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Air Quality and Acid Deposition Potential in the Bridger and Fitzpatrick Wildernesses

March 1984

AIR QUALITY AND ACID DEPOSITION POTENTIAL IN THE BRIDGER & FITZPATRICK WILDERNESSES

MARCH 1984 WORKSHOP PROCEEDINGS

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AIR QUALITY AND ACID DEPOSITION POTENTIAL IN THE BRIDGER & FITZPATRICK WILDERNESSES

PURPOSE

This workshop was convened by Regions 2 and 4 of the USDA Forest Service on the Colorado State University Campus, March 14 and 15, 1984. One purpose of the workshop was to assess the initial results of meteorology, geology, hydrology, biology and soils monitoring in the Bridger Wilderness managed by the Bridger-Teton National Forest and the Fitzpatrick Wilderness managed by the Shoshone National Forest. Both of these wilderness areas are located in southwest Wyoming. Another purpose was to present the preliminary findings to state and federal agencies, industry, wilderness-users, and the research community.

The knowledge gained from this workshop will be a basis for Forest Service recommendations to the Wyoming Prevention of Significant Deterioration (PSD) Air Quality permit process. Likewise, it will serve to prioritize additional data needs for future cooperative monitoring.

The cover photograph is of the Jean Lakes area in the Bridger Wilderness. Stroud Peak is to the extreme left and rises 12,222 feet above sea level. This is a typical scene from the 613 square mile Wilderness named after Frontiersman, Jim Bridger. The area was designated a mandatory Class I Protected Airshed in the 1977 Amended National Clean Air Act.

By Clif Benoit, Air Resource Management Coordinator, USFS, Ogden, Utah

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INTRODUCTION

This workshop has been organized by the Forest Service to assess the results of the first-year efforts to establish a baseline of information against which future trends and predictions concerning air quality and acid deposition in the Clean Air Act Class I designated Bridger and Fitzpatrick Wildernesses can be made. We are specifically concerned about how we are doing and where we are going in Wilderness management with particular regard to being able to predict impacts on Wilderness and air quality-related values.

There is some general misunderstanding of Wilderness as Congress and the early sponsoring publics originally intended it to be. Many people today think of Wilderness as only an area for primitive recreation experiences; an area where, at least for a short time, one could enjoy solitude, a closeness to nature and spiritual renewal; an area that is free of management controls and the evidence of man.

Wilderness, of course, is much, much more. Wilderness is and has always been intended to be a living museum, a place of historical and cultural research value, a multiple-use area that continues to provide clean water, wildlife habitat, grazing and mineral resources where appropriate. Every bio-physical component of Wilderness is absolutely essential to the whole. The zooplankton is as important as the phytoplankton, as the salamander, as the native cutthroat trout. The lichen is as important as the bristle cone pine. The hydrology, soil chemistry, meteorological affects and visibility are critical components of the Wilderness ecosystems that allow natural processes to evolve and be experienced. No one component can be altered without affecting the other components and so allow for the retention of the character of the Wilderness as required by the Wilderness Act. The loss of any one component may result in the loss of a unique gene pool, a loss of a research and discovery opportunity and possibly a future foregone.

I would like to ask two questions: Can we allow man-caused changes to take place within any Wilderness component? And, if so, what is the acceptable limit of that change? The loss of the grizzly bear, bald eagle or whooping crane from Wilderness would certainly be an emotional and critical situation. If we fully accept the concept of Wilderness, the pH change of a lake or stream, the loss of lichen species or a drop in soil productivity should be just as critical a loss.

In order to make wise decisions about Wilderness and Wilderness values related to air quality, it is essential to have a reliable data base, validated predictive models, understanding of causative agents and processes and integrated and coordinated decision criteria from all participating parties.

That brings us to why we are here today and tomorrow. We have a clear goal about where we want to be. And we know that everyone shares that goal. The voyage to attainment of that goal has started from a weak to non-existent data base and progressed out across uncharted waters. We feel we are cruising on a foggy ocean of uncertainty, but confident that our skills, ability and technical knowledge will pull us through.

Thousands of research hours, field application hours and dollars have already been spent trying to identify or predict impacts on the Wilderness resource. The oil and gas industry and the State of Wyoming have been patient as we develop an acceptable monitoring plan. We know we will be establishing a

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Presented by Workshop Chairman, Steve Deitemeyer, Deputy Forest Supervisor, Bridger-Teton National Forest precedent for Forest Service participation in the protection of areas designated Class I in the Clean Air Act. We want both the precedent and the monitoring plan to be the best we can produce within the state of our knowledge and financial capabilities.

We have assembled the best people for this workshop to help us assess how we are doing; is our direction correct? is it correlatable with other research or permitting efforts? is it contributing to the production of accepted predictive models? are there holes or gaps in the data base? and is it being done in the most economically efficient manner?

We will ask you to roll up your sleeves and professionally challenge any oversight or weakness you see in the research or application efforts to date. We want to make maximum use of the discussion periods and workshop time to critically evaluate the monitoring and modeling efforts. We want the end product to be acceptable to industry, to the scientific community as well as the state permitting agencies and all the affected land management agencies.

SCOPE

The format of the meeting will alternate between presentations and discussions to establish a common level of understanding with all of you that are here. This is the first time that we've had everybody in one place at one time. We have had a lot of activities going on the last couple of years, particularly through the field seasons. We've had soil and water groups doing their thing, air folks going their way, wildlife and plant specialists going their way. But, this is the first time everybody has been at one place. And we hope that will pay us great benefits.

We have established four discussion groups: A meteorology group, a geology and soils group, a vegetation and aquatic biology group, and a hydrology and aquatic chemistry group.

Dr. Doug Fox will serve as the panel chairman for the meteorology group. Jack Antweiler from USGS, the geology and soils group; Dr. David Brakke, the vegetation and aquatic biology group; and Dr. Richard Wright, the hydrology and aqautic chemistry group.

These panel chairmen, with the assistance of all the participants, are going to help you decide the future course of action for data monitoring, research studies and future decisions about Class I areas in the Bridger and Fitzpatrick Wildernesses. As I indicated earlier, we want very open discussion and critique throughout all the presentations and panel discussions.

We have employed a court recorder, and she will capture what is said and your responses so that we can publish a complete proceedings. You will each receive a copy of the proceedings this summer.

ACKNOWLEDGEMENTS

The Forest Service is very thankful to all authors who have contributed papers and to each attendee who expressed their ideas, concerns, and experiences to make this workshop a success.

Particular recognition is due the following persons who were instrumental in organizing the workshop and publishing this proceedings. Dr. Alan Galbraith,

Hydrologist, Bridger-Teton NF; Dr. Jim Blankenship, National Air Quality Coordinator, USDA FS; Dr. Doug Fox, Meteorologist, Rocky Mountain Research Station, USDA FS; Dennis Haddow, Air Quality Coordinator, Region 2, USDA FS; John Chapman, Fire & Air Officer, Bridger-Teton NF; Doug Turner, Range Conservationist, Big Piney Ranger District, Bridger-Teton NF; and Clif Benoit, Air Resource Coordinator, Region 4, USDA FS.

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

The objectives of the workshop were to assess the current status of air quality and acid deposition in the Bridger and Fitzpatrick Wildernesses, and to assist the Forest Service in evaluating the monitoring program. The workshop successfully accomplished these objectives. The workshop format allowed for a critical scientific review of the 1983 Air Quality Related Values (AQRV) Forest Action Plan. The plan directs field data collection and analysis needs necessary to establish baseline information from which change and impacts can be measured. Because there was no precedent for an AQRV action plan, it was decided that a thorough scientific challenge of the plan was necessary to assure its completeness. The workshop concluded that the AQRV plan was essentially complete and would generate data necessary to substantiate recommendations for Class I areas.

The presentations and discussions concerned with meteorology and visibility recommended additional measurement sites as well as increased types of measurements. Much discussion was given to meteorological modeling, and it became apparent that existing models would require data beyond that currently being collected. The question of the adequacy of the modeling approach, therefore, must wait upon the establishment of a sufficient foundation of field measurements to allow differing models to be tested. The same conclusion was reached for visibility evaluations. Until the appropriate instrumentation can be established within the Wildernesses to allow visibility parameters to be determined, the potential deterioration of wilderness visibility will remain speculation at best.

Considerably more information was available for the geology and soils of the Wildernesses. The main granitic core of the Wind River Mountains was found to be low in acid buffering elements such as calcium or magnesium. In addition, the chemical weathering process is considered to be very slow throughout most of the mountain range. Coupled with this low geologic reserve of buffering capacity is the finding that the soils have only a limited ability to neutralize acids, as indicated by the low base saturations shown in laboratory analysis. Furthermore, most of the lakes in the Wildernesses have a low areal coverage of soils in the first place. From the foregoing, it became readily apparent that the watersheds are quite limited in their potential to buffer acid deposition.

A principal conclusion of the aquatic chemistry discussion was that the Wildernesses are presently receiving a significant amount of acid deposition. A National Acid Deposition monitoring site near Pinedale, Wyoming, recorded precipitation weighted annual average pH of 4.62 or ten times more acid than natural, unpolluted rainwater. For the 1983 season, the lakes maintained their ability to buffer this acid deposition since lake pH measurements were in the 6.4 - 6.9 range. But it is not known how long the aquatic system can sustain this ability to buffer. A recent study, cited in the body of the proceedings, suggests that an annual precipitation pH of 4.7 is a natural threshold for granitic watersheds below which acidification will take place. In addition, a survey of nearly one hundred lakes revealed an extremely low buffering in the lake waters as determined by their alkalinity regime, which averaged between 60 and 90 ueq/l micro equivalents per liter.

By Reid Jackson, Forest Supervisor, Bridger-Teton National Forest

The vegetation and aquatic zoology discussions produced results which supported those of the preceding discussion. An elemental analysis of lichen samples discovered elevated concentrations of lead relative to samples obtained at similar elevations in the Colorado Rocky Mountains. The lead concentration also increased with elevation in the Bridger Wilderness suggesting an orographic effect. Lead is a man-made type of air pollutant. The evaluation of macroinvertebrates and zooplankton taken from the lakes and inlet or outlet streams demonstrated a population diversity indicative of pristine conditions. Several key indicator species believed to be intolerant of acid stress were identified for future reference. In a similar fashion, the fish populations of the monitor lakes were found to be self-sustaining and generally in good condition; although in one of the monitor lakes, some crowding was interpreted from condition factors.

RECOMMENDATIONS

During the workshop, four panel groups were formed to evaluate the effectiveness of the current monitoring program. The four groups were in the topic areas of (1) Meteorology, (2) Geology and Soils, (3) Vegetation and Aquatic Biology and (4) Hydrology and Aquatic Chemistry. At the conclusion of the presentations, the group panel chairmen summarized recommendations. The Vegetation and Aquatic Biology group decided to combine, and work with the Hydrology and Aquatic Chemistry group.

Hydrology, aquatic Chemistry, Vegetation, and Aquatic Biology Group Recommendations:

1. Approximately 100 additional lakes should be sampled for the basic water chemistry analysis as proposed in the original action plan.

2. Three or four additional wet acid deposition collection stations should be established.

3. Temporary rain gauges should be installed at the monitor lakes for water chemistry analysis.

4. Dry acid deposition collection site(s) should be established.

5. Snow collectors for chemical analysis of snowfall should be considered.

6. At least one monitor lake in the 20-30 ueq/l alkalinity range should be established.

7. Permanent water flow measurement station(s) combined with chemical water analysis should be located near if not within Wildernesses.

8. The fish, macroinvertebrate, and zooplankton survey should be continued throughout the period of the monitoring program.

9. A diatom and heavy metals analysis of the monitor lake bed sediments should be conducted.

10. One of the monitor lakes should be located east of the Continental Divide, probably in the Fitzpatrick Wilderness.

The Meteorology Group Recommendations:

1. Upper air information is needed at the northern end of the Green River Basin in the Pinedale vicinity.

2. Doppler accoustical sounding instrumentation is needed in the Pinedale area.

3. Visibility data is needed as quickly as possible in each Wilderness.

4. The climatology of the upper Green River Basin needs to be described.

The Geology-Soils Group Recommendations:

1. One area which needs additional soils and geology data is the tundra environment.

2. Better information is needed on acid deposition rates, particularly the dry component, to assist the soil column study, and to predict effects upon soil properties.

THE RILEY RIDGE PROJECT

by

Douglas G. Turner

In the early 1960's gas was discovered in Wyoming's Moxa Arch at depths of 14,000 -18,000 feet. By 1981 government and industrial economists felt that Moxa Arch gas could be produced economically by the middle of this decade.

The Moxa Arch is a geologic structure which lies immediately to the east of the Overthrust Belt in western Wyoming (see Map 1). It is estimated to hold from twenty to thirty trillion cubic feet of natural "sour" gas. The adjective "sour" indicates that the gas contains toxic hydrogen sulfide (H_2S). The Moxa Arch is known to contain about four percent H_2S. Other components are: carbon dioxide (CO_2), 67%; methane (CH_4), 20%; nitrogen (N_2), 8%; and helium (He), 1%.

In order to make the methane fraction of this gas marketable, the raw gas must be processed through a gas sweetener plant (see Fig. 1). Some of these are currently operating in southwestern Wyoming.

The sour gas is separated into its various components in these plants as represented by the schematic (see Fig. 2). The gas enters the plant and is fed into the gas sweetening unit. At this point there is a three way separation: the bulk of the CO_2 is taken out and either vented or put into a sales pipeline; a mixture of CH_4, N_2, and He is sent to the nitrogen rejection unit; and the remaining fraction of gas--mainly H_2S with some CO_2 is sent to the sulfur recovery unit. From the nitrogen rejection unit He and N_2 are vented to the atmosphere, and CH_4 of ninety-seven percent purity is recovered and

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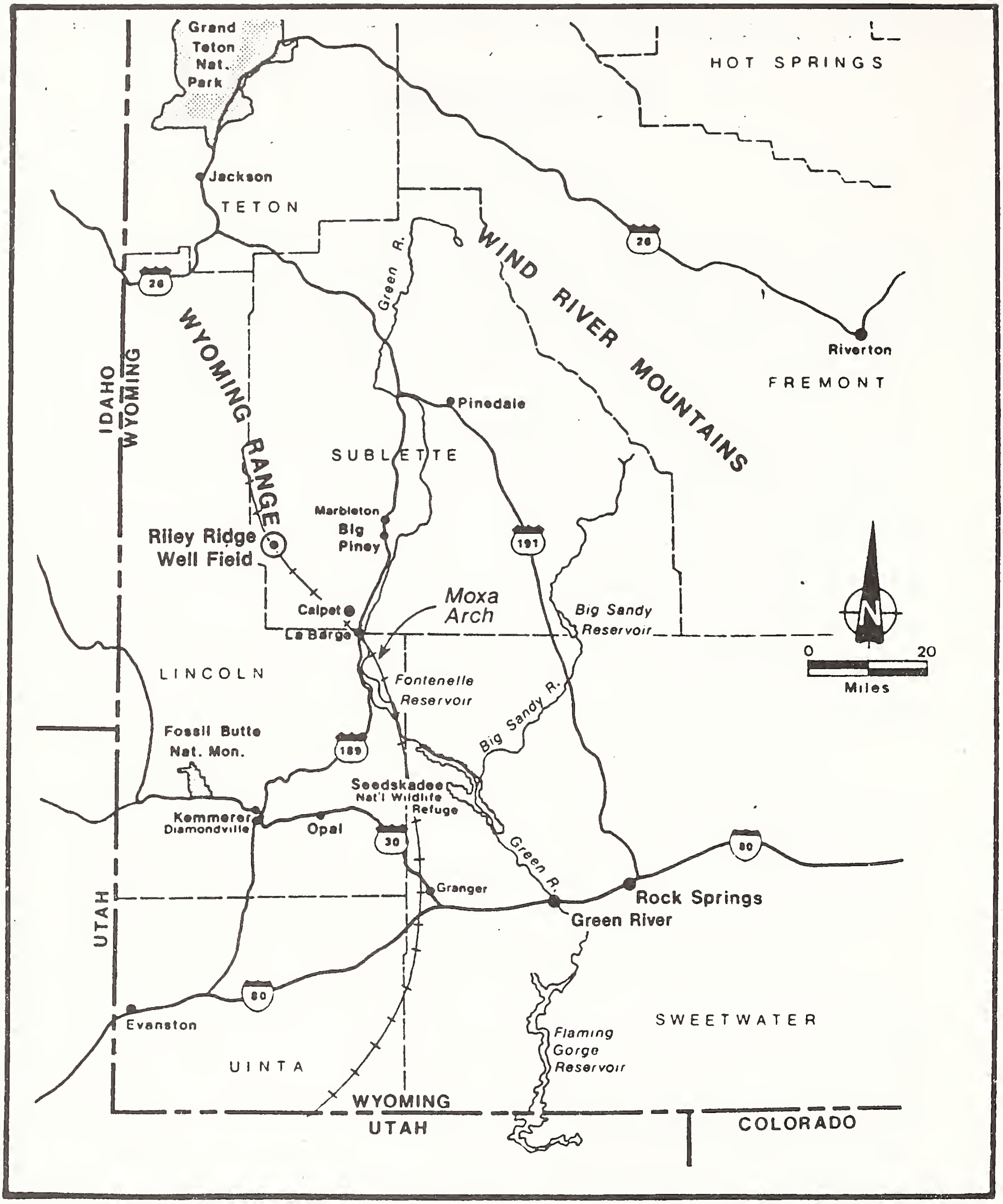
Douglas Turner, Big Piney Ranger District, Bridger-Teton National Forest, Big Piney, Wyoming



MAP 1 REGIONAL LOCATION MAP

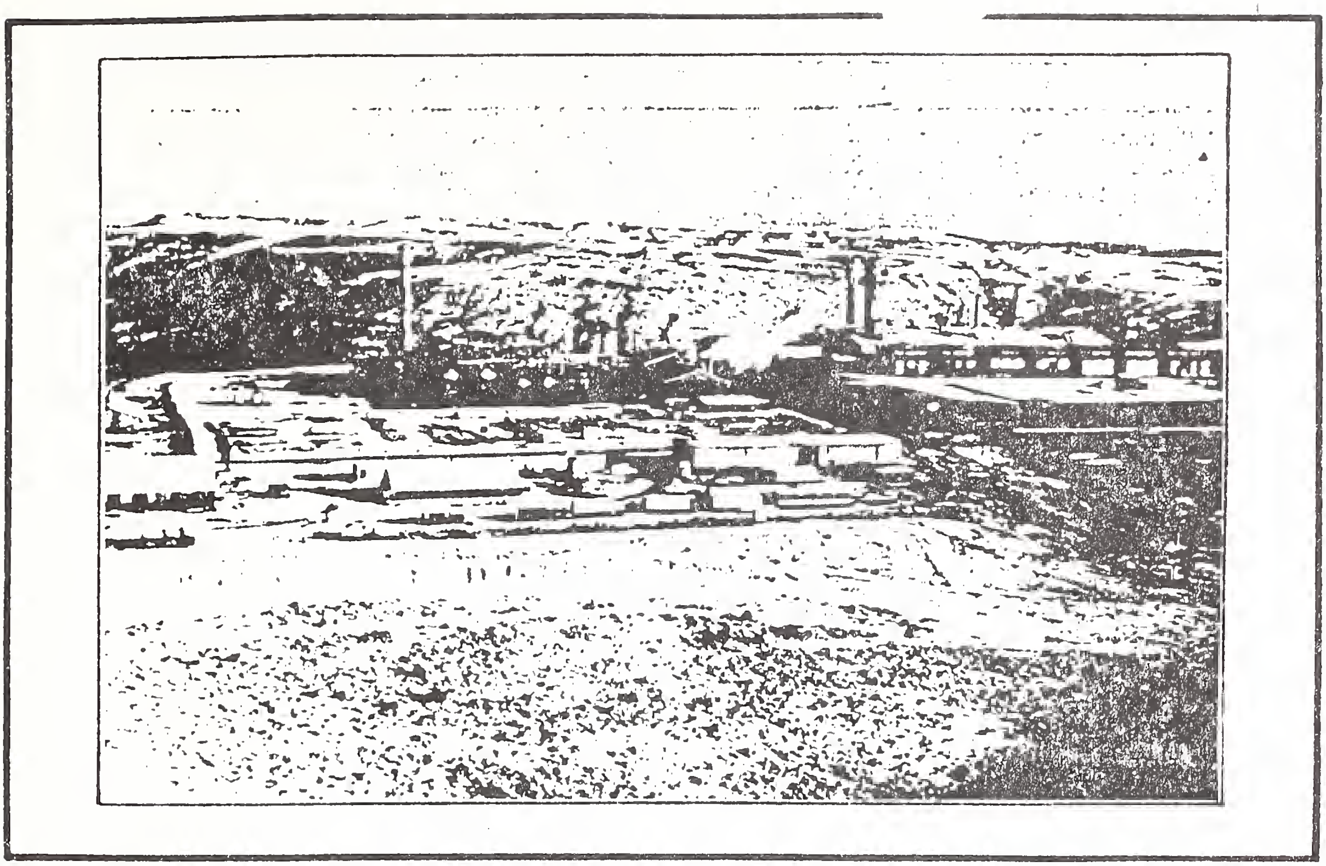


Fig. I Gas Sweetening Plant

shipped for sale. The remaining gases are processed through a SCOT tail gas cleanup unit and fed into an incinerator from which are emitted CO_2 and sulfur dioxide (SO_2). A small amount of H_2S is emitted with the CO_2 and can cause local odor problems.

Several petroleum companies formed a consortium in 1981 with the aim of extracting, processing, and selling natural gas. Exxon Company, USA, was to operate alone and proposed two plants, together processing 1.2 billion standard cubic feet per day (sft^3d^{-1}). American Quasar Petroleum Company and Williams Exploration Company were to operate one plant with the same capacity as Exxon; and Mobil Oil Corporation and Northwest Pipeline Corporation were to cooperatively produce 400 million sft^3d^{-1} in a fourth plant.

One of the purposes of the industrial liaison was to jointly fund, and otherwise cooperate in the preparation of an environmental impact statement (EIS).

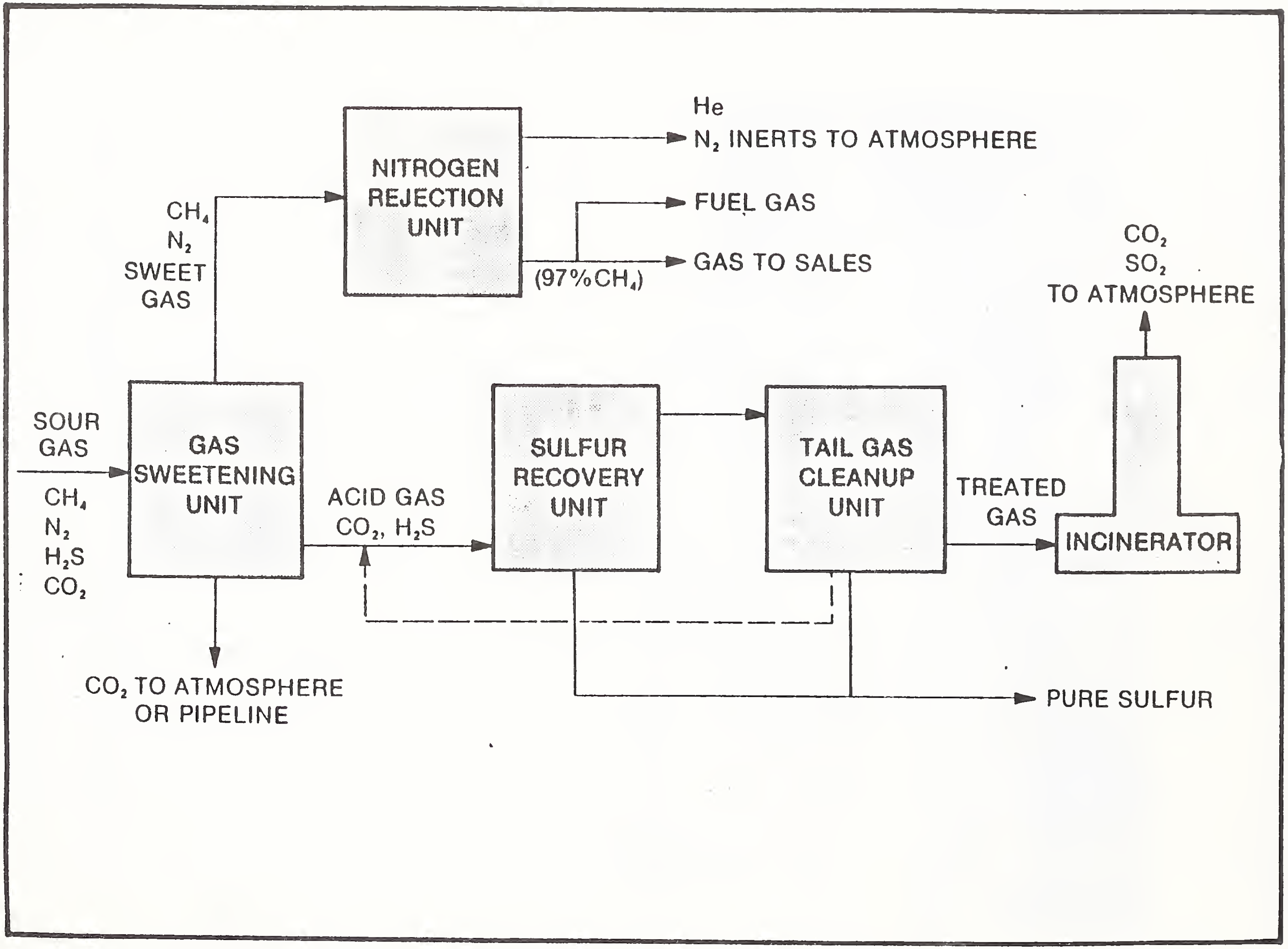


FIGURE 2 REPRESENTATIVE DIAGRAM FOR RILEY RIDGE TREATMENT PLANTS

Virtually all of the facilities would be on Federal lands and thus considered a major federal action. Such actions require an EIS. The scope of the EIS was to include a discussion of the impacts related to the extraction, transportation, and processing of natural gas from the Riley Ridge wellfield.

As in any EIS, alternatives had to be proposed and considered. In the case of the Riley Ridge EIS, the alternatives considered were plant locations, methods of sulfur transport, power supply routes, and employee housing. For this discussion, plant siting is the critical factor.

Public scoping meetings were held in Cheyenne, Kemmerer, Pinedale, and Big Piney in November of 1981. The most significant issues raised were: socio-economics, wildlife, air quality, and health and safety.

The proposed action would have placed Ameriacan Quasar's plant at East Dry Basin, Exxon's plants would have been located at West Dry Basin and Big Mesa, and Northwest's facility would have been built at Craven Creek.

The Buckhorn alternative would have located Quasar's plant farther east on Buckhorn Mesa and put both of Exxon's plants in Dry Basin. All three sites are near Big Piney. The Mobil/Northwest plant would have remained at Craven Creek.

The Northern alternative would have placed all facilities in the Big Piney area: American Quasar, Buckhorn; Exxon, West Dry Basin and Big Mesa; and Northwest at East Dry Basin.

The final alternative analyzed was called Shute Creek. It would have placed American Quasar at Buckhorn, near Big Piney, and the other plants near Kemmerer. Map 2 illustrates all plant locations that were studied.

The government's preferred alternative was Shute Creek, modified. The modification was to move Quasar's plant from Buckhorn Mesa to the Dry Basin area. The change was deemed necessary from a soils and fisheries standpoint and because of other problems associated with crossing the Green River with powerlines, roads, and pipelines. Map 3 illustrates the government preferred alternative. The government was primarily interested in the Shute Creek alternative because it represented the least overall environmental impacts. Air quality in the Wind River Mountains was an important criterion in making this selection.

In the EIS we listed the eight air quality related values (AQRV) that require protection in Class I areas. They are: flora, fauna, soils, water, visibility, odor, and cultural and geologic values. Each of these has a federally assigned set of parameters by which change is to be detected; but as yet no levels of acceptable change have been designated. Until these levels are defined, we are considering any measurable change as being significant.

The EIS states that even with the Shute Creek alternative there will be impacts to AQRV in the Bridger Wilderness. Specifically, a pH depression of 0.13 was predicted in wilderness lakes. We found that one tenth of a pH unit is reliably measurable in the field. The predicted change took into consideration the estimate that no violation of the Prevention of Significant Deterioration (PSD) standard would occur. The standard is 5 ugm^{-3}/24 hours.

TABLE 1

AIR QUALITY RELATED VALUES

1. Flora (plants)
2. Fauna (animals)
3. Soil
4. Water
5. Visibility
6. Cultural-Archeological (i.e., structures, petroglyphs)
7. Geologic (i.e., fossils)
8. Odor

EFFECTS - Flora and Fauna

Changes in:

1. Growth
2. Mortality
3. Reproduction
4. Diversity
5. Visible injury
6. Succession
7. Productivity

EFFECTS - Soil

Changes in:

1. Cation Exchange capacity
2. Base saturation
3. pH
4. Structure
5. Metals concentration

EFFECTS - Water

Changes in:

1. pH
2. Total alkalinity
3. Metal concentrations
4. Anion and cation concentrations

EFFECTS - Visibility

Changes in:

1. Contrast
2. Visual range
3. Coloration

EFFECTS - Odor

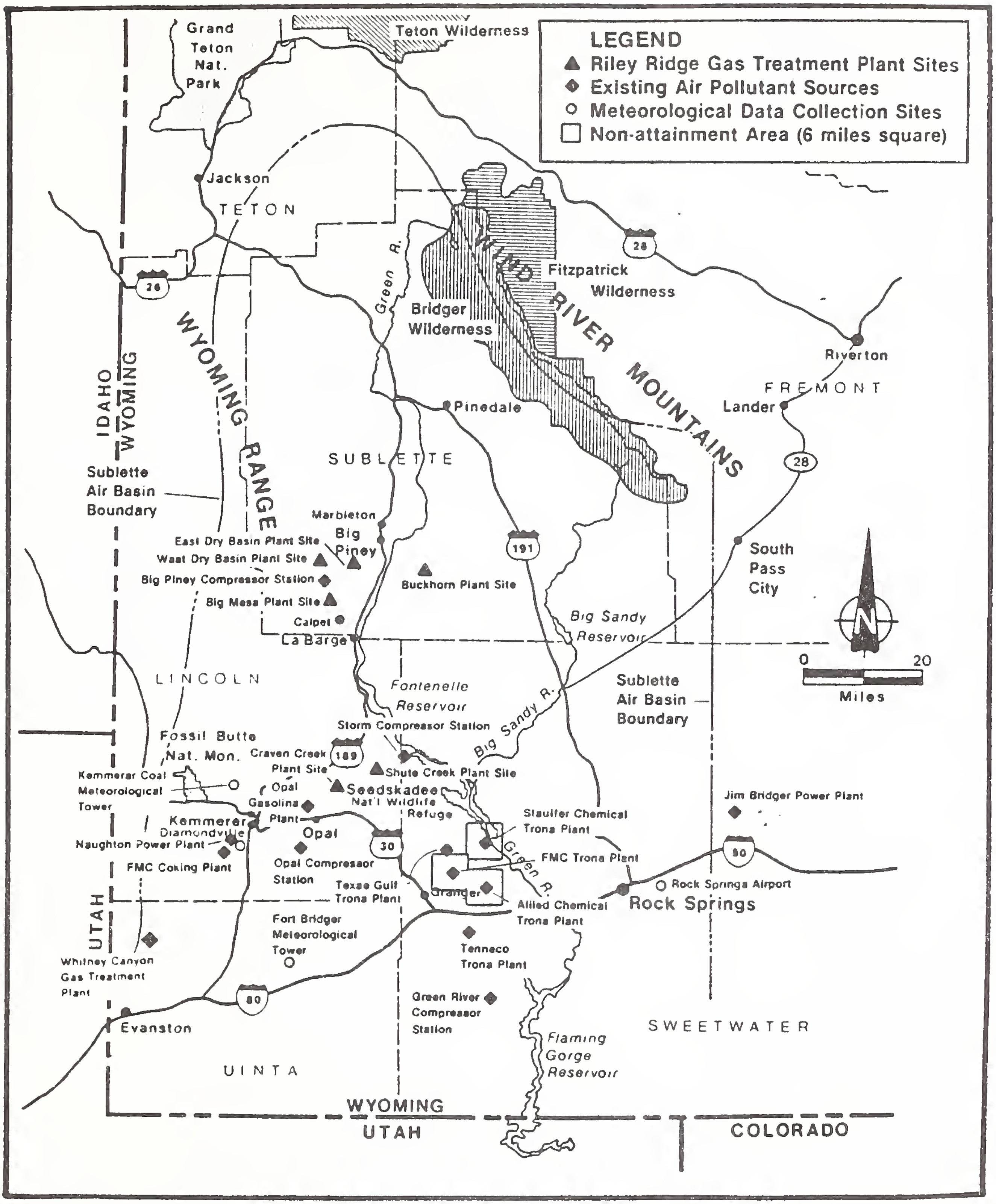
Changes in:

1. Odor

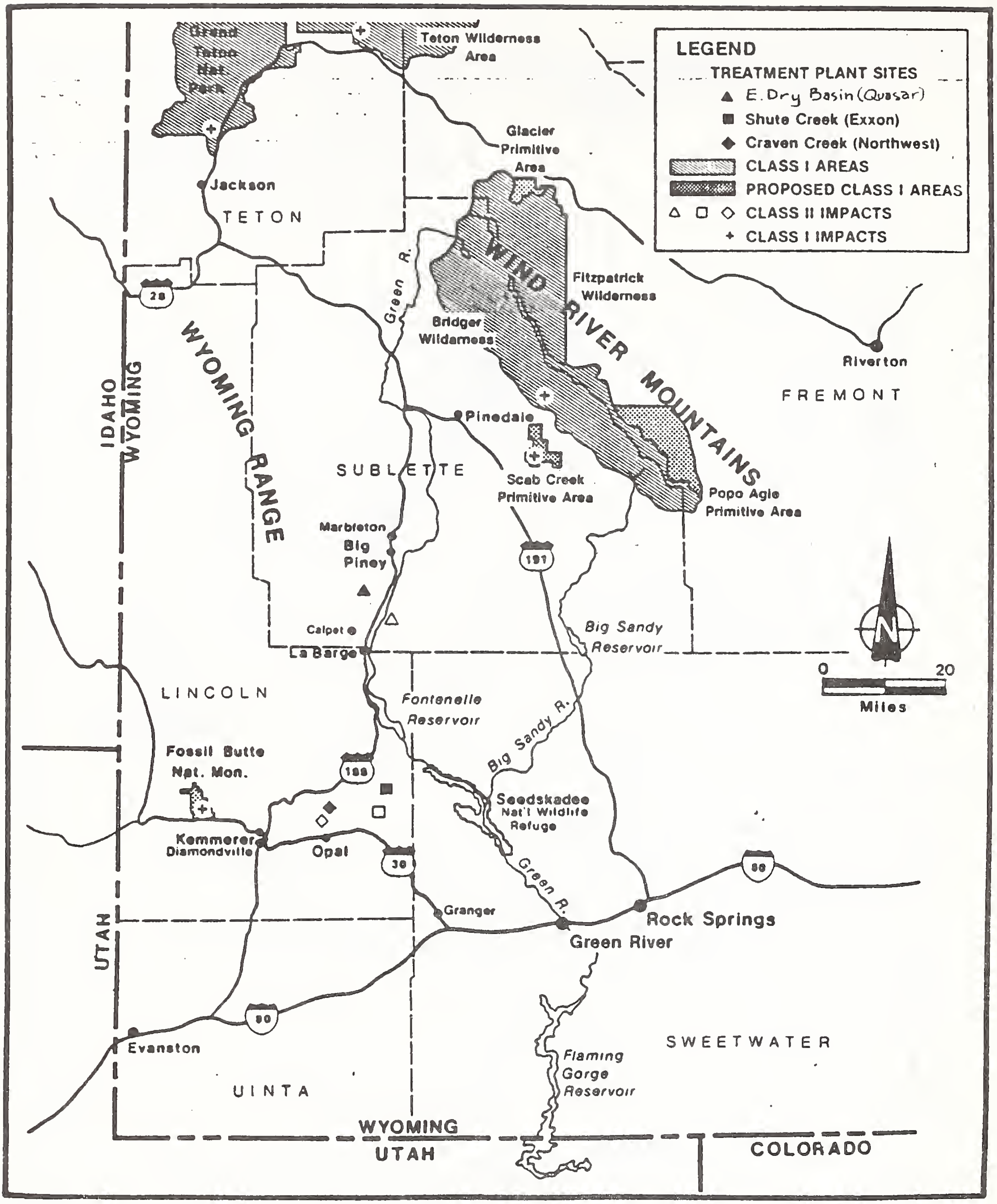
EFFECTS - Cultural, Archeological, Geologic

Changes in:

1. Decomposition rate



MAP 2 EXISTING EMISSIONS SOURCES AND PROPOSED PLANT SITES IN THE RILEY RIDGE AREA



MAP *3* LOCATIONS OF MAXIMUM 24-HOUR AVERAGE SO_2 CONCENTRATIONS IN PSD CLASS I AND CLASS II AREAS FOR THE SHUTE CREEK ALTERNATIVE

To date Exxon is the only company that has shown active interest in proceeding with the project. Their most recent production estimates range from 200 million to 600 million sft^{3}d^{-1} depending upon Exxon's markets. The estimated maximum is about twenty-one percent of the amount analyzed in the EIS. At this production rate, one could assume that far less than 0.13, if any, pH depression would occur in wilderness lakes.

However, there are several other projects in southwestern Wyoming that could be contributors to any anthropogenic AQRV changes (see Map 2). Indeed, Dr. Mason Hale has already reported concentrations of lead in certain lichens in the Wind River Mountains.

We have no alternative but to think of present conditions in the Wind River Mountains as being baseline. Those of us here from the Bridger-Teton National Forest are hoping that you will be able to tell us if our Air Quality Related Values Monitoring Plan will be able to give us a credible measure of anthropogenic departure from this baseline.

THE BRIDGER WILDERNESS

By Sam Warren, District Ranger

The Bridger Wilderness, containing approximately 392,169 acres, extends about 80 miles along the Continental Divide on the west slope of the Wind River Range in Wyoming. The Wilderness lies adjacent to the Popo Agie Primitive Area and the Fitzpatrick Wilderness Area of the Shoshone National Forest. A small portion of the Wind River Indian Reservation also lies adjacent to the Wilderness. The entire Bridger Wilderness is within the Pinedale Ranger District, most of which is within Sublette County, with a small portion on the southeast extending into Fremont County.

The area of the present Bridger Wilderness was designated a Primitive Area under a regulation of the Secretary of Agriculture on February 9, 1931. In 1960 the area was designated as a Wilderness Area and in 1964 was made part of the National Wilderness Preservation System with the passage of the Wilderness Act of September 3, 1964.

The area has great historical significance. Many famous trappers and explorers, including Jim Bridger, hunter, trapper, fur trader and guide; Kit Carson, William Sublette, Captain B. L. Bonneville, and Lieutenant John C. Fremont, entered or crossed through the area in the early 1800's. Many were in search of the beaver pelts which were important in the exploration of the Northwest. The expedition by Fremont in 1842 was one of the most important in Wyoming early history. Today, Fremont Peak bears his name.

The Bridger Wilderness is an area which provides outstanding opportunities for a wilderness experience. The extensive evidences of past glaciation, exposed geology, variety of vegetative zones, and active glaciers provide excellent opportunities for scientific study and the comparison of the natural features with those modified by man. Rugged terrain and superb scenery make it an outstanding area. Spectacular mountain peaks are striking in both height and grandeur.

Elevations in the Bridger Wilderness are from 7,500 feet above Fremont Lake to 13,804 feet at the summit of Gannett Peak, the highest point in Wyoming. Much of the mountainous terrain of the region is precipitous, with numerous pinnacles and spires. The ruggedness of the area, where no trails or other improvements exist or are planned provide a high degree of challenge and varying degrees of solitude. Mountain climbing is becoming increasingly popular in the Gannett Peak, Fremont Peak, and Cirque of the Towers areas. Vegetation includes dense timber stands of lodgepole pine, areas of stunted timber, and high alpine meadows above timberline. There are several active glaciers along both the east and west slope of the Wind River Mountains.

The Bridger Wilderness is one of the most heavily used wildernesses in the United States. In 1983 there were 25,397 visitors for 224,072 visitor days use. Most of this use is during the relatively short summer season from about June 25 through September 5. The majority of users are backpackers. There is also considerable use during the fall hunting season. There are 24 outfitters operating in the Wilderness. Winter use in the form of cross country skiing is increasing each year.

There are approximately 900 lakes in the Bridger Wilderness and over 500 of them are reported to have fish. Fishing is rated as good to excellent. There is an extensive trail system of 579 miles which provides access to most of the wilderness. Some areas have been left trailless to provide a more pristine experience.

FOREST SERVICE RESPONSIBILITIES IN THE PSD PERMITTING PROCESS

INTRODUCTION

This paper describes the involvement of the Forest Service in the Prevention of Significant Deterioration (PSD) permitting process. Also described are the direction and policies that Forest Service Regions 2 and 4 have developed to ensure wilderness protection in light of proposed development of new air pollution sources.

CLEAN AIR ACT REQUIREMENTS - PSD

The PSD provisions of the Clean Air Act (CAA) Amendments of 1977 identified a new program designed to ensure that those areas of the country which have ambient air pollution levels lower than those necessary to protect human health did not become significantly degraded by new source development.

The first part of this program identified three air quality classes (I, II, III), each with defined allowable levels (increments) of air quality deterioration.

An increment is an additional concentration in micrograms/meter^3 of air pollutant that can be added to an area (see Table 1). Class I areas have the smallest increments and therefore are supposed to have the least amount of new air pollution added to them.

Those areas identified as Class I include the following federal lands which were in existence at the enactment of the Act (August 7, 1977):

(1) international parks
(2) national wilderness areas which exceed 5,000 acres in size
(3) national memorial parks which exceed 5,000 acres in size, and
(4) national parks which exceed 6,000 acres in size.

The Forest Service manages 88 National Wildernesses which fall under this designation.

The CAA also identifies a permitting program for select new or modified stationary air pollution sources. Before such a new or modified source can commence construction, it must obtain a PSD permit from either EPA or the State air regulatory authority. In order to obtain a PSD permit, the source must demonstrate at least three things in their application

First, the applicant must demonstrate that it will apply the Best Available Control Technology (BACT) for each pollutant it has the potential to emit in significant amounts. BACT is determined on a case-by-case basis taking into account economics, environmental impacts, and energy requirements. BACT is usually expressed as an emission limitation.

Second, the applicant must provide an air quality analysis which demonstrates that neither the National Ambient Air Quality Standards (NAAQS) nor an

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allowable PSD increment will be violated. This analysis usually includes both pollutant monitoring and modeling.

Third, the applicant must identify its impacts, if any, on the Air Quality Related Values (AQRVs) of any Class I area. It is through this section of the preconstruction permitting process that the Forest Service may become involved.

The Clean Air Act states that "The Federal Land Manager and the Federal official charged with direct responsibility for management of such lands shall have an affirmative responsibility to protect the air quality related values (including visibility) of such lands within a Class I area and to consider . . . whether a proposed major emitting facility will have an adverse impact on such values."

It must be noted that the federal land manager (FLM) and the air regulatory authority (either EPA or the State) have separate, distinct roles in the PSD permitting process. In general, the air regulatory authorities enforce stack emission limitations and ambient air quality standards. The major FLM concern, however, is air pollution effects. This distinction is very clear in the area of acid deposition. Neither EPA nor any of the States have any acid deposition stack emission limitations or ambient air quality standards. In short, they currently have no regulatory method to directly control it. The FLM, however, is directed to protect AQRVs from any air pollutant which includes acid deposition. A narrow interpretation of the Clean Air Act is that the only area of the country where it is legally possible to control acid deposition is in the Class I areas and the only entity that can support such control is the FLM.

It must also be noted that for those PSD permit applications where the Class I increments are not exceeded, the FLM only makes a recommendation to the air regulatory authority. The air regulatory authority has the final responsibility to grant, modify or deny the permit.

REGIONAL POLICY AND DIRECTION

The only AQRV specifically identified in the Act is visibility. However, the Forest Service has identified those values shown in Table 2 as wilderness attributes which can be impacted by changes in air quality. Also shown in Table 2 are the specific AQRV indices that can be impacted (changed from the natural state).

In a monitoring program or permit review, it is not possible to monitor or predict impacts on all individual receptors of an AQRV. Therefore, the Forest Service is attempting to identify specific sensitive receptors, if any, for each AQRV. For example, for terrestrial flora, lichen appear to be the most sensitive to changes in air quality. If the lichen are not impacted, then no other terrestrial flora should be impacted. Also, if the terrestrial flora are not impacted, then the terrestrial fauna (animals) should not be impacted. By monitoring and making predictions on the most sensitive lichen, it should be possible to protect all terrestrial plants and animals.

It is important to remember that all Forest Service-managed Class I areas are Wildernesses. To the degree possible, the Forest Service is using the Wilderness Act of 1964 to determine exactly which wilderness components should be protected and to what degree they should be protected. As a result of reviewing the Clean Air Act, Wilderness Act, and Forest Service Wilderness management policy, Regions 2 and 4 have developed the following interrelated premises:

1. All components of the wilderness resource are equally important.

2. A wilderness component is important even if the wilderness users are not aware of its existence.

3. All trophic levels are equally important. For example, lichen and elk have equal importance as wilderness components.

4. In the wilderness the most sensitive component is to be protected, not just that component with average sensitivity.

5. Each wilderness component is important for itself, not only because of how it interacts with other components of the ecosystem.

6. For those AQRVs such as odor and visibility which directly impact the wilderness user, the key is to be sensitive to visitor experiences and expectations related to finding natural conditions rather than providing for visitor enjoyment and convenience. Enjoyment of a wilderness experience is strictly a personal decision of the wilderness user.

The value (benefits) of wilderness to humans is founded on a psychological perception that natural conditions are expected to exist in an area. Thus humans are able to enjoy the benefits of wilderness both directly, through use, and vicariously through the knowledge that areas with essentially unimpaired natural conditions are legally protected.

DEFINITION OF ADVERSE EFFECT

In developing a definition of "adverse effect," Regions 2 and 4 have relied on the Wilderness Act, Forest Service Wilderness Management policy, the Clean Air Act, the Senate Committee reports accompanying the Clean Air Act Amendments, and the data (or lack of data) available to predict air pollution impacts on the Wilderness resource. The Wilderness Act does not directly address air quality or air quality impacts. However, the Wilderness Act states in its purpose ". . . to secure for the American people of present and future generations the benefits of an enduring resource of wilderness . . . and . . . to provide for the protection of these areas, the preservation of their wilderness character, and for the gathering and dissemination of information regarding their use and enjoyment as wilderness; . . . ."

The Wilderness Act defines wilderness as ". . . an area where the earth and its community of life are untrammeled by man . . ." and ". . . an area of undeveloped Federal land retaining its primeval character and influence . . ." Untrammeled means not subject to human controls or manipulations that hamper the free play of natural forces.

The Clean Air Act gives the Federal Land Manager ". . . an affirmative responsibility to protect the air quality related values (including visibility) . . . and to consider . . . whether a proposed major emitting facility will have an adverse impact on such values."

The definition of "adverse impact" is left to the Federal Land Manager. However, the Senate Committee report accompanying the Clean Air Act Amendments gives the following direction to the Federal land manager to weigh uncertainty in favor of protecting AQRVs.

> While the general scope of the Federal Government's activities in preventing significant deterioration has been carefully limited, the Federal land manager should assume an aggressive role in protecting the air quality values of land areas under his jurisdiction. . . . In the case of doubt, the land manager should err on the side of protecting the air quality related values for future generations.
>
> (S. Rept. No. 95-127, 95th Cong., 1st Sess., 36.)

A literature search of air pollution effects data for the most sensitive receptors in alpine and subalpine ecosystems yields very little information. Most air pollution effects studies have been done at much lower elevations, usually using species of flora and fauna not found in Region 2 and 4 Wildernesses. For those studies where the species are the same, it is usually unclear how possible it is to transfer the data and models (usually developed in the East) to elevations often above 10,000 feet.

After reviewing the legislative mandates and lack of available effects data, Regions 2 and 4 have adopted the following definition of "adverse effect":

> Adverse Effect. The Region shall identify a level of acceptable change (LAC) for each sensitive receptor for each air quality related value except visibility in each wilderness area. Any predicted or measured change beyond the identified LAC shall be considered to be adverse.
>
> There is very little air pollution impact data available for ecosystems such as those found in Region 2 wildernesses. Until sufficient data exists for the Region to identify specific LAC's, the Region is defining the LAC for all air quality related values except visibility to be any measurable impact from the baseline condition. When the Region has sufficient information and programs to assure adequate wilderness protection for a specific air pollution impact beyond that which is measurable, the specific LAC may be modified.
>
> An adverse impact on visibility shall be determined on a case-by-case basis taking into account the geographic extent, intensity, duration, frequency and time of visibility impairments and how

these factors correlate with 1) times of visitor use, and 2) the frequency and timing of natural conditions that reduce visibility.

(FSM 11/82 R-2 Supplement 17.)

In short, adverse effect (impact) is defined as any measurable effect. This may be viewed as a conservative position for the Regions to take. However, it is also the most logical and defensible given the existing legislative mandates and availability of effects data and models. It must be emphasized that on a case-by-case basis for areas and specific sensitive receptors, the collection of effects related data and the development and validation of effects models may allow this definition to become less conservative.

DATA COLLECTION FOR PERMIT REVIEWS

There are a number of reasons why it is important that air pollution effect monitoring programs developed by the Regions have the best possible design, implementation, and quality assurance documentation. First, if the permitting authorities are not convinced that the Forest Service is doing a credible job, they will not give much weight to the Region's recommendations. Second, if the affected industry and environmental groups are not satisfied with the quality of our programs and recommendations, they will probably seek judicial relief. Most importantly, if the Regions do not do a good job, it is possible that it will allow degradation of some of the most primitive, unique wilderness resources in the United States.

TABLE 1

ALLOWABLE PSD INCREMENTS
(micrograms per cubic meter)

	Class I	Class II	Class III
<u>Sulfur Dioxide</u>			
° annual	2	20	40
° 24-hour	5[a]	91[a]	182[a]
° 3-hour	25[a]	512[a]	700[a]
<u>Total Suspended Particulate Matter</u>			
° annual	5	19	37
° 24-hour	10[a]	37[a]	75[a]

[a] Not to be exceeded more than once a year.

TABLE 2

AIR QUALITY RELATED VALUES

1. Flora (plants)
2. Fauna (animals)
3. Soil
4. Water
5. Visibility
6. Cultural-Archeological (i.e., structures, petroglyphs)
7. Geologic (i.e., fossils)
8. Odor

EFFECTS - Flora and Fauna

Changes in:

1. Growth
2. Mortality
3. Reproduction
4. Diversity
5. Visible injury
6. Succession
7. Productivity

EFFECTS - Soil

Changes in:

1. Cation Exchange capacity
2. Base saturation
3. pH
4. Structure
5. Metals concentration

EFFECTS - Water

Changes in:

1. pH
2. Total alkalinity
3. Metal concentrations
4. Anion and cation concentrations

EFFECTS - Visibility

Changes in:

1. Contrast
2. Visual range
3. Coloration

EFFECTS - Odor

Changes in:

1. Odor

EFFECTS - Cultural, Archeological, Geologic

Changes in:

1. Decomposition rate

Bridger and Fitzpatrick Wildernesses: Modeled Air Quality and Its Impacts

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Abstract

Outputs from industrial activities planned in the Riley Ridge natural gas project are modeled to determine the potential locations of air pollution impacts on the Bridger and Fitzpatrick Wildernesses in Wyoming. The nature of modeling, especially with regard to its realism, is discussed. Needs for critical meteorological information are identified.

Introduction

Air quality modeling is a tool to project the effects of pollution sources on the surrounding countryside. Modeling combines meteorological information with source emission data to estimate resulting pollution concentrations, usually as a function of distance from the source. The modeling attempts to simulate complex and stochastic atmospheric processes of both a physical and chemical nature. However, air pollution models track only gross features of the processes. These features generally do not resemble actual occurrences in nature. For example, standard air quality models applied in simple topographic situations can predict the maximum ground level concentration, but not when or where the maximum will occur (Fox et al. 1983). As a result of this unreality, standardization has proven useful when models are used in the regulatory process, e.g. for permitting new sources under the Prevention of Significant Deterioration (PSD) provisions of the Clean Air Act (Fox and Fairobent 1981). The Environmental Protection Agency has provided this standardization through an air quality modeling guideline (EPA 1979). Use of "guideline models" has reduced controversy associated with permitting new sources, although questions often arise as to the uncertainty associated with these models (Fox 1984a).

In areas of mountainous topography, air quality data have not been available in sufficient quantities to establish the validity of modeling techniques (Egan 1984). Efforts to make minor alterations to "guideline models" resulted in moderate success for impacts within a few kilometers from the source (Lavery et al. 1983). COMPLEX I seems to perform the best among this class of models. These modified guideline models are often applied to distances beyond their region of established validity, however. In mountainous terrain, the meteorology measured at the source in general will not represent the atmosphere even a few kilometers away. In this case, in order to realistically predict plume behavior, it is necessary to either measure or model the detailed wind distribution generated by the topography. Use of a wind field, although adding a degree of reality, also greatly complicates the modeling and thus has not yet been used for regulatory purposes. Use of wind field models also confuses the development of a worst case hypothesis for the modeling.

This paper presents results from the use of a combination of wind field and air quality models applied to evaluate pollution potentials in the Bridger and Fitzpatrick Wildernesses in Wyoming resulting from industrial development in the vicinity. Results from this application are contrasted with guideline modeling done for the Riley Ridge Environmental Impact Statements (EIS) and for PSD permits. A critical assessment suggests the need for further meteorological data and for the validation of modeling techniques.

Topographic Air Pollution Analysis System Results

The Topographic Air Pollution Analysis System (TAPAS) is a computer system that includes a number of modules that allow application of wind and dispersion models with terrain, emissions, and meteorological data (Fox et al. 1984). In this application, the two-dimensional wind field model was used with the Gaussian puff diffusion model to estimate potential impacts of the Riley Ridge sources on the Bridger and Fitzpatrick Wildernesses. Figure 1 is a map of the area simulated. Located on the map are six source areas which correspond with those identified in the Riley Ridge Environmental

Impact Statement (ERT 1983). Figure 2 represents the computer produced terrain data grid. Elevation contours are expressed in meters above sea level. Grid spacing is every 1° of latitude and longitude. The major terrain feature is a broad valley bounded by ridges on the northwest, north, and northeast (fig. 2). The predominant feature is the Wind River Mountains. Figures 3a and 3b are wind field simulations.

A primary issue in all air quality modeling is what meteorological data should be used. Guideline models use only one observation point; however, they use a full year's hourly data at that point. The year's data is used to calculate an annual average concentration, and to select the highest 24-hour average and 3-hour average for comparison against standards and increments.

Because use of a year's worth of data with a wind field model is prohibitively expensive, we have used a procedure designed to highlight the worst case condition (Dietrich et al. 1983). We study the frequency distribution of wind. From this distribution, known as a wind rose, it is possible to identify the dominant influences of direction and speed. Using these wind speeds and directions as the background flow, detailed wind patterns are produced. Figure 3a, for example, shows the pattern resulting from a west wind (wind from the west) at 4 m/s. Figure 3b shows the pattern resulting from a southwest wind also at 4 m/s. These are considered to be the predominant wind directions in the development area. To generate worst case conditions, we assume that these background winds will remain fixed for 24 hours. The atmospheric stability is also assumed fixed for this period at Class E (stable) for the cases shown here. The use of a 24-hour, worst case is common practice in the air quality field because of the numerical values of the standards. The 24-hour average is generally the easiest to exceed. If evidence suggests such persistence is overly conservative, it is reasonable to simulate the known condition. No attempt at numerical evaluation is done in this paper, so we simply illustrate the nature of the wind pattern.

Figures 4a and 4b illustrate the results of the puff model simulation using the wind model results shown in figures 3a and 3b. The locations where plumes encounter the wilderness are obvious from these figures. With the southwest wind direction, the plumes from southern development sites transport directly over the wilderness. The northern sites skirt the north end of the Bridger but they appear to bend around southerly toward the Fitzpatrick. With a west wind, the northern sites appear to be inclined to back up toward Lander.

These results of TAPAS modeling are not intended to be either comprehensive or quantitative. They simply illustrate that plumes from the various project locations are capable of reaching the wilderness areas. With more accurate emissions data, precise physical locations, and reasonable meteorological information, it would be possible to quantitatively model this region using TAPAS.

Regulatory Modeling Results

Modeling conducted by various consulting companies has indicated the magnitude of the impact from Riley Ridge sources as projected by guideline models. Table 1 indicates the impacts associated with various scenarios. The PSD permit value is presumably the most correct of these because it uses the correct plant location as well as one year's meteorological data taken from the site. It should also be recognized that this modeling is receptor specific, e.g., concentrations are calculated at specific receptors selected to produce a maximum impact. Since a straight line relationship is assumed to exist between the receptor and the source, any receptor is visited by the plume only when the wind is blowing precisely in the correct direction. A wind shift of only a few degrees causes the plume to miss that particular receptor. This factor raises some cautions about the conservative assumptions of guideline models applied in complex topography. The topography can constrain a wind direction so that, even if the source wind direction varies by 10-20°, the wind which actually transports pollution to the receptor may not change. The other wind field problem is illustrated in figure 4. Clearly, the receptor is not always in a straight-line downwind direction.

Effects of Modeled Air Quality

To determine if these projected concentrations are significant or not, it is necessary to carry the computation a bit farther toward assessing effects. Two steps are needed: first, a determination of how much of the modeled ambient concentration will deposit on the wilderness, and second, some indication of what the consequences of such deposition might be.

Relationships between ambient concentrations and the amount of chemicals deposited to an ecosystem are not easily established. Precipitation processes are able to remove chemicals from a very large volume of the atmosphere by a number of physical and chemical processes. To estimate the amount of such wet deposition, scientists have generally assumed that their removal is proportional to the amount of precipitation. Thus if one has detailed information about the historical concentration and precipitation, say a year of 24-hour average concentration and precipitation totals, then wet deposition can be estimated.

Pollution is also deposited by various physical and chemical processes ranging from absorption of SO_2 into open plant stomates to aerodynamic capture of small (<1 μm) particles on soil surfaces. These processes are lumped together under the title of dry deposition, and generally are simulated by assuming a relationship between the flux of chemical to the surface and the ambient air concentration. A simple ratio between these has dimensions of distance over time and is called a deposition velocity. Since deposition velocity must incorporate diverse physical processes, measurements of it show chemical-specific magnitudes, magnitudes that depend on the micrometeorology of the immediate environment, and magnitudes that depend on surface characteristics.

Within the first 100-150 km of a source, if conventional values for deposition velocities are assumed, calculations suggest that dry deposition of SO_2 is larger than both its wet deposition and wet and dry deposition of aerosol sulfates (Fox 1984b). For this reason, it seems possible to approximate deposition using a dry deposition velocity with concentration estimates from air quality modeling. If dry deposition of SO_2 dominates both wet deposition and dry deposition of sulfates, a conservative screening technique can be developed on this basis. Fox (1984b) describes such an approach in detail. The primary elements of the screening technique are estimating the annual concentration, assuming a magnitude for the deposition velocity, and assuming a ratio of dry to wet deposition to estimate total deposition. For SO_2, the likely magnitude of this deposition velocity is between 0.5-1.0 cm/sec; values in this range seem appropriate. Using this technique, Dames and Moore (1984), in the Exxon PSD permit, estimated elemental deposition at the Bridger Wilderness to be 0.09 kg sulfur/ha-year and 0.008 kg nitrogen/ha-year from the new source, and 0.8 kg sulfur/ha-year and 0.2 kg nitrogen/ha-year from existing sources. Estimates made for the Chevron Rock Springs phosphate fertilizer plant by the State of Wyoming using the same approach suggest deposition of 2.54 kg sulfur/ha-year and 0.91 kg nitrogen/ha-year from all existing sources including the new Chevron facility (Wyoming AQD 1984). These estimates can be compared with 1983 measured wet deposition (assumed in the analysis to represent half the total deposition) of 1.31 kg sulfur/ha-year and 0.66 kg nitrogen/ha-year. The measured deposition, especially for nitrogen, would be expected to exceed the modeled values because measurements include background values (natural sources as well as surrounding sources not specifically modeled). The fact that they do not suggests conservatism in the modeling technique.

A final step in the process of evaluating impacts involves identifying the most sensitive element of the ecosystem (Fox et al. 1981). For the Bridger and Fitzpatrick Wildernesses this appears to be the potential for acidification of low-alkalinity lakes (Haddow 1983). These lakes often are located in the alpine, with minimal soil development and vegetation surrounding them. They are subject to significant water input due to rapid melting of the seasonal snowpack. Fox (1984b) suggested a screening technique based on estimating the annual accumulation of deposited chemicals, assuming they are all concentrated in the snowmelt water volume and considering the result of introducing this water into the lake. Basically, it is assumed that all the sulfur ends up in the snowmelt as sulfuric acid and all the nitrogen as nitric acid. Resulting hydrogen ion concentration in this melt water is then balanced, assuming a simple bicarbonate reaction against the measured alkalinity of the lake. This screening technique applied to the Bridger and Fitzpatrick Wildernesses suggests that pH of very sensitive lakes, such as Klondike Lake (Fitzpatrick), could be reduced by 0.09 units. This was the greatest reduction estimated.

This type of information, uncertain as it is, can provide some perspectives for the public and hence for those who must make decisions on permits. Clearly, it is imperative that these analysis tools project a worst-case picture of what is likely to happen. The hypothesized conservative nature of the techniques needs to be quantified. The quantification will provide confidence to the public as well as suggest opportunities to reduce conservatism in order to accommodate development without unacceptable environmental impacts.

Further Studies

The various analyses described in this paper are uncertain. Although they are designed to be conservative, e.g., to overestimate worst-case impacts, there are few data available to confirm and quantify this conservatism. It is reasonably well accepted, for example, that turbulent diffusion aspects of both the TAPAS and the regulatory models used simulate less spreading of the plume than is likely to occur in nature. This is particularly true in complex topography where the irregular surface causes greater atmospheric turbulence than would be expected over flat terrain. However, the assumption made about a straight line trajectory for the plume is incorrect. Similarly, the wind field model incorporated in TAPAS is based on a number of assumptions that must be tested in the field. The only way to verify the conservative nature of these approaches is through the collection and analysis of data.

Data are needed to establish relationships between source and wilderness receptors. This requires measuring the distribution of wind speed and direction on a wide range of spacial scales, from those contributing to plume meandering (perhaps ½ km) up to the 100-150 km distance between source and receptor. There are a few ways this can be done, obviously none that is going to be completely successful. First there is the use of fixed stations that measure the wind as a time series at a point or a few points in the field. This is called an eulerian measurement: the fluid being studied passes the monitoring position. Second is a lagrangian measurement, one which moves with the fluid. Since diffusion is an inherently lagrangian phenomenon, this method provides relatively more data, but unfortunately it is generally difficult to interpret.

The Riley Ridge project is of sufficient magnitude and interest to warrant data collection by both of these techniques. First, three fixed meteorological monitoring sites have been established; one north of Pinedale, a second south of Pinedale (both on the Bridger-Teton National Forest), and the third on the east side of the Wind River Mountains about 16 km west of Lander on the Shoshone National Forest. Data from these fixed stations will supplement meteorological data collected at the source locations. These stations will provide surface meteorology; however, there remains a need for information above the surface. At present, the only aloft data available are from the Lander radiosonde once every 12 hours, and for limited time periods at various source locations. Data aloft are needed in the Pinedale vicinity.

To provide some of this information, a preliminary field study was conducted in August 1983. Three sites were selected in the Sublette Valley on a line between Big Piney and the Bridger Wilderness that passes through the southeast corner of the Scab Creek primitive area. Pilot balloons equipped with instrument packages that relay temperature and pressure were tracked at each site using an optical device. These balloons allowed the profile of wind and temperature with elevation to be determined. Although data have not yet been fully analyzed, they suggest a very complex wind system in the valley. For two of the soundings, a general southwest wind was prevailing. Balloons released, especially from the site at Pocket Creek near the Wind River Mountains, showed a tendency for wind below about 500 m to run parallel with the Wind Rivers but above that height to flow from the southwesterly direction over the mountains. One morning set of soundings showed what appeared to be establishment of a flow toward the mountains aloft, but with flow parallel to the mountains both at the lower levels and farther in the valley away from the mountains. These observations suggest, not particularly surprisingly, that complex flow patterns, inherently three-dimensional, exist in the valley. Long-term vertical profiles, such as are being collected by Exxon at their Shute Creek source location, may shed further light on this picture. Such instrumentation would be most valuable located near Pinedale.

