LONG-TERM ECOLOGICAL RESEARCH

IN LOCH VALE WATERSHED, ROCKY MOUNTAIN NATIONAL PARK

Annual Report, 1992

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INTRODUCTION

The National Park Service (NPS) and Colorado State University (CSU), as part of the Watershed Studies Cooperative Park Studies Unit of the Water Resources Division, studies the biogeochemical processes of alpine/subalpine watershed ecosystems to determine how they are affected by atmospheric deposition. Begun in 1981, this project assesses current precipitation patterns and ecosystem responses of the Loch Vale Watershed in Rocky Mountain National Park and evaluates them with the context of past conditions and trends. This research will be used to protect sensitive Rocky Mountain National Park ecosystems from damage from urban and industrial pollution.

The Loch Vale Watershed project is an ecosystem study, attempting to quantify major elemental and pollutant flux, identifying sources, sinks and controls of the major ions. We defined the boundaries of our ecosystem with the physical boundaries of Loch Vale Watershed, and adopted the small watershed technique as the overall context for study. Instead of "black-boxing" internal processes while quantifying watershed inputs and outputs, we attempt to understand and quantify inputs and outputs from each of the major ecosystem components of the landscape: bedrock, soils, vegetation and surface waters (Figure 1). Because so little was known about these components of the alpine and subalpine zones, early effort went into documenting basic characteristics and processes.

Rocky Mountain National Park is sensitive to acidic deposition (Eilers et al. 1986, Turk and Spahr 1989). Much of the park area is exposed granitic rock with 147 alpine and subalpine lakes and over 700 stream km. Naturally-reproducing populations of trout are present in 59 lakes (Rosenlund and Stevens 1990). It is well documented in the

literature (Schindler 1988, Gibson 1986) that deposition of strong acid anions can rapidly exhaust the acid neutralizing capacity (ANC) of systems underlain by slow weathering bedrock types, allowing lakes and streams to acidify. The acidity itself, and, more importantly, aluminum which becomes soluble at pH levels below 5.0, are extremely toxic to aquatic organisms.

Loch Vale Watershed (LVWS) was chosen for study for a number of reasons. A reconnaissance in 1981 of over 40 lakes and streams within four major drainages of Rocky Mountain National Park (Gibson et al. 1983) provided a chemical and geographical base of information which aided in the selection of a specific watershed study site. Of the drainages sampled, Loch Vale Watershed exhibited the lowest summertime alkalinities, and showed an inverse gradient of ANC with elevation. There are four lakes within the watershed, three alpine, and one located below tree line. This allows for comparison of alpine with subalpine lakes (Figure 2). There is sufficient soil development to allow characterization of different soil types and their influence on surface water chemistry. An old-growth Engelmann spruce-subalpine fir forest is within the valley basin. A controlled surface water outlet from the entire basin allows us to quantify stream discharge. One final reason for the selection of LVWS is that the watershed is accessible, although remote, throughout the year.

SITE DESCRIPTION

Loch Vale Watershed (LVWS) is a 660 ha northeast-facing basin located in Rocky Mountain National Park about 80 km NW of Denver, Colorado (Figure 3). The watershed ranges in elevation from 3110 m at the outlet of the lowest lake, The Loch, to 4010 m at the Continental Divide. More than 80% of the basin surface consists of bedrock outcrop and active talus slopes. Bedrock consists primarily of Precambrian-aged granitic gneiss and schist (Cole 1977; Mast 1989). Several permanent snowfields and an active rock glacier, remnants of neoglacial activity, occupy 1% of the watershed. In areas of relatively gentle slope, the valley floor is covered with glacial till of Pinedale age (Mast 1989).

Forest soils have developed on the moraine veneer below 3300 m elevation, covering about 5% of the area of the catchment. Soil pH (1:1 paste) ranges between 3.3 and 5.1. Cation exchange capacity of these soils ranges from 50 to 100 ceq kg^{-1}, but base saturations are quite low, with a mean of 23% in the organic surface layers and decreasing to below 10% in the deeper horizons. The exchange complex is dominated by calcium (Walthall 1985; Baron and Walthall 1985, Baron et al. 1992). Soil development is very heterogeneous, varying in depth from 1 to >100 cm. These soils support a mature forest of Engelmann spruce (Picea engelmanii) and subalpine fir (Abies lasiocarpa), which covers about 6% of the total land area (Arthur 1990). Alluvial and bog soils, classified as Cryaquents and Cryohemists, occupy only 1% of the watershed, but may have a disproportionate influence on surface water chemistry due to their position adjacent to stream channels. These highly organic soils are characterized by base saturations of less than 13% (Walthall 1985).

Snowpack accumulation in LVWS begins in November of each year, and the melt begins in mid- to late-April. More than 75% of the annual water input to the basin is in the form of snow. Midwinter melting events are extremely rare, and snowpack temperatures remain below 0°C above the "depth hoar" zone from about November through late March. Peak runoff occurs late May to early June, with 40 to 50% of annual runoff occurring by July 1 (Figure 4). Meltwater from the permanent snowfields contributes to stream discharge through September. Baseflow appears to be maintained by groundwater seepage.

PROJECT HISTORY

Years of activity are denoted with xx; startup years have only one x. MAB = Man and the Biosphere; NPS = National Park Service; BuRec = Bureau of Reclamation; SERI = Solar Energy Research Institute; NADP = National Atmospheric Deposition Program; CSU = Colorado State University; USGS = U.S. Geological Survey; U.Wy. = University of Wyoming; USFS = U.S. Forest Service; NSF = National Science Foundation; WEBB = Water, Energy and Biogeochemical Budgets Program; COLR GC = Colorado Rockies Global Change Program; PET = Potential Evapotranspiration.

Activity/ Sponsor	81	82	83	84	85	86	87	88	89	90	91	92
Paleolimnology /MAB;NPS	xx	xx	xx									
Met station /NPS;BuRec/SERI			x	x	xx	xx	xx	xx	xx	xx	xx	xx
NADP site/NPS;CSU			x	xx	xx	xx	xx	xx	xx	xx	xx	xx
Stream Gage /NPS;USGS			x	xx	xx	xx	xx	xx	xx	xx	xx	xx
Lake bathymetry /NPS			xx									
Lake and stream chem/NPS,USGS		xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Airshed study/NPS							xx	xx				
Soil studies /NPS;CSU			xx	xx	xx							
Bedrock studies /NPS;U.Wy.							xx	xx	xx			
Vegetation/ NPS,Cornell					xx	xx	xx	xx	xx	xx		
Algal dynamics /NPS,USGS;CSU				xx	xx		xx	xx	xx	xx		
Snowmelt dynamics /NPS;U.Wyo.; Cornell;USGS						xx	xx					xx
N dynamics/ NPS;USFS											xx	xx
Litter decomp. /NSF,NPS											x	xx
WEBB/USGS										xx	xx	xx
COLR GC/ NPS;USGS											x	x
PET measurements /NPS												x

SITE REPRESENTATIVENESS

The Loch was sampled in 1985 as a Special Interest Lake as part of the U.S. Environmental Protection Agency's Western Lake Survey (WLS, Landers et al. 1986, Eilers et al. 1986). The 719 lakes included in the WLS were selected by stratified random design, so as to represent the estimated 10,393 lakes in the Western United States (Landers et al. 1986). The median elevation of lakes sampled in the Southern Rockies was 3264 m, slightly higher than the elevation of The Loch, at 3048 m. The Loch is atypical of Front Range lakes that were sampled (Table 1). Overall, The Loch has a much greater watershed area to lake area ratio than other lakes of the Front Range, the Southern Rockies, and the eastern United States that were sampled by the WLS. It also has much more dilute waters. Mineral weathering contributes far less to solution chemistry of The Loch than to most other lakes within the Front Range, whereas Front Range lakes appear to be typical of other lakes within the Southern Rockies. For example, the sum of the base cations for The Loch is 110.3 μeq L^{-1}, compared with median values of 352.5 μeq L^{-1} and 367.4 μeq L^{-1} for the Front Range and the Southern Rockies, respectively. Acid-neutralizing capacity for The Loch is 48.9 μeq L^{-1}, compared with median values of 337.5 μeq L^{-1} and 317.0 μeq L^{-1} for the Front Range and the Southern Rockies. Silica in The Loch is only 1.77 mg L^{-1} compared to 2.30 mg L^{-1} and 2.12 mg L^{-1} for the subpopulations. This suggests that LVWS bedrock is far more resistant to weathering than is typical of the rest of the Southern Rockies, and may be more vulnerable to increasing acidic atmospheric deposition. Solution chemistry for The Loch is more characteristic of statistics for the West as a whole, and similar in composition to the very dilute lakes that are found in the Sierra Nevada (Landers et al.

1986). Dissolved organic carbon in The Loch is half that of the rest of the Rockies, probably because only 6% of LVWS supports evergreen forests, compared to 35.4% evergreen coverage for the Southern Rockies as a whole. Sulfate and chloride concentrations in The Loch are comparable to concentrations found in the Front Range and in the Southern Rockies, and this reflects their predominantly atmospheric origin (Turk and Spahr 1989). Sulfate in Southern Rocky Mountain lakes are higher than the median SO_4 concentration for the West, and may reflect regional emissions or sulfur-bearing bedrock minerals. Nitrate is much higher in The Loch than in other WLS lakes.

