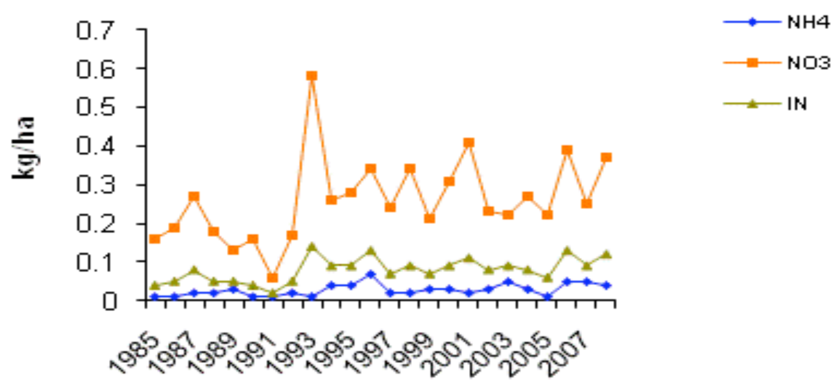

Figure 9—Gypsum Creek (WY98) NADP site winter nitrogen deposition from 1985-2008. IN represents measured winter inorganic nitrogen.

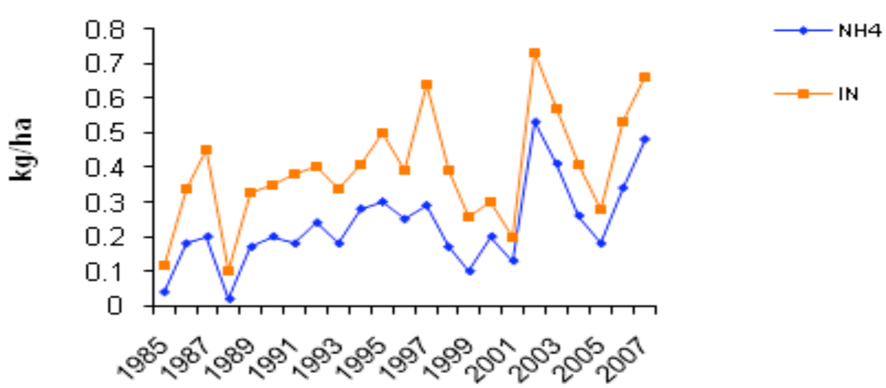

Figure 10—Gypsum Creek (WY98) NADP site summer nitrogen deposition from 1985-2007. IN represents measured inorganic nitrogen.

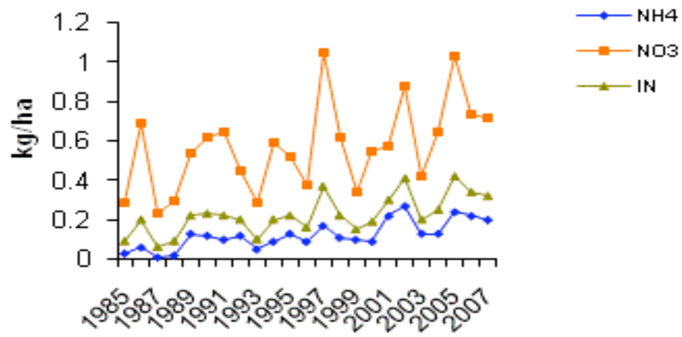

Figure 11—Gypsum Creek (WY98) NADP site fall nitrogen deposition from 1987-2007. IN represents measured inorganic nitrogen.

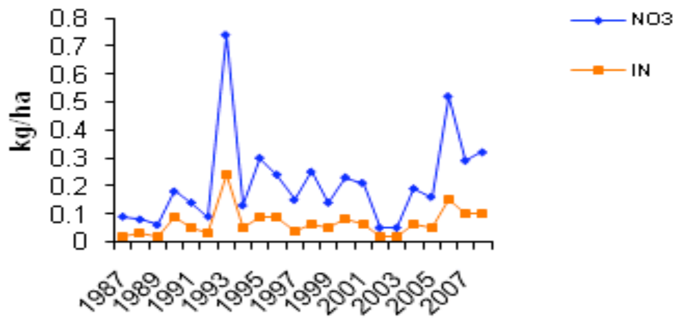

Figure 12—Murphy Ridge (UT08) NADP site winter nitrogen deposition from 1987-2008. IN represents measured inorganic nitrogen.

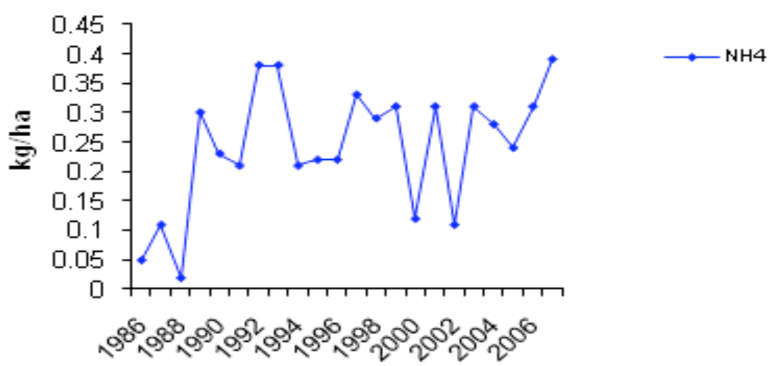

Figure 13—Murphy Ridge (UT08) NADP site summer NH_4^+ deposition from 1986-2007.

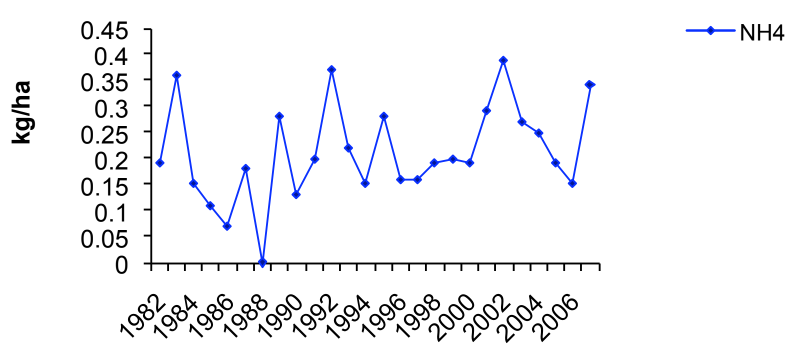

Figure 14—Pinedale (WY06) NADP site summer NH_4^+ deposition from 1982-2007.

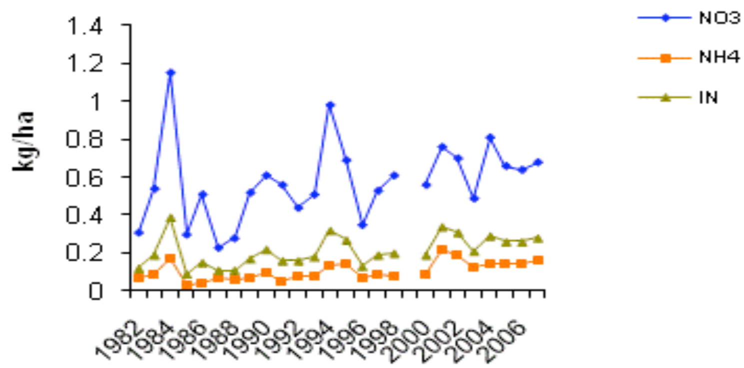

Figure 15—Pinedale (WY06) NADP site fall nitrogen deposition from 1982-2007. IN represents measured inorganic nitrogen.

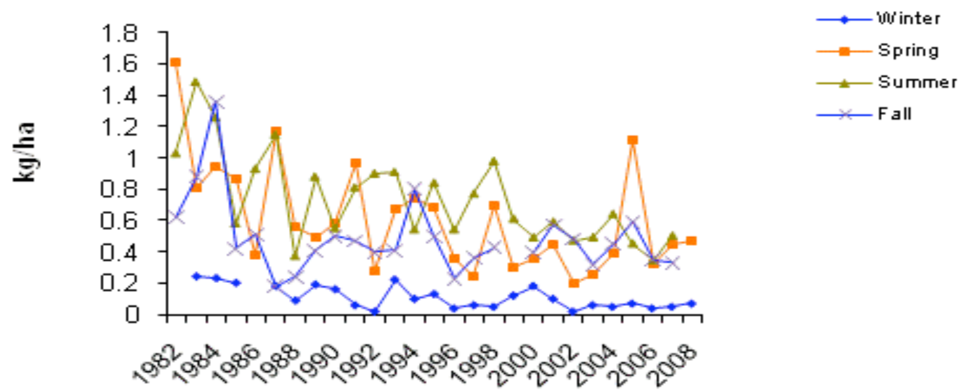

Figure 16—Pinedale (WY06) NADP site seasonal SO_4^{2-} deposition from 1982-2008.

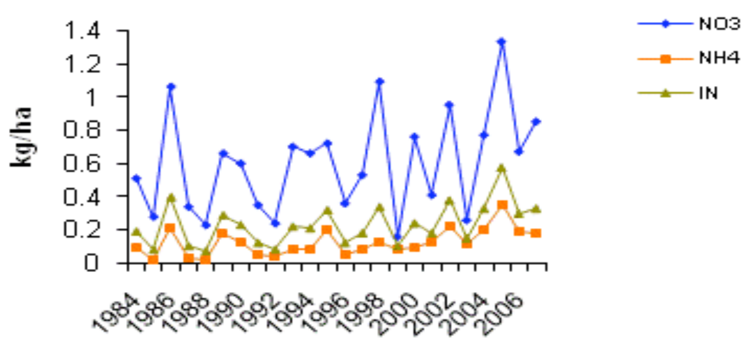

Figure 17—Sinks Canyon (WY02) NADP site fall nitrogen deposition from 1985-2007. IN represents measured inorganic Nitrogen.

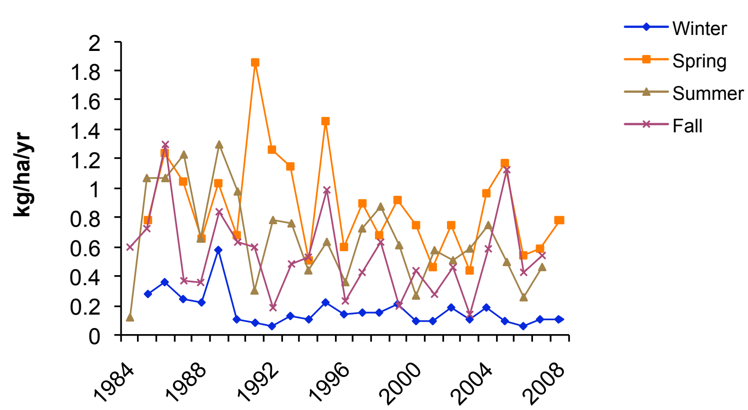

Figure 18—Sinks Canyon (WY02) NADP site seasonal SO_4^{2-} deposition from 1985-2008.

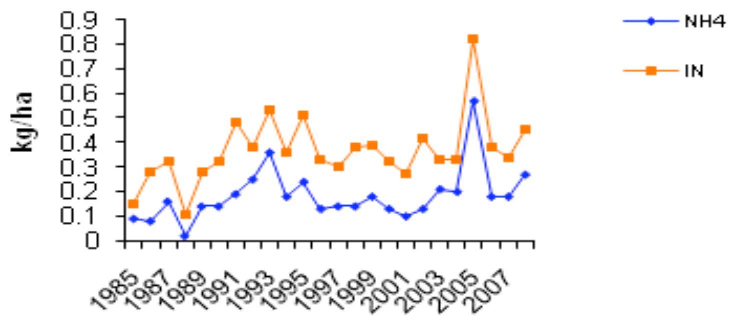

Figure 19—South Pass (WY97) NADP site spring nitrogen deposition from 1985-2008. IN represents measured inorganic nitrogen.

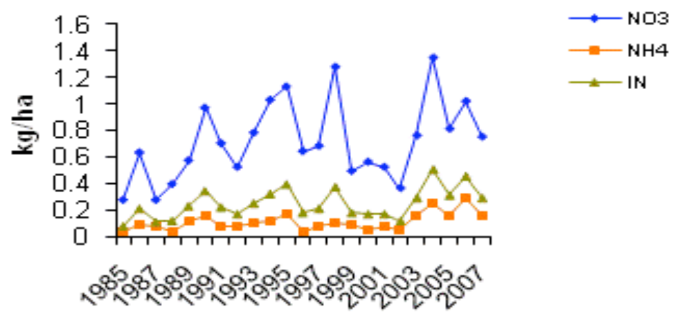

Figure 20—South Pass (WY97) NADP site fall nitrogen deposition 1985-2007. IN represents measured inorganic nitrogen.