An accurate picture of flow in this region will require lagrangian measurement techniques. Similar instrumentation to that discussed above, except that balloons are designed to fly at a fixed elevation above the ground, can be used to describe both the horizontal complexity of the flow, and vertical motion fields. Field studies using these techniques are being planned. Only when such studies are coupled with long-term data from fixed sites will it be possible to answer questions about the transport of pollution from the valley sources to the wilderness in a quantitative manner.

Table 1.--SO_2 impacts at Bridger Wilderness using COMPLEX I Modeling

	SO_2 PSD Increments (µg/m^3)		
Plant Site	3 Hour	24 Hour	Annual
Class I Increments[1]	25	5	2
Shute Creek			
EIS	1.6	0.4(0.7)[2]	0.02
PSD Permit (Exxon Sources)	1.4	0.2	0.02
PSD Permit (All Sources)	10.1	1.9	0.20
Buckhorn			
EIS	14.6	3.0(6.8[3])	0.28
Craven Creek			
EIS	2.1	0.4(0.9)	0.05
Rock Springs			
PSD Permit (Chevron)	2.37	0.43	0.03
PSD Permit (All Sources)	7.84	2.42	0.33

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[1] These values are the increments prescribed in the Clean Air Act which, when exceeded, will require the Federal Land Manager to certify that there are no adverse impacts on Air Quality Related Values before a PSD permit can be issued. Below this increment the Federal Land Manager must still so certify; however, such certification can be overridden by the regulatory agency.

[2] Numbers in parenthesis represent assumed meteorology where wind directions were held fixed for 24 hours.

[3] Underlined numbers represent exceedances of the Class I increments.

Figure Captions

Figure 1.--Map of the Riley Ridge Natural Gas Project, showing 6 proposed plant locations at Buckhorn, Big Piney, Shute Creek, Craven Creek, and the Bridger and Fitzpatrick Wildernesses.

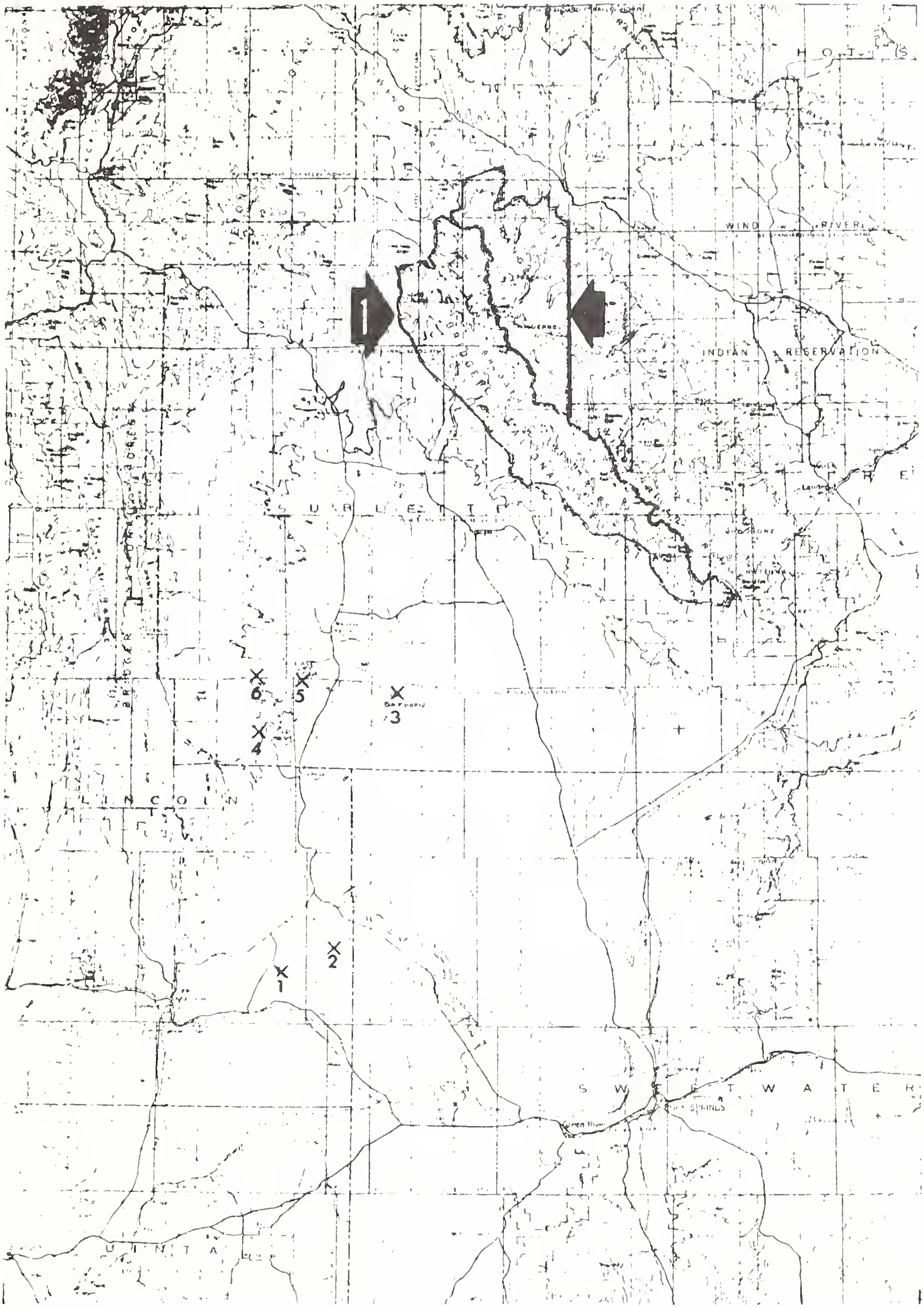
Figure 2.--TAPAS-produced terrain map. Contours are drawn above 2000 m ASL at 100 m intervals. The highest point is 3,850 m ASL.

Figure 3a.--TAPAS-produced wind vector field using the 2-D WINDS model with a background wind of 4 m/s from the west.

Figure 3b.--TAPAS-produced wind vector field using the 2-D WINDS model with a background wind of 4 m/s from the southwest.

Figure 4a.--TAPAS-produced puff trajectories and dispersion from 6 sources using the CITPUFF model with a west wind at 4 m/s.

Figure 4b.--TAPAS-produced puff trajectories and dispersion from 6 sources using the CITPUFF model with a southwest wind at 4 m/s.



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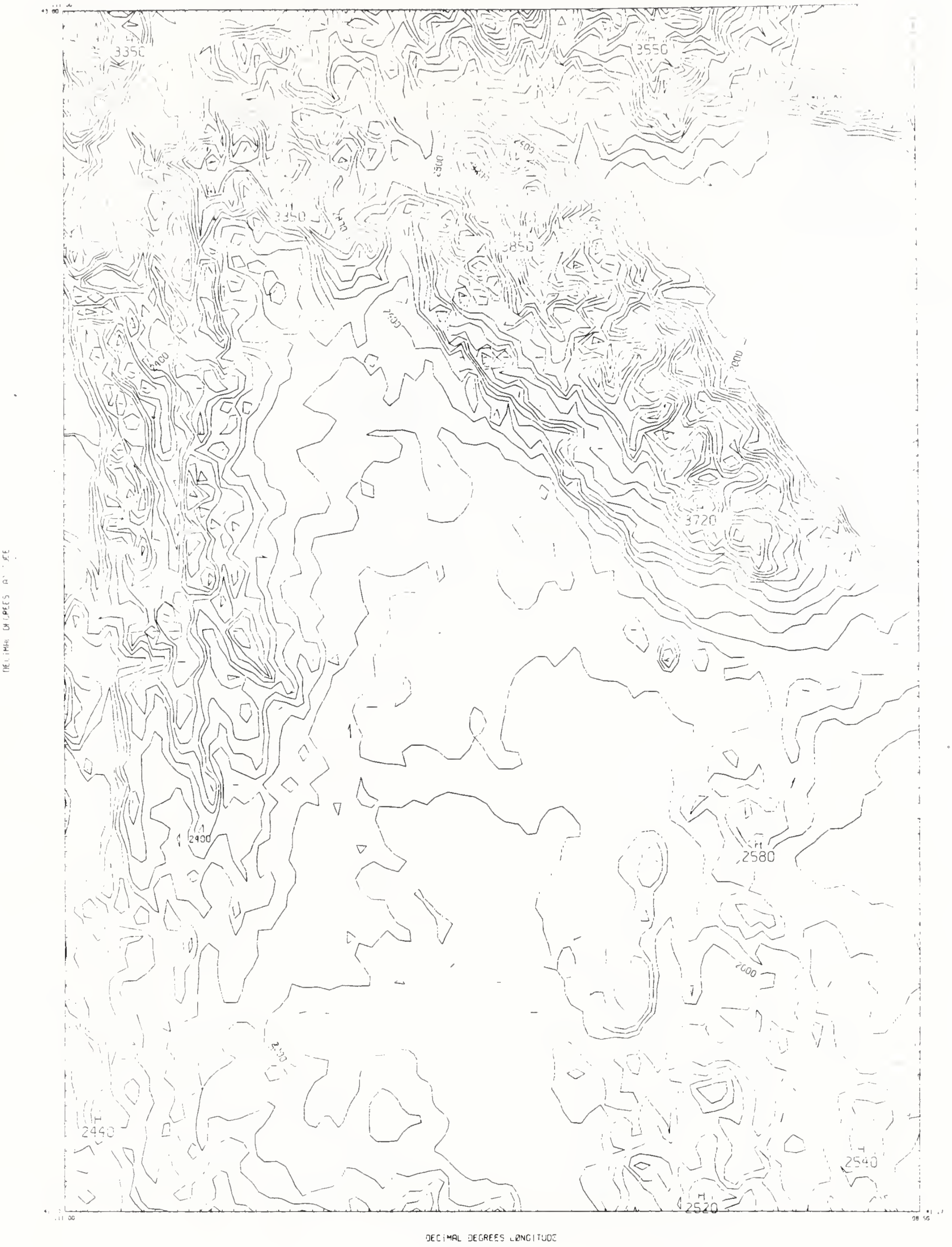

Figure 2.--TAPAS produced terrain map. Contours are drawn above 2000 m ASL at 100 m intervals. The highest point is 3,850 m ASL.

Figure 3a.--TAPAS produced wind vector field using the 2-D WINDS model with a background wind of 4 m/s from the west.

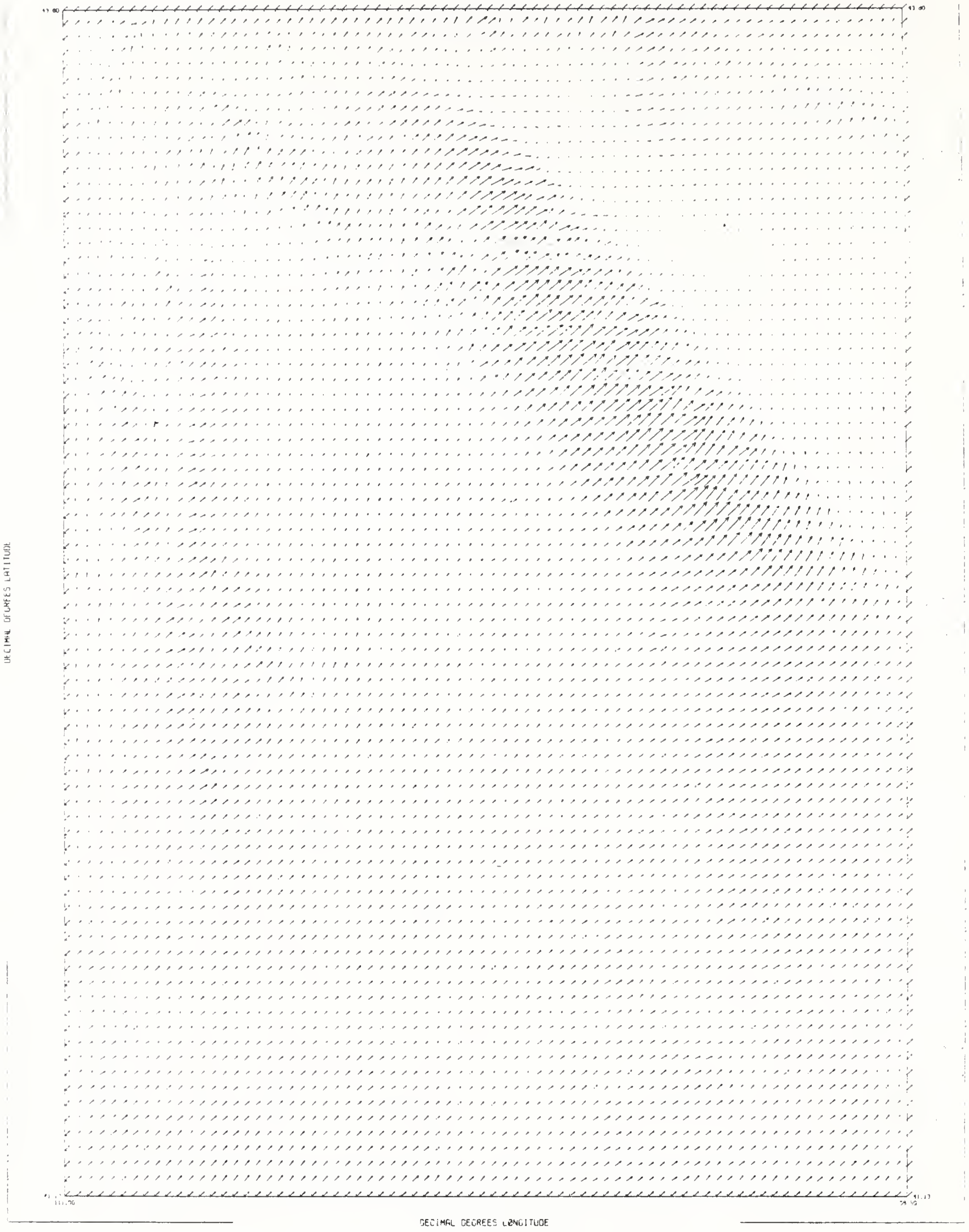

Figure 3b.--TAPAS produced wind vector field using the 2-D WINDS model with a background wind of 4 m/s from the southwest.

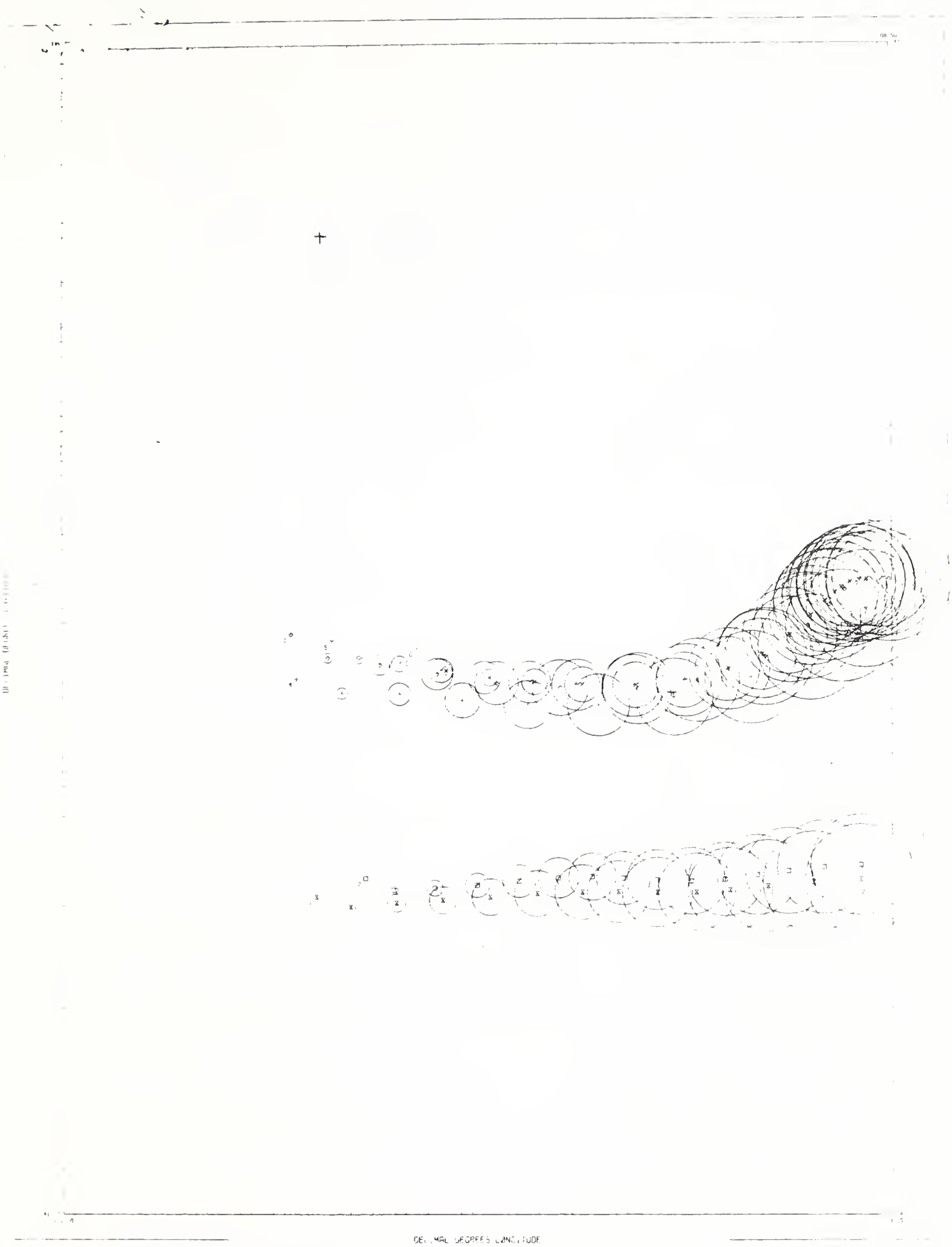

Figure 4a.--TAPAS produced puff trajectories and dispersion from 6 sources using a west wind at 4 m/s. The CITPUFF model was used.

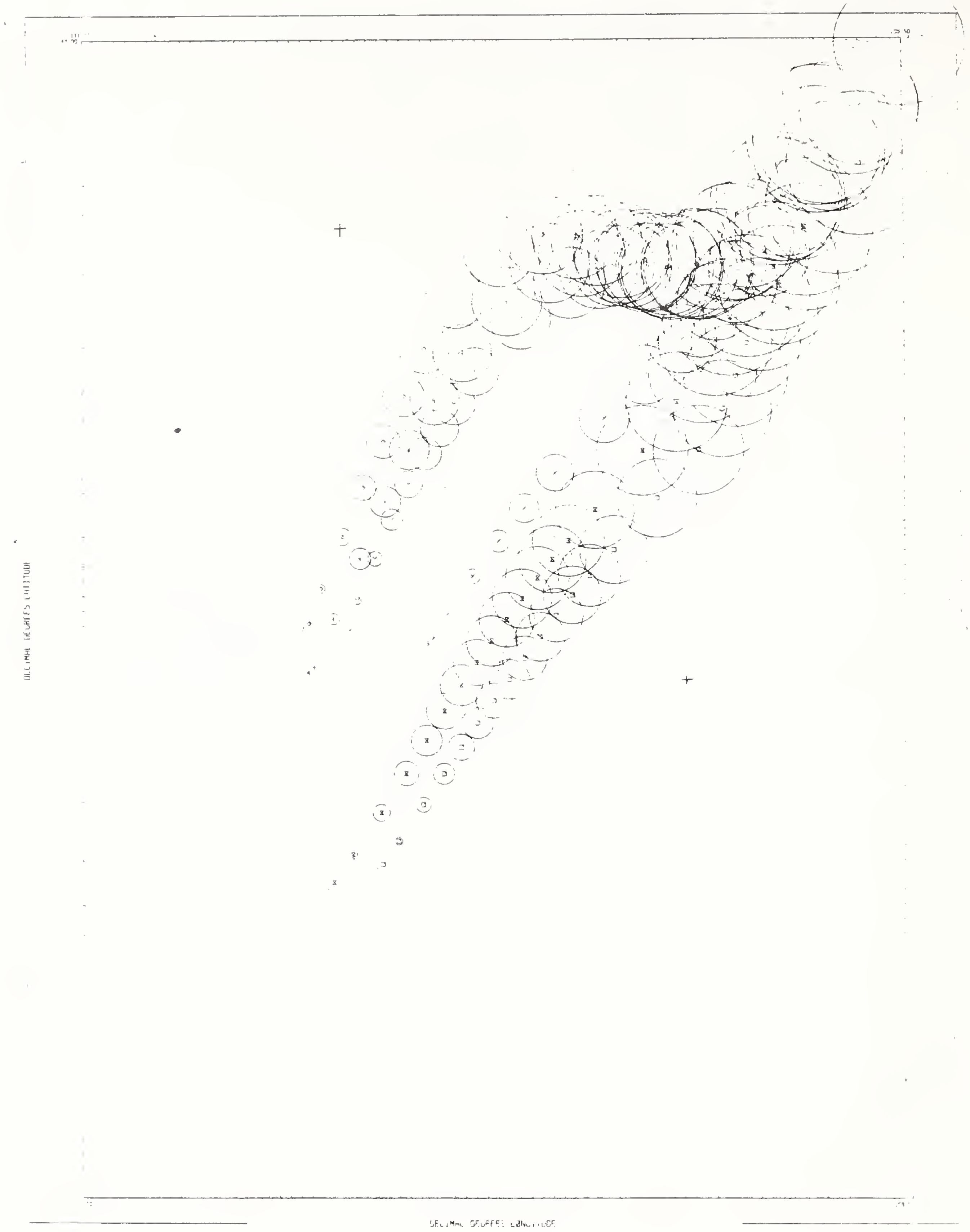

Figure 4b.--TAPAS produced puff trajectories and dispersion from 6 sources using a southwest wind at 4 m/s. The CITPUFF model was used.

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Visibility Requirements for the Bridger and Fitzpatrick Wildernesses

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Introduction

This paper discusses the protection of visibility as an air quality related value in the Bridger and Fitzpatrick Class I areas. Information about current visibility, probable sources of impairment, potential effects from proposed sources and a monitoring proposal are included.

Current Visibility

The only measured visibility data which may be applicable to the two Class I areas was collected between September and December 1983. This consists of teleradiometer data from Shute Creek, looking at targets to the west. It should be noted that the Class I areas are northeast of Shute Creek. Standard visual ranges calculated from these data are 408 kilometers - a relatively clean area.

Information from human observations indicate some visibility impairment exists in the upper Green River Basin, west of the Class I areas. Residents note that plumes and haze from industrial projects in the southern part of the Basin are evident during inversion conditions, especially when preceded by southerly wind flows. Bridger-Teton Forest Supervisor Reid Jackson made the following statement about visibility in the area in an air quality presentation at Marana, Arizona, in February 1984:

"I should also mention that in the spring of 1977 we received an early warning regarding deteriorating air quality that we did not pay enough attention to. At that time Finis Mitchell, a long time resident of Wyoming and a man who is intimately acquainted with and an expert on the Wind River mountains and their wildernesses, visited my office in Jackson to discuss the changing air quality he had noted in the Bridger Wilderness. After a short visit with me, he visited with our air quality officer to discuss the problem further. He later sent us some photos showing some of the "new haze" that was present during some summer days. Finis pointed out that most of the change had occurred since the coming of the mining and or chemical industry along I-80 in the Green River, Rock Springs areas."

Likely sources of current visibility impacts are industrial operations at Ryckman Creek, Whitney Canyon, Carter Creek and the Jim Bridger and Naughton power plants. The extent of visibility impairment in the Class I areas is uncertain, since no data or observations specific to the areas are available.

Potential Effects from New Sources

The principle pollutant of concern from new sources is sulfur dioxide. Introduction of additional high concentrations of SO_2 are of particular concern because of the effects of these light scattering aerosols on perceived visual air quality (PVAQ) in a relatively clean atmosphere. Studies have shown that introduction of a fixed amount of pollutant in a clean area has much greater effect on PVAQ than the same amount of pollution does when added to a "dirty" area (Malm 1983). In a "clean" atmosphere, this change in PVAQ peaks at about 40 km, but is still substantial at 140 km. Quantitative relationships between PVAQ and air pollution are further discussed in Malm et al. (1981) and Ross et al. (1984). These studies have shown that people are very sensitive to small incremental changes in air quality and can perceive low levels of air pollution. Several recent studies of wilderness and park users show that visibility related activities are consistently ranked very high in importance by these users. These studies suggest that visibility is an important value to users of the Bridger and Fitzpatrick Wildernesses.

Projected emissions from the Riley Ridge projects are approximately as follows:

H_2S	373 Tons Per Year
SO_2	15,833 Tons Per Year
NO_x	3,676 Tons Per Year
TSP	272 Tons Per Year

These projected emissions are much closer to the Class I areas and are more directly upwind than the existing sources. All of these pollutants affect visibility by either scattering or absorbing light, either directly or as sulfates and nitrates resulting from chemical transformations of the pollutants.

Potential visibility impacts of concern in the Bridger and Fitzpatrick areas are:

1. Plume blight - elevated or ground level plumes which impact visitor's enjoyment of wilderness;

2. Layered haze - "washing out" tops or bottoms of mountain views;

3. Regional haze - retention of aerosols in the area for several days during severe stagnation episodes. Soundings routinely collected by the National Weather Service at Lander show the area has one of the highest frequencies of such episodes of any location in the United States. These inversions may cause haze to build up in valleys within the wildernesses.

Three important vistas within the Bridger Wilderness have been identified. They are:

1. To Square Top Mountain from a point between upper and lower Green River Lakes;

2. Raid Peak from Fremont Peak;

3. West Atlantic Peak from Raid Peak.

Proposed Actions

Any important vistas in the Fitzpatrick Wilderness should be identified. Additional information on the importance of visibility to users of the two wildernesses should also be collected. The Wind River Range Visibility Monitoring Plan should be implemented.

This monitoring will provide data regarding current visibility conditions and future visibility trends. Recommended instrumentation for each monitoring site includes a teleradiometer, automatic camera, and fine particle monitor which can provide data needed to quantify cause and effect relationships, establish source-receptor relationships, and characterize impacts of haze layering and plume blight. Monitoring should begin during the 1984 field season.

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GEOLOGY AND GEOCHEMISTRY OF THE BRIDGER WILDERNESS AND THE GREEN-SWEETWATER ROADLESS AREA, WYOMING;

BACKGROUND DATA FOR AN ACID DEPOSITION MONITORING PLAN

BY

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ABSTRACT

The Bridger Wilderness and Green-Sweetwater Roadless Area are underlain by a Precambrian crystalline igneous and metamorphic rock complex that is mostly felsic gneiss and diorite to granite. Glaciation removed most soil and debris cover so that exposures are mainly bedrock covered by scattered glacial debris. Geochemical data obtained by previous studies indicate that the Precambrian rocks have low calcium and magnesium contents, but that natural buffering capacity neutralizes acids present. Addition of acids through acid rain could have deleterious effects. Soils are generally absent and thin where present and only low concentrations of alkaline cations remain after weathering of the crystalline rocks.

INTRODUCTION

The west slope of the Wind River Range, Wyoming, has a high concentration of alpine lakes and boasts of some of the most spectacular scenery in the United States. This area, the Bridger Wilderness and Green-Sweetwater Roadless Area, is a favorite of hikers, backpackers, mountain climbers, fishermen, photographers and hunters. Concern over the potential for an increase in the amount of acid rain over the area due to an increase in industrialization, has led the U.S. Forest Service to initiate studies to establish a baseline of information against which to measure future trends. The information provided in this report is intended to add to that baseline of information. The Section Corner Lake, Seneca-Hobbs Lakes, and Black Joe Lake watersheds within the Bridger Wilderness have been designated Monitor Watersheds for the purpose of detailed studies and evaluation. Reconnaissance geologic maps and descriptions are provided for each of the Monitor Watersheds.

A mineral and geological survey of the Bridger Wilderness and the Green-Sweetwater Roadless Area, hereafter called the study area, was conducted in 1980-1982 (Worl and others, 1984), under the provisions and mandates of the Wilderness Act (Public Law 88-577, September 23, 1964). Geologic and geochemical information and data presented here were collected during this survey. Mapping was at 1:50,000 scale with a few selected areas at 1:24,000 and 1:10,000.

Previous geologic investigations within the study area have been few and scattered. A wedge of Paleozoic and Mesozoic sedimentary rocks in the northern end of the range was mapped and described in detail (Richmond, 1945) and some of the glacial deposits studied (Richmond, 1973). The Precambrian rocks were largely unknown except in a few places (see, for example, Worl, 1968). Mineral resource studies in contiguous areas include the Fitzpatrick Wilderness, formerly known as the Glacier Primitive Area (Granger and others, 1971); the Popo Agie Primitive Area (Pearson and others, 1971); and the Scab Creek Instant Study area, a small U.S. Bureau of Land Management area along the west border of the Bridger Wilderness (Worl and others, 1980).

GEOLOGY

Regional setting

The Wind River Range is a large (40 x 125 mi) asymmetrical structural arch with a core of Precambrian basement rock (fig. 1). Paleozoic and Mesozoic sedimentary rocks flanking the east side of the range rest directly on Precambrian basement and dip gently east beneath the Wind River Basin. The same strata exposed in the northwestern edge of the range are in fault and depositional contact with the Precambrian rocks. Several small outliers of Paleozoic rocks just east of the town of Boulder are surrounded by Tertiary sedimentary rocks. The Wind River fault, a major fault along the west flank

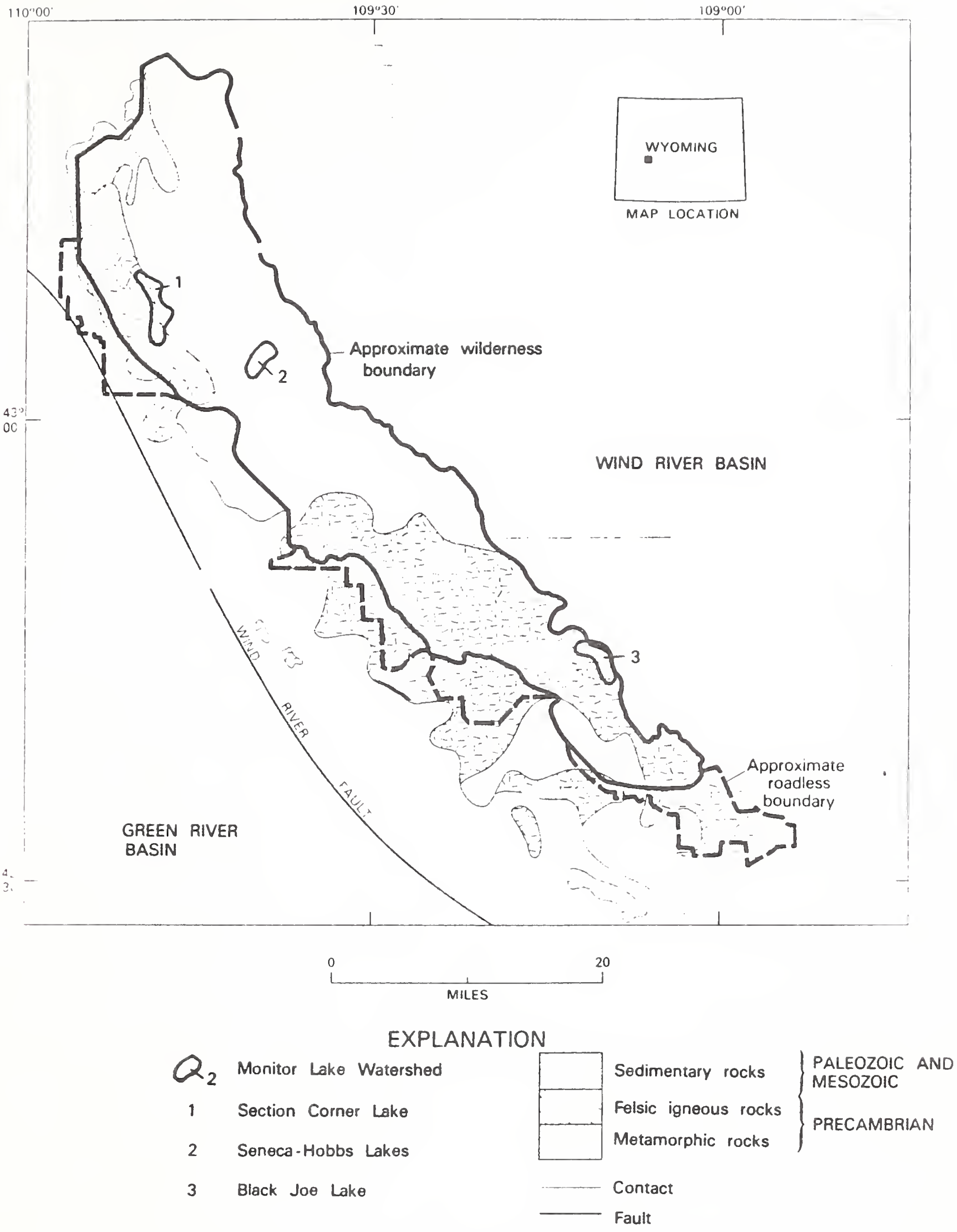

Figure 1.-- Geology of the Bridger Wilderness and Green-Sweetwater Roadless Area, Wyoming

of the range, dips eastward under the range and places Precambrian crystalline rocks over upturned and folded Paleozoic and Mesozoic sedimentary rocks of the Green River Basin. The west flank of the range and the trace of the fault are covered by Tertiary gravels and Pleistocene glacial deposits.

The Precambrian core of the range is mainly a high-grade metamorphic and igneous basement complex, with a belt of low- to medium-grade metamorphic rocks, entirely outside the study area, forming the southwestern tip of the range. Rocks of the basement complex within the study area are typical of high-grade regional metamorphic terrains: a mixture of migmatites, migmatitic gneisses, felsic gneisses and felsic plutonic rocks. Contacts are gradational and there is evidence for injection, metasomatic alteration, partial melting, and more than one period of penetrative deformation--in many places within a small area. These rocks formed in a zone of deep burial and partial melting.

Metamorphic rocks in the complex are migmatite, migmatitic gneiss and felsic gneiss with zones of pyroxene gneiss. There are generally two fractions to the metamorphic rocks: an igneous appearing (or geochemically mobile) felsic part and a metamorphic appearing (or geochemically immobile) mafic part. The felsic portion is equi-granular and ranges in composition from hornblende tonalite to biotite granite. Complexly intermixed with the light-colored felsic part is a dark, mafic part in bands, pods, and boudins. The mafic part is mainly amphibolite, biotite schist, or hornblende-biotite gneiss, but locally includes banded iron-formation (taconite), metagabbro, mafic gneiss, ultramafic rock, ferruginous-garnet gneiss, sillimanite gneiss, and diopside-hornblende gneiss. The migmatite and gneiss complex contains dike-like bodies of amphibolite and hornblende biotite gneiss that may represent metamorphosed and partially assimilated mafic dikes. The metamorphic rocks are foliated and generally layered, and boudins and ghost structures are common features.

Igneous rocks of the complex range from diorite to granite and are present as plutons, pods, dikes, and small irregular shaped bodies. Three general units of genetically related types were delineated in the study area--granodiorite, granite and porphyritic granite. Large diabasic dikes, commonly many miles long, intrude the complex.

Paleozoic and Mesozoic sedimentary rocks exposed in the northwestern part of the Wind River Range represent a complete section from Cambrian through Cretaceous. The sedimentary rocks are about 7,700 ft thick in the study area (Richmond, 1945). The basal formation, the Flathead Quartzite, is in depositional contact with the crystalline rocks and in places is flat lying. However, most of the strata are folded and faulted. Several large folds in the sediments parallel the trend of the range, and major faults with the same trend place crystalline rocks against the sedimentary rocks.

Precambrian rocks in the core of the Wind River Range are intensely fractured and sheared along major zones that generally trend parallel to the length of the Range and dip steeply east. The shear zones are broad mylonitic zones with extensive chlorite and epidote alteration, locally including easily erodible masses of brecciated rock and rock flour. A few of the shear zones place Paleozoic and Mesozoic sedimentary rocks against Precambrian rock and some extend into the sedimentary rock where they die out in fold structures. The extensive shearing and fracturing is related to movement during the laramide orogeny.

The Wind River Range began forming in the Late Cretaceous with major uplift and southwestward thrust faulting during Paleocene and Eocene times. Subsequent erosion exposed the Precambrian rocks and locally in the northern part of the Range exhumed the erosional surface that the Cambrian Flathead Quartzite was deposited upon. Thick sequences of coarse clastic sediments were deposited along the west flank of the Range and extensive peneplanes developed on the Precambrian rocks. Remnants of the Fremont Peneplane (Baker, 1946) form an upland along the west slope of the Range.

The Wind River Range was glaciated during the Pleistocene as evidenced by large cirques and sharp aretes in the higher peaks, U-shaped valleys, and abundant glacial debris. The major lakes along the west flank of the range are impounded behind terminal moraines of the Pinedale Stage of Glaciation (Richmond, 1973).

Bedrock geology of the Section Corner Lake watershed

The Section Corner Lake watershed (fig. 2) lies in an area of subdued topography in a timbered uplands. Elevation ranges from 9245 ft at Section Corner Lake to 10,361 ft at the top of Pine Mountain immediately south of Section Corner Lake. A major north-trending zone of sheared and fractured rock controls the drainage pattern above Section Corner Lake. Bedrock in this watershed is well exposed in numerous knobs and hills at higher elevation, but at lower elevation is mostly covered by a thin veneer of alluvium, colluvium and glacial debris.

Geologic relations in this monitor watershed are complex because of a gradational contact between two major rock types: felsic gneiss and porphyritic granite (fig. 2). Locally the contact is exposed in a single outcrop, but a gradual gradation from one rock type to the other across a zone as much as several hundred feet wide is most common. The watershed is along a major shear zone and most of the bedrock in the watershed has undergone some degree of shearing and fracturing.

The oldest rock in the watershed, felsic gneiss, is white to light-gray, medium-grained, equigranular, and composed of feldspar, quartz, hornblende, and biotite. Foliation, defined by alignment of biotite grains and lithologic

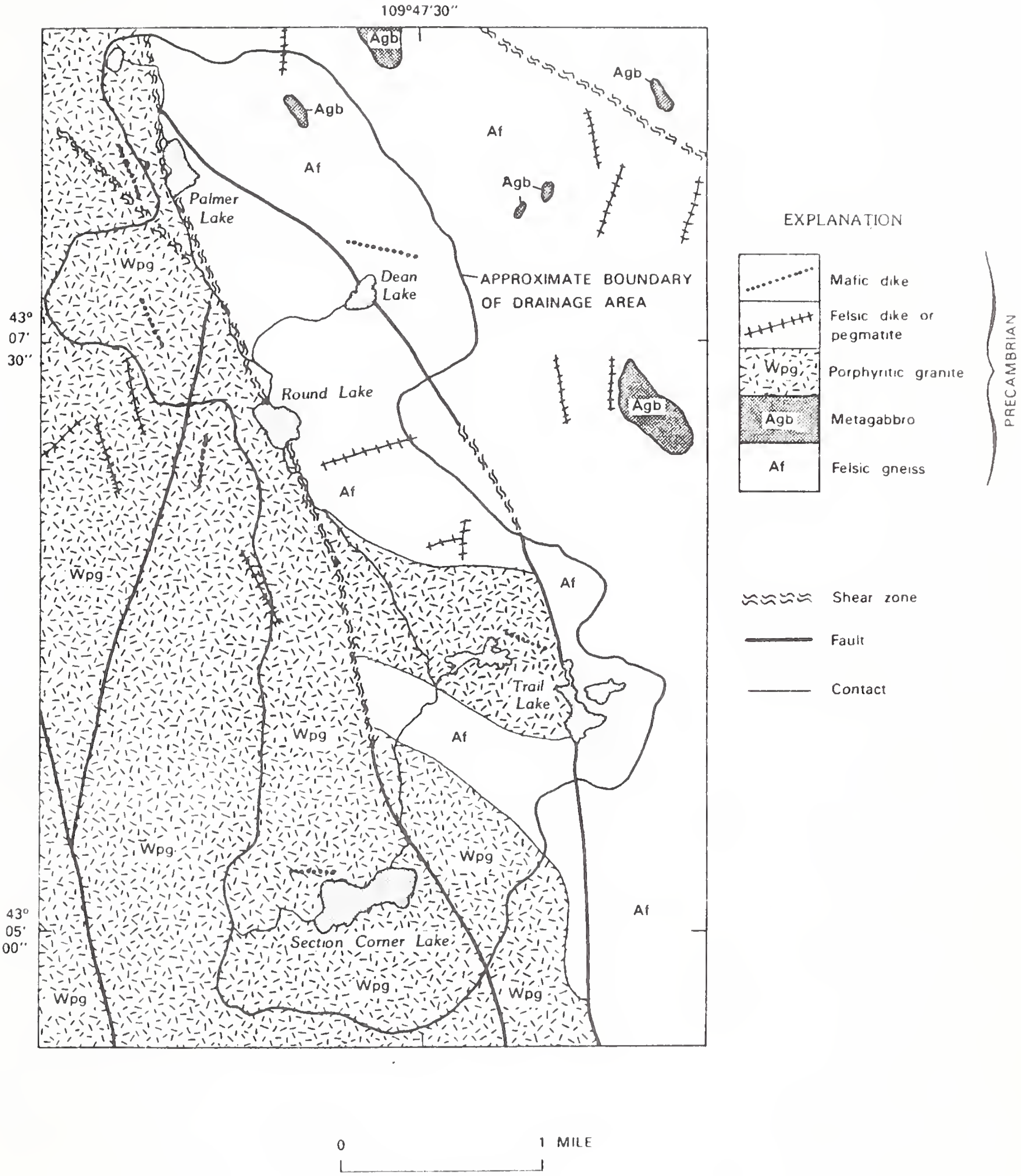

Figure 2.-- Geology of the Section Corner Lake Watershed

banding is weak, but regular. In areas close to the contact with the porphyritic granite, the felsic gneiss often contains large phenocrysts of gray and pink feldspar. These large feldspar crystals formed by metasomatism, probably from fluids emanating from the intrusion of the porphyritic granite. The felsic gneiss contains numerous small bodies of dark-greenish-gray to black metagabbro. This medium to coarse-grained rock, composed of hornblende, plagioclase and lesser amounts of quartz and biotite, locally contains large phenocrysts of white and pink feldspar.

The porphyritic granite is gray, medium- to coarse-grained, and composed of feldspar, quartz, hornblende, and biotite with large (1-2 in.) gray or pink feldspar phenocrysts. Locally, phenocrysts make up 40 percent of the rock giving the weathered surface a knobby appearance. Alignment of the feldspar phenocrysts define a moderate to strong foliation. Cross-cutting the felsic gneiss and the porphyritic granite are fine-grained felsic dikes, pegmatites, and fine- to medium-grained mafic dikes. Individual dikes are less than an inch to several feet in width.

The shear zone through the Section Corner Lake watershed is part of a major north-south system through the northwestern part of the range. Centers of the main strands of the shear zone comprise a pulverized mass of rock flour and broken rock fragments less than an inch in diameter. Clay mineral alteration products of the rock flour are common. The amount of sheared, fractured, and altered rock decreases away from the main strands, but most bedrock in the watershed was affected by movement along this shear zone. Rock adjacent to the main strands is gray-green, highly fractured, and crumbles easily. Chlorite and epidote alteration of feldspar, biotite, and hornblende, and relict quartz are the main components. Where the shear zone cuts metagabbro or other mafic rock the alteration products include carbonate minerals. Least affected rocks at a distance from the main strands contain veinlets of epidote and partial alteration of the biotite to chlorite. Best examples of fresh, unaltered felsic gneiss are north of Dean Lake, and of porphyritic granite, northwest of Section Corner Lake.

Bedrock geology of the Seneca-Hobbs Lakes watershed

The Seneca-Hobbs lake watershed (fig. 3) ranges in elevation from about 9,840 ft at the junction of the two drainages to 12,342 ft on top of Mount Lester. Hobbs Lake drains a partially wooded uplands of subdued topography. Seneca Lake drains a small west facing glacial cirque on the west slope of Mount Lester. Drainage from Seneca Lake may have gone through Hobbs lake in the past, but is now to the west, probably because of stream capture. Seneca Lake occupies a basin formed by glacial scouring along a shear zone.

Bedrock in this watershed consists of felsic gneiss with small bodies of amphibolite and metagabbro. Two major northwest-trending shear zones and numerous subsidiary parallel- and cross-fractures traverse the area.

The felsic gneiss unit includes medium-grained, equigranular, light-gray, slightly foliated granite gneiss, light-gray to dark-gray migmatitic gneiss with irregular to blocky banding, and fine- to medium-grained massive metadiorite. Mineralogy consists of varying amounts of feldspar, quartz, biotite, and hornblende. Large phenocrysts of gray plagioclase occur in amounts as much as 20 percent in some of the granite gneiss. Dark, gray-green metagabbro is comprised of hornblende, biotite, and light-gray lath-like plagioclase in a medium- to coarse-grained matrix. Magnetite is a common accessory mineral in the metagabbro, and a small body outside the north boundary of the watershed contains visible sulfide minerals. Several small dike-like bodies of gray, fine-grained, amphibolite cut the felsic gneiss.

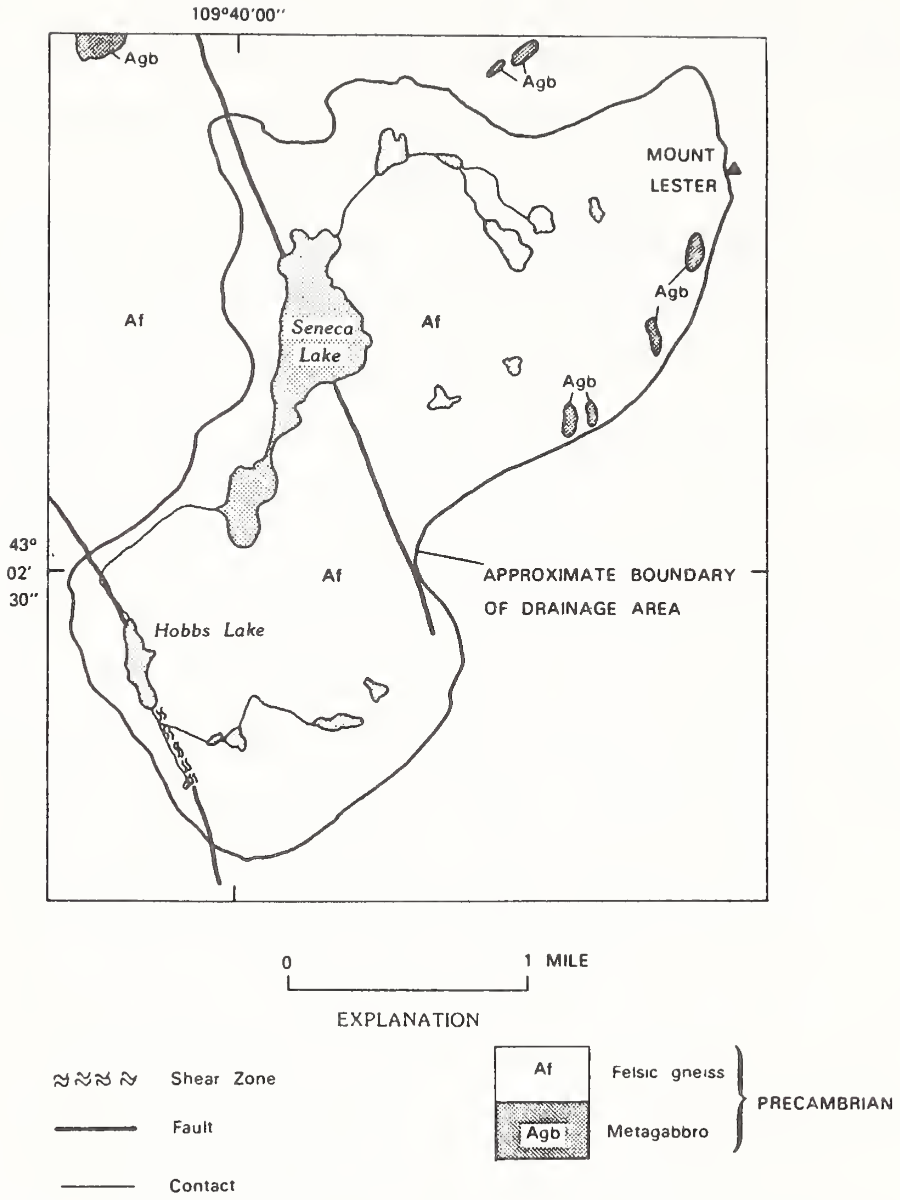

Figure 3.-- Geology of the Seneca-Hobbs Lakes Watershed

The two shear zones are major structures in the bedrock of the Wind River Range extending from Green River Lakes in the northern part of the range to Boulder Lake in the west central part. A matrix of fractured rock fragments 1 to 5 in. in diameter with an interconnecting thin network of rock flour stringers partially altered to clay minerals characterize the main strands of the shear zones. Alteration of biotite, hornblende and feldspar to chlorite and epidote is nearly complete in these strands. Carbonate minerals were not noted, but are probably present where the shear zones cut the more mafic rocks. The affect of shearing on the country rocks decreases rapidly away from these zones, so that most of the exposed bedrock in the watershed is unaltered. Small parallel and cross fractures are common and in places the rock is strongly jointed. Weathering controlled by the fractures and joints gives a blocky or fin structure pattern to outcrops.

Bedrock geology of the Black Joe Lake watershed

Black Joe Lake watershed (fig. 4) is a large north-facing glacial cirque with an elevation range from 10,258 ft at Black Joe Lake to 13,192 ft at Wind River Peak. The Continental Divide forms the eastern border of the watershed, and an arete, Haystack Mountain forms part of the west border. High alpine terrain of a U-shaped steep walled valley, knife-like mountain tops, impounded lakes, and glacial debris scattered along the valley floor dominate this watershed. An unglaciated uplands lies east of Black Joe Lake above 11,400 ft elevation. Exposures of unweathered bedrock are excellent in the valley walls and floor, but the uplands area is underlain by a jumbled mass of broken and weathered rock.

Bedrock in the Black Joe Lake watershed is porphyritic granite, cut by pegmatites and fine-grained dikes of the same composition and major northwest- and northeast-trending mafic dikes. A north-west trending shear zone and fault system bisects the watershed.

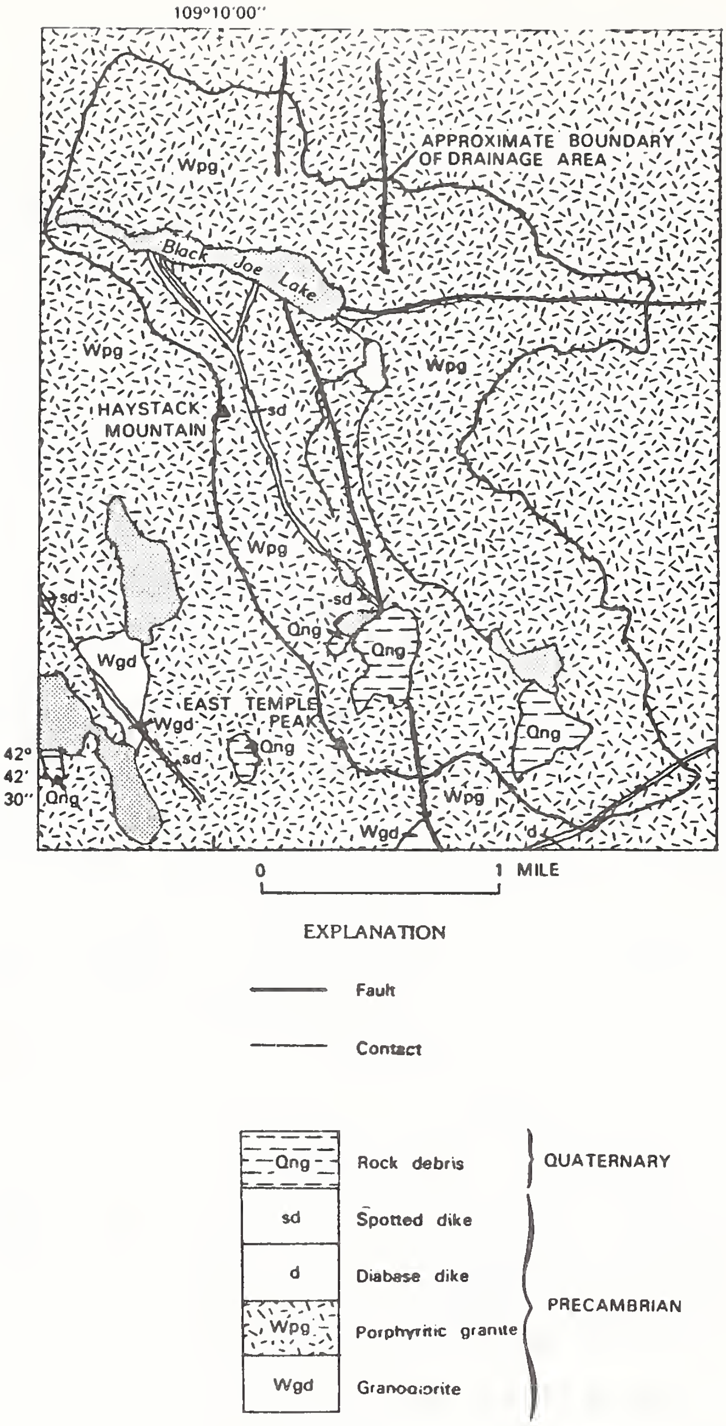

Figure 4 .-- Geology of the Black Joe Lake Watershed

Porphyritic granite is extensive in the central and southcentral parts of the Wind River Range where it intrudes an equigranular granodiorite. Typical porphyritic granite in the Black Joe Lake watershed is light gray with large- to medium-sized feldspar phenocrysts in a medium-grained groundmass of quartz, feldspar, biotite and minor hornblende. Sub-horizontal foliation is defined by oriented phenocrysts and biotite grains. Bands of equigranular granite as much as a meter thick are locally parallel to the foliation.

Two types of mafic dikes cut the Black Joe Lake watershed, diabase and spotted (fig. 4). Diabase dikes are black-green when fresh, but weather to a rust brown. Magnetite and pyrite are common accessory minerals. The spotted dikes are fine-grained, light gray-green, and variably specked with conspicuous white spots. Alteration minerals, sericite, epidote and chlorite are pervasive through the spotted dikes.

Molybdenite prospects at Schiestler Peak, about one mile west, occur in a geologic setting similar to that in the Black Joe Lake watershed. At Schiestler Peak, molybdenite and minor amounts of related sulfide minerals are mainly in the fine-grained granite bands. Minor amounts of molybdenite and related sulfides occur in fine-grained granite and pegmatites in the Black Joe Lake watershed, but not in unusual amounts for these rock types.

Shear zones in the watershed are poorly exposed because of talus, glacial debris, and alluvium. Where exposed they are typically a matrix of fractured and altered rock fragments, with stringers of clay minerals, pods and veinlets of green epidote, veinlets of reddish quartz, and locally, veinlets of carbonate. Chlorite and epidote are the most common alteration minerals, and a small amount of these minerals can be seen in most rock samples from this watershed.

GEOCHEMISTRY

Introduction

Geochemical samples collected during the survey of the Bridger Wilderness and Green-Sweetwater Roadless Area (Worl and others, 1984) consisted of 587 panned concentrates of stream sediments, 1,133 fine-grained (minus-80 mesh) stream-sediment samples, 1,938 igneous and metamorphic rock samples, 90 sedimentary rock samples, and 259 soil samples.

Sample design

Stream-sediment samples were collected from most active first order drainages as well as from all second order and larger drainages. At each sample site a composite of fine material from several localities within the stream was taken and later air dried and submitted to the laboratory for sieving and analysis.

Panned concentrates of stream sediments were collected from drainages which were large enough to deposit gravel size and coarser material. These samples were generally taken near the stream-sediment sample locations but were derived from coarser material representing a higher energy depositional environment. A heavy mineral concentrate was obtained by panning, after which the sample was sent to the laboratory for drying and analysis.

Rock and soil samples were collected to provide data for the determination of background abundances of elements and to identify and evaluate mineralized and altered ground. Rock samples were usually taken as representative composites of chips from outcrops. Soil samples were obtained at some of the rock sample locations and, in other cases, were taken where no outcrop was available. Data for the two media are not equivalent, and they must therefore be treated as separate data sets.

A few water samples were also collected, but the low content of dissolved solids, and the general lack of good ground-water sampling sites prompted the decision to abandon water sampling as part of the mineral survey. Some of the measurements on water samples, however, are of value in determination of acid rainfall effects, and will be discussed in that connection.

All rock samples were crushed, ground, split, and analyzed. Soil and stream-sediment samples were dried and sieved through an 80-mesh (177 micron) screen and the fraction finer than 80-mesh was analyzed. Panned concentrates were dried and a small split of each sample was separated for spectrographic analysis.

Six-step semiquantitative emission spectrographic analyses for 31 elements were made of all the samples by R. T. Hopkins, Jr. using the method of Grimes and Marranzino (1968). Some elements were not detected in any of the samples and are therefore omitted from the tables. Atomic absorption determinations for gold were made on panned concentrates and for antimony, bismuth, cadmium, lead, and zinc on selected rock samples.

Analytical data for the panned concentrates, minus 80 mesh stream sediments, soils, crystalline rocks and sedimentary rocks are published elsewhere (Hopkins and others, 1984) and summarized in tables 1-5. In order to determine the effects of acid rain that might result from proposed industrial plants west of the Wilderness, the U.S. Forest Service selected the drainage basins of three lakes for various types of detailed studies. These "monitor Lake" watersheds were not designated until after field work for the mineral-resource evaluation had been completed.

Geochemical results from samples taken in each of the three monitor drainage basins were retrieved from the data sets for the entire Wilderness Study Area, and the geometric means for calcium and magnesium were determined. Table 6 compares these values from the monitor basins with similar values for the entire area and with crustal abundances as listed by Goldschmidt (1958).

Discussion

The geochemical data collected for the mineral survey and summarized in tables 1-6 are evaluated here as related to possible affects of acid rain. Sources of acid in the natural environment, natural control of acidity, and acidity of waters in the study area are discussed.

Non-anthropomorphic sources of acidity in the study area are carbonic acid in precipitation, sulfuric acid from oxidation of sulfide minerals in rocks, and soil acids such as humic and fulvic acids related to growth and decay of vegetation. Acid strength (hydrogen ion concentration) is additive, whether derived from carbonic acid, inorganic acids, or organic acids and at certain times, even under normal conditions, is greatly increased. At the beginning of the spring thaw, and continuing for as long as three weeks, the concentration of acids in waters is 5 to 10 times greater than it is during other times of the year. The concentration of acids also increases during freeze-up time in the fall due to retention in the liquid phase of dissolved solids as water is frozen out. The freeze-up phenomenon is a dominant factor in areas not protected by snow cover and where penetration of frost is substantial.

Inorganic acids produced by processes of oxidation of the rocks in the study area are neutralized by alkaline species (calcium, magnesium, potassium, and sodium ions) about as quickly as they are formed. The abundant rock forming minerals--feldspar, quartz, mica, amphibole and pyroxene--weather mostly to clay minerals such as kaolin which are slightly alkaline; thus the pH of waters percolating through them will be raised. Offsetting this increase in pH is the acidity produced by humic, fulvic and other organic acids related to the growth and decay of vegetation. Pleistocene glaciers removed much of the weathered rock and soil, and crystalline rocks have less than 2 percent porosity and weather very slowly. Therefore, soil over a large part of the wilderness is absent or thin, as are the products of rock weathering that have accumulated during the time since retreat of the glaciers. Little control of acids in water entering alpine lakes can be expected where soils are sparse or absent.

A limited number of water pH measurements were obtained during the mineral survey. Small first-order streams range in pH from 5.6 to 6.5, except in swampy areas. Water in a bog on the west side of Schiestler Peak below the molybdenum occurrences had a pH of 4.3 in August, 1978 (J. C. Antweiler, unpublished data). The pH of water in second-order and larger streams gradually rises, most likely due to percolation of groundwaters through soils and over bedrock where natural buffering, ion exchange, and neutralization occur due to decomposition of silicate minerals. Streams that flow underground in some places, such as Fremont Creek between Gorge Lake and Long Lake, are buffered to a pH of 7.0. The waters of Fremont Lake in October, 1983, had a pH of 7.0 on the surface at the inlet, midway along the lake and at the outlet (R. L. Malcolm, personal communication, 1983). Also in October of 1983, New Fork Lake waters gave pH readings of 6.7 to 6.9 (R. L. Malcolm, personal communication).

Potential natural buffering capacity

Available geochemical data indicate that all rocks included in the mineral survey, except the sedimentary rocks in the northwest portion of the study area, are low in calcium and magnesium. Calcium is generally the most effective element in providing compounds useful in neutralizing or buffering acidic charges. Sodium and potassium compounds are also helpful, but available data do not include these elements.

The low content of calcium and magnesium can be appreciated by comparing the geometric mean values of data in tables 1-5 with crustal abundances (Goldschmidt, 1958) as compiled in table 6. The mean calcium content of the crystalline rocks (1.41 percent) for the Bridger Wilderness is less than half the average crustal abundance (3.63 percent). Soils were found to have even less calcium than the crystalline rocks although they vary considerably in the monitor lake watersheds. Obviously, much of the calcium in the rocks remains insoluble during weathering, as indicated by the relatively high calcium content of panned concentrates. Because the calcium content of soils is less than that of the crystalline rocks, the remainder of the calcium is either removed in solution in drainage waters, or is bound up in heavy resistate minerals that appear in the panned concentrates. The resistate minerals are of little value in acid neutralization. Although the calcium content of sedimentary rocks is greater than that in the crust of the earth as a whole, the sedimentary rocks comprise only a small fraction of the outcrop in the study area (fig. 1).

Although analytical data are not available for sulfur, most of the rocks in the study area also appear to have no greater than average crustal abundance for sulfur (about 900 ppm according to Hawkes and Webb, 1962). Observations indicate that the acidic compounds, particularly sulfuric acid, resulting from oxidation and weathering of the rocks are not likely to be excessive. Sulfide minerals occur in abundance at only a few localities. Most notable are pyrite-rich outcrops near the Continental Divide in the headwaters of Wells, Tourist, and Pixley Creeks. Other occurrences are in the vicinity of molybdenite prospects around Schiestler Peak and prospects west of Gutierrez Peak and near Moya Canyon. Sulfuric acid produced from weathering of rocks from these occurrences appears to be adequately buffered within short distances from the outcrop.

A natural balance now exists in the waters of the study area. Natural acidity derived from precipitation, chemical weathering of rocks, and organic acids from plants is neutralized by the alkaline species in the rocks and soils.

CONCLUSIONS AND RECOMMENDATIONS

Addition of acids through acid rain could have deleterious effects because soils are generally thin, and in places absent, especially at high elevations where soils have not developed appreciably since the latest glaciation. Because the rocks weather slowly and are low in calcium and magnesium, the buildup of adequate buffering capacity has been and will continue to be a slow process. Studies should be made immediately to determine the composition, particularly the acid content, of precipitation, as well as that of dry fall-out. Stations for sampling should include the most susceptible environment to harmful effects of acid rain-high lakes that support fish and other aquatic life, and that have little or no soil in most of their drainage basins. The lakes at the head of Boulder Creek are a good example. The bedrock geology, surficial geology, and geochemistry of the monitor areas should be studied in detail along with core samples of lake sediments for geochemical and biological information.

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EXPLANATION FOR TABLES 1-5

These tables were obtained by computer synthesis and statistical analysis of 6-step semiquantitative emission spectrographic analyses (S in element identification column) by R. T. Hopkins and partial chemical atomic absorption analyses (AA-Cd, -P, for example) by W. L. Campbell as reported by Hopkins and others (1984). Analyses are in parts per million except for Fe, Mg, Ca, and Ti, which are in percent. Only one or two numbers are significant. Additional numbers result from computer-formatting and do not imply greater accuracy. Columns shown under Raw Data are from the number of unqualified analytical values listed in the valid column. Analysts qualify some analyses as follows: B-no analysis made; N-not detected; L-detected, but present in an amount less than can be satisfactorily measured by analytical method used; G-present in an amount too great to be satisfactorily measured by method used; other-interferences or other reasons prevent reporting a satisfactory result. The symbol - in a column designates none. In order to broaden the statistical base, and thus obtain geometric means utilizing qualified analyses, values were arbitrarily substituted for qualified data as follows: B-no substitution; N-10 % of the lowest value that can be satisfactorily measured; L-next lower measurement interval; G-next higher measurement interval. Elements not detected in any samples are not shown.

