Chapter 10: Ecoregion 6.2.14 Southern Rockies: Glacier Lakes Ecosystem Experiments Site, Wyoming

Robert C. Musselman, Kathleen A. Dwire, John L. Korfmacher, and Mark Conrad[1]

Introduction

This chapter is a review and synthesis of research conducted at Glacier Lakes Ecosystem Experiments Site (GLEES) on stream nutrients and biological responses. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency and Wyoming Department of Environmental Quality (WDEQ), about existing results of relevant scientific studies that are available at GLEES, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at GLEES.

Site Description

GLEES is located in the Snowy Range of the Medicine Bow Mountains, southeast Wyoming (Musselman 1994). The site (lat. 41° 22’ 30’’ N, long. 106° 15’ 30’’ W) is 1297 ha within the Medicine Bow National Forest, 15 km northwest of Centennial, Wyoming. GLEES is at the alpine and subalpine ecotone, with an elevation range of 3120 to 3494 m. Vegetation consists of subalpine forest, dominated by mature Engelmann spruce (*Picea engelmannii*, Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) interspersed with wetlands and meadows (Musselman 1994, Regan et al. 1998). The site has three glacial cirque lakes within areas of glacial till and first-order streams that flow from late spring through fall, but are frozen in winter (fig. 10.1). The site was glaciated <15,000 years BP (Mensing et al. 2011) and has young, shallow, rocky soils and numerous areas of exposed bedrock and scree fields. Bedrock is primarily quartzite with intrusions of more weatherable mafic dikes. The growing season is short and relatively harsh, with snow on the ground from early November until mid-June, and lakes that are ice free only from mid-June to mid-October. Precipitation at GLEES averages 129 cm per year, with 85 percent falling as snow (Dwire, n.d.). Average daily temperature is about -10 ^{o}C in winter (January and February) and rarely exceeds 16 ^{o}C in mid-summer (fig. 10.2). Freezing temperatures can occur any month of the year.

[1] **Robert C. Musselman** is a research plant physiologist (retired), **Kathleen A. Dwire** is a research ecologist, **John L. Korfmacher** is a physical scientist, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 240 West Prospect, Fort Collins, CO 80526; **Mark Conrad** is a habitat protection biologist, Wyoming Game and Fish Department, 5400 Bishop Boulevard, Cheyenne, WY 82006.

