PLANNING DOCUMENT OF WATER, ENERGY, AND BIOGEOCHEMICAL-BUDGET (WEBB) RESEARCH PROJECT, LOCH VALE WATERSHED, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

by John T. Turk, Norman E. Spahr, and Donald H. Campbell

U.S. GEOLOGICAL SURVEY

Open-File Report 92-628

Denver, Colorado
1993

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary
U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center
Box 25425
Denver, CO 80225-0425

CONTENTS

FIGURE

TABLES

CONVERSION FACTORS

Multiply	*By*	*To obtain*
centimeter (cm)	0.3937	inch
centimeter per year (cm/yr)	0.3937	inch per year
cubic meter per second (m^3/s)	35.32	cubic foot per second
hectare (ha)	0.003861	acre
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per second (m/s)	3.281	foot per second
square kilometer (km^2)	0.3861	square mile

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5\ (°C) + 32.$$

PLANNING DOCUMENT OF WATER, ENERGY, AND BIOGEOCHEMICAL-BUDGET (WEBB) REASEARCH PROJECT, LOCH VALE WATERSHED, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

By John T. Turk, Norman E. Spahr, and Donald H. Campbell

ABSTRACT

The interaction of climate change with water, energy, and biogeochemical budgets will be most profound in watersheds having biotic communities at the limit of their tolerance to climatic conditions. One such class of watershed is the alpine/subalpine/montane watersheds typical of the Rocky Mountains. Minor shifts in climate can markedly alter boundaries of community structure that define transitions in the processes controlling watershed function. Because such transitions are especially well defined in these watersheds, and because such watersheds are widespread throughout the Rocky Mountains and other great mountain ranges worldwide, these transitions and watersheds are a critical element in understanding the most immediate effects of climate change on watershed processes and the feedback of watershed processes to climate change.

This report describes a plan of study for three research topics in which there is a critical lack of understanding of watershed processes in the alpine/subalpine/montane watersheds of the Rocky Mountains:

(1) Processes controlling weathering and biogeochemical budgets.
(2) Processes controlling the energy balance and chemistry of snowpacks.
(3) Processes controlling the flow path and flux of water.

Lack of understanding of weathering and biogeochemical budgets seriously affects calculation of the carbon dioxide budget. The quantity of atmospheric carbon dioxide converted to the bicarbonate that is measured as transported from a watershed is twice the quantity if feldspar weathering rather than carbonate weathering is the controlling process. The common assumption is that feldspar weathering is the controlling process because feldspars are the most common, weatherable mineral in the granitic bedrock of the Rocky Mountains; however, recent (1989) work indicates that carbonate weathering might be the controlling process. The effect of climate change on chemical weathering also depends on which of these is the controlling process. Stable strontium isotopes, as a tracer of the minerals being weathered, will be used to determine the controlling process. Confirmation of these results, using stable and radioactive carbon isotopes, also is proposed.

Lack of understanding of the energy balance and chemistry of snowpacks affects ability to predict runoff generation, the chemistry of runoff, and sediment transport and storage in response to climate change. The ability to determine the effect of changing albedo, from changing snowmelt characteristics, on climate also is affected. The study will evaluate in detail the metamorphosis of Rocky Mountain snowpacks, which are colder than most of the better studied snowpacks, and will include modeling of the interaction of energy, snowpack accumulation and melt, and runoff generation. This modeling will include the water and solutes that are transported through the watershed.

Lack of understanding of the flow path and flux of water within the watershed affects the ability to predict which geologic materials and biotic processes will have an opportunity to alter water flow and composition as it moves through the watershed. Under changing climatic conditions, processes that are important now, such as infiltration of unfrozen soil by snowmelt, might not occur at all. Such processes also affect climate by affecting evapotranspiration and other feedbacks to climate. The study will evaluate in detail the flow paths and relative quantities of water in various important landforms within the study watersheds and model the interaction of common climatic variables with the routing of water along selected flow paths.

It is clear that the processes controlling weathering and biogeochemical budgets, energy balance and chemistry of snowpacks, and the flow path and flux of water are closely related. Each requires a particular professional expertise at the level of data collection and interpretation, yet the integrated relations among these topics requires careful coordination and program design. The team approach in this study is the best method to provide the detailed expertise and the experienced program management necessary to achieve the program objectives.

The Loch Vale watershed is tributary to the South Platte River, one of the first 20 National Water-Quality Assessment (NAWQA) Program study units. Thus, the coincident study of the headwater Loch Vale watershed and larger South Platte River drainages provides a valuable opportunity to investigate the transferability of process-level research from intensive research sites to regionally important watersheds. Additionally, basin and chemical characteristics of the Loch Vale watershed are similar to alpine and subalpine watersheds throughout the Rocky Mountains; thus, it is possible to include more than about 50,000 km^2 of other such watersheds. Such transfer of results to other alpine and subalpine watersheds might be of even greater immediate use than transfer of results into the South Platte River.

The greatest potential for extrapolation of small-scale research results to larger areas exists for areas that are geographically extensive and little changed in land use from pre-Columbian time. Change in land use is largely a function of access, so areas not markedly changed tend to be dominated by physical barriers to roads and settlement. The alpine and subalpine of the Rocky Mountains are the most extensive and the least altered ecoregions in the Nation, and processes that affect such watersheds are likely to be transferable among research and nonresearch sites.

INTRODUCTION

Understanding and predicting global change has become one of the major scientific challenges of the late 20th century. Concern about potential climatic change has mobilized scientists from many disciplines and nations around the world in an effort to improve the ability to model the climate system and to predict its future patterns. For the past three decades, atmospheric scientists have made substantial progress in developing models that account for most of the important components of the climate system. Significant progress is needed, however, in areas such as cloud dynamics and the processes associated with the exchanges of water, energy, and carbon between the land surface (including vegetation) and the atmosphere. Progress in this latter area requires the knowledge and skills of specialists in fields such as hydrology, ecology, geology, and geochemistry, as well as the atmospheric sciences.