Table 1.--Bridger Wilderness Study Area Panned-Concentrate Samples -Summary of Basic Statistics-

Col No.	Column I.D.	Raw data Minimum	Maximum	Mean	Standard Deviation	B	N	L	G	Other	Valid	Replaced data Geom Mean	Geom Dev	Valid	Replacement values N	L	G	Col No.
1	S-Fe%	0.7000	50.00	19.900	12.900	-	-	-	15	-	572	16.500	2.100	587	--	--	70.0	1
2	S-Mg%	0.0700	7.00	1.650	1.310	-	-	-	-	-	587	1.160	2.524	587	--	--	—	2
3	S-Ca%	0.1500	20.00	4.400	2.650	-	-	-	1	1	586	3.630	1.981	587	—	--	70.0	3
4	S-Ti%	0.2000	1.00	0.735	0.276	-	-	-	502	-	85	1.335	1.398	587	—	--	1.5	4
5	S-Mn	100.0000	10000.00	2530.000	1710.000	-	-	-	-	-	587	2080.000	1.877	587	--	--	--	5
6	S-Ag	2.0000	10.00	5.400	3.210	-	582	-	-	-	5	0.103	1.428	587	0.100	--	—	6
7	S-B	20.0000	100.00	23.900	12.800	-	435	60	-	-	92	3.590	2.722	587	2.000	15.00	—	7
8	S-Ba	50.0000	5000.00	392.000	500.000	-	-	29	1	-	557	248.000	2.559	587	--	30.00	15000.0	8
9	S-Be	2.0000	200.00	3.870	17.800	-	231	232	-	-	124	0.743	2.975	587	0.200	1.50	—	9
10	S-Co	10.0000	150.00	22.200	14.500	-	1	5	-	-	581	19.600	1.567	587	1.000	7.00	—	10
11	S-Cr	30.0000	7000.00	304.000	449.000	-	-	-	-	-	587	205.000	2.222	587	--	--	—	11
12	S-Cu	10.0000	70.00	24.800	16.200	-	2	100	-	-	485	17.000	1.997	587	1.000	7.00	--	12
13	S-La	50.0000	2000.00	383.000	397.000	-	1	10	12	-	564	249.000	2.849	587	5.000	30.00	3000.0	13
14	S-Mo	10.0000	700.00	243.000	396.000	-	579	5	-	-	3	1.040	1.431	587	1.000	7.00	—	14
15	S-Nb	50.0000	200.00	63.500	25.600	-	122	341	-	-	124	24.000	2.363	587	5.000	30.00	--	15
16	S-Ni	10.0000	700.00	52.700	52.800	-	-	12	-	-	575	36.600	2.296	587	—	7.00	--	16
17	S-Pb	20.0000	2000.00	77.900	95.100	-	12	12	-	-	563	59.900	2.047	587	2.000	15.00	--	17
18	S-Sc	10.0000	100.00	26.500	15.800	-	-	48	-	-	539	20.500	1.855	587	--	7.00	—	18
19	S-Sn	20.0000	70.00	30.000	18.300	-	559	15	-	-	13	2.230	1.641	587	2.000	15.00	—	19
20	S-Sr	200.0000	2000.00	578.000	321.000	-	91	41	-	-	455	280.000	3.542	587	20.000	150.00	—	20
21	S-V	30.0000	1500.00	400.000	239.000	-	-	-	-	-	587	337.000	1.832	587	--	--	--	21
22	S-W	100.0000	700.00	425.000	320.000	-	583	-	-	-	4	10.200	1.339	587	10.000	--	—	22
23	S-Y	20.0000	3000.00	158.000	172.000	-	-	4	-	-	583	121.000	2.003	587	--	15.00	—	23
24	S-Zr	30.0000	2000.00	1020.000	613.000	-	-	-	282	-	305	1510.000	2.428	587	--	—	3000.0	24
25	S-Th	200.0000	2000.00	523.000	459.000	1	473	43	-	-	70	33.100	2.947	586	20.000	150.00	—	25
26	AA-Au-P	0.0500	30.80	2.140	7.650	6	346	219	-	-	16	0.011	2.793	581	0.005	0.03	--	26

Table 2.—Bridger Wilderness Study Area Stream-Sediment Samples -Summary of Basic Statistics-

Col No.	Column I.D.	Raw data										Replaced data			Replacement values			Col No.
		Minimum	Maximum	Mean	Standard Deviation	B	N	L	G	Other	Valid	Geom Mean	Geom Dev	Valid	N	L	G	
1	S-Fe%	0.3000	15.000	4.4900	2.2600	-	-	-	-	-	1133	3.9600	1.685	1133	--	--	--	1
2	S-Mg%	0.1500	7.000	1.5000	0.7350	-	-	-	-	-	1133	1.3300	1.675	1133	--	--	--	2
3	S-Ca%	0.3000	15.000	2.2200	1.2300	-	-	-	-	-	1133	1.9700	1.624	1133	--	--	--	3
4	S-Ti%	0.0700	1.000	0.6080	0.2250	-	-	-	14	-	1119	0.5670	1.553	1133	--	--	1.5	4
5	S-Mn	100.0000	5000.000	939.0000	523.0000	-	-	-	2	-	1131	835.0000	1.651	1133	--	--	7000.0	5
6	S-Ag	0.5000	7.000	1.8300	2.6000	-	1122	5	-	-	6	0.0512	1.293	1133	0.050	0.30	--	6
7	S-B	10.0000	200.000	26.800	25.0000	-	201	49	-	-	883	11.4000	3.667	1133	1.000	7.00	--	7
8	S-Ba	100.0000	3000.000	638.0000	361.0000	-	-	-	-	-	1133	564.0000	1.625	1133	--	--	--	8
9	S-Be	1.0000	5.000	1.6300	0.4410	-	2	42	-	-	1089	1.5200	1.382	1133	0.100	0.70	--	9
10	S-Co	5.0000	150.000	12.7000	7.1300	-	10	19	-	-	1104	11.0000	1.694	1133	0.500	3.00	--	10
11	S-Cr	10.000	5000.000	110.0000	219.0000	-	-	1	1	-	1131	75.8000	2.120	1133	--	7.00	7000.0	11
12	S-Cu	5.0000	200.000	26.4000	15.9000	-	-	3	-	-	1130	23.1000	1.651	1133	--	3.00	--	12
13	S-La	20.0000	700.000	108.0000	74.3000	-	-	3	-	-	1130	89.7000	1.824	1133	--	15.00	--	13
14	S-Mo	5.0000	20.000	6.3900	3.2300	-	1053	57	-	-	23	0.5750	1.680	1133	0.500	3.00	--	14
15	S-Nb	20.0000	20.000	20.0000	0.0000	-	549	568	-	-	16	5.6700	2.751	1133	2.000	15.00	--	15
16	S-Ni	5.0000	1000.000	36.8000	44.7000	-	-	10	-	-	1123	26.8000	2.167	1133	--	3.00	--	16
17	S-Pb	10.0000	200.000	50.7000	23.3000	-	-	1	-	-	1132	46.0000	1.557	1133	--	7.00	--	17
18	S-Sc	5.0000	70.000	13.2000	5.4800	-	-	19	-	-	1114	11.9000	1.577	1133	--	3.00	--	18
19	S-Sn	50.0000	50.000	50.0000	--	-	1131	1	-	-	1	1.0100	1.139	1133	1.000	7.00	--	19
20	S-Sr	100.0000	1000.000	341.0000	169.0000	-	3	18	-	-	1112	292.0000	1.761	1133	10.000	70.00	--	20
21	S-V	20.0000	300.000	115.0000	40.9000	-	-	-	-	-	1133	107.0000	1.469	1133	--	--	--	21
22	S-Y	10.0000	300.000	48.0000	26.5000	-	-	-	-	-	1133	42.3000	1.644	1133	--	--	--	22
23	S-Zn	200.0000	200.000	200.0000	0.0000	-	1113	8	-	-	12	20.8000	1.335	1133	20.000	150.00	--	23
24	S-Zr	30.0000	1000.000	314.0000	223.0000	-	-	-	55	-	1078	278.0000	2.074	1133	--	--	1500.0	24
26	S-Th	100.0000	300.000	135.0000	62.6000	14	1097	12	-	-	10	10.4000	1.366	1119	10.000	70.00	--	25

Table 3.--Bridger Wilderness Study Crystalline Rock Samples -Summary of Basic Statistics-

		Raw data										Replaced data			Replacement values			
Col No.	Column I.D.	Minimum	Maximum	Mean	Standard Deviation	B	N	L	G	Other	Valid	Geom Mean	Geom Dev	Valid	N	L	G	Col No.
1	S-Fe%	0.0500	20.000	3.750	3.4900	-	-	1	27	-	1910	2.6600	2.627	1938	--	0.03	30.0	1
2	S-Mg%	0.0200	20.000	1.540	1.7600	-	-	11	-	-	1927	0.8550	3.307	1938	--	0.02	--	2
3	S-Ca%	0.0500	20.000	2.240	2.2100	-	-	17	1	-	1920	1.4100	2.981	1938	--	0.03	30.0	3
4	S-Ti%	0.0020	1.000	0.368	0.2580	-	1	-	25	-	1912	0.2690	2.618	1938	.0002	--	1.5	4
5	S-Mn	10.0000	7000.000	559.000	603.0000	-	1	3	-	-	1934	365.0000	2.650	1938	1.000	7.00	--	5
6	S-Ag	1.0000	7.000	2.150	1.4700	-	1850	62	-	-	26	0.1110	1.612	1938	0.100	0.70	--	6
7	S-B	20.0000	150.000	35.300	33.7000	-	1583	338	-	-	17	2.9100	2.215	1938	2.000	15.00	--	7
8	S-Ba	20.0000	5000.000	1040.000	895.0000	-	10	41	2	-	1885	573.0000	3.841	1938	2.000	15.00	7000.0	8
9	S-Be	2.0000	70.000	2.900	4.5200	-	271	1421	-	-	246	1.2000	2.131	1938	0.200	1.50	--	9
10	S-Co	5.0000	2000.000	18.700	70.5000	-	135	208	2	-	1593	7.5700	3.035	1938	0.500	3.00	3000.0	10
11	S-Cr	10.0000	5000.000	137.000	462.0000	-	105	260	1	-	1572	22.8000	4.408	1938	1.000	7.00	7000.0	11
12	S-Cu	5.0000	7000.000	65.100	369.0000	-	44	656	-	-	1238	9.2500	3.868	1938	0.500	3.00	--	12
13	S-La	20.0000	1000.000	78.700	84.0000	-	58	138	2	-	1740	46.1000	2.703	1938	2.000	15.00	1500.0	13
14	S-Mo	10.0000	1500.000	79.800	290.0000	-	1711	201	-	-	26	1.2700	1.991	1938	1.000	7.00	--	14
15	S-Nb	50.0000	150.000	93.000	41.6000	-	1534	394	-	-	10	7.3000	2.102	1938	5.000	30.00	--	15
16	S-Ni	5.0000	3000.000	44.800	179.0000	-	26	268	-	-	1644	11.6000	3.444	1938	0.500	3.00	--	16
17	S-Pb	10.0000	500.000	41.600	29.9000	-	29	56	-	-	1853	32.2000	2.089	1938	1.000	7.00	--	17
18	S-Sc	5.0000	70.000	12.200	10.2000	-	173	497	-	-	1268	5.5000	2.821	1938	0.500	3.00	--	18
19	S-Sn	20.0000	50.000	30.000	13.6000	-	1896	28	-	-	14	2.1000	1.387	1938	2.000	15.00	--	19
20	S-Sr	100.0000	5000.000	481.000	386.0000	-	227	55	-	-	1656	236.0000	3.829	1938	10.000	70.00	--	20
21	S-V	10.0000	1000.000	85.300	81.9000	-	6	64	-	-	1868	56.1000	2.548	1938	1.000	7.00	--	21
22	S-Y	10.0000	2000.000	36.100	64.6000	-	185	231	-	-	1522	16.0000	3.262	1938	1.000	7.00	--	22
23	S-Zn	200.0000	1000.000	444.000	255.0000	-	1907	13	-	-	18	20.8000	1.392	1938	20.000	150.00	--	23
24	S-Zr	10.0000	1000.000	150.000	139.0000	-	40	32	25	-	1841	94.2000	3.290	1938	1.000	7.00	1500.0	24
25	S-Th	200.0000	1000.000	460.000	371.0000	-	1875	58	-	-	5	21.4000	1.453	1938	20.000	150.00	--	25
26	AA-Cu-P	1.0000	100.000	20.100	26.4000	1654	7	18	50	-	209	9.1800	7.812	284	0.100	0.70	150.0	26
27	AA-Pb-P	1.0000	92.000	9.450	11.6000	1654	-	6	7	-	271	6.3700	2.865	284	--	0.70	150.0	27
28	AA-Zn-P	5.0000	500.000	43.600	47.5000	1322	-	170	-	-	446	15.0000	3.705	616	--	3.00	--	28
29	AA-Ag-P	0.0500	10.000	0.378	0.9210	1654	60	80	-	-	144	0.0517	5.016	284	0.005	0.03	--	29
30	AA-Cd-P	1.0000	1.000	1.000	--	1322	193	422	-	-	1	0.3810	2.469	616	0.100	0.70	--	30
31	AA-Bi-P	2.0000	20.000	5.700	8.0000	1399	364	170	-	-	5	0.3880	2.617	539	0.200	1.50	--	31
32	AA-Sb-P	2.0000	3.000	2.330	0.5160	1406	313	213	-	-	6	0.4610	2.717	532	0.200	1.50	--	32

Table 4.--Bridger Wilderness Study Area Sedimentary Rock Samples -Summary of Basic Statistics-

		Raw data										Replaced data			Replacement values			Col
Col No.	Column I.D.	Minimum	Maximum	Mean	Standard Deviation	B	N	L	G	Other	Valid	Geom Mean	Geom Dev	Valid	N	L	G	No.
1	S-Fe%	0.050	10.000	1.110	2.060	-	3	9	2	-	76	0.2780	6.422	90	0.005	0.030	30.0	1
2	S-Mg%	0.020	10.000	2.830	3.600	-	-	-	-	-	90	0.8750	6.203	90	--	--	--	2
3	S-Ca%	0.050	20.000	9.940	8.370	-	-	4	16	-	70	4.1300	9.433	90	--	0.030	30.0	3
4	S-Ti%	0.002	1.000	0.126	0.190	-	5	6	-	-	79	0.0249	8.331	90	.0002	.0015	--	4
5	S-Mn	10.000	5000.000	366.000	763.000	-	-	-	-	-	90	148.0000	3.723	90	--	--	--	5
6	S-As	1000.000	1000.000	1000.000	--	-	89	-	-	-	1	20.9000	1.510	90	20.000	--	--	6
7	S-B	10.000	300.000	51.000	56.900	-	14	9	-	-	67	16.8000	4.505	90	1.000	7.000	--	7
8	S-Ba	20.000	2000.000	287.000	366.000	-	17	21	-	-	52	38.2000	6.964	90	2.000	15.000	--	8
9	S-Be	1.000	3.000	1.790	0.673	-	54	17	-	-	19	0.2620	3.418	90	0.100	0.700	--	9
10	S-Cd	150.000	150.000	150.000	--	-	89	-	-	-	1	2.1000	1.576	90	2.000	--	--	10
11	S-Co	5.000	70.000	11.700	13.800	-	60	6	-	-	24	1.2100	3.744	90	0.500	3.000	--	11
12	S-Cr	10.000	700.000	53.500	100.000	-	18	13	-	-	59	11.7000	4.718	90	1.000	7.000	--	12
13	S-Cu	5.000	70.000	13.100	13.400	-	4	46	-	-	40	4.6500	2.440	90	0.500	3.000	--	13
14	S-La	20.000	700.000	47.500	99.600	-	1	5	-	-	84	26.2000	2.161	90	2.000	15.000	--	14
15	S-Mo	5.000	1500.000	183.000	494.000	-	79	2	-	-	9	0.7620	3.603	90	0.500	3.000	--	15
16	S-Nb	20.000	20.000	20.000	--	-	83	6	-	-	1	2.3500	1.741	90	2.000	15.000	--	16
17	S-Ni	5.000	70.000	15.400	16.300	-	22	23	-	-	45	3.6300	3.944	90	0.500	3.000	--	17
18	S-Pb	10.000	1500.000	51.200	201.000	-	20	14	-	-	56	8.8900	4.005	90	1.000	7.000	--	18
19	S-Sc	5.000	20.000	8.380	4.290	-	53	21	-	-	16	1.2300	3.123	90	0.500	3.000	--	19
20	S-Sr	100.000	1000.000	256.000	183.000	-	40	9	-	-	41	48.8000	4.553	90	10.000	70.000	--	20
21	S-V	10.000	5000.000	118.000	607.000	-	-	22	-	-	68	20.0000	3.097	90	--	7.000	--	21
22	S-Y	10.000	300.000	47.500	72.600	-	30	16	-	-	44	6.9300	4.938	90	1.000	7.000	--	22
23	S-Zn	700.000	5000.000	2850.000	3040.000	-	88	-	-	-	2	22.1000	1.991	90	20.000	--	--	23
24	S-Zr	10.000	1000.000	176.000	232.000	-	24	8	1	-	57	21.9000	9.567	90	1.000	7.000	1500.0	24
25	AA-As-P	5.000	40.000	6.300	6.740	37	25	1	-	-	27	1.7400	3.403	53	0.500	3.000	--	25
26	AA-Zn-P	5.000	90.000	24.200	23.500	25	2	16	2	-	45	10.2000	3.523	65	0.500	3.000	150.0	26
27	AA-Cd-P	0.100	1.600	0.293	0.360	25	17	1	3	-	44	0.1070	6.200	65	0.010	0.070	15.0	27
28	AA-Bi-P	1.000	3.000	2.000	1.410	25	52	11	-	-	2	0.1520	2.361	65	0.100	0.700	--	28
29	AA-Sb-P	2.000	20.000	5.800	7.950	25	52	8	-	-	5	0.3190	2.692	65	0.200	1.500	--	29

Table 5.--Bridger Wilderness Study Area Soil Samples -Summary of Basic Statistics-

		Raw data										Replaced data			Replacement values			Col
Col No.	Column I.D.	Minimum	Maximum	Mean	Standard Deviation	B	N	L	G	Other	Valid	Geom Mean	Geom Dev	Valid	N	L	G	No.
1	S-Fe%	0.5000	20.000	4.1500	2.0600	-	-	-	-	-	259	3.7600	1.553	259	--	--	--	1
2	S-Mg%	0.5000	3.000	1.4000	0.5930	-	-	-	-	-	259	1.2800	1.531	259	--	--	--	2
3	S-Ca%	0.1000	10.000	1.3900	0.9970	-	-	-	-	-	259	1.2000	1.745	259	--	--	--	3
4	S-Ti%	0.1500	1.000	0.6180	0.1960	-	-	-	-	-	259	0.5850	1.414	259	--	--	--	4
5	S-Mn	100.0000	2000.000	746.0000	264.0000	-	-	-	-	-	259	694.0000	1.508	259	--	--	--	5
6	S-Ag	0.5000	2.000	0.8750	0.7500	-	249	6	-	-	4	0.0543	1.532	259	0.050	0.30	--	6
7	S-B	10.0000	150.000	42.3000	23.2000	-	7	3	-	-	249	31.6000	2.377	259	1.000	7.00	--	7
8	S-Ba	150.0000	2000.000	790.0000	512.0000	-	1	-	-	-	258	645.0000	2.003	259	2.000	--	--	8
9	S-Be	1.0000	3.000	1.6200	0.3720	-	-	12	-	-	247	1.5200	1.335	259	--	0.70	--	9
10	S-Co	5.0000	150.000	11.1000	9.4400	-	1	2	-	-	256	10.0000	1.489	259	0.500	3.00	--	10
11	S-Cr	10.0000	1000.000	69.3000	77.5000	-	-	2	-	-	257	53.1000	2.025	259	--	7.00	--	11
12	S-Cu	10.0000	1000.000	34.9000	65.8000	-	-	2	-	-	257	26.6000	1.764	259	--	3.00	--	12
13	S-La	20.0000	500.000	84.3000	54.0000	-	-	-	-	-	259	71.8000	1.748	259	--	--	--	13
14	S-Mo	5.0000	50.000	12.4000	14.5000	-	240	10	-	-	9	0.5920	1.885	259	0.500	3.00	--	14
15	S-Nb	20.0000	20.000	20.0000	--	-	90	168	-	-	1	7.4600	2.618	259	2.000	15.00	--	15
16	S-Ni	5.0000	200.000	27.8000	21.0000	-	-	2	-	-	257	22.9000	1.809	259	--	3.00	--	16
17	S-Pb	10.0000	150.000	44.1000	18.1000	-	-	1	-	-	258	40.8000	1.471	259	--	7.00	--	17
18	S-Sc	5.0000	20.000	9.8700	3.4100	-	-	3	-	-	256	9.2100	1.419	259	--	3.00	--	18
19	S-Sn	10.0000	15.000	12.5000	3.5400	-	257	-	-	-	2	1.0200	1.247	259	1.000	--	--	19
20	S-Sr	100.0000	700.000	233.0000	104.0000	-	6	6	-	-	247	194.0000	1.878	259	10.000	70.00	--	20
21	S-V	10.0000	200.000	102.0000	33.1000	-	-	-	-	-	259	96.3000	1.429	259	--	--	--	21
22	S-Y	15.0000	200.000	36.1000	22.3000	-	-	-	-	-	259	32.0000	1.576	259	--	--	--	22
23	S-Zn	200.0000	700.000	242.0000	144.0000	-	243	4	-	-	12	23.1000	1.757	259	20.000	150.00	--	23
24	S-Zr	50.0000	1000.000	296.0000	180.0000	-	-	-	3	-	256	264.0000	1.705	259	--	--	1500.0	24
25	S-Th	100.0000	100.000	100.0000	0.0000	-	254	3	-	-	2	10.4000	1.335	259	10.000	70.00	--	25

Table 6. Calcium and magnesium content of panned concentrates, rocks, soils, and stream sediments from the Bridger Wilderness, and from watersheds of three monitor lakes

[Analyses are 6-step semiquantitative spectrographic determinations by R. T. Hopkins; values are geometric means; n.d. = no data]

	Crustal Abundance		Bridger Wilderness			Hobbs Lake-Seneca Lake Watershed			Black Joe Lake Watershed			Section Corner Lake Watershed		
	Ca	Mg	No. of samples	Ca%	Mg%	No. of samples	Ca%	Mg%	No. of samples	Ca%	Mg%	No. of samples	Ca%	Mg%
Panned concentrates	n.d.	n.d.	587	3.63	1.16	4	5.23	1.61	2	8.66	0.837	10	4.05	1.04
Crystalline rocks	3.63[1]	2.10[1]	1934	1.41	0.86	17	1.14	0.39	13	1.16	0.76	69	1.44	0.88
Sedimentary rocks	n.d.	n.d.	90	4.13	2.83	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Soils	n.d.	n.d.	259	1.20	1.28	1	0.70	0.70	6	1.30	1.02	3	0.79	1.00
Minus-80 stream sediments	n.d.	n.d.	1133	1.97	1.33	8	1.74	1.59	7	1.80	1.52	16	2.08	1.54

[1] Goldschmidt, 1958

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Surficial deposits of the Bridger Wilderness

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Introduction

The Bridger Wilderness in the Wind River Range in northwestern Wyoming includes the high peaks and most of the uplands southwest of the Continental Divide that drain into the Green River. A small area at the south end of the range drains into the Sweetwater River. Altitudes in the Wilderness range from 8,000 to 13,800 feet.

The Bridger Wilderness is underlain chiefly by Precambrian granitic and associated crystalline rocks (see Worl and others, this volume). Only the northwestern end of the area is underlain by Paleozoic and Mesozoic rocks--sandstone, limestone, dolomite, and shale. The bedrock is cut by a large number of predominantly northwest-trending high angle faults which, in the Precambrian rocks, become shear zones that have greatly influenced the direction and extent of subsequent stream and glacial erosion.

Almost all of the Wilderness area was covered by an icecap several times during the Pleistocene, and glacial erosion is chiefly responsible for its present scenic grandeur.

Terrain types

The landscape of the western slope of the Wind River Range is divisible into seven terrain types in which the surficial deposits differ significantly in character and extent. All but one occur within the Bridger Wilderness.

1. Unglaciated mountain front
2. Unglaciated high divides
3. Glaciated high uplands
4. Cirques and upper canyons
5. Western plateau and upland valleys
6. Large canyons of major drainage ways
7. Piedmont end moraine belts

Unglaciated mountain front

The southwestern and southern front and adjacent upland of the Wind River range is thickly mantled with gruss. The gruss consists of sand and pebble-size aggregates of quartz, feldspar, and mica. Locally, the material contains angular to subround fragments of partially weathered crystalline rock. Irregularly weathered bedrock tors, commonly mantled with residual joint-block core boulders, project through the gruss along ridge crests and summit areas. This terrain represents the remnant of a deeply weathered regolith that mantled the entire range throughout Tertiary time. The regolith was removed by the glaciers throughout most of their extent and has been extensively reworked by mass wasting beyond the glacial limit at the margin of the range both in and adjacent to the Wilderness.

Unglaciated high divides

The unglaciated high divides along the crest of the range are mantled chiefly by sandy block rubble. In a few areas, large joint-block core boulders and gruss testify to the former presence of the Tertiary regolith, but that ancient mantle has been almost wholly stripped by periglacial processes that were extensively active in these areas during the Pleistocene and still are active locally today.

Flat to gentle uplands are typically covered with sandy blocky felsenmeer, including extensive areas of sorted polygons, sorted stripes, and broad solifluction lobes or terraces. In some areas, the mantle is chiefly sand and is characterized by non-sorted polygons and non-sorted stripes. Drainage ways have closely fitted, evenly surfaced block pavements along them in places.

Moderate to steep slopes are chiefly mantled with subangular to subround blocky solifluction debris. Block garlands and small block streams are present on some moderate slopes. Boulder lag deposits are common where snowmelt streams descend the slopes.

Most of the high upland deposits are stable and support a lichen or tundra vegetation, the latter where fine-grained material is at the surface. However, deposits downslope from snowbanks that last throughout all or most of the summer tend to remain saturated throughout the meltwater season, and commonly exhibit evidence of activity in the form of freshly scarred boulders, displaced sediment, or disrupted vegetation, that indicate upheaval, collapse, churning or downslope movement.

Glaciated high uplands

The glaciated high uplands are above treeline, and chiefly between altitudes of 10,500 and 11,500 feet. Slopes range from gentle to steep; cliffs are present in places. This terrain is underlain mostly by barren glaciated bedrock that locally is striated, grooved, and polished. Glacial boulders, ranging from less than a foot to more than 30 feet in long dimension, are scattered over the rock surface. Thin stony sandy till partly fills the many small depressions. In places, lee slopes are mantled with thin patches of eolian silt. The terrain includes numerous lakes, both large and small, which in many places contain subaqueous marginal benches of sandy, blocky solifluction debris that has flowed into the lakes from adjacent slopes. Active or stable sorted polygons are present on many of the benches. Where stable, the polygons are mantled with silt similar in all respects to that on lee slopes. Small deltas commonly are present where streams enter the lakes.

Alluvial deposits are chiefly sandy to bouldery and are characterized in places by evenly-surfaced block pavements. Pebbles and cobbles in intermittent meltwater channels on gentle slopes commonly have a brownish rind as much as 1/8 inch thick. Boulder-lag deposits are abundant along the channels on moderate to steep till-covered slopes.

Small deposits of talus occur at the base of cliffs, and banks of boulders and till, collapsed from higher positions during deglaciation, occur at the base of many steep slopes.

Cirques and upper canyons

Cirques and the upper parts of canyons heading in the vicinity of the Continental Divide are cliffed. Glaciated rock surfaces characterize most of the valley floors. The base of the cliffs are bordered by extensive rock-fall debris, including talus, talus flows, and protalus ramparts. Alpine mudflow channels are common on talus deposits. Locally, solifluction rock glaciers, rock slides, and rock-fall avalanche deposits are present along the margins of the canyons.

Some north or northwest facing cirques contain moraines and/or glacial rock glaciers, but remarkable few of these deposits are present west of the Continental Divide. Small modern glaciers are similarly distributed. Larger glaciers occur in the higher northern part of the range but, except in the Gannett Peak area, are east of the Continental Divide.

Most axial streams flow on rock surfaces, and alluvium is sparse and thin. The largest deposits are in alluvial fans where tributary streams enter the canyons. Tarns and rock-bound chain lakes are abundant, many with small deltas at their upper ends. Some lakes, such as Seneca Lake, are deep.

The western plateau and upland valleys

The broad western plateau and intruding upland valleys are below treeline, but include a large area of grassland in the southern part of the range. The terrain as a whole is characterized by glaciated rock surfaces and areas of sandy till. Four subcategories of terrain are recognized.

1. Areas that are underlain mostly by glaciated bedrock littered with boulders, but include small patches of thin till.
2. Areas in which till is more abundant than glaciated bedrock, but most of the till is thin.
3. Areas that are underlain chiefly by till, but include some glaciated bedrock. The till in these areas is variably thick or thin.
4. The grassland area in the southern part of the range, including some adjacent forested terrain, that is underlain by thick till and a relatively few rock outcrops. It also is characterized by numerous drumlins oriented predominantly southwest. Some of the drumlins are wholly of till; others, in part of rock. A few, known as rock drumlins, are wholly of rock. Those wholly of till commonly comprise an upper layer of bouldery sandy till and an underlying layer of older compact till on which a weathered zone is locally preserved. In a few, the upper till overlies pale gray sandy gruss, remnant from the ancient Tertiary regolith.

Along the eastern limit of the plateau, where canyons open onto it from sources along the Continental Divide, small end moraines at an altitude of about 10,400 feet mark the outer limits of a secondary readvance of the glaciers following recession from their maximum position on the piedmont during the last major glaciation, discussed below. Similar small end moraines outline a contemporaneous local icecap on the higher part of the plateau in the northern part of the range.

Block fields, block streams, boulder-lag channel deposits and small circular block pits are developed in the till on the floor and slopes of many upland valleys. Boulder pavements are rare, but present along some streams.

Many small lakes contain solifluction benches on which inactive sorted polygons are covered by as much as 20 inches of silt of possible eolian origin. The benches support a sedge vegetation beyond which a lake may be partly or wholly covered by a floating vegetation matte. At lower altitudes many former lake basins are completely filled with sandy silt, locally with peat. Around larger lakes, that have notched perennial outlets, solifluction benches tend to be remnant on adjacent slopes a few meters above present water level.

At the southern end of the range coarse blocky scree extends downslope from the high unglaciated divides to the stony gruss and rock tors along the mountain front.

Large canyons of major drainage ways

The large canyons of major drainage ways are deep U-shaped glacial troughs that extend headward from the front of the range across the western plateau to tributary canyons in the inner part of the range. During at least the last Pleistocene glacial maximum they were the dominant avenues of flow from the ice-cap on the range to the piedmont southwest of the mountain front.

The floor of the canyons are underlain chiefly by sand and gravel; locally by till. Glaciated rock knobs or high rock steps occur where the canyons are crossed by faults. Rock dammed lakes or chains of lakes occur upstream from faults in some canyons, for example, that of Fremont Creek.

Within the plateau, the canyon floors are bordered by talus cones above which glaciated bedrock cliffs rise as much as 2000 feet. Above the cliffs, the glaciated canyon shoulders and adjacent floors of tributary upland valleys are characterized by abundant joint-controlled glaciated bedrock knobs, separated by scanty deposits of thin bouldery sandy till.

The lower parts of the canyons, near the margin of the range are mantled with thick till, and large lateral moraines, commonly representing at least two glaciations, are present along the canyon rims. Much of the area of the lower parts of the canyons is beyond the Wilderness boundary.

Piedmont end moraine belt

The piedmont end moraine belt is at and beyond the front of the range and is entirely outside the Wilderness. It includes the largest and most characteristic deposits of the Pleistocene glaciers.

Almost all of the major canyons in the northern half of the range terminate in large deep glacial lakes on the piedmont. Surrounding each of the lakes is a series of nested bouldery end moraines representing the terminal deposits of successive glacial advances and readvances. End moraines of two major glaciations are present around some lakes, end moraines of only the last glaciation around others. The older glaciation was named Bull Lake, and the younger was named Pinedale by Eliot Blackwelder in 1916. The Bull Lake glaciation is commonly represented by two gently sloping, smooth-crested moraines that outline the maximum limits of two different advances. The Pinedale glaciation is commonly represented by six or seven commonly steeply sloping, sharp-crested, hummocky moraines that outline the maximum limits of three major and four minor readvances of the ice.

In the southern half of the range, glacial lakes are lacking at the mouth of canyons and deposits of only the Pinedale glaciation are present. As in the northern part of the range, these include six or seven end moraines. The overall extent of the ice at the southern end of the range was much less than to the north, and the Pinedale end moraines tend to occur at intervals along the entire length of the canyons rather than nested on the piedmont.

SOIL SURVEY OF THREE LAKE WATERSHEDS
IN THE BRIDGER WILDERNESS

Hobbs Lake
Black Joe Lake
Section Corner Lake

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Introduction

This soil survey was made as a part of a multidisciplinary study of selected watersheds in the Bridger Wilderness, administered by the Bridger-Teton National Forest. Intent of the survey is to provide detailed baseline data on the soil resource of three watersheds: Hobbs Lake, Black Joe Lake and Section Corner Lake. Mapping was done by soil scientists from the University of Wyoming under terms of Contract 53-8555-3-00015 between the Bridger-Teton National Forest and the University.

Location

The Bridger Wilderness is located in west-central Wyoming and encompasses a major portion of the higher elevations of the Wind River Mountains. Access to Hobbs Lake watershed was by way of the Fremont Lake Drainage at Pinedale. Black Joe Lake watershed was accessed through the Big Sandy Opening, and Section Corner Lake watershed was accessed from the Willow Creek Drainage.

Methods

Field procedures appropriate for making an Order 1 soil survey (Soil Survey Staff, 1984) were used in making the surveys. Map scale chosen by the Forest Service was 1:15,840. Smallest size of delineations shown is approximately 1 ha. Because of the large amount of soil variability over very short horizontal distances, most of the mapping units in the survey are complexes.

During the course of the field work in July and August, 1984, the soils in the three watersheds were examined in detail. Soils in each mapping unit delineation were identified by traversing. The boundaries of each unit were observed throughout their length. Notes on soil morphological characteristics and landform setting were recorded at numerous stops along the traverses. Pedons selected to be representative of the major soils in the mapping units were examined for detailed description and sampled for laboratory characterization (Soil Survey Staff, 1981). Pedons of major soils and inclusions were classified in accordance with Soil Taxonomy (Soil Survey Staff, 1975).

Laboratory Analysis

Soil samples were analyzed utilizing facilities of the Soil Testing Laboratory at the University of Wyoming. Fine-earth fractions were examined for texture using the Bouyoucos hydrometer method (Day, 1965). Organic matter was determined using a modified Walkley-Black method (Sims and Haby, 1971). Soluble cation content (using an atomic absorption spectrophotometer), pH of saturated paste, electrical conductivity and extractable cations were determined using procedures outlined by the U.S. Salinity Laboratory Staff (1961).

Soil Formation

The soil forming environment in the Wind River Mountains is harsh in terms of climate (cryic temperature regimes) and restrictive in terms of parent materials (coarse textured granite residuum, and alluvium, colluvium, and glacial debris derived from granitic materials). The soils are relatively young on landscapes which show considerable indication of glacial scouring. Significant portions of the watersheds are steeply sloping. All of the soils observed were either Inceptisols (major soils) or Entisols (inclusions).

Generally the soils mapped occured in three settings: upland forest, upland meadows and wet meadows. Lithic Cryrochrepts and Dystric Cryochrepts occurred under forest (*Pinus contorta*, *Picea engelmannii*, *Abies lasiocarpa* and *Pinus albicaulis*,with varying amounts of herbaceous understory) on upland positions. Typic Cryumbrepts occurred in upland meadows under grasses and forbs. Finally, Humic Cryaquepts and Typic Cryofluvents occurred in wet areas along the margins of lakes and streams. Vegetation here was sedges, grasses, forbs and willows (Salix spp.)

Both the Lithic Cryochrepts and Dystric Cryochrepts have leached A or E horizons (ochric epipedons) and cambic horizons showing color and structural developement. The Lithic subgroup soils are typically 40 cm to bedrock whereas the Dystric subgroup soils are moderately deep (75 cm to 1 m) to bedrock. Where the herbaceous understory is prominent, these soils have A horizons. Where the overstory canopy is denser and the understory is limited to grouse whortleberry (Vaccinium scoparium), the typical horizon sequence is Oi, E, Bw. The Lithic subgroup soils also exhibit low base saturation (<60%). Cryochrepts also occur on harsh sites (snow-bank sites, sites with thin vegetation) under alpine turf vegetation. Horizonation of these profiles is very weak.

The Typic Cryumbrepts are developed on moderately well- and well-drained sites under grass and forb vegetation. Typically they occur in small (2-10 ha) openings within the forest or in well-watered alpine meadows. In the latter situation they are found on north aspects and along meltwater channels. These soils exhibit accumulations of organic matter in the umbric epipedons, but have low base saturation percentages similar to associated Cryochrepts (15-45%).

The Humic Cryaquepts and Typic Cryofluvents occur along streams and around lake margins. The Cryaquepts typically have very shallow water tables (0-50 cm) and show stratification of alluvial materials in C horizons. These soils have accumulated considerable quantities of organic matter in their A horizons and many nearly level pedons have peat-like O horizons. The Cryofluvents occur on landscape positions similar to those where the Cryaquepts occur but have thin ochric epipedons (O and A horizons) over alluvial C horizons.

The Cryofluvents have C horizons with bright chromas but Cryaquepts occur as inclusions in mapping unit complexes, primarily where thicker deposits of fine textured materials overlie the alluvial gravels. Vegetation for these wet soils consists of sedges, grasses and willows. Development of B horizons in these soils has apparently been slowed by high water tables, cool temperatures, and continual deposition of materials during flooding and overflow events.

Mineral materials in all of the soils in the three watersheds are apparently derived from the granitic core of the Wind River Mountains (Branson and Branson, 1941). Black Joe Lake watershed and Hobbs Lake watershed showed evidence of extreme glacial scouring. Section Corner Lake watershed also showed evidence of glacial scouring, and there were some thin glacial deposits (drift) on the north side of the lake. Apparently because of spheroidal weathering of the granite bedrock, areas of lithic subgroup soils were smaller than might be expected in landscapes with this much bedrock outcrop. Average soil depth on upland positions was 40-90 cm and soils in topographic low spots, while deeper, had shallow water tables (0-50 cm). Because of a combination of high rock contents, shallow sola, high water tables, and the large proportion of rock outcrop, the total quantity of soil fine-earth materials available for ion-exchange is greatly reduced.

Map Legend -- Hobbs Lake Watershed

Unit No.	Composition	% of Watershed	Total Area	Average Size Delineation
			- - - - (ha) - - - -	
1	Rock Outcrop	27	131	26
2A	Humic Cryaquepts-Rock Outcrop Complex, 0-6% slope	1	6	2
2B	Humic Cryaquepts-Rock Outcrop Complex, 6-15% slope	13	69	5
3A	Dystric Cryochrepts-Rock Outcrop Complex, 0-10% slope	25	121	12
3B	Dystric Cryochrepts-Rock Outcrop Complex, 10-30% slope	24	123	9
4A	Lithic Cryochrepts-Dystric Cryochrepts-Rock Outcrop Complex 15-35% slope	1	6	3
4B	Lithic Cryochrepts-Dystric Cryochrepts-Rock Outcrop Complex 35-60% slope	1	7	4
Hobbs Lake		2	---	---
Other Lakes		6	---	---

Map Legend -- Black Joe Lake Watershed

Unit No.	Composition	% of Watershed	Total Area	Average Size Delineation
			- - - - (ha) - - - -	
1	Rock Outcrop	65	731	731
2	Rock Outcrop-Lithic Cryochrepts Complex, 35-75% slope	15	170	170
3	Dystric Cryochrepts-Lithic Cryochrepts-Rock Outcrop Complex 20-45% slope	5	53	27
4A	Dystric Cryochrepts-Lithic Cryochrepts Complex, 8-15% slope	1	5	5
4B	Dystric Cryochrepts-Lithic Cryochrepts Complex, 15-30% slope	11	125	125
5	Humic Cryaquepts, 6-10%	1	1	1
Black Joe Lake		4		

Map Legend -- Section Corner Lake Watershed

Unit No.	Composition	% of Watershed	Total Area	Average Size Delineation
			- - - -	(ha) - - - -
1	Rock Outcrop	2	10	10
2	Dystric Cryochrepts, 15-45% slope	16	93	93
3	Typic Cryumbrepts, 0-10% slope	3	14	2
4	Typic Cryofluvents, 0-10% slope	3	16	16
5	Dystric Cryochrepts-Lithic Cryochrepts-Rock Outcrop Complex, 6-25% slope	52	317	106
6	Rock Outcrop-Lithic Cryochrepts-Dystric Cryochrepts Complex, 35-70% slope	17	98	20
7	Dystric Cryochrepts-Rock Outcrop, 10-25% slope	2	10	10
Section Corner Lake		4	---	---
Other Lakes		1	---	---

Mapping Unit Descriptions - Hobbs Lake Watershed

Unit 1: Rock Outcrop. This unit consists of gently sloping to steep bedrock outcrops with inclusions of Lithic Cryochrepts, Dystric Cryocrepts and Humic Cryaquepts. Small bodies of water occur ephemerally in solution cavities in the rock, and small lakes (~0.1 ha) occur surrounded by the Humic Cryaquept inclusion. Inclusions make up approximately 5% of the unit.

Unit 2A: Humic Cryaquepts - Rock Outcrop Complex, 0-6% slope. This unit consists of nearly level to gently sloping wet soils and rock outcrops along drainges and around lake margins. Water table in these soils is at the surface or within a depth of 50 cm. The soils in this unit typically show stratification of fine materials over gravelly alluvium and have high A horizon organic matter contents. Lithic Cryochrepts occur as a minor inclusion along the margins of rock outcrops. The soil component makes up approximately 90% of the unit, the rest is rock outcrop and water. Vegetation is primarily sedges and grasses.

Unit 2B: Humic Cryaquepts - Rock Outcrop Complex, 6-15% slope. This unit consists of gently sloping to moderately steep wet soils and rock outcrop along drainageways. Water table in the soils is usually at 10 to 50 cm of the surface. The soils show stratification of finer textured materials over coarser alluvium. Lithic Cryochrepts and Dystric Cryochrepts occur as inclusions along the margins of rock outcrop (15% of the unit). The Humic Cryaquepts make up 80% of the unit, rock outcrop and other inclusions the remainder. Vegetation is primarily sedges and grasses.

Unit 3A: Dystric Cryochrepts - Rock Outcrop Complex, 0-10% slope. This unit consists of nearly level to gently sloping moderately deep soils and rock outcrop. Inclusions of Lithic Cryochrepts occur along the margins of some rock outcrops and inclusions of Humic Cryaquepts along small waterways. The Dystric Cryochrept soils make up approximately 60% of the unit, Rock Outcrop 35%, and the balance is inclusions. Typical vegetation is lodgepole pine with grouse whortleberry as understory under dense tree canopy cover and mixed grasses and forbs under sparse canopies.

Unit 3B: Dystric Cryochrepts - Rock Outcrop Complex, 10-30% slope. This unit consists of gently sloping to moderately steep, moderately deep soils and rock outcrops. Soil composition and vegetation are similar to unit 3A except that sola are somewhat thinner; the proportion of Rock Outcrop is greater; and, on north aspects, most pedons have O horizons. The units have inclusions of Lithic Cryochrepts (5%), and average 40% Rock Outcrop with the remainder Dystric Cryochrepts.

Unit 4A: Lithic Cryochrepts-Dystric Cryochrepts - Rock Outcrop Complex, 15-35% slope. This unit consists of moderately sloping to steep, shallow and moderately deep soils, and rock outcrops. Typic Cryorthents and Lithic Cryorthents are minor inclusions in this unit (3%). Small, flat benches on steep slopes are typical sites for Dystric Cryochrepts. The Lithic Cryochrepts occur along margins of rock outcrops. Rock Outcrops comprise approximately 27% of the unit, shallow soils 40%, and moderately deep soils 30%. Vegetation consists primarily of thin stands of lodgepole pine with grouse whortleberry understory. Tree canopy cover is denser on small benches.

Unit 4B: Lithic Cryochrepts-Dystric Cryochrepts - Rock Outcrop Complex, 35-60% slope. This unit is composed of moderately steep to very steep, shallow and moderately deep soils, and rock outcrops. The unit is generally similar to 4A, except that the small benches on which the

Dystric Cryochrepts occur are very short (2-5 m wide) and the proportion of Rock Outcrop and shallow soils is greater (35% and 50%). The inclusions of Entisols are also greater (approximately 5%).

Mapping Unit Descriptions - Black Joe Watershed

Unit 1: Rock Outcrop. This unit consists of gently sloping to very steep outcroppings of granitic bedrock. Considerable areas of talus also occur in the unit. Small areas of Lithic Cryochrepts, Humic Cryaquepts, Typic Cryumbrepts, and Lithic Cryorthents and small water bodies occur as inclusions (approximately 3 to 5% of the unit). Scattered trees (lodgepole pine) and grasses grow in clefts in the rock.

Unit 2: Rock Outcrop - Lithic Cryochrepts Complex, 35-75% slope. This unit consists of strongly sloping to very steep, shallow soils and rock outcrops. The Lithic Cryochrepts occur on very short benches on the slopes and at the margins of rock outcrops (15%). Inclusions of Dystric Cryochrepts, Humic Cryaquepts, and Lithic Cryorthents occur (approximately 5% of the unit). Vegetation is generally grasses and forbs or thin stands of conifers.

Unit 3: Dystric Cryochrepts-Lithic Cryochrepts - Rock Outcrop Complex, 20-45% slope. This unit consists of moderately deep and shallow soils and rock outcrop on strongly sloping to steep slopes. Dystric Cryochrepts, the major soil in this unit (55%), occur on short benches and on longer lengths of slopes between rock outcrops. The Lithic Cryochrepts occur primarily along the margins of bedrock outcrops. These shallow soils make up approximately 25% of the unit. Minor inclusions (3%) of Humic Cryaquepts and Typic Cryothents occur in some delineations. Rock outcrops comprise the remainder (17%) of the unit. Vegetation consists of either thin stands of conifers or grasses and forbs.

Unit 4A: Dystric Cryochrepts-Lithic Cryochrepts Complex, 8-15% slope. This unit consists of moderately sloping moderately deep and shallow soils on benches and short slopes. Rock Outcrop is a major inclusion in this unit

(10%) and Humic Cryaquepts and Typic Cryumbrepts as minor inclusion (5%). Most pedons in the units are the moderately deep soil (70%) with the shallow soil occurring mainly along margins of rock outcrops. Vegetation is primarily thick stands of lodgepole pine.

Unit 4B: Dystric Cryochrepts-Lithic Cryochrepts Complex, 15-30% slope. This unit is composed of moderately deep and shallow, well drained soils on moderately sloping to steep hillsides. The delineations often occur along the bases of long, steep canyon slopes. Rock Outcrop is a major inclusion in this unit (12%) and Typic Cryumbrepts, a minor inclusion (3%), occur along points of water concentration which support lush growth of grasses and forbs. Typical vegetation in this unit consists of dense stands of lodgepole pine or, in areas subject to avalanche, stands of drawfed conifers and willow. Shallow soils occur along margins of rock outcrops and comprise approximately 40% of the unit.

Unit 5: Humic Cryaquepts, 6-15% slope. This unit comprises only a small portion of the watershed and occurs on moderately sloping areas along the lake margins. Humic Cryaquepts are the major soil in the unit (90%) with Typic Cryofluvents occurring immediately adjacent to the lake shore and in eroded areas (10% of unit). Typical vegetation is grasses and sedges.

Mapping Unit Descriptions - Section Corner Lake

Unit 1: Rock Outcrop. This unit consists of gently sloping to very steep outcrops of granitic bedrock. Inclusions in the unit (15%) include Lithic Cryochrepts, Dystric Cryochrepts, and Humic Cryaqupets. Scattered trees (lodgepole pine) and grasses grow in clefts in rocks and on inclusions.

Unit 2: Dystric Cryochrepts, 15-45% slope. This unit consists of moderately deep soils on sloping to steep hillsides. The vegetation consists of thick stands of spruce and fir, or lodgepole pine, with an understory of grouse whortleberry. Rock outcrop is the major inclusion in this unit (10%) with minor inclusions of Humic Cryaquepts (2-3%).

Unit 3: Typic Cryumbrepts, 0-10% slope. This unit consists of nearly level to gently sloping, moderately deep soils in well drained meadows. Vegetation is mixed grasses and forbs. Inclusions in this unit are Humic Cryaquepts along stream courses (2-3%), and Dystric Cryochrepts where the epipedon is not thick enough to be umbric (~5%).

Unit 4: Typic Cryofluvents, 0-10% slope. This units consists of nearly level to gently sloping deep and moderately deep soils on an alluvial fan at the upper end of Section Corner Lake. Vegetation is willow, sedges and grasses. Inclusions of Typic Cryumbrepts occur on well drained sites (10%), and Humic Cryaquepts occur as inclusions along old stream channels and where the soil has developed in fine textured materials (~20%). The Cryaquepts are often hummocky.

Unit 5: Dystric Cryochrepts-Lithic Cryochrepts - Rock Outcrop Complex, 6-25% slope. This unit consists of shallow and moderately deep, well drained soils and rock outcrops on gently sloping to moderately steep slopes. Vegetation is predominately lodgepole pine, whitebark pine and Engelmann spruce with an understory of gruose whortleberry, forbs, and grasses. Parent materials for this unit are residuum and thin glacial deposits. Inclusions in the unit include small bodies of water and Humic Cryaquepts (~5%). The Lithic Cryochrepts occur as narrow bands along margins of rock outcrops and comprise 20% of the unit. Rock Outcrop is 20% of the unit.

Unit 6: Rock Outcrop - Lithic Cryochrepts-Dystric Cryochrepts, 35-70% slope. This unit consists of rock outcrops, shallow soils and moderately deep soils on steep and very steep hillsides. Rock Outcrop composes approximately 40% of the unit. Lithic Cryochrepts occur as bands along margins of rock outcrops (35% of unit), and the moderately deep Dystric Cryochrepts occur in pockets between the rock outcrop and boulders. Lithic Cryorthents are a minor inclusion in this unit (~2%). Vegetation is spruce, whitebark pine, and lodgepole pine with an understory of grouse whortleberry.

Unit 7: Dystric Cryochrepts - Rock Outcrop Complex, 10-25% slope. This unit consists of moderately sloping to strongly sloping, moderately deep soils and rock outcrops. Inclusions of Humic Cryaquepts occur along small watercourses (2-3% of unit), and the Rock Outcrop comprises approximately 15% of the unit. The Cryochrepts occur in pockets between rock outcrops and on short expanses of slope. Vegetation is relatively dense spruce and fir with understory of grouse whortleberry and forbs. Rock outcrops in this unit are larger than in unit 2 and tree canopy cover is generally denser than in unit 5 in response to site quality.

Pedon Descriptions and Characterization Data

Following are descriptions of represenstative pedons described in the three watersheds and corresponding characterization data.

Watershed: Hobbs Lake
Pedon Classification: Humic Cryaquept, fine-loamy over
sandy-skeletal
Mapping Unit: 2A
Vegetation: wet meadow grasses, sedges, scrub willow
Parent Material: Granitic alluvium
Physiography: meadow along drainage into Hobbs Lake
Slope: 5%
Aspect: N-NW

Profile Number: 1

Date: 7-21-84

Drainage: Pooly drained
Ground Water: 33 cm
Epipedon: Umbric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-19	10 YR 10 YR	5/2 d 3/1 w	1 1	3 vf gr	fr so-po	none	5	as
Ab	19-25	10 YR 10 YR	5/2 d 2/1 w	sil	3 vfgr to 1 m sbk	fr so-po	none	5	as
Bw	25-30	10 YR 10 YR	4/2 d 3/2 w	1	2 m sbk	fr so-po	none	10	as
C1	30-47	10 YR 2/5 YR	5/4 d 3/2 w	gsl	s	fr so-po	none	20	as
C2	47+	10 YR 2.5 YR	5/4 d 3/2 w	vg sl	s	fr so-po	none	45	--

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Hobbs Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Profile Number: 2

Mapping Unit: 3B
Vegetation: Whitebark pine, spruce, grouse whortleberry, grasses, forbs
Parent Material: Residual Granite
Physiography: Mountainous uplands
Slope: 30%
Aspect: SW

Date: 7-21-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
O1	2-0	10 YR 5 YR	3/1 d 2.5/2 m				none	10	as
E	0-17	5 YR 5 YR	6/3 d 4/3 m	g sl	2 f gr	vfr so-po	none	30	cs
Bw1	17-36	2.5 YR 5 YR	5/4 d 5/4 m		2 f gr to 1 m sbk	fr so-po	none	20	as
Bw2	36-62	2/5 YR 2/5 YR	5/6 d 4/8 m	g sl-scl	2 m sbk	fr so-po	none	35	as
Cr	62-73	10 YR 10 YR	5/6 d 3/6 m	vg sl	s	fi so-po	none	50	as
R	73+								

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Hobbs Lake
Pedon Classification: Humic Cryaquept, fine-loamy over sandy-skeletal
Mapping Unit: 2B
Vegetation: Wet meadow grasses, sedges

Profile Number: 3

Date: 7-21-83

Parent Material: Granitic Alluvium
Physiography: Meadow surrounding Hobbs Lake
Slope: 10%
Aspect: W

Drainage: Poorly drained
Ground Water: 48 cm
Epipedon: Umbric
Diagnostic Subhorizons: none

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
O1	9-0	10 YR 10 YR	4/2 d 3/1 m			so-po	none		as
A1	0-26	10 YR 10 YR	5/1 d 3/1 m	1-sil	1 m sbk	fr so-po	none		cs
A2	26-35	10 YR 10 YR	5/1 d 3/1 m	1	1 m sbk	fr so-po			as
Cg	35-53	10 YR 10 YR	6/2 d 4/2 m	vg 1s	s	fr so-po	none	60	not reached

Comments: Common, medium, prominent mottles in A1 and A2 horizons.
Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, 1s = loamy sand, sl = sandy loam, 1 = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, 1 = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Hobbs Lake
Pedon Classification: Lithic Cryochrept, loamy-skeletal

Profile Number: 4

Mapping Unit: 4A
Vegetation: Whitebark pine, spruce, grouse whortleberry

Date: 7-21-83

Parent Material: Residual Granite
Physiography: Narrow bench on a steeper slope
Slope: 12%
Aspect: N

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
Oi	2-0	10 YR 10 YR	5/3 d 2/1 m			vfr so-po	none	1	as
A	0-11	10 YR 10 YR	5/3 d 4/2 m	1	2 vf gr to 1 med sbk	fr so-po	none	30	as
Bw	11-23	10 YR 10 YR	6/6 d 4/4 m	vg sl	2 med sbk	fr ss-ps	none	50	cs
Cr	23-45	10 YR 7.5 YR	8/4 d 4/6 m	vg sl	s		none	60	as
R	45+								

Comments: Lithic contact varies from 30 to 50 cm. Depth of solum varies with fissures in rock. Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:

d = dry, m = moist, w = wet;

Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam

Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.

Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.

Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Hobbs Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Mapping Unit: 3A
Vegetation: Whitebark pine, grouse whortleberry, grasses

Parent Material: Granitic residuum and colluvium
Physiography: Mountainous uplands
Slope: 8%
Aspect: SW

Profile Number: 5

Date: 1-22-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-10	10 YR 10 YR	5/2 d 3/2 m	vg 1	2 f gr	vfr so-po	none	45	as
Bw1	10-25	10 YR 10 YR	6/4 d 4/4 m	vg sl	1 m sbk	fr ss-ps	none	40	cs
Bw2	25-38	2.5 YR 10 YR	6/4 d 6/8 m	vg sl	2 m sbk	fr so-po	none	40	cs
Cr	38-60	2.5 YR 2.5 YR	7/2 d 6/4 m	vg sl	s	fi so-po	none	60	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Hobbs Lake
Pedon Classification: Lithic Cryochrept, loamy-skeletal

Profile Number: 6

Mapping Unit: 4B
Vegetation: Whitebark pine, grouse whortleberry, grasses, elk sedge, forbs
Parent Material: Residual granite
Physiography: Mountainous uplands
Slope: 35%
Aspect: E

Date: 7-22-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-11	10 YR 10 YR	5/3 d 3/2 m	vg l	2 f gr	vfr so-po	none	45	as
Bw1	11-26	10 YR 10 YR	6/4 d 4/3 m	vg l	2 f-m sbk	fr so-po	none	40	cs
Bw2	26-47	10 YR 10 YR	6/6 d 4/3 m	vg l	2 m sbk	fr so-po	none	45	as
R	47+								

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Lithic Cryochrept, loamy-skeletal

Profile Number: 1

Mapping Unit: 2
Vegetation: Alpine turf

Date: 8-2-83

Parent Material: Granitic residuum and colluvium
Physiography: Mountainous uplands
Slope: 26%
Aspect: S

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-10	10 YR	3/2 d	g sl	3 f gr	fr so-po	none	20	as
		10 YR	3/1 m						
Bw	10-29	10 YR	5/4 d	g sl	2 f-m sbk	fr so-po	none	50	cs
		5 YR	3/4 m						
C	29-38	10 YR	6/4 d	vg sl	s	1 so-po	none	70	as
		5 YR	4/4 m						
R	38+								

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Profile Number: 2

Mapping Unit: 4B
Vegetation: Whitebark pine, grasses

Date: 8-3-83

Parent Material: Granitic colluvium
Physiography: Mountainous uplands
Slope: 25%
Aspect: S

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color Hue	Color Value Chroma	Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
A	0-14	10 YR 10 YR	5/2 d 3/2 m	1	2 m gr	fr so-po	none	10	as
Bw	14-43	10 YR 7.5 YR	6/3 d 3/4 m	g 1	2 m sbk	fr ss-ps	none	15	as
C	43-74+	2.5 YR 7.5 YR	6/4 d 3/4 m	vg 1	s	fr so-po	none	40	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Humic Cryaquept, fine loamy over sandy
Mapping Unit: 5
Vegetation: Wet meadow grasses, sedges

Parent Material: Granitic alluvium
Physiography: Drainage leading to lake
Slope: 8%
Aspect: SW

Profile Number: 3

Date: 8-3-83

Drainage: Poorly drained
Ground Water: 73 cm
Epipedon: Ochric
Diagnostic Subhorizons: none

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A1	0-18	10 YR 7.5 YR	4/2 d 3/2 m	l	3 f gr	fr so-po	none	1	cs
A2	18-37	10 YR 10 YR	5/2 d 3/1 m	l	3 f sbk	fr so-po	none	5	as
C	37-85+	10 YR 7.5 YR	5/3 d 3/2 m	vg sl	s	fr so-po	none	25	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Lithic Cryochrept, loamy-skeletal

Mapping Unit: 4B
Vegetation: Whitebark pine, grouse whortleberry, grasses

Parent Material: Residual granite
Physiography: Mountainous uplands
Slope: 28%
Aspect: S

Profile Number: 4

Date: 8-3-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-10	10 YR 10 YR	4/2 d 3/1 m	g l	1 f gr	fr so-po	none	30	as
Bw	10-35	10 YR 10 YR	6/4 d 4/4 m	g l	2 m sbk	fr ss-ps	none	30	cs
Cr	35-40	2.5 YR 7.5 YR	6/6 d	vg sl	s	fr so-po	none	65	as
R	40+								

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Typic Cryumbrept, loamy-skeletal

Profile Number: 5

Mapping Unit: 3
Vegetation: Grasses and forbs

Date: 8-3-83

Parent Material: Granitic residium and colluvium
Physiography: Mountainous uplands
Slope: 45%
Aspect: N

Drainage: Well drained
Ground Water: Not reached
Epipedon: Umbric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-18	10 YR 10 YR	4/2 d 2/2 m	vg l	1 f gr	fr so-po	none	40	cs
Bw1	18-35	10 YR 10 YR	3/3 d 3/2 m	vg l	2 f gr to 1 m sbk	fr ss-ps	none	45	as
Bw2	35-58	10 YR 10 YR	5/4 d 3/4 m	vg sl	1 m sbk	fi ss-ps	none	70	cs
Cr	58-75+	10 YR 10 YR	6/3 d 4/3 m	vg ls	s	l so-po	none	80	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Black Joe Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Profile Number: 6

Mapping Unit: 4A
Vegetation: Whitebark pine, spurce, grouse whortleberry, forbs
Parent Material: Granitic colluvium and reworked till
Physiography: Mountainous uplands
Slope: 8%
Aspect: N-NW

Date: 8-3-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
Oi	9-0	10 YR 10 YR	3/2d 2/1 m				none		as
A	0-15	10 YR 10 YR	4/2 d 3/1 m	g l	1 m sbk	fr so-po	none	30	as
Bw	15-33	10 YR 10 YR	6/4 d 4/3 m	vg sl	2 m sbk	fr so-po	none	50	cs
C	33-58+	2.5 YR 5 YR	6/4 d 4/6 m	vg ls	s	fr so-po	none	75	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Typic Cryumbrept, loamy-skeletal

Profile Number: 1

Mapping Unit: 3
Vegetation: Meadow grasses and forbs

Date: 8-8-83

Parent Material: Granitic alluvium
Physiography: Gently sloping upland meadow
Slope: 2%
Aspect: S

Drainage: Well drained
Ground Water: Not reached
Epipedon: Umbric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-17	10 YR 7.5 YR	5/3 d 3/2 m	sl	3 vf gr	fr so-po	none	10	cs
Bw	17-36	10 YR 5 YR	3/3 d 3/3 m	g sl	1 m sbk	fr so-po	none	25	as
C	36-82+	2.5 YR 2.5 YR	5/4 d 3/6 m	vg s-ls	s	l so-po	none	80	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - l = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Mapping Unit: 5
Vegetation: Lodgepole pine, whitebark pine, spruce,
grouse whortleberry, forbs
Parent Material: Granitic residual material and reworked till
Physiography: Mountainous uplands
Slope: 8%
Aspect: SE

Profile Number: 2

Date: 8-8-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-12	10 YR 7.5 YR	4/3 d 3/2 m	1	3 vf gr	fr so-po	none	15	cs
Bw1	12-35	10 YR 7.5 YR	5/4 d 3/4 m	g sl	1 m sbk	fr ss-ps	none	25	cw
Bw2	35-50	7.5 YR 7.5 YR	5/6 d 5/8 m	g sl	1-2 m sbk	fr ss-ps	none	30	as
Cr	50-65+	10 YR 7.5 YR	5/6 d 5/8 m	vg sl	s	fr so-po	none	70	not reached

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Typic Cryofluvent, sandy-skeletal

Profile Number: 3

Mapping Unit: 4
Vegetation: Willow, grasses, sedges

Date: 8-8-83

Parent Material: Granitic alluvium
Physiography: Drainage along inlet to lake
Slope: 4%
Aspect: S

Drainage: Moderately well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: none

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-7	10 YR 2.5 YR	4/2 d 3/4 m	sl	2 vf gr	fr so-po	none	1	cs
C1	7-26	10 YR 2.5 YR	5/3 d 3/6 m	sl	1 m sbk	fr so-po	none	3	as
C2	26-85+	10 YR 2.5 YR	5/3 d 3/4 m	vg s	s	fr so-po	none	70	not reached

Comments: Hummocky terrain within mapping unit 4. Hummocks range between 15 to 20 cm in height and have a vegetative cover of willows. A and C1 horizon thickness increases in soils developing directly under hummocks. Very thin laminations in C1

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Dystric Cryochrept, loamy-skeletal

Profile Number: 4

Mapping Unit: 2
Vegetation: Spruce, fir, grouse whortleberry

Date: 8-8-83

Parent Material: Residuum and colluvium from granite
Physiography: Mountainous uplands
Slope: 22%
Aspect: N-NW

Drainage: Well drained
Ground Water: 75 cm
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
Oi	2-0	10 YR 10 YR	3/2 d 3/1 m				none	1	as
E	0-11	10 YR 10 YR	7/1 d 4/2 m	sl	1 f pl	fr ss-po	none	5	as
E/B	11-23	10 YR 10 YR	7/4 - 7/6 d 5/2 - 4/3 m	g sl	1 m sbk	fr so-po	none	20	cs
Bt1	23-54	10 YR 7.5 YR	6/4 d 4/4 m	g sl	3 m sbk	fr ss-ps	none	40	cs
Bt2	54-80+	10 YR 5 YR	6/4 d 4/4 m	g sl	2 m sbk	fr ss-ps	none	65	not reached

Comments: Common, moderately thick clay films on the face of peds and lining pores in the Bt1 and Bt2 horizons. Bt horizons are not argillic because of insufficient clay increase.