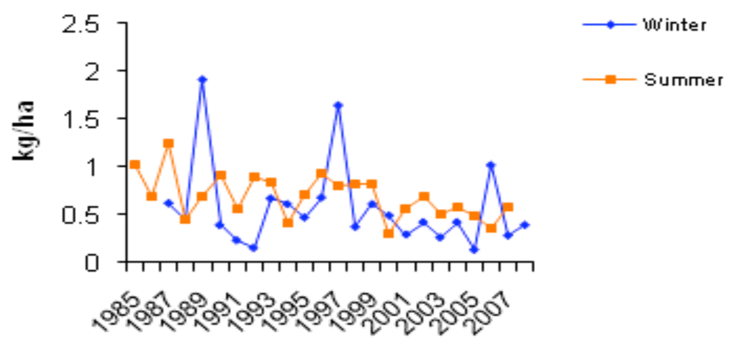

Figure 21—South Pass (WY97) NADP site seasonal SO_4^{2-} deposition from 1985-2008.

NADP Discussion

NADP reports precipitation chemistry for weekly snow and rain; therefore, the calculated deposition amounts only represent wet deposition. Total deposition also includes dry and fog deposition. In the Northern Rocky Mountains, dry deposition can be a substantial component of total deposition. Data from the EPA Clean Air Status and Trends Network (CASTNET) (http://www.epa.gov/castnet/) estimates dry deposition of inorganic nitrogen in this area to account for about 25 to 33 percent of total deposition (Ingersoll and others 2008).

The NADP samplers (Aerochem Metrics) were designed to collect rainfall in relatively calm environments. The sampler and buckets are not 100 percent efficient at collecting samples in environments that are windy and or/snow-laden (such as that found in and around the Wind River Range). Winter conditions often pose difficulties for data collection (i.e., iced solar panels, burned out or frozen motors, and difficulties with site accessibility) (Goodison and others 1998; Yang and others 2000).

Ammonia concentration and deposition increased at all NADP sites that were analyzed. Consistent increases in ammonia concentration and deposition have been documented over much of the western United States (Fenn and others 2003; NADP data report 2007). Ingersoll and others (2008), Bevenger (2008), and Grenon and Story (2009) also documented a moderately significant upward trend in NH_4^+ concentration at NADP sites in the Northern Rockies. Results of the analysis by Bevenger (2008) are included in the Appendix. Analysis of NADP trends from 1985 to 2002 and from 2002 to 2004 documented nationwide NH_4^+ increases, particularly in agriculture areas of the Midwest and western United States (Lehmann and others 2005, 2007). Fenn and others (2003) evaluated NO_3^- and NH_4^+ concentrations at NADP sites in Oregon and Washington and found that concentrations have been increasing since monitoring began in 1980. Campbell (2004) indicates that for the Intermountain West, ammonia makes up about one third of the total nitrogen deposition at many sites. The increase in atmospheric NH_4^+ has been attributed to fertilizer production and volatilization from animal feedlots, waste lagoons, and land-based waste application.

Gypsum Creek (WY98) and South Pass (WY97) showed increasing trends in annual NO_3^- deposition and concentration respectively. All NADP sites had at least one season in which there was an increasing trend in NO_3^-. In general, NO_3^- concentrations have decreased in the Northeast and Midwest due to the 1990 Clean Air Act amendments that mandated emission reductions for stationary sources (EPA 2008). Concentrations in the Rocky Mountains have generally increased, particularly around urban areas (Fenn and others 2003; Lehmann and others 2005), for example, NO_3^- in wet deposition is elevated in the Colorado Front Range (Nanus and others 2008).

Annual inorganic nitrogen (IN) deposition revealed statistically significant increasing trends at all the NADP sites except at Pinedale, Wyoming. All sites had at least one season in which IN deposition increased. The increase in IN is due primarily to the increase in NH_4^+. An increase in IN can act as a fertilizer and enrich sensitive ecosystems, cause acidification to soils, and eutrophication to aquatic systems.

Significant decreasing trends in SO_4^{2-} concentration and deposition were detected at all sites except for deposition at Gypsum Creek (WY97). This pattern is consistent with Lehmann (2005) who documented sulfate decreases in the 1985 to 2002 period at all of the NADP sites in the western United States. The EPA has documented a national decrease in SO_2 emissions of 43 percent from 1990 to 2007 and 24 percent from 2001 to 2007 (EPA 2008). Oxidation of SO_2 emissions can lead to SO_4^{2-} formation and deposition (Kellogg and others 1972); concentrations of the two S species often closely track each other (Debell and others 2006). The Yellowstone NP NADP site had a 27 percent decrease in net SO_2 deposition from 1990 to 1999 (EPA 2008). This widespread decrease in SO_2 emissions and resulting SO_4^{2-} deposition is largely a result of the Clean Air Act of 1990 (http://www.epa.gov/air/caa/)

emission reduction provisions amendment, the Highway Low Sulfur Diesel Rule (http://epa.gov/cleandiesel/documents/420f04034.htm), and the closure and/or emission reductions of several smelters and coal burning power plants in the western United States.

All of the NADP sites showed statistically significant decreasing trends in Cl^-, Na^+, and Mg^{2+} for both concentration and deposition (except for South Pass which did not show trends for Mg^{2+}). Recent trends in Colorado report 9 of 10 high elevation (over 2,700 meters) NADP sites had statistically significant decreasing Na^+ and Cl^- ($p \leq 0.01$) (Mast, and others 2010). These findings also are consistent with reported declines in base cations for the eastern United States, other parts of the Northern Rockies, and parts of Europe. (Grenon and Story 2009; Hedin and others 1994). The trends in Na^+ and Cl^- may also be caused, in part, by changes in protocols. In 1994 a change was made in the type of filter used for NADP protocol/procedures at the CAL (Lynch and others 1996). Both of these changes may account for a portion of the cation and anion decreases observed, but not all. Emission decreases or other environmental factors may contribute to cation and anion decreases, but this trend is not, at present, entirely explainable.

Bulk Deposition

The bulk deposition program in the Bridger Wilderness was established at four sites in 1985: Hobbs Lake, Black Joe Lake, Lester Pass, and Indian Park. All four sites were developed to establish a high elevation deposition for the Bridger Wilderness. The sites at Hobbs and Black Joe Lakes were initiated to investigate possible cause-and-effect relationships between atmospheric deposition and surface water chemistry since both lakes are part of the B-T long-term lake monitoring program. In 1985 bulk precipitation collectors were established at three NADP sites in and around the Wind River Mountains, (Gypsum Creek WY98, South Pass WY97, and Pinedale WY06), to determine a correlation among the NADP collectors. These three co-located bulk collectors and the Lester Pass and Indian Park bulk collectors were discontinued in 1991 since the precipitation chemistry from these sites corresponded well with the Hobbs Lake bulk collector. Current bulk deposition sampling locations evaluated in this report are shown in figure 1. Bulk deposition chemical analysis is done at the USFS Air Resource Management (ARM) Laboratory in Fort Collins, Colorado (http://www.fs.fed.us/waterlab/). The sites are sampled about every 2 weeks in the summer, and every 4 weeks in the winter. The summer season generally runs from July to October and the winter season from November to June. The bulk precipitation program calculates deposition based on concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, NH_4^+, nitrogen(N) as NH_4^+, NO_3^-, N as NO_3^-, Total N, SO_4^{2-}, S as SO_4^{2-}, and precipitation (cm). Annual trends from the data analysis are shown in table 13 and graphs are depicted in figures 22 to 26.

Table 13—Bulk deposition: Mann-Kendall output for annual trends at Hobbs Lake and Black Joe Lake sites (rain and snow). Red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

	Hobbs Lake		Black Joe Lake	
Variable (kg/ha)	Sen's slope	p-value	Sen's slope	p-value
Ca^{2+}	0.078	**0.009**	0.087	**0.011**
Mg^{2+}	0.013	**0.008**	0.013	**<0.001**
K^{+}	0.004	0.711	0.004	0.459
Na^{+}	-0.007	0.615	-0.001	0.916
Cl^{-}	-0.03	**0.010**	-0.020	**0.019**
NH_4^{+}	0.042	**0.002**	0.041	**0.035**
N as NH_4^{+}	0.027	**0.002**	0.026	**0.035**
NO_3^{-}	0.124	**0.007**	0.151	**0.065**
N as NO_3^{-}	0.028	**0.007**	0.034	**0.065**
Total N	0.055	**0.005**	0.061	**0.027**
SO_4^{2-}	0.052	0.224	-<0.001	1
S as SO_4^{2-}	0.017	0.224	-<0.001	1
Precipitation	1.458	**0.027**	0.150	0.792

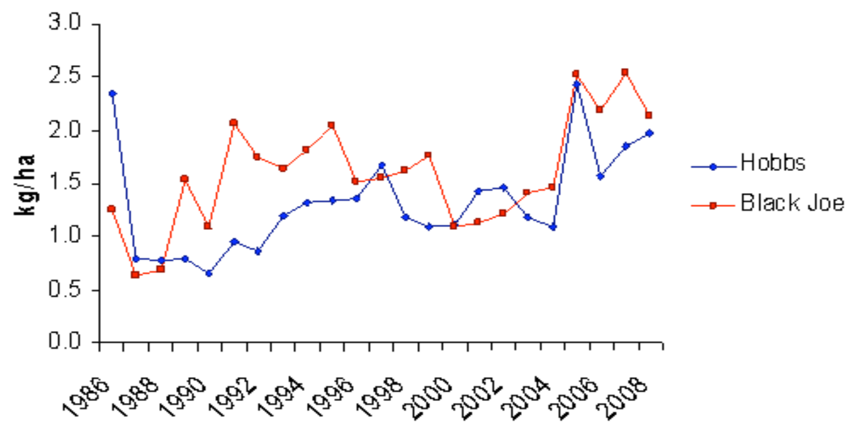

Figure 22—Annual NH_4^{+} trends from Hobbs and Black Joe bulk deposition sites from 1986-2008.

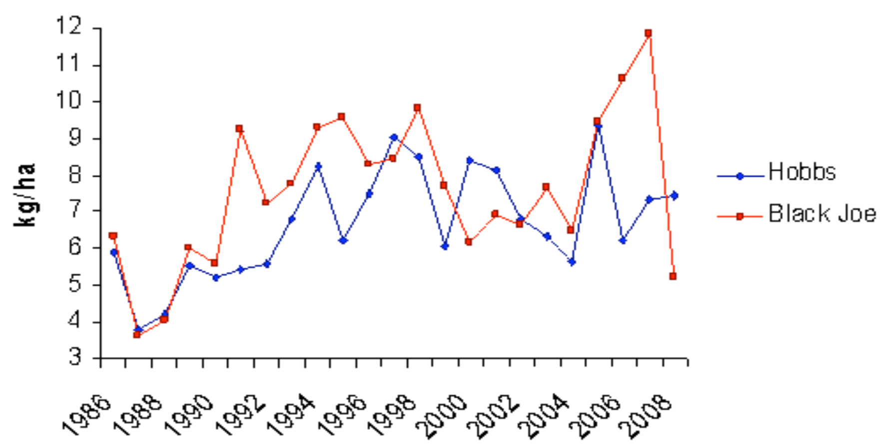

Figure 23—Annual NO_3^{-} trends from Hobbs and Black Joe bulk deposition sites from 1986-2008.

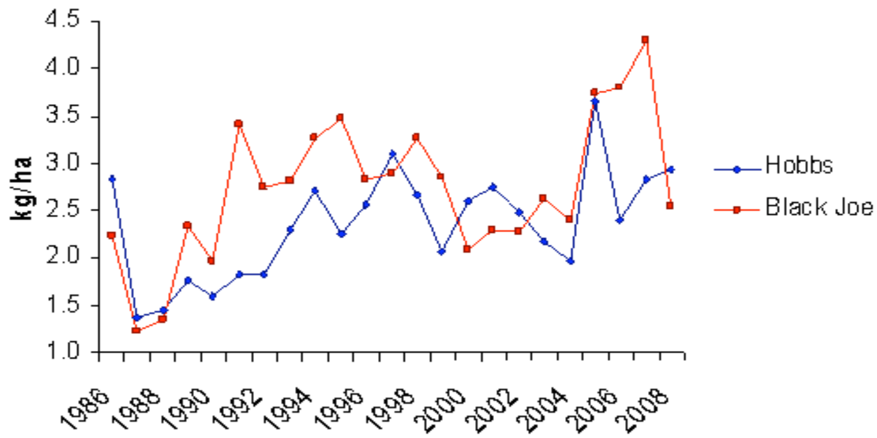

Figure 24—Total annual nitrogen trends from Hobbs and Black Joe bulk deposition sites from 1986-2008.