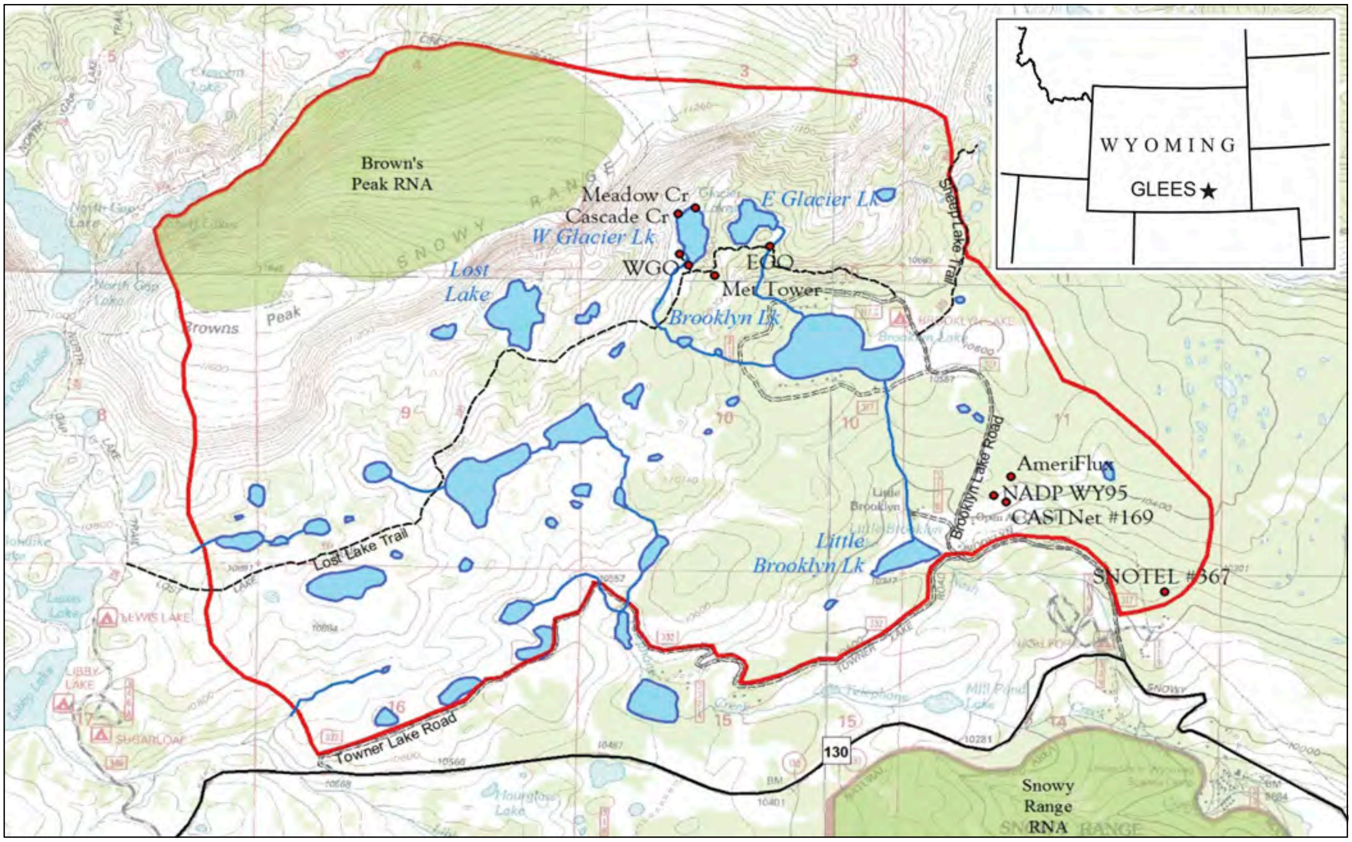

Figure 10.1—The Glacier Lakes Ecosystem Experiments Site (GLEES) showing access roads and trails, primary surface waters, and monitoring facilities. Experimental facilities include the meteorological tower and national networks: National Atmospheric Deposition Program (NADP), Clean Air Status and Trends Network (CASTNet), Snow Telometry (SNOTEL), and AmeriFlux. Parshall flumes are located at Meadow Creek, Cascade Creek, West Glacier Outlet (WGO), and East Glacier Outlet (EGO). RNA = research natural area.

Research History

GLEES was established in 1987 to examine the response of subalpine ecosystems managed as wilderness to long-term atmospheric deposition and climate changes. Research instrumentation and infrastructure can be installed at GLEES because it is not within an officially designated U.S. Forest Service wilderness area where such equipment would be prohibited. Baseline vegetation plots were established in the late 1980s and early 1990s (Regan et al. 1998), when meteorology and hydrological monitoring at East and West Glacier Lakes, and associated streams were also initiated (fig. 10.1) (Musselman 1994). The site is not used for vegetation manipulation studies, such as silvicultural treatments, that might alter ecosystem structure and processes. The primary focus of GLEES research is to examine changes to surface waters and ecosystems over time. The site is now also used to study ecosystem response to bark beetle mortality of mature forest overstory trees at the treeline ecotone that were killed in a recent bark beetle epidemic. The spruce beetle (*Dendroctonus rufipennis*) is attacking Englemann spruce, and the western balsam bark beetle (*Dryocoetes confusus*) is attacking subalpine fir.

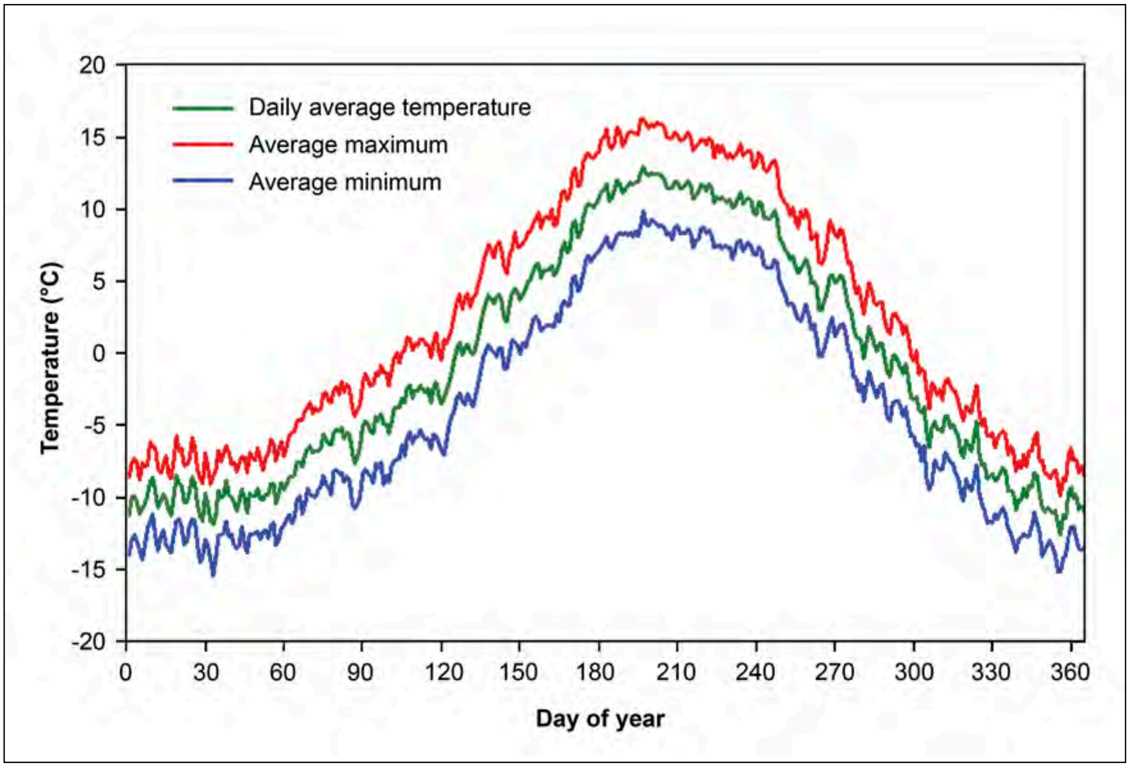

Figure 10.2—Average daily temperature ranges at Glacier Lake Ecosystem Experiments Site (GLEES), 1989–2014.

Stream discharge and water chemistry have been monitored since 1987 at four Parshall flumes located at the East Glacier Lake outlet stream, West Glacier Lake outlet stream, and Meadow Creek and Cascade Creek at their inlets to West Glacier Lake (fig. 10.1). Water chemistry was monitored at various depths at the deepest location in West Glacier Lake (9 m), East Glacier Lake (6.5 m), and Lost Lake (25 m), but this sampling was discontinued in the late 1990s. Dry and wet atmospheric deposition is monitored at three locations at GLEES (table 10.1): a Clean Air Status and Trends Network (CASTNet) site (Centennial 169) (1989 to present), and two National Atmospheric Deposition Program (NADP) sites, WY95 (1992 to present), and WY00 (1986 to present). The two NADP sites are near each other (fig. 10.1), with WY00 80 m higher in elevation than WY95, permitting comparison of deposition at two elevations. A Snow Telemetry (SNOTEL) site within GLEES has monitored snowpack depth and snow water equivalent since the 1930s, with data available electronically since 1980.