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:

d = dry, m = moist, w = wet;

Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam

Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.

Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.

Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Lithic Cryochrept, loamy-skeletal

Mapping Unit: 5
Vegetation: Whitebark pine, spruce, fir, grouse whortleberry
Parent Material: Residium and colluvium from granite
Physiography: Mountainous uplands
Slope: 28%
Aspect: E

Profile Number: 5

Date: 8-8-83

Drainage: Well drained
Ground Water: Not reached
Epipedon: Ochric
Diagnostic Subhorizons: Cambic

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
Oi	2-0	10 YR 10 YR	3/2 d 3/1 m				none	8	as
A	0-10	10 YR 7.5 YR	5/3 d 4/6 m	g sl	3 vf gr	fr so-po	none	20	as
Bw	10-31	10 YR 2.5 YR	5/4 d 4/6 m	vg sl	1 m sbk	fr so-po	none	60	as
R	31+								

Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Watershed: Section Corner Lake
Pedon Classification: Humic Cryaquept, fine-loamy over sandy-skeletal
Mapping Unit: 4
Vegetation: Willow, sedges, grasses, forbs

Parent Material: Granitic alluvium
Physiography: Drainage along inlet to lake
Slope: 3%
Aspect: S

Profile Number: 6

Date: 8-9-83

Drainage: Poorly drained
Ground Water: 15 cm
Epipedon: Ochric
Diagnostic Subhorizons:

Horizon	Depth (cm)	Color		Texture	Structure	Consistency m, w	Reaction	% Coarse Fragments	Boundary
		Hue	Value Chroma						
A	0-15	10 YR 10 YR	3/1 d 2/1 w	sl	1 f gr	fr so-po	none	5	as
C1	15-50	10 YR 2.5 YR	5/4 d 3/4 w	s	sg	fr so-po	none	10	as
C2	50+	10 YR 2.5 YR	5/4 d 3/4 w	vg s	sg	fr so-po	none	85	not reached

Comments: Finer textured pedons have low chorma mottles.
Coded according to Soil Survey Staff (1981). Horizon nomenclature follows Soil Survey Staff (1981). Colors are Munsell notations. Codes are as follows:
d = dry, m = moist, w = wet;
Texture - s = sand, ls = loamy sand, sl = sandy loam, l = loam, sil = silt loam, scl = sandy clay loam
Structure - 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, c = coarse, gr = granular, sbk = subangular blocky, sg = single grained, s = structureless, g = gravelly, vg = very gravelly.
Consistency - moist: vfr = very friable, fr = friable, l = loose, fi = firm; wet: so = non-sticky, ss = slightly sticky, po = non-plastic, ps = slightly plastic.
Boundary - a = abrupt, c = clear, g = gradual, s = smooth, w = wavy.

Soil Series in the Survey Area

Mapping Units are named at the subgroup level of Soil Taxonomy. Soil series representative of the soils in the mapping units are the Leighcan, Black Joe (proposed), Moran, Melton and Lost Trail (proposed) series. A key to the series classification of the mapping units and representative soils is given in the following table. Range in characteristics for the two proposed series are given in following the pages.

Key to Soil Series, Pedons and Mapping Units

Soil Series	Family Classification	Pedons[#,+]	Mapping Unit[#]
Leighcan	Dystric Cryochrepts, loamy-skeletal, mixed	HL2, HL5 BJ2, BJ6, SC2, SC$	BJ3, BJ4A, BJ4B, HL3A, HL3B, HL4A, HL4B, SC2, SC6, SC7
Black Joe (proposed)	Lithic Cryochrepts, loamy-skeletal, mixed	HL4, HL6, BJ1, BJ4, SC5	BJ2, BJ3, BJ4A, BJ4B, HL4A, HL4B, SC5, SC6
Moran	Typic Cryumbrepts, loamy-skeletal, mixed	SC1, BJ5	SC3, BJ3
Melton	Humic Cryaquepts, fine-loamy over sandy or sandy-skeletal, mixed	HL1, HL3, BJ3, SC6	BJ5, HL2A, HL2B, SC4
Lost Trail (proposed)	Typic Cryofluvents, sandy-skeletal,	SC3	SC4

[#] HL = Hobbs Lake, BJ = Black Joe Lake, SC = Section Corner Lake

[+] Representative pedon for proposed soil survey area is underlined.

Black Joe Series (proposed). The Black Joe Series is a member of the loamy-skeletal mixed, Lithic Cryochrepts. The soils typically have gravelly sandy loam or gravelly loam A horizons over gravelly sandy loam Bw horizons. Depth to hard granitic bedrock ranges from 30 to 50 cm. Mean annual soil temperature is approximately 1.5°C.

Type Location: Sublette County, Wyoming. Typifying pedon is pedon BJ4 in the Black Joe Lake watershed. The area is unsurveyed.

Range in Characteristics. The A horizon ranges in color from 10 YR 3/1 or 10 YR 3/2 to 10 YR 4/2 moist and from 10 YR 5/3 or 10 YR 5/4 to 10 YR 6/4 dry. Some pedons have thin Oi horizons. The Bw horizon ranges in color from 5 YR 3/4 or 7.5 YR 4/6 to 10 YR 4/3 or 10 YR 4/4 moist and from 10 YR 5/3 or 10 YR 5/4 to 10 YR 6/4 or 10 YR 6/6 dry. Gravel content ranges from 20 to 50% in the A horizon and from 30 to 65% in the B horizon.

Competing Series. These are the Cowood, Winberry, and Hechtman series. Hechtman soils have developed from rhyolite bedrock. Cowood soils have developed from basalt. Winberry soils have loam or silt loam matrix textures and have a mean annual soil temperature greater than 2.2°C.

Geographic Setting. Black Joe soils are on nearly level to very steep mountain sides. They typically occur along the margins of outcrops of granite bedrock between the outcrop and deeper soils. Elevation is 2740 to 3350 m. Average annual air temperature is -1 to 1°C.

Associated Soils. These are Leighcan and Melton soils. Leighcan soils are greater than 50 cm to hard bedrock. Melton soil shave umbric epipedons and aquic moisture regimes.

Drainage and Permeability. Well drained, low runoff, rapid permeability.

Use and Vegetation. These soils are used primarily for recreation, wildlife habitat, and watershed. Vegetation is whitebark pine, subalpine fir, lodgepole pine, Engelmann spruce, grouse whortleberry and mixed forbs and grasses.

Distribution and Extent. In the high mountains of Wyoming. The series is of moderate extent.

Series Proposed. Sublette County, Wyoming. Bridger Wilderness Area. 1983.

Lost Trail Series (proposed). The Lost Trail series is a member of the sandy-skeletal mixed Typic Cryofluvents. The soils have thin sandy loam A horizons over very gravelly sand textured C horizons. Lenses of loamy sand or sand often overlie the gravelly layers. Mean annual soil temperature is approximately 1.5°C.

Type Location: Sublette County, Wyoming. Typifying pedon is pedon SC3 in the Section Corner Lake watershed. The area is unsurveyed.

Range in Characteristics. The A horizon ranges in thickness from 5 to 12 cm. A horizon colors range from 2.5 YR 3/4 to 5 YR 3/4 or 4/4 moist and from 7.5 YR 4/2 to 10 YR 4/2 or 10 YR 4/3 dry. Gravel content of the C horizons varies from 0 (sand lenses) to 80%.

Competing Series. These are the Tetonville, Wilsonville and Melton soils. Tetonville soils have A horizons greater than 15 cm thick with color values less than 3.5 moist. Wilsonville soils have less than 35% coarse fragments in the control section and have thicker A horizons. Melton soil shave umbric epipedons and some pedons have cambic horizons.

Geographic Setting. Lost Trail soils occur on alluvial fans at elevations of 2740 to 3350 m. The alluvium is of granitic origin. Average annual air temperature is -1 to 1°C.

Associated Soils. These are the competing Melton soils. Melton soils have umbric epipedons and aquic moisture regimes. They are developed from finer textured alluvial materials than the Lost Trail soils.

Drainage and Permeability. Lost Trail soils have ephemeral high water tables but are moderately well drained because of their coarse texture. Permeability is rapid.

Use and Vegetation. These soils are used primarily for recreation, wildlife habitat and watershed. Vegetation is low willows (*Salix* spp.), sedges, grasses and forbs.

Distribution and Extent. In the high mountains of Wyoming. The series is of moderate extent.

Series Proposed. Sublette County, Wyoming. Bridger Wilderness Area. 1983.

Laboratory Data: Black Joe Lake

	Sample No.	pH	EC	% Sand	% Silt	% Clay	% O.M.	CEC meq/100 g	Exchangeable Cations (meq/100 g) K^+	Exchangeable Cations (meq/100 g) Na^+	Exchangeable Cations (meq/100 g) Ca^{++}	Exchangeable Cations (meq/100 g) Mg^{++}	Soluble Cations (meq/100 g) K^+	Soluble Cations (meq/100 g) Na^+	Soluble Cations (meq/100 g) Ca^{++}	Soluble Cations (meq/100 g) Mg^{++}	Percent Base Saturation
Profile 1																	
A	2001	5.6	0.3	72	15	13	6.0	17.8	1.91	.06	7.37	1.41	.03	.02	.12	.04	60
Bw	2002	5.3	0.3	64	23	13	3.4	20.4	1.87	.10	8.34	1.76	.02	.01	.09	.03	59
C	2003	4.9	0.3	72	17	11	1.1	13.0	1.68	.08	3.87	.75	.01	.01	.05	.01	49
Profile 2																	
A	2007	5.3	0.3	50	29	21	6.7	24.2	2.56	.09	6.83	1.04	.05	.02	.14	.03	43
Bw	2008	5.2	0.2	41	37	22	3.3	15.1	2.26	.10	5.42	.91	.04	.02	.08	.02	57
C	2009	5.9	0.2	41	50	9	1.6	5.5	1.72	.08	.50	.04	.02	.01	.04	.01	43
Profile 3																	
A1	2010	5.2	0.2	38	39	23	12.4	28.2	1.95	.09	6.52	.73	.10	.09	.23	.04	33
A2	2011	5.4	0.1	38	39	23	6.7	30.7	1.82	.08	3.39	.42	.02	.02	.09	.02	19
C	2012	5.7	0.1	67	20	13	2.1	12.4	1.76	.06	1.84	.24	.03	.01	.05	.01	31
Profile 4																	
A	2013	5.3	0.3	38	41	21	11.8	27.8	2.50	.07	9.62	1.45	.10	.03	.30	.06	49
Bw	2014	5.1	0.2	41	41	18	4.4	23.9	1.76	.07	2.20	.46	.04	.02	.10	.02	19
Cr	2015	--	--	55	34	11	2.8	19.0	.72	.28	.94	.37	--	--	--	--	12
Profile 5																	
A	2016	5.5	0.3	40	41	19	12.2	42.6	2.30	.10	11.81	1.71	.10	.03	.34	.07	37
Bw1	2017	5.4	0.2	42	37	21	6.3	21.8	1.87	.11	5.98	1.02	.07	.01	.15	.03	41
Bw2	2018	5.4	0.2	72	14	14	2.2	11.0	1.91	.09	3.37	.63	.03	.01	.05	.01	55
Cr	2019	5.7	0.2	85	7	8	1.3	7.8	1.76	.09	1.71	.29	.03	.01	.04	.01	49
Profile 6																	
Oi	2020	4.9	0.5	--	--	--	63.8	104.8	2.58	.11	22.97	2.89	.54	.16	1.26	.25	27
A	2021	4.9	0.2	39	40	21	8.8	31.6	1.86	.09	3.49	.55	.08	.03	.18	.03	19
Bw	2022	5.1	0.2	73	12	15	1.7	12.6	1.65	.15	1.26	.20	.04	.01	.05	.01	26
C	2023	5.7	0.2	86	7	7	0.8	5.4	1.64	.10	.26	.02	.01	.01	.03	.01	37

Laboratory Data: Section Corner Lake

	Sample			%			%	CEC	Exchangeable Cations (meq/100 g)				Soluble Cations (meq/100 g)				Percent Base Saturation
	No.	pH	EC	Sand	Silt	Clay	O.M.	meq/100 g	K$^+$	Na$^+$	Ca^{++}	Mg^{++}	K$^+$	Na$^+$	Ca^{++}	Mg^{++}	
Profile 1																	
A	2024	5.4	0.2	57	26	17	7.6	22.4	1.83	.11	7.83	.86	.06	.01	.18	.03	48
Bw	2025	5.5	0.2	65	23	12	3.8	22.3	1.80	.12	6.04	.72	.04	.01	.09	.02	39
C	2026	5.8	0.2	87	8	6	0.7	13.3	1.67	.08	6.77	.70	.02	.01	.05	.01	69
Profile 2																	
A	2027	5.3	0.2	50	33	17	6.6	24.0	1.97	.06	5.20	.78	.08	.02	.18	.03	33
Bw1	2028	5.4	0.2	54	32	14	3.7	21.1	1.85	.07	1.81	.25	.04	.01	.09	.01	19
Bw2	2029	5.5	0.1	63	28	9	3.3	17.7	1.84	.07	1.52	.17	.05	.01	.08	.01	20
Cr	2030	5.7	0.2	66	23	11	3.6	18.2	1.96	.13	1.81	.20	.03	.01	.08	.01	23
Profile 3																	
A	2031	5.5	0.2	62	27	11	7.8	25.8	1.98	.10	11.83	1.38	.07	.02	.22	.04	59
C1	2032	5.8	0.2	67	22	11	2.3	18.8	1.85	.12	8.37	.89	.04	.02	.11	.02	59
C2	2033	6.0	0.2	88	5	7	1.5	12.1	1.63	.10	6.12	.62	.01	.01	.04	.01	69
Profile 4																	
Oi	2034	4.7	0.5	--	--	--	57.0	84.4	.99	1.34	14.84	.10	.47	.10	1.13	.31	20
E	2035	4.8	0.2	53	33	14	3.0	13.6	.17	.15	2.20	.10	.03	.02	.10	.02	19
E & B	2036	5.2	0.2	68	22	10	1.2	10.0	.08	.08	1.05	.10	.02	.01	.05	.01	13
Bt1	2037	4.9	0.2	70	20	10	1.0	8.8	.06	.05	.76	.10	.02	.01	.04	.01	11
Bt2	2038	5.5	0.1	69	19	12	1.2	13.5	.08	.05	.86	.10	.02	.01	.04	.01	8
Profile 5																	
Oi	2039	5.5	0.3	--	--	--	38.9	61.8	.74	2.48	23.30	.10	.19	.03	.65	.12	43
A	2040	5.3	0.2	64	23	13	5.6	21.5	.33	.33	4.36	.10	.03	.01	.13	.02	24
Bw	2041	5.6	0.1	68	19	13	2.8	15.0	.18	.14	2.04	.10	.03	.01	.06	.01	16
Profile 6																	
A	2041	5.0	0.2	56	30	14	17.2	37.1	.37	.34	5.03	.10	.07	.05	.26	.05	16
C1	2043	5.6	0.1	89	5	6	1.7	9.1	.03	.12	1.76	.10	.02	.01	.04	.01	22
C2	2044	5.6	0.1	93	1	6	.28	4.7	.01	.07	.95	.10	.02	.01	.05	.01	24

Laboratory Data: Hebbs Lake

	Sample			%			%	CEC	Exchangeable Cations (meq/100 g)				Soluble Cations (meq/100 g)				Percent Base Saturation
	No.	pH	EC	Sand	Silt	Clay	O.M.	meq/100 g	K^+	Na^+	Ca^{++}	Mg^{++}	K^+	Na^+	Ca^{++}	Mg^{++}	
Profile 1																	
A	2045	5.2	0.3	31	46	23	11.2	33.4	.39	.59	7.64	.10	.11	.04	.34	.05	26
Ab	2046	5.4	0.1	29	54	17	6.6	32.8	.38	.38	4.73	.10	.06	.02	.16	.02	17
Bw	2047	5.5	0.1	36	47	17	6.1	27.7	.27	.31	4.05	.10	.06	.03	.14	.02	17
C1	2048	5.4	0.2	65	27	8	2.7	15.1	.09	.15	2.02	.10	.04	.02	.08	.01	16
C2	2049	- -	- -	- -	- -	- -	- -	- -	NOT SAMPLED		- -	- -	- -	- -	- -	- -	- -
Profile 2																	
Oi	2050	5.0	0.3	--	--	--	61.7	48.7	.44	.57	7.31	.10	.12	.02	.37	.08	17
E	2051	5.0	0.3	69	18	13	3.3	13.8	.27	.22	3.16	.10	.04	.02	.13	.03	27
Bw1	2052	5.0	0.1	73	14	13	1.3	8.4	.13	.12	1.94	.10	.01	.01	.06	.01	27
Bw2	2053	5.9	0.1	73	20	7	2.1	10.3	.08	.03	.83	.10	.09	.03	.17	.02	10
Cr	2054	5.6	0.1	78	17	5	1.1	6.9	.27	.03	.54	.10	.03	.01	.06	.01	14
Profile 3																	
Oi	2055	4.6	0.5	--	--	--	46.2	80.5	.55	.85	12.22	.10	.17	.13	.68	.15	17
A1	2056	5.1	0.1	26	50	24	14.8	30.1	.11	.33	4.70	.10	.06	.02	.10	.02	17
A2	2057	5.3	0.1	28	48	24	17.6	31.2	.07	.29	4.20	.10	.05	.02	.09	.02	15
Cg	2058	5.2	0.2	82	9	9	2.2	6.2	.01	.04	.76	.10	.02	.01	.04	.01	15
Profile 4																	
Oi	2059	5.1	0.3	--	--	--	35.8	67.0	.38	.72	.77	.10	.11	.02	.31	.10	3
A	2060	5.0	0.2	38	39	23	9.0	22.0	.20	.41	5.59	.10	.04	.01	.10	.03	29
Bw	2061	5.0	0.2	58	23	19	3.2	13.8	.22	.26	3.83	.10	.01	.01	.06	.02	32
Cr	2062	5.4	0.2	72	20	8	0.7	6.0	0.0	.04	.58	.10	.01	.01	.02	.01	12
Profile 5																	
A	2063	5.5	0.2	47	35	18	6.3	14.1	.33	.33	4.63	.10	.02	.01	.06	.02	38
Bw1	2064	5.3	0.1	57	31	12	1.5	9.9	.01	.06	1.18	.10	.01	.01	.02	.01	14
Bw2	2065	5.7	0.1	65	29	6	1.2	10.2	.80	.01	.29	.10	.02	.01	.01	.01	12
Cr	2066	5.4	0.1	60	33	7	0.7	4.4	.67	.73	.19	.10	.01	.01	.01	.01	39
Profile 6																	
A	2067	5.3	0.3	41	40	19	9.0	27.3	.19	.14	9.23	.05	.01	.01	.15	.05	35
Bw1	2068	5.5	0.1	48	37	15	3.3	15.2	.11	.06	2.26	.10	.03	.01	.04	.01	17
Bw2	2069	5.7	0.1	48	39	13	3.4	15.1	.57	.49	1.15	.10	.03	.01	.05	.01	15

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HYDROLOGY AND AQUATIC CHEMISTRY
OF MONITOR LAKE WATERSHEDS IN THE
WIND RIVER MOUNTIANS, WYOMING

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Atmospheric Deposition Monitoring

Evidence supports the hypothesis that atmospheric deposition can increase concentrations of hydrogen ions and other chemicals in surface waters (1, 2). Increases in precipitation volumes can result in increased loadings of hydrogen ions to watersheds and surface water (3, 4). This can increase geological weathering rates, and thereby increase concentrations of weathered ions in runoff waters (5, 6).

An attempt was made to look at wet deposition within the Wind River Mountains, and determine effects on monitored watersheds. Deposition monitoring included ten snow sampling sites, one NADP monitor near Pinedale, Wyoming, and one National Weather Service station at Farson, Wyoming (Figure 1).

The National Weather Service climatological station was operated by Scott Swistowicz, a high school teacher at Farson, Wyoming. Scott obtained samples for pH measurement in a gallon sized polyethylene container. Precipitation volumes were measured using standard Weather Service instrumentation.

Figure 2 shows individual pH measurements taken on storms from February through May of 1983. The values ranged from a high of 6.40 to a low of 4.10 with a volume weighted mean of 4.66. It was speculated by Scott that the high pH of 6.40 was influenced by storms coming from the direction of trona plants located in the southwest near Green River, Wyoming. Data collected from this same station in October and November of 1983 shows the same trend.

Snow samples were collected from ten locations within the Wyoming and Wind River Mountain Ranges (Figure 1). Samples were collected using a Mount Rose snow sampler, and analysed at Western Wyoming College Water Quality Laboratory. These samples were very dilute with conductance ranging from 3.7 umhos to 5.4 umhos. Loomis Park was an exception with a conductance value of 20 umhos on May 2, 1983 (Table 1). The pH values ranged from 4.73 to 5.51, with an average $[H^+]$ equal to a pH of 5.04.

The high pH and conductivity values at Loomis Park could again be attributed to trona plant contamination. Sodium and bicarbonate concentrations were high at this site, which would be expected if trona ($Na_2CO_3NaHCO_3H_2O$) was a contaminant.

Upper and lower layer samples were taken at two stations. There appeared to be no significant difference between the two layers. Samples taken in the Wyoming Range (Blind Bull and Spring Creek Divide) did not differ significantly from those along the Wind River Range (Tables 1, 2, and 3).

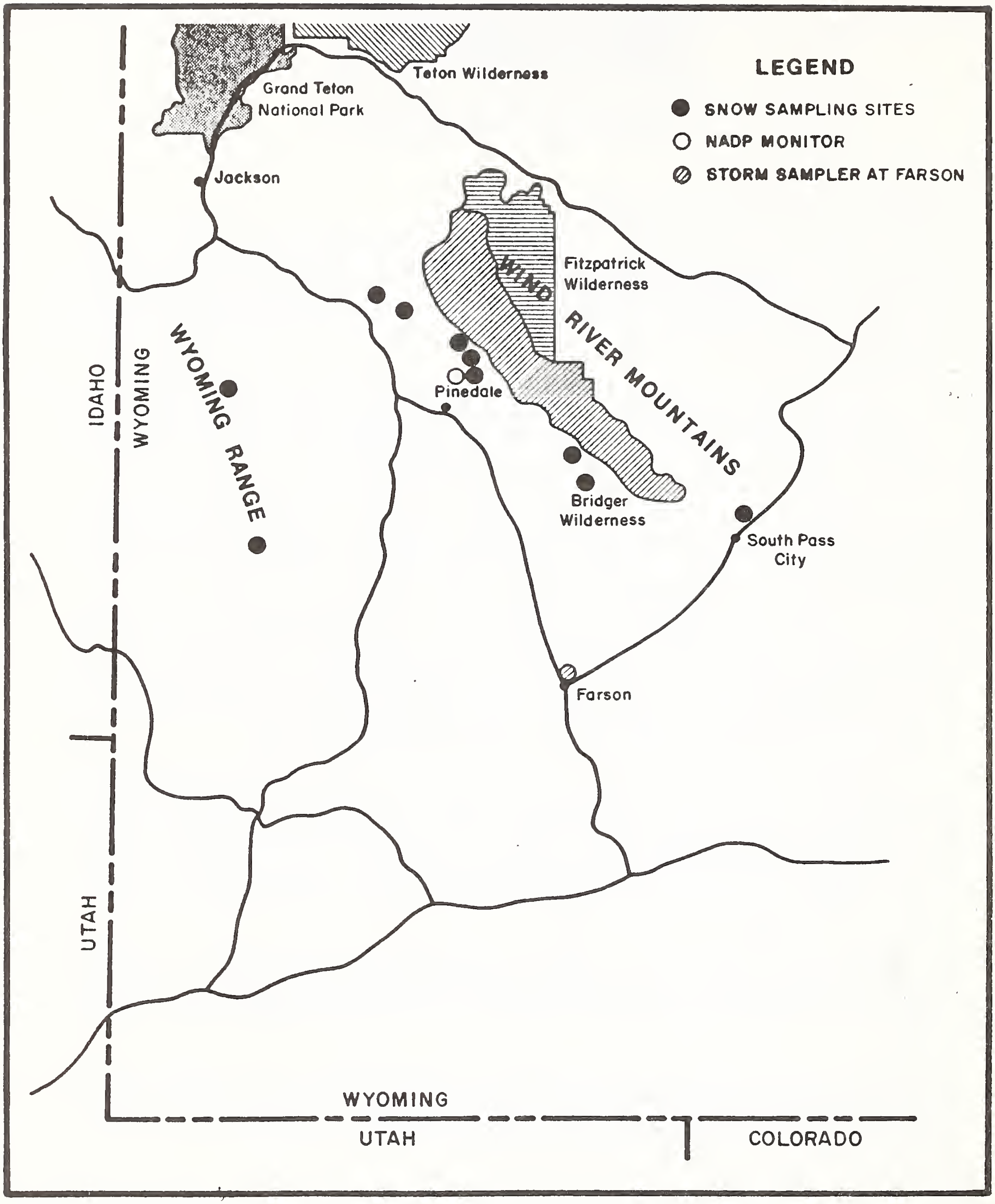


Fig. 1. Deposition monitoring sites used in 1983

Fig. 2. pH MEASUREMENTS FROM INDIVIDUAL STORMS AT FARSON, WYOMING 1983

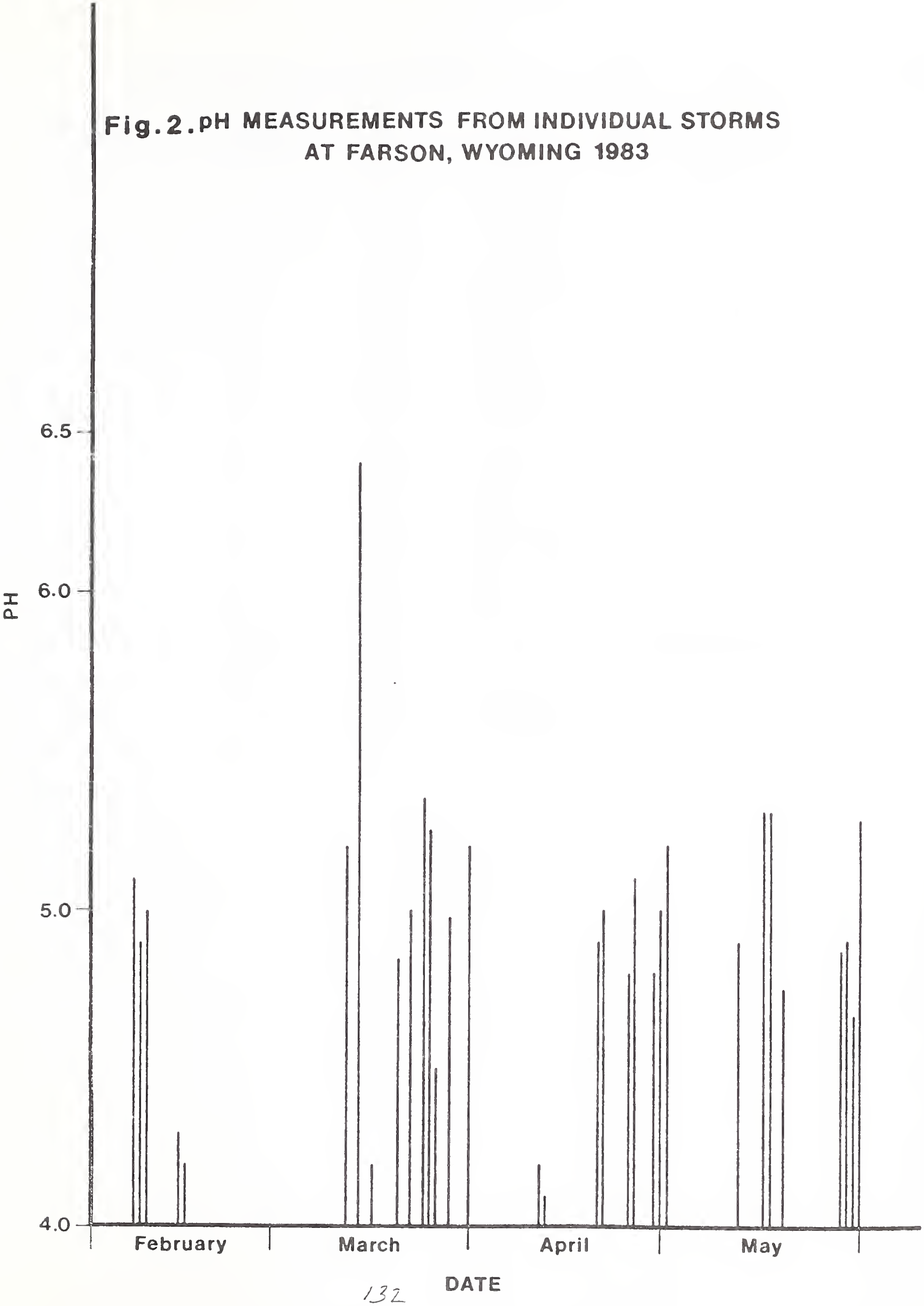


TABLE 1. pH, Alkalinity and Conductance for 1983 Snow Samples

Sample Location	Date	pH	Alkalinity (ueq/l)	Conductance (umhos)
South Pass Lower	04/20/83	4.85	8.6	5.4
South Pass Upper	04/20/83	4.81	11.4	4.1
Spring Creek Divide	04/27/83	5.41	26.0	4.9
Pocket Creek	05/02/83	5.33	22.0	4.9
Blind Bull	05/02/83	5.10	26.0	3.7
Elkhart Park	04/06/83	4.99	26.0	4.7
Elkhart Park	05/02/83	5.42	22.0	4.1
White Pine Upper	04/20/83	4.78	1.8	4.9
White Pine Lower	04/20/83	4.73	2.4	5.0
Half Moon	04/20/83	5.12	8.4	4.9
Gypsum Creek	04/20/83	4.93	3.8	4.2
Muddy Creek Feed Lot	04/20/83	5.28	38.0	4.0
Loomis Park	04/06/83	4.96	9.2	4.5
Loomis Park	05/02/83	5.51	56.0	20.0

Table 2. Major Cations (mg/l) for 1983 Snow Samples

Sample Location	Date	Ca	Mg	K	Na
South Pass Lower	4/20	.30	.039	.13	.23
South Pass Upper	4/20	.15	.023	.05	.14
Spring Creek Divide	4/27	.78	.096	.30	.09
Pocket Creek	5/2	.32	.050	.14	.16
Blind Bull	5/2	.11	.025	.07	.05
Elkhart Park	4/6	.28	.048	.47	.05
Elkhart Park	5/2	.26	.030	.06	.11
White Pine Upper	4/20	.10	.014	.02	.03
White Pine Lower	4/20	.19	.023	.06	.10
Half Moon	4/20	.38	.060	.34	.07
Gypsum Creek	4/20	.21	.031	.08	.10
Muddy Creek Feed Lot	4/20	.18	.089	.12	.26
Loomis Park	4/6	.27	.035	.08	.07
Loomis Park	5/2	.33	.048	.94	2.20

Table 3. Major Cations (mg/l) for 1983 Snow Samples

Sample Location	Date	HCO_3	SO_4	NO_3-N	Cl
South Pass Lower	4/20	.52	.54	.11	.083
South Pass Upper	4/20	.69	.36	.10	.054
Spring Creek Divide	4/27	1.6	---	.11	---
Pocket Creek	5/2	1.3	---	.10	---
Blind Bull	5/2	1.6	---	.12	---
Elkhart Park	4/6	1.6	.51	.067	.039
Elkhart Park	5/2	1.4	---	.10	---
White Pine Upper	9/20	.11	.40	.05	.030
White Pine Lower	4/20	.14	.51	.11	.140
Half Moon	4/20	.51	.36	.10	.130
Gypsum Creek	4/20	.23	.38	.07	.081
Muddy Creek Feed Lot	4/20	2.3	.24	.09	.180
Loomis Creek	4/6	.56	.49	.076	.041
Loomis Creek	5/2	3.4	---	.12	---

Sulfate loadings ranged from .84 Kg/Ha/Yr to 2.47 Kg/Ha/Ur. Trace elements were dilute and showed no significant trend (Table 4).

The NADP monitor is located near Half Moon Lake just outside of Pinedale, Wyoming. Values for pH were lower than the snow samples, with a volume weighted mean of 4.53. The pH values ranged from 3.99 to 5.13 (Table 5). Conductivity values were also higher, ranging from 5.6 umhos to 62.5 umhos. Sulfate deposition ranged from .03 kg/Ha/yr to .23 kg/Ha/yr, with a total of .9 kg/Ha/yr for May through July of 1983. Deposition rates for other ions are in Table 6.

Table 4. Trace Elements (mg/l) for 1983 Snow Samples

Sample Location	Date	Al	Fe	Mn	Zn
South Pass Lower	4/20	.028	.010	.011	.018
South Pass Upper	4/20	.053	.004	.0072	.037
Spring Creek Divide	4/27	.48	.15	.0062	.0005
Pocket Creek	5/2	.003	.004	.0052	.0072
Blind Bull	5/2	.007	.003	.0041	.0005
Elkhart Park	4/6	.015	.007	.0078	.0011
Elkhart Park	5/2	.009	.006	.0062	.014
White Pine Upper	4/20	.025	.006	.0068	.015
White Pine Lower	4/20	.020	.029	.012	.0042
Half Moon	4/20	.018	.016	.0064	.0066
Gypsum Creek	4/20	.008	.006	.0065	.0064
Muddy Creek Feed Lot	4/20	.15	.11	.001	.013
Loomis Park	4/6	.023	.025	.0097	.0032
Loomis Park	5/2	.008	.004	.0064	.011

Table 5. pH Conductivity and Precipitation Volumes for NADP Monitor near Pinedale, Wyoming

Date	pH	Conductivity (umhos)	Precipitation (inches)
5/03/83	4.8	12.9	.30
5/10/83	4.95	5.6	1.02
5/17/83	4.94	6.3	.23
5/31/83	4.67	12.8	1.00
6/07/83	4.36	28.6	.24
6/21/83	4.71	19.5	.27
7/19/83	4.39	41.1	.32
7/26/83	4.18	40.5	.24
8/09/83	4.12	53.9	.93
8/06/83	4.54	15.7	1.49
8/30/83	3.99	62.5	.51
9/06/83	5.13	28.9	.97

Table 6. Deposition Rates for Various Ions at the NADP Monitoring Site from 5/3/83 - 7/26/83

Ion	Deposition Rate meq/m^2
Ca^{++}	1.10
Mg^{++}	.29
K^{+}	.10
Na^{+}	.28
NO_3^{-}	1.16
Cl^{-}	.26
$SO_4^{=}$	1.88

Monitoring of Spring Runoff

During snowmelt it appears that the first meltwaters contain higher concentrations of ions than bulk snow. Seip (7) reported that 50 to 80% of the pollutants in snow are released when the first 30% of the snow melts.

Alkalinity and pH measurements were taken at the inlet of Boulder Lake during the spring of 1983. Even though Boulder Lake is situated at a lower elevation outside the wilderness, it was anticipated that any depression in pH during snowmelt runoff could be detected. Alkalinity values did show a downward trend during 1983 (Figure 3). pH showed no trend and low values did not last for more than a day (Figure 4).

Early spring monitoring was also done for Hobbs Lake within the Bridger Wilderness. Again, no trend was evident for either pH or Alkalinity (Figure 5, 6). Alkalinity values ranged from 20 to 200 ueq/l, and pH values ranged from 6.05 to 7.17. Difficulties were experienced in both equipment and timing of measurements.

General Lake Survey within the Wind River Mountain Range

From 1969 through 1975, the Wyoming Game & Fish Department conducted a survey of 230 lakes within the Bridger Wilderness area. The survey included bathymetry, some chemical analysis (dissolved oxygen, alkalinity, pH, temperature), plankton counts, fish sampling, and other physical measurements such as secchi disk and stream flow. Although the survey was extensive in nature, there were several drawbacks. Alkalinities were determined using the methyl orange method, and only had a detection limit of 7 mg/l, with a precision of 3.4 mg/l. A Hellige pH colorimeter was used to determine pH, and was only recorded to the nearest .25 units. Although the data was useful in determining general sensitivity of the lakes, it was not useful for an acid deposition monitoring program.

Alkalinities of 272 ueq/l or less were recorded for 162 lakes, but only 59 of these were less than 136 ueq/l. Only 68 lakes had a surface alkalinity greater than 272 ueq/l.

No correlation could be seen between altitude and alkalinity (r = -.0045), although this could have been masked by the insensitivity of the method used. Correlations between alkalinity and latitude did not exist either (r = .52).

In general, the lakes were seen as highly oligotrophic and sensitive, with fish populations fairing from good to poor.

In 1983, a broad survey again was undertaken in both the Bridger and the Popo Agie Wildernesses. This time, however, alkalinities were determined using potentiometric titration and run on a Gran Plot. This gave us far more sensitivity and precision.

A total of 92 lakes were tested for alkalinity and had values ranging from 10.3 ueq/l to 160.2 ueq/l. The lakes ranged in elevation from 7,875 feet to 12,000 feet, and extended the length of the range. Unlike the earlier survey, all of the lakes were below 200 ueq/l, which is considered the cutoff for sensitive lakes. Again, no correlation was found between elevation and alkalinity (r = .35) or latitude and alkalinity (r = -.37).

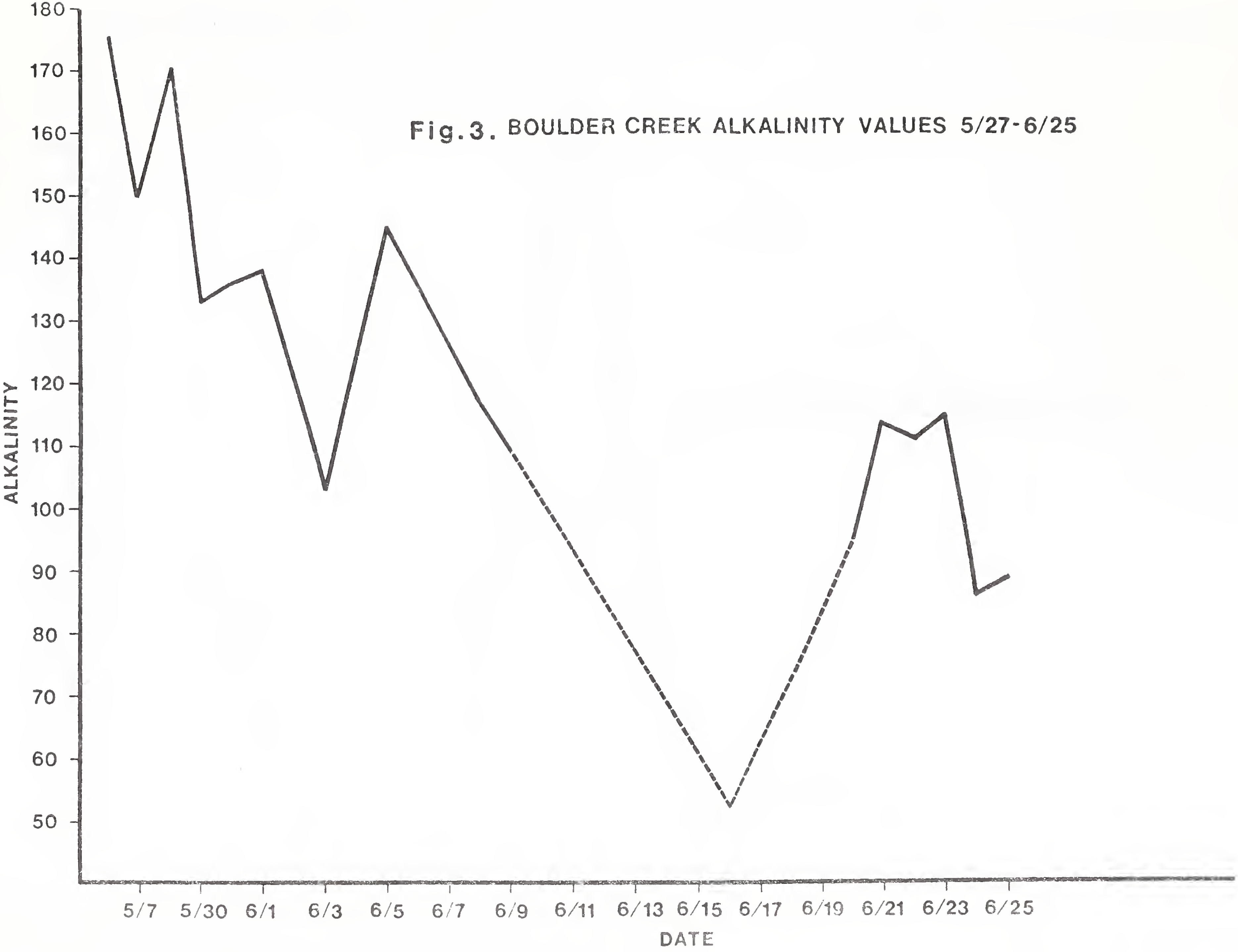


Fig. 3. BOULDER CREEK ALKALINITY VALUES 5/27-6/25

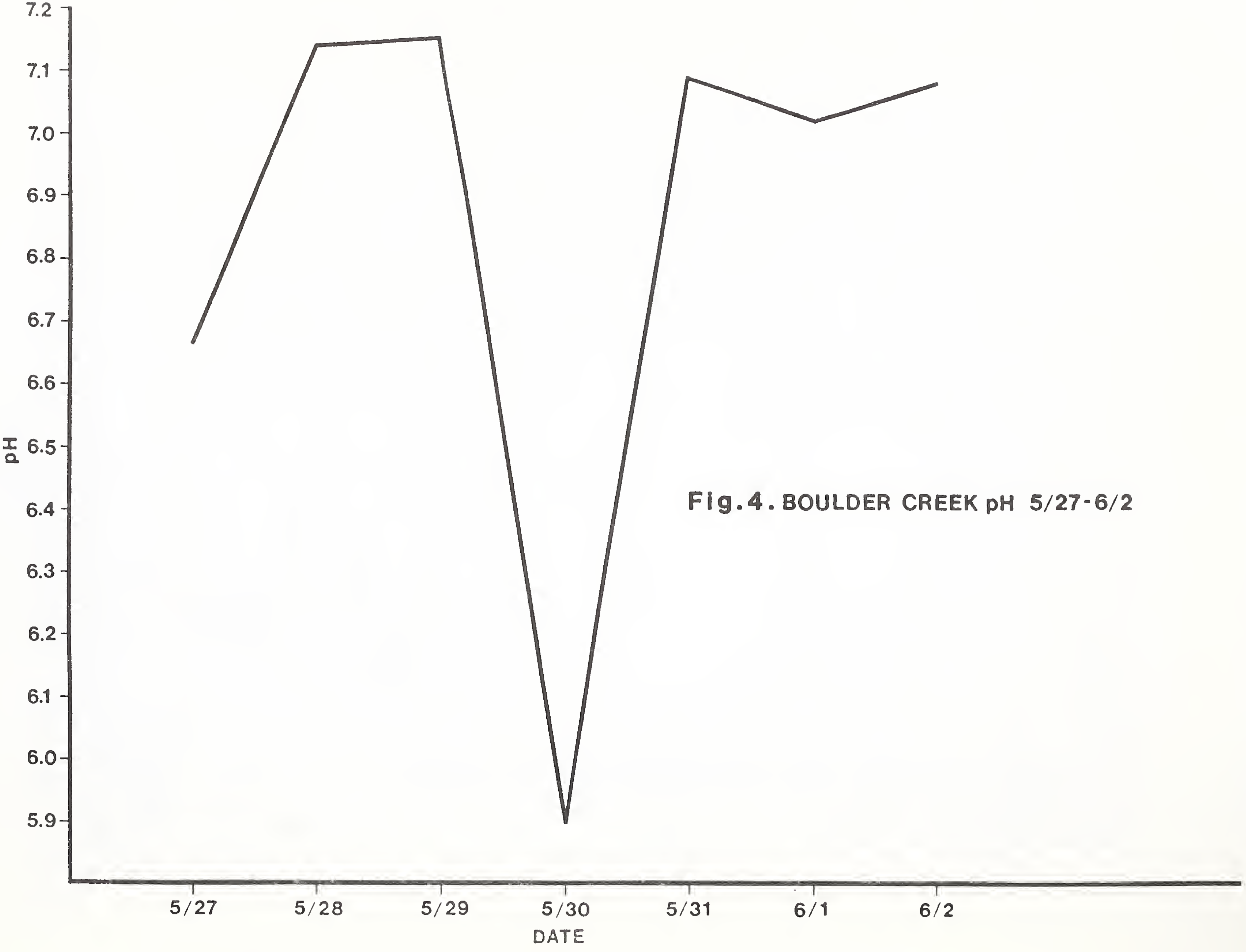


Fig.4. BOULDER CREEK pH 5/27-6/2

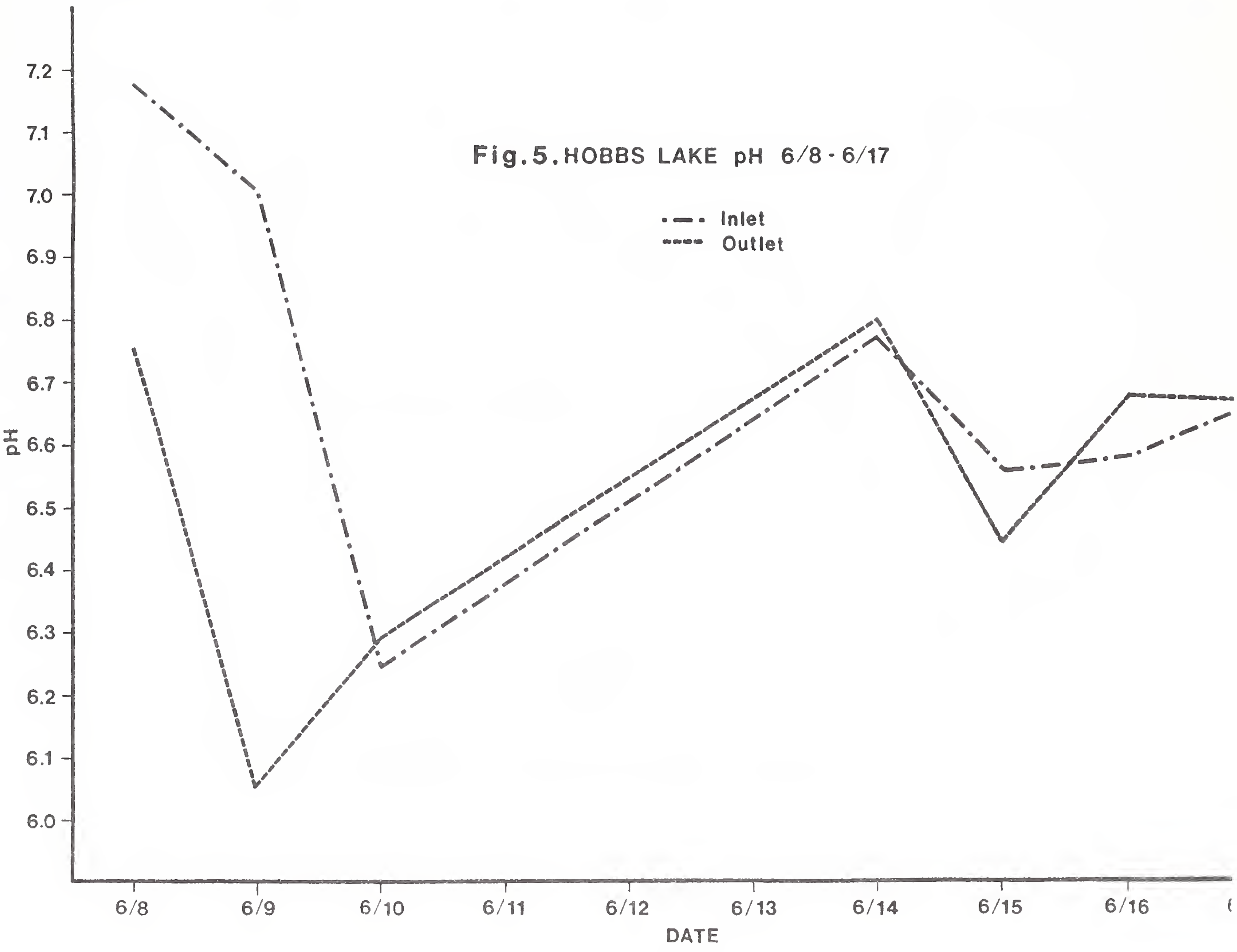
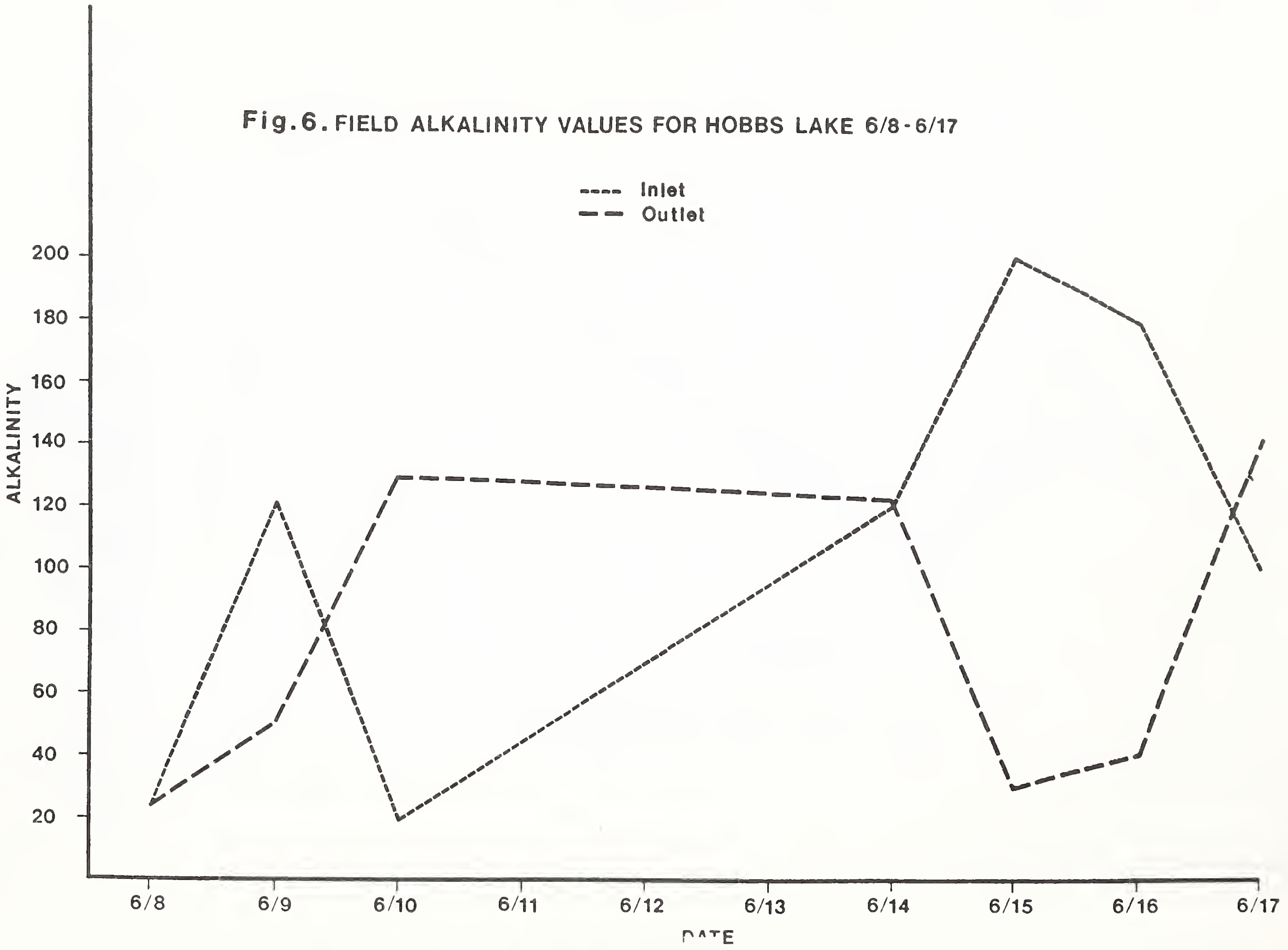


Fig.5.HOBBS LAKE pH 6/8-6/17

Fig. 6. FIELD ALKALINITY VALUES FOR HOBBS LAKE 6/8-6/17



Selected Lakes Monitoring

Four lakes were selected for more intensive study during 1983. Lakes were selected that would be sensitive chemically and biologically to acid deposition as well as be within the dispersion from any gas sweetening plants.

Samples for chemical analysis were collected every other week during the summer. The lakes were sampled at the inlet, outlet, and at the deepest part of the lake, both in the epilimnion and hypolimnion. Field measurements were also taken, which included pH, alkalinity (using a Hach Digital Titrator), conductance, dissolved oxygen, temperature, and flow measurements.

Black Joe Lake

Black Joe is a cirque lake, 10,258 feet in elevation. The surface area is 76.2 acres, with a maximum depth of 85 feet. The mean depth is 34 feet, and has a volume of 2,590 acre-feet. The area of the drainage basin is 2,560 acres, and has a drainage basin:lake volume ratio of 0.98. The relative flushing time (lake volume:watershed volume ratio) is 0.35 (Figure 7).

Black Joe is the least stratified of the four monitor lakes, both in duration and intensity. This is largely due to the lack of sunlight hitting the lake. The lake did not start to stratify until the end of July (Figure 8). After July 30, the temperature of the epilimnion rose and reached its peak of 13°C in mid-August. The hypolimnion, as with all the lakes, stayed fairly constant at 6°C. From mid-August until mid-September, the temperature of the epilimnion gradulally declined until fall turnover. The weak stratification lasted approximately 54 days.

Field measurements of pH were difficult at Black Joe, as it was with all the lakes. This was due to several reasons. One major problem was condensation moisture within the meter itself, which caused irregular readings. Other problems encountered included temperature changes in the sample once removed from the stream, dilute waters causing precipitation of silver and plugging of the annular junction, and temperature differences between the buffers and sample. These waters were very dilute in nature, and measurements were difficult simply due to the poor conductance. Values ranged from 6.15 to 7.00, and no specific trend could be seen (Figure 9).

Alkalinity values ranged from 43 ueq/l to 87 ueq/l. Field alkalinity values, although consistently higher, provided a good check on lab alkalinity values. Samples taken to the lab were titrated potentiometrically, and data plotted using the Gran technique. No real trend can be seen in the data other than alkalinities appeared to be consistent throughout the summer periods (Figure 10).

Specific conductance ranged from 10 umhos to 27 umhos. Values appear to peak around mid-August, then decline until the end of summer. Conductivity, as in all the lakes, appeared to be extremely low, corresponding with the nature of the lakes (Figure 11).

Dissolved oxygen was saturated for most of the summer, and corresponded with temperature values.

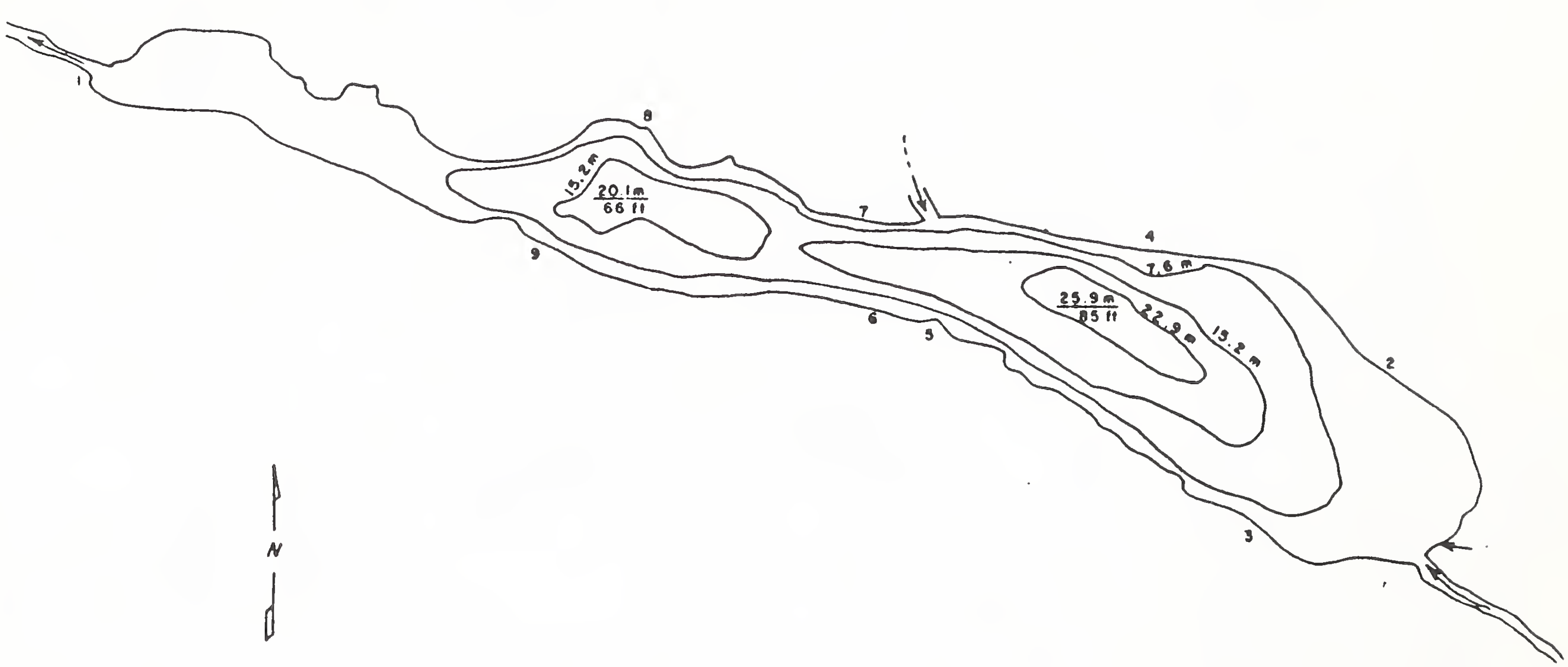


Fig.7. Bathymetric map of Black Joe Lake

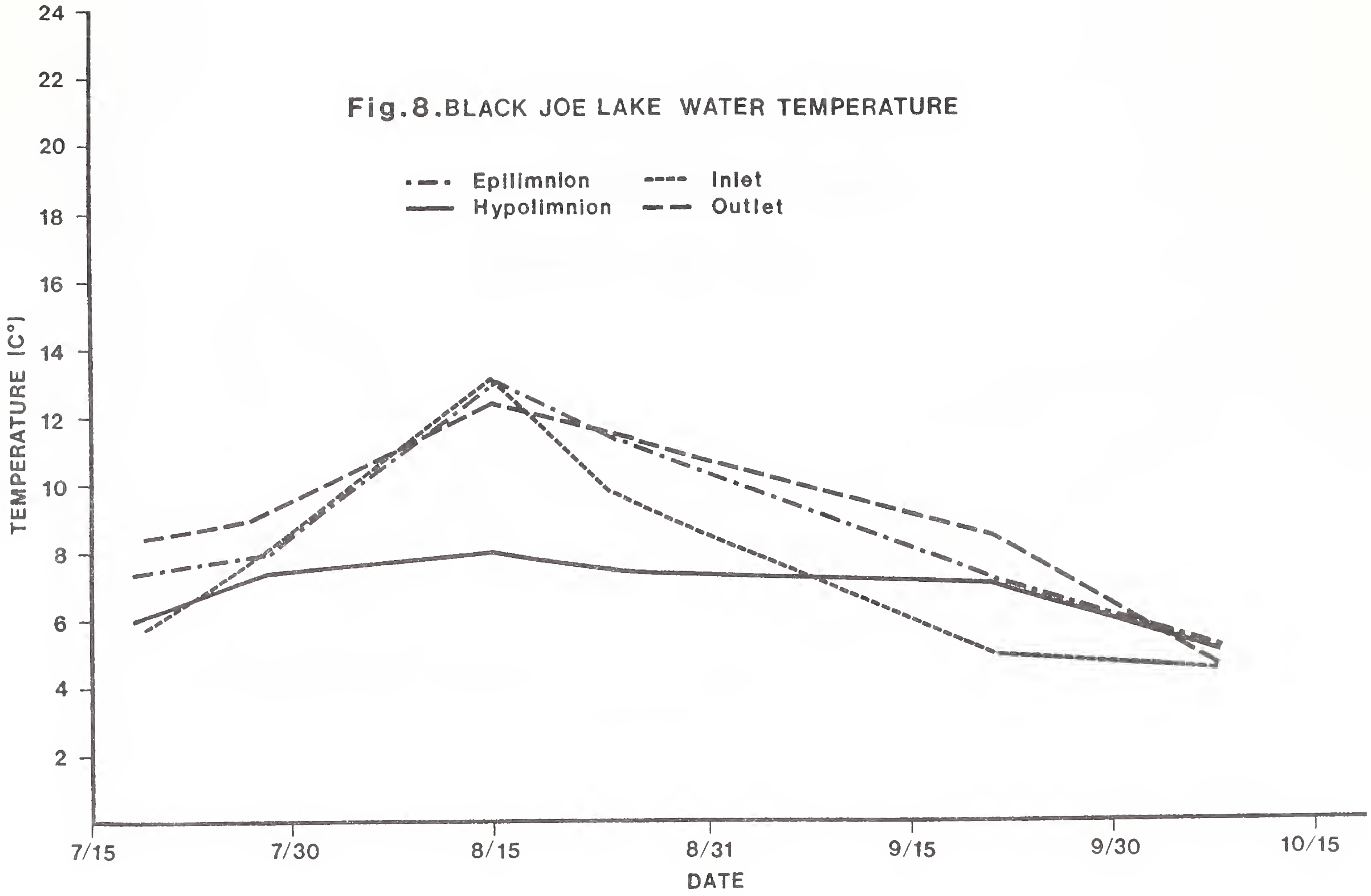
Black Joe Lake

Elev: 3,127 m (10,260 ft)

Scale: 3: 24,000

Max Depth 25.9 m (85 ft)
Mean Depth 10.2 m (34 ft)
Surface Area 30.84 hectares (76.2 A)
Shoreline Dev. 2.14
Shoal Area 28 %

Fig.8.BLACK JOE LAKE WATER TEMPERATURE



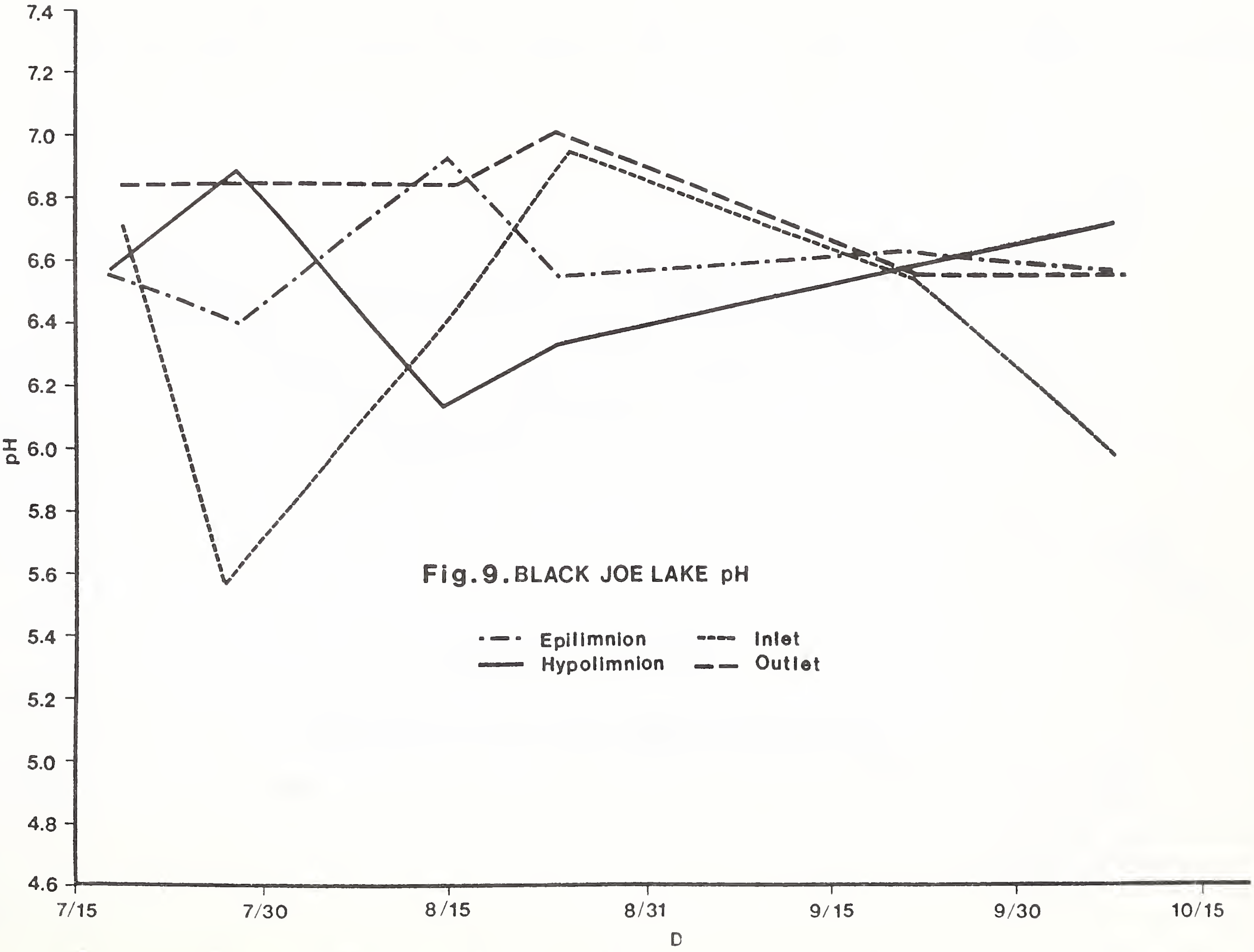


Fig. 9. BLACK JOE LAKE pH

Fig. 10. BLACK JOE LAKE LAB ALKALINITY

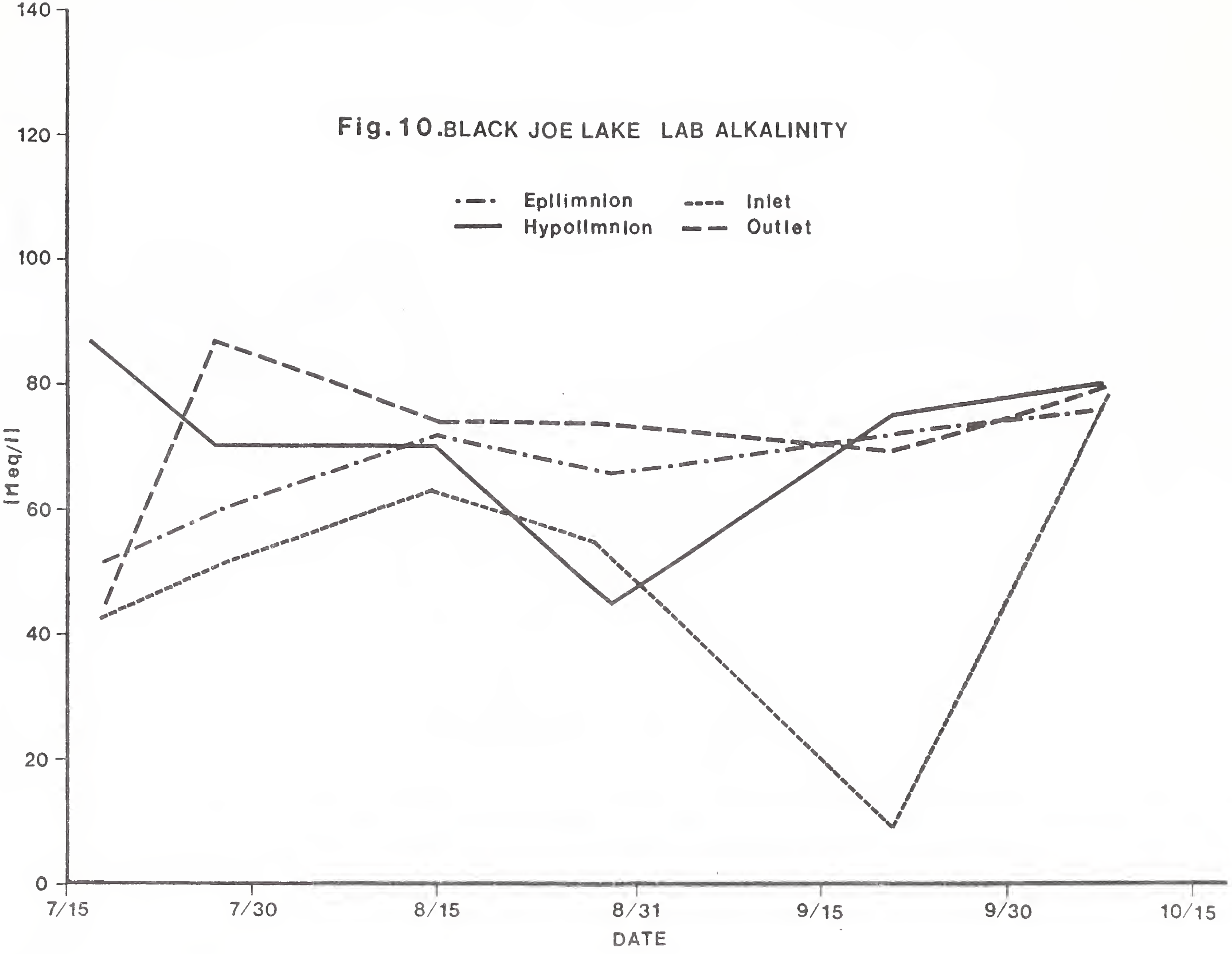
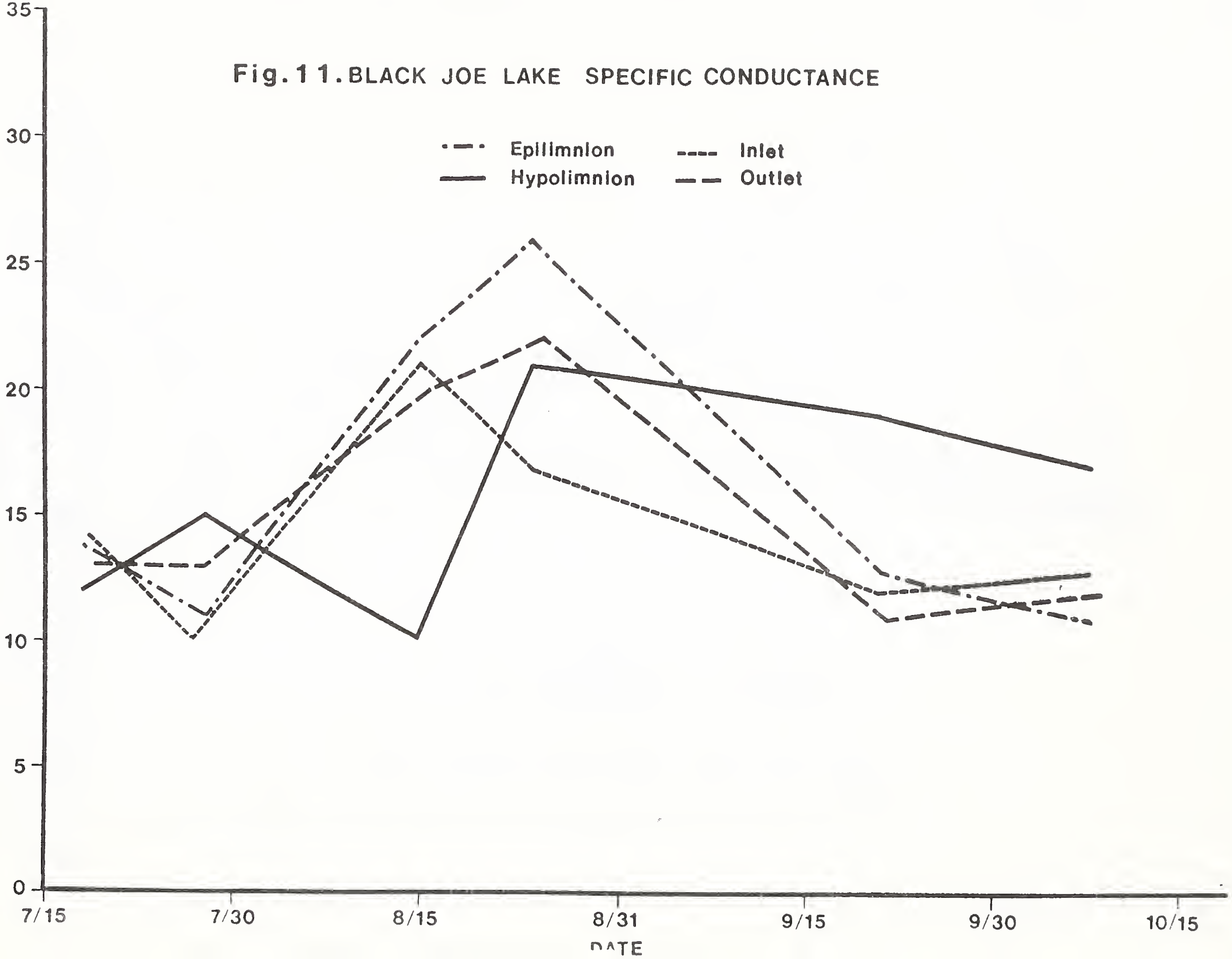


Fig. 11. BLACK JOE LAKE SPECIFIC CONDUCTANCE



Chemical analysis indicated very dilute waters, with trace metals and nutrients often below the detectable limits (Table 7). Unfortunately, sulfates were not done on every sample. The one set of samples that were analysed, however, did not show excessive amounts, and the lake appeared to still be in a bicarbonate situation.