BASIC PREMISE AND QUESTIONS

There are five objectives of the LVWS research:

1. To understand biogeochemical process response to increasing acidic deposition in alpine-subalpine ecosystems through intensive study of the Loch Vale Watershed system in Rocky Mountain National Park. Use past, present, and future levels of acidity and its indicators to assess the influences of precipitation, bedrock weathering, soils, vegetation, lake biotic and abiotic dynamics on surface water composition, and quantify hydrologic patterns and processes.

2. To interact frequently with NPS managers, and other federal and state officials, and the scientific community to share research information in alpine and subalpine responses and responses to acidic deposition from airborne pollutants in Rocky Mountain National Park.

3. To apply information gained in Rocky Mountain National Park to other NPS and federally-managed lands in Colorado, nationwide, and worldwide.

4. To provide a program of graduate education and research develops future scientists and knowledgeable resource managers.

5. To continue the Loch Vale Watershed long-term ecological research project as a successful example of ecosystem study design, long-term continuity of quality-assured data collection, data base management, and applied better natural resource management

Research in LVWS assumes biogeochemistry of the catchment is a defineable and predictable combination of precipitation chemistry, weathering and exchange reactions of soil and parent materials, and the chemical products of biological activity. Within that context, the following questions serve as guides to research in LVWS.

Question 1. Are current levels of acidity in precipitation falling in Rocky Mountain National Park greater than historical levels? Are there trends in the chemical composition of precipitation? Regular analysis of precipitation is used to assess current levels and trends. The analysis of sediment cores was used to assess historical levels.

Question 2. Does buffering of surface waters come from soil processes such as weathering of inorganic soil materials and exchange reactions from soil organic matter? Characterization of solid and solution phases of soils has been augmented by flowpath studies.

Question 3. What are the controls of surface water chemical composition? The composition of lakes and streams fluctuates over time, influenced by hydrologic processes, and their interaction with the products from bedrock weathering, soils, and biota. Pertinent research includes characterizations of bedrock and geochemical weathering, vegetation, and the physical, chemical, biological, and hydrologic characterization of lakes and streams within LVWS.

Question 4. What are the likely effects of climate change on the alpine-subalpine areas of the southern Rocky Mountains? Past research has indicated that LVWS is strongly influenced by the volume, chemistry, and seasonal pattern of precipitation. Thus, changes in regional climate that affect these parameters may create a fast and significant response in LVWS and similar subalpine watersheds. Proposed research will tie together climate and ecosystem modelling efforts with field data from Loch Vale, in an attempt to quantify effects of possible climate change on similar resources within the National Park system and throughout the Rockies.

PRESENT PROGRAM

Current research in LVWS includes; (1) continuation of the long term monitoring program, (2) several projects addressing specific aspects of alpine flowpaths, weathering of alpine soils, nutrient cycling, and decomposition of organic matter, (3) participation in the WEBB program of the USGS, and (4) climate change studies for the COLR GC program.

Jill Baron, Rob Edwards and Jennifer Back are responsible for the long term monitoring program. The goal is to continue accurate measurements of inputs and outputs, and to monitor surface water quality throughout the watershed. One hundred thirty samples, including QA blanks and duplicates, were collected in water year 1992 (1 Oct 1991 through 30 Sept 1992). This research produces annual budgets of material flow through Loch Vale, and provides the framework on which more detailed process studies can be built.

Dave Clow completed his Ph.D. dissertation, which examined weathering processes in the alpine environment. Input, output and meteorological data were collected for a $10m^2$ soil-bedrock site ("nanocatchment"). Weathering rates of soil minerals were 3 to 40 times lower in the field than in laboratory experiments. These results were ascribed to lower flow rates, which, combined with the field soil structure, resulted in less interactive mineral surface area. Experiments with soil columns showed that the amount of exchangeable cations affected the weathering rates of divalent cations, but amorphous oxides on soil particles had no effect on base cation release rates. Clow is continuing this work with USGS support.

Michael Martin completed fieldwork for his master's degree research. Two hundred ten surface water, snow, glacier ice, and precipitation samples were collected in the upper Sky Pond drainage of LVWS. Samples were analyzed for nitrate, chloride, sulfate, ammonium, and phosphate. These data will be used to characterize alpine watershed hydrochemistry with particular focus on spatial and temporal variation of nitrate and ammonium.

Jennifer Back's research on stable isotopes as tracers of hydrologic inputs continued through of 1992. This study compares the isotopic signature of inputs and outputs to Sky Pond, Andrews Tarn, and Loomis Lake. The majority of sampling was completed in 1991. Most early summer lake water ^{18}O values fall between -19.00 and -17.00 per mil. Deuterium values range from -135.0 to -115.0 per mil. Initial results indicate that the isotopic composition of lake water becomes heavier later in the summer. The primary focus of this year's effort was to obtain more extensive precipitation samples. Bulk precipitation collectors were installed at Andrews Tarn and at Andrews meadow. Samples from the two collectors were periodically collected to obtain a clearer picture of the effect of elevational differences on isotopic signatures.

We are continuing investigations into sources and sinks for N in LVWS lakes and streams. Nitrogen oxides are important precursors of Front Range acidic deposition. An experiment was conducted in 1992 to determine whether there was significant dry deposition of N to snow. Brian Rader, a CSU undergraduate, collected and analyzed snow from plastic containers. He compared the NO_3 and NH_4 content between snow that had been exposed for 2-3 days with that from the time when containers were set out. The experiment was preliminary, and most 2-3 day intervals were disqualified on account

of rain events. It appears the method has promise and there might be up to 1 mg L^{-1} dry deposition per interval. We are grateful for analytical support from the Niwot Ridge LTER project.

The first year sampling of the Long Term Ecological Research network study of plant litter decomposition (LIDET 1990) was completed in the fall of 1992. Andrea Zuur, a student volunteer with the LVWS project, and Rob Edwards collected 44 litter samples, that had been placed at four sites within the subalpine forest of LVWS in the fall of 1991. The samples were analyzed for their one-year weight loss at CSU, then were sent to Oregon State University for chemical analysis. The study will last ten years and compare the decomposition rates of different types of litter decomposing in different environments.

The Loch Vale USGS WEBB program is overseen by John Turk with research activities coordinated by Norm Spahr and Don Campbell. The WEBB program is exploring detailed hydrologic pathways, isotopic signatures of different minerals, and sources of solutes in surface waters. Three meteorological stations have been set up and two gaging stations were installed on Icy Brook and Andrews Creek to give a more detailed picture of climate and flow in the upper watershed. Intensive surveys of snow depth and chemistry began in the spring of 1991. These will be coordinated with studies of surface water quality during snowmelt and sulfur sources within the watershed.

Steve Bachman continued his study of hydrologic processes in the wet meadows near Icy Brook. Twenty-one wells were instrumented with shaft encoders and continuously recording data loggers. Four sets of nested piezometers were installed in each study site to determine vertical gradients. Field saturated hydraulic conductivity was measured with a Guelph permeameter. A system for determining soil moisture release

curves for wetland soils was constructed at the CSU Land Use Hydrology Laboratory. Research will continue through 1993. This project is supported by the USGS WEBB Program.

Field work on snow depth and water content was initiated in 1992 in LVWS to support the COLR global change research. Don Cline is a Ph.D. student responsible for this work, which will compare remotely sensed snow data with snow courses set up in LVWS and adjacent to Soil Conservation Service SNOTEL sites along the northern Front Range. Eleven snow courses of five 3 m stakes each were installed in Loch Vale Watershed in September and October. These were surveyed in, along with markers at known elevations for rectifying remotely-sensed data. Stereo photography (1:24,000 scale) of LVWS with minimum snow cover was flown in October. Additional flights will occur in April 1993, continuing through the snowmelt season. These photographs will be scanned and digitized to derive digital elevation maps with approximately 1 m resolution. The elevational difference between map overlays, in conjunction with the snow depth and water content values from the on-the-ground snow courses, will be used to determine the total amount of precipitation in the Watershed. Cline is a student at CU-Boulder, and has submitted a Dissertation Improvement Proposal to NSF to augment NPS GC research funds.

Eleven undergraduate students from a CSU Natural Resource Conservation class assisted with field work during the fall, 1992. The students assisted with many parts of the project, including installing snow courses and ground control markers, collecting monthly lake and stream water quality samples, and sampling soil moisture and depth.

METHODS, QUALITY ASSURANCE AND DATA MANAGEMENT

Meteorology

In the Loch Vale Watershed, measurements of meteorological parameters, chemical deposition parameters, stream and lake water chemical composition, and stream discharge have been collected continuously since 1983. Meteorological data are collected with a Remote Area Weather Station (RAWS) centrally located in LVWS. This solar-powered station has instruments that measure wind speed, wind direction, relative humidity, barometric pressure, solar radiation, air temperature, and precipitation amount. Data are gathered every 15 minutes by a Handar 524 data collection platform (DCP), and relayed hourly to the National Oceanographic and Atmospheric Administration ground station at Wallops Island, Virginia by the GOES West satellite. This information is transmitted up to DOMSAT, a commercial communications satellite, and received (DRS) at the Denver Federal Center. Proper functioning of the DCP and sensors are periodically checked by an electronics technician. A source of RAWS replacement equipment was located this year through Phil Seiloff of the Bureau of Land Management in Boise, ID.