Availability of publications and data—

GLEES publications are available at the GLEES website (USDA FS 2016). As noted above, GLEES is part of several national networks, including NADP, CASTNet, AmeriFlux, and SNOTEL (table 10.1). Data from these networks are available from their websites. Meteorological and hydrological data are available from the Rocky Mountain Research Station data archive (USDA FS 2015).

Table 10.1—National monitoring networks that include the Glacier Lakes Ecosystem Experiments Site (GLEES) site[a]

Monitoring network	GLEES sites	Attributes/analytes monitored	Frequency of sample or data collection	Duration of monitoring at GLEES	Network website
Clean Air Status and Trends Network	CNT169	Ozone, gaseous, and particulate chemistry (particulate: SO_2, SO_2^{-4} HNO_3, NO_{3-}, NH_4^+; base cations: Mg^{++}, Ca^{++}, K^+, Na^+, Cl^-)	Filter pack collected weekly for S, N, and cation and anion measurements; ozone recorded hourly	1989 to present	USDE 2017b
National Atmospheric Deposition Program (NADP) National Trends Network	WY95 WY00	In wet deposition; pH, SO_4, NO_{3-}, NH_4^+, Ca++, Mg^{++}, K^+, Na^+, Cl; reported as concentration and equivalents	Wet deposition samples collected weekly; precipitation recorded every 15 minutes	1992 to present 1986 to present	NADP 2019a NADP 2019b
Passive Ammonia Monitoring Network part of NADP)	WY95	Ambient NH_3 concentration in dry deposition	Passive samplers collected and redeployed every 2 weeks	2007 to present	NADP 2019c
AmeriFlux	US-GLE	Micrometeorological measurements of ecosystem carbon dioxide (CO_2), water vapor, sensible heat, and momentum fluxes; meteorology; soil water and thermal properties; stable isotopes of ^{13}C in CO_2 and $^2H/^{18}O$ in water vapor.	Micrometeorological data collected at 20 Hz, meteorological data collected every 5 minutes, AmeriFlux data product produced every 30 minutes.	1999 to present	USDE 2017a
Snow Telemetry	Brooklyn Lake No. 367	Precipitation (accumulated); snow depth; snow water equivalent; air temperature	Data from all sensors recorded hourly, and summarized for 3-hour intervals	1980 to present	USDA NRCS 2017

Particulates: SO_2 = sulfur dioxide, SO_2^{-4} = sulfate, HNO_3 = nitric acid, NO_{3-} = nitrate, NH_4^+ = ammonium; base cations are: Mg^{++} = magnesium, Ca^{++} = calcium, K^+ = potassium, Na^+ = sodium, Cl^- = chloride, S = sulfur, N = nitrogen.

[a] For each network, raw data are summarized and modeled to increase detection of site, regional, and national trends, as described on the websites.

Biological Responses to Stream Nutrients N and P

Issues of Concern

The primary issue of concern for the WDEQ is providing for continued recreational enjoyment of unpolluted streams and lakes and maintaining high drinking water quality in the state's surface waters.

WDEQ is developing numeric nutrient criteria intended to protect Wyoming's streams, rivers, lakes, and reservoirs from excessive nitrogen (N) and phosphorus (P) pollution. Numeric nutrient criteria are intended to ensure a level of water quality that will protect assigned designated uses of these water bodies, such as fisheries, aquatic life other than fish, and recreation. The highest priority sites in Wyoming for collection of nutrient data are aquatic ecosystems that have the most potential for nutrient loading, such as those that receive agricultural runoff or discharge from municipal wastewater treatment plants. However, it will also be useful to have nutrient, phytoplankton and periphyton data from headwater streams and oligotrophic lakes that have few anthropogenic impacts, such as those at GLEES.

A potential source of N in high-elevation waters may be N deposition from air pollution generated by extensive oil and gas development upwind of GLEES since 1990. Oil and gas well permits increased dramatically in the western United States in the 1990s and early 2000s, but the development peaked in 2007. Wildland fires may also be a significant source of emissions of volatile N compounds during summer fire seasons. The size and intensity of wildland fires has increased in recent decades (McKenzie et al. 2004, Morgan et al. 2008) driven by regional drought and climate change. There is concern that N deposition from wildland fire may increase as climate warms in the future. Given that winds are predominantly from the west, deposition may also result from air masses moving from the Wasatch urban front in Utah and from an upwind coal-fired power plant west and upwind of GLEES.

Enrichment of lakes with N can cause algae blooms, a concern in waters used for recreation. Slight changes in nutrient levels have occasionally produced blooms of blue-green algae at West Glacier Lake. Many waters from alpine-subalpine basins in the Colorado Front Range are sources of drinking water for communities downstream. Increased N export from mountain areas can contribute to eutrophication of reservoirs and decrease the quality of drinking water.

Atmospheric deposition of N can contribute to acidity in surface water, especially in basins with low acid-neutralizing capacity. Acidity stresses fish and invertebrates in mountain streams and lakes, and at acute levels, can extirpate sensitive aquatic organisms such as trout.

Findings From Studies

Analyses of N wet and dry deposition since 1990 at GLEES (NADP 2019a, 2019b, 2019c) indicated no significant increases in N deposition at the site. Since 1989, East Glacier Lake has had a small but significant decrease in nitrate (NO_3^-) output (Dwire, n.d.), although N output from West Glacier Lake has not significantly changed over the period.