In general, the lake appears to be very oligotrophic in nature, and remaining in a bicarbonate category. Trends beyond that are weak and further analysis is necessary.

Hobbs Lake

Hobbs Lake is located at 10,069 feet in rolling terrain. The lake itself has a maximum depth of 57 feet, with a mean depth of 34 feet. The lake surface area is 20 acres, with a volume of 680 acre feet (Figure 12). The watershed area is 962 acres, with a drainage basin:lake volume ratio of 1.41. Because of its shallower depth, Hobbs Lake has a relative flushing time of 0.24.

Hobbs Lake is somewhat better stratisfied than Black Joe (Figure 13). Stratification started prior to July 15, 1983. This should be expected due to its largely sunny exposure. The epilimnion temperature reached its peak on August 12 with a temperature difference of 12°C from the hypolimnion. Fall turnover had occurred by the first of October, with stratification lasting close to 80 days.

The pH at Hobbs Lake increased from a low of 5.52 on July 15, 1983, and then remained constant for the remainder of the summer at around 6.6 (Figure 14). This low may or may not be the result of pH depression due to spring snowmelt runoff. There are data gaps between early spring and summer measurements.

Alkalinity values ranged from 50 ueq/l to a high of 134 ueq/l. There appears to be no real trend in alkalinity values at this time (Figure 15).

Specific conductance remained relatively constant throughout the study period, ranging from 10 umhos to 23 umhos (Figure 16). As in pH and somewhat alkalinity, the inlet, outlet, epilimnion, and hypolimnion paralleled each other. This was unique to this lake.

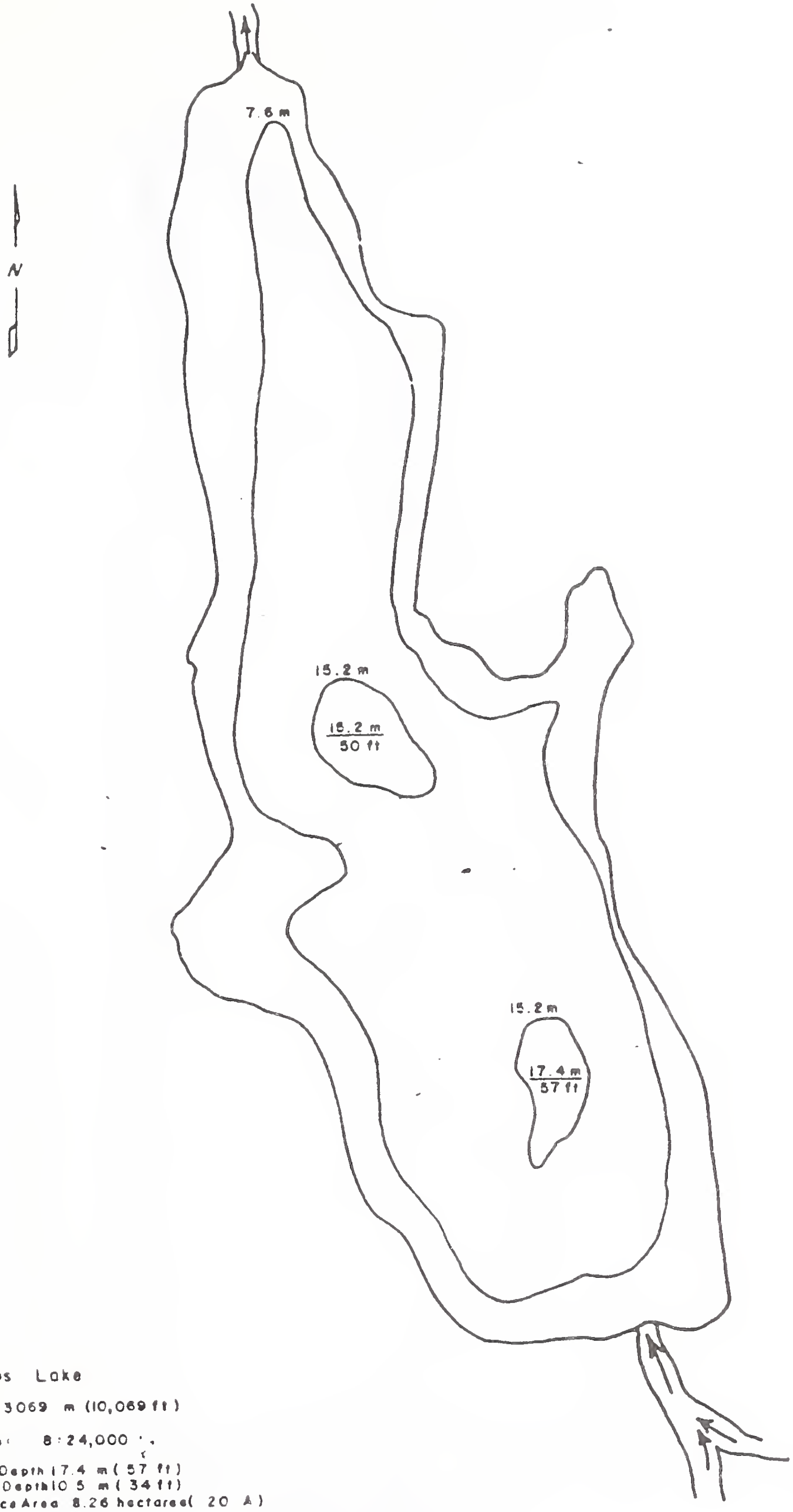
Dissolved oxygen did not closely correspond to water temperature, and fluctuated greatly, even in the hypolimnion. The values, however, remained within 2 mg/l of saturation.

Nutrients, as in the other lakes, were extremely low and often below detectable limits. Aluninum and iron, however, are at detectable limits (Table 8). Calcium and magnesium are at higher levels than Black Joe, which corresponds to the higher alkalinity values. Again, the lake is in a bicarbonate regime, and although sensitive, does not appear to be in transition.

Table 7. Mean Values for Chemical Constituents (mg/l) of Black Joe Lake 1983.

Location	Cl	F	NO_3-NO_2	O-P	TOC	NH_3-N	Al	Fe	Ca	Mg	Na	SO_4
Inlet	3.5	.02	.090	.006	1.2	*.01	*.020	*.005	1.2	.16	.7	1.3
Outlet	3.8	.02	.010	*.005	*.8	.02	*.020	*.005	1.3	.19	.9	1.2
Epilimnion	3.4	.02	.020	.006	1.2	*.01	*.020	*.005	1.2	.18	.6	1.2
Hypolimnion	3.4	.02	.018	*.005	.8	*.01	*.020	*.005	1.3	.20	.7	1.2

(* means less than)



Hobbs Lake

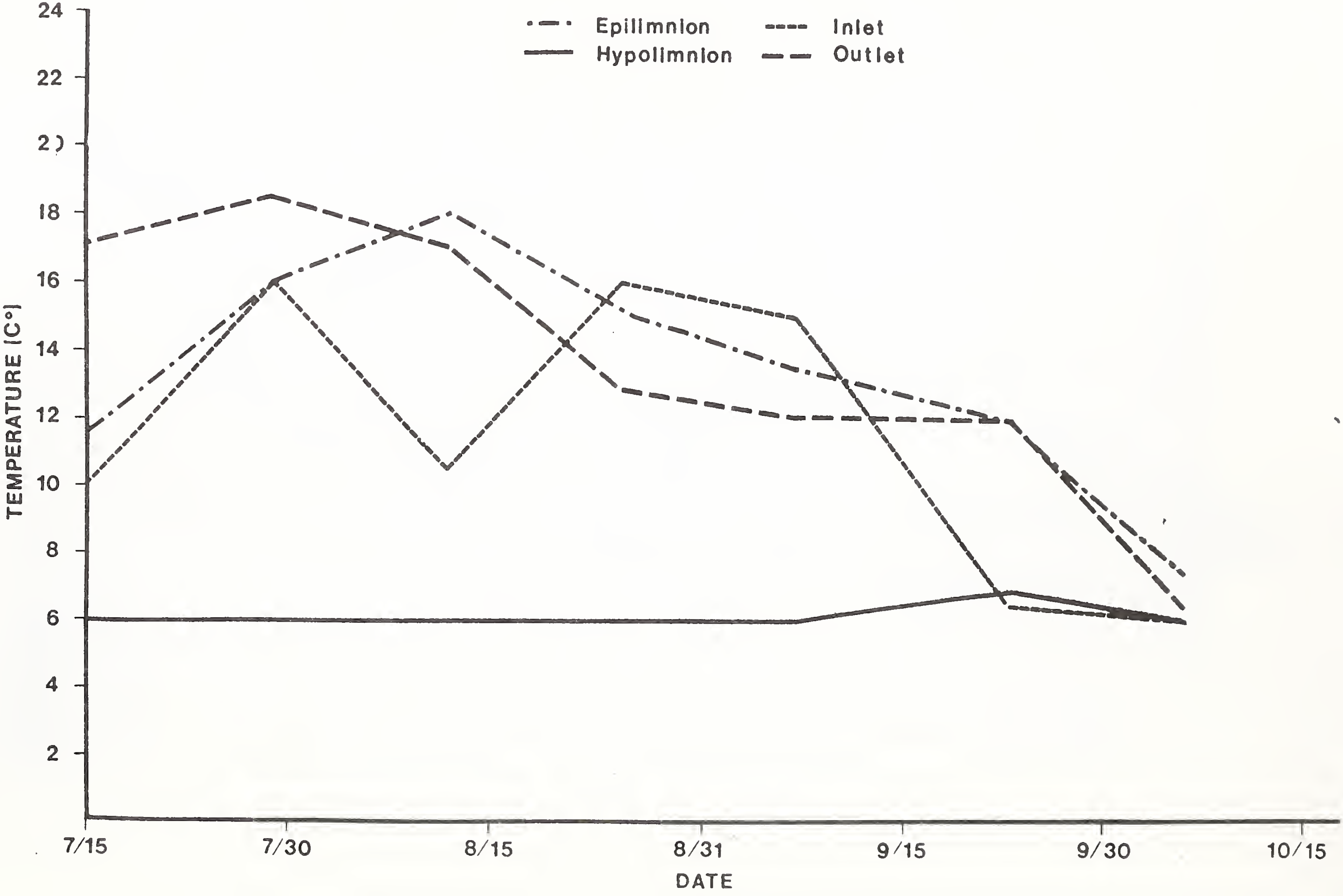
Elev: 3069 m (10,069 ft)

Scale: 8:24,000

Max Depth 17.4 m (57 ft)
Mean Depth 10.5 m (34 ft)
Surface Area 8.26 hectares (20 A)
Shoreline Dev. 1.59
Shoal Area 22 %

Fig. 12. Bathymetric map of Hobbs Lake

Fig. 13. HOBBS LAKE WATER TEMPERATURE



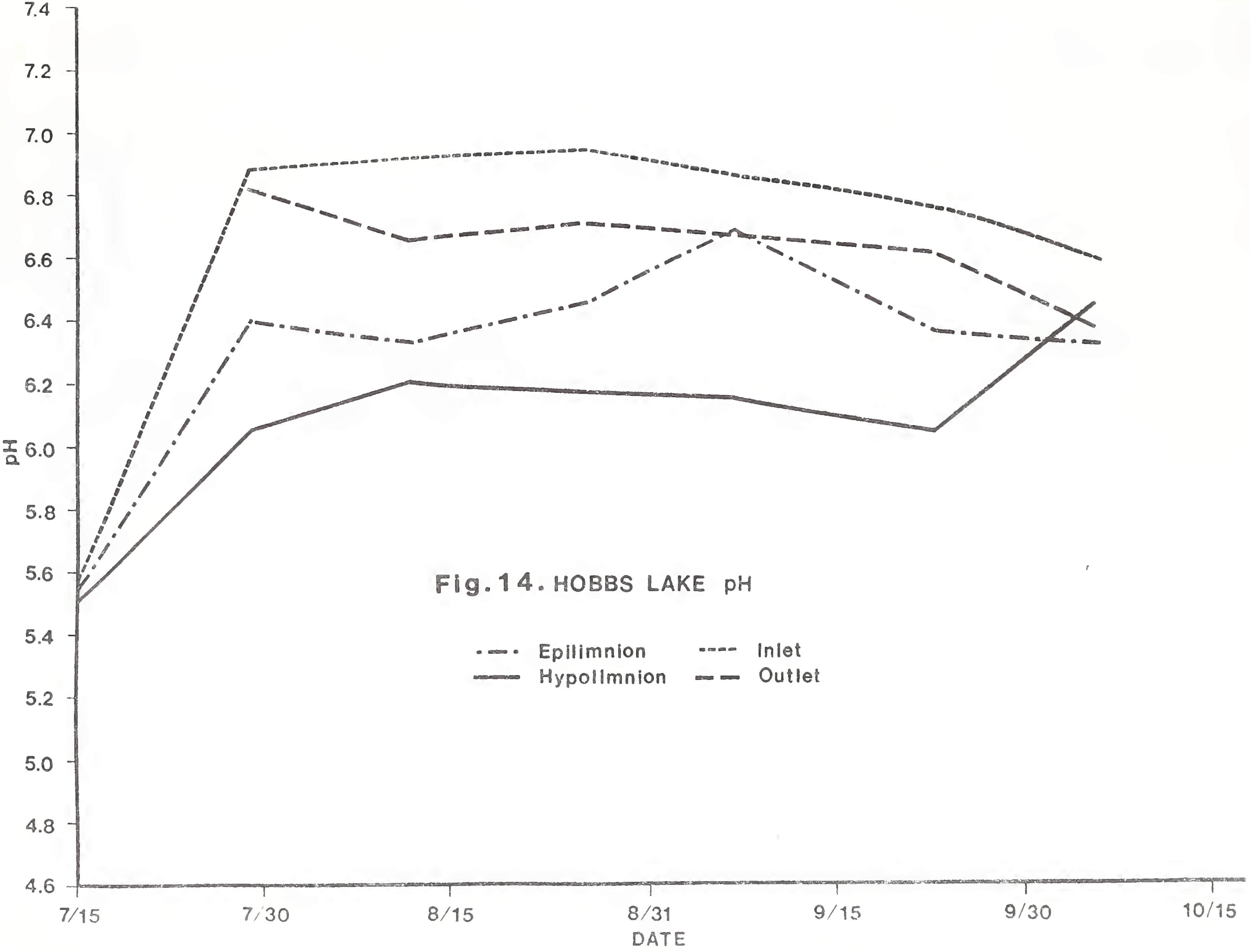
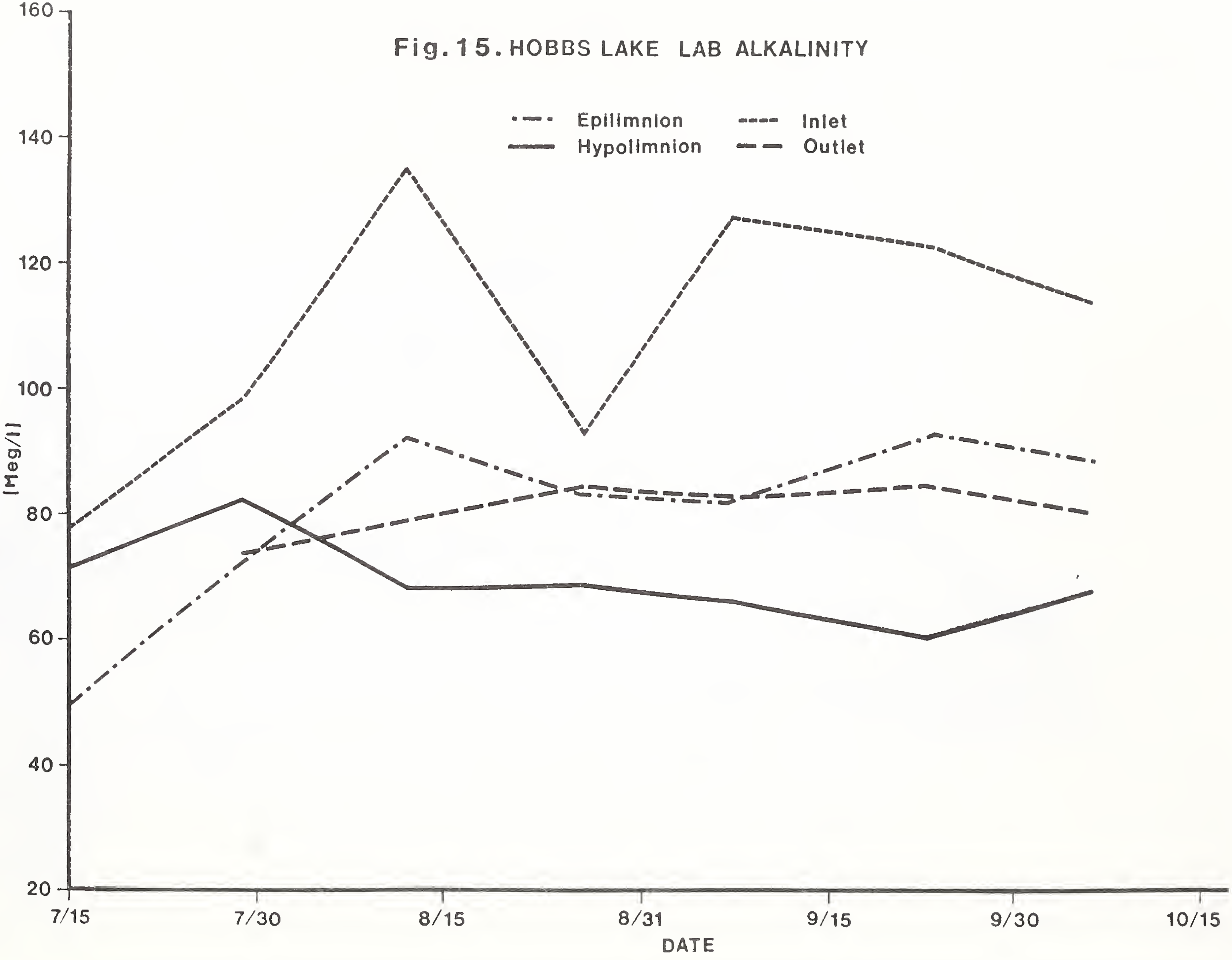


Fig. 14. HOBBS LAKE pH

Fig. 15. HOBBS LAKE LAB ALKALINITY



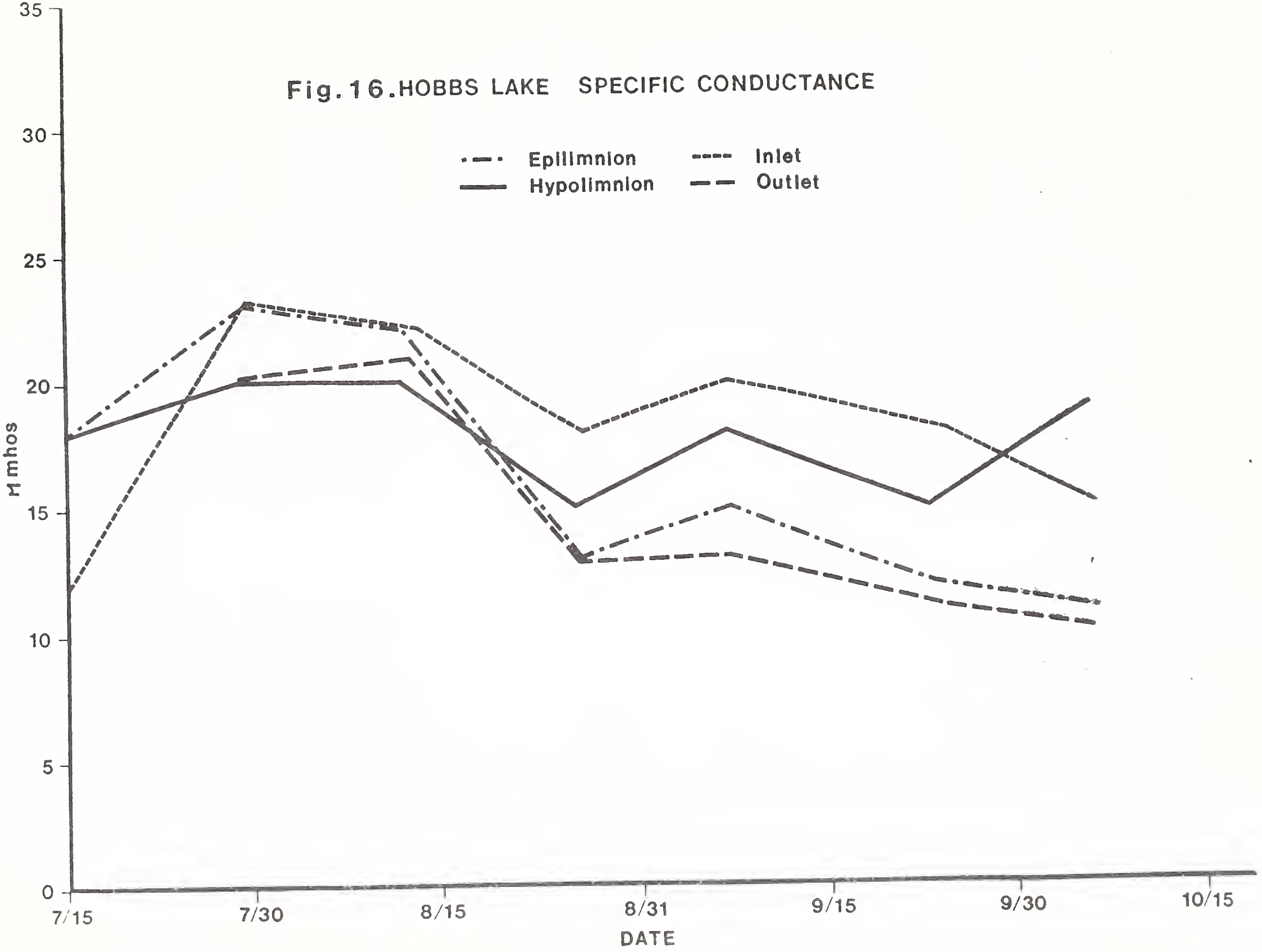


Fig. 16. HOBBS LAKE SPECIFIC CONDUCTANCE

Table 8. Mean Values for Chemical Constituents (mg/l) of Hobbs Lake 1983

Location	Cl	F	NO_3-NO_2	O-P	TOC	NH_3-N	Al	Fe	Ca	Mg	Na
Inlet	3.7	.05	.02	*.005	1.3	*.01	.030	.008	2.0	.21	.6
Outlet	2.9	.02	*.01	*.005	1.9	*.01	.021	.006	1.4	.21	.7
Epilimnion	3.7	.02	*.01	*.005	3.4	*.01	.021	.005	1.4	.20	.5
Hypolimnion	3.3	.02	*.01	.005	2.5	*.01	.021	.018	1.2	.19	.6

(* means less than)

Seneca Lake

Seneca Lake is the largest and deepest of the monitor lakes (Figure 17). It has a surface area of 159 acres, and a maximum depth of 246 feet, making it the deepest lake within the Bridger Wilderness itself. The mean depth is 83 feet, with a volume of 13,200 acre feet. The drainage area is 2,216 acres, giving it a drainage basin:lake volume ratio of 0.17. Seneca has a relative flushing time of 2.04, which should make it the most stable of all the lakes tested. The lake itself is fairly exposed, with a westerly aspect to the watershed.

Seneca is probably the most strongly stratified of all the lakes (Figure 18). Stratification probably starts around early to mid-July. Maximum epilimnion temperatures rose to 18°C in mid-August, then gradually declined from mid-August to late September. Fall turnover was complete by mid-October.

Values for pH ranged from 5.68 to 6.98, and seemed relatively stable from mid-August on (Figure 19). Alkalinity values were erratic at best, but were in the range of 70 ueq/l (Figure 20). Specific conductance was more stable, but still ranged from 5 to 24 umhos (Figure 21). Dissolved oxygen, as usual, was always near saturation.

Chemically, as in the other lakes, Seneca is highly oligotrophic, with both nutrients and trace metals beyond the detection limits (Table 9). Again, the lake appears to be in a bicarbonate condition. Due to its great depth, one would not expect this lake to be as sensitive to acid deposition as Black Joe or Hobbs.

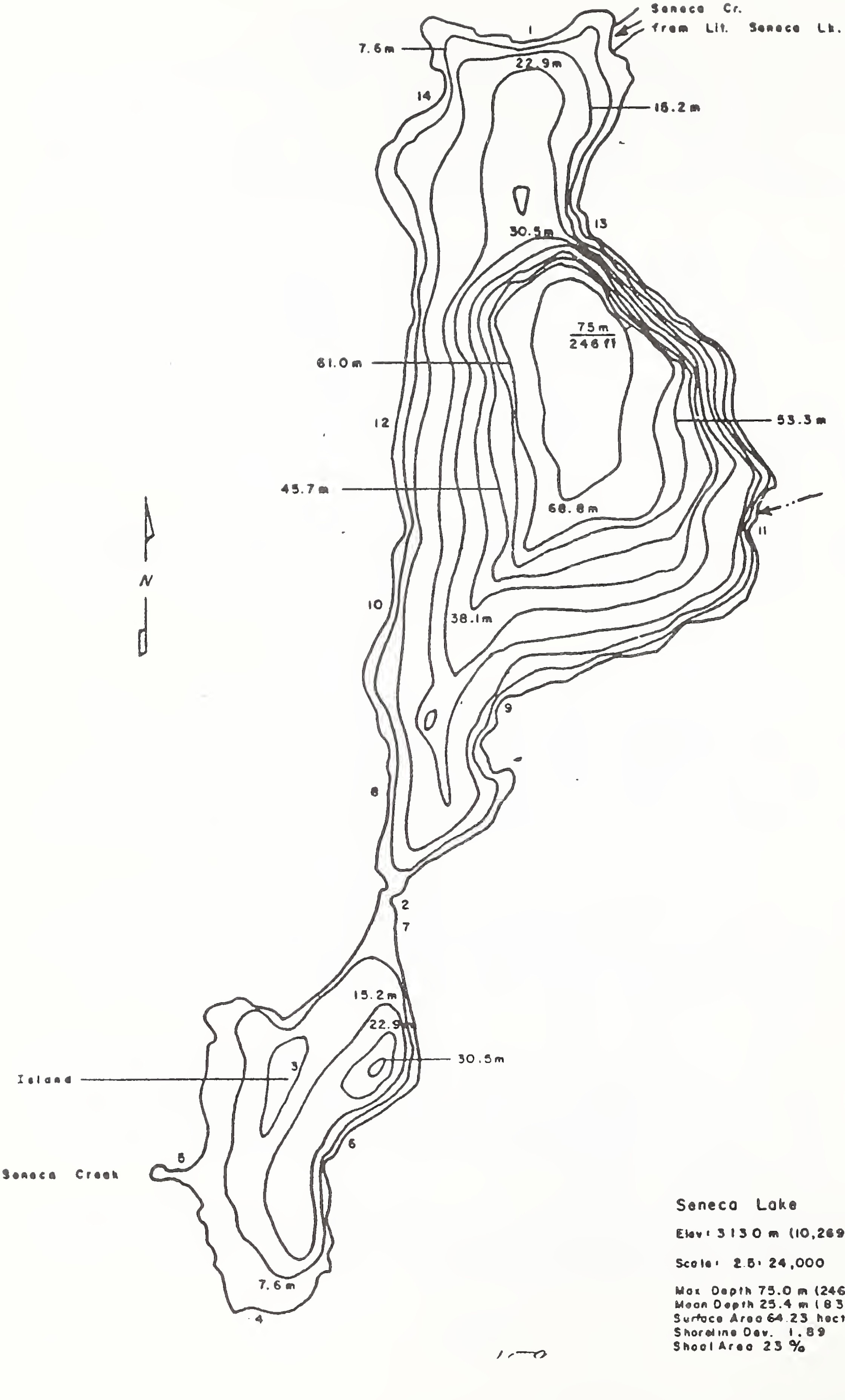
Section Corner Lake

Section Corner Lake is probably the least sensitive of the four lakes to acid deposition. The maximum depth is 84 feet, with a mean depth of 23 feet (Figure 22). Lake volume is 1,280 acre feet, and drainage basin area is 3,913 acres. This gives a high drainage basin:lake volume ratio of 3.07, and a relative flushing time of 0.11. The surface area of the lake is 55.5 acres, and unique in that the lake is almost divided in two with shallow water in the middle.

Like Hobbs and Seneca Lakes, initial stratification occurred prior to July 15, 1983 (Figure 23). The hypolimnion temperature was not as constant as the other lakes, due in part to its shallow nature. Mid-August was again the time of maximum stratification, with a temperature difference of 10°C. Fall turnover was probably completed by the end of September, with at least some form of stratification lasting 75 days.

Both alkalinity and pH values were consistently higher for Section Corner Lake. This may be due in part to the greater soil development around the lake. Values for pH ranged from 6.30 to 7.34 (Figure 24), and alkalinities ranged from 86 ueq/l to 167 ueq/l (Figure 25). Values for pH appeared to remain fairly constant throughout the summer. Alkalinity values appeared to increase as the summer progressed.

Specific conductance also remained relatively stable, ranging from 12 umhos to 27 umhos (Figure 26). Dissolved oxygen corresponded well with temperature, and was close to saturation during the year.



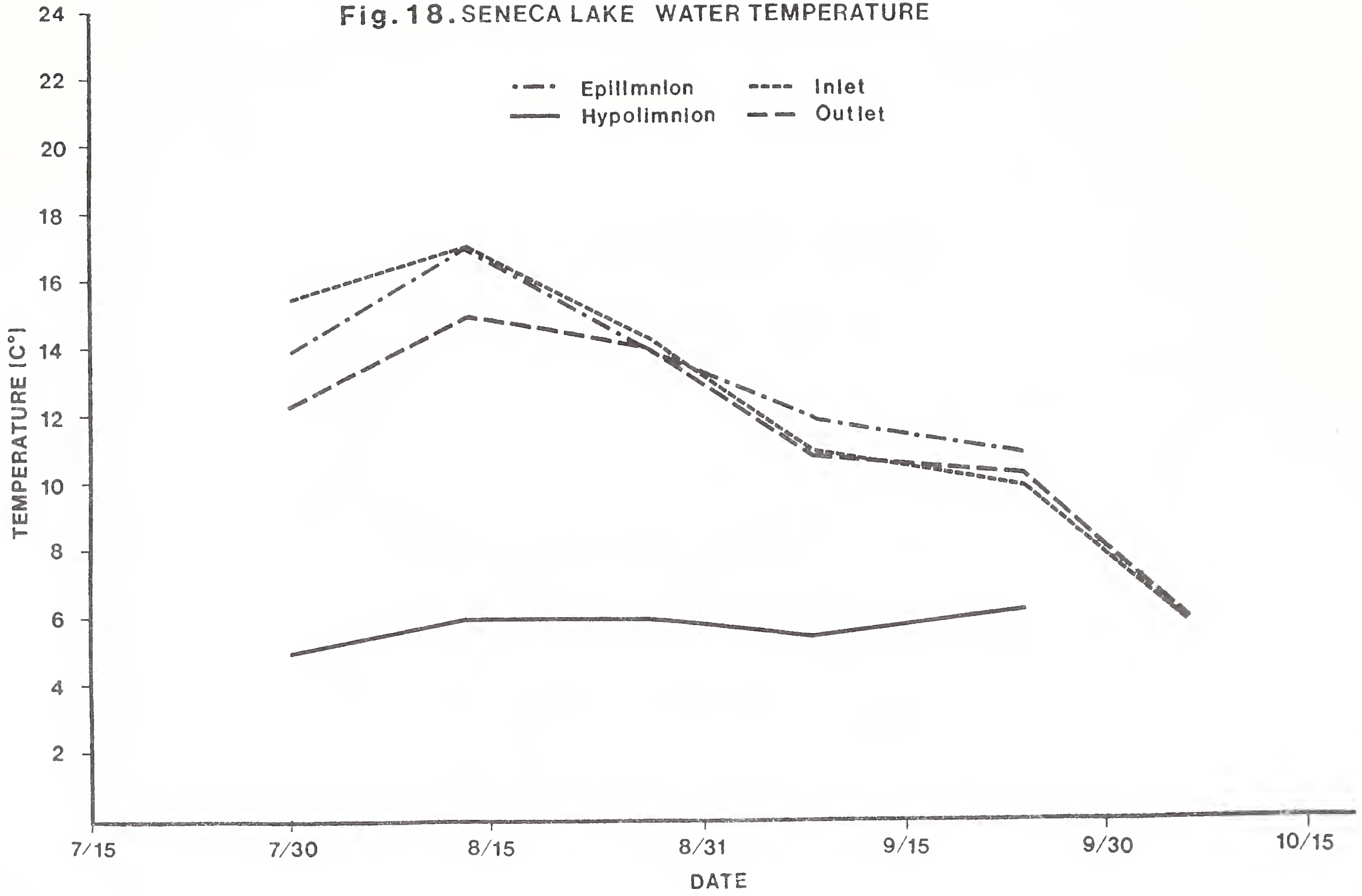
Seneca Lake

Elev: 3130 m (10,269 ft)

Scale: 2.5: 24,000

Max Depth 75.0 m (246 ft)
Mean Depth 25.4 m (83 ft)
Surface Area 64.23 hectares (159 A)
Shoreline Dev. 1.89
Shoal Area 23 %

Fig. 18. SENECA LAKE WATER TEMPERATURE



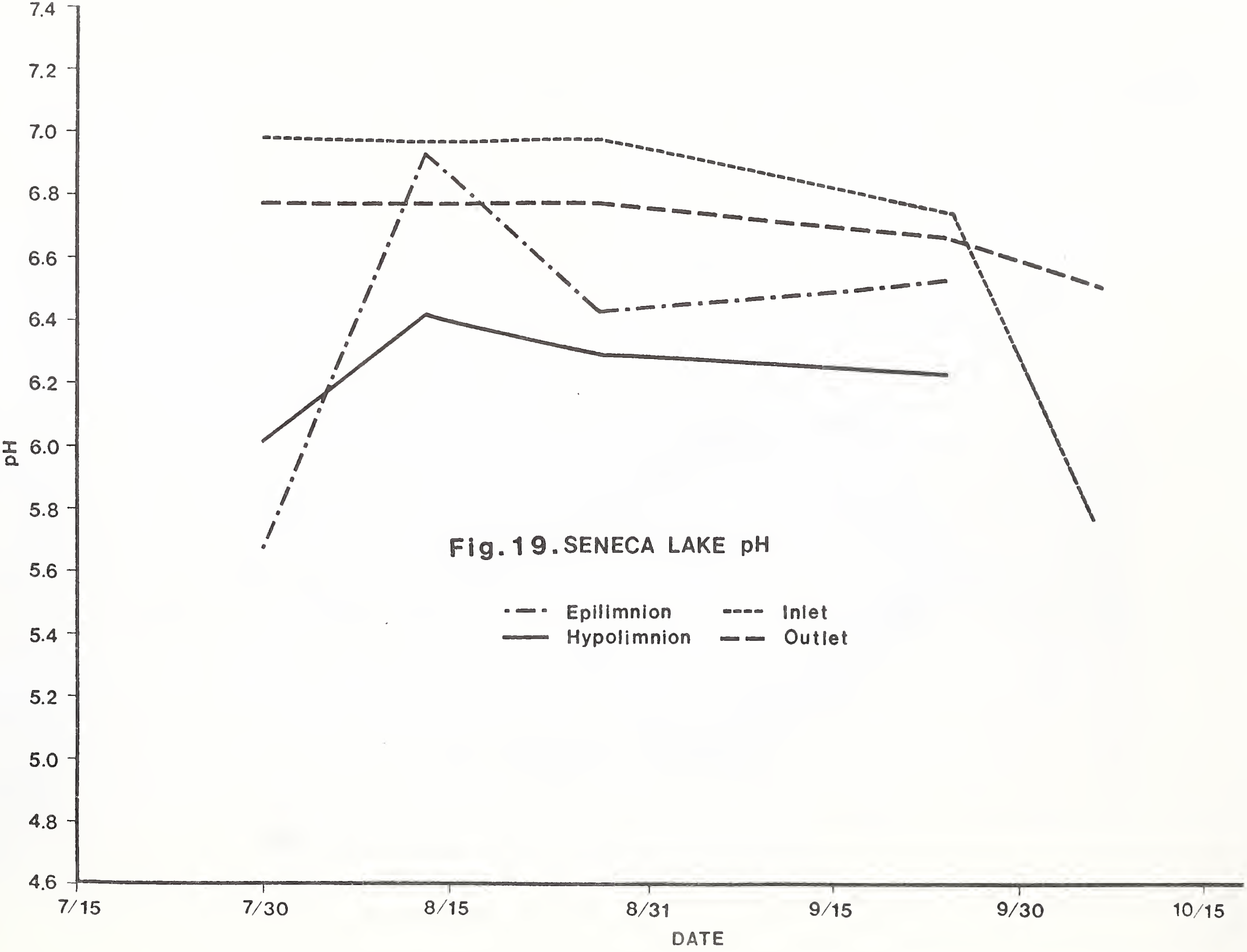


Fig. 19. SENECA LAKE pH

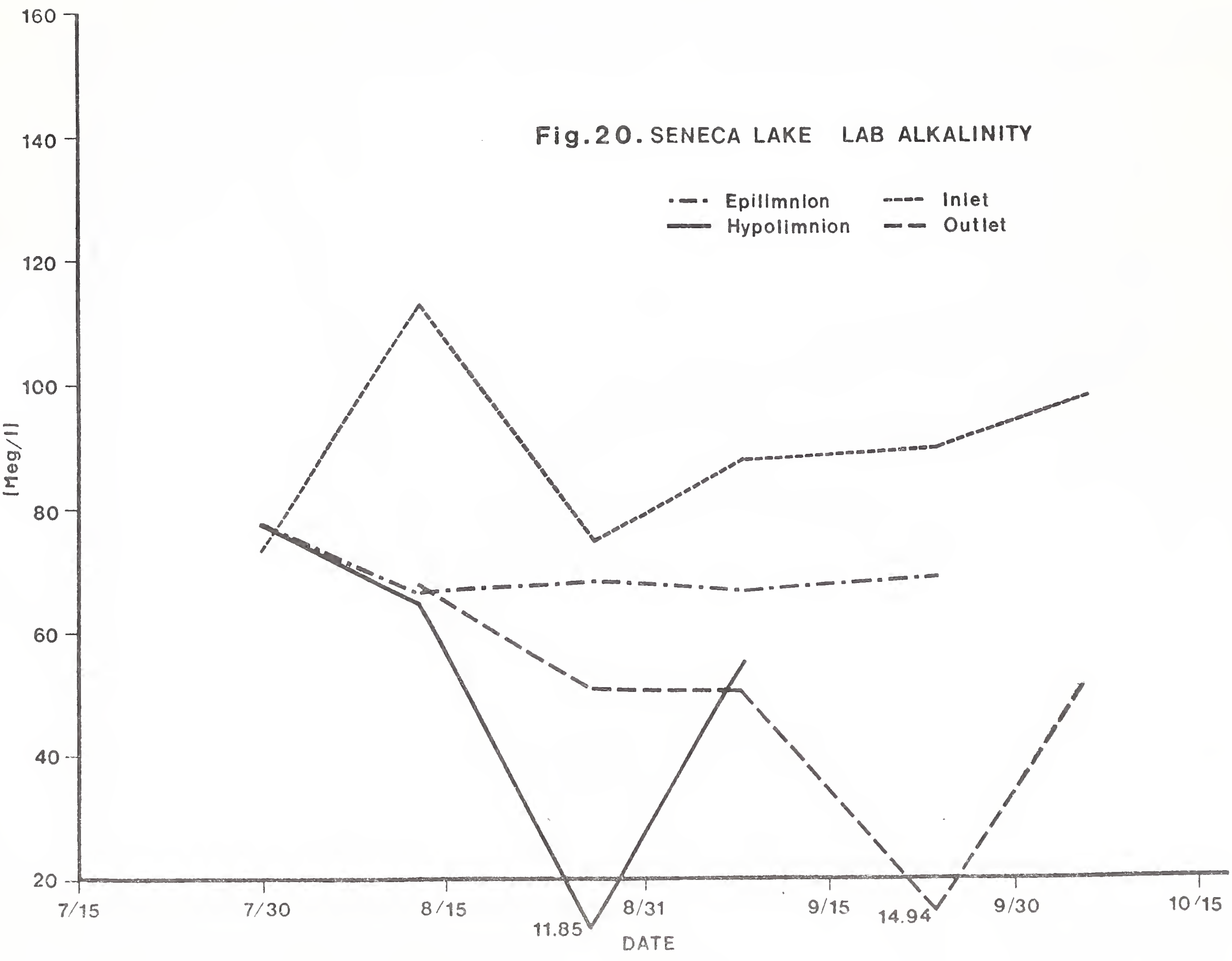


Fig.20. SENECA LAKE LAB ALKALINITY

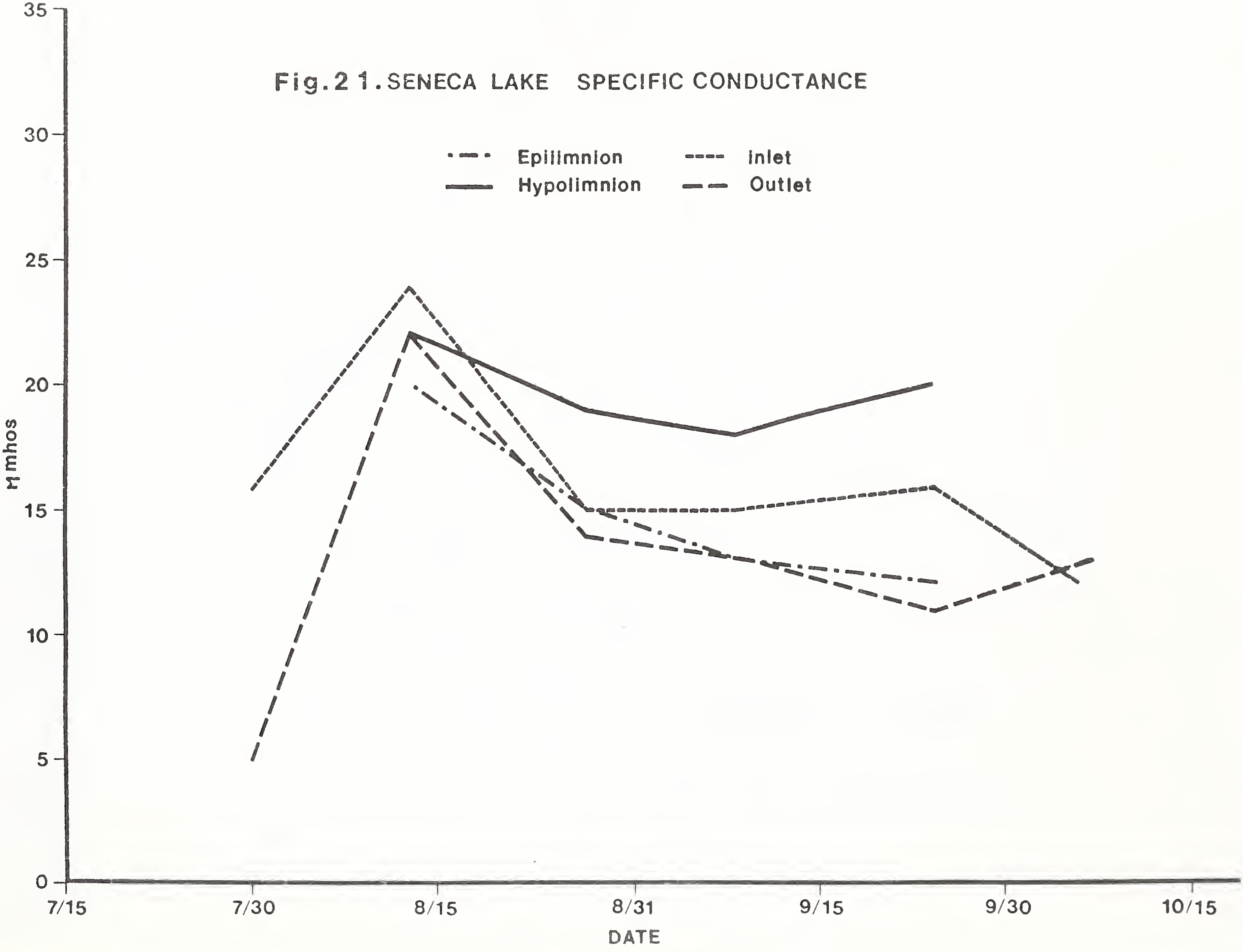


Fig. 2 1. SENECA LAKE SPECIFIC CONDUCTANCE

Table 9. Mean Values for Chemical Constituents (mg/l)
Seneca Lake 1983

Location	Cl	F	NO_3-NO_2	O-P	TOC	NH_3-N	Al	Fe	Ca	Mg	Na
Inlet	2.9	.02	.017	*.005	1.2	*.01	*.02	*.005	1.4	.18	.5
Outlet	2.9	.02	.01	*.005	.9	*.01	*.02	*.005	1.2	.16	*.5
Epilimnion	3.2	.02	*.01	*.005	1.3	*.01	*.02	*.005	1.1	.15	.5
Hypolimnion	2.9	.02	*.01	*.005	1.4	*.01	*.02	*.005	1.1	.15	.5

(*means less than)

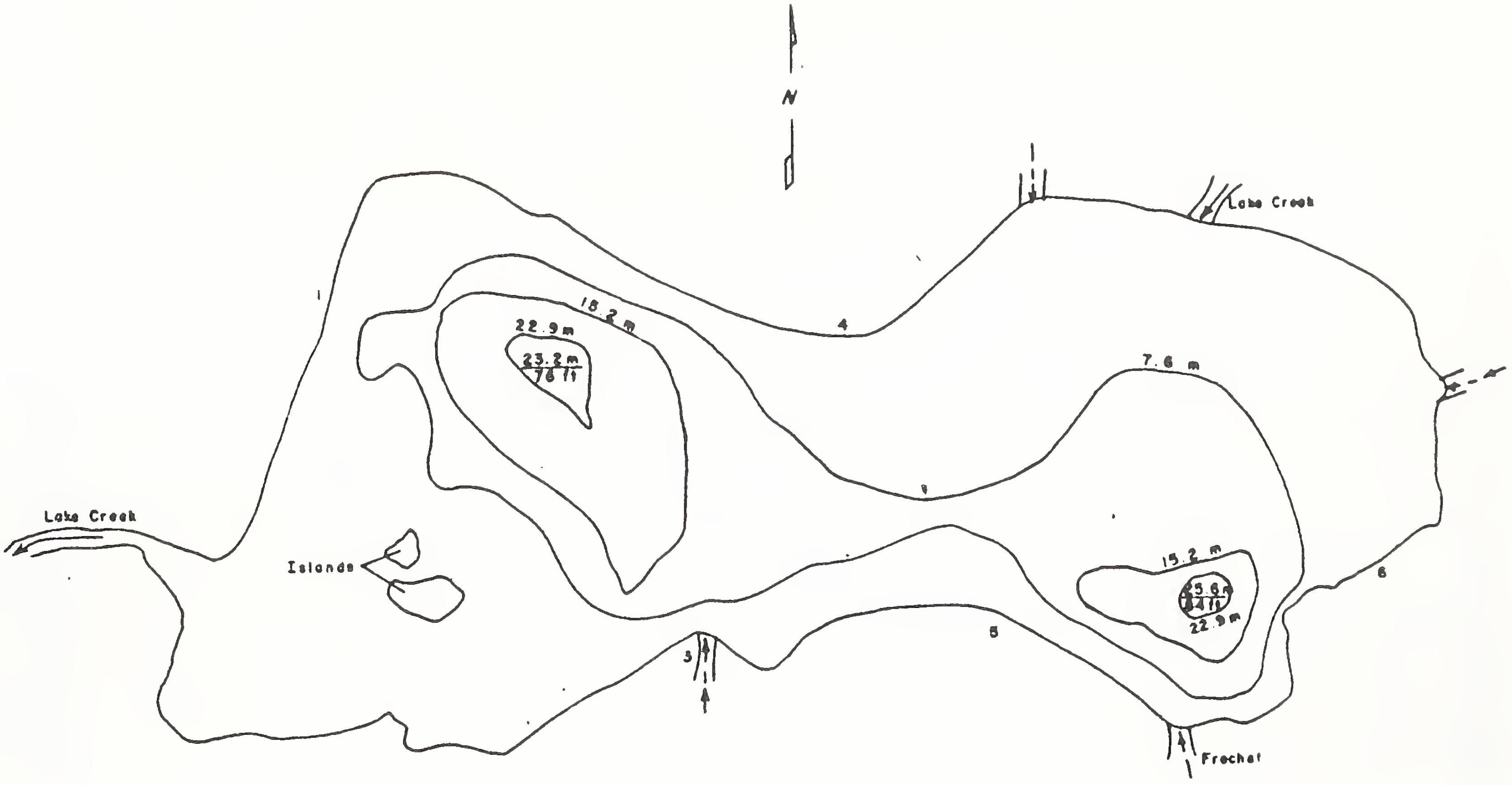


Fig.22. Bathymetric map of Section Corner Lake

Section Corner Lake

Elev: 2,818 m (9,245 ft)

Scale: 1:24,000

Max Depth 25.6 m (84 ft)
Mean Depth 7.0 m (23 ft)
Surface Area 22.46 hectares (55.50 A)
Shoreline Dev 1.45
Shoal Area 67.2 %

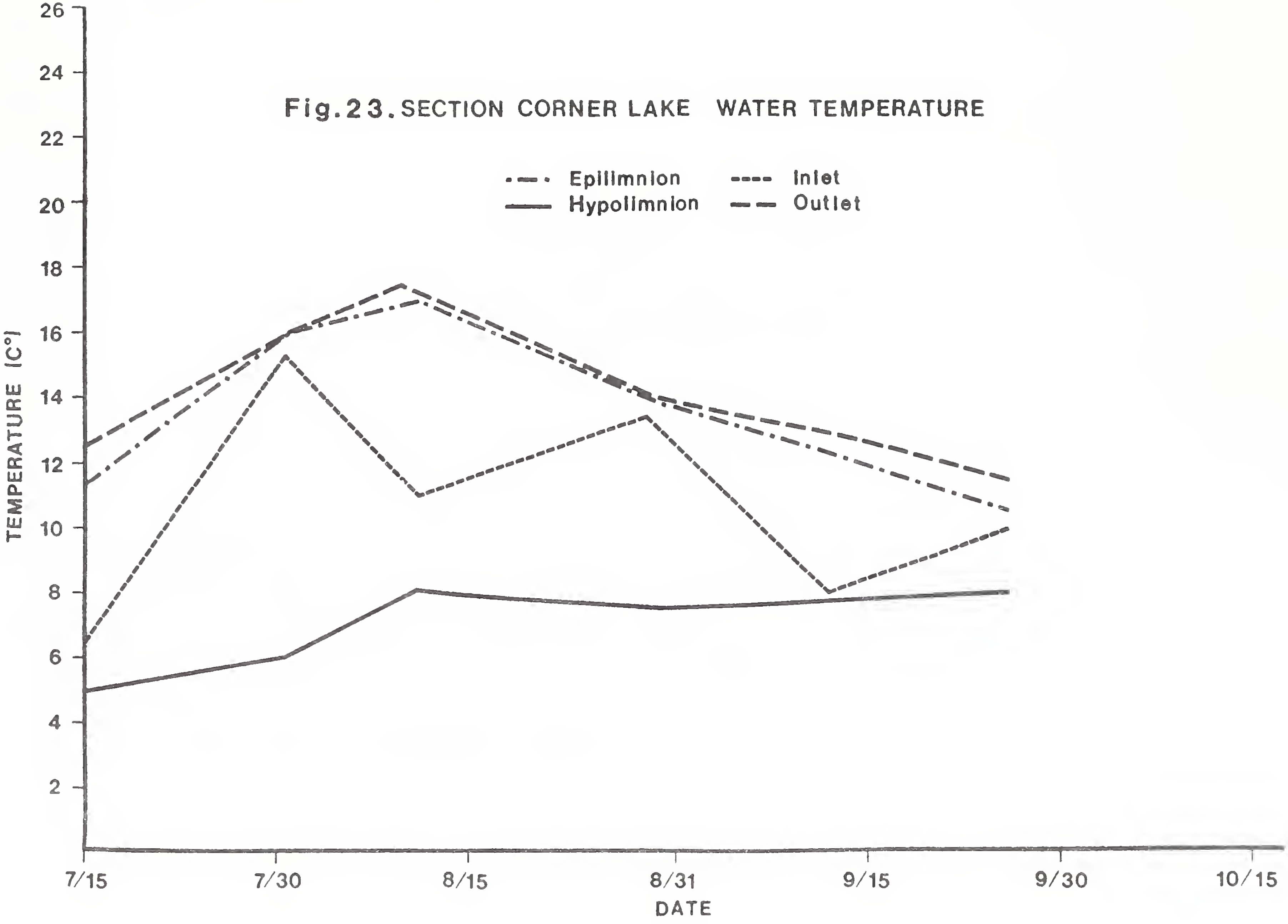


Fig. 23. SECTION CORNER LAKE WATER TEMPERATURE

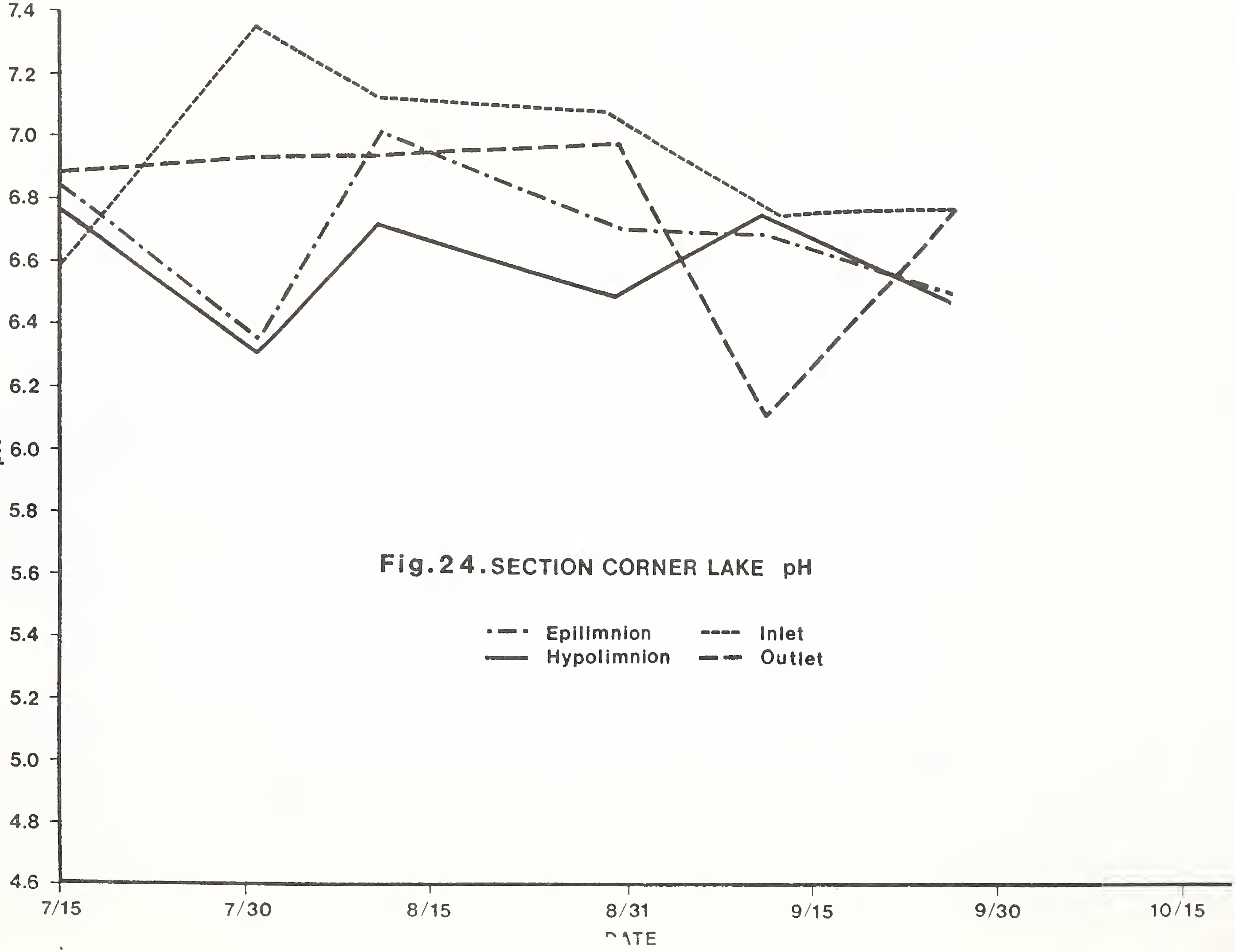


Fig.24. SECTION CORNER LAKE pH

Fig.25. SECTION CORNER LAKE LAB ALKILINITY

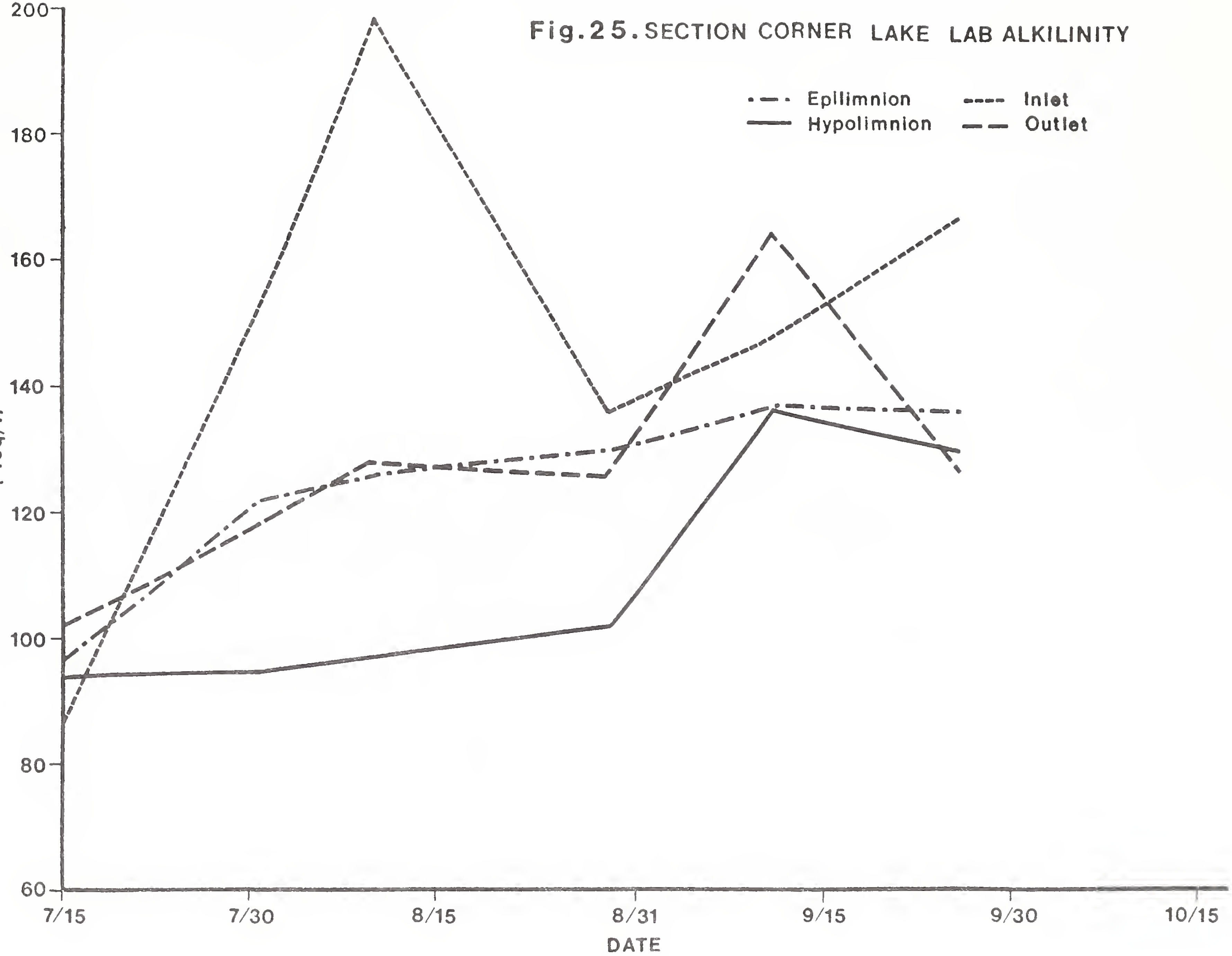
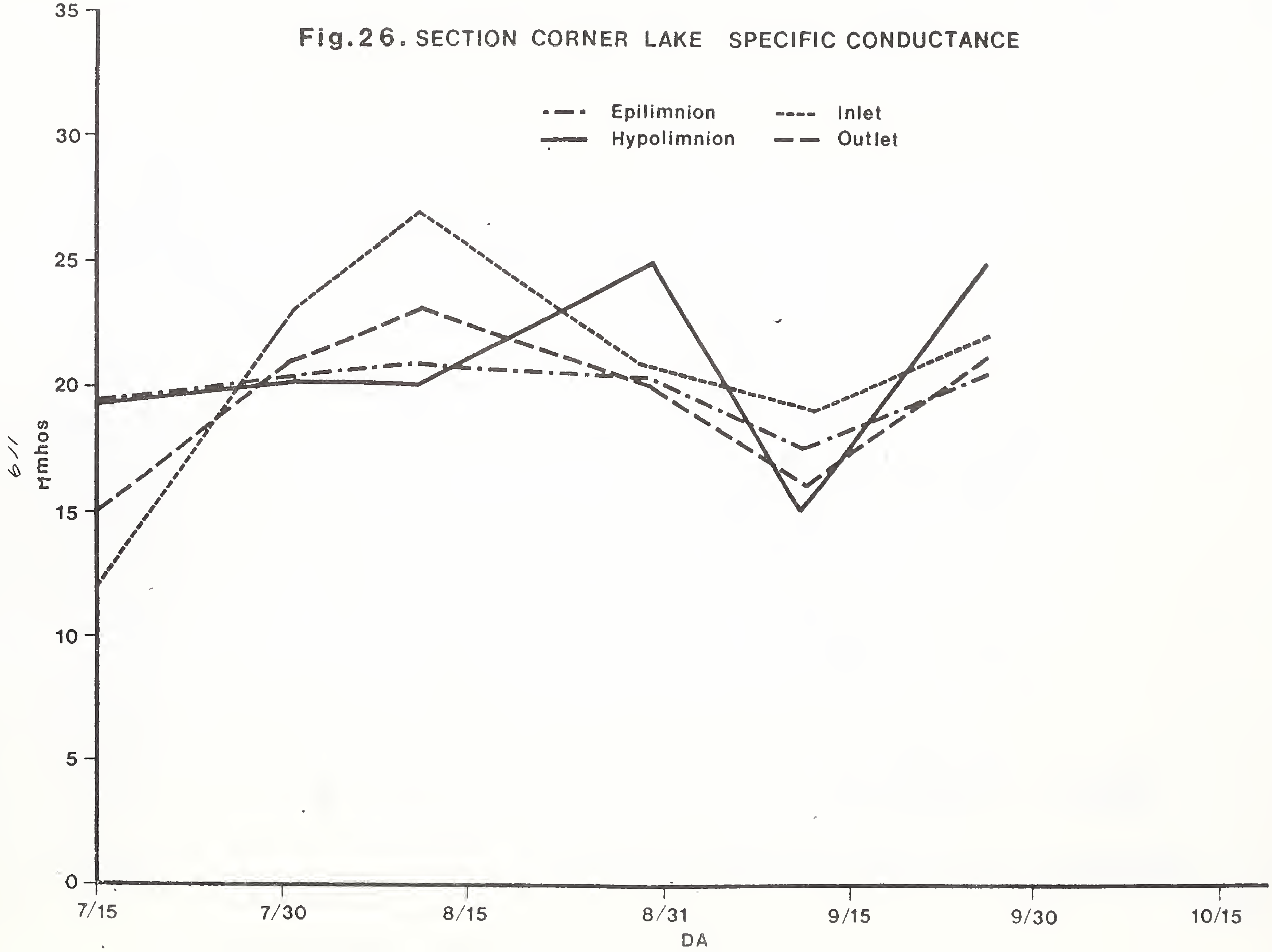


Fig.26. SECTION CORNER LAKE SPECIFIC CONDUCTANCE



Section Corner Lake is the most bicarbonate of all the lakes, and appears to be the least sensitive to acid precipitation (Table 10). Although it is the least sensitive, it is still very oligotrophic, with extremely low nutrients. Like Hobbs, iron is there in trace amounts.