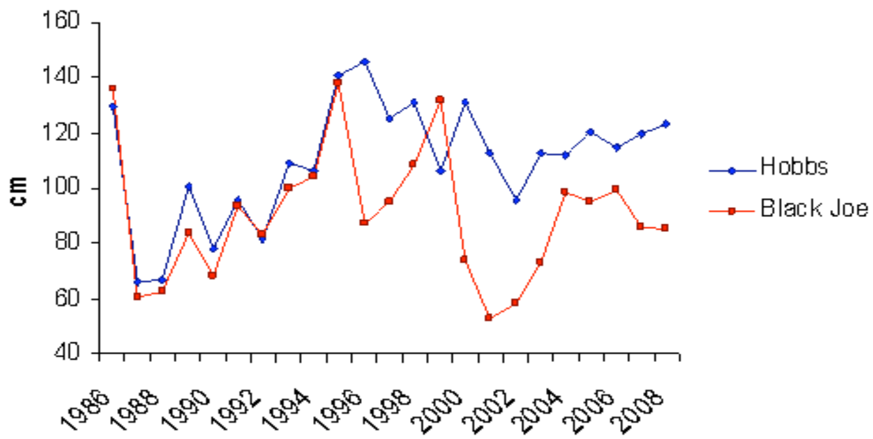

Figure 25—Annual precipitation amount (cm) at Hobbs and Black Joe bulk deposition sites from1986-2008. Only Hobbs had a statistically significant trend.

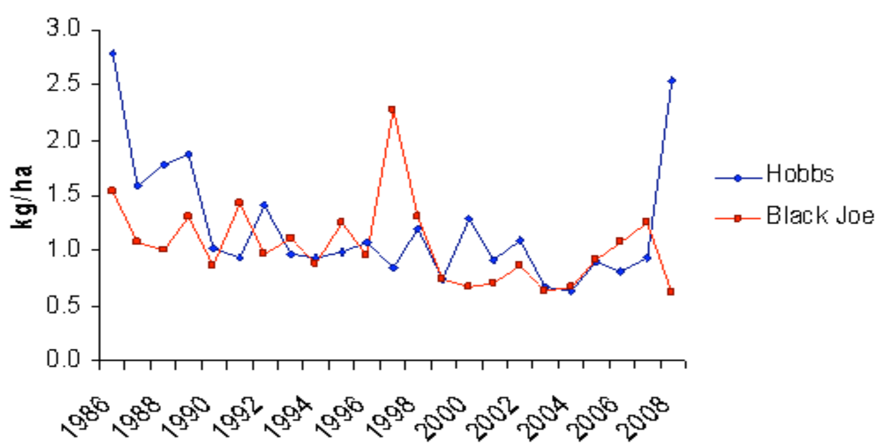

Figure 26—Annual Cl^- trends from Hobbs and Black Joe bulk deposition sites from 1986-2008.

Bulk Deposition Discussion

The Hobbs bulk deposition site generally has slightly higher annual precipitation averages than the Black Joe site. Reduced precipitation at the bulk deposition sites in the early 2000s, especially at the Black Joe site, which may have influenced deposition amounts.

Bulk deposition trends of decreasing Cl^- and increasing Mg^{2+}, Ca^{2+}, NH_4^+, and NO_3^- are consistent with the long-term lake and NADP data analyses. The consistent statistically significant increasing trends in nitrogen are particularly notable. Annual nitrogen deposition in terms of both NO_3^- and NH_4^+ at the bulk sampling sites is higher than deposition at the NADP sites (see NADP website for annual deposition amounts). Annual NO_3^- deposition at the NADP sites analyzed tends to average around 1.5-3.5 kg/ha/yr sometimes exceeding an annual average of 4 kg/ha/yr (South Pass City WY97 site). This may be due in part to the sampling equipment. The bulk samplers collect both wet and dry deposition whereas the NADP sites collect only wet deposition. In the drier climates of the West, dry deposition is thought to account for a significant proportion of total deposition. As mentioned above, data from CASTNET samplers estimate total nitrogen dry deposition in the Rockies to be about 25 percent to 33 percent of total deposition (Ingersoll and others 2008). This still does not account for the discrepancy in annual nitrogen deposition amounts recorded by the two monitoring programs. The bulk sampler sites are located 760 m higher than the NADP sites. Higher elevations in the Rocky Mountains typically experience higher precipitation and, therefore, higher wet deposition (Baron and others 2000). Also, the bulk collectors have an open design that allows for insects, plant debris, and other material to fall or get blown into the collectors. The open design also allows for evaporation, which has the potential to concentrate the chemical constituents that are measured. Bird droppings sometimes end up in the collectors; as a precaution, samples that show abnormally high phosphate levels are discarded in the screening process.

SO_4^{2-} deposition at the bulk sites did not show any trends in annual deposition. This coincides with the SO_4^{2-} concentration findings in the lake data, but opposes the decreasing trends in annual SO_4^{2-} deposition found at the NADP sites in the B-T and opposes the nation-wide trends of decreasing SO_4^{2-} mentioned above.

Long-Term Lake Monitoring

The lake monitoring program on the B-T National Forest began in 1984. The four lakes (Black Joe, Hobbs, Upper Frozen, and Deep lakes) (fig. 1) that are currently monitored were chosen based on elevation (above 2,900 meters), size (greater than 15 acres), and low acid neutralization capacity (ANC) (table 14). Chemical analyses are conducted at the USFS Air Resource Management (ARM) Laboratory in Fort Collins, Colorado (http://www.fs.fed.us/waterlab/). Lake data for the B-T National Forest can be obtained from the USFS NRIS-Air database for chemistry of lakes, streams, and bulk deposition on and near the National Forests (http://www.fs.fed.us/waterdata/). The lake sampling followed protocols highlighted in the Bridger-Teton National Forest Wind River Mountains Air Quality Monitoring Program

Table 14—Lakes: Physical features of sampled lakes.

Lake	Elevation (m)	Depth (m)	Area of lake (acres)
Black Joe	3,121	28.9	80.4
Deep	3,218	27.0	60.5
Hobbs	3,083	18.3	17.3
Upper Frozen	3,487	42.9	23.5

Methods Manual (USDA FS 2002). Lakes were typically sampled three times per year at the inlet and outlet. Season 1 is after ice begins to break up (May to July 21). Season 2 was taken mid- to late summer when the lakes are stratified (July 22 to August 31). Season 3 sample was taken closest to lake freeze-up after fall overturn (September 1 to mid November). In addition epilimnion and hypolimnion samples were collected during season 2.

Samples are marked "regular" (those taken every time), "duplicate" (taken every couple samples), and "blank" (deionized water). In the data analysis, duplicate samples were averaged with their corresponding regular sample if the concentrations were within 10 percent of each other. If not, then the preceding and following samples were averaged and the sample data closest to the value of the newly averaged sample was used (see Appendix). Data from blanks were used for QA/QC in the lab and were not included in the analysis for this report. Missing data were left blank. The revised data sets were used for the SAS analysis. The long-term lake monitoring program has used three labs throughout its duration. The B-T lake monitoring program started with the USGS lab in Denver, Colorado, and then switched to the CAL lab in Illinois in the late 1980s. A switch was again made in 1996 to the current ARM lab in Fort Collins, Colorado. Split samples were sent to the CAL and ARM for 2 years to ensure a smooth transition of QA/QC.

Data from Black Joe, Hobbs, Deep (fig. 27), and Upper Frozen lakes were analyzed for trends in concentrations of lab specific conductance (Lcond), ANC (acid neutralizing capacity μeq/L), Ca^{2+}, Cl^- , K^+, Mg^{2+}, Na^+, NH_4^+, NO_3^-, lab pH, and SO_4^{2-} (all in μeq/L). Data from each lake was analyzed for annual trends in chemistry at the lake inlet, outlet, epilimnion, and hypolimnion. Tables 15 and 16 show results from epilimnion and hypolimnion analysis respectively. Figures 28 to 31 show trends in the hypolimnion. Due to its remote location, Upper Frozen Lake is sampled once a year at the outlet during season 2. Tabular and graphical information for Upper Frozen Lake are found in table 17 and figures 32 to 33. Inlet and outlet datasets from Black Joe, Hobbs, and Deep lakes had enough observations to analyze for seasonality and to analyze for trends within each season (tables 18 to 25 and figs. 22 to 26 and 28 to 43).

Figure 27—Deep Lake, one of the long-term lakes sampled by the Bridger-Teton National Forest since 1984 (photo by Hank Williams).

Table 15—Lakes: Epilimnion, Mann-Kendall output for annual trends at three lakes: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Black Joe Lake		Hobbs Lake		Deep Lake	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	1.025	0.925	0.025	0.161	0.550	0.673
Ca^{2+}	0.936	**0.012**	-0.148	0.528	0.499	0.130
Cl^-	-0.046	0.216	-0.107	**0.088**	-0.041	0.107
Lcond	0.003	0.870	-0.115	**0.025**	0.006	0.709
H^+	0.001	0.469	0.005	**0.027**	0.001	0.747
K^+	0.090	**0.044**	-0.025	0.454	0.059	**0.056**
Mg^{2+}	0.128	0.440	-0.015	0.888	0.165	**0.063**
Na^+	0.373	**0.003**	0.259	**0.015**	0.310	**0.008**
NH_4^+	0.020	0.439	0.035	0.309	<0.001	0.743
NO_3^-	<0.001	0.253	-0.152	**0003**	0.000	**0.013**
Lab pH	-0.006	0.440	-0.024	**0.025**	-0.004	0.519
SO_4^{2-}	0.182	0.374	-0.039	0.544	0.058	0.980

Table 16—Lakes: Hypolimnion, Mann-Kendall output for annual trends at three lakes: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Black Joe Lake		Hobbs Lake		Deep Lake	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	1.121	0.944	0.060	0.168	0.290	0.612
Ca^{2+}	0.921	**0.068**	0.075	0.691	0.257	0.888
Cl^-	-0.037	**0.080**	-0.090	**0.062**	-0.060	**0.026**
Lcond	0.003	0.657	-0.095	0.141	0.000	0.572
H^+	0.005	0.304	0.014	**<0.001**	0.009	0.159
K^+	0.127	**0.015**	0.012	0.944	0.055	0.195
Mg^{2+}	0.129	0.743	0.036	0.691	0.122	0.397
Na^+	0.284	**0.058**	0.232	**0.023**	0.082	0.910
NH_4^+	0.161	**0.058**	-0.015	0.356	0.068	**0.006**
NO_3^-	0.037	0.574	-0.008	**0.071**	<0.001	**0.005**
Lab pH	-0.012	**0.025**	-0.028	**0.001**	-0.018	**0.030**
SO_4^{2-}	0.177	0.797	-0.059	0.414	-0.097	0.142

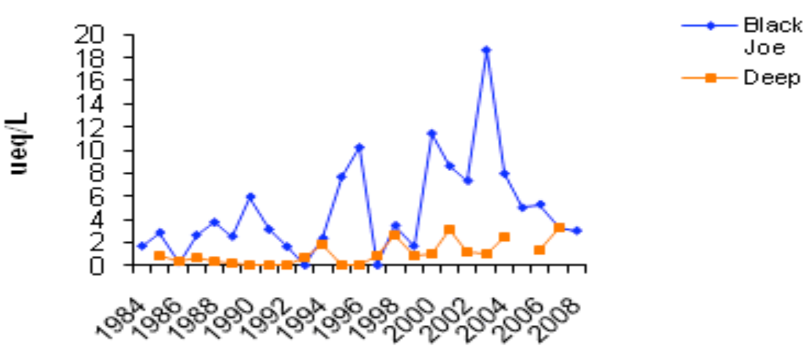

Figure 28—Annual hypolimnion NH_4^+ trend at Black Joe and Deep lakes from 1984-2008.

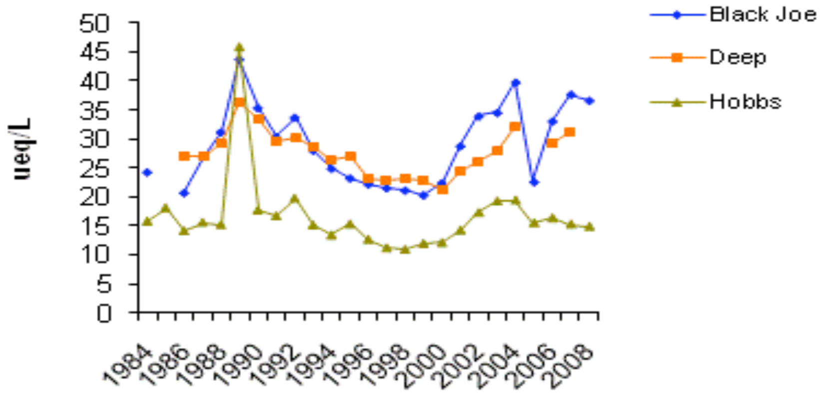

Figure 29—Annual hypolimnion SO_4^{2-} at Black Joe, Deep, and Hobbs lakes from 1984-2008.