Baseline condition of the aquatic biotic communities in GLEES lakes was well characterized with checklists and densities of phytoplankton and zooplankton (Musselman 1994). Limited periphyton data are available for the West Glacier outlet stream. In small lakes and ponds without fish, we have also documented occurrence of a rare fairy shrimp species (*Branchinecta paludosa*), not reported in North America outside of Alaska and Canada (Belk et al. 1993). The study lakes have been stocked with cutthroat trout (*Oncorhynchus clarkii* Richardson), nonnative brook trout (*Salvelinus fontinalis* Mitchill), and rainbow trout (*O. mykiss* Walbaum) (see under "Responses to Management and Natural Disturbances").

Other Factors Relevant to Stream Nutrients N and P

Meteorological data, including soil and air temperature, relative humidity, solar radiation, windspeed, and wind direction (fig. 10.3), have been collected at GLEES since the late 1980s (Musselman 1994). Several other long-term monitoring datasets have been collected at GLEES as part of national networks (table 10.1).

Air temperature has significantly increased during summer (July to September) in the two decades of meteorological monitoring at GLEES (USDA FS 2015), but no long-term record of water temperature has been collected.

West Glacier Lake inlets and outlet have seasonal streamflow patterns with implications for N export. Winter streamflow is characterized by very low inflows from a few springs, and lake outflow ceases when the outlet stream freezes. During winter, the West Glacier Outlet stream receives a trickle of flow several hundred meters downstream of the lake outlet from emerging subsurface flow and springs. Surface flow in West Glacier Outlet stream resumes as snow melts in early May.

Stream chemistry shows a pulse of N and acidity at snowmelt initiation, and N export at the lake outlet during snowmelt indicates that rapid lake turnover exceeds the capacity of the aquatic biota to absorb increased available N entering the lake (Ruess et al. 1995). The source of the increased N is NO_3^- deposited in winter snow and stored in the snowpack. Most of the stored NO_3^- is released in the early period of snowmelt when N is preferentially eluted. At mid-summer, lakes receive lower inflows and show algae blooms, with Secchi depths less than 2 m. In that period,

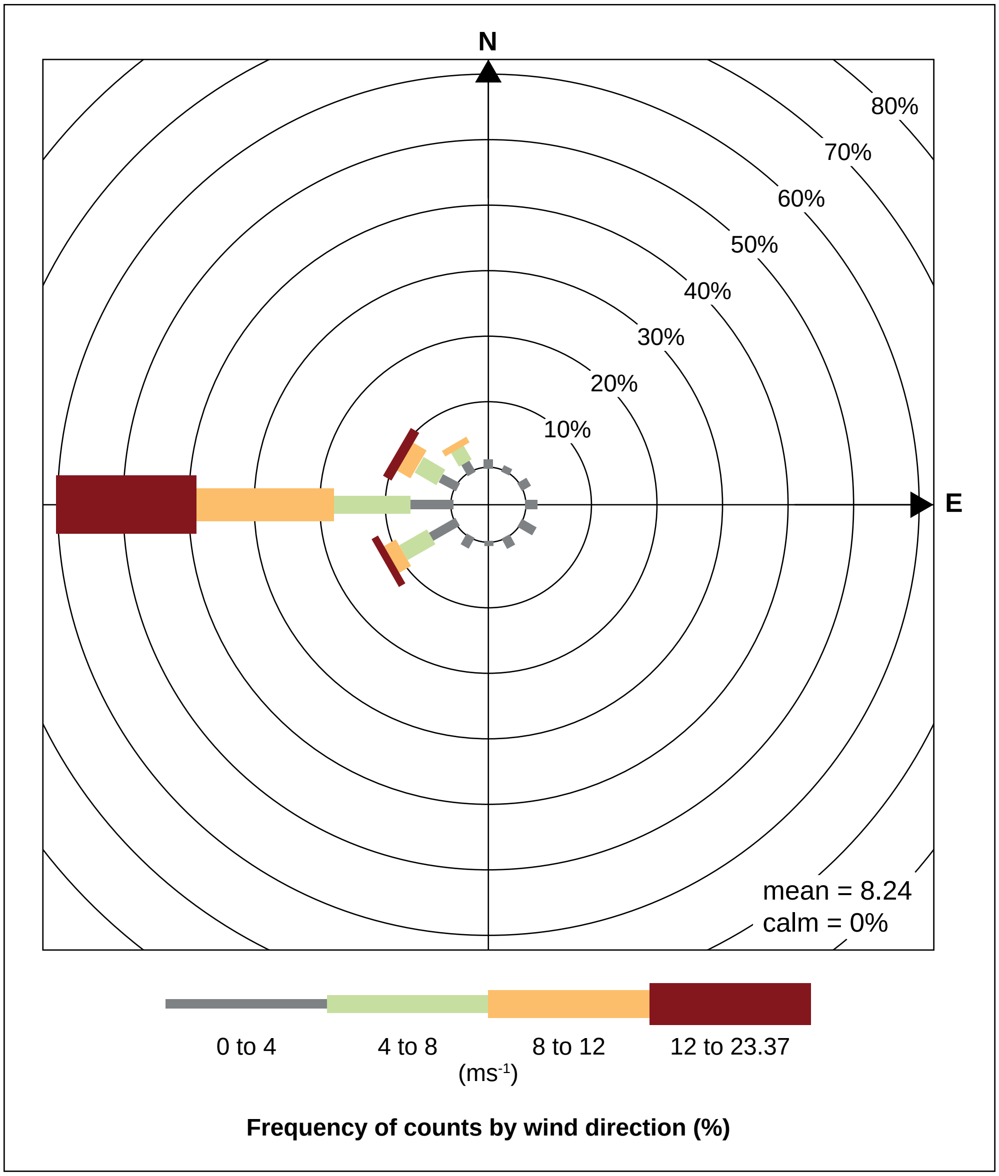

Figure 10.3—Wind rose showing predominant westerly wind direction. Much of the more recent oil and gas development is located to the east and north of the Glacier Lakes Ecosystem Experiments Site.