Table 10. Mean Values for Chemical Constituents (mg/l)
of Section Corner Lake 1983

Location	Cl	F	NO_3-NO_2	O-P	TOC	NH_3-N	Al	Fe	Ca	Mg	Na
Inlet	3.2	.03	.01	*.005	1.6	*.01	*.02	.009	2.4	.32	.6
Outlet	3.9	.03	*.01	*.005	5.9	*.01	*.02	.008	2.0	.29	.6
Epilimnion	3.1	.03	*.01	*.005	2.6	*.01	*.02	.006	2.0	.29	.6
Hypolimnion	3.3	.03	*.01	*.005	3.1	*.01	*.02	.014	2.0	.30	.6

(* means less than)

Conclusion

The lakes within the Bridger Wilderness appear to be even more oligotrophic than originally indicated in earlier surveys. All alkalinity values were below the 200 ueq/l cutoff for sensitive lakes, and many were below 50 ueq/l. Nutrients and trace metals were often below the detection limits.

The monitor lakes, although oligotrophic, appeared to be normal bicarbonate lakes, and not under acid "stress" at this time. Although sulfates were not routinely tested for, excess sulfate was not evident in amounts that would indicate the lakes were in transition.

Two of the lakes were less sensitive to acid deposition. This was due to either more of an alkaline situation present, or slow flow through time such as Seneca.

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AQUATIC BIOLOGY OF SELECTED LAKE ECOSYSTEMS IN THE WIND RIVER MOUNTAINS, WYOMING
1983

INTRODUCTION

In 1983 as part of an intensive inventory of ecosystems around selected lakes in the Bridger-Teton National Forest´s Bridger Wilderness area, samples of zooplankton and aquatic macroinvertebrate biota were taken in the lakes and associated inlet and outlet streams. The purpose was to gain an understanding and record of existing conditions and communties present. This information could provide a warning system to evaluate effects of future management activities. Land managers are using aquatic macroinvertebrates and zooplankton more and more extensively as living indicators of habitat quality. Since some taxa or species are more sensitive than others this tool can provide a depth of focus upon positive or negative trends in aquatic ecosystems. If carefully monitored these indicators can serve as an early warning system to detect stress conditions before they become irreversibly damaging.

METHODS

Samples of zooplankton were taken from a raft. Three vertical tows were made from 20 to 50 foot depths with a 12.7 cm (5 inch) mouth, 80 micron mesh plankton net. This composite sample was collected from each lake every two weeks from mid-July thru early October, with a total of 6 sampling dates on Section Corner Lake and Black Joe Lake, 7 dates on Hobbs Lake and 5 dates on Seneca Lake.

Aquatic macroinvertebrate samples were taken with a modified Surber net. For each lake three stratified random samples were taken in the inlet stream and three from the outlet stream on a monthly basis, for a total of 3 sampling dates per station. The best rubble substrate was selected for sampling at each station. Biotic Condition Index (BCI) values (Winget and Mangum, 1979) are included for each stream sampled.

By Dr. Fred Mangum, Aquatic Ecologist, U.S. Forest Service, Provo, Utah

RESULTS

SECTION CORNER LAKE

The aquatic macroinvertebrate samples from the inlet stream indicated that it was in good condition and there were some sensitive species which could be used to monitor conditions, including changes in acidity. The clean water mayflies found were *Epeorus*, *Rithrogena*, *Ephemerella doddsi*, and *Ephemerella spinifera*, and the sensitive stoneflies were *Podmosta*, *Capniidae*, *Dorinueria*, and *Zapada*. In addition to these species there were six moderately tolerant species including the mayfly *Cinygmula*, stoneflies in the family Leuctridae and the genus *Megarcys*, caddisflies *Micrasema* and *Glossosoma*, and a dipteran *Dicranota*.

The outlet stream showed that there were some environmental stress conditions associated with this stream particularly in September when the BCI value dipped down to 60. There were some sensitive species present in this stream, however, which indicated that stress conditions were not severe since one clean water mayfly *Epeorus* species and two stoneflies *Kogotus* and *Zapada*, were found in this outlet stream along with some moderately tolerant species including the mayflies *Ephemerella tibialis*, *Paraleptophlebia*, *Ephemerella coloradensis*, and two stonefly genera *Hesperoperla* and *Megarcys*.

There were indications of sedimentation and organic enrichment in the reach of outlet stream sampled, particularly in early August. The observed number of shredders in the communities on the inlet and outlet stream are generally found where there is good riparian habitat.

The potential for a resident fishery in these streams would be very good in the inlet stream where the clean water species indicated that there would be suitable spawning substrate and good water quality. However, in the reach of outlet stream sampled it appeared that spawning activities could be somewhat limited by the amount of sedimentation. The number and size of fish in these streams would be somewhat limited by the low standing crop of aquatic macroinvertebrates which, was somewhat lower than would be expected even in a topography dominated by granitic geologic formations.

The pH range of 6.1 to 7.4 was compatible with the environmental requirements of macroinvertebrates in the inlet and outlet streams and zooplankton in the lake. The pH range of 6.1 to 7.4 was the best found in inlet streams of lakes sampled.

A total of five zooplankton species were found within the lake community. The Cladocerans were sparse in July with just $100/m^3$ they increased in August to about $3,000/m^3$ and in September to $6,000/m^3$. Cladocerans found in the zooplankton samples included *Daphnia rosea* which was found on each sample date, July through September, *Holopedium gibberum* which was found on all but the July sampling date, and *Polyphemus pediculus* which was found only on the three August sampling dates.

The Copepods were also low in numbers in July with $30/m^3$. They increased to $2,000/m^3$ in August and $7,000/m^3$ in September. There were two Copepod species found including *Cyclops bicuspidatus* which was found in all samples on all sampling dates, and *Diaptomus lintoni* which was found in early August and late September samples.

TABLE 1. MACROINVERTEBRATE ANALYSIS ELEMENT DATA FOR SECTION CORNER LAKE

Station	Date(s)	Diversity Index DAT(mean)	Standing Crop gm/m^2 (Mean)	Condition Index BCI
2 (Inlet)	7-07-83	3.1	0.2	77
1 (Outlet)	8-01-83	8.0	1.1	70
1	8-11-83	7.7	0.7	81
2	8-10-83	12.6	0.4	91
1	9-12-83	7.7	0.4	60
2	9-12-83	10.0	0.3	88

Scale:	DAT	Standing Crop	BCI
Excellent	18-26	4.1-12.0	above 90
Good	11-17	1.6-4.0	75-90
Fair	6-10	0.6-1.5	below 75
Poor	0-5	0.0-0.5	below 75

BLACK JOE LAKE

With the exception of the July samples the aquatic macroinvertebrates indicated that the outlet stream was in much better condition than the inlet stream. There was a dominance among those taxa tolerant to sedimentation and organic enrichment in the inlet stream. The habitat condition appeared to improve somewhat progressively through the months as samples were taken on the outlet stream. The number of shredders in the community in the outlet stream are generally found where there is excellent riparian habitat, whereas there were few shredders in the inlet stream samples which often indicates vegatation is sparse. There were some sensitive species in the Inlet Stream however, which included a mayfly *Ephemerella doddsi*, a stonefly *Doroneuria* and a caddisfly *Neothremma*. The moderately tolerant species included two mayflies *Cinygmula* and *Ephemerella coloradensis* and a stonefly *Megarcys*.

Reflecting a superior condition in the outlet stream were several clean water and moderately tolerant species. Sensitive species included four stoneflies *Kogotus*, *Podmosta*, *Zapada*, and *Cultus*, and two caddisflies *Parapsyche*, and *Neothremma*. The moderately tolerant taxa in the outlet stream were the mayfly *Ephemerella coloradensis*, two stoneflies *Hesperoperla* and *Megarcys*, a caddisfly *Lepidostoma*, and a dipteran *Dicranota*.

The potential for a resident fishery in the streams appeared to be much better in the outlet than in the inlet stream. The number of clean water species present indicated that there would be some suitable substrate for spawning, particulalrly in the outlet stream. The macroinvertebrate standing crop was lower than expected in the inlet stream but was about what was expected in the outlet stream which could support a good fishery.

The Black Joe inlet stream pH range of 6.0 to 6.9 did not exceed macroinvertebrate tolerance limits but the 5.6 reading on July 30 could have been detrimental. The outlet stream had a good pH range of 6.5 to 6.8 and the pH range in the lake of 6.1 to 6.9 did not exceed the observed tolerance limits of zooplankton.

Within the lake itself the zooplankton samples included just one species in the order Clodocera, *Daphnia rosea* which was present on all of the sampling dates. They had an increase from 100/m^3 in July to 2,500/m^3 in August and 10,000/m^3 in

September. One representative of the order Copepoda, *Cyclops bicuspidatus* was also present on each of the sampling dates. These Copepods had an early population explosion with 8,000/m^3 in July 13,000/m^3 in August and 18,000/m^3 in September.

TABLE 2. MACROINVERTEBRATE ANALYSIS ELEMENT DATA FOR BLACK JOE LAKE

Station	Date(s)	Diversity Index DAT(mean)	Standing Crop gm/m^2 (Mean)	Biotic Condition Index BCI
1 (Outlet)	7-19-83	4.3	0.5	60
2 (Inlet)	7-19-83	2.9	0.3	69
1	8-16-83	9.1	1.3	76
2	8-15-83	7.6	0.5	64
1	9-21-83	9.4	1.1	85
2	9-22-83	4.6	0.8	68

Scale:	DAT	Standing crop	BCI
Excellent	18-26	4.1-12.0	above 90
Good	11-17	1.6-4.0	75-90
Fair	6-10	0.6-1.5	below 75
Poor	0-5	0.0-0.5	below 75

HOBBS LAKE

The aquatic macroinvertebrates indicated only fair stream conditions in the outlet stream of Hobbs Lake, but the inlet stream appeared to be in considerably better condition. When sampled in early July the outlet stream had an extreme dominance of Simuliid which generally indicates organic enrichment, and moderately high numbers of sediment tolerant Chironomids. Also present were some clean water and moderately tolerant species which indicated that there was some good instream substrate. The observed number of shredders from the inlet stream samples indicate fairly good riparian habitat and the number of shredders found in outlet stream samples is generally found where riparian habitat is sparse. Low numbers of species and low numbers of individuals per species were found at each of the inlet and outlet stream stations. This along with the dominances among tolerant species gave very low DAT Diversity Index values.

In spite of this there were some sensitive indicators which could be used for monitoring acid rain conditions, particularly in the inlet stream where the clean water species included one mayfly *Epeorus*, two stoneflies *Podmosta* and *Zapada* and one dipteran in the family Blephariceridae. Moderately tolerant species in the inlet stream included the mayfly *Cinygmula*, a stonefly in the family Leuctridae, two caddisflies *Lepidostoma* and a Philopotamid and a dipteran *Dicranota*. In the outlet stream the sensitive species were all stoneflies including *Podmosta*, *Cultus*, and *Zapada*. Moderately tolerant species in the outlet stream were a mayfly *Paraleptophlebia*, caddisfly, *Glossosoma*, and a dipteran *Dicranota*.

The potential for a fishery in these inlet and outlet streams appeared to be fairly good, particularly in the inlet stream where the number of clean water species indicated that there would be some suitable spawning substrate. However the amount of sedimentation indicated by the communities in the sampled reach of outlet steam indicates that spawning success could be limited. The BCI values indicated stress conditions in the reach sampled in the outlet stream and fairly good conditions in the inlet stream.

The pH levels below 5.6 on July 15 for both the inlet and the lake could have been at least temporarily limiting to the most sensitive species of macroinvertebrates and zooplankton. The range of 6.0 to 6.9 found in the inlet and lake on other sampling dates would not be limiting. The outlet stream had a good pH range of 6.4 to 6.8.

Within Hobbs Lake there was a rich zooplankton community. The Cladocerans numbered 2,000/m^3 in July, 4,500/m^3 in August and 12,000/m^3 in late September. There were three Cladoceran species including *Daphnia rosea*, which was present in each of the samples, particularly abundant on the September 23 sampling date, *Holopedium gibberum* which was present on all of the sampling dates and particularly abundant on the August 26 sampling date, and *Polyphemus pediculus* which was present in both the July and August samples.

A different pattern was observed in the numbers of Copepods. The highest number, 1,000/m^3 was found in July with the numbers declining to 350/m^3 in August and 500/m^3 in late September. There were three species of Copepods including *Cyclops vernalis*, *Cyclops bicuspidatus* and *Diaptomus lintoni*. *Cyclops* species were present in the July and August samples and *Diaptomus* immature stages were present in late July and early August and the mature forms on all the rest of the sampling dates. *Diaptomus* is a large Copepod, which is known to be a preferred food item of trout.

TABLE 3. MACROINVERTEBRATE ANALYSIS ELEMENT DATA FOR HOBBS LAKE

Station	Date(s)	Diversity Index DAT(mean)	Standing Crop gm/m^2 (Mean)	Biotic Condition Index BCI
1 (Outlet)	7-08-83	3.2	0.5	62
2 (Inlet)	7-08-83	5.8	0.4	76
1	8-12-83	1.4	0.6	67
2	8-12-83	5.4	0.3	70
1	9-07-83	1.7	0.1	62
2	9-07-83	6.7	0.2	78

Scale:	DAT	Standing crop	BCI
Excellent	18-26	4.1-12.0	above 90
Good	11-17	1.6-4.0	75-90
Fair	6-10	0.6-1.5	below 75
Poor	0-5	0.0-0.5	below 75

SENECA LAKE

Of the lake ecosystems sampled Seneca Lake appeared to be the best. In both the inlet and outlet stream stations there were aquatic macroinvertebrates that indicated good water quality and good instream substrate. Although there were some dominances among those taxa tolerant to sedimentation, it did not appear to be severe except on the September 8 sampling date when the BCI dropped to 66 on the inlet stream there appeared to be some stress conditions.

Both the inlet and outlet stream had sensitive species which could be used to monitor possible acid rain impacts on this aquatic ecosystem. In the inlet stream the clean water species found included four stonefly species *Zapada*, *Podmosta*, *Kogotus*, and *Doronuria*, and one caddisfly species *Parapsyche elsis*. The moderately tolerant species included three mayflies *Cinygmula*, *Paraleptophlebia*, and *Ephemerella tibialis*, two stoneflies *Megarcys* and *Hesperoperla*, and one dipteran *Antocha*. In the outlet stream the sensitive species included two mayflies *Epeorus* and *Rithrogena*, two stoneflies *Doronuia* and *Zapada*, and two caddisflies *Parapsyche elis* and *Neothremma*. Moderately tolerant species included the mayfly *Cinygmula*, three stonefly species *Megarcys*, *Hesperoperla*, and a *Leuctrid*, a caddisfly species *Micrasema*, and a dipteran *Dicranota*.

The observed number of shredders in the community in the outlet stream generally are found where there is good to excellent riparian habitat. The scaricity of shredders in the community in the inlet stream is often found where the riparian habitat is very sparse.

The potential for a resident fishery in the inlet and outlet streams appears to be fairly good. The number of clean water species indicates that there should be suitable spawning substrate available but the standing crop of aquatic macroinvertebrates could be a limiting factor. It was lower than expected even in an aquatic ecosystem where there is low alkalinity and could limit the number and size of fish that could be supported within these reaches of stream. Being closely associated with the lake however, the energy budget and nutrients available within the lake would probably be the determining factor in the number and size of fish in this aquatic ecosystem.

The pH of 5.7 recorded for the inlet stream in early October and the epilimnion of the lake on July 30 may have been limiting to the macroinvertebrates and zooplankton. The pH for all parts of this ecosystem was in a good range of 6.0 to 7.0 on all other sampling dates and the outlet stream had the most stable pH range of 6.6 to 6.8.

Seneca Lake had a good zooplankton community. The number of Cladocerans found in July was $82/m^3$, in August there were $2,000/m^3$ and in September $1,000/m^3$. *Daphnia rosea*, was found only in the September samples and *Holopedium gibberum* was present on all of the sampling dates July through September. As found in Hobbs Lake the numbers of Copepods were highest in early samples and then declined. There were about $3,000/m^3$ in July, $1,500/m^3$ in August and $1,000/m^3$ in September. In the order Copepoda there were three species, an immature *Cyclops* which could not be identified was found in September, *Diaptomus arapahoensis* which was found on all of the sampling dates except in July, and *Diaptomus lintoni* which was found in the late September sample.

In summary there are sensitive macroinvertebrate species found in each of the inlet and outlet streams of the four lake ecosystems sampled which could be used as part of a warning system of possible impacts from acid rain. There were also good populations of zooplankton in each of the lakes, the diversity and possibly the numbers of which could be significant as indicators of acid rain pollution.

TABLE 4. MACROINVERTEBRATE ANALYSIS ELEMENT DATA FOR SENECA LAKE

Station	Date(s)	Diversity Index DAT(mean)	Standing Crop gm/m^2 (Mean)	Biotic Condition Index BCI
1 (Outlet)	7-30-83	9.1	1.6	75
2 (Inlet)	7-30-83	8.5	0.6	88
1	8-13-83	9.8	0.5	102
2	8-13-83	7.7	1.0	71
1	9-08-83	12.7	0.3	88
2	9-08-83	2.5	0.3	66

Scale:	DAT	Standing crop	BCI
Excellent	18-26	4.1-12.0	above 90
Good	11-17	1.6-4.0	75-90
Fair	6-10	0.6-1.5	below 75
Poor	0-5	0.0-0.5	below 75

DISCUSSION

Studies have been conducted to determine effects of pH upon various aquatic maroinvertebrates. Bell (1970) found that the midge, *Tanytarsus dissimilis* life cycle could not be completed in waters with pH below 5.5. Bell (1971) observed in a laboratory study the tolerances of species in four aquatic insect orders to pH values from 1.0 to 7.0.

The TL_{50} values (pH at which 50% of the organisms died) at 30 days ranged from 2.45 (*Brachycentrus americanus*) to pH 5.38 (*Ephemerella subvaria*). All species tested were most sensitive to low pH during the period of emergence. The mayfly life cycle could not be completed at a pH below 5.9. EPA research and studies have indicated that most freshwater aquatic life require a pH range of 6.5 to 9.0.

Sutcliffe and Carrick (1973) found that in acidic streams (pH less than 5.7) mayflies, some caddisfly genera and *Gammarus* were rare even though they were abundant in downstream reaches with a higher pH. Roback (1974) found that mayfly and caddisfly species were absent in streams affected by acidic mine drainage.

Hall (1980) observed that the scrapers in the benthic community are lost when a stream becomes acidic. Female mayfly adults beatis did not lay eggs on otherwise suitable substrates in water pH less than 6.0 although three different species were found in a non-acidic reach of stream within 200 meters of the experimental station.

In their 1982 annual report to the President of the United States, the Interagency Task Force on Acid Precipitation, Washington, D. C. proposed to conduct stream and lake ecosystem studies to assess impacts of freshwater acidification and recover on biotic structure and function and to survey potentially sensitive waters.

Magnuson (1983) found literature as early as 1959 which indicated that atmospheric deposition was affecting aquatic ecosystems. In some cases increases in acidity of aquatic ecosystems were found to be associated with local fish extinctions and eliminations of macroinvertebrates and zooplankton in those waters.

Studies of faunal species found in lakes and streams with naturally low pH can be helpful to indicate what species are not found in acid waters. The ecosystem data collected during the summer of 1983 in the Wind River Mountains will be good indication of pH and other environmental factors to which the macroinvertebrates and zooplankton have become adapted in that area. Continued monitoring of the physical, chemical and biological factors to detect positive or negative trends will be the most effective means of identifying cause and effect changes.

Most of the energy and nutrients in lakes and streams ultimately pass through the benthos (bottom-dwelling macroinvertebrates), so any alteration of this community is likely to affect plankton fish and water chemistry. Benthic macroinvertebrates process debris, wich facilitates its decomposition by microorganisms. Without macroinvertebrates organic detritus decomposes very slowly.

The pH of the water in part controls the breakdown of inorganic constituents and determines whether they will be available for recycling by plants. Benthos aerate sediments by burrowing movements. Chemistry of the top few centimeters of sediments is greatly affected by changes or loss of benthos.

R. Singer (1983) indicates that loss of fish populations is one of the *last* biological effects of acidification.

The ultra-oligotrophic lakes characteristic of sensitive areas harbor ecosystems which are unique. These ecosystems may be damaged by levels of acidification (pH <6.5) that may not affect fish at all.

The concept of an endangered ecosystem is as viable as the more generally accepted view of the endangered species. Observed effects of acidifying a lake or stream are:

1. Reduction in bacterial decompositon of debris.

2. Algal mats up to 1.5 meters are often found in waters with pH below 5.0.

3. Many invertebrates are very sensitive to pH. Amphipods cannot tolerate pH below 6.0. Fingernail clams can survive in sediments with overlying waters having pH as low as 4.8. Many species of stoneflies (Plecoptera), mayflies (Ephemeroptera), and caddisflies die at pH less than 5.0 as determined by laboratory bioassays and field observations. Insects are often limited by mechanisms not related directly to toxicity.

Food chains change in acidified lakes. The predator's niche, generally occupied by fish, may be filled by dragon flies (Odonata) predacious beetles (Coleoptera) and true bugs (Hemiptera) which are tolerant to acid waters. The number of zooplankton species has been observed to be fewer in acidic lakes.

In 14 field surveys in Europe, Canada and the United States fewer species of zooplankton were found in acidic lakes than in non-acidic lakes. Several of the crustacean zooplankters such as Cladoceran species appear sensitive to acidity. Few *Daphnia* species were found where pH was less than 6.0. *Holopedium gibberum* was found mainly where pH was greater than 4.9. *Polyphemus pedculus* is found mainly in lakes with pH higher than 6.0. Standing crop of Cladocerans was maximum between pH 5 to 6 but reduced by pH below 5. *Cyclops bicuspidatus* were found in lakes with pH of 4.4 to 6.8, mainly in non-acid lakes.

In New York studies *Polyphemus pediculus*, *Holopedium gibberum*, and *Diaptomus minutus* were found in waters with a pH range of 4.7 to 7.2.

In Great Britian *Polyphemus pediculus* was found in waters with a pH range of 4.6 to 9.2 and *Cyclops vernalis* in waters with pH of 4.4 to 9.2.

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WYOMING GAME AND FISH DEPARTMENT

FISH DIVISION

ADMINISTRATIVE REPORT

Title: Fisheries Characteristics of Four Acid Rain Monitoring Lakes in the Bridger Wilderness

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Project: 4083-07-8301

Author: Ron Remmick

Date: February 1984

INTRODUCTION:

The Wyoming Game and Fish Department (WGF) was requested by the United States Forest Service (USFS) to provide trout population information from four alpine lakes in the Bridger Wilderness. This information as well as other physical, chemical and biological data will be used as baseline information to monitor potential changes due to the proposed gas sweetener plants west of the Wind River Range. Possible impacts to the environment concerning acid deposition and its affect in the poorly buffered waters of the Bridger Wilderness were addressed in the Riley Ridge Final EIS (November 1983). To monitor changes in the fishery it was necessary to have relatively stable trout populations that relied on natural recruitment and were not influenced by stocking. The four lakes selected were known to have long-time wild trout populations. These lakes were Section Corner Lake, Seneca Lake, Hobbs Lake and Black Joe Lake (Figure 1).

Section Corner Lake is located about 16 miles north of Pinedale. It covers approximately 56 acres with a maximum and mean depth of 84 feet and 23 feet respectively. It is situated at an elevation of 9,245 feet (Table 1). Brook trout, brown trout and grayling were present although brook were the dominant trout species. Brook trout were last stocked in 1924 and the brown trout in 1925. Grayling were never stocked, but probably moved downstream from Trail Lake which is located about one mile above Section Corner Lake (Table 2).

Seneca Lake is located approximately 7.5 miles southeast of Section Corner Lake. It covers 159 acres (the largest monitor lake) with a maximum and mean depth of 246 feet and 83 feet respectively. It is situated at an elevation of 10,269 feet. Only rainbow trout have been collected in Seneca Lake. There are no firm records of when rainbow were first stocked, but reports suggest 1925.

Hobbs Lake is approximately 1.0 mile south of Seneca Lake. It covers 20 acres (the smallest monitor lake) with a maximum and mean depth of 57 feet and 34 feet respectively. It is situated at an elevation of 10,069 feet. Rainbow and golden trout were found in the lake. There are no records indicating when the rainbow were stocked, but they were reported to be abundant in 1937. The golden trout drifted down from Nancy Lake (one mile upstream from Hobbs Lake) which was initially stocked in 1975.

Figure I Location of the four monitor lakes ✻ in the Bridger Wilderness.

Table 1. Summary of physical characteristics for four alpine lakes in the Bridger Wilderness Area (From Hudelson et.al., 1980)

Lake	Location	Elevation(ft)	Maximum Depth(ft)	Mean Depth(ft)	Surface Area (acre)
Section Corner Lake	R108,109W,T36N S12,18,24,19	9,245	84	23	55.6
Seneca Lake	R107W,T36N,S29,32	10,269	246	83.3	158.7
Hobbs Lake	R107W,T35N,S6	10,069	57	34.4	20.4
Black Joe Lake	R103W,T32N,S17SW, 18SE,20NENW	10,258	85	33.5	76.2

Table 2. Summary of Management History of four alpine lakes in the Bridger Wilderness area (From Hudelson, et.al.,1980)

Lake	Management Concept	Species Managed for	Stocking Policy	Remarks
Section Corner Lake	wild	Brook, Brown, Grayling	No stocking	Brook stocked between 1915-1924. Brown stocked in 1925. Grayling probably drift from Trail Lake.
Seneca Lake	wild	Rainbow	No stocking	No records when stocked but some reports suggest 1925
Hobbs Lake	wild	Rainbow	No stocking	No records of stocking. Rainbow abundant in 1937. Golden have drifted from Nancy Lake since an initial plant in 1975.
Black Joe Lake	wild	Cutthroat	No stocking	Last stocked in 1940

Black Joe Lake is located near the southern end of the Bridger Wilderness. It covers 76 acres with a maximum and mean depth of 85 feet and 34 feet respectively. It is situated at an elevation of 10,258 feet. Cutthroat trout were the only trout found in the lake and they were last stocked in 1940. The cutthroat have the meristic characteristics of the native Colorado River cutthroat although no taxonomic analysis has been accomplished to date.

The fisheries data collected from these lakes in 1983 as well as past data will provide baseline information for the acid rain monitoring program. The fisheries information gained will include length-weight relationships, age-growth characteristics and relative abundance. Future sampling will take place to monitor possible changes in the trout population and if these changes can be linked to changes in the physical and chemical parameters of the water due to acid deposition.

Methods:

Light weight nylon experimental gill nets approximately 100 feet long were set at each lake. The nets remained in the lake long enough to capture a representative fish sample. All the trout collected were measured to the nearest 0.1 inch and 0.01 pound. Scales were taken from each fish at a site on their left side immediately behind and below the posterior portion of the dorsal fin.

Each fish's condition was calculated using the formula:

$C = \frac{W \times 10^5}{L^3}$ where C=condition factor, W=weight in pounds and L=length in inches. A length-weight regression for each fish species at each lake was calculated using the least squares fit to a line corresponding to the equation: $\text{Log}(W)=a+b(\text{Log } L)$ where W=weight in pounds, L=length in inches, a=intercept and b=slope.

Scales were used to age each fish. The scales were cleaned then mounted between two glass slides. They were then magnified using a Bruning Micro Design 4010 microfiche reader with a 17mm lens (40x magnification). The annuli were located where "cutting over" and/or crowding of the circuli occurred (Lagler 1956). Each annulus indicated one year of growth. A measurement was made from the scale focus to each annulus and also the scale's anterior edge. Back-calculated lengths at each annulus were then estimated using the formula: $L=(s/S)Li$, where L=total length of fish at annulus, Si=length from focus to annulus, S=length from focus to scale's anterior edge and Li=total length of fish.

A Walford line was also calculated to estimate the theoretical maximum length each fish species could attain. In addition it gave a general condition of a species' growth rate using the annual growth increments. The Walford line is determined by graphing length at age n (abscissa) versus length at age n+1 (ordinate). Using least squares linear regression a line can be fit to the data and the ultimate length (Lu) can be calculated from the formula: Lu=intercept/1-slope (Everthart, et. al., 1981).

RESULTS:

Section Corner Lake

Section Corner Lake was sampled on 8/1/83. Thirteen brook trout, two grayling and one brown trout were captured. The brook trout's average length, weight and condition factor were 8.2 inches, .28 pounds and 36.5. The grayling's average length, weight and condition factor were 8.3 inches, .12 pounds and 21.1. The brown trout captured was 22.5 inches long, weighed 3.0 pounds and had a condition factor of 26.3. The gill net catch rate for the brook, grayling and brown trout was 3.3, .5 and .3 fish/hour respectively (Table 3).

The brook trout were the only fish used for the monitoring study because of their abundance in the sample as well as in the lake. They were represented by four age groups; 1+, 2+, 3+ and 4+. The relative abundance of each age group was: 17%, 41%, 25% and 17% respectively (Figure 2). Estimated average lengths at one, two, three and four years old were 3.1, 5.4, 8.1 and 9.7 inches. The annual growth increment indicates good growth for the first three years of life but slowed down after that (Table 4). The Walford line estimated the maximum attainable length to be 20.4 inches (Figure 3).

Brook trout collected from Section Corner on 6/28/74 (Hudelson, et, al., 1980) averaged 7.8 inches and .18 pounds. Their condition factor was 35.9 (Table 5). A comparison of the 1974 and 1983 length-weight relationships displayed similar conditions for all fish in both samples of the same size groups (Figure 4). No scales were taken in 1974 so age-growth comparisons could not be made.

Seneca Lake

Seneca Lake was sampled from 8/17 to 8/18/83. Nineteen rainbow trout were captured. Their average length, weight and condition factor were 11.7 inches, .53 pounds and 30.3. The gillnet catch rate was .95 fish/hour (Table 3).

These trout were represented by three age groups: 2+, 3+ and 4+. The relative abundance of each group was: 21%, 53% and 26% respectively (Figure 2). Estimated average lengths at one, two, three and four years old were 3.1, 7.0, 10.5 and 11.5 inches. The annual growth increment indicates good growth the first three years but a sharp decrease thereafter (Table 6). The Walford line indicates a maximum attainable size of 14.1 inches (Figure 3).

Rainbow trout collected on 9/7/73 averaged 11.1 inches, .67 pounds and had a condition factor of 39.6 (Table 5). A comparison of the length-weight relationships between the two samples indicates the rainbow were in better condition in 1973 than those collected in 1983 (Figure 5). No scales were collected in 1973 so age-growth comparisons could not be made.

Hobbs Lake

Hobbs Lake was sampled from 8/17 to 8/18/83. Sixteen rainbow trout and seven golden trout were captured. The rainbow average length, weight and condition factor were 9.6 inches, .27 pounds and 30.8. The golden average

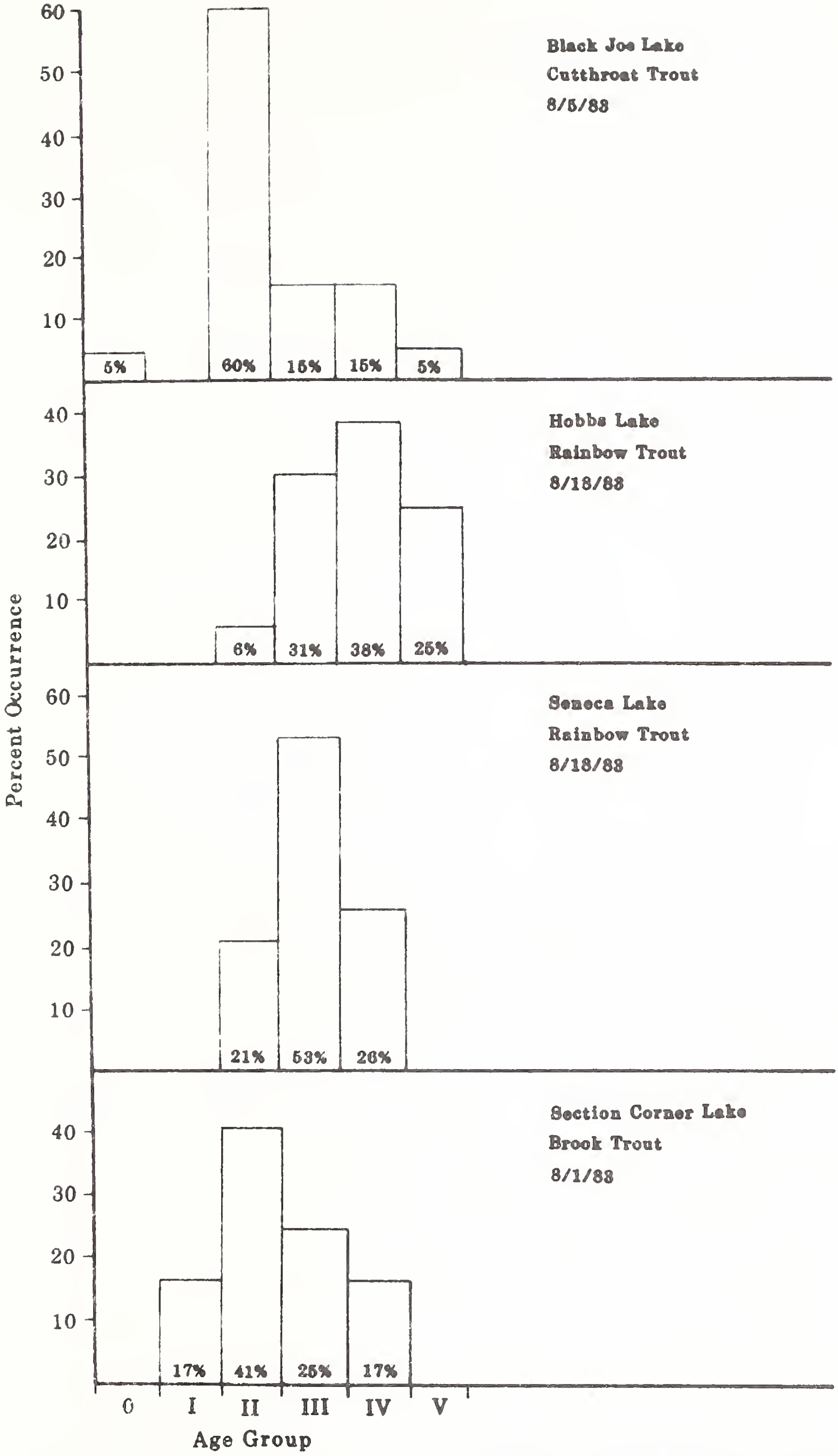

Figure 2. The relative abundance of each age group (percent of total captured) from the four monitor lakes.

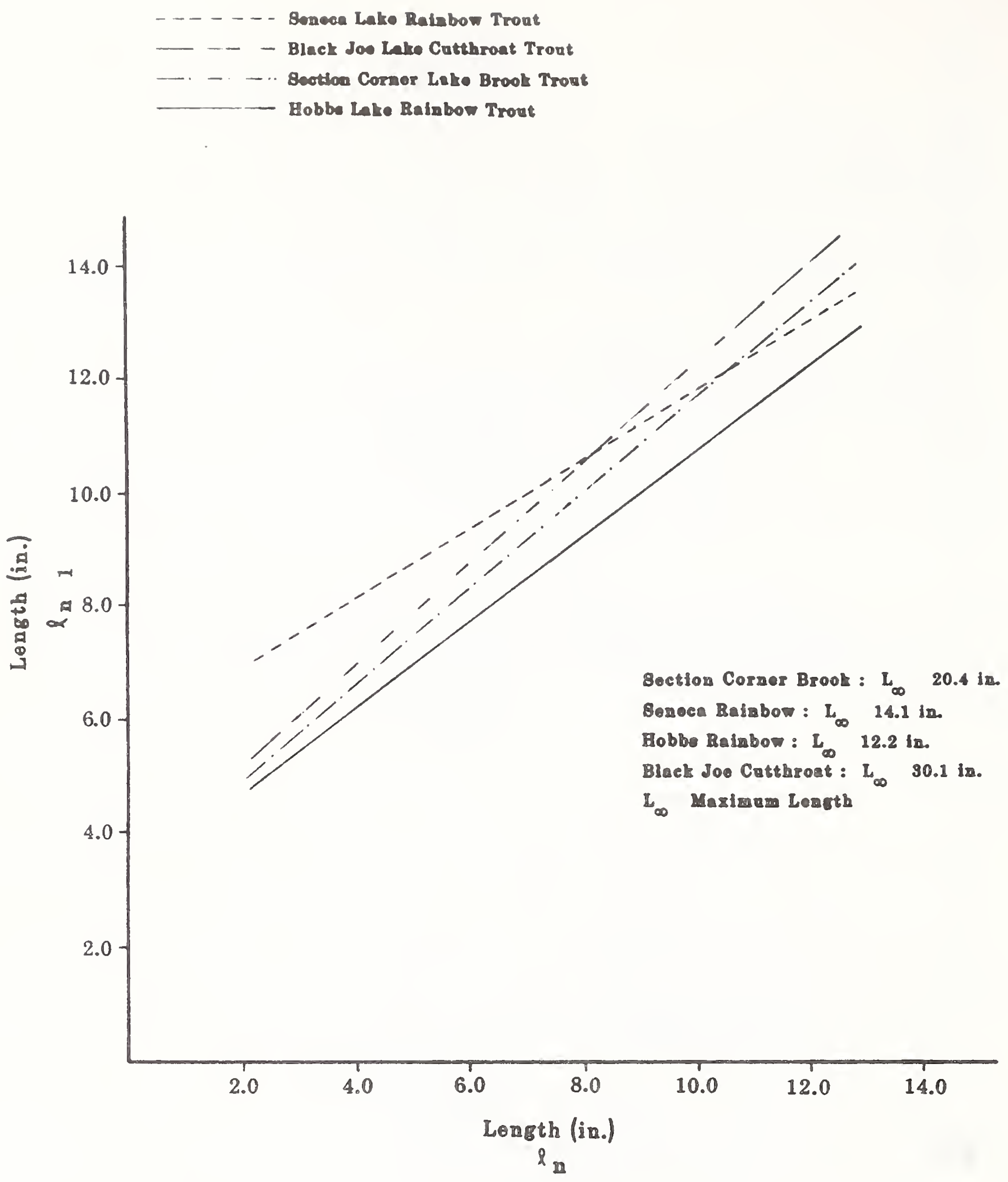

Figure 3. The Walford lines and the predicted maximum lengths for selected trout species collected in August, 1983 from the four monitor lakes.

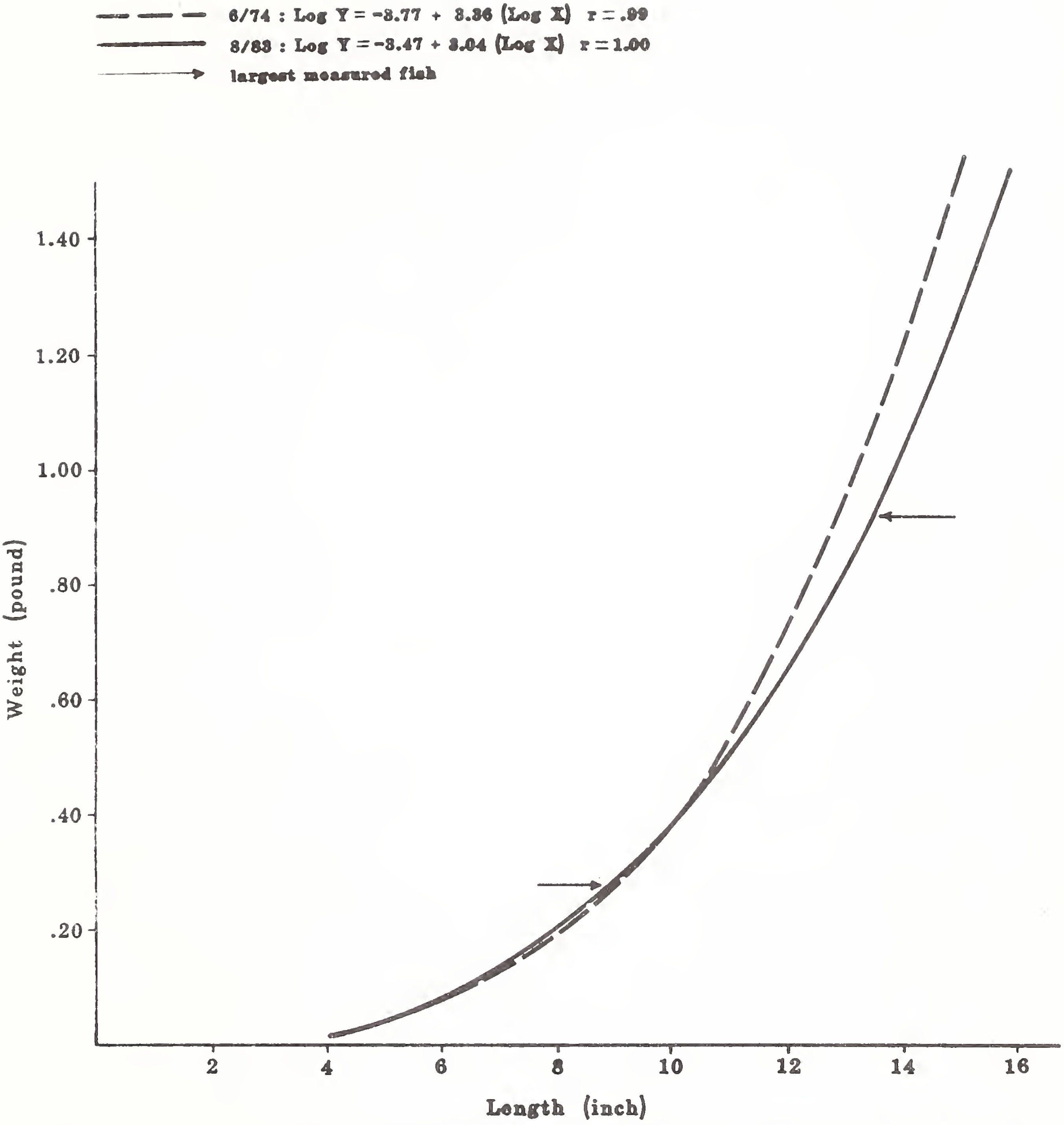

Figure 4. The length-weight relationships of brook trout captured from Section Corner Lake in 1974 and 1983.

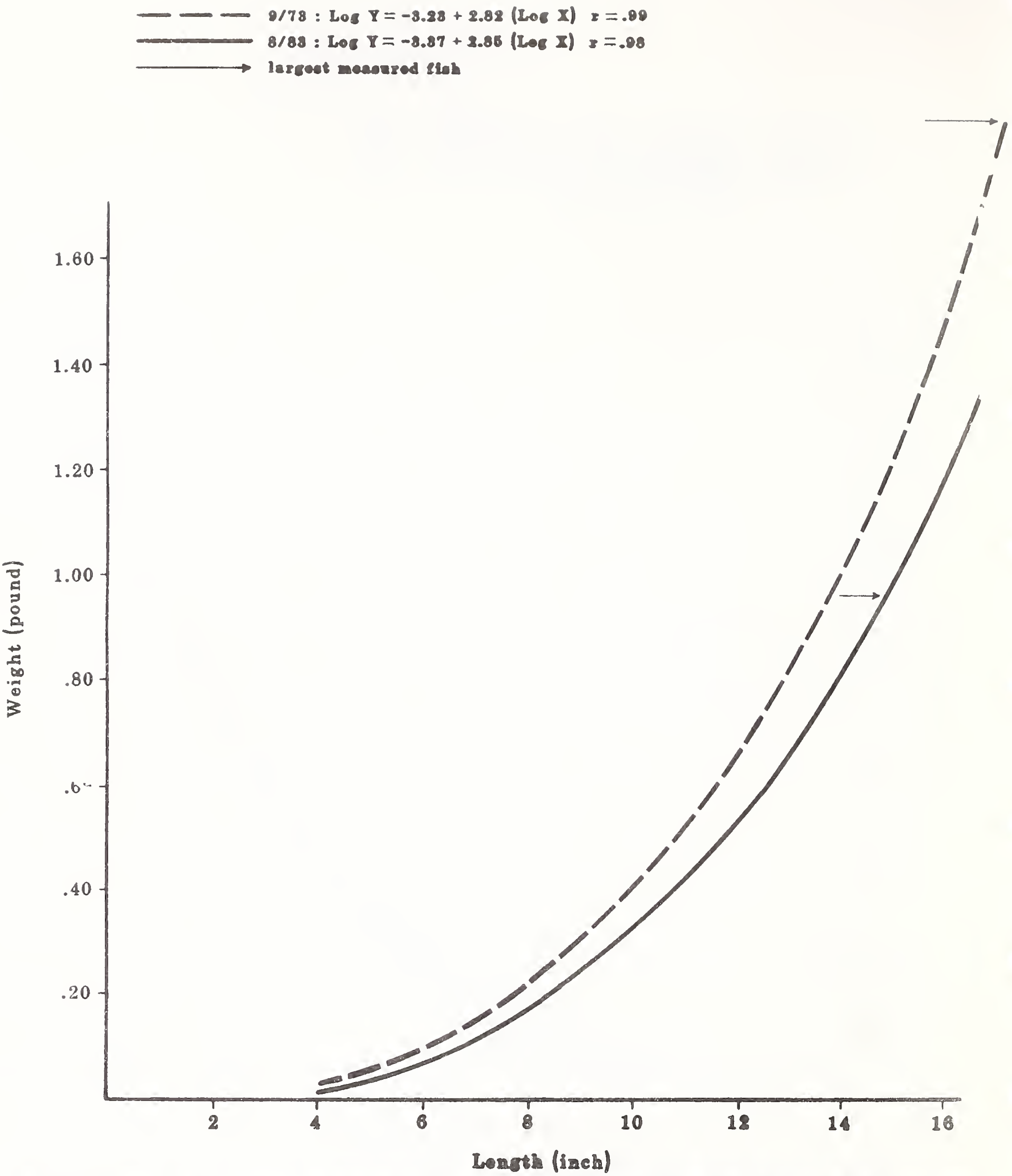

Figure 5. The length-weight relationships of rainbow trout captured from Seneca Lake in 1978 and 1983.

Table 3. Gill Net summary from four alpine lakes in the Bridger Wilderness Area during August, 1983.

Lake	Date	Species	Numbers	Average Length(in) (Size Range)	Average Weight(lbs) (Size Range)	Average Condition (Range)	Catch/hr
Section Corner Lake	8/1/83	Brook	13	8.2(3.8-13.5)	.28(.02-1.03	36.5(33.7-41.9)	3.3
		Grayling	2	8.3(8.0-8.3)	.12(.09-.14)	21.1(17.6-24.5)	.5
		Brown	1	22.5	3.0	26.3	.3
Seneca Lake	8/18/83	Rainbow	19	11.7(6.5-14.8)	.53(.09-.88)	30.3(21.6-35.8)	.95
Hobbs Lake	8/18/83	Rainbow	16	9.6(8.2-11.0)	.27(.17-.42)	30.8(26.5-35.8)	.79
		Golden*	7	13.3(12.1-15.0)	.81(.63-1.02)	33.7(28.8-40.0)	.35
Black Joe Lake	8/5/83	Cutthroat**	21	9.0(3.2-13.6)	.32(.02-.91)	35.7(29.5-41.0)	1.2

* Golden were probably recent drift from Nancy Lake during spawning season

** Physical features were typical of Colorado River cutthroat

Table 4. Age-growth characteristics of brook trout taken from Section Corner Lake on 8/1/83.

Age Group	Number of Fish	Average Length(in)	Average Weight(lbs)	Calculated total length in inches at beginning of year			
				I	II	III	IV
1+	2	3.8	.02	2.5			
2+	5	7.0	.13	3.2	5.6		
3+	3	10.2	.39	3.6	5.8	8.5	
4+	2	11.7	.68	2.6	4.5	7.4	9.7
		Calculated Average Length in Inches		3.1	5.4	8.1	9.7
		Annual Growth Increment		3.1	2.3	2.7	1.6

Table 5. Gill net summary from four alpine lakes during Bridger Wilderness Survey (Hudelson, et al, 1980)

Lake	Date	Species	Number	Average Length(in) (Size Range)	Average Weight(lbs) (Size Range)	Average Condition (Range)	Catch/hr
Section Corner	6/28/74	Brook	18	7.8(4.2-9.3)	.18(.02-.34)	35.9(26.9-42.3)	*
Seneca	9/7/73	Rainbow	23	11.1(4.3-17.3)	.67(.03-1.8)	39.6(27.6-47.6)	1.09
Hobbs	7/23/72	Rainbow	3	9.3(8.4-9.8)	* *	* *	*
Black Joe	8/18/71	Cutthroat	12	11.6(7.3-13.6)	.54(.14-8.3)	33.3(29.7-36.0)	3.2

* Information not available from report

** Weights not available due to measurement error

Table 6. Age-growth characteristics of rainbow trout taken from Seneca Lake on 8/18/83.

Age Group	Number of Fish	Average Length(in)	Average Weight(lbs)	Calculated total length in inches at beginning of year			
				I	II	III	IV
2+	4	8.7	.22	3.2	7.0		
3+	10	12.5	.59	3.4	7.5	11.0	
4+	5	12.7	.66	2.6	6.1	9.5	11.5
		Calculated Average Length in Inches		3.1	7.0	10.5	11.5
		Annual Growth Increment		3.1	3.9	3.5	1.0

length, weight and condition factor were 13.3 inches, .81 pounds and 33.7. The catch rates for the rainbow and golden trout were .79 and .35 fish/hour respectively (Table 3).

Only the rainbow trout were considered for baseline information. As stated earlier the golden trout drifted downstream from Nancy Lake and no known reproduction was occurring since all golden sampled were large adult fish. The rainbow were represented by four age groups: 2+, 3+, 4+ and 5+. The relative abundance of each age group was: 6%, 31%, 38% and 25% (Figure 2). Estimated average lengths at one, two, three, four and five years old were 3.8, 5.8, 7.7, 8.7 and 9.6 inches. The annual growth increments indicate a decrease of growth after the second year of life (Table 7). The Walford line predicts the maximum attainable size for rainbow trout in Hobbs Lake to be 12.2 inches (Figure 3).

Only three rainbow trout were collected during the wilderness survey (7/23/72) even though observations at that time indicated a dense popuation (the records state the trout were difficult to capture in the net). Comparisons could not be made between the 1972 and 1983 samples but the three fish collected in 1972 averaged 9.3 inches (Table 5). A length-weight relationship was calculated for the 1983 sample (Figure 6).

Black Joe Lake

Black Joe Lake was sampled from 8/4 to 8/5/83. Twenty-one cutthroat were captured with an average length, weight and condition factor of 9.0 inches, .32 pounds and 35.7. The catch rate was 1.2 fish/hour (Table 3).

The cutthroat were represented by five age groups: 0+, 2+, 3+, 4+ and 5+. The relative abundance of each age group was: 5%, 60%, 15%, 15% and 5% (Figure 2). Estimated average lengths at one, two, three, four and five years old were 3.1, 6.1, 8.3, 10.5 and 12.7 inches. The annual growth increments showed a small decrease in growth between two and three years old but remained consistent after that (Table 8). The Walford line predicts the maximum attainable size for the cutthroat at 30.1 inches (Figure 3).

Cutthroat trout were also collected on 8/18/71. Their average length, weight and condition factor were 11.6 inches, .54 pounds and 33.3. The catch rate was 3.2 fish/hour (Table 5). Length-weight comparisons between the 1971 and 1983 samples indicated near identical conditions (Figure 7). No scales were collected so age-growth comparisons could not be made.

CONCLUSIONS:

Establishing acid rain monitoring lakes required that each lake have a relatively stable trout population supported by natural recruitment. Since the last lake was stocked in 1940 (Black Joe Lake) it can be assumed this requirement was met. It was also necessary to document the condition of the trout population in each lake before any impacts occurred that could be linked to acid deposition. The alpine lakes' remoteness limited the time available to obtain detailed data (population estimates, hatching success, etc.), so inferences had to be made about each fish population using length-weight relationships and age-growth characteristics from the data collected.

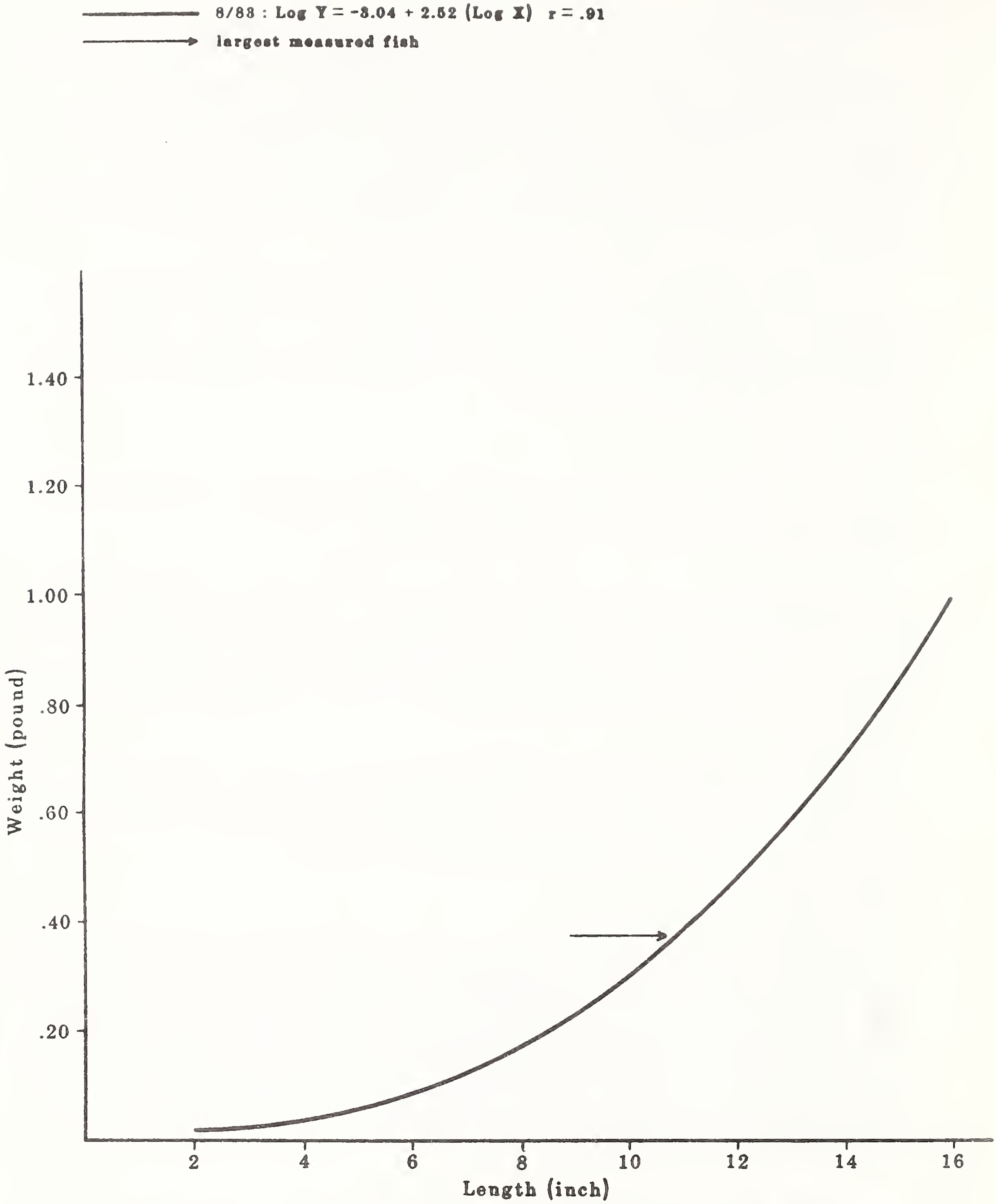

Figure 6. The length-weight relationship of rainbow trout captured from Hobbs Lake in 1983.