Precipitation

Loch Vale Watershed participates in the National Atmospheric Deposition Program, a nationwide network of precipitation monitoring sites. Loch Vale (CO98), the Loch Vale Watershed site, is co-located with the meteorological station. Wet deposition samples are collected from an Aerochemetrics wet/dry deposition sampler each Tuesday according to NADP sampling protocol (Bigelow and Dossett 1988). Field specific conductance and pH are determined by Loch Vale field personnel at the Water Laboratory in Rocky Mountain National Park or at the Natural Resource Ecology Laboratory in Fort Collins.

Major ions in all NADP wet deposition samples are determined by the Central Analytical Laboratory of the Illinois State Water Survey according to methods described in Peden (1986). Quality Assurance reports from the Central Analytical Laboratory (Aubertin et al. 1990), address network-wide and site-specific quality assurance goals (e.g. James 1991). In addition, Loch Vale field personnel conduct their own quality control exercises when measuring field pH and specific conductance. Loch Vale field analyses have always met NADP Quality Assurance criteria.

A low percentage of dry snow that falls under windy conditions is captured by the Aerochemetrics collector, so there is a discrepancy between what is caught by the collector and what is recorded by the Belfort precipitation gage. However, we assume snow chemistry from the collector to be representative of the total snow that falls. The underestimate in catch from Belfort rain gages has been estimated to be 60%, and this value is used to bracket the uncertainty in flux calculations (Goodison et al. 1978, Baron and Denning 1992).

Surface Water Chemistry

During water year 1992, samples were collected weekly at The Loch outlet, monthly during the summer from inlets and outlets of Sky Pond and the Loch as well as additional sites throughout LVWS, and every other month during the winter from two depths in Sky Pond and the Loch. Temperature is measured on site with either a hand-held thermometer or a YSI temperature probe. Samples for inorganic chemical analyses are filtered through 0.4 Nucleopore filters into acid-washed 250 mL LDPE plastic bottles within 5 hours of collection. Inorganic analyses are run at the US Geological Survey Central Laboratory in Denver according to methods of Fishman and Friedman (1985). In general,

anions are determined by ion chromatography, and cations by ICP. Samples for dissolved organic carbon (DOC) are filtered through pre-combusted glass-fiber filters into 100 mL precombusted borosilicate glass bottles within 5 hours of collection. Dissolved organic carbon is analyzed by the US Geological Survey Laboratory using a Dohrmann Organic Carbon Analyzer. Quality assurance estimates of surface water chemistry show that, in general, water quality QA goals are being met (Denning 1988, Edwards 1991).

Hydrology

Surface water flow is gaged in Icy Brook, just below the outlet of The Loch. A Parshall Flume with a stilling well was installed in 1983. Stage height data are collected both electronically (Omnidata stage height recorder) and mechanically (Leupold and Stevens strip chart recorder) when there is measurable flow through the flume, typically May through October. Field verification of the recorded gage heights occur weekly. Annually, data are adjusted by comparing the electronic, chart and field data. Data are converted to flow with a rating formula provided by the Thompson Pipe and Steel Company. Discharge is estimated for the period when there is insufficient flow to gage, based on the last and first recorded discharge values and an estimate of the percent flow decrease during the mid-winter minimum.

Data Management

All Loch Vale Watershed data reside at the Natural Resource Ecology Laboratory Colorado State University. Data are stored in a relational data base, INGRES (Relational Technology 1986), on Sun workstations. As part of normal procedures, all new data are backed up weekly and stored on tape; system level dumps and backups occur monthly. Data reduction programs are written in Fortran or in C; these programs, as well as all field

and laboratory procedures are maintained and updated in the Loch Vale Watershed Methods Manual (in prep.). Data management activities are concentrated in three major areas: day-to-day management of data, streamlining data collection and reporting, and restructuring in-house data quality assurance methodology. These activities were given a great boost this year with the addition of Brian Newkirk, half-time data manager, to the staff of the LVWS project.

Analytical results from surface water samples are posted by the National Water Quality Laboratory to the National Water Information System (NWIS) computer located at the Denver Federal Center in Lakewood, CO. The Loch Vale water chemistry data base is periodically updated from the NWIS. Loch Vale meteorological data are updated weekly and entered into our INGRES database. Other day-to-day data management activities include preparing data files for model runs, associated analysis of simulation outputs, and filling data and training requests that arise from both inside NREL and from outside agencies.

One of the main data management activities is to streamline data collection and reporting. Historically, we received data via a modem link from the host site, a time consuming process. Advances in networking availability have allowed us to increase data collection efficiency. Internet access is used now to retrieve all data.

We are currently developing a water chemistry data quality assurance system that will allow automatic sample tracking, determine if water chemistry re-analysis is required, and flag questionable sample data. Previously, data quality was assessed periodically on a case-by-case basis; the new system will provide more timely and consistant quality control.

FINDINGS

A detailed review and discussion of research conducted in LVWS through 1988 is presented in Baron (1992). Presented here are some general results related to the basic questions listed earlier. Average annual precipitation is not acidified, although individual events may exhibit significant anthropogenic inputs. There is a large difference in precipitation amount and concentrations between LVWS and a close (~15km) but lower (672m difference in elevation) site at Beaver Meadows. Loch Vale is less likely to be influenced by anthropogenic inputs from the Front Range urban area than the lower elevation Beaver Meadows site. Loch Vale soils have a limited ability to buffer increased amounts of acidity from deposition (Walthall 1985). The influence of soil processes on surface water composition is restricted to a short period at the beginning of snowmelt. The major source of ANC appears to come from microcalcite veins in the bedrock, which are exposed to weathering through physical breakdown of primary minerals by freeze-thaw, avalanches, and debris flows (Mast et al. 1990). Hydrologic processes exhibit the major influence on surface waters, with concentrations increasing with decreasing winter flow, and decreasing with snowmelt after the early flush of materials from soil solution.

The annual chemical budgets through 1991 are presented in Table 2. Chemical data are not yet complete for water year 1992. Outputs are not available for 1989 due to quality control problems with the analytical laboratory results. Water year 1992 had both the lowest total precipitation (5.42×10^6 m^3) and the smallest Loch outlet discharge (3.89×10^6 m^3) since measurements began in 1984 (see also Figures 4,9). These are measured inputs and outputs only, not taking into account snow blowing in near the ridge tops and losses due to evaporation. Due to the location of the single precipitation

collector and the physical processes dictating collection efficiency, it is likely that the inputs represent an underestimate of actual values. The solute budgets show a net consumption of NH_4, H, and to a lesser degree, NO_3, which is balanced by a net production of base cations. The Front Range exhibits the highest nitrate deposition of all Colorado locations, and high NO_3 concentrations are present throughout LVWS surface waters. Cl appears conservative, with long term outputs balancing inputs. More SO_4 is exported from LVWS than enters via wet deposition, and sulfur isotope analyses conducted by John Turk suggested a mineral source for some sulfur. Rocks containing pyrite were found in the summer of 1991, confirming the presence of sulfur-bearing minerals. Alkalinity and SiO_2 are not measured in the inputs.

Barometric pressure, solar radiation, temperature, and wind speed and direction exhibit clear seasonal trends (Figures 5-9). In the summer, the average barometric pressure is high, and the range of pressure is small (Figure 5). Mid-winter spikes of higher pressure are associated with higher temperatures. The monthly solar radiation data appear to show lower December values than would be expected just from the seasonal change in extraterrestrial solar radiation (Figure 6). This is probably due both to an increase in cloudiness (formation of a "divide cloud"), and to the fact that the angle of the sun becomes low enough that it stays below the canyon walls for most of the day. The missing radiation data from the beginning of 1992 occurred because the sensor was being re-calibrated by the manufacturer. The daily variation in radiation is due to cloudiness, and shows that the most consistant clear weather occurred in the fall. Seasonal trends in temperature exhibit the greatest difference in maximum and minimum temperatures in the summer (Figure 7). Typically, summer nights are clear and allow

rapid radiative cooling in Loch Vale, thus reducing daily temperature minima. Regressions of yearly seasonal temperatures show no long-term trends except perhaps for summer maxima (slope = -.02, r^2 = .10). However, this is driven primarily the high temperatures in the first year of record. Wind speeds can be greater than eight m/sec any time of the year, but generally are higher in winter when there is strong westerly flow in the upper troposphere (Figures 8). The wind in Loch Vale is constrained by the canyon walls primarily to two directions, northeast or southwest, with the dominant winds in the latter direction. Thus the monthly average wind direction is an indicator of the amount of upslope (northeasterly) wind, with a lower value indicative of upslope events. This variable does not show as strong a seasonality as the wind speed data, though generally is lower in the summer. The precipitation record is not strongly seasonal (Figure 9). Commonly there are large precipitation events in the spring, and 1992 was no exception. A more detailed analysis of the weather record in Loch Vale will be prepared for the next annual report.