To strengthen terrestrial process research, especially that associated with the interactions of water, energy, gases, nutrients, and vegetation, the U.S. Geological Survey, as part of its Global Change Research Program, began an intensive study of Water, Energy, and Biogeochemical Budgets (WEBB). The purpose of WEBB is twofold: to improve understanding of processes controlling terrestrial water, energy, and biogeochemical fluxes, their interactions, and their relations to climatic variables; and to improve the capability to predict continental water, energy, and biogeochemical budgets for a range of spatial and temporal scales.

WEBB process studies are being implemented as a systematic program of intensive, long-term field investigations. Study sites are selected on the basis of geographical and environmental diversity. Sites where data collection or WEBB-related process investigations or both are already underway, especially such established, multidisciplinary research locations as the National Science Foundation sponsored Long-Term Ecological Research (LTER) sites, the U.S. Forest Service Experimental Forests, United Nations Educational, Scientific, and Cultural Organization (UNESCO)-designated International Biosphere Reserves, and other similar research sites, are given priority. A major emphasis of WEBB investigations is the development and maintenance of strong collaborative research relations with scientists in other Federal agencies and with the academic community. This report describes the characteristics, data collection, research, and cooperative activities of one such WEBB site, the Loch Vale watershed.

BASIN CHARACTERISTICS

Physical and Chemical Characteristics

The Rocky Mountains cover a large part of the Nation and are similar to many metamorphic high-elevation areas worldwide. The orographic effect and rapid physical weathering result in large loading rates of water, sediment, and dissolved constituents that determine the initial conditions for downstream reactions and processes. There is remarkable similarity in water chemistry (Turk and Spahr, 1990) that seems indicative of similar watershed processes throughout the Rocky Mountains. These processes might be directly applicable to other related provinces worldwide.

The Loch Vale watershed (LVWS) is an alpine-subalpine drainage basin located entirely within Rocky Mountain National Park about 80 km northwest of Denver, Colorado (fig. 1). LVWS is designated as a UNESCO Biosphere Reserve and is coordinated with other sites nationally and internationally. The watershed is a 1-hour drive from the National Park Service office in Fort Collins and a 2.5-hour drive from the U.S. Geological Survey office in Denver. This drainage, which faces northeast, encompasses 660 ha and ranges in elevation from 3,050 m at the outlet to 4,026 m at the Continental Divide. Average annual precipitation ranges from about 96 to about 128 cm/yr. Generally, more than 70 percent of this precipitation is snow (table 1). More than 80 percent of the watershed consists of bare rock surfaces and active talus slopes. Bedrock is crystalline granite, gneiss, and schist. Tree line is at about 3,300 m, above which is alpine tundra and meadow. The lower 6 percent of the basin is covered by a mature forest of subalpine fir, Engelmann spruce, and limber pine. The most extensive soils are medium- to coarse-textured Cryoboralfs of forested areas.

Table 1.--*Recent annual precipitation and flow for Loch Vale watershed*

[Data adapted from Baron and Denning, 1992]

Year	Precipitation, in centimeters			Flow, in centimeters
	Rain	Snow	Total	
1984	44.9	70.4	115.3	88.0
1985	29.3	86.4	115.7	64.8
1986	35.8	92.4	128.2	91.8
1987	33.6	62.6	96.2	71.2
1988	27.0	84.5	115.5	70.8

The soils typically are less than 50 cm deep and have pH values that range from 3.3 to 4.2. About 1 percent of the basin is boggy, wet, sedge meadows in the subalpine. Taylor and Andrews Glaciers and Taylor rock glacier compose about 1 percent of the basin.

The climate of LVWS is typical of high-elevation, continental areas. The maximum temperature is 18°C, minimum is -20°C, and mean is 1.5°C. Maximum windspeed is 17 m/s and mean is 5 m/s. Relative humidity averages 67 percent.

The chemistry of LVWS is typical of dilute, high-elevation lakes in the Colorado Front Range. Calcium and sodium are the major cations, whereas alkalinity (bicarbonate), sulfate, and nitrate are the major anions (table 2).