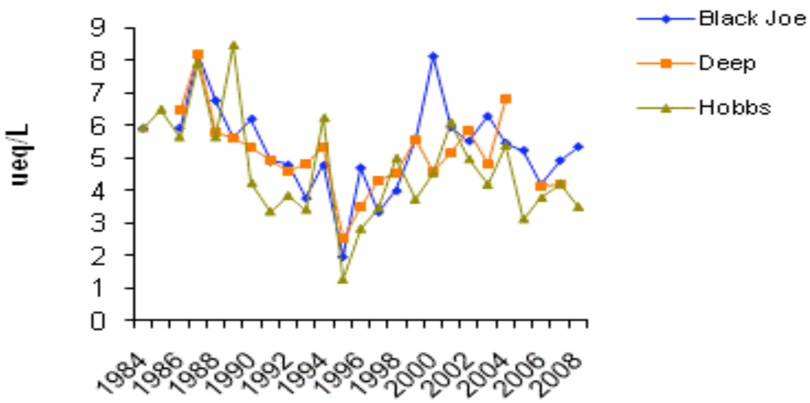

Figure 30—Annual hypolimnion Cl^- trend at Black Joe and Deep lakes from 1984-2008.

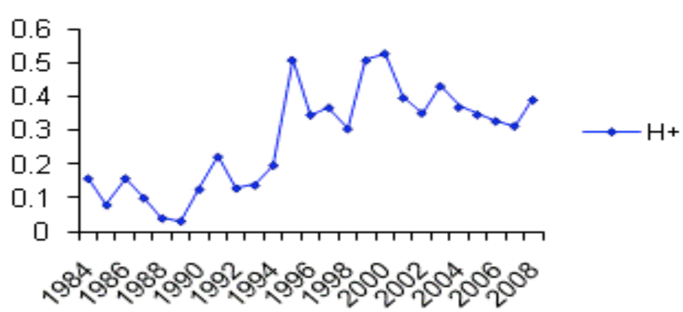

Figure 31—Annual hypolimnion H^+ trend at Hobbs Lake from 1984-2008.

Table 17—Upper Frozen Lake: outlet, annual trends from Mann-Kendall test. Red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Sen's slope	p- value
ANC	0.700	**0.087**
Ca^{2+}	1.148	**0.013**
Cl^-	-0.005	0.876
Lcond	-0.004	0.938
H^+	-0.072	**0.005**
K^+	0.084	**0.029**
Mg^{2+}	0.366	**0.013**
Na^+	0.526	0.119
NH_4^+	-0.061	0.135
NO_3^-	-0.228	0.276
Lab pH	0.043	**0.008**
SO_4^{2-}	0.264	**0.029**

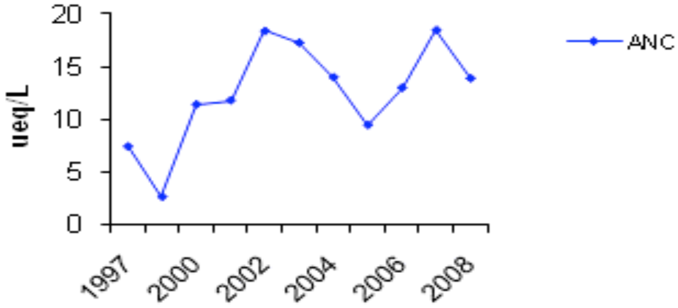

Figure 32—Upper Frozen Lake annual outlet ANC trend from 1997-2008.

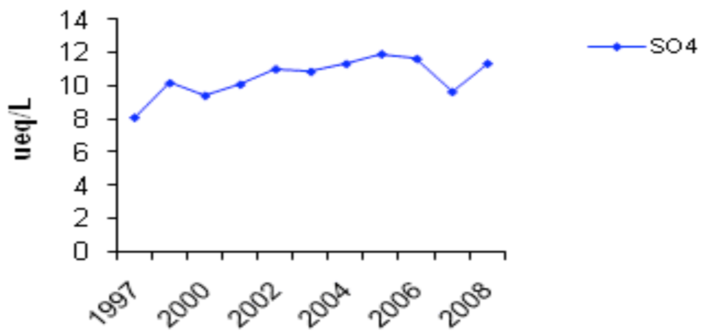

Figure 33—Upper Frozen Lake annual outlet SO_4^{2-} trend from 1997-2008.

Table 18—Lakes: Inlets, Seasonal Mann-Kendall output for annual trends at three lakes: p represents p-value and is significant when p<0.1. Numbers marked with an * mean those variables required the Seasonal Mann Kendall test for analysis; all other numbers come from the Mann-Kendall test. Bolded red numbers signify significant trends. A negative Sen's slope represents a decreasing slope.

Variable (μeq/L)	Black Joe Inlet		Hobbs Inlet		Deep Inlet	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	*0.959	*0.739	*0.407	*0.335	*0.859	*1
Ca^{2+}	*1.236	***<0.001**	*0	*1	*1.763	***<0.001**
Cl^-	*-0.015	*0.567	*-0.093	***0.006**	*-0.035	*0.224
Lcond	*0.003	*0.861	*-0.097	***0.071**	*0.067	*0.532
H^+	0.004	0.191	0.006	**0.027**	0.004	0.142
K^+	*0.068	***0.024**	0.024	0.441	*0.069	***0.018**
Mg^{2+}	*0.149	***0.032**	*0.004	*0.821	*0.212	***0.003**
Na^+	*0.295	***<0.001**	*0.270	***0.008**	*0.350	***0.002**
NH_4^+	-0.004	0.926	0.091	**0.036**	0	1
NO_3^-	*0.203	***0.029**	*-0.003	*0.277	*0.127	*0.272
LabpH	-0.019	0.141	-0.025	**0.014**	-0.018	0.154
SO_4^{2-}	*0.290	***0.056**	*-0.104	*0.259	*0.390	*0.128

Table 19—Lakes: Outlets, Seasonal Mann-Kendall output for annual trends at three lakes: p represents p-value and is significant when p<0.1. Numbers marked with an * mean those variables required the Seasonal Mann Kendall test for analysis; all other numbers come from the Mann-Kendall test. Bolded red numbers signify significant trends. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Black Joe Outlet		Hobbs Outlet		Deep Outlet	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.815	0.963	*-0.169	***0.017**	0.891	0.726
Ca^{2+}	0.927	**0.002**	0.034	0.870	*0.811	***<0.001**
Cl^-	-0.022	0.513	-0.084	**0.068**	-0.075	**0.035**
Lcond	0.007	0.852	-0.081	**0.050**	-0.018	0.743
H^+	0.003	0.129	0.005	0.168	0.003	0.129
K^+	0.072	**0.03**	-0.071	**0.018**	0.028	0.293
Mg^{2+}	0.210	**0.003**	0.014	0.779	0.200	**<0.001**
Na^+	0.461	**<0.001**	0.120	0.154	0.162	0.234
NH_4^+	0.061	**0.093**	0.037	**0.065**	0.000	1
NO_3^-	*0.010	0.870	-0.020	**0.068**	-0.009	0.130
LabpH	-0.014	0.118	-0.018	0.141	-0.012	0.141
SO_4^{2-}	0.310	0.118	0.031	0.640	0.008	0.926

Table 20—Lakes: Concentration, trends (three seasons) from Mann-Kendall test, Black Joe Lake inlet: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Black Joe Inlet Season 1		Season 2		Season 3	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.738	0.526	1.251	0.561	1	0.450
Ca^{2+}	0.413	0.492	2.046	**0.012**	1.435	**0.090**
Cl^-	-0.057	0.224	-0.015	0.692	0.038	0.450
Lcond	-0.129	0.341	0	0.937	0.140	0.184
H^+	0.005	0.673	0.002	0.672	0.004	0.155
K^+	0.031	0.398	0.102	**0.039**	0.090	0.365
Mg^{2+}	0.082	0.561	0.048	0.578	0.483	**0.006**
Na^+	0.220	0.102	0.313	**0.014**	0.387	**0.022**
NH_4^+	0	0.495	0.026	0.523	-0.002	0.808
NO_3^-	0.053	0.950	0.205	0.125	0.552	**0.023**
LabpH	-0.011	0.616	-0.008	0.315	-0.015	0.165
SO_4^{2-}	-0.104	0.615	0.583	**0.020**	0.701	0.124

Table 21—Lakes: Concentration, trends (three seasons) from Mann-Kendall test, Black Joe Lake outlet: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

Variable (µeq/L)	Black Joe Outlet Season 1		Season 2		Season 3	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.652	1	0.982	0.309	0.086	**0.039**
Ca^{2+}	0.881	**0.012**	1.087	**0.011**	1.020	**0.039**
Cl^-	0.015	0.853	-0.043	0.254	-0.054	0.197
Lcond	0	0.958	0.030	0.747	0.074	0.333
H^+	0.003	0.291	0.002	0.254	0.004	**0.078**
K^+	0.077	**0.068**	0.066	0.101	0.030	0.552
Mg^{2+}	0.215	**0.003**	0.061	0.637	0.267	**0.005**
Na^+	0.403	**0.002**	0.430	**<0.001**	0.458	**0.006**
NH_4^+	0.043	0.525	0	0.615	0	0.900
NO_3^-	0.024	0.812	0.002	0.980	0.022	0.564
LabpH	-0.011	0.278	-0.008	0.214	-0.018	**0.070**
SO_4^{2-}	0.312	**0.068**	0.350	0.130	0.411	**0.056**

Table 22—Lakes: Concentration, trends (three seasons) from Mann-Kendall test, Hobbs Lake inlet: p represents p-value; red numbers equal significant trends when $p<0.1$. A negative Sen's slope represents a decreasing slope. Variables with only seven observations and are not statistically valid since at least eight observations are needed.

	Hobbs Inlet					
	Season 1		Season 2		Season 3	
Variable (μeq/L)	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.438	0.673	2.125	1	0.133	0.232
Ca^{2+}	0.244	0.691	0	1	-0.554	0.484
Cl^{-}	-0.085	**0.087**	-0.389	0.184	-0.146	**0.052**
Lcond	-0.049	0.519	-0.460	0.640	-0.207	**0.026**
H^{+}	0.006	0.150	0.013	**0.072**	0.008	**0.044**
K^{+}	-0.006	0.960	-0.068	0.585	0.142	0.248
Mg^{2+}	0.066	0.205	0.155	0.938	-0.281	**0.090**
Na^{+}	0.317	**0.035**	0.359	0.640	0.142	0.125
NH_4^{+}	0.111	**0.039**	0.263	**0.085**	-0.017	0.740
NO_3^{-}	-0.005	0.214	0.132	0.436	0.003	0.591
LabpH	-0.019	0.150	-0.065	**0.072**	-0.033	**0.044**
SO_4^{2-}	-0.004	0.960	-0.541	**0.043**	-0.190	0.303

Table 23—Lakes: Seasonal concentration, trends from Mann-Kendall test, Hobbs Lake outlet: p represents p-value; red numbers equal significant trends when $p<0.1$. A negative Sen's slope represents a decreasing slope.

	Hobbs Outlet					
	Season 1		Season 2		Season 3	
Variable (μeq/L)	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	-0.055	0.197	-0.115	0.417	-0.727	**0.036**
Ca^{2+}	0.016	0.980	0.322	0.330	0.194	0.551
Cl^{-}	-0.084	0.130	-0.093	0.330	-0.103	**0.054**
Lcond	-0.090	0.164	-0.100	0.475	0	1
H^{+}	0.006	0.254	0.004	0.330	0.003	0.726
K^{+}	-0.041	0.157	-0.133	0.119	-0.007	0.806
Mg^{2+}	-0.003	0.960	0.091	0.299	0.071	0.506
Na^{+}	0.249	**0.074**	0.189	0.183	0.136	0.381
NH_4^{+}	0	0.565	0.084	0.133	0.069	0.379
NO_3^{-}	-0.032	**0.006**	-0.015	0.579	0	0.547
LabpH	-0.015	0.243	-0.015	0.346	-0.015	0.462
SO_4^{2-}	0.015	0.862	0.043	0.627	0.069	0.624

Table 24—Lakes: Seasonal concentration, trends (three seasons) from Mann-Kendall test, Deep Lake inlet: p represents p-value; red numbers equal significant trends when $p<0.1$. A negative Sen's slope represents a decreasing slope.

	Deep Inlet					
	Season 1		Season 2		Season 3	
Variable (μeq/L)	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.870	0.692	0.937	0.692	0.475	0.483
Ca^{2+}	0.832	0.323	2.745	**0.002**	1.580	**0.093**
Cl^{-}	-0.028	0.352	-0.038	0.444	-0.075	0.779
Lcond	0.015	0.693	0.172	0.178	0	1
H^{+}	0.005	0.632	0.001	0.653	0.002	0.362
K^{+}	0.051	0.382	0.075	**0.091**	0.083	0.132
Mg^{2+}	0.131	0.225	0.288	**0.026**	0.370	**0.093**
Na^{+}	0.382	**0.016**	0.340	0.125	0.315	0.160
NH_4^{+}	0	0.585	-0.014	0.488	-0.012	0.273
NO_3^{-}	0.061	0.821	0.084	0.561	0.448	**0.074**
LabpH	-0.014	0.632	-0.006	0.634	-0.009	0.123
SO_4^{2-}	0.064	0.800	0.539	0.132	1.145	0.441

Table 25—Lakes: seasonal concentration, trends (three seasons) from Mann-Kendall test, Deep Lake outlet: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope.