CONTINUING RESEARCH

Loch Vale Watershed is beginning its tenth year of continuous monitoring of precipitation, hydrologic, and surface water parameters. We had originally planned to reduce our level of field activity after the 1990 NAPAP Final Assessment. Instead, the data record and interesting features of LVWS have made it a focal point of new research, and both field activity and research funding in 1991 are greater than ever before. The LVWS is recognized as a long-term research location in the Rocky Mountain National Park Natural Resource Management Plan. The second annual Rocky Mountain National Park Loch Vale Watershed/Water,Energy, and Biogeochemical Budgets/Global Change Research Meeting was held in the park in April 1992, with over 50 scientists and managers in attendance.

Loch Vale Watershed and its data base remain available to investigators who build upon the existing information in order to enhance our overall knowledge of alpine and subalpine ecosystems. Several master's level students from Colorado State University are continuing their research in LVWS this year because of existing information. The U.S. Geological Survey's Water, Energy, and Biogeochemical Budgets (WEBB) program was funded for LVWS because of past scientific activities. The WEBB program, which will run for 5 years, initiated an intensive investigation of hydrologic pathways and local and eolian sources of minerals in 1991. Three additional weather stations, a new flume, stream sequential samplers, and a number of groundwater wells and piezometers were installed in 1991 and 1992 as part of WEBB. Sampling of these stations began in 1992.

Loch Vale Watershed has become the foundation of the NPS Colorado Rockies Global Change (COLR GCC) program. This program will continue to increase

understanding of alpine and subalpine processes by addressing them within the context of global change. The COLR GCC program is designed within a conceptual and simulation model framework to build predictive capability on several regional and local scales of the meteorological, hydrologic, aquatic and terrestrial ecological responses to global change (Figure 26). A series of models were parameterized for LVWS in 1992 to address weather across the landscape (MT-CLIM), vegetation nutrient cycling and water fluxes (CENTURY and FOREST-BGC), and hydrology (TOPMODEL). These will be linked together in 1993 to run on each LVWS landscape unit using the RHESSys model structure (Band et al. in press).

On a regional and LVWS scale, RAMS, the Colorado State University Regional Atmospheric Modeling System will be parameterized for LVWS and run under GCM (Global Climate Model) outputs of double atmospheric CO_2. RAMS model output will be compared to existing MM4 (the Pennsylvania State University Mesoscale Model version 4) model outputs for the Colorado Rockies. Both MM4 and RAMS will be used to bracket possible changes in temperature, precipitation seasonality and amount, storm tracks and storm intensity.

The work on remote-sensing of snow volume (noted in Present Program section) will provide spatial and temporal data that will be used a number of ways: as a test for scaling to larger drainage basins, as a means of validating the results of energy-based snowmelt models, and as input to TOPMODEL for simulating hydrologic processes.

MEETINGS AND PRESENTATIONS

National Research Council Planning Session: Interdisciplinary research and education in the study of inland waters. Jan 1992. Washington, D.C. Baron was an invited participant.

National Park Service/Ecological Society of America Sustainable Biosphere Program Workshop. February 1992, Albuquerque, NM. Baron was an invited participant.

American Society for Limnology and Oceanography Annual Meeting, Feb 1992. Santa Fe, NM. Jennifer Back presented a poster: Stable isotopes as tracers of hydrologic inputs to alpine lakes.

American Society for Limnology and Oceanography Annual Meeting, Feb 1992. Santa Fe, NM. Michael Martin presented a paper: Spatial and temporal variation of nitrate and ammonium in an alpine watershed. Co-author was J. Baron.

American Society for Limnology and Oceanography Annual Meeting, Feb 1992. Santa Fe, NM. Baron presented a paper: Annual and seasonal nitrogen budgets to high elevation Sky Pond, Loch Vale Watershed, Colorado. Co-authors were Mike Martin and Rob Edwards.

Range Science Seminar, March 10, Colorado State University. Baron presented summary of nitrogen budgets in Loch Vale Watershed.

LVWS/WEBB/COLR Second Annual Meeting, March 24-25. Estes Park, CO. All project members attended, including Baron, Edwards, Back, Martin, Cline, Newkirk, Zuur. Presentations were given by Jill Baron, Rob Edwards, Jennifer Back, Mike Martin.

Institute for Arctic and Alpine Research Seminar, March 1992, University of Colorado, Boulder. Baron presented a summary of nitrogen budgets in Loch Vale Watershed.

Watershed Studies CPSU Annual Meeting, April 14-16, Fort Collins, CO. Baron and Edwards attended, presented brief summary of planned research.

INGRES Relational Data Base Training, April 21-23, Denver CO. Baron, Edwards, Newkirk, and Back attended.

Agricultural Engineering Seminar, May 8, 1992, Colorado State University. Baron presented summary of Loch Vale Watershed research.

National Atmospheric Deposition Program Training Session, Central Analytical Laboratory, June 16-17, 1992. Champaign, IL. Jennifer Back attended training.

Upward Bound High School Student Training, June 29, 1992, Colorado State University. Baron presented introduction to acid deposition and effects.

Ecological Society of America Annual Meeting Aug, 1992. Honolulu, HI. Baron presented a paper: Validation of a mountain meteorological model for high elevation ecolo gical research. Co-authors include Steve Running, Tim Seasdedt, and Brian Newkirk.

Rocky Mountain Hydrologic Research Center, 47th Annual Meeting. "Emerging Issues in Water and Environmental Sciences", Aug, 1992, Allenspark, CO. Jennifer Back and Rob Edwards attended, and Back presented paper: Stable isotopes as tracers of hydrologic inputs to alpine lakes.

First Annual Niwot Ridge Long-Term Ecological Research All-Scientists Meeting, August 1992, Ward, Colorado. Baron presented the poster developed for the ESA . meeting: Validation of a mountain meteorological model for high elevation Co-authors included Steve Running, Tim Seastedt, and Brian Newkirk.

First Annual Niwot Ridge Long-Term Ecological Research All-Scientists Meeting, August 1992, Ward, Colorado. Edwards and Baron presented a poster summarizing mass fluxes from Loch Vale Watershed.

Environmental Conservation, Natural Resources 120 class. October 19, 1992. Colorado State University. Baron presented overview of LVWS research to students who were interns with the project.

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Arthur, M.A. and T.J. Fahey. 1989. Mass and nutrient content of decaying boles in an Englemann spruce - subalpine fir forest, Rocky Mountain National Park. Can. J. For. Res. 20:730-737.

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Table 1. Comparison of Western Lake Survey population statistics with The Loch. All data are from Landers et al. (1986) except WA:LA for the Loch. The WLS reports a WA:LA of 650 for the Loch. The Loch was sampled as a special interest lake on 10/10/85. WA:LA denotes the ratio of watershed area to lake area.

	West (n=719)	Southern Rockies (n=132)	Front Range (n=51)	The Loch (n=1)
pH	7.16	7.60	-	6.55
Ca (µeq L^{-1})	92.4	233.1	222.6	68.3
Mg (µeq L^{-1})	26.4	91.5	91.6	16.9
Na (µeq L^{-1})	23.9	33.8	33.1	21.8
K (µeq L^{-1})	5.6	9.0	5.2	3.3
NH_4 (µeq L^{-1})	0.0	0.0	-	0.0
Cl (µeq L^{-1})	4.1	4.2	3.6	4.3
SO_4 (µeq L^{-1})	18.9	34.6	35.2	30.4
NO_3 (µeq L^{-1})	0.4	0.5	-	15.2
ANC (µeq L^{-1})	119.4	317.0	337.5	48.9
Total P (µg L^{-1})	4.7	8.1	-	9.5
SiO_2 (mg L^{-1})	2.21	2.12	2.3	1.77
Fe (µg L^{-1})	13.7	17.8	42.5	18.0
DOC (mg L^{-1})	1.21	1.48	1.51	0.87
Conductance (µS cm^{-1})	16.5	37.1	37.5	12.6
Site Depth (m)	7.8	5.1	6.7	2.4
Lake Area (ha)	4.6	3.5	3.7	5.0
WA:LA	23.7	23.5	23.8	132
Secchi Disk Transparency (m)	4.8	3.4	2.4	2.4

Table 2. Measured annual fluxes of major ions through Loch Vale watershed. 1984-1987 are water years beginning Nov. 15, 1988-1991 are water years beginning Oct. 1.