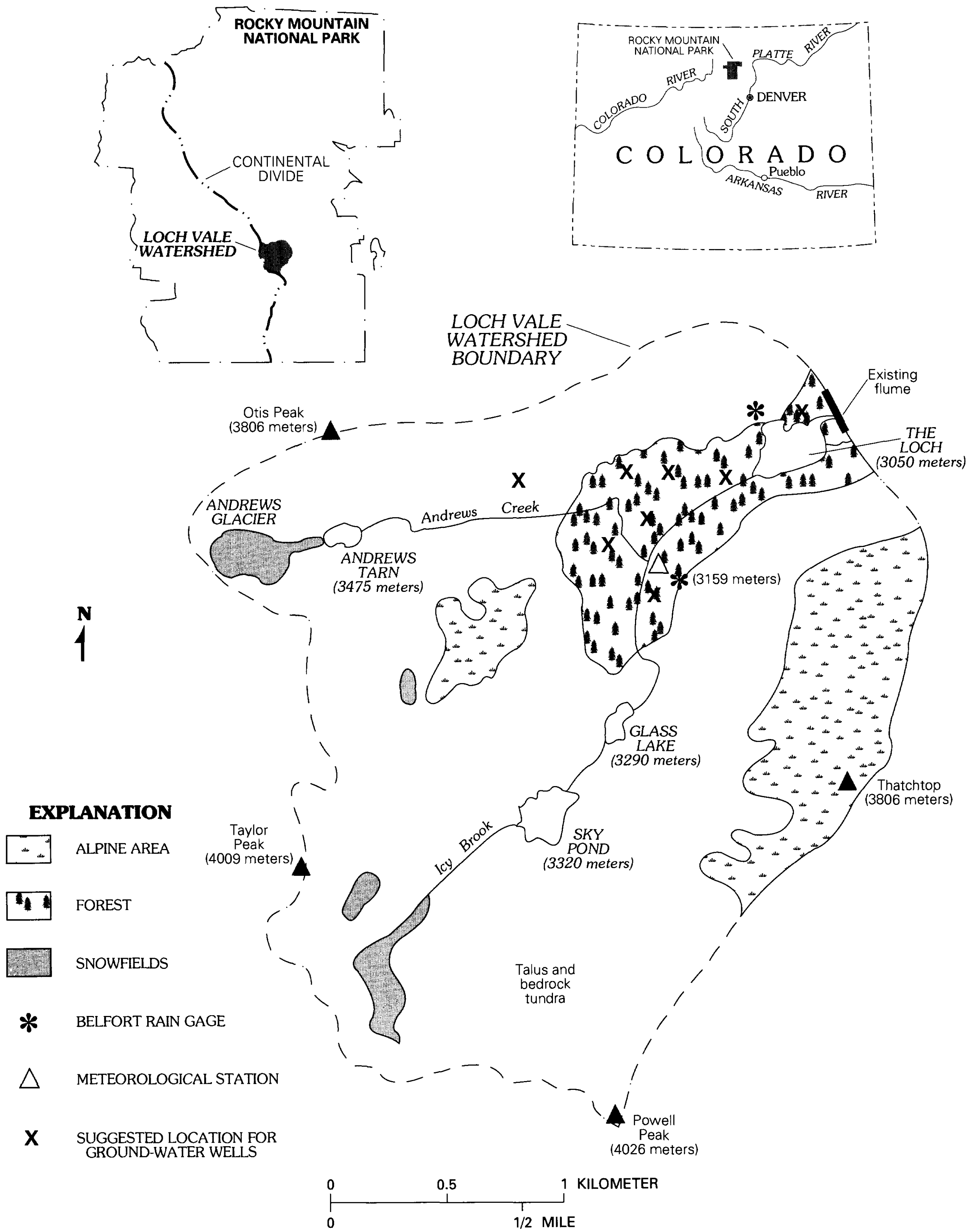

Figure 1.--Location of the Loch Vale watershed.

Table 2.--*Mean concentrations and standard deviation of chemical constituents in the Loch Vale watershed*

[Number of observations = 602; all constituents in milligrams per liter except alkalinity and H^{+1}; which are in microequivalents per liter; data from Baron, Denning, and Schoepflin, 1988]

Constituent	Mean	Standard deviation
Alkalinity	54.7	29.5
H^{+1}	.55	.38
Ca^{+2}	1.47	.47
Mg^{+2}	.24	.09
Na^{+1}	.56	.24
K^{+1}	.22	.09
$NH_4{}^{+1}$	.04	.03
$NO_3{}^{-1}$	1.01	.40
$SO_4{}^{-2}$	1.76	.58
Cl^{-1}	.20	.09
SiO_2	2.15	.90

LVWS drains into the Big Thompson River, which is tributary to the South Platte River. Watershed characteristics change from alpine and subalpine, to montane, to semiarid plains in the South Platte River. Much of the drainage for about the first 35 km of stream length is in Rocky Mountain National Park or Roosevelt National Forest. After leaving the Front Range, the river passes through the urban corridor and into agricultural land. Agricultural usage includes grazing and dryland and irrigated farming. Remnant native short-grass prairie occurs in the Pawnee National Grasslands LTER site downstream.

Site Background and Studies in Progress

The LVWS has been used by many researchers to investigate the hydrology, geochemistry, and biology of Rocky Mountain alpine-subalpine watersheds. Because of the large number of studies, it is impractical to give a detailed description of each. The nature of the studies can be determined from the following bibliographic information for the site. Additional detail is available in each of the following: Baron, 1983; Baron and Beeson, 1984; Heit and others, 1984; Baron and Walthall, 1985; Baron and others, 1985; Norton and others, 1985; Walthall, 1985; Baron and others, 1986; McKnight and others, 1986; Baron, 1987; Baron and Bricker, 1987; Denning and others, 1988; Klein, 1988; Mast and others, 1988; McKnight and others, 1988; McLaughlin, 1988; Mast, 1989; Arthur, 1990; Bigelow and others, 1990; Turk and Spahr, 1990; Arthur and Fahey, 1990; Mast and others, 1990; McKnight and others, 1990; and Denning and others, 1991.

The following studies currently (1991) are in progress: (1) Weathering reaction rates and mechanisms, by David Clow, University of Wyoming; (2) Study of stream periphyton responses to nutrient limitations, by C.M. Tate, Kansas State University; (3) Research into ozone and fine particulate matter, by Ad van den Berg, University of Wageningen, The Netherlands; and (4) Research into the use of stable-sulfur isotopes as a means of determining atmospheric and watershed sources of sulfate, by John Turk, U.S. Geological Survey.

AVAILABILITY OF DATA

The historic data collected at LVWS and downstream in the South Platte River and its tributaries are summarized below. The information for LVWS includes virtually all work that has been conducted; however, the information pertaining to downstream areas is much more abbreviated. To facilitate access to the historic data, the information is presented by subject and bibliographic citation for published work.

Loch Vale Watershed

Biological and Ecological Studies

Aquatic:

1. Fish surveys conducted (Rosenlund and Stevens, 1990).
2. Stream periphyton characterization and nutrient enrichment bioassays in 1987, by C.M. Tate, Kansas State University.
3. Winter phytoplankton survey (Spaulding, 1991).
4. Summer phytoplankton evaluation of productivity and response to nutrient enrichment and acidification (McKnight and others, 1988).
5. Surface sediment diatom characterization in 1981, by S.A. Beeson.