	Deep Outlet					
Variable (μeq/L)	Season 1		Season 2		Season 3	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
ANC	0.983	0.976	0.880	0.611	-0.106	0.434
Ca^{2+}	0.925	**0.030**	0.893	**0.013**	0.620	0.138
Cl^-	-0.075	**0.046**	-0.062	0.114	-0.099	0.126
Lcond	0	1	-0.007	0.799	-0.037	0.509
H^+	0.005	0.608	-0.002	0.778	0.007	0.232
K^+	0.052	**0.061**	0.039	0.310	0.023	0.509
Mg^{2+}	0.227	0.103	0.132	**0.032**	0.367	**0.004**
Na^+	0.261	**0.070**	0.004	0.910	0.398	**0.008**
NH_4^+	0.078	0.198	0	1	-0.009	0.421
NO_3^-	0.000	0.492	0	0.180	0	0.668
LabpH	-0.011	0.629	0.005	0.756	-0.024	0.343
SO_4^{2-}	0.012	0.976	0.017	0.651	-0.144	0.509

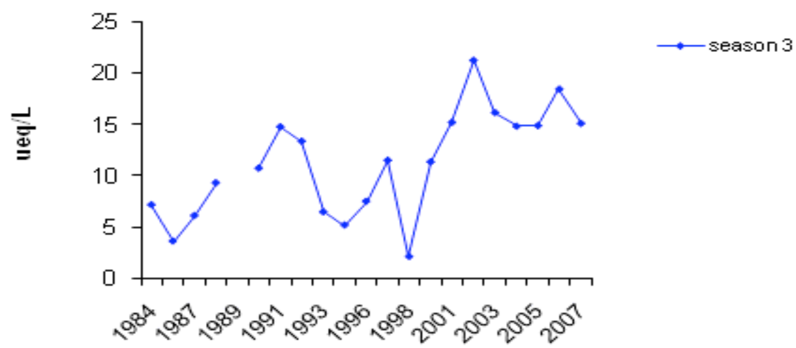

Figure 34—Black Joe inlet annual NO_3^- trend for season 3 from 1984-2007.

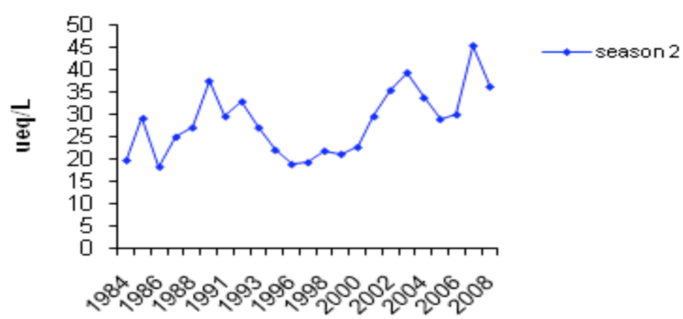

Figure 35—Black Joe inlet annual SO_4^{2-} trend for season 2 from1984-2007.

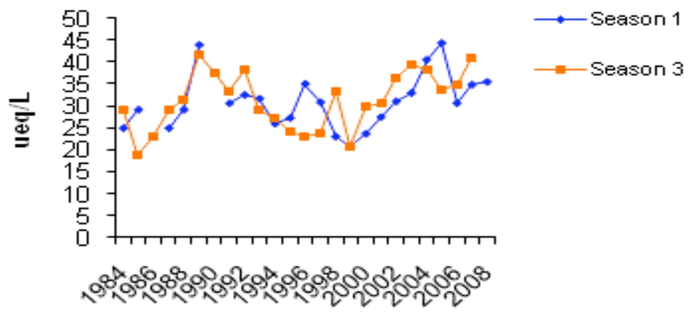

Figure 36—Black Joe outlet annual SO_4^{2-} trend for seasons from 1984-2007.

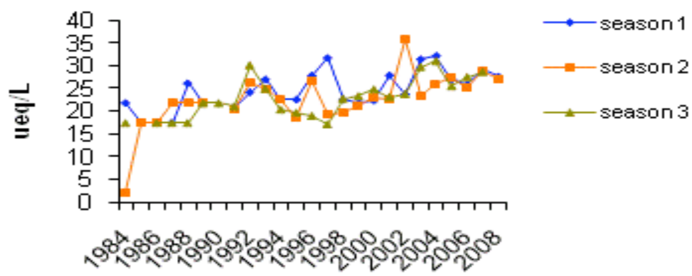

Figure 37—Black Joe outlet annual sodium trends through seasons from 1984-2008.

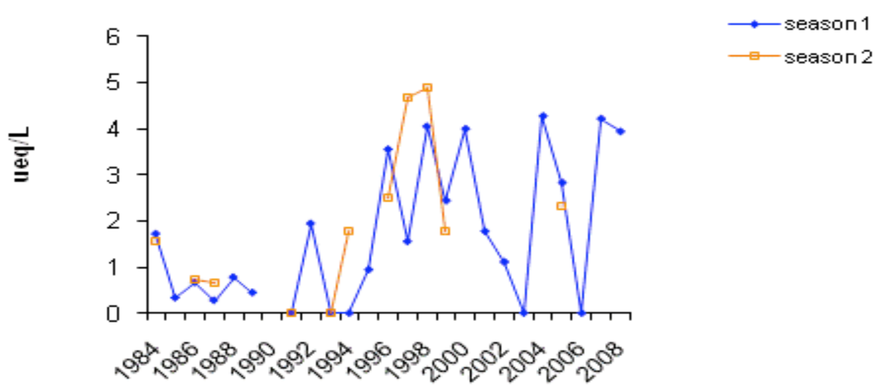

Figure 38—Hobbs inlet annual NH_4^+ trends for seasons 1 and 2 from 1984-2008. Samples at the 0 μeq/L represent values that were below lab detection limits.

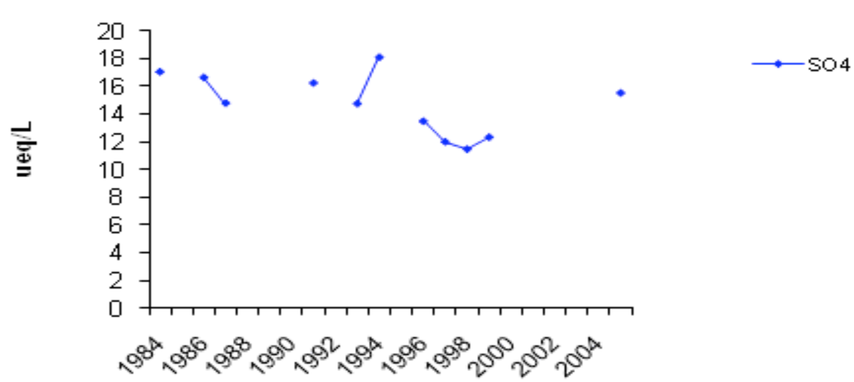

Figure 39—Hobbs inlet annual SO_4^{2-} trend for season 2 from 1984-2005. Line gaps are caused by years of missing data, which make it hard to extrapolate whether a trend is actually present.

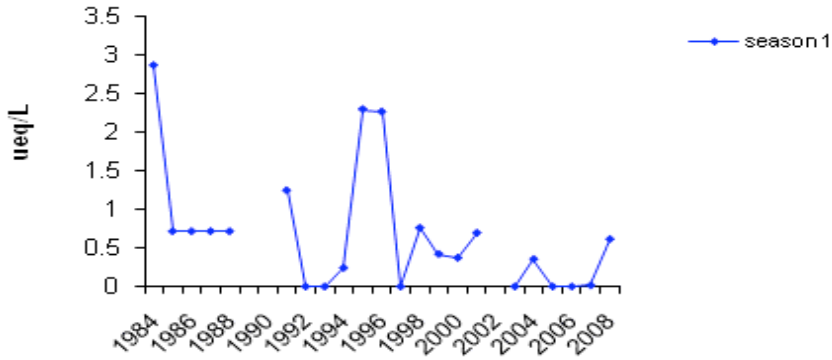

Figure 40—Hobbs outlet annual NO_3^- trend for season 1 from 1984-2008.

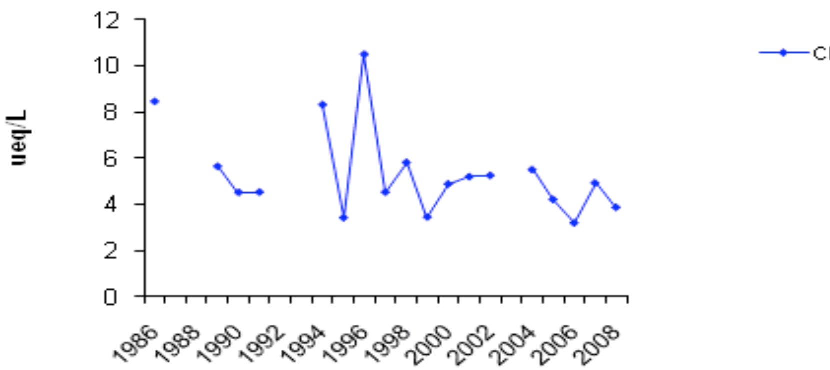

Figure 41—Hobbs outlet annual Cl^- trend for season 3 from 1986-2008.

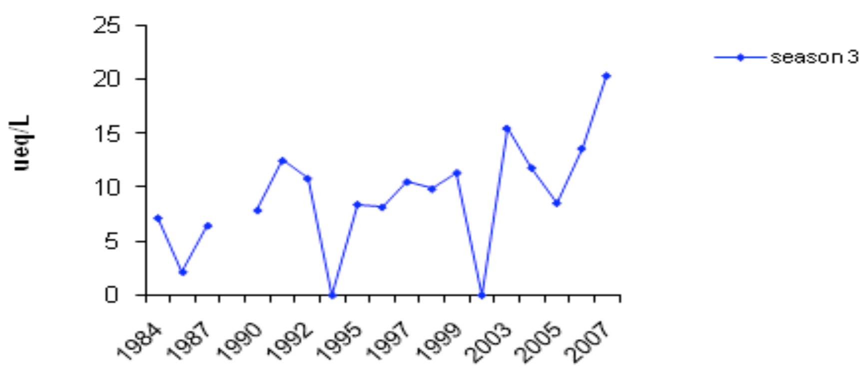

Figure 42—Deep Lake inlet annual NO_3^- trend for season 3 from 1984-2008.

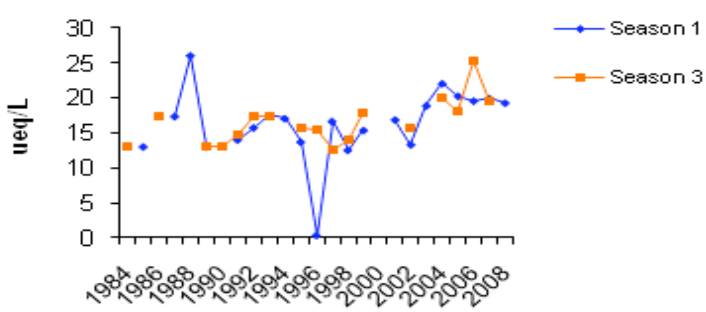

Figure 43—Deep Lake outlet annual Na^+ trends for season 1 and 3 from 1984-2008.

Lake Trend Discussion

More significant trends appeared in the seasonal inlet samples than the outlet samples, most likely due to Lake Watershed processes such as biological activity and mixing. Black Joe and Deep lakes may be particularly influenced by melting snowfields and bedrock weathering. Chemical concentrations in lakes may be influenced by weather and the time of year samples were collected since lake chemistry is increasingly influenced by groundwater after the snowmelt surge is over (Guerri 2010, personal communication).

Two trends in nitrogen concentration were present. First was the increase in NO_3^- present for Black Joe and Deep Lakes for season 3. This trend is not as prevalent in other sections of the lakes that were sampled, which may be due to uptake of NO_3^- by aquatic biota. An increasing trend in NO_3^- concentration was also found in lakes that were sampled in the Shoshone National Forest (Bevenger 2008). USFS Region 1 (Montana and Idaho) Phase 3 lake sampling only reported one lake with a statistically significant increase trend in NO_3^-. It should be noted that the Region 1 lake monitoring program started 9 years after Region 4 (Grenon and Story 2009). The inlet sampling locations, where most of the NO_3^- trends have been detected, were not sampled in the Region 1 lakes. In the Rocky Mountains, many lakes may be at or near nitrogen saturation levels (Burns 2003 and Campbell 2004) where lake nitrogen supply exceeds uptake. Increasing trends in nitrate concentrations have occurred in at least two water catchments in the Colorado Front Range (Williams and others 1996). In these two catchments, NO_3^- levels have increased from below detection limits to about 10 μeq/L (0.62 mg/L). Nanus and others (2008) also reported a correlation between NO_3^- ($p<0.05$) from lakes and NO_x emissions within 300 km from Rocky Mountain NP, Grand Teton NP, Great Sand Dunes NP, and Yellowstone NP with the strongest correlations in the central and southern Rockies in Colorado.