Year		Parameters (Kg)											
		H	Alk[a]	Ca	Mg	Na	K	NH_4	NO_3	SO_4	Cl	SiO_2	H_2O[b]
1984	Input	90	-	1060	220	380	140	900	4790	5010	630	-	7.33
	Output	2.3	12850	6580	1140	2410	930	280	6190	7500	660	9230	5.81
	Ratio (Out/In)	.03	-	6.2	5.2	6.4	6.8	.31	1.3	1.5	1.0	-	.79
1985	Input	90	-	1620	290	580	260	790	5180	5380	790	-	6.57
	Output	2.0	8380	5270	790	1640	670	60	4300	5950	497	6540	4.28
	Ratio (Out/In)	.02	-	3.3	2.7	2.8	2.6	.08	.83	1.1	.6	-	.65
1986	Input	90	-	1510	250	520	200	1010	6260	6150	680	-	7.75
	Output	3.9	11820	6250	1060	1990	950	50	5450	7930	645	9050	6.06
	Ratio (Out/In)	.04	-	4.1	4.2	3.8	4.7	.05	.9	1.3	.9	-	.78
1987	Input	70	-	550	90	450	80	570	3280	2770	380	-	5.70
	Output	1.6	10510	5170	890	1910	850	60	4300	6400	570	7740	4.70
	Ratio (Out/In)	.02	-	9.4	10.4	4.2	10.7	.10	1.3	2.3	1.5	-	.82
1988	Input	69	-	726	85.8	343.2	79.2	330	3234	3102	396	-	6.00
	Output	2.6	11030	5580	874	1940	712	43.3	4120	6760	613	7560	4.67
	Ratio (Out/In)	.04	-	7.7	10.2	5.7	9.0	0.13	1.3	2.2	1.5	-	.78
1989	Input	76	-	990	125.4	495	72.6	792	3894	3432	396	-	5.47
	Output	-	-	-	-	-	-	-	-	-	-	-	4.31
	Ratio (Out/In)	-	-	-	-	-	-	-	-	-	-	-	.79

Year		Parameters (Kg)											
		H	Alk[a]	Ca	Mg	Na	K	NH_4	NO_3	SO_4	Cl	SiO_2	H_2O[b]
1990	Input	60	-	1452	198	462	118.8	990	5610	3960	660	-	7.57
	Output	3.4	10085	6417	1006	2534	804.6	113.9	5946	7720	725.1	8196	4.93
	Ratio (Out/In)	.06	-	4.4	5.1	5.5	6.8	0.12	1.1	1.9	1.1	-	.65
1991	Input	67	-	1031	127	413	136	851	4928	3529	569	-	6.44
	Output	2.5	10858	6365	841	2094	660	68.9	4412	6284	670	6799	4.75
	Ratio (Out/In)	.04	-	6.2	6.6	5.1	4.9	.08	.9	1.8	1.2	.73	.74
1992	Input	-	-	-	-	-	-	-	-	-	-	-	5.42
	Output	-	-	-	-	-	-	-	-	-	-	-	3.89
	Ratio (Out/In)	-	-	-	-	-	-	-	-	-	-	-	.72

a : alkalinity as $^-HCO_3$
b : unit for water (H_2O) is 1×10^6 m^3
- : data are not available

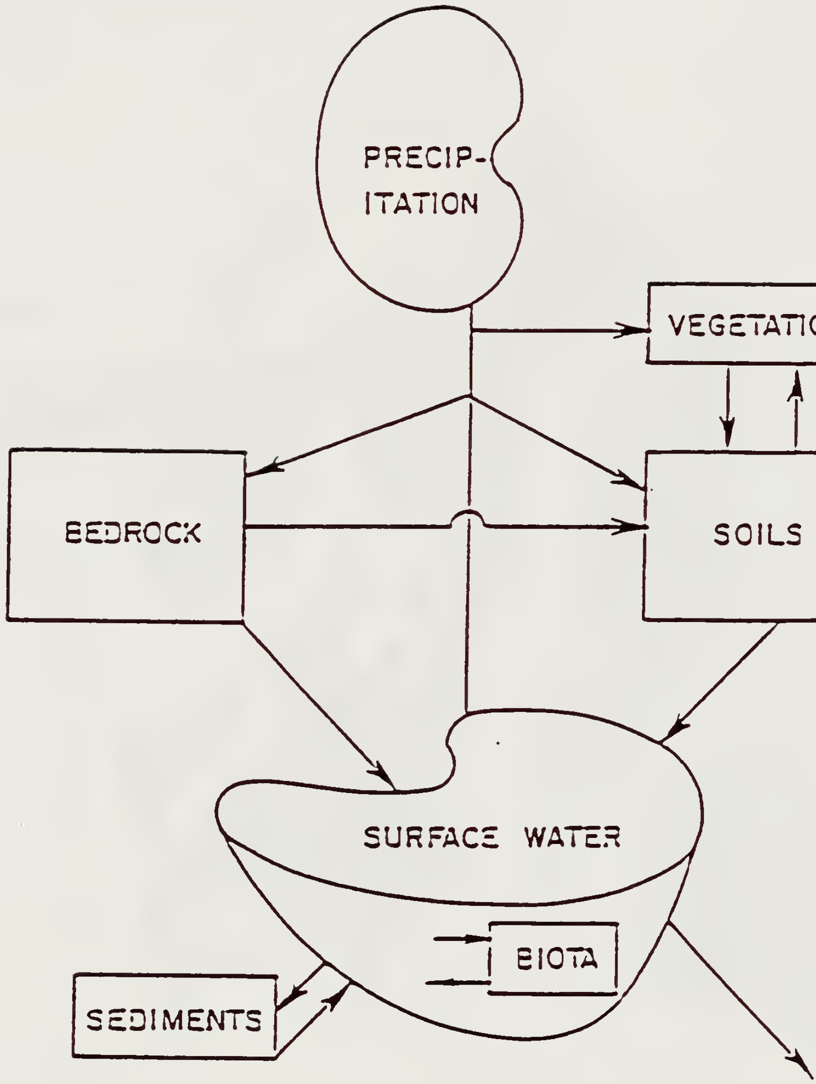

Figure 1. Conceptual model of components and fluxes of Loch Vale Watershed.

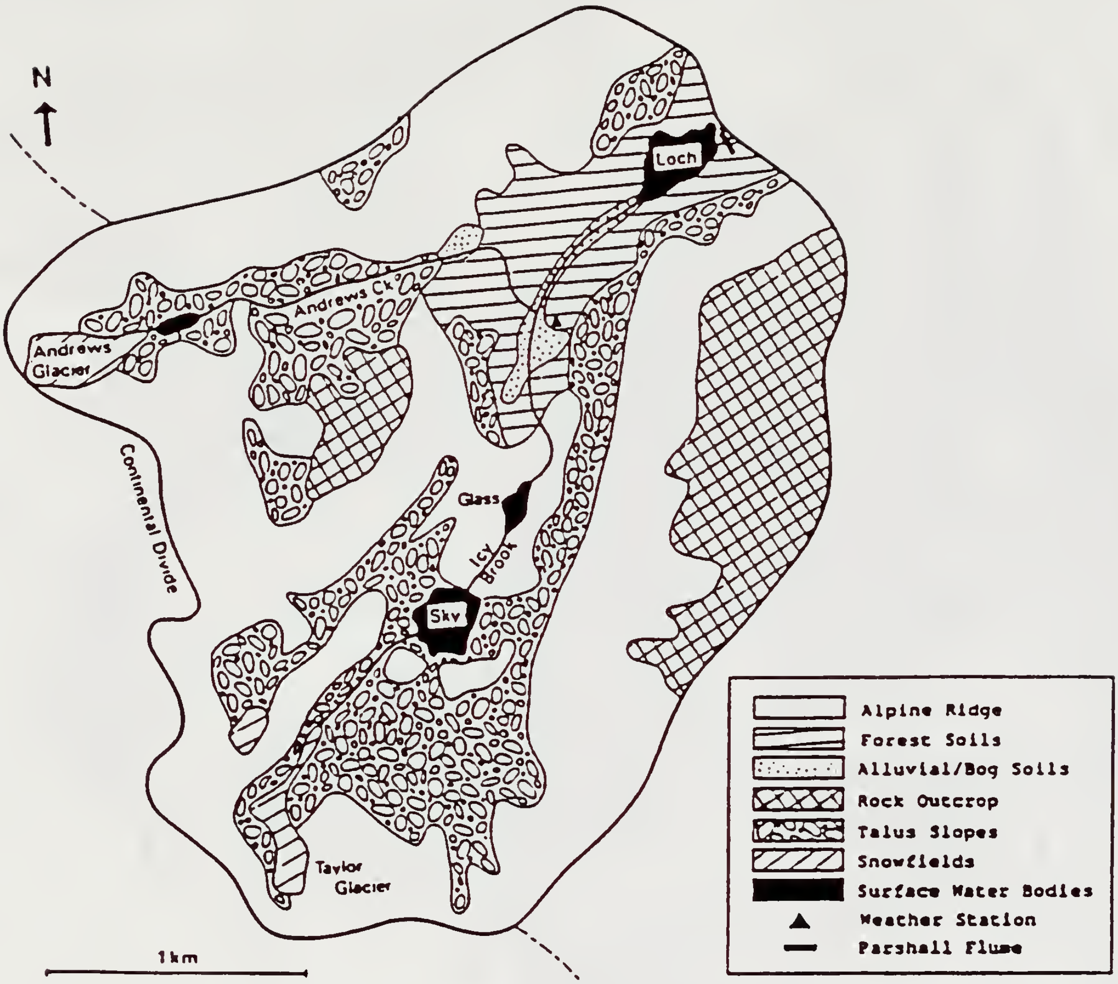

Figure 2. Surface features of Loch Vale Watershed, showing spatial relationship of surface waters.