Terrestrial:

1. Twenty, permanent forest-vegetation plots installed in 1985 (Arthur, 1990)
2. Forest age structure and dynamics study of decomposition of roots, leaf litter, and dead wood (Arthur, 1990).
3. Forest nutrient cycling (Arthur, 1990).

Physical and Chemical Studies

Meteorological:

1. Site CO98 of National Atmospheric Deposition Program operated since 1983. Provides chemistry of wetfall for major ions and nutrients.
2. A Remote Area Weather Station operated since 1982. Hourly readings are telemetered and recorded for windspeed and direction, relative humidity, solar flux, barometric pressure, quantity of precipitation, and air temperature.

Stream discharge:

Discharge measured with flume since 1984. Peak discharge of 1.5 to 1.8 m^3/s is associated with the yearly snowmelt, which dominates the hydrologic cycle. Flow ceases during December to February.

Ground water:

Seismic surveys indicate depth to bedrock along several transects. No measurements of head are routinely made. Soil solution chemistry is available from analysis of water samples collected in lysimeters.

Water quality:

1. Surface-water samples are collected weekly from the outlet of the Loch Vale watershed.
2. Monthly to bimonthly samples, at several depths, are collected in the lakes at their deepest point.
3. Tributaries are sampled several times per year.
4. Record since 1981.

To determine the water, energy, and biogeochemical budgets of the Loch Vale watershed, the following additional information will be needed.

Additions to the water budget include:

1. Annual synoptic measurements of the snowpack near the time of maximum accumulation.
2. Synoptic measurements of streamflow upstream from the existing flume.
3. Additional meteorological information to enable refinement of the calculated evapotranspiration.
4. Information about the flow of ground water near the stream channel.
5. Measurement of precipitation quantity above tree line.
6. Measurement of stable isotopes of oxygen and hydrogen to determine the source of streamflow.

Additions to the energy budget include:

1. Measurement of windspeeds at additional heights in the vicinity of the existing meteorological station.
2. Measurement of long and shortwave radiation.
3. Measurement of windspeed, air temperature, and relative humidity above tree line.

Additions to the biogeochemical budgets include:

1. Synoptic measurements of water chemistry from springs, lakes, and streams during late summer.
2. Use of stable and radioisotopes to determine variations in the source of sulfur, strontium (as a surrogate for calcium), and carbon throughout the watershed.
3. Measurements of major ions and nutrients in ground water and soils that represent the dominant landscape units of the watershed.

South Platte River and Tributaries

The historic interest in water availability has resulted in a large number of stations that measure flow and, to a lesser extent, water quality downstream from LVWS. Other drainages from related terrain nearby also are heavily monitored. Some of the surface-water flow records date back to the 1880's, and records extending back to the early 1900's are fairly common. Water-quality records most commonly begin in the 1970's; however, a few earlier records exist. Thus, the ability to increase the scope of coverage in a downstream order is enhanced by availability of these data, especially with respect to flow generation. Because of the changes in major controls on water quality, for example geology, that occur as a function of downstream order, the increased scope of water-quality analysis is better accomplished by extropolation to other alpine and subalpine watersheds.

Processes Controlling Weathering and Biogeochemical Budgets

In the terrestrial part of the global carbon cycle, chemical weathering is one of the most important processes affecting the flux of carbon. The reaction of silicate or carbonate minerals with CO_2 from the atmosphere or from plant decay produces HCO_3^{-1}. Because it is difficult to directly measure the quantity of atmospheric CO_2 consumed in this reaction, the transport of HCO_3^{-1} from the watershed commonly is measured, and the nature of the weathering reaction is assumed, based on knowledge of the dominant minerals available to do this weathering. For example, in a limestone area, it is assumed that the mineral calcite reacts with CO_2. In granitic areas, it has been assumed that the reaction is between the feldspars, which are the most common reactive mineral, and CO_2. However, recent work (Mast and others, 1988; Mast, 1989; Mast and others, 1990; Turk and Spahr, 1990) indicates that throughout the Rocky Mountains, carbonate weathering rather than feldspar weathering might be the main source of HCO_3^{-1}. Uncertainty about the chemical-weathering reaction affects the CO_2 budget by a factor of two; all of the HCO_3^{-1} from feldspar weathering is from the atmosphere, whereas only half of the HCO_3^{-1} from carbonate weathering is from the atmosphere. Similarly, there is uncertainty regarding the effect of climate change on weathering, depending upon the nature of this weathering reaction. Feldspar weathering probably is controlled by chemical kinetics, whereas weathering of trace quantities of calcite disseminated through the host rock probably is controlled by the rate of exposure of the calcite by physical weathering.

Objectives

The objectives of the study are to:

1. Determine stable strontium-isotope ratios in feldspar, hydrothermal calcite, soils, and water of LVWS and selected other watersheds in the Rocky Mountains. The hypotheses are that: (a) Stable strontium-isotope ratios differ among the mineral end members, and (b) the ratio in water is within that range.
2. Determine stable carbon-isotope ratios in hydrothermal calcite, soils, and water and C-14 content in water of LVWS and selected other watersheds in the Rocky Mountains. Hypothesis analogous to those in item 1.
3. Use differences among the phases in items 1 and 2 to decide which isotopic data are suitable to discriminate among the possible sources of chemical weathering. The hypothesis is that the signal-to-noise ratio of the strontium- and carbon-isotope data differ, where signal is the difference in ratio between the component in water and in the possible mineral end members.
4. Determine whether feldspar, hydrothermal calcite, or eolian-deposited minerals (as indicated by isotopes in soil) are the source of weathering products in water. The initial hypothesis is that the isotopic ratio of the component in water matches, within analytical precision, the isotopic ratio in one of the sources, and differs from the ratio in all other sources. Additional hypotheses would be needed if mixed sources are present.