Ammonia (NH_4^+) concentrations have also been increasing at Black Joe, Hobbs, and Deep lakes. Significant increasing trends were present in the hypolimnion at Black Joe and Deep lakes, the inlet and outlet at Hobbs Lake, and the outlet at Black Joe Lake. The lakes on the Shoshone National Forest were not analyzed for NH_4^+ trends (Bevenger 2008).

The major concern associated with increasing inorganic nitrogen in aquatic ecosystems is the potential to cause acidification (via increasing hydrogen ions) and/or eutrophication through increased primary producers (Camargo and Alonso 2007).

The data suggest an increasing trend in sulfate (SO_4^{2-}) at Upper Frozen and Black Joe lakes. This is opposite the pattern of decreasing trends in SO_4^{2-} concentrations observed in precipitation across the United States, including the trends found in the NADP data discussed above and in Hobbs Lake. SO_4^{2-} concentrations in lake water may be influenced by internal weathering sources such as sulfur-bearing minerals in the bedrock (FeS_2), newly exposed bedrock due to melting snow fields (with the exception of Hobbs Lake), or local and/or regional emissions. In the neighboring Shoshone National Forest, Bevenger (2008) found no significant trends in SO_4^{2-} at Saddlebag Lake and significant decreasing trends at Ross Lake for the outlet and hypolimnion. USFS Region 1 lake analysis revealed an overall lack of an SO_4^{2-} trend, with only Stepping Stone Lake reporting a significant decreasing trend. On the other hand, some lakes in Colorado are exhibiting increases or no trend in SO_4^{2-} concentrations when analyzed (Mast 2009, personal communication). The cause of the increased trend in SO_4^{2-} in the B-T lakes is not readily understood.

Overall, cations (Na^+,Ca^{2+}, Mg^{2+}, and K^+) showed significant increases in concentrations over time in some portions of the lakes. A significant decreasing trend in the anion Cl^- was found, most notably in the hypolimnion and outlet samples of Black Joe and Deep lakes.

IMPROVE (Interagency Monitoring of Protected Visual Environments)

The IMPROVE program was established in 1985 as a tool to monitor and protect visibility in 156 Federal Class I areas (a stipulation from the 1977 amendments to the Clean Air Act). The goals of the IMPROVE network are to establish existing visibility conditions in Class I areas, to identify the pollutants that are impairing visibility, and to assess progress toward the national visibility goal of no manmade impairment in support of the Regional Haze Rule (IMPROVE information can be found at: http://vista.cira.colostate.edu/improve/).

Two IMPROVE sites in Wyoming have a sufficient period of record to run meaningful statistical analyses: YELL1 and YELL2 in Yellowstone National Park and BRID1 near the boundary of the Bridger Wilderness 10 miles east of Pinedale, Wyoming. Both sites were established in 1988. YELL1 was moved about a mile west from its original site in 1996 due to dust exposure, and the new site was named YELL2. The MOZI1 IMPROVE site was started in 1994 and is located on Buffalo Pass northeast of Steamboat Springs, Colorado, and monitors the Mount Zirkel Wilderness. Data from MOZI1 was also analyzed to give a more regional perspective. Both MOZI1 and BRID1 are operated by the Forest Service and YELL2 is operated by the Park Service.

The IMPROVE data analyzed were sent directly from the Forest Service Visibility Data Analyst at CIRA (Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado), because the 2007 data were not yet available on their public website (http://views.cira.colostate.edu). Seasonal data was used as part of the analysis when possible. The seasons are the same as those used in the NADP section where winter is defined as January, February, and March; spring as April, May, and June; summer as July, August, and September; and fall as October, November, and December. The analysis started with the first full year of NADP site establishment (1989). The Regional Haze Rule has strict data quality assurance guidelines to determine whether the data collected for a given year is adequate to represent the visibility conditions from that year. All data that did not meet these adequacy requirements were removed from the analysis.

Annual trends for BRID1, YELL1&2, and MOZI1 were analyzed for the arithmetic means of the following variables (the "E" signifies that the variable represents the atmospheric extinction due to the indicated species): ESO_4^{2+} (ammonium sulfate), ENO_3^- (ammonium nitrate), EOMC (organic mass from carbon), ELAC (light-absorbing carbon or elemental carbon), ESoil (fine soil), ECM (coarse mass), ESalt (Sea salt), dv (deciview), VR (visual range), Rb_{ext} (sum of aerosol extinctions - ES04, ENO3, EOMC, ELAC, ESoil, ESalt, and ECM), and FMass ($PM_{2.5}$). Seasonality was taken into account in all variables except ESalt, which is comparatively small and showed no seasonality. Annual trends for each season were also analyzed for all variables. Statistically significant trends are shown in tables 26 to 29 and figures 44 to 49.

Table 26—IMPROVE: Visibility, Seasonal Mann-Kendall[a] output for annual trends at three sites: p represents p-value; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope. Decreasing trend indicates improving air quality except for VR. The period of record analyzed for BRID1 and YELL1&2 was 1988 to 2007, and MOZI1 was 1994 to 2007.

Variable (Mm-1) (dv is dv and VR is km)	BRID 1		YELL 1&2		MOZI 1	
	Sen's slope	p	Sen's slope	p	Sen's slope	p
dv	-0.074	**0.001**	-0.105	**0.007**	-0.141	**0.004**
Rbext	-0.118	**0.009**	-0.198	**0.043**	-0.264	**0.020**
ESO_4^{2-}	-0.039	**0.011**	-0.018	0.220	-0.083	**0.020**
ENO_3^-	0.008	0.136	0.014	**0.056**	0.008	0.342
EOMC	-0.019	0.511	-0.053	0.242	-0.042	0.299
ELAC	0.006	0.483	-0.028	**0.032**	-0.018	0.142
ESOIL	-0.003	0.380	-0.018	**0.002**	-0.004	0.666
ECM	-0.070	**<0.001**	-0.144	**<0.001**	-0.134	**<0.001**
VR	1.453	**0.009**	1.771	**0.043**	2.392	**0.020**

[a]Sea salt was analyzed with the Mann Kendall test and no statistically significant trends were found.

Table 27—IMPROVE: Visibility, Mann-Kendall output for seasonal trends at BRID1: p represents p-value; ss represents Sen's slope; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope. Decreasing trend indicates improving air quality except for VR. The period of record analyzed for BRID1 and YELL1&2 was 1988 to 2007, and MOZI1 was 1994 to 2007.

Variable (Mm-1) (dv is dv and VR is km)	BRID1 Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
dv	-0.062	**0.060**	-0.033	0.343	0.046	0.685	-0.163	**<0.001**
Rbext	-0.101	0.113	-0.062	0.537	0.218	0.260	-0.299	**<0.001**
ESO_4^{2-}	-0.042	0.276	0.015	0.387	-0.045	**0.017**	-0.071	**0.012**
ENO_3^-	0.029	**0.060**	0.006	0.537	0.005	0.444	-0.003	0.902
EOMC	-0.027	0.198	0.038	0.434	0.306	**0.096**	-0.097	**0.012**
ELAC	0.006	0.621	0.017	0.266	0.017	0.344	-0.011	0.266
ESOIL	0.003	0.767	-0.001	0.967	<0.001	1	-0.007	**0.064**
ECM	-0.057	**0.023**	-0.061	0.149	-0.044	**0.053**	-0.113	**<0.001**
VR	1.616	0.113	0.461	0.537	-1.263	0.260	4.120	**<0.001**

Table 28—IMPROVE: Visibility, Mann-Kendall output for seasonal trends at YELL1 & 2: p represents p-value; ss represents Sen's slope; red numbers equal significant trends when p<0.1. A negative Sen's slope represents a decreasing slope. Decreasing trend indicates improving air quality except for VR. The period of record analyzed for BRID1 and YELL1&2 was 1988 to 2007, and MOZI1 was 1994 to 2007.

Variable (Mm-1) (dv is dv and VR is km)	YELL 1&2 Winter		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
dv	-0.111	**0.086**	0.013	0.945	-0.092	0.127	-0.204	**0.024**
Rbext	-0.179	0.150	0.016	1	-0.160	0.537	-0.385	**0.024**
ESO_4^{2-}	-0.032	0.537	0.086	**0.086**	-0.020	0.202	-0.078	**0.064**
ENO_3^-	0.079	0.304	0.026	0.115	0.004	0.484	0.020	0.537
EOMC	-0.091	**0.005**	-0.107	0.150	0.696	**0.029**	-0.165	**0.034**
ELAC	-0.029	0.115	-0.014	0.304	<0.001	1	-0.057	**0.016**
ESOIL	-0.005	0.304	-0.007	0.945	-0.051	**0.009**	-0.015	**0.086**
ECM	-0.075	0.193	-0.027	0.945	-0.318	**0.001**	-0.100	**0.047**
VR	2.390	0.150	-0.157	1	0.666	0.537	4.217	**0.024**

Table 29—IMPROVE: Visibility, Mann-Kendall output for seasonal trends at MOZI1; p represents p-value; ss represents Sen's slope; red numbers equal significant trends when $p<0.1$. A negative Sen's slope represents a decreasing slope. Decreasing trend indicates improving air quality except for VR. The period of record analyzed for BRID1 and YELL1&2 was 1988 to 2007, and MOZI1 was 1994 to 2007.

Variable (Mm-1) (dv is dv and VR is km)	MOZI1 Winter[a]		Spring		Summer		Fall	
	ss	p	ss	p	ss	p	ss	p
dv	-0.321	**0.009**	-0.073	0.193	-0.026	0.756	-0.246	**0.048**
Rbext	-0.472	**0.004**	-0.118	0.244	0.045	1	-0.359	0.175
ESO_4^{2-}	-0.053	0.174	0.003	0.945	-0.143	**0.020**	-0.132	0.175
ENO_3^-	-0.018	0.711	0.021	0.373	0.012	0.436	0.008	0.917
EOMC	-0.175	**0.019**	-0.052	0.244	0.218	0.119	-0.042	0.466
ELAC	-0.013	0.902	-0.016	0.451	-0.033	0.436	-0.018	0.348
ESOIL	0.010	0.386	0.009	0.732	-0.019	0.213	-0.011	0.466
ECM	-0.183	**0.035**	-0.097	0.150	-0.109	**0.043**	-0.184	**0.048**
VR	8.027	**0.004**	1.087	0.244	-0.351	1	6.447	0.175

[a]Winter had only eight observations, which is the minimum number required by the DAP to recognize statistical significance.

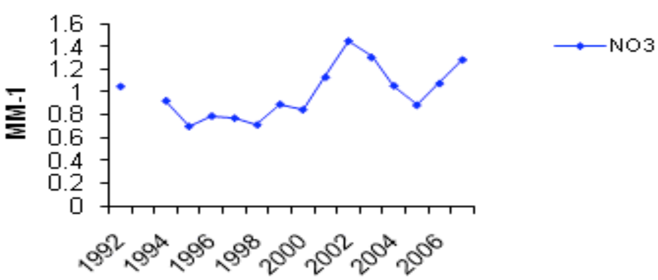

Figure 44—BRID1 IMPROVE site winter extinction attributed to NO_3^- from 1992-2007.

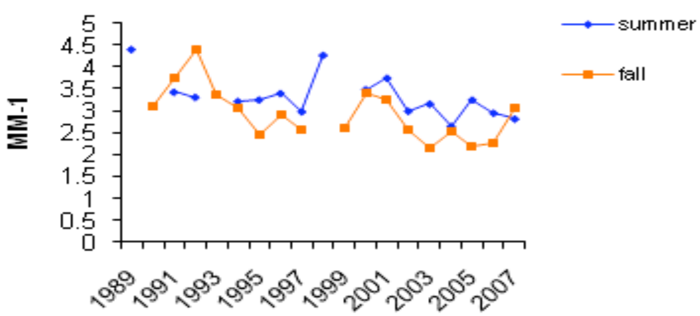

Figure 45—BRID1 IMPROVE site seasonal extinction attributed to SO_4^{2-} trends from 1989-2007.

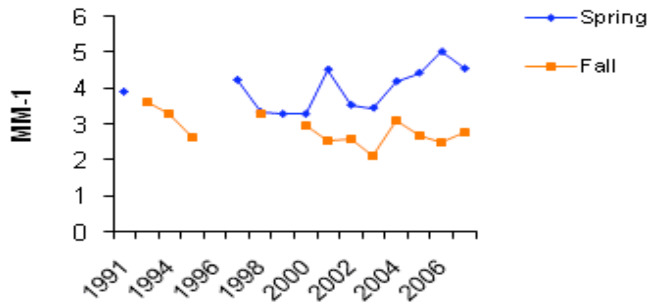

Figure 46—YELL1 & 2 IMPROVE site seasonal extinction attributed to SO_4^{2-} trends from 1991-2007.