Figure 3. Topographic map with vertical contours (interval = 40 feet), showing Loch Vale Watershed (USGS 7.5′ quad, McHenry's Peak, Colo.).

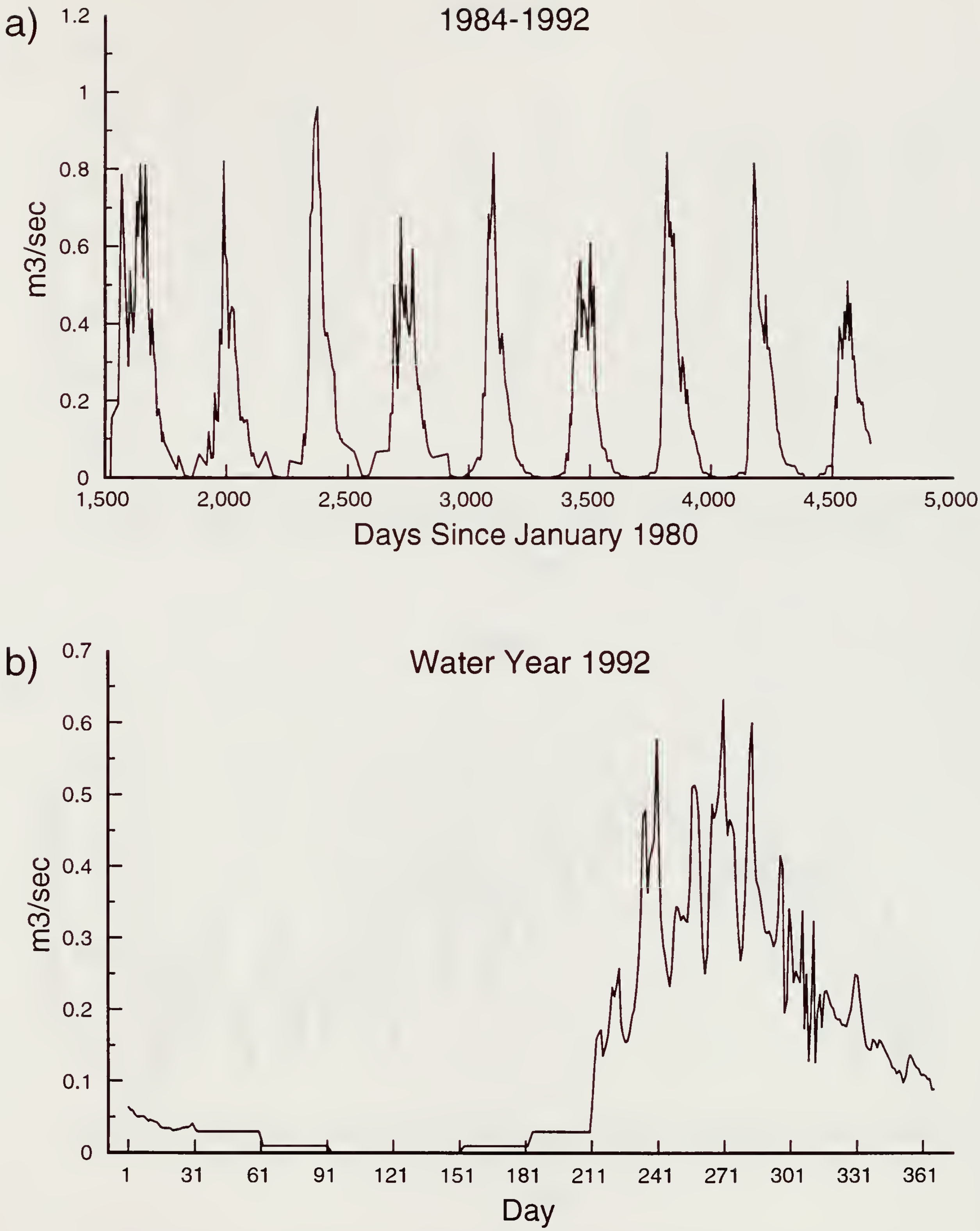

Figure 4. Loch Outlet Discharge. a) Average weekly discharge. b) Average daily discharge.

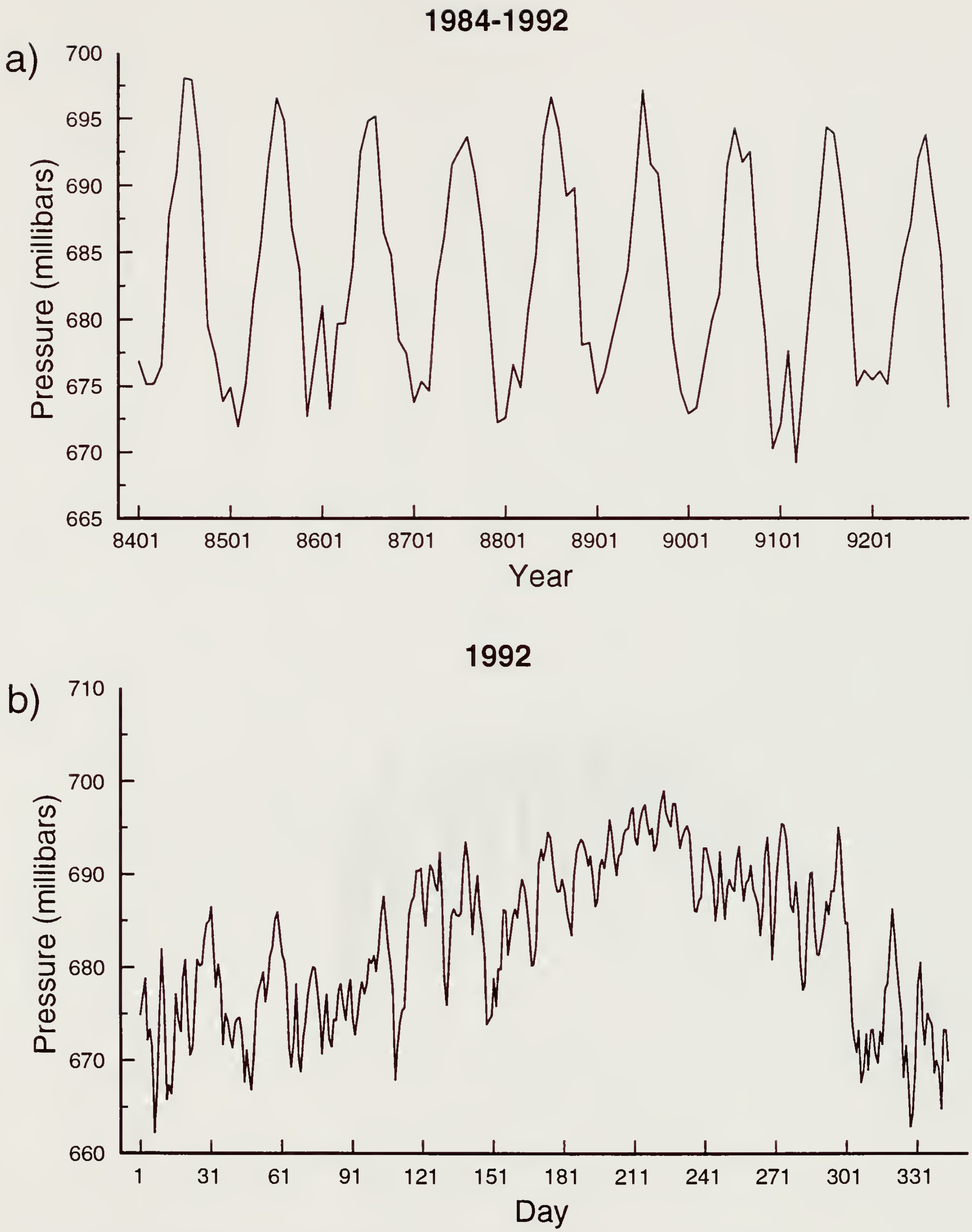

Figure 5. Barometric Pressure at LVWS Weather Station.
a) Average monthly pressure. b) Average daily pressure.