Approach

Strontium occurs as an impurity in calcium minerals and is released with the calcium as those minerals weather. Data from the Western Lake Survey (Turk and Spahr, 1991) indicate that throughout the Rocky Mountains most of the CO_2 used in chemical weathering weathers calcium minerals. The study includes use of strontium isotopes in the minerals and in water to determine which calcium minerals account for this chemical weathering. The stable isotopes Sr-87 and Sr-86 have been used to demonstrate the importance of eolian sedimentary minerals to weathering in a granitic watershed (Gosz and others, 1983). If the several possible minerals that control weathering in a watershed have differing strontium-isotope ratios, then the ratio of strontium isotopes in surface and ground water can be used to calculate the relative contributions of the source minerals.

In addition to use of strontium isotopes, carbon isotopes are appropriate to determine the significance of trace quantities of highly reactive carbonate minerals. Both the stable isotopes C-12 and C-13, and radioactive C-14 can be used to evaluate the importance of carbonate minerals in the production of alkalinity. Because alkalinity can result from the reaction of atmospherically derived carbon dioxide with carbonate or silicate minerals, the ratio of the stable isotopes should indicate whether atmospheric carbon dioxide alone, or in combination with carbonate minerals, has contributed to the isotope ratio in dissolved HCO_3. Carbonate minerals also should have no C-14, whereas atmospheric carbon dioxide has a measurable concentration. Thus, the extent of dilution of atmospheric C-14 by dead carbon from carbonate minerals also is a measure of the importance of carbonate versus silicate weathering. Both stable and radioactive carbon isotopes will be used to confirm the conclusions derived from strontium isotopes; however, potential exchange with CO_2 from the atmosphere will make the carbon isotopes less reliable as the primary method than are the strontium isotopes.

Collection of rock samples and separation of minerals for analysis of Sr and C isotopes will use a statistically designed subsampling of parent rock, hydrothermal veins, secondary minerals along fractures, and soil. Initial sampling began in October 1990 to enable optimization of laboratory methods of separation; however, most sampling was completed in summer 1991. Sampling was most extensive in LVWS but also was done within selected representative watersheds within the Colorado Front Range. After initial methods development and selection of the best mix of approaches, this sampling will be expanded to the Wind River Range of Wyoming and the Bitterroot Range of Idaho and Montana to further represent the Rocky Mountains.

Collection of water samples and extraction of Sr and C for isotopic analysis will be hydrologically driven to represent the changing flow volume and changing source of water to the surface-water system. Sampling began in March 1991 and will be ongoing for the duration of the study. Sampling is at selected tributaries, main-stem sites, and within ground water in LVWS. After initial review of the data from the first year of sampling, critical sampling times will be selected for a synoptic sampling of surface water within selected watersheds of the Colorado Front Range. This synoptic sampling will be expanded to the Wind River Range and the Bitterroot Range.

Processes Controlling the Energy Balance and Chemistry of Snowpacks

Although much work has been done on snowmelt processes in Europe, the Eastern United States, and the Sierra Nevada, the snowmelt processes in the Rocky Mountains are poorly understood. The high elevation and inland location of the Rocky Mountains result in a snowpack very different from that of the rest of the Nation. The snowpack is very cold, continuously accumulating through much of October to April, and released as a single, long-duration event. Much of the present metamorphosis of snowpack is caused by radiative energy transfer from sunlight to the snowpack rather than from conductive transfer from air to the snowpack. Thus, changes in cloud cover, air temperature, relative humidity, and windspeed can greatly alter the basic nature of the Rocky Mountain snowpack. Present water management of the scarce water resource is designed to store and distribute the single snowmelt peak for the various municipal and agricultural needs. The geomorphology of streams is dominated by the extreme flows produced during the single snowmelt peak. A decrease in peak flow, in combination with the rapid physical weathering of the Rocky Mountains, would likely result in accumulation of sediment to the detriment of obligate stream spawners, such as the cutthroat trout. The duration of snow cover also is an important feedback mechanism of solar radiation that affects atmospheric properties.

The chemistry of snowmelt also is poorly understood, especially in cold snowpacks such as those of the Rocky Mountains. The chemistry of snowmelt is greatly affected by the number of freeze-thaw cycles that occur in the snowpack. An increase in these cycles probably would intensify the preferential elution of pollutants from the snowpack, which results in increasing severity of acidic pulses to lakes and streams. Processes such as preferential elution of solute and the nonuniform flow of melt along and through ice lenses complicate quantification of snowpack inputs to hydrologic flow paths in a real-time sense. Previous efforts have relied upon a combining of the inherent variance by considering only large areal scales; however, this is unsuitable when considering the input to local flow paths of ground-water recharge or initial surface-water flow.

Objectives

The objectives of the study are to:

1. Determine the present processes of snowpack metamorphosis and melt generation in the Rocky Mountains. The hypotheses are that: (a) Physical and chemical composition of the snowpack change as the snowpack ages, (b) physical and chemical composition of the snowpack varies among the layers of the snowpack, and (c) release of solutes and water are a function of the physical and chemical composition of individual layers rather than the bulk composition of the snowpack.
2. Use the results of previous studies in warmer snowpacks to determine which processes differ between warm and cold snowpacks. The hypothesis is that the physical and chemical composition of the Rocky Mountain snowpack differ from those of warmer snowpacks.

3. Do a rigorous energy balance combined with a statistically designed subsampling of snowpack and melt to determine the spatial scale below which preferential elution and flow within snowpacks needs to be treated as a heterogeneous process. The hypothesis is that the variance in flow and chemistry among sites in a catchment is greater than the variance among catchments once some critical catchment size is exceeded.

4. Provide input chemistry and flow to selected flow paths for work to be done in the section "Processes controlling or controlled by the flow path and flux of water." The hypothesis is that at the local flow path scale, the critical catchment size has not been exceeded (see objective 3).