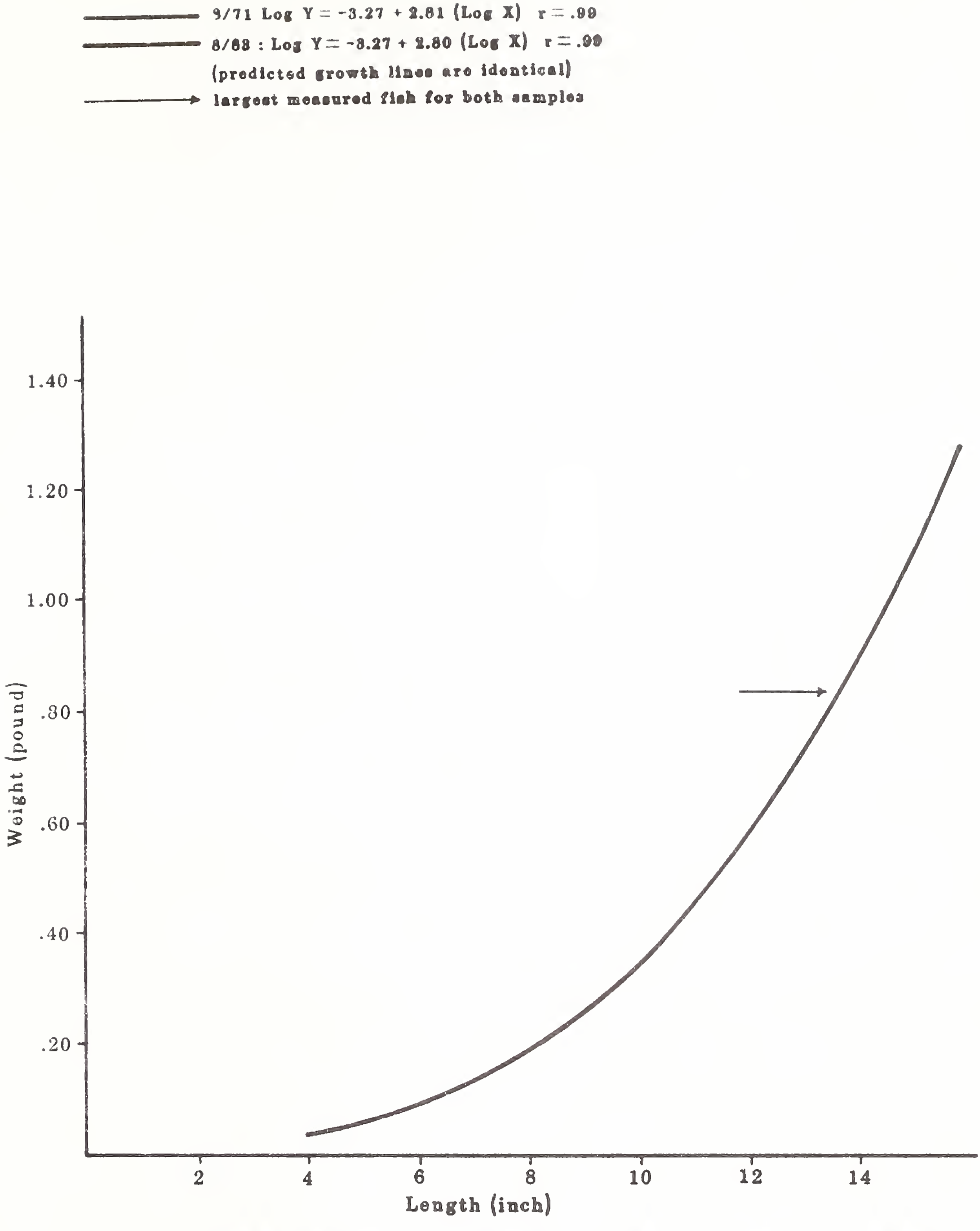

Figure 7. The length-weight relationships of cutthroat trout captured from Black Joe Lake in 1971 and 1983.

Table 7. Age-growth characteristics of rainbow trout taken from Hobbs Lake on 8/18/83.

Age Group	Number of Fish	Average Length(in)	Average Weight(lbs)	Calculated total length in inches at beginning of year				
				I	II	III	IV	V
2+	1	8.2		4.9	7.1			
3+	5	9.2		3.8	5.6	8.6		
4+	6	9.7		3.6	6.0	7.6	9.0	
5+	4	10.1		3.8	5.4	6.9	8.3	9.6
		Calculated Average Length in Inches		3.8	5.8	7.7	8.7	9.6
		Annual Growth Increment		3.8	2.0	1.9	1.0	0.9

Table 2. Age-growth characteristics of cutthroat trout taken from Black Joe Lake on 8/5/83.

Age Group	Number of Fish	Average Length(in)	Average Weight(lbs)	Calculated total length in inches at beginning of year				
				I	II	III	IV	V
0+	1	3.2	.02					
2+	12	8.1	.19	3.1	6.3			
3+	3	9.4	.31	2.6	5.6	8.3		
4+	3	11.6	.58	3.3	5.8	8.5	10.6	
5+	1	13.6	.91	3.2	5.3	7.8	10.0	12.7
		Calculated Average Length in Inches		3.1	6.1	8.3	10.5	12.7
		Annual Growth Increment		3.1	3.0	2.2	2.2	2.2

The Section Corner Lake brook trout population appeared to be a stable population in good balance with the available habitat. The length-weight relationships of the 1974 and 1983 samples were very similar for fish in the same size groups. The average condition factor was high which would suggest there was adequate food for the trout present. The population is represented by four age groups with the age group 2+ most dominant. It would be expected that the 1+ fish should be more dominant but net selectivity favors fish approximately five inches or greater. The Walford line predicted a maximum size of 20.4 inches which is high for brook trout. Although this prediction may only be approximate it does indicate growth is good for the brook trout in Section Corner Lake.

The Seneca Lake rainbow trout population density appeared to have increased since the 1973 survey and may be over-utilizing the food base. The average condition factors and length-weight relationships show a decrease in body condition between 1973 and 1983. Although the average condition of the 1983 sample could be considered "average" (30.3), 42% of the fish collected had condition factors in the 20's and appeared "skinny". Trout growth was good the first three years but slowed considerably after that. The Walford line predicted a maximum size of 14.1 inches which was smaller than a 14.8 inch trout captured but it does indicate the slow growth presently occurring. Because the rainbow do not appear to be "stunted" there is probably not a problem with overcrowding in this large lake, but the population is large enough to create a food shortage particularly for the larger rainbow.

The Hobbs Lake rainbow trout population appeared to be overcrowded and underfed. The average condition factor is "average" (30.8) but 50% of the fish had condition factors in the 20's and appeared "skinny". The growth of these fish began to slow early and the Walford line predicted a maximum growth of 12.2 inches, the smallest of the four monitor lakes. Generally, if condition factors are low and growth slows at an early age then an overcrowded population is suspected. The appearance of "stunted" rainbow supports this observation.

The Black Joe Lake cutthroat trout population appeared to be in good balance with the available habitat. Condition factors were high and nearly identical to those observed in 1971 indicating a stable population. The 2+ age group was dominant and growth was excellent for the cutthroat's first five years of life. The Walford line predicted a maximum length of 30.1 inches which is probably high but reflects the good growth in the lake.

One of the major problems created by acid deposition is stress to trout eggs or newly hatched fry. Mortalities can result in a partial or total loss of a year class. This recruitment failure would result in fewer surviving fish and may temporarily decrease competition between the surviving fish and possibly improve the condition and growth of these fish. Changes like this would be most noticeable in Seneca and Hobbs lakes where large trout populations have significantly lowered the food base. These temporary improvements would not be as obvious at Section Corner and Black Joe lakes since competition has not caused problems. But the dominance of the 2+ fish at Section Corner and Black Joe Lake would be an indicator if two years after acid stress caused recruitment failure, there would be an absence of this group.

Ideally, sampling of newly hatched trout would occur immediately after an acid stress event took place. The time, equipment and manpower involved for this undertaking would be considerable and impractical at these remote lakes. Mortalities could also occur to adult fish but it would be difficult to document because of their low occurrence during sampling efforts. This leaves, for future monitoring, the collection of length-weight and age-growth data to compare with the results presented in this report.

Recommendations:

1. Immediately before the first Riley Ridge sweetener plant begins operation sampling should occur at each lake. This would check the consistency of the previous data and any fluctuations that may be naturally occurring in the populations.

2. After the plants are in operation fish sampling need only occur every three years unless the more frequent water sampling indicates a problem.

3. Should the water quality change because of acid deposition then fish should be collected as soon as possible after the problem occurs. Sampling should then occur every two years to observe any changes in the more dominant younger age group.

4. It is important that all monitoring agencies keep the other responsible agencies informed of their work so any subsequent action can be taken as soon as possible.

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A Lichen Biomonitoring Program in the Bridger Wilderness, Wyoming

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The impact of air pollution and acid rain can be measured by a number of different physical and biological methods. Various kinds of plants have been used: Pine needles, grasses, twigs, etc. None of these is entirely satisfactory since most plant parts die off in the winter or have relatively short longevity.

Lichens have been used successfully as biomonitors of point source sulfur dioxide, fluorine and zinc pollution, especially in Europe. They are long-lived, accumulate pollutants efficiently during the whole year and harmlessly bind otherwise toxic pollutants at cationic sites in the thick cell walls. They resist fairly high levels of chronic pollution but will, of course, die off after severe pollution stress.

The distribution and relative concentrations of lead-containing automobile exhaust pollution along highways have been measured with lichens for the past 20 years in Europe and North America. The studies show so far that low atmospheric concentrations of lead (and other metals) are picked up by lichens very rapidly, apparently within months. Some typical results of these studies are shown below:

Comparison of lead content in foliose lichens along highways and in remote areas

Shenandoah, VA (moderate traffic)	
Remote site:	92 ppm
Roadside:	280 ppm
Buford, CO (light traffic)	
Remote site:	35 ppm
Roadside:	85 ppm
Plummers Island, MD (heavy traffic)	
1938 (no traffic):	106 ppm
1958 (no traffic):	270 ppm
1970 (heavy traffic):	1300 ppm

On a broader scale, lichens are being used as biomonitors and baseline indicators of air pollution in the Flat Tops Wilderness Area, Colorado. The lichens here have been inventoried, 12 study plots set up for observations of growth rates and succession, and samples collected for elemental analysis. Of most immediate ineterest are the data for the main indicator species, <u>Xanthoparmelia cumberlandia</u>. For lead, the average content was 51 ppm (range 38-76 ppm), a value which had no correlation with elevation or rock type. This level in fact would be considered close to a baseline value for unpolluted areas. Zinc in the same series was 59 ppm (range 48-74 ppm). These two elements are stressed because they are known components of fly ash from coal-fired power plants and probably carried in acid rain.

The proposed program in the Bridger Wilderness will follow the general outline of the Flat Tops study. A preliminary study along a transect from Boulder Lake to Lake Victor in 1983 gave these results:

	ug/g		
Site	Pb	Zn	Sulfate-S
Lower Boulder Creek Trail	68	52	0.07%
Lake Vera	92	60	0.11%
Lower Fire Hole Lake	118	73	
Lake Isabella	77	60	
Lake Ethel	117	85	
Lake Perry	153	85	

The data show that these lichens are accumulating heavy metals in higher than expected concentrations and suggest that the Bridger Wilderness is now being impacted by air-borne pollutants in biologically measurable amounts. The lichens also indicate a correlation with elevation, the 9000' level having the highest values.

The program for the coming season will follow up these preliminary results with an intensive sampling program. Hopefully a grid map of concentrations of heavy metals and sulfates will pinpoint the most impacted areas.

LICHENS AS BIOINDICATORS AND MONITORS OF AIR POLLUTION

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INTRODUCTION

Lichens were first systematically used as bioindicators of air pollution by Skye (1958) in Sweden in the early 1950's, and in the last 20 years research activity in this field has grown tremendously. Excellent summaries on the theory and application of lichens in pollution studies have been published by Saunders (1970), Ferry et al. (1973), Gilbert (1974), LeBlanc and Rao (1975), Hawksworth and Rose (1976), and Skye (1979), and mostly recently by Richardson and Nieboer (1981). The rapidly growing literature is now regularly indexed in the British journal The Lichenologist (1974-1981).

At this time, there is good agreement among workers that lichens can be used to bioassay air pollution caused by SO_2, fluorine, heavy metals, and photochemical pollutants. Lichens are economical in the sense that they can be used as monitors in sites where physicochemical instruments cannot be placed or maintained. They are valuable for long-term studies since they have life spans of 20-50 years. Their occurrence and behavior around pollution sources can monitor distribution, severity, and long-range effects of pollutants emitted. The resulting data can assist in environmental planning, abatement, and pollution control in expanding urban and industrial areas, as proposed, for example, by Vick and Bevan (1976) in Liverpool, and in siting power plants (Windler, 1977).

In spite of the progress made to date, practical applications of lichens to monitor pollution are still not fully developed or appreciated. We assume that loss or absence of lichens in an area is directly related to air pollution, but as Hoffman (1974) points out, the mere absence of

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lichens may mean nothing ecologically unless one knows whether a given species formerly occupied the habitat and what factors may have eliminated it. Transplant studies have helped establish a cause-and-effect relation between occurrence of lichens and air pollution, but many more baseline studies and controlled experimentation are needed.

This report will attempt to review the important literature on the use of lichens as bioindicators of pollution in the last 10-15 years and to provide a critique of the methodology.

BIOLOGICAL TRAITS OF LICHENS

Lichens are lower plants consisting of a fungus and an alga growing together symbiotically. As a green, chlorophyll-containing, photosynthetic organism, the alga provides nutrients to the fungus, a heterotrophic organism making up the bulk of the plant body (the thallus). The lichen thallus is a perennial, stable, and remarkably long-lived structure occurring in a wide variety of habitats throughout the world. Chlorophyll content, however, is much lower than in green leafy plants and the delicate symbiotic balance is easily upset, leaving the fungus with no food source.

One of the unusual physiological traits of lichens is that they absorb elements very efficiently over the entire thallus surface from air, precipitation, and stemflow, whether the elements are beneficial (as minerals) or phytotoxic (as pollutants). They lack a waxy cuticle or stomates which partially protect higher plants.

Many of the pollutants are bound in the heavily gelatinized hyphal cell walls and stored harmlessly. With this mechanism lichens may accumulate phytotoxins in much higher amounts than higher plants and can accurately monitor fallout at distances of 30 miles or more (Nieboer et al., 1972). However, some of the most important pollutants (SO_2, NO_2, F) when dissolved in water to form acids, attack the algal symbiont in the thallus. This can result in chlorosis, phaeophytin formation, or plasmolysis. Under these stress conditions a lichen will show rapid and severe damage and often poor recovery, depending on the intensity of the fumigation. Since lichens differ in sensitivity to air pollution, it is possible to select for study indicator species which have a proven response to pollution stress They should also have a fairly wide distribution, and be easily identified. Workers in Europe are fortunate in that the lichen flora is uniform from country to country; indicator species have been pinpointed and their behavior studied for the last 20 years. For example, Hypogymnia physodes, also common in New England and the northern Rocky Mountains, is an excellent indicator species and when present in a site indicates ambient SO_2 levels of 70-80 $\mu g/m^3$ or less. At greater concentrations it dies off. Controlled fumigation experiments have also helped establish a more precise ordering of sensitivity of lichen species (Türk et al., 1974, Steubing, 1977). The results generally correspond to the order of sensitivity observed in field studies.

In North America we have little information on sensitivity except where it can be extrapolated for species identical with those in Europe. Many American species do not occur in Europe. A few studies, however, show that Umbilicaria, a common umbilicate lichen in the Rocky Mountains, is quite sensitive (Nieboer et al., 1972; Sigal, 1981). Another common western species, Lecanora muralis, is considered to be an excellent bioindicator (Seaward, 1976).

SOURCES AND KINDS OF POLLUTANTS

The primary, man-made sources of air pollution are coal fired electric generation stations, any ore reduction mills using pyrites, various kinds of paper mills, sour gas plants, shale oil processing plants, industries and homes using coal or oil as energy sources, and automobile exhaust. The pollutants are emitted as aerosols or are bound to particulates coming out of the stacks. They are transported in air masses and deposited directly on plant and soil surfaces as dry fallout or entrained in clouds, scavenged by water droplets, and returned to earth as acid rain.

The main types of pollutants are tabulated below with notes on their effect on lichens and examples of their use in bioassaying pollution.

Sulphur dioxide

Sulphur dioxide is a by-product of coal or fuel oil combustion, ore reduction, paper manufacture, many industrial processes, and automobile exhaust. It is the most widespread and abundantly produced air-borne phytotoxin in our environment. The natural background concentration is 0.28-2.8 $\mu g/m^3$, but values near pollution sources are much higher, 200 $\mu g/m^3$ or more. The threshold for many lichens is about 60 $\mu g/m^3$.

SO_2 in Cities

Under natural conditions, lichens are common almost everywhere and can be found on trees in almost any small to medium-sized city in the world. However, as long ago as the mid 19th century, botanists noticed that the lichen flora of large cities was either declining in richness or entirely destroyed. They equated disappearance of lichens with environmental pollution, if other factors remained unchanged, and from the very first assumed that SO_2 was the prime phytotoxin affecting lichens in cities.

A now classic study by Skye (1968) in Stockholm revealed a lichen-free zone in the city center with a gradual increase in lichen diversity and abundance as one moved out to unpopulated areas. In the United States, Brodo (1966) concluded that pollutants from New York City had eliminated or reduced the native lichen flora up to 40 miles away on Long Island. LeBlanc and De Sloover (1970) carried out extensive research in Montreal and found similar damaging effects, often called the "city effect."

These kinds of urban studies have become popular, and the occurrence and distribution of lichens in nearly 100 cities has been used for pollution mapping, especially in Europe, e. g., Copenhagen (Søchting & Johnsen, 1974), Port Talbot, England (Pyatt, 1970, 1973), Newcastle, England (Gilbert, 1970) but also in the United States, Houghton, MI, (Brown, 1974), and Seattle, WA, (Johnson, 1979), Brisbane, Australia, (Rogers, 1977), and tropical cities such as Hong Kong, (Thrower, 1980). Metzler (1980) applied this approach to the whole state of Connecticut.

However, while lichens have been used as bioindicators of air pollution, it was not till the late 1950's that this susceptibility was actually correlated with physicochemical measurements of SO_2 and not till the 1960's that it was experimentally verified (Nieboer et al., 1976). Still, the enormous amount of research in Europe has resulted in a more or less standardized methodology for conducting surveys and interpreting results (Hawksworth & Rose, 1970). The same sensitive indicator species occur in most of the countries and their occurrence has been firmly correlated with actual levels of SO_2 (usually 6-month winter averaged concentration). By noting the presence or absence of indicator species around urban areas one can delineate zones (in England 10 zones, from zone 0 ($>170 \mu g/m^3$ SO_2) to zone 10 ($<30\ \mu g/m^3$). The presence of a given species can then be used to estimate the SO_2 burden at that point (Gilbert, 1970a), the indicator lichens actually supplementing recording gauges.

Much more limited work in North America shows similar results with a high correlation between SO_2 damage to lichens and distance from the city center (LeBlanc & De Sloover, 1970). However, few North American cities have long established centers comparable to those in Europe nor is the lichen flora (and therefore a scale of sensitive indicator species) equivalent. Each worker has to set up his own scale so that results are not so readily compared.

Industrial SO_2 Pollution

The first well designed study of a nonurban pollution source was carried out by Skye (1958). He sampled 58 cities around a shale oil plant in Sweden and found good correlation between presence and condition of lichens and measured SO_2 emissions. An even more spectacular example was found by Rao and LeBlanc (1967) at Wawa, Canada, where an iron-scintering plant had destroyed lichens over a large discrete area. The zones of lichens damage there were also correlated with the known SO_2 fallout patterns. The same phenomenon has been observed and studied around sulphite paper mills in Sweden (Westmann, 1975), Austria (Hafellner & Grill 1981), Montana (Sheridan et al., 1976), and

Washington (Hoffman, 1974), and around an oil refinery in England (Morgan-Huws & Haynes, 1973). Many studies in the United States have centered on coal-fired electric generation plants: Ohio (Showman, 1975), Maryland (Windler, 1977), Wisconsin (Will-Wolf, 1980, 1980a), Wyoming (Gough & Erdman, 1977), Montana (Sheridan et al., 1976; Eversman, 1979), and Arizona (Nash, 1974; Marsh & Nash, 1979). Lichens have also been useful in monitoring pollution at oil-pumping stations in Alaska (Hanson, 1978) and at tar sand and gas processing plants in Canada (Skorepa & Vitt, 1976; Kumar, 1979; and Case & Krouse, 1980).

Correlations between SO_2 and Lichen Damage

The main flaw in many studies relating loss of lichens with SO_2 is that the conclusions are based mostly on observed correlations. The loss of lichens could be caused by an urban-modified microclimate, by removal or death of native lichen-bearing trees and replacement with lichen-free nursery stock, or by other historical factors. Only now are baseline studies being undertaken to survey floras before pollution begins, mostly around newly constructed or planned power plants (Eversman, 1975; Lulman et al., 1977; Will-Wolf, 1980).

In the past 10 years field transplants (LeBlanc & Rao, 1973) and controlled laboratory experiments on SO_2 fumigation of lichens have at least answered the question of mechanisms of the damage. Hill (1971), for example, immersed various lichen species in sulphite solutions and measured ^{14}C incorporation as an indication of physiological activity. Least affected were lichens known to grow in polluted areas with little damage. Baddeley et al. (1972, 1973), and Showman (1972) used SO_2 fumigations and found impaired photosynthesis and respiration. A number of papers in 1973 (Nash, Puckett et al.; Richardson & Puckett; and Sundström & Hällgren) continued experiments on photosynthetic activity, confirming an SO_2-induced conversion of chlorophyll to phaeophytin and destruction of chlorophyll by other irreversible oxidation processes, even with low-level fumigation. The latest research has focused on the effects of SO_2 on cell wall permeability, since SO_2 exposure causes potassium efflux (Puckett et al., 1977; Tomassini et al., 1977).

Sulphur Content of Lichens

Few studies have actually used measurements of SO_2 (sulfates) in lichen thalli as an index of air pollution (Olkkonen & Takala, 1975). Analytical methods are not as reliable as with other pollutants. In an early study Seaward (1973) found very high values (12,691 ppm) in lichens 5.3 km from Leeds, England. Sheridan et al. (1976) measured 700 to 2350 ppm in lichens near a paper mill in Montana, broadly correlated with distance from the mill. Hoffman (1974) found 556 ppm at 14 km from a paper mill and 2050 at 2 km in Physconia detersa. At the famous ore-smeltering Sudbury site Tomassini et al. (1976) report 400 to 2500 ppm in a polluted transect, 160-950 ppm in unpolluted lichens. The most recent study, around a sour gas plant in Alberta (Case & Krouse, 1980), gave values of 85-2540 ppm, roughly correlated with distance from the stacks. In general the values of SO_2 content vary considerably and may overlap for polluted vs. unpolluted lichens.

Fluorine

Fluorides are primarily by-products of aluminum, zinc, and phosphate ore reduction but also occur in fly ash from coal-burning installations. Nash (1971) carried out one of the first studies, reporting considerable damage to lichen vegetation around a chemical plant in Pennsylvania. Recent studies in Finland (Takala et al., 1978), Poland (Olech et al., 1981), England (Gilbert, 1971b; Perkins et al., 1980), and Canada (LeBlanc et al., 1972a; Roberts & Thompson, 1980) have all found high correlations between fluorine content of lichens and distance from the pollution source. Perkins measured a background of 9-16 μm/g F in lichens around a newly opened plant in England, increasing to 241μg/g over a 7-year period. Roberts and Thompson sample 77 sites and found 5-6 ppm in lichens 59 km from an aluminum plant and 2830 ppm 1 km away. In general, obvious damage to the lichens began at levels of 50-70 ppm. Under severe pollution stress rocks may be left totally barren of lichens (Gilbert, 1971).

Lead

Lead is the most important heavy metal pollutant in the atmosphere and its occurrence and toxic effects are well documented in a huge literature over the last 20 years. In cities the main source of lead is leaded gasoline, in rural or isolated industrial areas, any process involving coal combustion or ore reduction.

Lichens are very efficient accumulators of lead, more efficient for example than pine needles (Laaksovirta et al., 1976). The lead reaches the lichen thallus as aerosols, particulate metallic fallout, or acid rain. It is absorbed, bound to insoluble anionic sites, accumulated extracellularly, and concentrated in the medulla, a storage site in the thallus consisting entirely of fungal cells (Garty et al., 1979). Once bound to the fungal cell walls, the lead cannot be removed by rain or wind. It accumulates to maximum levels of about 2000 ppm but does not continue to increase, indicating some degree of physiological turnover.

The toxic effects of lead on lichens are minimal. Puckett (1976) found some reduction in ^{14}C fixation with long-term exposures but less induction of potassium efflux from the algae than produced by copper, mercury, and magnesium. Garty et al. (1977) found an apparent effect on the condition of *Caloplaca aurantia* in Israel, but their maximum reported lead concentration (174 ppm) is quite low. Brown and Slingsby (1972) concluded that lead has no direct effect on cell metabolism in lichens. After analyzing the results of one growing season along a highway near Washington, D. C., Lawrey and Hale (1979) observed that juvenile plants of *Xanthoparmelia conspersa* grew more slowly with lead burdens of about 1600 ppm than controls but that mature plants were unaffected (Lawrey & Hale, 1977). In Japan Saeki et al. (1975) also reported the survival of *X. conspersa* under severe lead pollution stress.

Surveys of lead content have proved to be very useful in establishing "background" (pre-industry and pre-leaded gasoline) values which can be referenced with present-day levels to show the pervasive increase in the atmospheric lead burden. As an example, Lawrey and Hale (1982) have measured lead accumulation in a broad retrospective study in eastern U. S. A. Using the same lichen species at the same localities, they measured about 80 ppm for specimens collected in 1907, 130 ppm in 1938, and 275 ppm in 1979. Pollution-free areas in virginia mountains contained about 200 ppm, but samples from Connecticut--an area believed to be affected by acid rain--had 300 ppm.

Baseline values in Europe are closer to 25-75 ppm (Seaward, 1973, Takala & Olkhonen, 1976), rising to 1000 ppm or more near pollution sources (Brown & Slingsby, 1972; Pilegaard, 1979). Heavily industrialized Poland, however, has 10 times the background levels of rural Scandinavia when identical species are analyzed (Grodzińska, 1978).

Preliminary studies by Hale (1981) illustrate the potential value of lead analyses of lichens for environmental planning. Lead levels in Wolf Lichen (Letharia vulpina) in Yosemite National Park are low (24 ppm) away from heavy traffic, somewhat higher (33 ppm) in the heavily utilized Valley. This increase is paralleled by slight but perhaps significant increases in iron, zinc, and nickel, other components of exhaust pollution.

Nickel

Nickel is a by-product of coal combustion, industrial processes, and automobile exhaust. It is taken up by algal cells in lichens and affects cell physiology directly. Most data on nickel as a phytotoxic pollutant come from Sudbury, Canada, a huge smelter site. Nieboer et al. (1977) recorded levels of 8 to 310 ppm in lichens in polluted habitats in contrast to 1 ppm in nonpolluted arctic sites (Tomassini et al., 1976).

Values in Yosemite National Park (3-4 ppm), rural Virginia (4-9 ppm), and Connecticut (9 ppm) appear to represent typical background levels in the U. S. A. (Hale, 1981). For comparison, roadside values near Washington, D. C. (24-30 ppm) suggest that lichens can be used to monitor low-level metallic fallout (Hale, 1981).

Mercury

Mercury is a minor component in air-borne pollution, but it is readily accumulated by lichens. In a broad study in Finland Lodenius (1981) surveyed the mercury content of a common lichen at 155 sites. The background values--those remote from obvious pollution sources--were 0.223 ± 0.076 ppm while specimens 8 km from a mercury-emitting chlor-alkali plant contained 0.53 ppm. Lodenius concluded that mercury is transported long distances in the atmosphere. On a smaller scale near an industrial area in Norway Steinnes and Krog (1977) measured background values of 0.29-0.40 ppm and under pollution stress 1.3-1.4 ppm for *Hypogymnia physodes*.

Zinc

Zinc in fairly concentrations (200-600 ppm) in lichens, as found near zinc smelters, is damaging to lichens (Nash, 1975). This element is also produced in automobile exhaust. Hale (1981) found a baseline level of 30-78 ppm near Washington, D. C. for 1907 and a rise to 120-130 ppm by 1958. With increased vehicular traffic it is now about 150 ppm. Comparable lichen species in Connecticut, where acid rain is common, are 200 ppm, approaching the lower limit of the toxic level.

Chromium

Air-borne chromium has not been studied in connection with pollution effects on lichens. It is a component of stack fly ash and would presumably be transported long distances in the atmosphere. One study (Schutte, 1977) reports chromium accumulation has risen two to ten times over historical background levels in Ohio in 80 years. It can be correlated with industrial centers.

Photochemical Toxins

These toxins are generally associated with automobile exhaust pollution in cities but arise from burning of fossil fuels as well. They are most visible in the landscape as smog.

An important element in photochemical smog is ozone. While ozone is toxic to many higher plants, it appears that heavy traffic flow has little visible effect on roadside lichens (Brawn & Ogden, 1977; Lawrey & Hale, 1979) and at most might have more of a synergistic effect when combined with other pollutants (e. g.,PAN, heavy metals). Controlled experimental evidence is ambiguous: Rosentreter and Ahmadjian (1977) and Brown and Smirnoff (1978) were not able to detect any significant damage with ozone fumigations. Nash and Sigal (1979) observed reduced photosynthesis at high concentrations, much higher than expected ambient levels.

Another smog component, NO_2, is altered photochemically to PAN (peroxyacetylnitrate). It is also produced from coal combustion and makes up one-third to one-half of the acidic component of acid rain (the remainder being SO_2) (Cowling & Linthurst, 1981). Experimental fumigation with PAN induces chlorophyll loss and a consequent reduction of photosynthesis (Nash, 1976). Field studies in the Los Angeles Basin (Sigal & Taylor, 1979; Sigal & Nash, 1980; Nash & Sigal, 1980a) show a broad correlation between lichen loss over the past 80 years and increases in PAN and other elements in smog. This is, however, a difficult area of research since photochemical toxins are produced over very large areas in low concentrations and have at the most long-term or chronic effects on lichens.

Acid Rain

While lichenologists were busy studying effects of pollution around sites with obvious SO_2 fallout patterns, enforcement of clean air acts during the 1970's had the effect of raising stack heights from 60-80 m to over 275 m as a simple means of dispersing pollutants more widely. Ground levels of SO_2 have actually fallen or been kept to acceptably low levels in many areas, but the sum total of all air-borne pollutants now reappears as acid rain in localities distant from the source (Likens et al., 1979). Acid rain was first noticed in Scandinavia where many fresh water lakes were becoming so acidified that fish were killed. The same kind of fish kill has occurred in the last few years in the Adirondacks of New York and southern Canada.

Rain becomes acidified by large-scale air mass entrainment of SO_2 and NO_2 (Cowling & Linthurst, 1981). The air mass may travel hundreds of miles before the pollutants are released at ground level as rain or snow. Research in this new area is growing rapidly, but much chronic damage has already taken place before baseline surveys could be started (Rose, 1980).

Workers using lichens as pollution monitors have long noted that the pH of tree bark is lower near pollution sources (Haynes & Morgan-Huws, 1970). Johnsen and Søchting (1973), for example, sampled 147 stations up to 25 km from Copenhagen, finding a mean bark pH of 2.9 at the center and pH 4.0-4.5 in nonpolluted areas for the same trees. Similar values and high correlation with bark SO_2 content were reported by Lötschert (1977) in Frankfurt. Robitaille et al. (1977) emphasize the effect of acid rain in reducing pH of both bark and lichen thalli. They regard stemflow as critical. Gilbert (1970) found no pollution-sensitive lichens near Newcastle, England, where bark pH was less than 3.6 (normal bark was pH 4.4). The same phenomenon has been reported in Poland (Grodzińska, 1979).

Acid rain transported long distances has the same physiological effect on lichen metabolism as dryfall SO_2 from a nearby, discrete pollution source, in particular acid hydrolysis of chlorophyll

(Sheridan & Rosentreter, 1973). Acidification of the substrates is known to kill off submacroscopic propagules such as soredia which normally function in vegetative propagation of lichens (Margot, 1973), even while mature lichen thalli survive until their life span is completed. The long-term effect could prove disastrous for such sensitive organisms as lichens (Gilbert, 1980). The lichen flora of the Netherlands, for example, has been virtually wiped out by acid rain which originates in Germany, to be replaced by the resistant alga Protococcus. It is quite possible that the slow but measurable decline in lichen cover and richness in Pennsylvania, New York, and New England is caused by acid rain from Ohio (Hale, 1981).

Phytotoxins listed above are not the only cause of lichen death. Lichens normally harbor many invertebrates (mites, collembola, psocids, etc.). Under pollution stress these organisms may destroy lichen colonies (Hale, 1972), especially the small propagules. This loss, together with changes in the substrate which might prevent lichen growth, such as acidification, could effectively prevent recolonization and result in a complete loss of lichens in polluted habitats.

Community Simplification

Air pollution does not necessarily kill off all lichens. Selective loss because of chronic low-level pollution may simply result in a poorer, florisitically altered community. Nash (1972, 1975) stressed this effect in his studies around zinc factories. Lawrey (1981) stresses the importance of simplification in community structure as more pollution-resistant lichens expand into niches opened up by loss of pollution-sensitive species on rocks near Washington, D. C. In this instance pollution is altering community structure and diversity. In such cases there may also be an accompanying reduction in the diversity of invertebrates associated with and often feeding on the lichens (Gilbert, 1971a).

One measure of simplification is to compare the lichen species in a polluted area with those reported before pollution occurred. Unfortunately, very few lichenologists are (or have been) provident enough to design studies of this nature and extremely few baseline studies are available. To cite one example, Degelius surveyed the botanical garden in Gothenburg, Sweden in 1961 and found 65 species. Barely 20 years later Arvidson (1980) could only find 38, a reduction correlated with the increased pollution in this industrial city. A similar study in northern Sweden around a recently built sulphite paper mill reported only 17 of 30 common species first collected in 1930 (Westman, 1975).

Lichen Recolonization

When sources of pollution are stopped or reduced or patterns of transport are altered, lichens will recolonize sites where they were formerly killed off. In Sweden this stage was followed by Skye & Hallberg (1969) after a shale-oil plant was cleaned up. Hafellner and Grill (1981) found reinvasion in Austria only 8 years after a cellulose mill was closed. This phenomenon has also been seen in cities, such as London, where recolonization by lichens can be correlated with a drop in average SO_2 levels from 300-400 $\mu g/m^3$ to the present 100 $\mu g/m^3$ or less (Rose & Hawksworth, 1981) Henderson-Sellers and Seaward (1979), however, are hesitant to establish an SO_2 threshold value for *Lecanora muralis* in West Yorkshire since a number of factors are involved in recolonization.

CRITIQUE OF METHODOLOGY

There are basically two ways in which lichens have been used to monitor air pollution:

1. To measure actual pollutants accumulated in the lichen thallus, taking advantage of their proven capacity to absorb and store phytotoxins and using this information to extrapolate the presence, location, and transport distance of the pollutants. In addition changes in cell physiology brought about by pollution can be measured. These ecophysiological methods obviously depend on lichens actually being present in a polluted site, although transplants can overcome this problem.

2. To map all (or selected) lichen species around a pollution source to measure the effect, intensity, and distribution of pollutants by recording the presence or absence. Grodzińska and Yorks (1981) recognize two types of lichens here: (1) scale or indicator species (present or absent) and (2) true bioindicators (persisting and showing damage proportional to dose). In this phytosociological approach the field data can be reduced to mathematical indices of air purity.

Ecophysiological Methods

1. Assay of Elemental Content

Lichens accumulate many pollutants, some of which eventually kill them and some of which are stored harmlessly. Several grams (or less) of lichen thallus are usually collected at various sites, pulverized, treated, and analyzed by any of several available physicochemical techniques (Lawrey & Hale, 1982). Commonly analyzed elements include S, F, Pb, Ni, Cu, Fe, Mg, Mn, Cr, Cd, Zn, Ca, and several rare earch elements.

A large body of information is building up on elemental content of lichens both in their natural state remote from pollution sources and under pollution stress (Addison &Puckett, 1980). Representative values are summarized above in the discussion of individual pollutants (see pp. 7-15). Much work remains to be done, and it is imperative that every baseline lichen study include elemental analyses of the important indicator lichen species for future reference.

2. Physiological Measurements

A recent trend in biomonitoring with lichens is to measure changes in physiology under pollution stress. For example, plasmolysis of algal cells can be measured microscopically (Eversman, 1979; Will-Wolf, 1980a). Changes in the fine structure of chloroplasts were observed by Ikonen and Kärenlampi (1976). Chlorophyll content, determined spectroscopically or by microfluorometry, is another measure of SO_2 damage (Eversman, 1979; Beltman et al., 1980; Kauppi, 1980; Kauppi & Mikkonen, 1980). These new techniques have yet to be applied over the long term, and in fact much more needs to be learned about the normal variation in algal cell physiology before the data can be interpreted intelligently.

Even more involved measurements can be made for respiration rates of indicator lichen species (Eversman, 1976), but here also our overall ignorance of the norm makes interpretation of results difficult. In addition both respiration and chlorophyll measurements require expensive, sophisticated equipment.

3. Transplants of Lichen Thalli

When lichens have been killed off at a pollution source or for some ecological or historical reason do not occur in a study area, it is still possible to take advantage of their sensitivity as bioindicators by using transplants. One of the first studies of this type was conducted by Brodo (1966) who took cores of tree bark with attached lichens from eastern Long Island (see also Hoffman (1971) for techniques) and transplanted them on trees along a transect going into New York City. Those nearest the city were obviously stressed within 4 months and were dying off after one year. LeBlanc and Rao (1973) carried out similar studies at the heavily polluted Sudbury site and used discoloration of a foliose lichen (*Parmelia sulcata*) as a measure. Death of transplants was closely correlated with previously established zones of SO_2 concentration. LeBlanc (LeBlanc et al., 1972) also successfully bioassayed fluorine accumulation in Canada with a transplant method. A number of similar studies have been carried out in Europe (Søchting & Johnsen, 1978; Pilegaard, 1979; Johnsen & Søchting, 1973; Steinnes & Krog, 1977).

Kauppi (1976) used soil-inhabiting Reindeer Moss (*Cladina stellaris*), held in plastic containers placed on trees at various distances from Oulu, Finland, in an interesting modification of this technique. In one year net assimilarion was reduced. Kauppi concluded that such lichen transplants would be useful bioindicators of short-term pollution peaks.

One must still be cautious in interpreting results of transplant experiments. It is well known that lichens are extremely sensitive to habitat changes when transplanted to different sites. Indeed most transplants fail (Hale, 1959), not because of pollution but because the microclimate of the new habitat has not been matched. For this reason trials with transplanted lichen in polluted areas must be carefully designed with adequate samples in both polluted and nonpolluted sites.

Phytosociological Methods

1. Mapping

The simplest way to use lichens in pollution monitoring is to map the occurrence and distribution of lichen species around a pollution source (Hawksworth, 1973) and to relate, when possible, the floristic or phytosociological characteristics of the lichens to ambient SO_2 concentrations (Seaward, 1976). This straightforward approach gives a rough estimate of the distance and direction of pollution fallout. Gilbert (1976) has written a brief summary of mapping techniques.

When studying urban pollution, lichenologists usually select a large number of trees at random or along transects and record presence or absence of species. In his classic study in Stockholm Skye (1968) examined 659 trees. A typical example of primary mapping around a coal-fired power plant is a study by Showman (1975) in Ohio. He selected 128 collecting sites and recorded presence or absence of the species. In his and Skye's results the dot distribution maps clearly show gaps--where species are absent--coinciding with the highest pollution levels. Similarly Marsh and Nash (1979) recorded lichens at 110 sites as far as 41 miles from the Four Corners power plant.

2. Phytosociological Indices

While presence-absence maps of lichens around a pollution source are valuable in biomonitoring, they project little quantitative information about the intensity of fumigations. In order to enhance data from field surveys, De Sloover and LeBlanc (1968) proposed a phytosociological index called Index of Atmospheric Purity (IAP), calculated as follows (as later modified in LeBlanc & De Sloover (1970) and LeBlanc et al., 1974):

$$IAP = \sum_{i=1}^{n} (Q_i X f_i)/10$$

where n = number of species at the site, Q_i = ecological index of toxiphoby of the ith species expressed as the average number of other species found with it, and f_i = frequency-coverage on a scale of 1 to 5. When values are plotted, isobaric lines connecting similar values represent gradations of pollution stress.

The IAP has been adopted and is still being used by many workers studying pollution in urban and industrial areas. The method does give a good quantitative picture in a given region but suffers from the same constraints as a simple mapping survey, that is, it must be carried out by a lichenologist well versed in species identification (Gilbert, 1976). It is also highly influenced by--and in reality no more than a refined expression of--the total number of species at a sample site (=n). This presents no problem in long-polluted areas where n = 0 (no lichens are found) at the pollution source and a fairly high number (n= 20 or more) in adjacent unpolluted sites. In North America, especially, the pollution sources being studied are often too recent to bring about a severe loss of lichens so that n will be nearly equal in polluted and nonpolluted areas.

Ironically LeBlanc (1971) subjected his IAP values for Montreal to various computer simulations, only to discover that the data on just total lichen species at each site, or a few indicator species, or even just one indicator species gave equally satisfactory information on pollution zones. Vick and Bevan (1976) used a few easily recognized species at Merseyside, England, and achieved good results. Seaward (1976) concluded the same in a multivariate analysis study of mapping methods.

The IAP has been modified by Case (1980) to:

$$IAP = \sum_{i=1}^{n} (C_i + V_i)\, Q_i/10$$

where C_i = average coverage rating (1-5) of the ith species and V_i = average vitality rating (1-3) of the ith species.

Species diversity in an ecosystem is an important response parameter reflecting degree of pollution. It can be measured with the Shannon-Wiener Diversity Index H':

$$H' = \sum_{i=1}^{s} p_i \ln p_i \qquad s = \text{total number of species}$$

where $p_i = n_i/N = C_iV_i/ \quad C_iV_i$. Case (1980) showed that IAP, using selected monitor species in standarized quadrats, was significantly correlated with H' values for the same sites and as such provide a reliable indication of lichen community diversity. Thus H' is not simply an expression of number of species in a stand.

A less restrictive index has been proposed by Moore (1974), an Index of Lichen Abundance:

$$ILA = \frac{1}{n} \left[\frac{Q_a}{Q_s} X C \right] X10$$

where C = cover scale (arbitrary), Q_a = average resistivity (average number of species escorting a particular species regardless of substrate), and Q_s = degree of substrate tolerance (= average number of species escorting a particular species on a particular substrate).

Another index, called Luxuriance-Relative Density, has been used by Skorepa and Vitt (1976) to monitor pollution from a gas plant in Alberta. They selected stands in the forest nearby, randomly sampled trees in each, and estimated density and coverage on a scale of 1 to 5:

$$LD_j = \sum \frac{L_j D_j}{N} X10$$

where N = number of quadrats sampled, L = luxuriance (1-5) and D = density (1-5). They claim that this index is less sensitive to actual number of species and would be better for monitoring changes around a new source of pollution.

All of the indices described above--and others that will undoubtedly be proposed in the future--have the advantage of quantifying field data and to some extent permitting statistical analyses. The drawbacks are (1) that the sampler must have considerable experience in lichen taxonomy and phytosociological techniques and (2) that many of the items, such as coverage, luxuriance, etc., are based on quite subjective estimates that are not reproducible between different workers (Gilbert, 1976).

Photography

Photography provides an alternative method of recording changes in sample plots that can be used alone or in combination with the indices. Photographic prints accurately record the presence of species and can be examined and analyzed at a later time. One of the oldest continuous photographic studies in the U. S. A. was started by Hale (1959) in 1949 in Connecticut. Rock quadrats 20 X 29 cm were permanently marked by drilling corner holes and have been photographed every 2-4 years for 32 years. So far they have provided valuable data on dynamics of lichen communities and could be useful in interpreting the possible effects of acid rain in the area over the next 10-20 years. Smiley and George (1974) have already documented the possible effects of acid rain in New York state by comparing archival photographs of lichen-covered rock cliffs with present-day photographs. They show significant but unexplained losses.

Lawrey and Hale (1977) are using photography to assess community changes in lichens subjected to automobile exhaust stress near Washington, D. C. Rock quadrats about 20 X 20 cm are photographed at various intervals. Gilbert (1971) was able to follow cessation of lichen colonization over a 6-year period near a power plant in southern England. Skorepa and Nussbaumer (1975) in Tennessee and Windler (1977) in Maryland are using tagged 20 X 20 cm photographic plots on trees near power stations. An extremely detailed study by Westman (1975) around a sulfite paper mill in northern Sweden was based on .25 m^2 permanent photographic quadrats.

In an extensive baseline study in Big Bend National Park, Texas, Wetmore (1981) photographed a number of quadrats from 1966 to 1970 in conjunction with a floristic inventory. A new set of photographs taken in 1970 seemed to indicate no damage yet to the lichens caused by possible increases in air pollution in the area.

While changes in photographic plots over a period of years may be caused by pollution, one must also consider changes that may be part of the natural cycle of lichens or losses due to predation by animals (Hale, 1972). Lulman et al. (1980), for example, photographed 20 X 20 cm quadrats on trees in Albert in 1976 only to find that three years later there was considerable loss of lichen thalli on loose bark, a natural phenomenon that had nothing to do with pollution effects.

LONG-TERM RESEARCH INTO THE EFFECTS OF ATMOSPHERIC DEPOSITION IN ROCKY MOUNTAIN NATIONAL PARK

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There can be no doubt that in the eastern United States, Canada, and Scandinavia increased acidic deposition has caused acidification of lakes and streams with a concurrent loss of fish populations. The kind of area which is sensitive to increased acidity, areas underlain by granite and other slow weathering rock material with thin soil veneers is present in abundance in Rocky Mountain National Park. And the kinds of resources which were so noticeably acidified in the East, lakes and streams, are present in almost alarming abundance in the Park. There are over 250 lakes alone.

Knowing of this probable sensitivity, we set out in 1981 to quantify and thus identify the actual threat to Rocky Mountain National Park from increased acidic deposition. We didn't want just a survey, but rather to understand what makes an alpine-subalpine ecosystem behave the way it does. What are the biogeochemical processes controlling the fate of precipitation entering Rocky Mountain watersheds?

This is a report on what has been found since the study began in 1981. While there is a long way to go toward achieving our goals, we are able to say there has been some progress. The approach to this question has been two-fold: 1) to characterize the state of the resource with respect to acidic deposition; and 2) to understand the processes involved in creating and maintaining Rocky Mountain ecosystems. We went about the first by looking backwards in time. Using biological and physical indicators from paleoenvironments, we have been able to compare present day conditions to past. The approach to the second has been to investigate biogeochemical processes by focussing on the inputs and outputs of the ecosystem components of one chosen drainage.

Paleoecological Work

A paleological approach was taken to characterize the state of the resource because of the lack of adequate meterological and limnological data during the past few decades. Analysis of diatom community remains extracted from lake sediments has proven to be an acceptable method of determining historical pH conditions in dilute lakes (DelPrete and Schofield 1981, Davis and Anderson 1984).

Analysis of heavy metal deposition in lake sediments have also been used to indicate effects of fossil fuel combustion (Tolonen and Jaakkola 1983, Davis etal. 1983, Norton and Hess 1980). There are numerous advantages of using diatoms as indicator organisms that service paleolimnological work, baseline studies and monitoring programs:

1) Numerous species exist (≈30,000 for fresh and backish waters) allowing analysis at a community level with a good statistical base.

2) As primary producers these algae are ecologically important to any aquatic habitat.

3) Morphological and physiological adaptations provide for cosmopolitan existence in all aquatic environments.

4) Fast reproductive potential and sessile growth provide a quick record of water quality changes.

5) Silica cell wall structure provide permanent taxonomic records of communities after death of the cell.

6) Much ecological information is available at a species level.

7) Collection and processing methods are simple and inexpensive.

In Rocky Mountain National Park, Lake Husted was one of four lakes chosen to characterize the present day conditons with respect to acid precipitation. The lakes shown in Fig. 1 were chosen on the basis of morphology and elevation, and in pairs due to geologic substrate. A sediment core was obtained from the deepest portion of each lake and sectioned in the field into 0.5 cm increments, followed by Pb^{210} isotope dating techniques. Coring and dating procedures were performed by Dr. S.A. Norton, University of Maine. Preparation of diatom slides, counting and taxonomy was done at the Natural Resources Ecology Lab, Colorado State University.

The diatom stratigraphy for Lake Husted from the present to a level downcore corresponding to the year 1819 are presented in Fig. 2. The pH spectral categories represented by the identified taxa follow the system proposed by Husted (1939) and the percentage of the total diatom values counted that could be used for stratigraphic analysis is indicated.

The relationship between the diatom stratigraphy and the inferred pH value was calculated by Index B of Renberg and Hellberg (1982) where,

$$\text{INDEX B} = \frac{(\%\ \text{IND} + 5)(\%\ \text{AC} + 40)(\%\ \text{ACB})}{(\%\ \text{IND} + 3.5)(\%\ \text{ALK} + 108)(\%\ \text{ALB})},$$

$$\text{pH} = 6.4 - (.85\ \text{Log Index B})$$

with IND = indifferent taxa, AC = Acidophilic taxa, ACB = Acidobiontic taxa, ALK = Alkaliphilic taxa, and ALB = Alkalibiontic taxa. No acidobiontic taxa or alkalibiontic taxa were counted or identified from Lake Husted diatom analyses. Inferred pH values from the present, to a level downcore corresponding to the year 1819 are presented in Fig. 3. The mean hydrogen ion concentration as

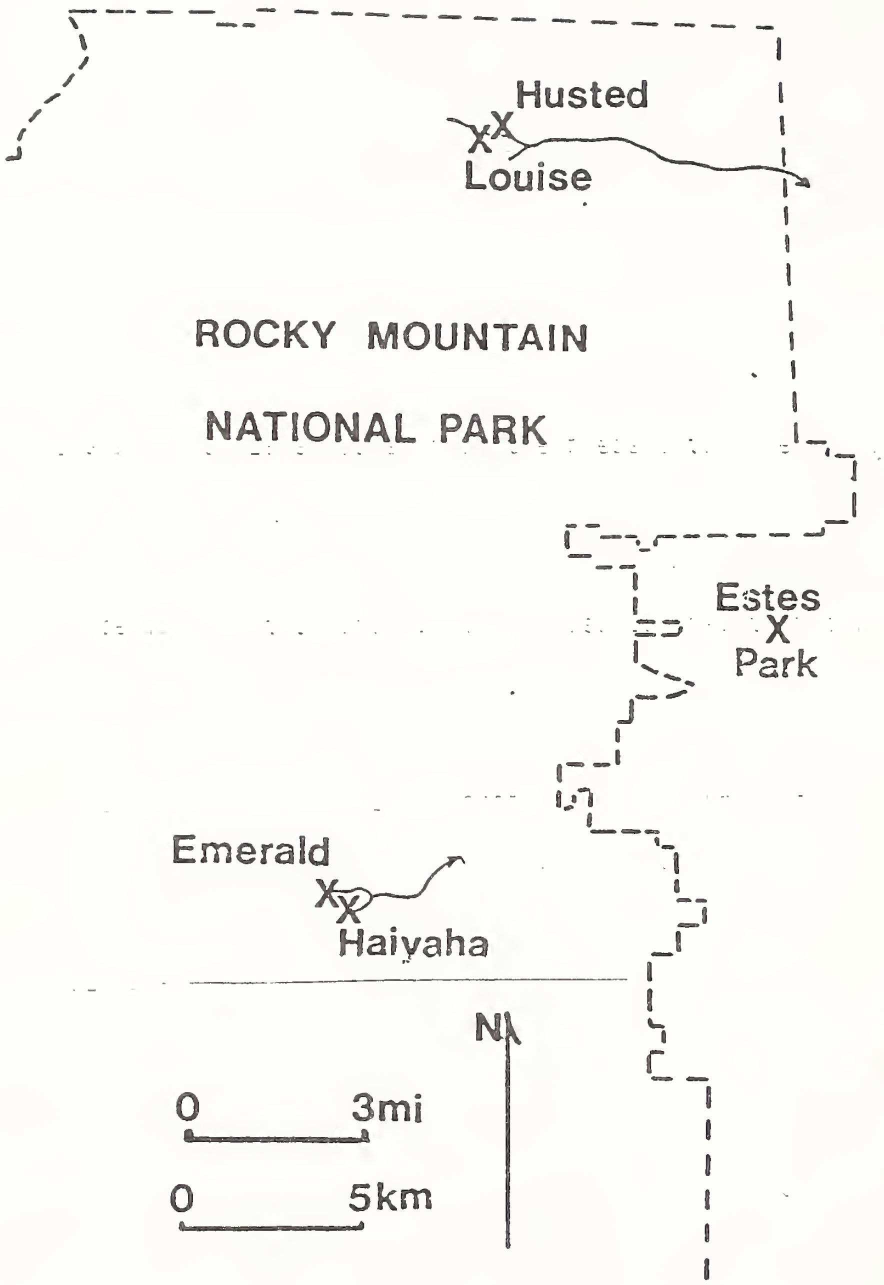

Figure 1: Location of the four study lakes

DIATOM STRATIGRAPHY

LAKE HUSTED

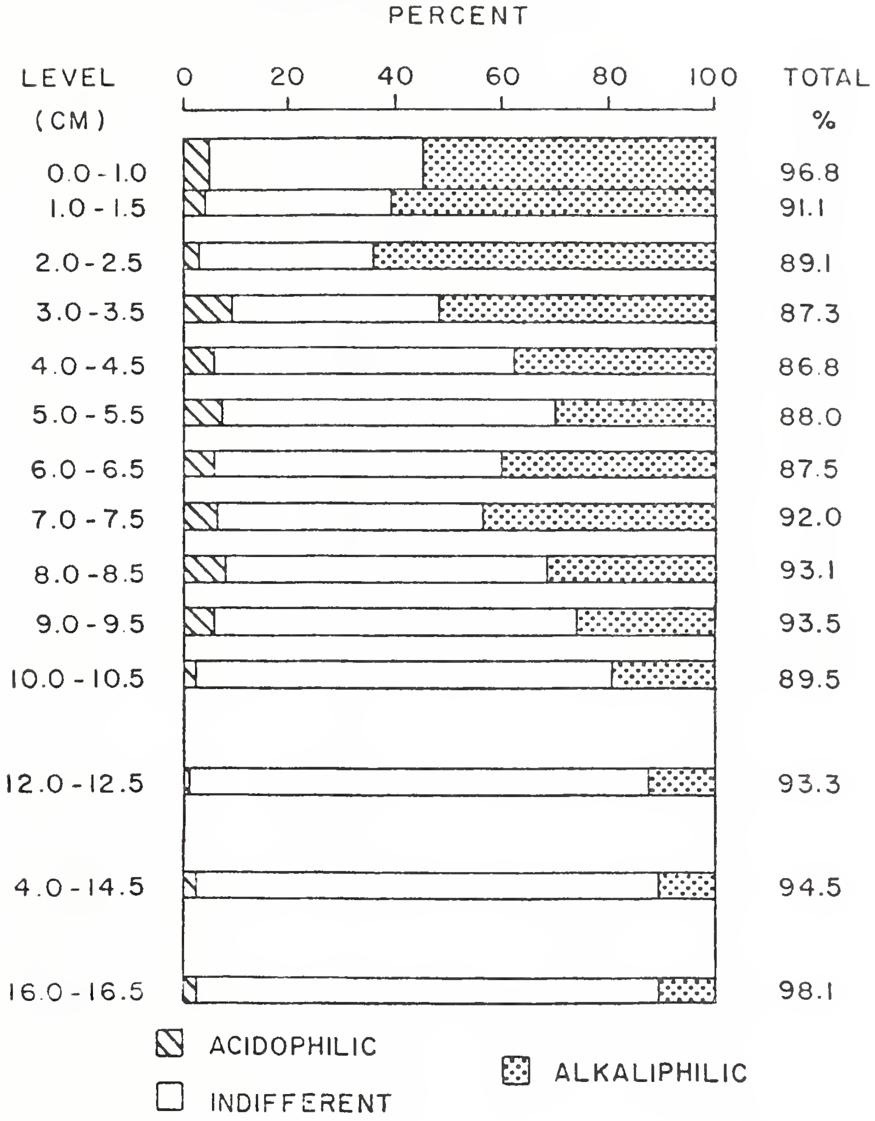

Figure 2.

INFERRED pH STRATIGRAPHY

LAKE HUSTED

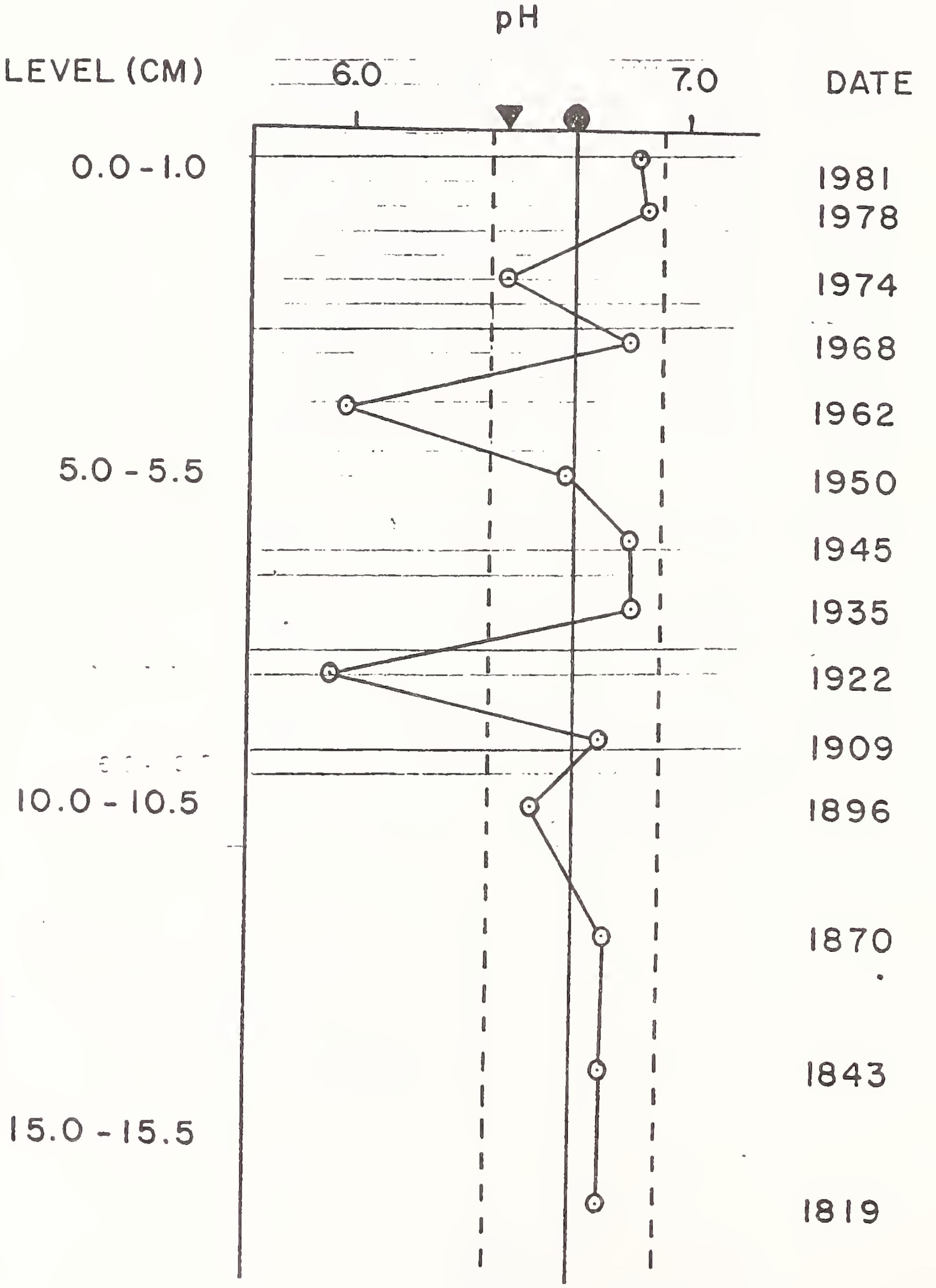

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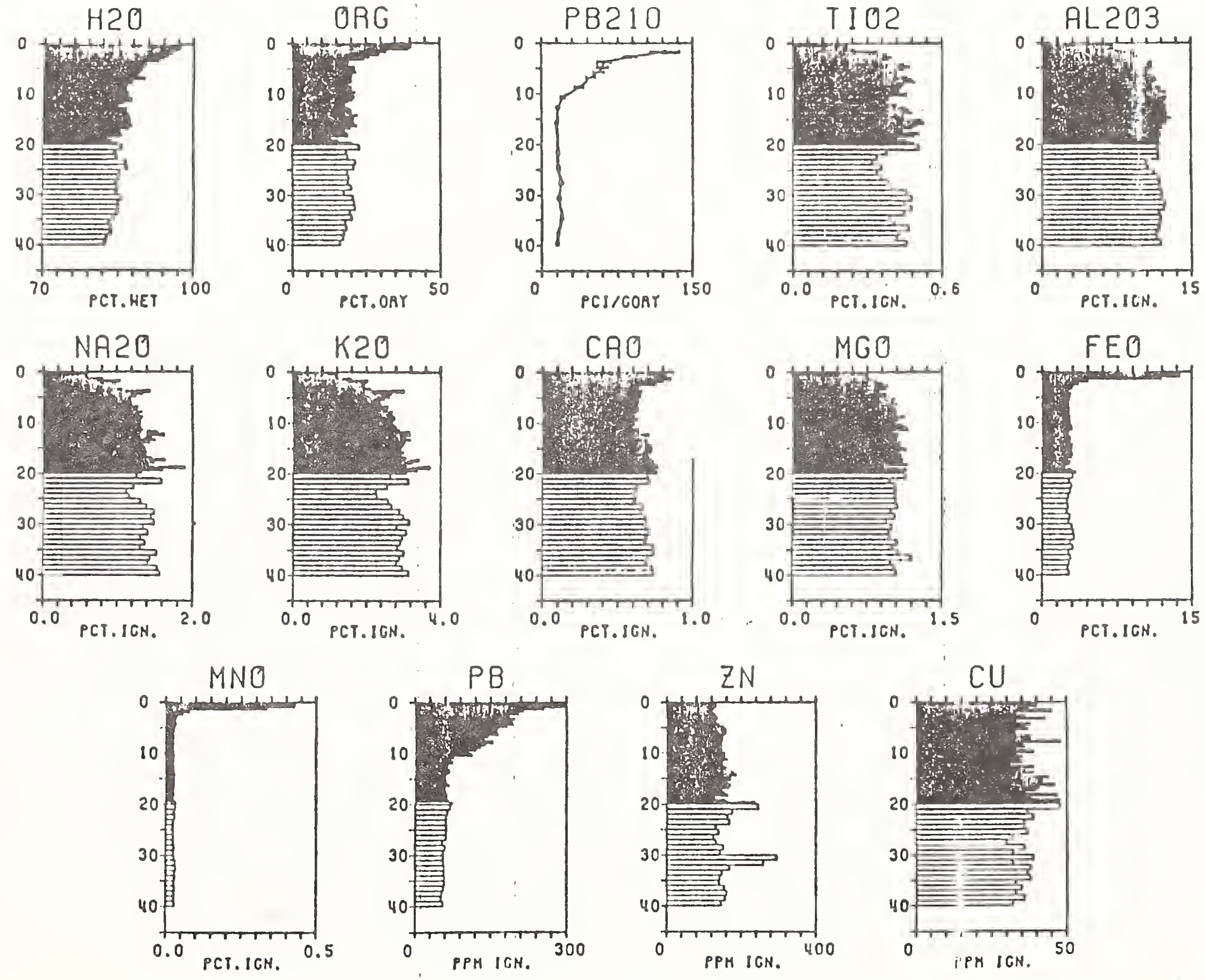
Figure 3.

calculated from field measured values from the water column during 1981 and 1982 (N=9) is indicated by a large dot at pH 6.68. The dashed lines corresponding to pH of 6.41 and 6.92 represent the 95% limits of field measured values. The mean of the hydrogen ion concentration from inferred pH calculations is pH 6.49, indicated by a triangle on the pH scale. A t-test for paired observations indicated the inferred pH mean was not different from the 95% limits represented by field measured data (t=1.68 n.s., t.05=1.77, df=9). An f-test was performed to check equalness of variance indicating no difference in variance between inferred pH values and field measured values (f=1.55 n.s., f.05=2.85).