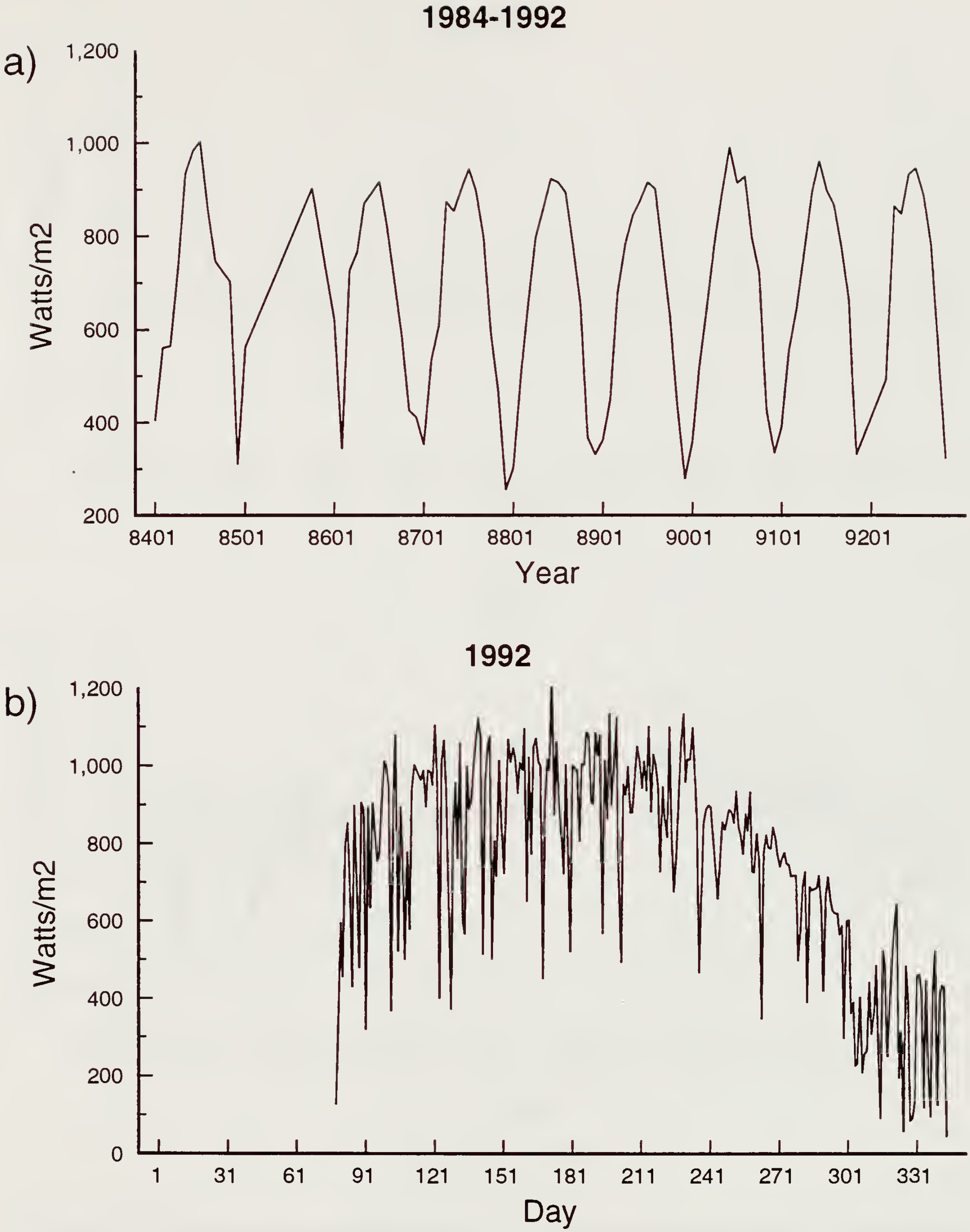

Figure 6. Solar Radiation at LVWS Weather Station.
a) Average monthly maximum solar radiation. b) Daily maximum solar radiation.

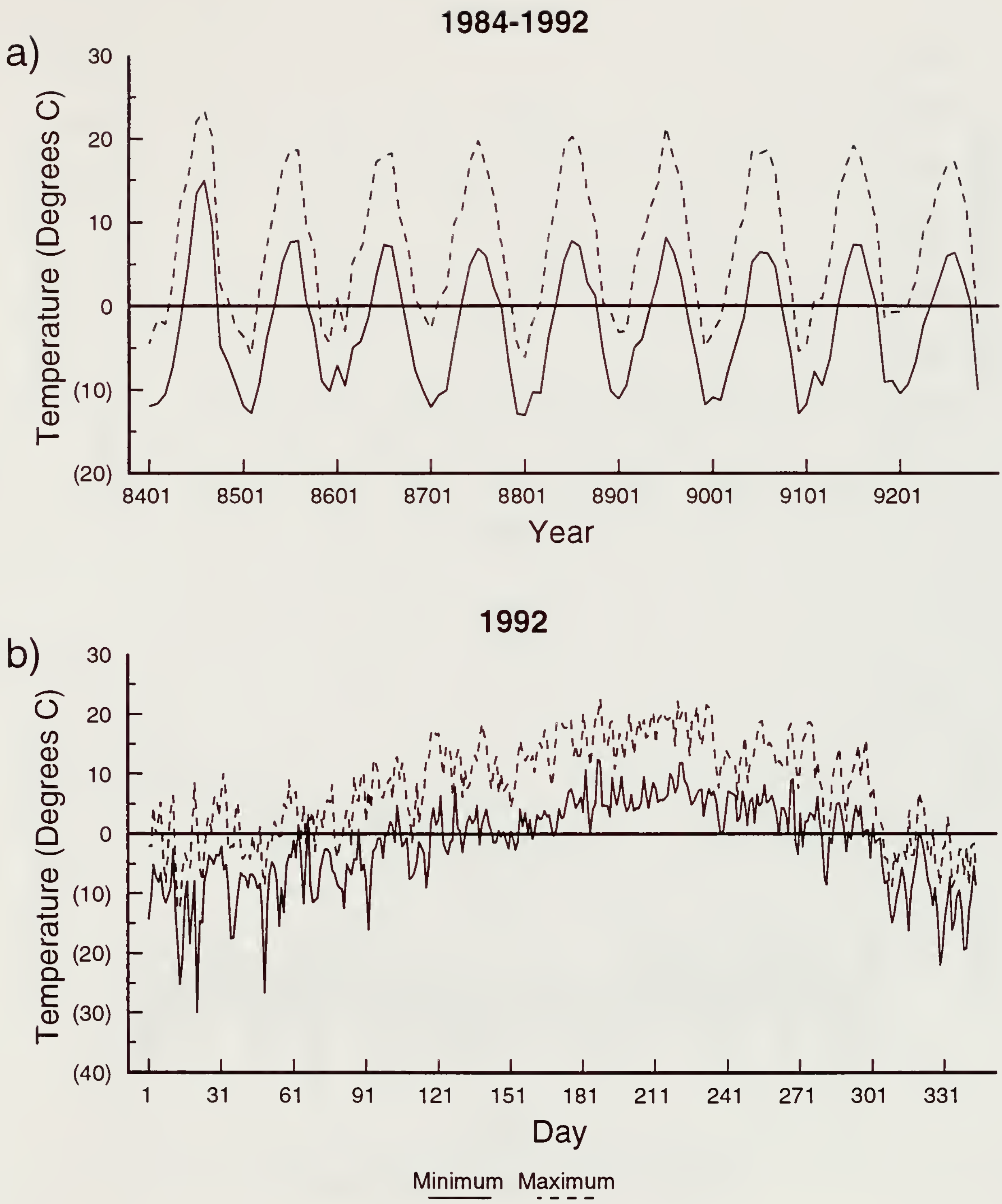

Figure 7. Minimum and Maximum Temperature at LVWS Weather Station. a) Average monthly minimum and maximum temperature. b) Daily minimum and maximum temperature.