Approach

The understanding of snowpack processes in the Rocky Mountains is hampered by a general lack of information about the changing physical and chemical characteristics of the snowpack in this region and by problems of heterogeneity of flow within the snowpack. Thus, the initial approach emphasizes collection of basic data for snowpack characteristics in a statistically driven, stratified subsampling of snowpacks. Stratification will be by primary independent variables of elevation, aspect, location within assumed "snowshed" (analogous to stream order or location in flow path), forest cover, and vertical zonation within the snowpack.

The physical and chemical metamorphoses are assumed to be fundamentally related to one another in that recrystallization and refreezing of melt are processes that have good potential to preferentially partition solutes into various parts of the snowpack. Essentially, the more perfect the ice structure of the water molecules becomes, the less "soluble" are impurities in this structure, including the common chemical solutes. In addition to testing for the ability of common physical characterization of the snow structure to account for variance in chemistry of discrete samples, a rigorous energy balance of the layered snowpack will be used to provide a quantitative, mechanistic description of the status and metamorphic history of individual layers within the snowpack. The energy balance of the snowpack and individual layers within the snowpack will be tracked with the use of a point-energy and mass-balance model of snow cover (Anderson, 1976). Thus, it will be possible to test for the effect of one or more variables, such as total watts of solar radiation per unit area that a layer received before new snowfall, on the physical (for example, density) and chemical (for example, percent of change in initial sulfate concentration) characteristics of discrete points within the snowpack.

One of the main constraints on research in snowmelt-dominated watersheds is measurement of input water and solutes to the watershed. The effect of wind on deposition and redistribution of snow is much more pronounced than for rain. Further, in alpine and subalpine environments, the avalanche hazard can make monitoring of the snowpack difficult or impossible by classical snow-survey techniques. The study will include an investigation of innovative new techniques to overcome these problems. In particular, acoustic transceivers to measure the distance from a fixed point to the snow surface below and laser ranging devices to measure distance from fixed surveying locations to selected snowpack surfaces will be evaluated.

Processes Controlling or Controlled by the Flow Path and Flux of Water

The movement of water within and from watersheds in the Rocky Mountains is poorly understood. There are no alpine or subalpine watersheds that have been instrumented to determine flow paths through geologic and biologic materials that regulate biogeochemical processes. Some work has been done at the plot scale using lysimeters to examine initial processes that modify inputs from atmospheric deposition. Moderate monitoring and process-oriented research has been done at the watershed scale using outputs to combine processes or to infer which are or are not important. Most work at the river-basin scale has been directed at the hydraulic response to snowmelt for runoff forecasting to prepare for floods and to manage the filling of reservoirs for agricultural and domestic use. Thus, most work has been capable of only generating hypotheses of the primary controls on biogeochemistry and flow at the watershed, catchment, and plot scales rather than testing hypotheses. To test such hypotheses, it will be necessary to isolate flow paths and document the sequential effects of processes along these flow paths. The flow paths also are expected to change as a function of volume of snowmelt, season, and so forth. Thus, the importance of individual processes also likely will change. Changes in flow path also will affect the hydraulic response of the watershed, so models of snowmelt runoff need to incorporate actual flow path information to realistically predict changes in watershed response to changing climate. The independent variables controlling snowmelt in the Rocky Mountains also need to be ranked with respect to their importance, both as a function of watershed characteristics (elevation, slope, aspect, forest cover) and of susceptibility to modification by climate change.

Objectives

The objectives of the study are to:

1. Determine the relative contribution of weathering products from selected zones; for example, exposed rock surface, litter, mineral soil zones, buried bedrock, stream channel, and in-lake. The hypothesis is that the quantity of weathering products released per unit area and time differ among weatherable surfaces.

2. Determine controls on the present composition of exchangeable cations and anions. The hypothesis is that soil has preferential sorption of some ions.

3. Determine controls on evapotranspiration. The hypothesis is that evapotranspiration differs as a function of catchment variables, such as elevation, slope, aspect, quantity and type of vegetative cover, and so forth.

4. Determine the effect of watershed characteristics on the controls of snowmelt generation. The hypothesis is that incoming solar radiation, air temperature, relative humidity, and windspeed of catchments control snowmelt and vary in relative and absolute importance as a function of elevation, slope, aspect, and forest cover.

Approach

To meet the objectives of this study, actual measurement of flow paths and processes in selected segments of the flow paths will be done. Although some steps in the approach would be identical for all objectives--for example, selection and instrumentation of flow paths--evaluation of processes is dependent on the actual process being studied. For brevity, a generic approach follows:

1. Select likely flow paths in plots or catchments that represent the major biogeochemical zones; for example, alpine tundra, scree, and forested.
2. Install lysimeters, wells, and flumes to monitor and sample the changing chemistry and flux of water. (This is to be done in conjunction with the snowmelt monitoring discussed in the section "Processes controlling the energy balance and chemistry of snowpacks.")
3. Use standard ground-water and surface-water techniques and data from item 2, and calibrate the response of water flow to selected, measured stresses such as snowmelt, summer evapotranspiration loss, and so forth.
4. Isolate sites of important processes based on data from item 2; for example, litter, individual mineral soil horizons, and bedrock.
5. Formulate testable hypotheses of the actual processes that occur along the monitored flow paths.
6. Use appropriate chemical and isotopic techniques, or manipulation of input, and test the proposed hypotheses to determine their presence and magnitude.

Testing of hypotheses can be done by analysis of the data from the Glacier Lakes, Wyoming, site, which has been designated as an experimental watershed. At the LVWS site, testing probably will require dependence on natural-isotope techniques. Among the anticipated approaches would be the use of the naturally occurring stable and radioisotopes of strontium, carbon, nitrogen, sulfur, oxygen, and hydrogen. These isotopes offer wide application to test sources and processes related to chemical weathering, biological processes, and mixing of ground and surface waters.