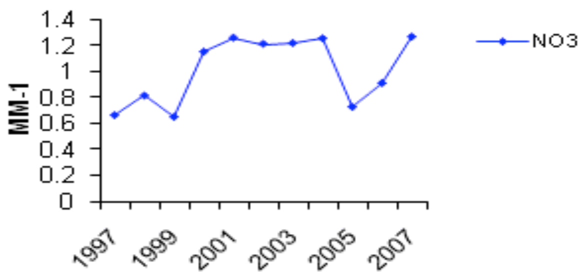

Figure 47—YELL1 & 2 IMPROVE site spring extinction attributed to NO_3^- from 1997-2007. (This graph was included even though the NO_3^- trend was not statistically significant at $p<0.1$.)

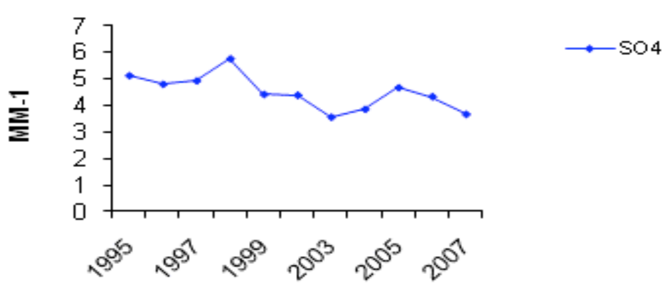

Figure 48—MOZI1 IMPROVE site summer extinction attributed to SO_4^{2-} trend from 1995-2007.

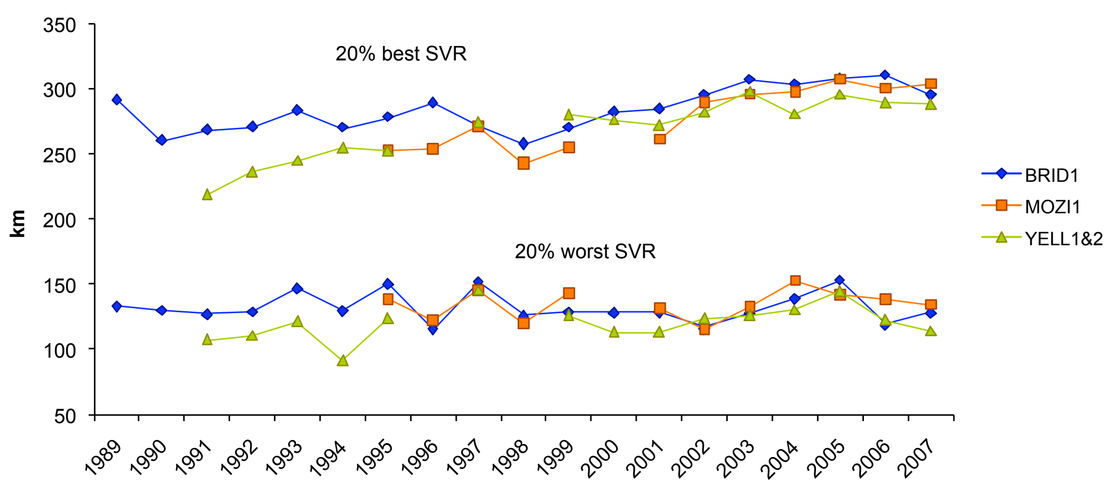

Figure 49—The 20% best and 20% worst annual average SVR at BRID1, MOZI1, and YELL1&2 IMPROVE sites.

IMPROVE Discussion

The original IMPROVE site in Yellowstone National Park, YELL1, was moved in 1996 due to dust exposure. Some decreasing trends in crustal components analyzed for YELL 1 and YELL2 may be explained by monitor relocation.

The results from the IMPROVE data analysis show trends of increased average visibility across the region. This is consistent with visibility trends elsewhere in the western United States (Debell and others 2006; Grenon and Story 2009). A consistent reduction in dv and increase in VR occurred at all sites for most seasons observed. It should be noted that in some seasons the dv showed significant decreasing trends while the corresponding VR did not show significant increasing trends; this may be due to the logarithmic scale of dv, but the matter was not further investigated in this report. The analysis also found decreasing trends at all sites in Rb_{ext} and ECM along with a decreasing trend at some of the sites for SO_4^{2-}, FMass, ELAC, and ESoil. The decrease in SO_4^{2-} is consistent with the roughly 250,000 tons per year decrease in western electricity generating units (EGU) of SO_2 emissions since 1996.

A statistically significant increasing trend occurred in annual NO_3^- at YELL1 and YELL2 and BRID1 showed a significant increasing trend in NO_3^- during the winter season. An increasing NO_3^- trend in and around the B-T National Forest is opposite to the consistent decreasing NO_3^- observed trend at IMPROVE sites found throughout Region 1 (Grenon and Story 2009). NO_x emissions from the western United States have declined by roughly 75,000 tons per year since 1996, which suggests that some new or other source of nitrate is counteracting the expected improvements in visibility. It is also possible that the NO_x reductions have occurred at facilities that do not impact Bridger and Yellowstone (fig. 1). The MOZI1 IMPROVE site in Colorado did not have a NO_3^- trend.

These findings are generally consistent with EPA (2008) findings that no Class 1 IMPROVE site had statistically significant upward trends for any of the extinction parameters evaluated (the noteworthy exception is the localized NO_3^- increase trends discussed above).

Conclusions

This report is intended to provide useful information for better understanding and management of air quality in southwest Wyoming. This report provides air quality information and associated resource information for NEPA and PSD, and establishes a baseline for detection and characterization of effects from natural and anthropogenic emission sources and climate change. The Forest Service, Wyoming DEQ Air Quality Division, EPA, USGS, BLM, and universities regularly use the data from these monitoring programs for model validation and to assess the effectiveness of mitigation efforts—mostly associated with energy development—that are taking place in the local area and the region. Continued monitoring of these AQRVs is important for the agencies ability to demonstrate fulfillment of their responsibilities under the Clean Air and Wilderness Acts.

Analysis of the B-T NF air monitoring assessment documents a consistently increasing trend in nitrogen deposition. NH_4^+ showed an increasing trend at all NADP sites, bulk deposition sites, and in lake concentrations, but the trend was less pronounced. NO_3^- showed a increasing trend in lake samples, primarily the inlets and at both bulk deposition sites. A sporadic increasing NO_3^- trend also was detected in deposition at NADP sites for some seasons. An increasing trend in NH_4^+ is occurring over much of the western United States and may be partially due to increased agriculture emissions (feedlots, fertilizer, etc.).

This increasing deposition of nitrogen into the Bridger Wilderness is of concern. Total nitrogen deposition at the Hobbs Lake and Black Joe Lake sites have averaged 2.35 and 2.66 $kg/ha^{-1}year^{-1}$ respectively over the last 22 years with min/max ranges of 1.23 to 4.3 kg/

$ha^{-1}year^{-1}$. Using hindcasting of diatom communities, Baron (2006) found the background critical load—the level of atmospheric pollutant deposition or concentration above which negative ecosystem effects can occur—for nitrogen in the high alpine lakes of Rocky National Park to be about 1.5 $kg/ha^{-1}year^{-1}$. Saros and others (2010), using fossil diatom assemblages, determined a critical load for the Greater Yellowstone of 1.5 $kg/ha^{-1}year^{-1}$. In mixed conifer forests of California, Fenn and others (2008) suggest the critical load for nitrogen deposition among lichen communities to be around 3.1 $kg/ha^{-1}year^{-1}$. This data suggest that sensitive and pristine high-elevation (over 3,000 meters) lakes in the B-T could be near or at levels where adverse ecosystem effects may occur.

The overall decrease in SO_4^{2-} at NADP sites analyzed is consistent with decreasing SO_4^{2-} trends in precipitation across the United States. This trend is most likely due to reductions of industrial sulfur emissions from power plants and the 1993 Highway Low Sulfur Diesel Rule (http://epa.gov/cleandiesel/documents/420f04034.htm). Sulfate concentration trends in the lake, bulk deposition samples, and IMPROVE data are not as clear. Black Joe and Upper Frozen lakes showed an increasing SO_4^{2-} trend for some seasons. The bulk deposition sites had no sulfate trend.

Lake cations concentrations generally showed increasing trends especially for Ca^{2+} and Mg^{2+} while Cl^- appears to be decreasing in lake concentrations. This is the same pattern found in the NADP and the bulk deposition data. The increase in base cations may be due to melting snowfields and glaciers and possibly an increase in bedrock weathering associated with climate change. However, in contrast, lakes in Montana showed overall decreasing trends in both anions and cations (Grenon and Story 2009). Visibility improvements, evidenced by increasing VR, decreased dv, and reduced light extinction were observed at all three of the IMPROVE sites.

EPA (1996) reports that the Rb_{ext} in northwestern United States urban regions peaks in the winter due to an increase in light scattering from ammonium nitrite and organics (presumably due to winter inversions). In the interior western United States, ammonium sulfate light scattering is unique in that it does not peak in the summer months as it does elsewhere but has been shown in Boise, Idaho, and Missoula, Montana, to peak in the coldest months (Debell and others 2006). The general decreasing Rb_{ext} trends in the Bridger Teton NF are consistent with the overall pattern of increasing VR in the northwestern United States.

The observed trends in this report should be used only as indicators of possible current and future changes in air quality and water chemistry. Because the periods of record for the datasets are relatively short, the trends identified may change in the future as more data is collected over time. Continued analysis will be required to evaluate trends and help determine their causes.

Considerations

Sampling lake sediment cores has potential to help understand trends of metal accumulation from atmospheric deposition sources (Baron and others 1986) and nitrogen critical loads (Baron 2006). Baron (2006) has explored the utility of examining high-elevation lake sediment cores and further investigating the relationship between shifting diatom communities, hindcasting nitrogen emissions, and then deriving critical loads. Analyzing metal concentrations, diatom diversity, and nitrogen concentration from sediment cores at one or more of the B-T lakes used for long-term monitoring could be diagnostic of long-term air quality trends and help determine critical load values for sensitive ecosystems in the Bridger-Teton National Forest.

Additional analysis could be done with the NADP dataset to address trends at a site or regional level. Deposition from NADP sites could be assessed and used with other available data (such as the 1985-1991 co-located bulk / NADP collectors and the two discontinued bulk sites) to help establish more accurate baseline values in order to predict N and S critical loads and to help guide decision making processes.

Preliminary review suggests that NO_3^- concentrations in the Bridger Wilderness are much higher in the summer than winter at the bulk deposition sites (Svalberg and Porwoll 2008). It would be useful to analyze the bulk data seasonally for both deposition and concentration of all variables analyzed. The winter portion could then be compared with the results from snowpack sampling.

IMPROVE monitoring provides an invaluable historic and current look at visibility conditions (including wildland fire smoke), which could be useful in assessing visibility impacts and for regional haze analysis. Due to the nitrogen and sulfate trend increases—which are in contrast to predominant national trends—it is strongly recommended that all the USFS R4 IMPROVE sites continue to be re-analyzed for statistically validated trends. In the fall of 2009, a new IMPROVE site was added near Pinedale, Wyoming, near Boulder Lake. This site is significant because theoretical models predict the Boulder drainage to be a major “hotspot” for ozone and emission clustering in Sublette County. Data from the Boulder IMPROVE site should be compared with annual results from the other IMPROVE sites in the area.

This report did not review the lichen monitoring (St. Clair 2000) or the yearly USGS snow chemistry sampling network along the Rocky Mountains Continental Divide (Ingersoll and others 2008). Lichens are useful indicators of long term pollution impacts, and are typically sampled every 5 to 8 years. Lichens were sampled from the Bridger Wilderness in 2004. Lichens can provide useful air quality information specifically on sulfur and nitrogen compounds and metals. Analyzed lichen data could provide a valuable addition to the lake chemistry, deposition, and visibility information in this report.

The USGS Rocky Mountain Snowpack Network provides the only air quality related sampling directly adjacent to some of the USFS Wilderness areas and is useful for winter bulk deposition analysis. It is recommended the USFS Region 4 continue support of and coordination with the USGS Snow Chemistry sampling program (Ingersoll and others 2008).

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Appendix: Shoshone National Forest Air Quality Data Trend Analysis

Greg Bevenger, Hydrologist, Shoshone NF, Cody, Wyoming 2008

In 2008, staff on the Shoshone National Forest conducted a comprehensive analysis of air quality monitoring data for the Forest portion of the Wind River Range. The data set that was analyzed was collected at the South Pass NADP site and Ross and Lower Saddlebag Lakes. The record dates back to 1986.

Data analysis protocols used for the NADP site and lakes assessment is identical to the protocols explained in the main body of this GTR.

South Pass NADP Site—Analysis of data collected between 1986 and 2006 (2007 data was not yet available) was completed in early 2008. Both wet deposition and precipitation-weighted deposition data sets were analyzed. The analysis indicates change over time, with statistically significant upward or downward trend depending upon the parameter (Figures 1 through 4).