NO_3^- is utilized by increased growth of phytoplankton. September and October N concentrations at the outlet are below detection levels, suggesting the lake is not N saturated at this time of year. These seasonal patterns are repeated each year, although the timing of initiation of snowmelt, the amount of flow, and the magnitude of a spring pulse in NO_3^- concentration vary depending on the size of the winter snowpack and the timing of spring temperatures.

Reference Watersheds

GLEES is managed as an undisturbed watershed, with no tree harvesting permitted, and it is considered a reference watershed. Disturbance of soil or vegetation by management activities is only allowed to protect public safety. Before establishment of GLEES, selective timber cutting occurred prior to 1930, and some small, abandoned mining pits indicate past mineral extraction (Thybony et al. 1986). Grazing of sheep was heavy in the 1930s and tapered off until the 1990s when grazing permits were discontinued (Musselman 1994). Tree invasion of subalpine meadows has increased since grazing was removed, although it may also be a response to warming climate (Moir et al. 1999).

GLEES and the surrounding area receive recreational use for hiking, camping, and fishing in summer and snowmobiling and backcountry skiing in the winter. Recreational disturbance to vegetation and soils is generally confined to trails and edges of lakes. Recreation use has increased significantly since the 1980s, but is still considered to be light with minimal impact on surface waters.

Brooklyn Lake is located downstream of most GLEES streams and lakes that have been regularly monitored for water chemistry. This lake has about a dozen permitted, seasonally occupied, shorefront cabins with septic systems. Water chemistry data from the outlet of Brooklyn Lake since 1994 has shown that NO_3^- has not exceeded 1 mg/L at baseflow in September, suggesting that septic leaching has had minimal impact on water quality.

GLEES probably represents conditions in lakes and streams in wilderness and other relatively undisturbed areas near tree line in the Front Range. With the exception of permanent research instrumentation, deviations from wilderness management have been minor and are similar to activities in many backcountry, high-elevation areas in the region.

Responses to Management and Natural Disturbances

Similar to most wilderness areas in the southern Rockies, GLEES lakes have historically been stocked with nonnative cutthroat, brook, and rainbow trout. Although originally fishless, West Glacier Lake, East Glacier Lake, Lost Lake, Brooklyn Lake, Little Brooklyn Lake, and the Telephone Lakes were stocked beginning in the 1930s or 1940s. Stocking was discontinued in lakes with self-sustaining trout populations. Brooklyn Lake continues to be stocked annually, and East Glacier Lake is stocked every other year. Detailed stocking records are available from the Wyoming Game and Fish Department or from the authors. This fisheries management likely has altered aquatic communities and food webs in these lakes, but these potential effects have not been studied.

Spruce beetles have recently infested Engelmann spruce trees in subalpine forests throughout the southern Rocky Mountain region, including the GLEES. Since 2008, researchers have been studying the effects of beetle-caused canopy mortality on ecosystems processes near the AmeriFlux tower (fig. 10.1) (Frank et al. 2014) and on understory vegetation. Although forest harvest is not allowed within GLEES, removal of selected trees is planned along the Brooklyn Lake Road (fig. 10.1) for safety reasons. The immediate impacts of tree loss on ecosystem carbon and water fluxes will be monitored at the AmeriFlux tower, while the effects of canopy mortality on vegetation succession will be investigated over coming decades. Effects of tree mortality on stream nutrients or aquatic communities have not been studied.

Dose-Response Studies

Dose-response studies have not been conducted at the GLEES.

Cross-Site and Regional Studies

Data on deposition of N from NADP and CASTNet monitoring at GLEES have been used in regional and national analyses of atmospheric deposition that are periodically updated (Baron et al. 2011; Burns 2003, 2004). Data from GLEES are also regularly incorporated in SNOTEL regional snow cover and snowpack summaries and water supply forecasts.

Reliability and Limitations of Findings

Findings from GLEES could be expected to apply to other high-elevation catchments in the southern Rocky Mountains with similar geology and terrain features. At sites where elevation, geology, wind dynamics, snow distribution, or aspect, differ from GLEES, or where a high degree of accuracy is required, we suggest validation studies or monitoring to test how well the GLEES findings represent conditions elsewhere in the region.

Research Needs

The highest priority research need that could be filled at GLEES, from the perspective of the regional water quality regulatory community, is more recent, detailed limnologic water column data, including water chemistry, at the GLEES lakes. These data would be useful to water quality regulatory agencies for the development of nutrient criteria for oligotrophic lake systems. Although such data were collected at GLEES from 1989 to 1999, they may be outdated. More recent observations are needed to assess current conditions. This need could be filled by resuming regular monitoring of detailed water column nutrient concentrations at several depths at the deepest location in the GLEES lakes.

Other research needs that could be filled at GLEES, but of lower priority to the regulatory community, include the following:

- Understanding the level of atmospheric deposition of N that would exceed critical thresholds of nutrient enrichment that cause undesirable biological responses in high-altitude lakes. Critical N deposition loads have been published for high-elevation lakes elsewhere in the Western United States (Baron 2006, Nanus 2012, Saros et al. 2011), but their applicability to GLEES needs to be validated.
- Impacts of climate change on water temperature, snowmelt, streamflow, and stream chemistry.
- Potential interactive effects of climate warming and N deposition on lake water quality and primary productivity.
- Impacts on water quality of wilderness recreational use, particularly in the summer.
- Responses of algal populations to changes in N levels in high-altitude lakes.