For some of the simpler flow paths, it likely will be inappropriate to model response; for example, weathering and flow from rock surfaces. In such situations, the response to inputs of water and energy may be a simple function of mineral dissolution and snowmelt generation, and little modification along the flow path. In other, more complex flow paths, it probably will be best to combine flow and chemistry by presently available models. Depending on complexity of the processes, reaction-path models or watershed models may be appropriate.

This research topic serves as the means to determine the transferability of the previous research topics to other areas where intensive study is not possible. Research topic 1, parts 1 and 2, seeks to determine the mineralogic controls on weathering and the generation of base cations and alkalinity. Research topic 2 seeks to determine the climatic and watershed physical controls on release of water and of solutes contributed by atmospheric deposition from snowpacks to provide overland flow and recharge to ground water.

Research topic 3 seeks to determine the effect of watershed processes, as a function of watershed physical characteristics, on inputs from processes discussed in research topics 1 and 2. The distribution of watershed characteristics in a less-studied site, therefore, can be used to predict which processes could be significant in controlling the generation of flow and solutes. A subsample of the Western Lake Survey watersheds (Eilers and others, 1987; Landers and others, 1987) will be used to test the ability of this approach to explain lake chemistry throughout the Rocky Mountains. The Western Lake Survey used rigorous, stratified, random sampling of 411 Rocky Mountain lakes to represent the identified population of 8,500 lakes. In a similar fashion, the 414 snowpack telemetry sites within the Rocky Mountains will be used to test the ability of this approach to explain snowmelt generation. Finally, the National Mapping Division of the U.S. Geological Survey selected Colorado for a pilot study in fiscal year 1991 that is to facilitate use of land data resources from remote sensing by using Geographic Information System management of the data at multiple scales within one integrated program. Acquisition of watershed characteristics throughout the southern Rocky Mountains would be done by coordination with this pilot study.

COLLABORATIVE RESEARCH

LVWS has operated as part of the interagency National Acid Precipitation Assessment Program (NAPAP) as a key site for process-level study of acidification in alpine areas. In a more general capacity, the site is part of the international Biosphere Reserve Program of UNESCO. The site has an established history of being used by universities, the U.S. Geological Survey, the U.S. Environmental Protection Agency, and so forth. This cooperative use of LVWS as a focus of alpine and subalpine research has been especially productive in the study of processes that include chemical weathering, community structure and response, and atmospheric deposition.

LVWS continues to operate as a long-term study site for watershed research. The National Park Service provides support in the form of salary for a principal investigator and assistants and operating money for basic data collection. The U.S. Geological Survey provides funds to cover analytical costs.

The site has been proposed for National Park Service funding under the National Park Service Global Change Program. Collaborators in this proposed study would be:

- Colorado State University--
  - Center for Analysis of Dynamics of Regional Ecosystems (CADRE)
  - Natural Resource Ecology Laboratory (NREL)
  - Department of Atmospheric Science
  - Geographic Information System (GIS)/Remote Sensing Unit
  - Central Plains Experimental Range LTER site (Pawnee Grasslands)
- University of Colorado--
  - Niwot Ridge Long-Term Ecological Research LTER (co-site)
  - Institute for Arctic and Alpine Research (INSTAAR)
- U.S. Geological Survey--
  - National Mapping Division (Colorado prototype study)
  - Water Resources Division (hydrology, geochemistry)
- U.S. Forest Service--
  - Fraser Experimental Forest (co-site)

REFERENCES

Anderson, E.A., 1976, A point energy and mass balance model of a snow cover: Silver Spring, Md., National Oceanic and Atmospheric Administration, NOAA Technical Report NWS 19, 150 p.

Arthur, M.A., 1990, The effects of vegetation on watershed biogeochemistry at Loch Vale Watershed, Rocky Mountain National Park, Colorado: Ithaca, N.Y., Cornell University, Ph.D. dissertation.

Arthur, M.A., and Fahey, T.J., 1990, Mass and nutrient content of dead and decaying boles in an Englemann spruce/subalpine fir forest, Rocky Mountain National Park, Colorado: Canadian Journal of Forest Research, v. 20, p. 730-737.

Baron, Jill, 1983, Comparative water chemistry of four lakes in Rocky Mountain National Park: Water Resources Bulletin, v. 19, p. 897-902.

_____1987, Acidic deposition in Colorado, *in* Loftis, W.A., ed., Colorado Water Management and Engineering Conference: Fort Collins, Colo., April 1987, [Proceedings], p. 357-367.

Baron, Jill, and Beeson, D.R., 1984, Long-term research into the effects of atmospheric deposition in Rocky Mountain National Park, *in* Galbraith, A.L., and Stuart, S.I., eds., Air quality and acid precipitation potential in the Bridger and Fitzpatrick Wildernesses: Jackson, Wyo., Bridger-Teton National Forest, workshop proceedings, p. 237-267.

Baron, Jill, Beeson, S.A., Zary, S.A., Walthall, P.M., Lindsay, W.L., and Swift D.M., 1985, Long-term research into the effects of atmospheric deposition Rocky Mountain National Park -- summary report 1980-1984: National Park Service Technical Report 84-ROMO-2, 43 p.

Baron, Jill, and Bricker, O.P., 1987, Hydrologic and chemical flux in Loch Vale watershed, Rocky Mountain National Park, *in* Averett, R.C., and McKnight, D.M., eds., Chemical quality of water and the hydrologic cycle: Ann Arbor, Mich., Lewis Publishers, p. 141-156.

Baron, Jill, and Denning, A.S., 1992, Hydrologic budget estimates *in* Baron, Jill, ed., Biogeochemistry of a subalpine ecosystem: New York, Springer-Verlag, 247 p.

Baron, Jill, Denning, A.S., and Schoepflin, K.C., 1988, Long-term research in Loch Vale Watershed, Rocky Mountain National Park: Ft. Collins, Colo., National Park Service, Annual Report 1988, National Park Service, Ft. Collins, Colo., 46 p.