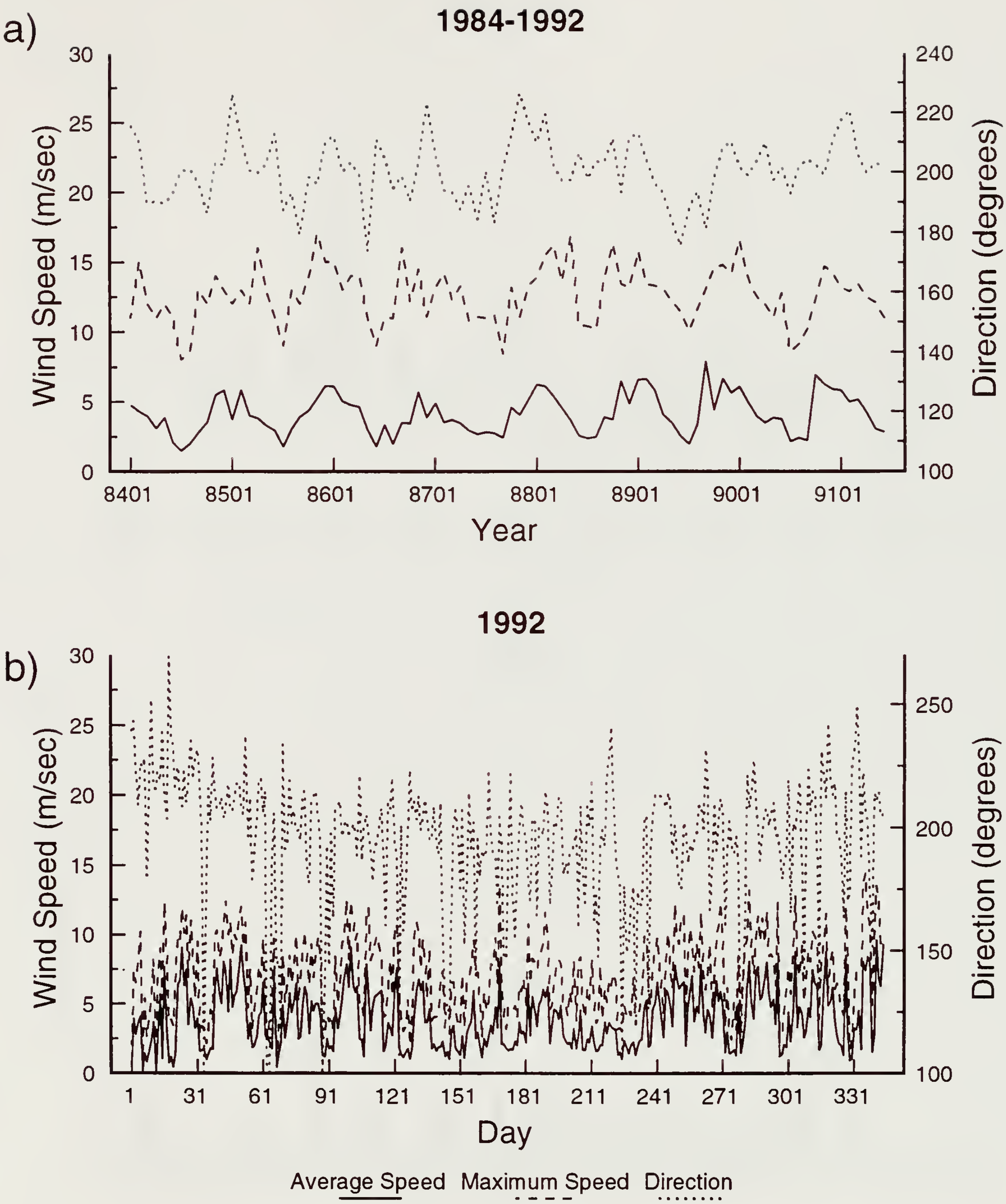

Figure 8. Wind Speed and Direction at LVWS Weather Station. a) Average monthly wind speed and direction. b) Average daily wind speed and direction.

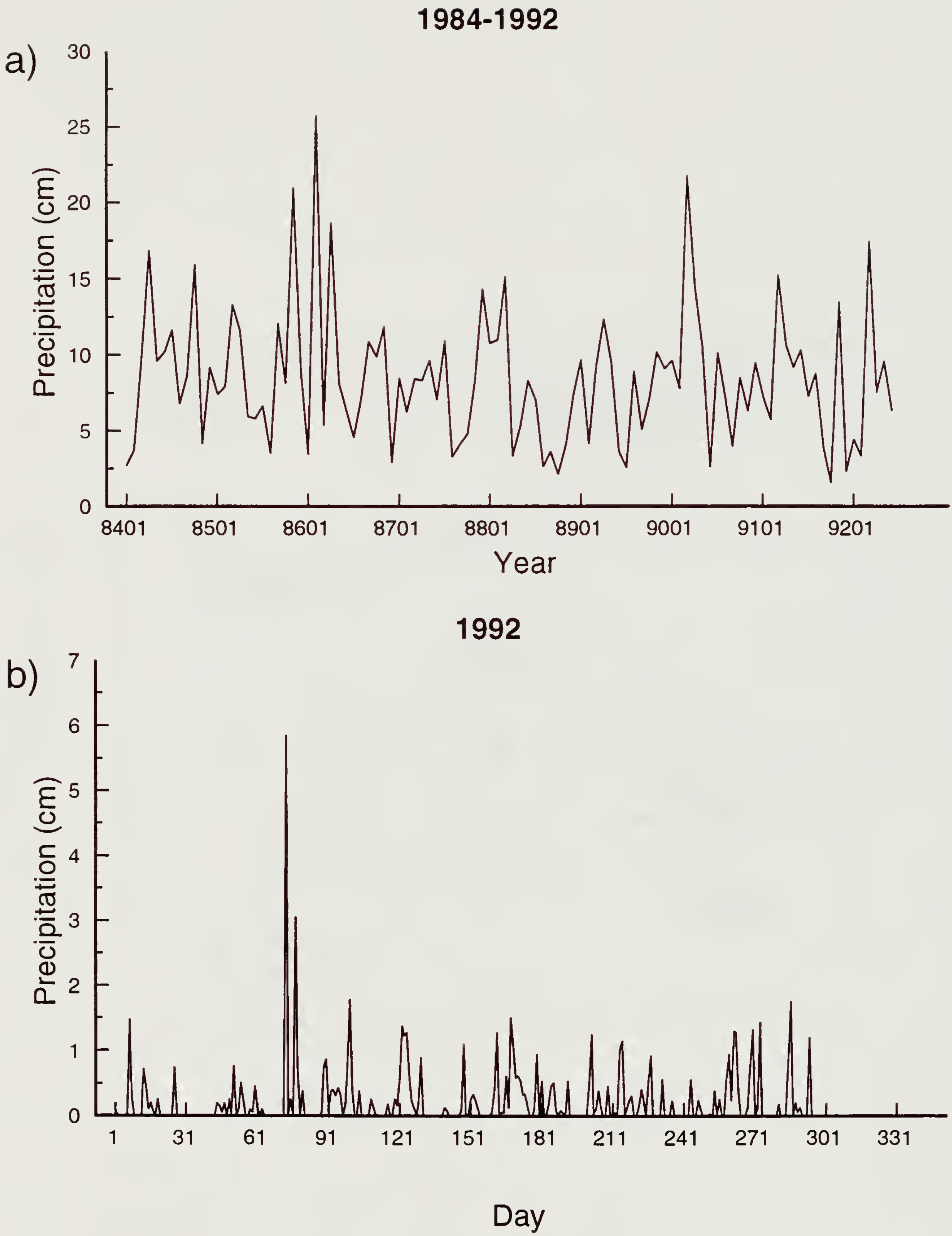

Figure 9. Precipitation at LVWS Weather Station.

a) Total monthly precipitation. b) Total daily precipitation.

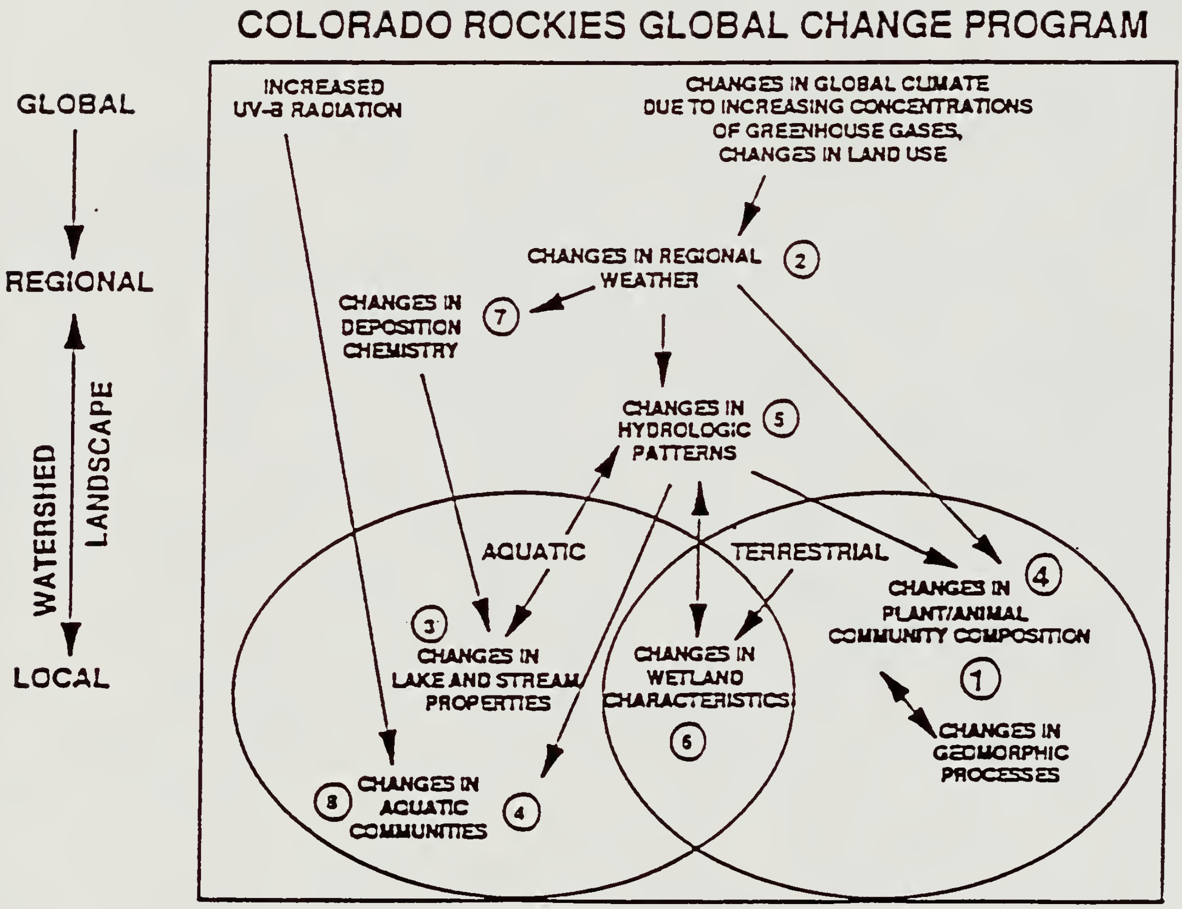

Figure 10. Conceptual research model for the Colorado Rockies Global Change Program (COLR GC).