Potential Utility to Water Quality Regulatory Agencies

The 25-year database of baseline hydrological, biological, and meteorological record for first-order, surface-water catchments at GLEES could be useful to the WDEQ for water quality criteria development, total maximum daily load (TMDL) modeling, and determination of trends in high-elevation surface water quality. Similar databases are generally lacking for development of WDEQ nutrient criteria. Based on regional assessments, GLEES can be considered a relatively undisturbed, reference watershed (Baron et al. 2011, Nanus et al. 2012). Because most pollutants associated with land use have been controlled at GLEES, long-term changes in surface-water chemistry from atmospheric deposition or climate change are more likely to be detected there. This relatively undisturbed area with no nearby agricultural or urban emissions and with minimal previous impact from atmospheric deposition from energy development, is especially useful for numeric nutrient criteria development.

Data of interest to the WDEQ for development of nutrient criteria for lakes include alkalinity (as calcium carbonate [$CaCO_3$]), conductivity, ammonium (NH_4^+), NO_3^-, nitrite (NO_2^-), total N, dissolved oxygen, oxidation reduction potential, P, water temperature, chlorophyll a, phytoplankton species and biomass, Secchi depth, and geographic positioning system location of the data source. Because WDEQ has collected little data from alpine lakes, data collected from the GLEES, using WDEQ-approved standard operating procedures and quality assurance/quality control, would contribute to development of nutrient criteria in mountain ecoregions.

Although these data are available for East and West Glacier Lake at GLEES, similar data from the outlet streams at GLEES is limited, except for the West Glacier outlet stream. Both the West Glacier and East Glacier outlet streams are less than 500 m in length and flow into Brooklyn Lake, which is the source of the Nash Fork of the Little Laramie River. Monitoring these additional streams and lakes at GLEES would be of interest to regulators because they are the headwaters of the Laramie River, which is a tributary of the North Platte River. WDEQ might consider collaborating with the U.S. Forest Service to add these GLEES sites to its statewide water quality monitoring network.

Key points:

- The GLEES physical and biological monitoring serves as a valuable resource for the WDEQ in the development of nutrient water quality criteria for oligotrophic aquatic ecosystems, a high research priority from the perspective of the regulatory community.
- Data collected at GLEES might also contribute to determination of the level of water quality necessary to protect the designated uses of these surface waters, including fisheries, other aquatic biota, and recreation.
- Studies at GLEES might be useful to investigate in high-altitude lakes what levels of N atmospheric deposition would exceed critical thresholds of nutrient enrichment that cause undesirable biological responses.
- Environmental datasets from GLEES could also be used by regulatory agencies for practical purposes such as water quality criteria development, total maximum daily load modeling, and measurement of trends in high-elevation surface water quality.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Sulfur (S), in the form of sulfate (SO_4^{2-}), is a primary constituent of atmospheric deposition from fossil fuel combustion upwind of the Medicine Bow Mountains. High-elevation streams and lakes could be acidified if the combined deposition of SO_4^{2-} and N increased to exceed the low acid-neutralizing capacity of these sensitive water bodies. Aquatic plants, including phytoplankton, and fauna, especially fish and invertebrates, could be negatively affected by lake and stream acidification. Loss of aquatic biota may detract from users' wilderness experience and recreational fishing opportunities. Wilderness lakes and streams that become altered by pollutants might no longer be perceived by the public as pristine.

Fossil fuel combustion upwind of the Snowy Range from electric generation power plants, drilling rigs, pumps and field processing of oil and gas generate airborne S compounds, particulates, and toxic organic compounds. These compounds are also generated locally by vehicle traffic and snowmobiles. The impact of deposition of these chemicals on downwind ecosystems and surface waters, especially in wilderness areas, is unknown. Increased S and toxics in surface waters from deposition are a primary concern as their impact on drinking water and fisheries in these headwaters is unknown.

Findings Related to Stream Nutrients Other Than N and P

Surface water monitoring at the four Parshall flumes has been conducted seasonally from early May through mid-October since the late 1980s. Water samples collected have been analyzed for pH, conductivity, alkalinity, cations, including calcium ($Ca^{2+)}$, magnesium ($Mg^{2+)}$, sodium (Na^{+}), and potassium (K^{+}), and anions, including fluoride (F^{-}), chloride (Cl^{-}), and SO_4^{2-}. Stream chemistry at West Glacier Outlet has had a small but significant increase in Na^{+}, Ca^{2+}, and acid-neutralizing capacity since 1989 (Dwire, n.d.).

Other Factors Relevant to Stream Nutrients Other Than N and P

Extensive research has been conducted at GLEES on ecosystem carbon (C) stocks and fluxes, water fluxes, and heat and energy exchange. The C stock in biomass at GLEES is about 330 Mg C/ha, higher than at other Rocky Mountain Front Range alpine/subalpine study sites at Fraser Experimental Forest (see chapter 9) and Niwot Ridge in Colorado (Bradford et al. 2008). Recent studies have found that forest overstory mortality from bark beetles has increased albedo and sensible heat flux, and reduced evaporation and net C exchange at GLEES (Chen et al. 2014, Frank et al. 2014).

Reference Watersheds

As was described earlier, regular monitoring of nutrients other than N and P, has been conducted on streams in reference watersheds because all of the monitored watersheds at GLEES are functionally reference watersheds.

Response to Management and Natural Disturbance

GLEES is managed similarly to U.S. Forest Service wilderness ecosystems, including the prohibition of manipulations of vegetation or soils. Despite tight controls of on-the-ground human disturbances, effects of regional and global influences, such as weather modification, are unavoidable.