Baron, Jill, Norton, S.A., Beeson, D.R., and Herrmann, R., 1986, Sediment diatom and metal stratigraphy from Rocky Mountain lakes with special reference to atmospheric deposition: Canadian Journal of Fisheries and Aquatic Sciences, v. 43, p. 1350-1362.

Baron, Jill, and Walthall, P.M., 1985, The nature of precipitation, soil and surface water chemistry in a subalpine ecosystem, *in* Caldwell, D.E., Brierly, J.A., and Brierly, C.L., eds., Planetary ecology: New York, Van Nostrand Reinhold Company, p. 497-509.

Bigelow, D.S., Denning, A.S., and Baron, Jill, 1990, Differences between Nipher and Alter shielded universal Belfort precipitation gages at two Colorado deposition monitoring sites: Environmental Science and Technology, v. 24, p. 758-760.

Denning, A.S., Baron, Jill, and Mast, M.A., 1988, Effect of soil-water interactions on stream chemistry during snowmelt in an alpine-subalpine watershed in Colorado: EOS, v. 69, p. 1202.

Denning, A.S., Baron, Jill, Mast, M.A., and Arthur, M.A., 1991, Hydrologic pathways and chemical composition of runoff during snowmelt in Loch Vale watershed, Rocky Mountain National Park, Colorado, United States of America: Water Air and Soil Pollution, v. 59, p. 107-123.

Eilers, J.M., Kanciruk, P., McCord, R.A., Overton, W.S., Hook, L., Blick, D.J., Brakke, D.F., Kellar, P.E., DeHaan, M.S., Silverstein, M.E., and Landers, D.H., 1987, Characteristics of lakes in the western United States--Volume II, Data compendium for selected physical and chemical variables: Washington, D.C., U.S. Environmental Protection Agency, EPA-600/3-86/054b.

Gosz, J.R., Brookins, D.G., and Moore, D.I., 1983, Using strontium isotope ratios to estimate inputs to ecosystems: Bioscience, v. 33, p. 23-30.

Heit, M., Klusek, R., and Baron, Jill, 1984, Evidence of deposition of anthropogenic pollutants in remote Rocky Mountain lakes: Water, Air, and Soil Pollution, v. 22, p. 403-416.

Klein, E.J., 1988, The variations in wet precipitation chemistry with elevation in Colorado: Colorado State University, M.S. thesis, 112 p.

Landers, D.H., Eilers, J.M., Brakke, D.F., Overton, W.S., Kellar, P.E., Silverstein, M.E., Schonbrod, R.D., Crowe, R.E., Linthurst, R.A., Omernik, J.M., Teague, S.A., and Meier, E.P., 1987, Characteristics of lakes in the western United States--Volume I, Population descriptions and physico-chemical relationships: Washington, D.C., U.S. Environmental Protection Agency, EPA/600/3-86/054a.

Mast, M.A., 1989, A field and laboratory study of chemical weathering with special reference to acid deposition: Laramie, University of Wyoming, Department of Geology and Geophysics, Ph.D. thesis, 174 p.

Mast, M.A., Drever, J.I., and Baron, Jill, 1988, Sources of solutes in the Loch Vale watershed, Rocky Mountain National Park, Colorado: EOS, v. 69, p. 1213.

_____1990, Chemical weathering in the Loch Vale watershed, Rocky Mountain National Park: Water Resources Research, v. 26, p. 2971.

McKnight, D. M., Brenner, M.V., Smith, R., and Baron, Jill, 1986, Seasonal changes in phytoplankton in lakes in Loch Vale, Rocky Mountain National Park: U.S. Geological Survey Water-Resources Investigations Report 86-4101, 64 p.

McKnight, D.M., Miller, C., Smith, R., Baron, Jill, and Spaulding, Sarah, 1988, Phytoplankton populations in lakes in Loch Vale, Rocky Mountain National Park, Colorado--Sensitivity to acidic conditions and nitrate enrichment: U.S. Geological Survey Water-Resources Investigations Report 88-4115, 102 p.

McKnight, D.M., Smith, R.L., Bradbury, J.P., Baron, Jill, and Spaulding, Sarah, 1990, Phytoplankton dynamics in three Rocky Mountain lakes, Colorado, United States of America: Arctic and Alpine Research, v. 22, p. 262-271.

McLaughlin, P.W., 1988, The effect of storm trajectory on precipitation chemistry in Rocky Mountain National Park: Colorado State University, M.S. thesis, 70 p.

Norton, S.A., Hess, C.T., Blake, G.M., Morrison, M.L., and Baron, Jill, 1985, Excess unsupported 210Pb in lake sediment from Rocky Mountain lakes--A groundwater effect: Canadian Journal of Fisheries and Aquatic Sciences, v. 42, p. 1249-1254.

Rosenlund, B.D., and Stevens, D.R., 1990, Fisheries and aquatic management--Rocky Mountain National Park 1988-1989: Golden, Colo., U.S. Fish and Wildlife Service, Colorado Fish and Wildlife Assistance Office.

Spaulding, Sarah, 1991, Phytoplankton dynamics under ice-cover in a subalpine lake: Ft. Collins, Colo, Colorado State University, M.S. thesis.

Turk, J.T., and Spahr, N.E., 1990, Rocky Mountains--Controls on lake chemistry, *in* Charles, D.F., ed., Acidic deposition and aquatic ecosystems--Regional case studies: New York, Springer-Verlag, p. 471-501.

Walthall, P.M., 1985, Acidic deposition and the soil environment of Loch Vale watershed in Rocky Mountain National Park: Ft. Collins, Colo., Colorado State University, Ph.D. dissertation, 148 p.

*U.S. GOVERNMENT PRINTING OFFICE: 1993-774-207/60026