Ammonia (NH4) is on an upward trend and has basically doubled, but there are seasonal differences. The greatest deposition occurs during fall and winter. Potential sources of ammonia are upwind feedlots and machinery, e.g., drill rigs, that does not use catalytic converters.

Precipitation-weighted nitrate (NO3) deposition is on an upward trend for all four seasons. There is no statistically significant trend with wet deposition nitrate levels, but values have increased substantially for the winter, spring, and fall seasons. The differences between wet and precipitation-weighted deposition are explained by units of measure, i.e., volume by weight by period versus concentration by precipitation volume, respectively. The statistically insignificant trend in wet deposition is due to differences between seasons and variability within and across seasons. A potential source of nitrate is upwind emissions from oil and gas developments.

Sulfate (SO4) is on a downward trend through all seasons. Values have decreased by 25-50%. The trend could be related to 1990s-era reductions in the use of high sulfur diesel fuel. Controls on emissions at refineries and coal-fired power plants, on a western U.S. regional basis, could also be a cause.

There is no trend with inorganic-nitrogen (Inorg-N) at the 95% confidence level but there is an upward trend at the 90% level. A potential source of inorganic nitrogen is upwind agricultural activities.

In addition to Forest Service uses, Wyoming Department of Environmental Quality and other agencies continually utilize data collected from this site. These data, along with data from other National Atmospheric Deposition Program sites in Wyoming, are used to model and track emissions and acid deposition across southwest Wyoming, which includes the Class I Fitzpatrick and Class II Popo Agie Wilderness areas on the Forest. Because of industrial development in southwest Wyoming and growth of several major cities upwind of the Forest, continued monitoring of this site is important relative to Forest managers being able to demonstrate compliance with the Clean Air and Wilderness Acts.

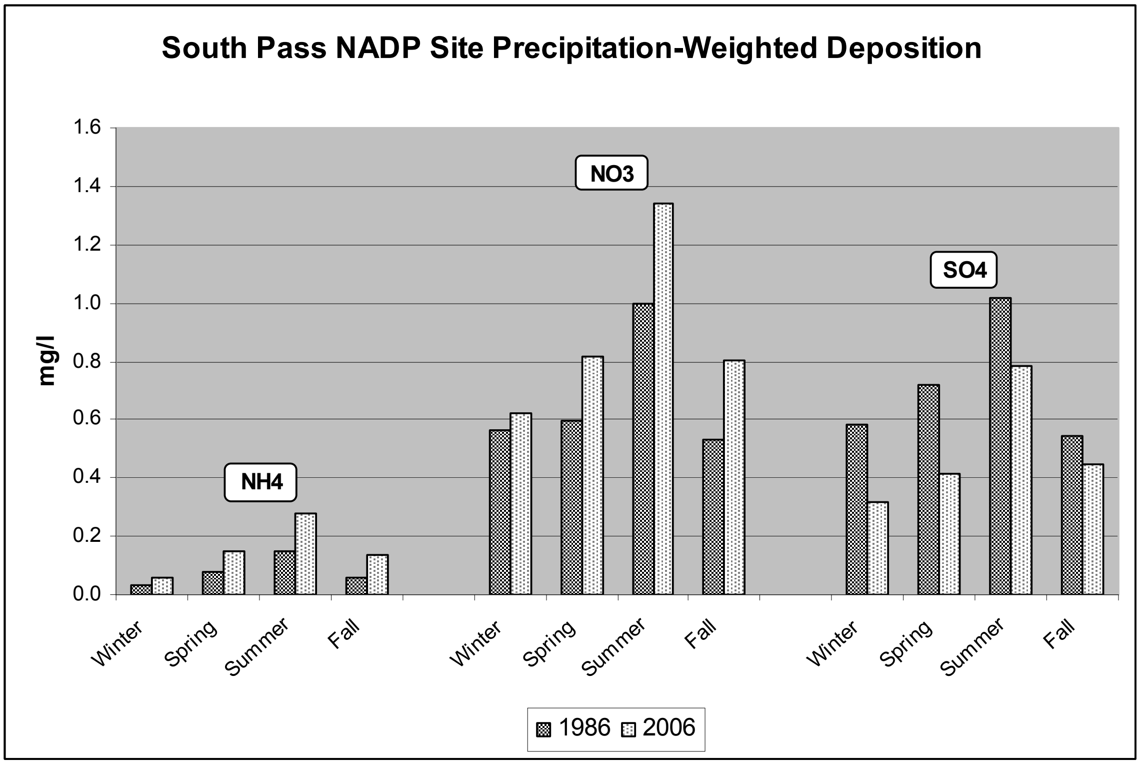
Figure 1. South Pass NADP Site Wet Deposition Trend Analysis.

Wet Deposition (kg/ha)								
Parameter	**Seasonality**	**Season**	**1986**	**2006**	**Difference**	**Change**	**Trend**	**Significant**
NH4	Yes	Winter	0.041	0.077	0.036	88%	Up	0.05
		Spring	0.122	0.206	0.084	69%		
		Summer	0.141	0.194	0.053	38%		
		Fall	0.060	0.139	0.079	132%		
NO3	Yes	Winter	0.621	0.755	0.134	22%	None	--
		Spring	0.823	1.170	0.347	42%		
		Summer	0.910	0.892	-0.018	-2%		
		Fall	0.415	0.863	0.448	108%		
SO4	Yes	Winter	0.638	0.377	-0.261	-41%	Down	0.01
		Spring	0.900	0.643	-0.257	-29%		
		Summer	0.950	0.508	-0.442	-47%		
		Fall	0.599	0.410	-0.189	-32%		
Inorg-N	Yes	Winter	0.160	0.247	0.087	54%	Up	0.10
		Spring	0.282	0.406	0.124	44%		
		Summer	0.353	0.377	0.024	7%		
		Fall	0.148	0.316	0.168	114%		

Figure 3. South Pass NADP Site Precipitation-Weighted Deposition Trend Analysis.

Precipitation-Weighted (mg/l)								
Parameter	**Seasonality**	**Season**	**1986**	**2006**	**Difference**	**Change**	**Trend**	**Significant**
NH4	Yes	Winter	0.033	0.061	0.028	85%	Up	0.05
		Spring	0.076	0.147	0.071	93%		
		Summer	0.147	0.280	0.133	90%		
		Fall	0.056	0.133	0.077	138%		
NO3	Yes	Winter	0.565	0.623	0.058	10%	Up	0.05
		Spring	0.596	0.816	0.220	37%		
		Summer	1.000	1.340	0.340	34%		
		Fall	0.534	0.806	0.272	51%		
SO4	Yes	Winter	0.584	0.318	-0.266	-46%	Down	0.01
		Spring	0.719	0.417	-0.302	-42%		
		Summer	1.020	0.782	-0.238	-23%		
		Fall	0.542	0.447	-0.095	-18%		

Figure 4. South Pass NADP Site Precipitation-Weighted Deposition Trend Analysis.



Lower Saddlebag and Ross Lakes—Analysis of data collected between 1986 and 2007 was completed in early 2008. The analysis indicates change over time, with statistically significant upward or downward trend depending upon the parameter, season, and lake sampling location (Figures 5 and 6).

Acid neutralizing capacity (ANC) is on a downward trend at both lakes. There is a greater change at Ross Lake. The change is occurring at all sampling locations, i.e., inlet, outlet, epilimnion, and hypolimnion. The inlet at both lakes exhibits seasonality, but the outlets do not. The change at Lower Saddlebag, at the outlet and hypolimnion, is statistically non-significant, while at Ross it is significant.

The commonly accepted threshold for ANC, when ANC values are greater than 25, is no more than a 10% change. Thus, the downward trend at Ross Lake is a significant concern. The downward trend at Lower Saddlebag is approaching the threshold level, so it is a concern as well. The downward trend in ANC at each lake may be due to the upward trend in nitrate (NO3) at both lakes.

Nitrate (NO3) is on an upward trend at the inlet of both lakes. Lower Saddlebag Lake exhibits seasonality, while Ross Lake does not. There is no trend at either lake at the outlet or epilimnion. The hypolimnion at Lower Saddlebag is on an upward trend while at Ross there is no trend.

The upward trend at the inlet of both lakes is a significant concern and could explain the downward trend in ANC. Since there is no trend at the lake outlets, it is possible the influx of nitrogen (N) is being used by aquatic biota (both plant and animal) living in the lakes. Increases at each lake in the hypolimnion are also a significant concern because this zone is typically void of nitrogen. Thus, this increasing trend could be the enrichment phase of eutrophication, meaning these once stable lakes (in terms of N) are becoming acidified. NO3 sources could be emissions from upwind locations, such as oil and gas developments, or from what was stored in glaciers and large snow fields that have been rapidly melting over the last decade.

Sulfate (SO4) at Lower Saddlebag Lake does not exhibit a statistically significant change, but there has been a 20% decrease (approximately). SO4 is on a downward trend at Ross Lake at the inlet, outlet, and hypolimnion, but not the epilimnion. This trend at the Ross Lake inlet is not statistically significant, but it is statistically significant at the outlet and hypolimnion. Lower Saddlebag does not exhibit seasonality, but Ross does.

The downward trend could be related to 1990s-era reductions in the use of high sulfur diesel fuel. Controls on emissions at refineries and coal-fired power plants, on a western U.S. regional basis, could also be a cause.

In addition to Forest Service uses, Wyoming Department of Environmental Quality and other agencies continually utilize data collected from these lakes. These data, along with data from other lakes in the Wind River Mountain Range, are used to model and track emissions and acid deposition across southwest Wyoming, which includes the Class I Fitzpatrick and Class II Popo Agie Wilderness areas on the Forest. Because of industrial development in southwest Wyoming and growth of several major cities upwind of the Forest, continued monitoring of these lakes is important relative to Forest managers being able to demonstrate compliance with the Clean Air and Wilderness Acts.

Figure 5. Lower Saddlebag Lake Trend Analysis.

Lower Saddlebag Lake									
Parameter	**Location**	**Seasonality**	**Season**	**1986**	**2007**	**Difference**	**Change**	**Trend**	**Significant**
ANC (ueq/l)	**Inlet**	Yes	Spring	66	62	-4	-6%	Down	Yes
			Summer	77	67	-10	-13%		
			Fall	71	75	4	6%		
	Outlet	No		68	67	-1	-1%	Down	No
	Epilimnion	N/A		73	69	-4	-5%	Down	Yes
	Hypolimnion	N/A		76	68	-8	-10%	Down	No
NO3 (mg/l)	**Inlet**	Yes	Spring	0.126	0.784	0.658	522%	Up	Yes
			Summer	0.079	0.434	0.355	449%		
			Fall	0.024	0.662	0.638	2658%		
	Outlet	Yes	Spring	0.233	0.326	0.093	40%	None	--
			Summer	0.051	0.046	-0.005	-10%		
			Fall	0.034	0.037	0.003	9%		
	Epilimnion	N/A		0.011	0.014	0.003	27%	None	--
	Hypolimnion	N/A		0.001	0.201	0.200	20000%	Up	Yes
SO4 (mg/l)	**Inlet**	No		1.030	0.838	-0.192	-19%	None	--

	Outlet	No		1.030	0.824	-0.206	-20%	None	--
	Epilimnion	N/A		0.969	0.816	-0.153	-16%	None	--
	Hypolimnion	N/A		0.975	0.971	-0.004	0%	None	--

Figure 6. Ross Lake Trend Analysis.

Ross Lake									
Parameter	**Location**	**Seasonality**	**Season**	**1986**	**2007**	**Difference**	**Change**	**Trend**	**Significant**
ANC (ueq/l)	**Inlet**	Yes	Spring	74	59	-15	-20%	Down	Yes
			Summer	66	50	-16	-25%		
			Fall	66	60	-6	-9%		
	Outlet	No		69	61	-8	-11%	Down	Yes
	Epilimnion	N/A	Summer	76	55	-21	-28%	Down	Yes
	Hypolimnionn	N/A	Summer	74	65	-9	-12%	Down	Yes
NO3 (mg/l)	**Inlet**	No		0.033	0.395	0.362	1097%	Up	Yes
	Outlet	No		0.022	0.049	0.027	123%	None	--
	Epilimnion	N/A	Summer	0.014	0.079	0.065	464%	None	--
	Hypolimnion	N/A	Summer	0.027	0.034	0.007	26%	None	--
SO4 (mg/l)	**Inlet**	Yes	Spring	1.020	0.881	-0.139	-14%	Down	No
			Summer	0.890	0.808	-0.082	-9%		
			Fall	1.020	0.698	-0.322	-32%		
	Outlet	Yes	Spring	1.060	0.894	-0.166	-16%	Down	Yes
			Summer	0.914	0.826	-0.088	-10%		
			Fall	0.963	0.872	-0.091	-9%		
	Epilimnion	N/A	Summer	0.884	0.837	-0.047	-5%	None	--
	Hypolimnion	N/A	Summer	1.050	0.926	-0.124	-12%	Down	Yes

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