To test the feasibility of artificially augmenting precipitation, the state of Wyoming, and its partners, recently injected silver iodide (AgI) crystals into the atmosphere in a 6-year cloud seeding pilot study, conducted in the Snowy Range (Breed et al. 2014). GLEES and its surrounding areas were in the zone affected by the regional experiment. Silver (Ag) is a metal that is potentially toxic to plants and animals. Modeling analyses (WWMPP 2014) found that Ag input to the ecosystem from cloud seeding was likely negligible because it was equivalent to only a small fraction of ambient Ag already present. Increases in deposition of N, S, and other nutrients were also expected to be small because precipitation was predicted to increase by 5 to 15 percent. The experiment was expected to increase streamflow 0.4 to 3.7 percent (WWMPP 2014). Routine monitoring of precipitation, streamflow, snowpack, atmospheric deposition of N and S, and stream export of N and S were conducted at GLEES during the cloud seeding pilot. However, these GLEES data were not collected to detect effects of the pilot and have not been analyzed for that purpose. For example, neither silver nor iodide were monitored in precipitation at GLEES. Potential effects of beetle-caused tree mortality on stream nutrients other than N and P have not been studied.

Dose-Response Studies

Dose-response studies have not been performed at GLEES.

Cross-Site and Regional Studies

Data on deposition of SO_4^{2-}, Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, and hydrogen ion from the NADP monitoring at GLEES, plus ozone (O_3) and sulfur dioxide from CASTNet monitoring, have been used in regional and national analyses of atmospheric deposition (Baron et al. 2011; Burns 2003, 2004; Nanus et al. 2013) that are periodically updated and available on those network websites.

Reliability and Limitations of Findings

The same limitations of findings that apply to N and P studies at GLEES also apply to studies on other nutrients.

Research Needs

The highest priority research question of the regulatory community, related to nutrients that might be answered at GLEES is, What would be the impacts on high-elevation surface waters and aquatic biological systems in the Rocky Mountain Front Range if acidifying effects of atmospheric deposition of SO_4^{2-} and N were to increase? This information is potentially important for regional water quality regulatory agencies because it would provide a scientific basis to anticipate what changes in water chemistry are likely to occur if the combined effects of atmospheric deposition of SO_4^{2-} and N increased the acidity in high-elevation surface waters and what biological responses might accompany those water chemistry changes. Future research to answer these questions at GLEES would include resumption of monitoring limnologic water column data at the GLEES lakes; additional monitoring of water chemistry in the GLEES outlet streams, such as Nash Fork below Brooklyn Lake; and experiments or monitoring to determine what taxa would be sensitive in surface waters to the acidifying effects of increased atmospheric deposition.

Another question of regulatory interest, but of lower priority, would be, What are the effects of long-term climate change on nutrients other than N and P and biological responses to them in high-elevation lakes in the Front Range?

Potential Utility to Water Quality Regulatory Agencies

Long-term monitoring datasets from GLEES of atmospheric deposition and high-altitude stream and lake water concentrations of SO_4^{2-} and N might be useful for including potential effects of acidification driven by atmospheric deposition of air pollutants in water quality criteria development, TMDL modeling, and determination of temporal trends in high-elevation surface-water quality.

Key points:

- GLEES has extensive long-term datasets of atmospheric deposition and high-altitude stream and lake water concentrations of SO_4^{2-} and other nutrients other than N and P.
- These data are potentially useful to water quality regulatory agencies for developing water quality standards, TMDL modeling, and determining temporal trends in water quality in high-elevation lakes and streams.
- The highest priority research need that could be filled at GLEES on this topic is, What impacts on high-elevation surface waters and aquatic biological systems in the Rocky Mountain Front Range could result from increases in acidification owing to atmospheric deposition of SO_4^{2-} and N?

Overview and Synthesis

GLEES is a relatively undisturbed and well-studied high-elevation site downwind of considerable energy development. Prevailing westerly winds carry emissions to GLEES from energy development in central Wyoming and northern Colorado, but less frequent easterly winds also carry emissions. Although emissions such as nitrogen oxides, volatile organic compounds, and O_3 from energy development have been well monitored and modeled in Wyoming upwind of GLEES, little is known about their ecological effects on high-elevation ecosystems such as GLEES. Glacier

Lakes Ecosystem Experiments Site monitoring data have spanned the period of recent expansion in energy development and could be analyzed for temporal trends. Because land uses that might confound effects of air pollution have been controlled at GLEES, it is well-suited for detection of deposition of N and S compounds and toxic organic chemicals from oil and gas development, and their ecological effects on high-elevation surface waters.

The existing GLEES database is potentially useful to the WDEQ to examine long-term change in mountain ecosystems and surface waters to climate change. No other database in Wyoming provides comparable detailed long-term information on high-elevation surface waters, or has the potential to detect changes over time in response to a warming climate.

Key points:

- GLEES is a high-elevation research site with extensive baseline data of meteorology, water chemistry, hydrology, and aquatic and terrestrial biology that can be used by the Wyoming Department of Environmental Quality.
- These data are most relevant for detecting the effects of atmospheric deposition of N, P, S, and other chemicals on surface water quality and aquatic resources in high-altitude headwater ecosystems.
- The highest priority science needs of the regulatory community that could be filled at GLEES are (1) the long-term collection of limnologic water column data, (2) the biological responses in high-elevation waters to enrichment by the nutrient N, and (3) the acidifying effects of both S and N if these elements were to increase in atmospheric deposition.
- The spatial location of GLEES is important for regional detection of increasing global change and atmospheric deposition effects. There are no other long-term monitoring sites at this high elevation in Wyoming.

References

Baron, J.S. 2006. Hindcasting nitrogen deposition to determine an ecological critical load. Ecological Applications. 16(2): 433–439.

Baron, J.S.; Driscoll, C.T.; Stoddard, J.L.; Richter, E.E. 2011. Empirical critical loads of atmospheric nitrogen deposition for nutrient enrichment and acidification of sensitive US lakes. BioScience. 61(8): 602–613.

Belk, D.; Dufford, R.; Saunders, J.F. 1993. Persistence of *Branchinecta paludosa* (Anostraca) in southern Wyoming, with notes on zoogeography. Journal of Crustacean Biology. 13(1): 5.

Bradford, J.B.; Birdsey, R.A.; Joyce, L.A.; Ryan, M.G. 2008. Tree age, disturbance history, and carbon stocks and fluxes in subalpine Rocky Mountain forests. Global Change Biology. 14: 2882–2897.

Breed, D.; Rassmussen, R.; Weeks, C.; Boe, B.; Deshler, T. 2014. Evaluating winter orographic cloud seeding: design of the Wyoming Weather Modification Pilot Project (WWMPP). Journal of Applied Meteorology and Climatology. 53: 282–299.

Burns, D.A. 2003. Atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming—a review and new analysis of past study results. Atmospheric Environment. 37(7): 921–932.

Burns, D.A. 2004. The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA—a critical review. Environmental Pollution. 127(2): 257–269.

Chen, F.; Zhang, G.; Barlage, M.; Zhang, Y.; Hicke, J.A.; Meddens, A.J.H.; Zhou, G.; Massman, W.J.; Frank, J.M. 2014. An observational and modeling study of impacts of bark beetle-caused tree mortality on surface energy and hydrological cycles. Journal of Hydrometeorology. 16: 744–761.

Dwire, K.A. [N.d.]. GLEES precipitation, stream, and lake monitoring data. On file with: USDA Forest Service, 240 West Prospect Road, Fort Collins, CO 80526.

Frank, J.M.; Massman, W.J.; Ewers, B.E.; Huckaby, L.S.; Negrón, J.F. 2014. Ecosystem CO_2/H_2O fluxes are explained by hydraulically limited gas exchange during tree mortality from spruce beetles. Journal of Geophysical Research: Biogeosciences. 119: 1195–1215.

McKenzie, D.; Gedalof, Z.; Peterson, D.; Mote, P. 2004. Climatic change, wildfire and conservation. Conservation Biology. 18: 890–902.

Mensing, S.; Korfmacher, J.; Minckley, T.; Musselman, R. 2011. A 15,000 year record of vegetation and climate change from a treeline lake in the Rocky Mountains, Wyoming, USA. The Holocene. 22(7): 739–748.

Moir, W.H.; Rochelle, S.G.; Schoettle, A.W. 1999. Microscale patterns of tree establishment near upper treeline, Snowy Range, Wyoming, U.S.A. Arctic, Antarctic, and Alpine Research. 34(4): 379–388.

Morgan, P.; Heryerdahl, E.K.; Gibson, C.E. 2008. Multi-season climate synchronized widespread forest fires throughout the 20^{th}-Century, Northern Rocky Mountains, USA. Ecology. 89: 717–728.

Musselman, R.C. 1994. The Glacier Lakes Ecosystem Experiments Site. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 94 p. http://www.fs.fed.us/rm/pubs_rm/rm_gtr249.pdf. (1 March 2021).

Nanus, L.; Clow, D.W.; Saros, J.E.; Stephens, V.C.; Campbell, D.H. 2012. Mapping critical loads of nitrogen deposition for aquatic ecosystems in the Rocky Mountains, USA. Environmental Pollution. 166: 125–135.

National Atmospheric Deposition Program [NADP]. 2019a. NTN [National Trends Network] Site WY00. Snowy Ridge. http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=WY00. (1 July 2019).

National Atmospheric Deposition Program [NADP]. 2019b. NTN [National Trends Network] Site WY95. Brooklyn Lake. http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=WY95. (1 July 2019).

National Atmospheric Deposition Program [NADP]. 2019c. AMon [Ammonia Monitoring Network] Site WY95. Brooklyn Lake. http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=AMoN&id=WY95. (1 July 2019).

Natural Resources Conservation Service [NRCS] 2017. SNOTEL. http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=367. (31 October 2017).

Regan, C.M.; Musselman, R.C.; Haines, J.D. 1998. Vegetation of the Glacier Lakes Ecosystem Experiments Site. Res. Pap. RMRS-RM-1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 36 p.

Reuss, J.O.; Vertucci, F.A.; Musselman, R.C.; Sommerfeld, R.A. 1995. Chemical fluxes and sensitivity to acidification of two high-elevation catchments in southern Wyoming. Journal of Hydrology. 173: 165–189.

Saros, J.E.; Clow, D.W.; Blett, T.; Wolfe, A.P. 2011. Critical nitrogen deposition loads in high-elevation lakes of the Western US inferred from paleolimnological records. Water Air & Soil Pollution. 216: 193–202.

Thybony, S.; Rosenberg, R.G.; Rosenberg, E.M. 1986. The Medicine Bows; Wyoming's mountain country. Caldwell, ID: The Caxton Printers, Ltd. 180 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2015. Research Data Archive.https://www.fs.usda.gov/rds/archive/Catalog?freesearch=GLEES&searchfield=. (1 March 2021).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2016. GLEES [Glacier Lakes Ecosystem Experiments Site]. http://www.fs.fed.us/rm/landscapes/Locations/Glees/GLEES.shtml. (1 March 2021).

U.S. Department of Energy [USDE]. 2017. Ameriflux. http://ameriflux-data.lbl.gov:8080/SitePages/siteInfo.aspx?US-GLE. (1 March 2021).

U.S. Department of Energy [USDE]. 2017. Clean Air Status and Trends Network **[CASTNet].** http://www.epa.gov/castnet)/javaweb/site_pages/CNT169.html. (1 March 2021).

Wyoming Weather Modification Pilot Program [WWMPP]. 2014. Executive summary. http://wwdc.state.wy.us/weathermod/WYWeatherModPilotProgramExecSummary.pdf. (1 March 2021).