The results from the stratigraphic diatom analysis suggests that acidic deposition has not affected the pH of Lake Husted from the early 1800's to the present. The mean hydrogen ion concentration of inferred pH values is within the variation of pH values exhibited by field measurements.

Stack emissions of NO_x and SO_2 from fossil fuel combustion contain aerosols of Pb, Zn, and Cu. These aerosols have been recorded from lake sediments in Scandinavia, Canada and New England as excellent indicators of industrial pollution and acidic deposition. Stratigraphic profiles of heavy metals and other selected parameters for Lake Husted are shown in Fig. 4. The increase in Pb concentration beginning at a core depth of 12.0 cm corresponds with a date of about 1870, but is not accompanied by concurrent increasing concentrations of Zn or Cu. Deposition rates ($uq/cm^2/yr$) instead of sedimentation rate (cm/yr) can signal concentration increases of elements independent of enrichment factors that add bulk material such as water and organic content. The deposition rate of Pb mirrors the chemical profile of Pb shown in Fig. 4, again not accompanied by concurrent increases in

LAKE HUSTED



CONC. VS. DEPTH (CM)

ure

deposition rate of Zn and Cu. The increased deposition rate of Pb was observed to occur simultaneously in all four lakes (Fig. 5) at comparable magnitude suggesting an atmospheric origin (Norton unpublished). Combustion of fossil fuel must be ruled out, however, due to no increases of Zn and Cu concentration suggesting particulate deposition of Pb from increased mining activity in Colorado during this time period and/or a global industrial signal similar to results found by Murozumi etal. (1969) in Greenland ice cores.

In summary, this investigation has shown no indication that acidic atmospheric deposition has affected Lake Husted, a high alpine lake in Rocky Mountain National Park. Biologic investigation by stratigraphic diatom community analysis shows no change in mean pH or Lake Husted since the early 1800's. Chemical stratigraphy analysis indicates an increase in the deposition of Pb, presently believed to be particulate deposition from increased mining activities in Colorado since 1850-1880 or a global Pb deposition phenomenon. The lack of associated increases in Zn or Cu concentrations suggest the source of increased Pb is not from fossil fuel combustion.

Ecosystem Process Work

The work investigating ecosystem processes was organized around testable hypotheses and the following assumption: surface waters serve as integrators of upstream processes. If a lake or a stream acidifies due to acidic deposition, then, it is due not only to acidic substances falling on the water directly, but to reactions within the different "water groups" above, that contribute water to that surface water body. A conceptual diagram was drawn of the ecosystem components thought responsible for influencing deposition as it becomes lake or stream water (Fig. 6) and studies were initiated to understand the role of each. The Loch Vale

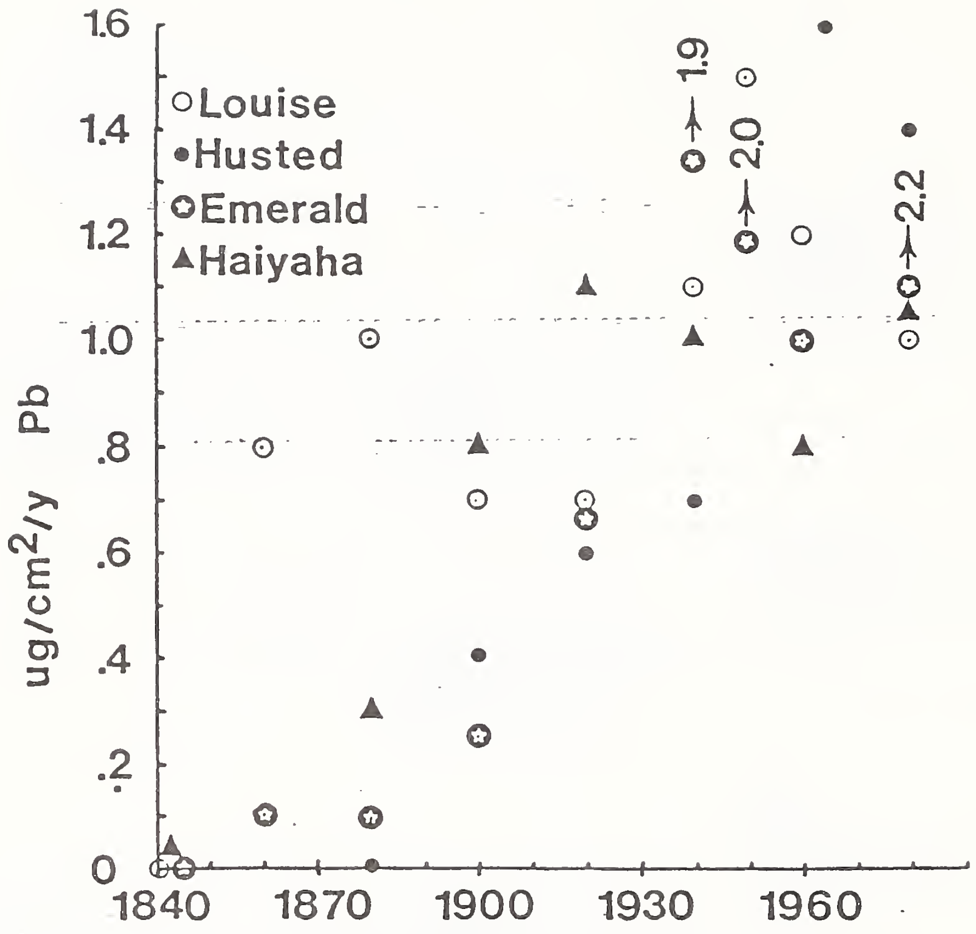


Figure 5: Deposition rate of Pb for the four study lakes

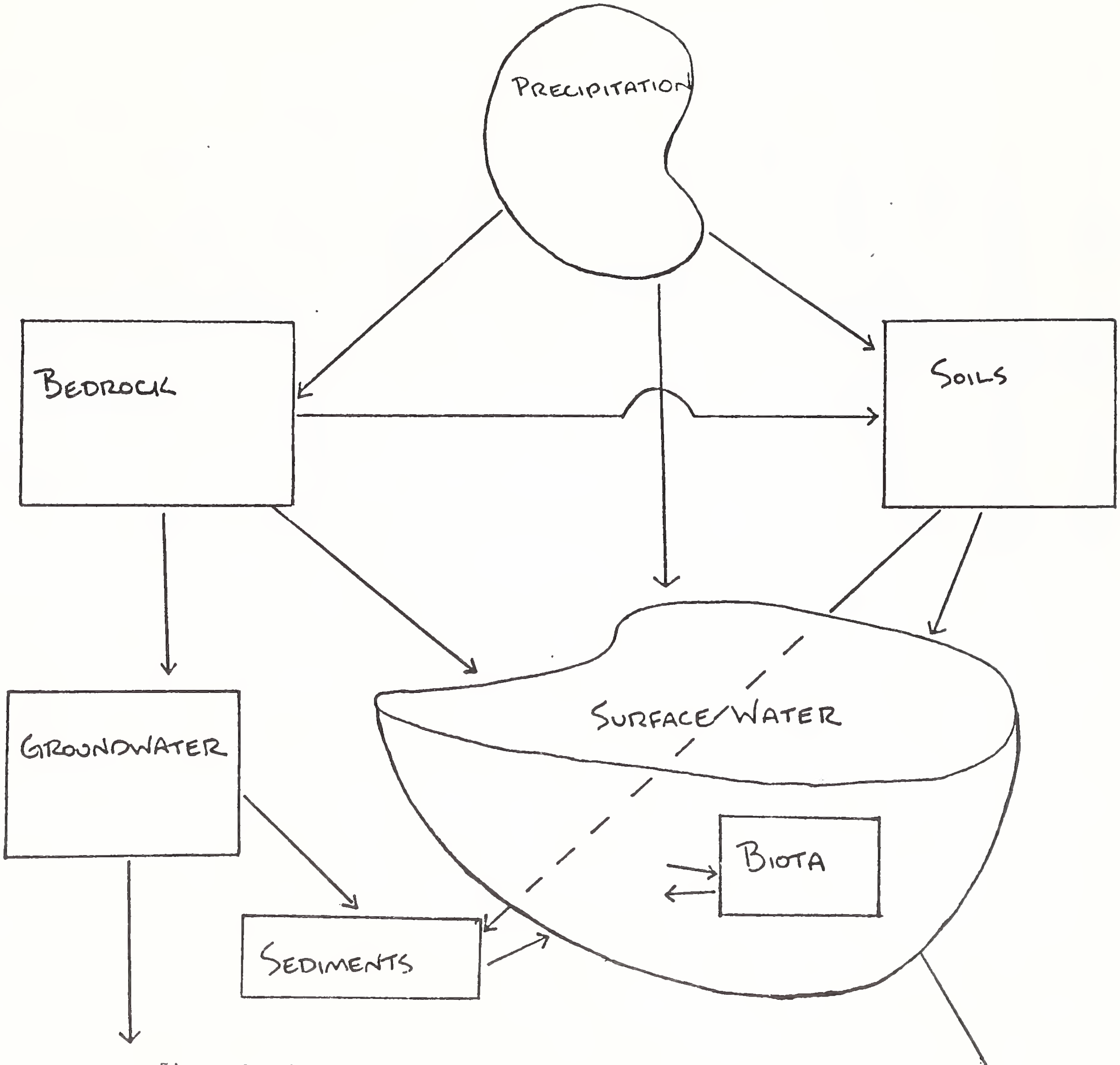


Figure 6 Conceptual model of biogeochemical flow through Loch Vale

drainage, (Fig. 7), in the Glacier Gorge area of the Park was chosen for in-depth study for the following reasons:

1) Of 40 lakes within Rocky Mountain National Park surveyed for water chemistry in 1984 (Gibson etal. in press), these had among the lowest summertime alkalinity.

2) It is a relatively small (960 ha.), simple (only two first order streams) drainage from which inputs and outputs can be gauged.

3) Three lakes in the main drainage are linked by a connecting stream. Two lakes above treeline and one below, give opportunity for comparison along an elevational gradient.

4) The drainage has a NE facing aspect, lessening a direct upslope influence from metropolitan Denver.

5) There is a wide representation of alpine/subalpine soil types enabling intensive study of the chemistry and influences of the soil component.

6) One can gain access to all parts of the drainage at all times of the year.

Precipitation Chemistry

Precipitation chemistry has been collected at an elevation of 3050 m since 1981 to characterize inputs to Loch Vale. The collector is part of the National Atmospheric Deposition Program. More recently we have measured precipitation volume intensively throughout the sample drainage in an attempt to quantify inputs. Rather than discuss the results from Loch Vale, we think it might be more informative to place deposition chemistry in perspective with the rest of the State of Colorado. Table 1 shows volume weighted concentration for some major components of precipitation in five Colorado NADP sites for 1981. Two other sites, Olympic National Park and Parsons, WV, are included for comparison. Alamosa and Sand Springs are located west of the Colorado Front Range, while Rocky Mountain (headquarters station), Manitou, and Pawnee are located along the Front Range on the eastern side of the Continental Divide. Several items can be mentioned concerning the information in this table:

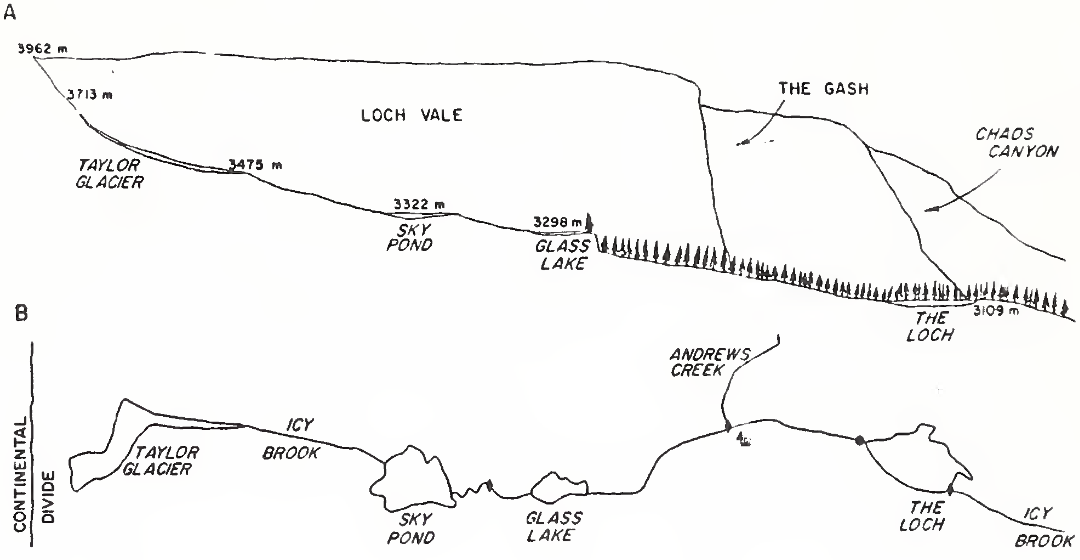


Figure 7. A) cross-sectional and B) plan view of Loch Vale drainage. Diamonds are planned locations of Parshall flumes. The square and triangle shows location of weather station and NADP monitor.

Table 1. Average annual concentration, 1981.

Site	pH	SO_4	NO_3	NH_4	Ca & Mg
	μeq/l - precipitation weighted				
Alamosa, CO	5.2	38.0	17.0	23.0	28.0
Sand Springs, CO	5.0	33.0	16.0	10.0	31.0
Rocky Mountain National Park, CO	5.0	33.0	23.0	19.0	26.0
Manitou, CO	4.8	34.0	24.0	13.0	24.0
Pawnee, CO	5.1	45.0	28.0	39.0	29.0
Olympic National Park, WA	5.4	8.0	1.5	1.0	10.0
Parson, WV	4.2	74.0	30.0	16.0	18.0

1) Values for pH range from 4.8-5.2 in the Colorado sites, compared to 5.4 in Olympic National Park, and 4.2 in Parsons, WV. The threshold values for environmental degradation in sensitive systems has been proposed at 4.7 by Wright (1983).

2) Sulfate values are comparable across the state and are much higher than values reported for Olympic. The values are a fraction of the concentration recorded from Parsons. The evenness of SO_4 values suggests limited influence from local emission sources. (95% of all inland sulfate deposition is due to the combustion of fossil fuels.)

3) Nitrate concentration values are greater in all Colorado sites than in Olympic, but, at least for the three eastern locations are comparable to those in Parsons. An influence from the metropolitan Denver area is likely. This elevated NO_3 deposition for Rocky Mountain National Park needs to be examined further.

4) The cations, ammonium, calcium and magnesium, represent significant levels of alkalizing materials which are responsible for lower acidities than would be expected from the concentrations of sulfate and nitrate if these originated as sulfuric and nitric acid.

A look at annual deposition for 1981 for these same sites (Table 2) gives another perspective. Hydrogen input is an order of magnitude lower than the clean comparison site, Olympic, and almost two orders of magnitude lower than the acidified site, Parsons. Sulfate deposition is similarly low, reflecting the differences in precipitation amounts in Colorado compared to the more mesic west coast and eastern sites (Olympic sulfate has not been corrected for marine sulfate). NO_3, while higher in concentration, is now comparable in loading to the values reported from Olympic for all Colorado sites, and is 4-6x lower than the Parsons NO_3 deposition values.

One can conclude that Rocky Mountain National Park is currently the recipient of more nitrate, possibly as nitric acid, than if there were no metropolitan influence, but pH values are well above a threshold constituting acidic deposition. Deposition would have to increase four or fives times to equal values for strong acids reported from acidified locations in the eastern United States. (Gibson and Baron 1984).

Table 2. Annual deposition, 1981.

Site	H^+	SO_4	NO_3	ppt (cm)
	kg/ha			
Alamosa, CO	0.01	5.4	2.7	22.0
Sand Springs, CO	0.04	7.3	4.4	40.0
Rocky Mountain National Park, CO	0.03	4.9	4.5	32.0
Manitou, CO	0.07	6.7	6.2	40.0
Pawnee, CO	0.03	7.2	5.7	30.0
Olympic National Park, WA	0.10	18.0	4.4	366.0
Parson, WV	0.90	46.0	24.0	130.0

Soil Distribution and Properties

Six major land forms and soil regimes have been identified within the watershed (Baron and Walthall 1983). The aerial and proportionate extent of these units and surface areas are given in Table 3. The forest soils cover 5% of the watershed and have developed under spruce and fir forest types. Two major soil types, a Cryoboralf from the forest floor, and a Cryumbrept where talus and glacial till deposits occur, were recognized. Drainage from these soils is expected to have an influence on the lowest of the study lakes, the Loch. While alluvial soils comprise only 0.5% of the drainage, they are found adjacent to the stream channel and are expected to influence the surface waters into which they drain. Two organic soils were found here: Cryohemists occur where a minimal slope creates conditions for bog development, and Cryofluvents occur in forested, low-relief areas more characteristic of a depositional environment.

Chemical data characterizing the soil environment is given in Table 4 for typical pedons of the major soil types occurring in the forest and alluvial regimes. Extremely acid soil pH values were found to occur in all of the pedons ranging from a maximum of 4.8 to a minimum of 3.7. Such extreme acidity would indicate that some source other than H_2CO_3 dominates the soil system with respect to pH. Organic acids originating in surface litter and preserved by the cool temperatures of this alpine environment are most likely responsible for this extreme acidity (Ugolini etal. 1977). Two distinct patterns exist within the soil profiles of the forest and alluvial soil regimes. In both of the forest soils, the Cryoboralf and the Cryumbrept, pH values are highest in the organic layers and decrease with depth. In the alluvial soils, the cryohemist and the cryofluvent, the opposite trend occurs with a slight increase in pH with depth.

TABLE 3. Approximate aerial and proportionate extent of soil regimes.

Soil Regime	Hectares	Percent
Forest Soils	45	5
Alluvial Soils	4	0.5
Rock Outcrop - Organic Soils	15	1.5
Rock Outcrop	465	54.0
Rock Slides	230	27
Alpine Ridge	91	11
Surface Water	10	1.0
	860	

TABLE 4. CHEMICAL PROPERTIES OF SOILS

HORIZON	DEPTH	pH	Exchangeable Bases				E.A.	C.E.C.	B.S.	O.M.
			Ca^{2+}	Mg^{2+}	K^+	Na^+				
	(cm)		(meq/100g)						(Percent)	
Cryoboralf										
Oe	9- 0	4.8	53.1	4.3	2.3	0.2	35.7	95.5	62.6	--[1]
E	0-19	3.8	6.7	0.6	0.3	0.1	12.3	20.0	38.7	2.7
B^t	19-32	3.7	5.2	0.4	0.3	0.1	22.8	28.9	21.0	3.1
BC	32-56	3.7	1.7	0.2	0.3	0.1	14.3	16.5	13.7	1.6
R	56+									
Cryumbrept										
Oi	1- 0	4.8	20.1	2.7	1.3	0.1	26.7	50.9	47.6	--
A	0-15	4.3	7.2	0.9	0.4	0.1	28.4	36.9	23.2	11.9
2Bw1	15-46	4.2	1.9	0.2	0.1	0.1	13.7	16.0	14.3	2.1
2Bw2	46-74	4.1	1.1	0.1	0.1	0.1	12.9	14.3	9.9	1.3
2R	74+									
Cryohemist										
Oi	0- 4	3.8	8.0	1.2	1.2	0.6	38.5	49.4	22.1	--
Oe1	4-15	4.0	2.9	0.2	0.3	0.3	38.1	41.8	8.8	--
Oe2	15-25	4.1	4.3	0.2	0.2	0.2	34.9	39.8	12.3	--
Oa	25-33	4.3	5.6	0.2	0.1	0.2	35.1	41.3	14.9	--
Cg	33-43	4.4	5.7	0.4	0.1	0.2	19.0	25.4	25.2	7.0
R	43+									
Cryofluvent										
Oi	9- 0	3.8	10.0	2.5	1.9	0.4	34.1	48.9	30.2	--
A	0-10	3.8	2.4	0.2	0.2	0.2	34.9	37.9	7.9	11.5
Ca1	10-24	4.0	2.5	0.2	0.1	0.2	26.4	29.4	10.1	6.8
Cg2	24-30	4.0	4.0	0.5	0.1	0.3	25.1	30.0	16.4	12.7
Cg3	30-37	4.2	5.0	1.0	0.1	0.3	28.9	35.4	18.3	26.9
Ob	37-47	4.4	7.5	1.3	0.1	0.4	33.1	42.4	21.9	--
R	47+									

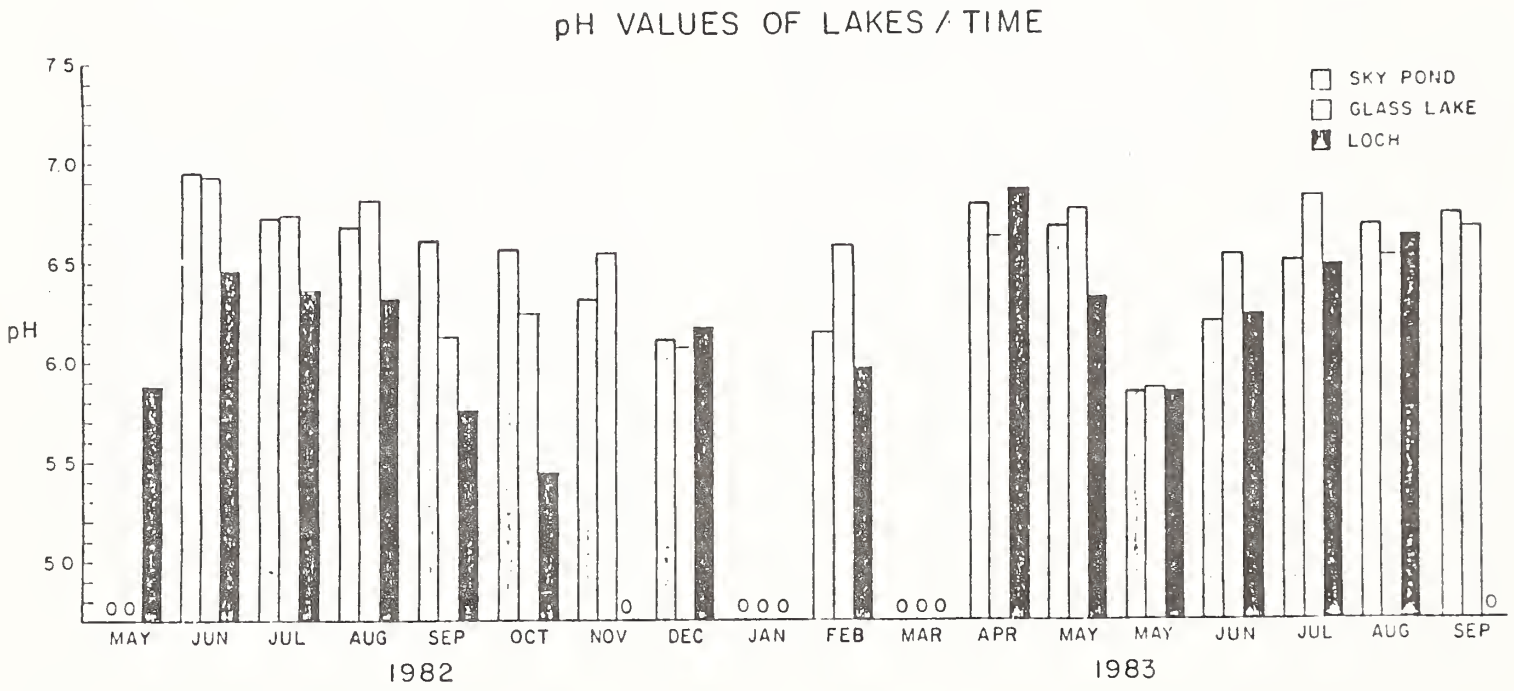
[1] --: Organic matter percentages were not determined for organic horizons.

Cation exchange capacities are relatively high and originate from two primary sources: 1) the organic component of these soils, and 2) the mineralogy of the clay fraction which was found to be dominated by smectite. The exchange complex in organic matter is highly pH dependent and for the humic fraction is expected to have an exchange capacity of approximately 90meq/100g at a pH of 4.0 (Brady 1974). It is important to point out that this value is for the humic fraction and not for the entire organic mass as reflected in CEC values found in the organic surface layers which have an average value of approximately 50meq/100g. The organic surface of the Cryoboralf (pH 4.8) was noted to be more highly decomposed than the other surface layers and was found to have a value of 95.5meq/100g.

The clay mineral group of smectites has a characteristic CEC value of 100meq/100g that is largely independent of pH. X-ray analysis and CEC determinations of the coarse and fine clay fractions indicate a dominance of this material. This mineral is believed to be a weathering product of biotite and chlorite commonly occurring in the parent rock of this environment. Smectites are not generally considered to be stable weathering products in acidic environments. However, their occurrence in such environments has been noted when accompanied by high silica levels (Borchardt 1979). The highest clay percentages were found in the sediments of the alluvial soils and ranged from 19.7 to 24.6 percent. Clay distribution in the Cryoboralfs was highest in the argillic horizon at 15.7 percent with 9.1 and 5.6 percent occurring in the E and BC horizons respectively. The Cryumbrept had a maximum of 13.4 percent clay in the A horizon and dropped to 4.2 and 4.4 percent in the 2Bw1 and 2Bw2 horizons respectively.

Base saturation percentages were extremely low for the soil environment as a whole with maximums occurring in the organic surface layers ranging from 22.1 to 62.6 percent. Extremely low values ranging from 7.9 to 38.7 percent were found in underlying horizons. The sum of the exchangeable bases Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} plus the exchangeable acidity, equal the exchange capacity of the soil. Calcium was found to be the dominant basic cation followed by lesser amounts of Mg^{2+}, Na^{+}, and K^{+}. Concentration of these cations in surface layers is apparently a result of nutrient cycling. This process seems quite effective in recovering K^{+} from the soil solution as evidenced by its significantly higher concentrations in the organic surface layers compared to Na^{+}. In underlying horizons these two cations occur at similarly low levels. Total aluminum values determined on saturated-paste extracts ranged from 6.5mg/1 to 1.4mg/1. Aluminum activities (Al^{3+}) speciated from total concentrations were found to be extremely high, approaching a level that would be supported by amorphous $Al(OH)_3$. These activities ranged from $10^{-4.46}\underline{M}$ to $10^{-5.36}\underline{M}$.

The buffering capability provided by these soils to the surface water environment is minimal compared to less acidic, less organic soils. Aluminum and hydrogen dominate the soil solution chemistry and are flushed into surface waters at the same time as exchangeable bases and carbonic acid which provide buffering. An example is presented in Fig. 8 by observing pH values of surface samples from the three study lakes. The Loch, the only lake surrounded most visibly by a soil environment, shows significantly lower pH's throughout the hydrologic year which may be explained by input of soil water. The aluminum contained in the soil waters cannot remain in solution at the higher pH of the surface waters and either settles into the sediments or is flushed downstream as it precipitates out.



pH VALUES OF LAKES / TIME

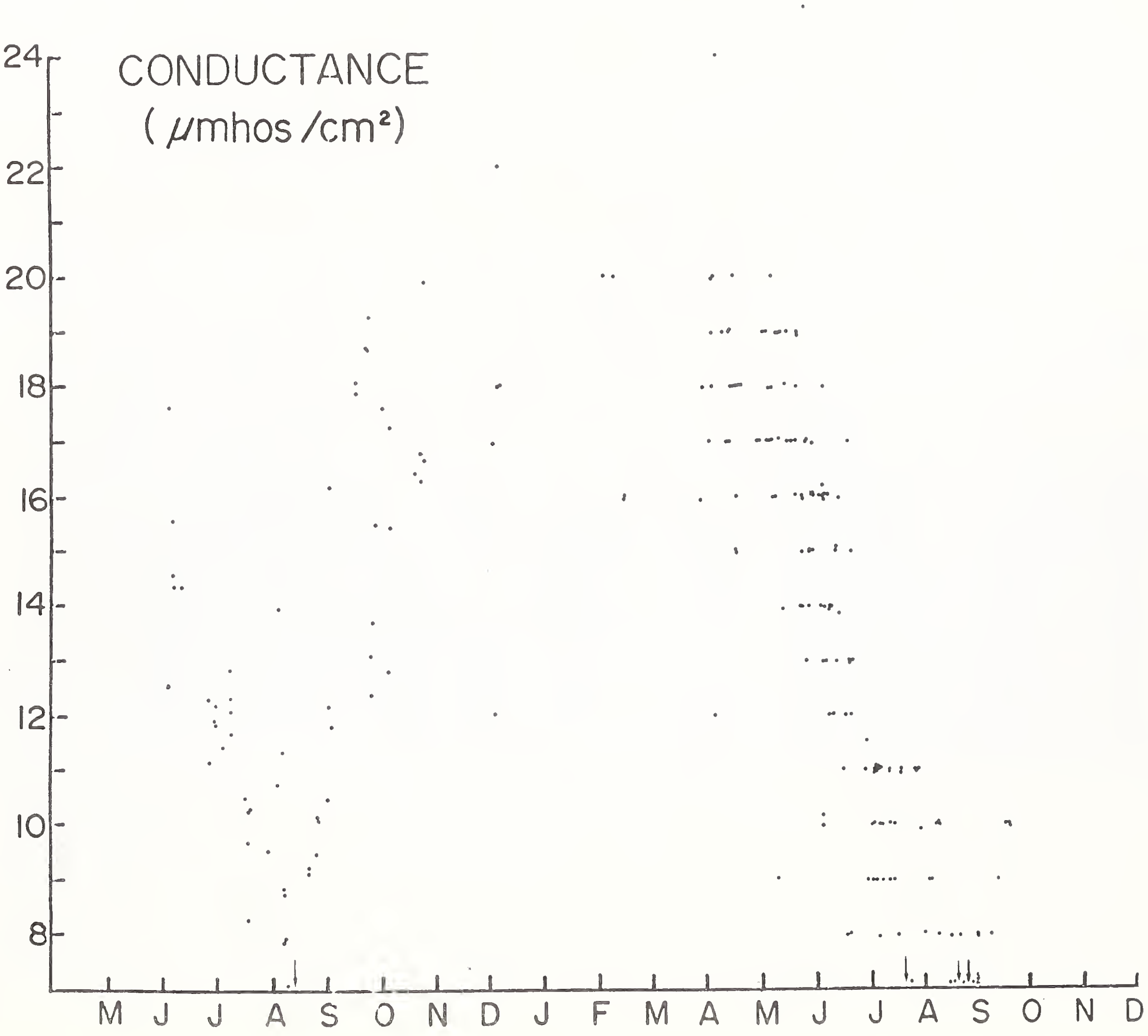
Figure 8.

Surface Waters

The three lakes of the drainage, Sky, Glass, and the Loch, are oligotrophic, dilute cirque lakes connected by a perennial stream, Icy Creek. Samples have been taken monthly since 1982 at all inlets, outlets, and from three depths within each lake. Gaging stations are located at the inlet and outlet of the Loch, and daily samples were collected Apr-July 1983 to record the snowmelt volume and chemistry. While some differences in water chemistry are noted from the different sample locations (Fig. 8), the lakes did not stratify, nor do there appear to be much spatial variation between lake and stream waters. All waters sampled exhibit a temporal variation corresponding to the hydrologic cycle and this is shown in Figures 9-11. Conductance, $CaSO_4$, and to a lesser degree NO_3 (Fig. 12) exhibit a seasonal undulation in concentration which is explained as follows: the lack of flushing due to winter ice cover allows an accumulation of cations and anions resulting in increased conductance. The advent of snowmelt (Apr-July) causes dilution of these solutions and the ionic concentration decreases dramatically. The summer months of Aug-Sept. show water chemistry at its most dilute, perhaps due to maximal terrestrial biological activity immobilizing nutrients and ions available for flushing. These waters typically freeze over during Oct-Nov. which again corresponds with a rise in ionic concentration.

Our work in Loch Vale to date has focussed on chemically characterizing three components of the alpine-subalpine ecosystem; precipitation, soils, and surface waters. Any quantitative linkage of ecosystem components must be firmly based upon an understanding of hydrologic flow. Fig. 13 conceptualizes Loch Vale basin as a three-dimensional porous medium with surficial expressions. Inputs must be gauged throughout the basin and outputs must be measured from stream flow, groundwater loss and evapotranspiration including an estimate of the measurement error involved.

26A


CONDUCTANCE
(µmhos /cm²)
24
22
20
18
16
14
12
10
8
M
J
J
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S
O
N
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J
F
M
A
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O
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Figure

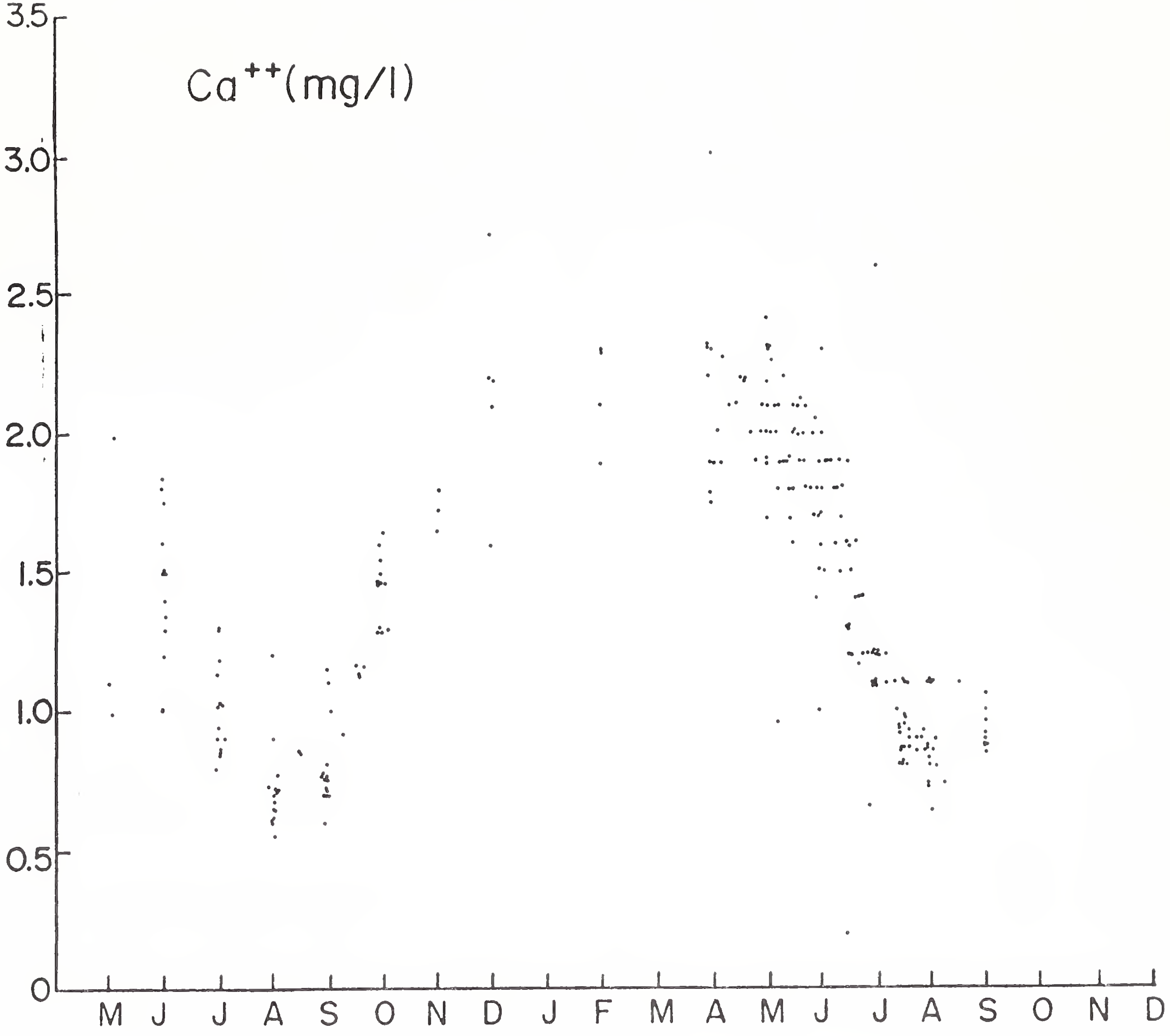

Figure 10.

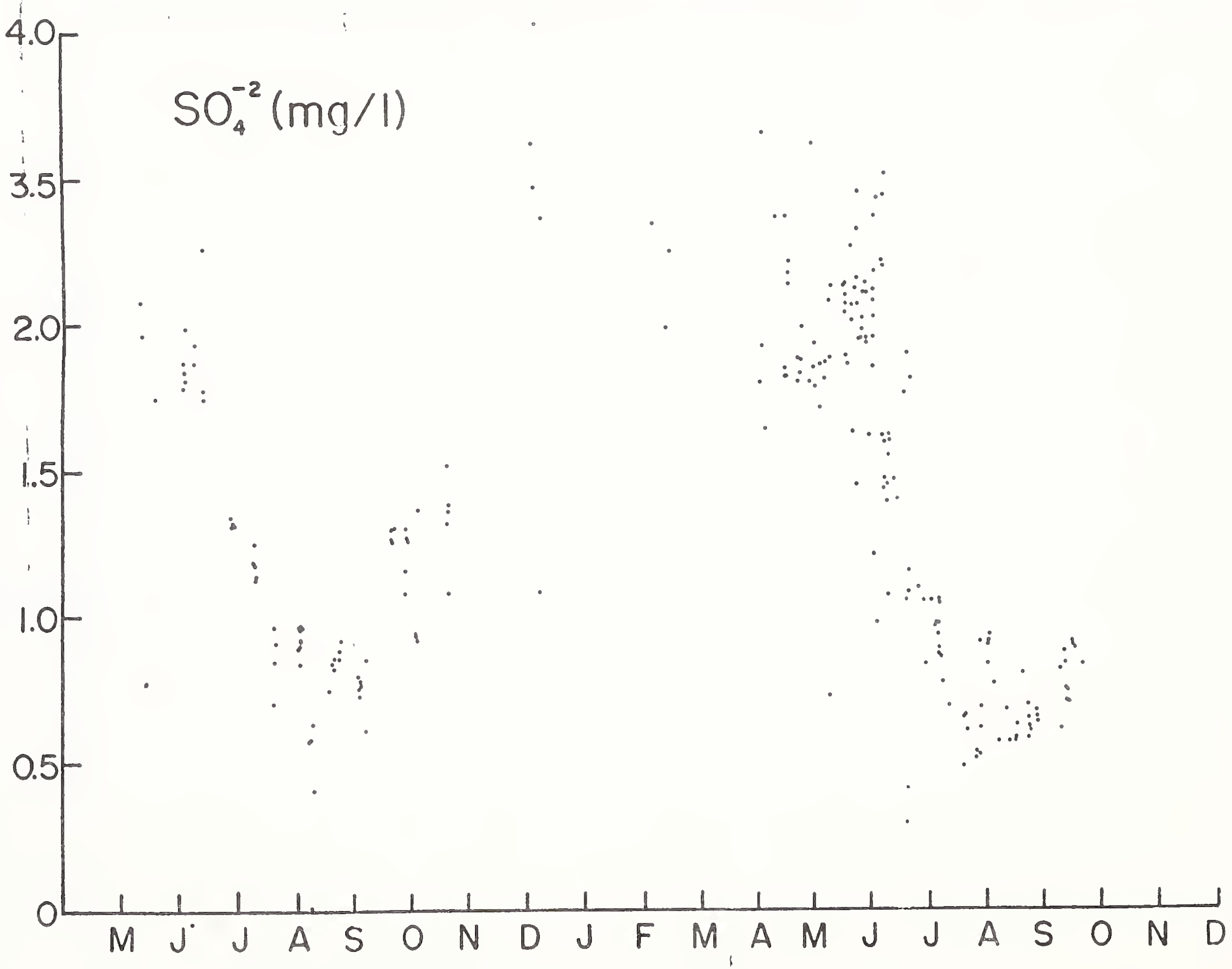

Figure 11.

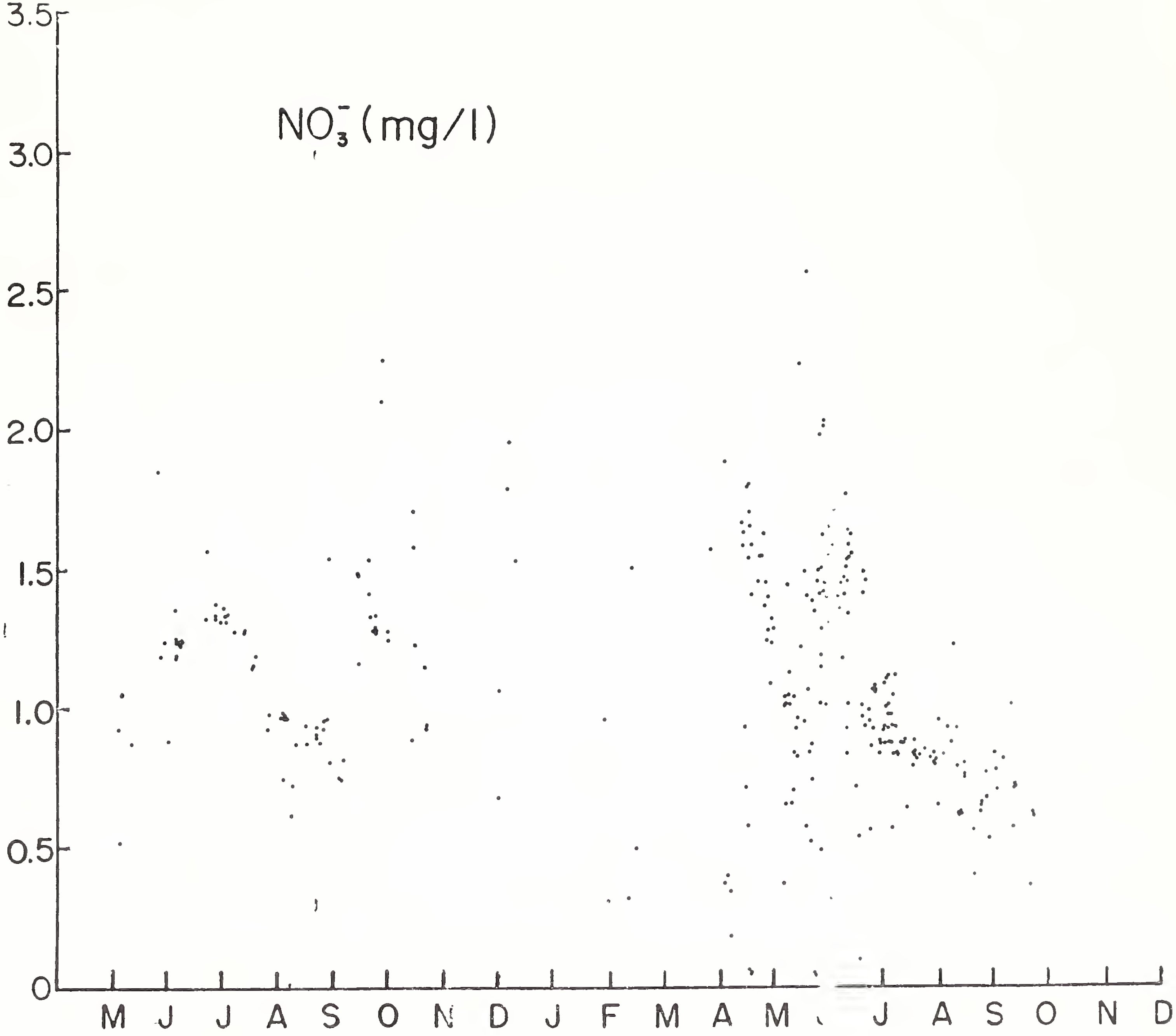

Figure 12.

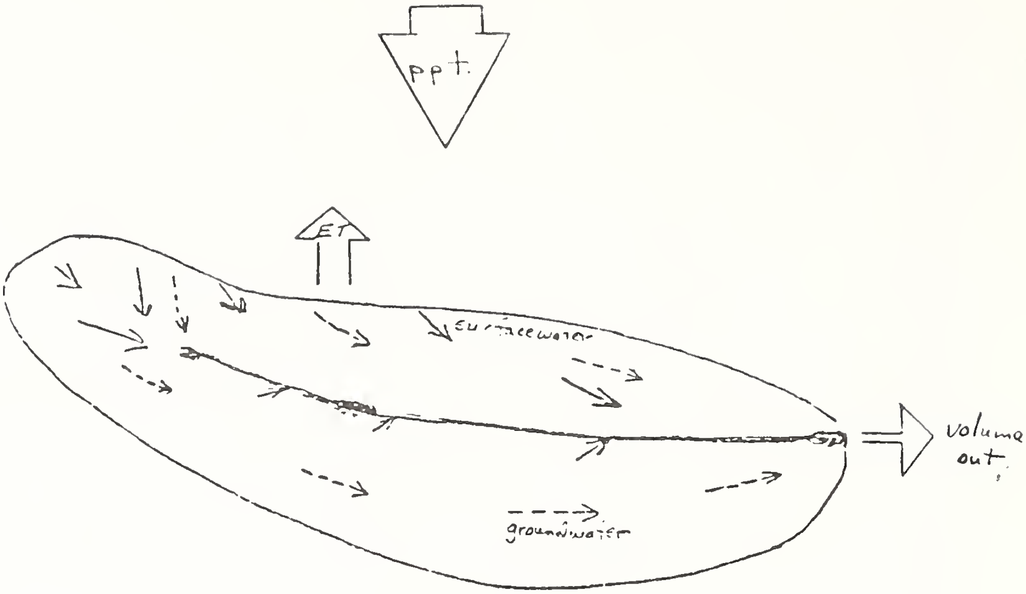

FIGURE 13: Loch Vale basin as a 3-dimensional porous medium with surficial expressions.

By knowing the rates of movement of solutions through Loch Vale drainage, and understanding the biogeochemistry which controls the compartments under study, we will finally be in a position to explain the current processes with the potential of predicting changes due to increased acidic deposition.

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PREDICTION OF LAKE ALKALINITY IN THE ROCKY MOUNTAINS, WESTERN UNITED STATES

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ABSTRACT

Lake alkalinity in the Rocky Mountains, western United States, can be regionalized from a subsample of lakes in basalt or granitic terranes. Preliminary results indicate that lake alkalinity also can be predicted in these terranes. Regionalization is most effective in explaining variance in lake alkalinity if region-specific variables, such as altitude, are used. Prediction of lake alkalinity is most successful if non-region-specific variables, such as rock type and topographic slope, are used. In the Flat Tops Wilderness Area, a basalt mesa in northwestern Colorado, lake altitude explains 76 percent of the variance in alkalinity. A regression of lake alkalinity versus topographic slope, calibrated with data from the Flat Tops, is not significantly different from a regression of data from Grand Mesa in west-central Colorado. Thus, this regression seems to be a useful predictive technique. Rock type explains 70 percent of the variance in alkalinity of lakes in the Mt. Zirkel Wilderness Area, a granitic area in northwestern Colorado. No verification of predictive capability is available at this time.

INTRODUCTION

Concern about the possible effects of energy development in the Overthrust Belt and in other areas in the Rocky Mountains, western United States, has increased the need for information on lake chemistry. This information is necessary for predicting the sensitivity of lakes to acidification and other stresses, and for evaluating any changes in response to these stresses. Many high-altitude lakes in the western United States are sensitive to acidification (Turk and Adams, 1983). Unfortunately, lake chemistry is difficult and expensive to determine in remote, high-altitude lakes. Thus, methods of predicting the chemistry from readily available information are necessary to adequately deal with the large, remote wilderness areas common to the region. The ability to predict the chemistry of areas unaffected by man also is useful in evaluating the magnitude of change that has occurred in areas that are presently effected but that have a minimal historical data base.

PURPOSE AND SCOPE

This report presents the results of recent attempts at regionalization of lake alkalinity. Some attempts have been successful in explaining much of the variance in lake alkalinity within specific areas. Other attempts, while less successful as measured by the degree of variance explained, seem to have broader application and may be a useful beginning in developing a mechanism-based understanding of controls on lake chemistry. Most of the approaches we have tried are being presented as an aid in attempts at regionalization by others. Knowledge of both successful and unsuccessful approaches should be useful in saving time and effort as new data are acquired.

Although understanding of the mechanisms controlling the hydraulics and chemistry of watersheds is the ultimate goal of this work, there is a need for the statistically based approaches presented here. Many high-altitude lakes are located in designated wilderness areas. Access to these areas is restricted to non-mechanized means and instrumentation generally may not be installed nor the watersheds modified. Thus, direct measurement of controlling processes generally is impossible. Statistical approaches can aid in the development of hypotheses of the relative importance of various controlling processes. These hypotheses then can be evaluated in selected, accessible areas outside designated wilderness areas. The proper selection of such index watersheds, combined with proper evaluation of the statistical approaches should lead to valid extrapolation of index-watershed results to wilderness areas.

BASALT MESAS

The Flat Tops Wilderness Area in northwestern Colorado initially was selected for study because of its close, downwind proximity to oil-shale and coal development in the area. To meet the objectives of the first phase of study, information about the sensitivity of lakes in the area was needed. The wilderness classification of this area made detailed sampling of the area impossible within realistic manpower and funding levels. Thus, samples were collected with the objective of developing predictive relationships by which unmeasured lakes could be assigned various degrees of sensitivity. Equation 1,

$$\text{Alkalinity} = -1.87(\text{Altitude}) + 6524 \quad [n=23], \qquad (1)$$

a linear regression of alkalinity on lake altitude, proved most effective in predicting alkalinity with the least data requirements (Turk and Adams, 1983). In equation 1, alkalinity is in microequivalents per liter and altitude is in meters. Equation 1 is slightly different than that previously reported (Turk and Adams, 1983) because four lakes on the Tertiary siltstones of the Browns Park Formation are omitted here. This regression explained 76 percent of the variance in alkalinity, and also allowed estimation of the sensitivity of the unsampled lakes to acidification.

Because this regression and several others in this report use surrogate variables, such as altitude, for the mechanisms actually controlling lake chemistry they need to be used with caution. Such regression models assume that the surrogate variable covaries with the most important controlling mechanisms and that other potentially important controls, such as rock type, do not vary.

The success of the linear regression of alkalinity versus lake altitude was sufficient to address the immediate needs of the regional study of the Flat Tops Wilderness Area. However, collecting even the few data necessary for this approach was costly and time-consuming. The usefulness of such an approach also is limited to the geographic area in which the data are actually collected. Extrapolation to other areas is difficult to justify, unless controlling processes are similar in both areas.

To evaluate the utility of the results from the Flat Tops study, equivalent data were collected for a geologically related environment--Grand Mesa, located about 100 kilometers south-southwest from the Flat Tops Wilderness Area. The alkalinity versus altitude regression of Grand Mesa data was successful in explaining 45 percent of the variance in alkalinity among 21 lakes (equation 2).

$$\text{Alkalinity} = -1.43(\text{Altitude}) + 4832 \quad [n=21]. \qquad (2)$$

Thus, mechanisms controlling lake alkalinity appear to correlate with altitude in both the Flat Tops and Grand Mesa systems.

To determine whether the actual mechanisms controlling lake alkalinity have the same altitude dependence in both mesa systems the alkalinity versus altitude regressions for each system were compared with one another. An F-test of the regression slopes and intercepts indicated that the slopes were not significantly different (P = 0.10, in this report P is the probability of a greater value of the F statistic); however, the intercepts were significantly different (P = 0.0001). Thus, alkalinity varied with altitude at an equal rate in both systems; although, at any altitude, a smaller value of alkalinity was predicted for Grand Mesa than for the Flat Tops.

The difference in intercept values for the alkalinity versus altitude regressions for the Flat Tops and Grand Mesa decreases the utility of equations 1 and 2, because equations of this type cannot be used to predict the alkalinity in other regions, without having sufficient data to calculate a new intercept. To evaluate whether differences in altitude range between the two regions accounts for the variation in intercept coefficient, the lake-altitude data were subtracted from the average altitude of the mesa environments for both regions. This approach is based on the following conceptual model. Precipitation falling on these mesas falls mostly on the flat-lying mesa tops, because of orographic effects, and because of the large percentage of total mesa area that the tops comprise. Lakes located on the mesa tops receive water primarily from snowpack melt that has had minimal interaction with minerals in the soils and basalt bedrock. Lakes located at altitudes below the mesa tops commonly are on the sides or bottoms of canyons formed by erosion of the original basalt flows. Water in these lakes comes both from precipitation near the lake and from surface and ground water from the mesa tops. The lower the lake altitude is relative to the mesa top the greater is the potential flow path; hence, the greater reaction time with minerals that weather to increase alkalinity. Results of this approach are summarized in equations 3 and 4, where flowpath, in meters, is the lake altitude minus the approximate average altitude of the mesa top in each area, 3,353 meters for the Flat Tops (eq.3) and 3,048 meters for Grand Mesa (eq.4):

$$\text{Alkalinity} = -1.84(\text{Flowpath}) + 258, \text{ and} \qquad (3)$$
$$\text{Alkalinity} = -1.31(\text{Flowpath}) + 474. \qquad (4)$$

The percentage of variance in alkalinity explained by equations 3 and 4 is 75 and 40, respectively. Although the difference in the intercept is decreased by this modification it is still significant (P = 0.0006). A more careful measurement of the altitudes of the mesa tops may make the difference insignificant.

A slightly different conceptual model also was tested. In this model, the topographic relief around a lake is assumed to approximate the ground-water potentiometric gradients. This conceptual model assumes that the effect of fractures on ground-water flow averages out over large distances. Lakes with large gradients above the lake have large potential ground-water inflow and alkalinity, because of the reaction between ground water and minerals. Lakes with large gradients below the lake are assumed to recharge ground water and receive their inflow primarily from snowmelt rather than ground water. Thus, these lakes would be predicted to have small alkalinity values. Lakes located at the bottoms and tops of cliffs would be end-member examples.

Calculation of the topographic variable in this model was done by determining the land-surface altitude at various distances north, south, east, and west of each lake from topographic maps. These values were averaged and subtracted from the lake altitude. Regressions of alkalinity on these topographic variables were compared, by examining the change in the R-square statistic as a function of the distance from the lake at which the land surface was determined. Distances from 500 to 6,000 meters were used. Maximum values of the R-square statistic were obtained for a distance of 2,000 meters. Equations 5 and 6 indicate the relation between alkalinity and Topo2000, the topographic variable at 2,000 meters for the Flat Tops and Grand Mesa, respectively:

$$\text{Alkalinity} = -0.181(\text{Topo2000}) + 326 \quad [n=23], \text{ and} \quad (5)$$

$$\text{Alkalinity} = -0.107(\text{Topo2000}) + 381 \quad [n=21]. \quad (6)$$

Equation 5 explains 57 percent of the variance of alkalinity among Flat Tops lakes, whereas equation 6 explains only 15 percent of the variance of alkalinity among Grand Mesa lakes. However, the equations are not significantly different ($P = 0.10$) in either intercept or slope coefficients. Deletion of one lake (Carp) from the Grand Mesa data increases the degree of variance explained by the regression to 34 percent. The lake has virtually no watershed, which may explain its apparent difference from the other Grand Mesa lakes. Equation 7 expresses the regression for the Grand Mesa data with the one deletion:

$$\text{Alkalinity} = -0.146(\text{Topo2000}) + 389 \quad [n=20]. \quad (7)$$

Equation 7 is not significantly different ($P = 0.10$) from equation 5. Even though equation 7 explains only about one-third of the variance in alkalinity among the Grand Mesa lakes its lack of difference from equation 5 is a very significant finding. Equation 7, developed for Grand Mesa lakes can be considered a verification of equation 5, developed from data for Flat Tops lakes, because it does not differ in slope or intercept. Thus, one could use equation 5 to predict the alkalinity of the Grand Mesa lakes and know both the approximate limits of alkalinity and the relative alkalinities among the lakes.

Various attempts to predict lake alkalinity for the basalt-mesa systems indicate the tradeoffs that are necessary to develop predictive equations for regions outside specific regions used to develop the equations. The ability most accurately to predict lake alkalinity is improved by information that is specific to a particular region or system. The ability to predict alkalinity in other regions is improved by sacrificing some accuracy, that is, using information that is not region-specific.

GRANITIC AREAS

Success with regressions of alkalinity versus lake altitude for basalt-mesa systems indicated that the same approach might be useful in other geologic terranes. A regression of this type explained 55 percent of the variance in alkalinity among 70 lakes sampled in the Mt. Zirkel Wilderness Area during 1983. The regression is expressed by equation 8, with the same units as equation 1 and 2:

$$\text{Alkalinity} = -0.37(\text{Altitude}) + 1247 \quad [n=70]. \quad (8)$$

It is noteworthy that both the intercept and slope of equation 8 are smaller than for the two basalt-mesa systems, even though the altitude range sampled is similar in the granitic and basalt areas. This indicates that the weathering processes responsible for producing alkalinity are much smaller in magnitude in granitic terranes than in basalt terranes. Granitic systems have a large proportion of their mineralogy dominated by relatively inert minerals, such as quartz and orthoclase feldspar. Other controls, such as rock-surface area exposed to weathering per unit area of watershed, are difficult to quantify without detailed investigation within the specified terranes. Because equations 1,2, and 8 contain lake altitude as the independent variable, a variable that seems to be region-specific, they are only valid for the specific regions in which the samples were collected. Their use in other regions might be justified, if the unsampled areas were similar in altitude and other important characteristics to those described here. Such characteristics would include slope, climate, soil development, mineralogy, and ground water-surface water relationship. For example, basalt mesas or granitic areas with maximum altitudes much lower than the altitudes for the areas reported here, probably have smaller alkalinity values at any altitude, than would be predicted from equations 1, 2 and 8. This is because the water-rock interactions that produce alkalinity would only be beginning in the headwaters of such low-altitude areas at altitudes far down the likely flowpaths in the Flat Tops, Grand Mesa, and Mt. Zirkel wilderness areas. Similarly, equations 1, 2, and 8 predict negative-alkalinity values (net strong acidity) at altitudes above about 3,500 meters. This is an unlikely occurrence in lakes controlled by natural weathering processes.

In the basalt-mesa systems, extrusive basalt covers most other rock types; thus, rock type is constant. However, in the Mt. Zirkel Wilderness Area, variations in surficial geology are common. A test of differences in the mean alkalinity among lakes, grouped by principal rock type, was performed. Rock type was determined from Snyder (1980a,b). Rock type (exclusive of altitude) is very significant in predicting alkalinity, accounting for 70 percent of the alkalinity variance. Lakes with large alkalinity values most commonly have Quaternary till and terrace gravel deposits as the dominant mapped geology. Lakes with small alkalinity values have large areas of Precambrian crystalline rocks as the dominant mapped geology, typically felsic gneiss or quartz monzonites. Because of the large degree of variance in alkalinity explained by most-common rock type as an independent variable, no attempt has been made to refine predictive ability by using percentages of each mapped rock type present. Adding this and other variables, such as hydrologic variables, could further improve predictive ability.

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The Acid Deposition Potential for the Streams and Lakes of the Wind River Mountains

INTRODUCTION

In this paper an attempt will be made to draw together information given in other reports at this workshop and address three basic questions:

1. How sensitive are the lakes and streams in the Wind River Mountains to acid deposition?

2. Has acidification of these streams and lakes taken place?

3. Can we develop a predictive capability which would allow us to evaluate the effects of increased levels of acid deposition?

As will be demonstrated, we cannot at this time present conclusive results to any of these questions, although the information is more persuasive in dealing with the overall sensitivity of the lake systems. Questions 1 and 2 are so closely interrelated that they will be combined for analysis in the section to follow.

SENSITIVITY AND POTENTIAL ACIDIFICATION

Previous Studies

Most acid deposition investigations make comparisions with historical measurements of lake pH and alkalinity levels where available. For the Wind River Mountains there are two sets of investigations which have taken place in the past of comparative value. One by Simon (1) was conducted in the mid 1930's and reported pH and alkalinity measurements of several lakes and streams in the Upper Green River drainage. A few of the lakes were within the Bridger Wilderness. As this study only recently came to light, we have not yet had an opportunity to make repeat measurements, nor discover what instrumentation was used then. The pH measurements generally are in the mid-to-high pH 6-7 range and at first glance do not appear to differ significantly from pH measurements taken as part of this investigation. For the 3 lakes measured in Simon's investigation (for which we have 1983 measurements of alkalinity), the comparison shows the 1983 alkalinities to be approximately one-half of those in 1935 for two of the lakes. The other lake shows the alkalinity value to be essentially the same. Since the methyl orange method was used in 1935, as compared to Gran titration in 1983, the results are not directly comparable. We have found methyl orange determinations in a later investigation, to be discussed next, to overestimate alkalinity by 100% or more in many instances. This observation, coupled with the fact that the 1935 and 1983 measurements were taken at different times of the year, leads us to discount any interpretation of the Simon's results at this time. We plan to explore this 1935 study more thoroughly in the future, attempting to duplicate the measurements as closely as possible, both as to technique and time of year.

The next study in the Wind River Mountains we can reference was a joint Forest Service-Wyoming Department of Game and Fish lakes survey made between 1969 and 1975 in the Bridger Wilderness (2). Using Hach field measurement techniques,

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a total of 231 lakes received pH and alkalinity measurements along with bathymetric, zooplankton, and fish sampling. Again the pH measurements do not appear to vary from our 1983 measurements. The alkalinity measurements suffer from the limitation discussed earlier. Each drop of titrant in the methyl orange field method is equivalent to 112 ueq/l alkalinity. As a result, the lakes in this 1975 survey are bracketed in classes below 112, 225, 337, ueq/l, etc. In most instances where comparisons between 1975 and 1983 alkalinities could be made, the 1983 values were considerably lower. One main reason for the difference lies in the insensitivity of the 1975 method. Therefore, despite the availability of earlier pH and alkalinity measurements, we cannot at this time come to any definite conclusion about the acidity trend of the lakes.

Analysis of Alkalinity Regime

In the first place it might be instructive to look at the current acid deposition rate as presented by Stuart in the workshop to establish a perspective. Taking only the chemical analyses from the Elkhart snowpack and the Half Moon NADP site, the annual deposition of the major cations and anions is as shown in Table 1.

Table 1. Annual Deposition (1982-1983) of Major Cations and Anions

	Deposition Rate
Ion	meq/m^2
H^+	10.78
Na^+	1.29
K^+	4.66
Mg^{+2}	1.97
Ca^{+2}	6.97
Cl^-	0.96
NO_3^-	2.35
SO_4^{-2}	7.11

When the results from Table 1 are extrapolated to the Wilderness lakes to account for the orographic effect of increasing precipitation, the hydrogen ion deposition rate becomes 30.6 $meq/m^2/yr$. This rate can be compared to a recent study in Rocky Mountain National Park (3), which on page 62 shows a comparison between Rocky Mountain National Park at 3.0 meq/m^2 and Hubbard Brook, New Hampshire. 71.1 meq/m^2 for 1982 data. It should be kept in mind that our deposition data is for a different time period. These deposition rates equate to pH 4.62 for our area and 5.07 for Rocky Mountain National Park. Nonetheless, if the year-to-year deposition rates remained relatively constant, then the Wind River Mountains would appear to be experiencing considerably higher rates of acid deposition than Rocky Mountain National Park. Additionally, the deposition rate calculated for our area does not attempt to account for dry deposition in the non-winter season (it is assumed the snowpack acts as a bulk collector, containing both wet and dry deposition).

The next step is to examine the alkalinity results from this past year. Nearly 100 lakes in the Wind River Mountains were analyzed for alkalinity, using the Gran titration method. The lakes in the Bridger Wilderness west of the Continental Divide, ranging in elevation from just over 3,000 to 3,200 meters, averaged 90 ueq/l alkalinity. To the east of the Continental Divide in the Fitzpatrick Wilderness and Popo Agie Primitive Area, at elevations from 3,100 to 3,700 meters, the lakes averaged 60 ueq/l. It is likely the difference on either side of the Divide can be explained by the higher elevations to the east. This finding would agree with Turk's results in the Flat Top Wilderness, Colorado (4). It is commonly recognized that areas in which surface waters have less than 200 ueq/l alkalinity are sensitive to acid deposition (5). By this classification, well over half of the 2,000 lakes in the Bridger and Fitzpatrick Wildernesses are highly sensitive.

Another popular analysis is to plot lakes data on the Henriksen nomograph (6). Our four monitor lakes are plotted on this nomograph in Figure 1. All the lakes are in the bicarbonate category, using this approach, but as can be seen, a shift toward decreasing pH, could bring two of the lakes easily into the transitional category. It is quite likely that some of our lakes with measured alkalinities below 30 ueq/l are already in this transitional category. Henriksen also has provided an approximate method of estimating to what degree acidification may have occurred by relating alkalinity and calcium concentrations (7). The expected alkalinity, EA, can be calculated as follows:

$$EA = 1.42\ (Ca\ ueq/l) - 32$$

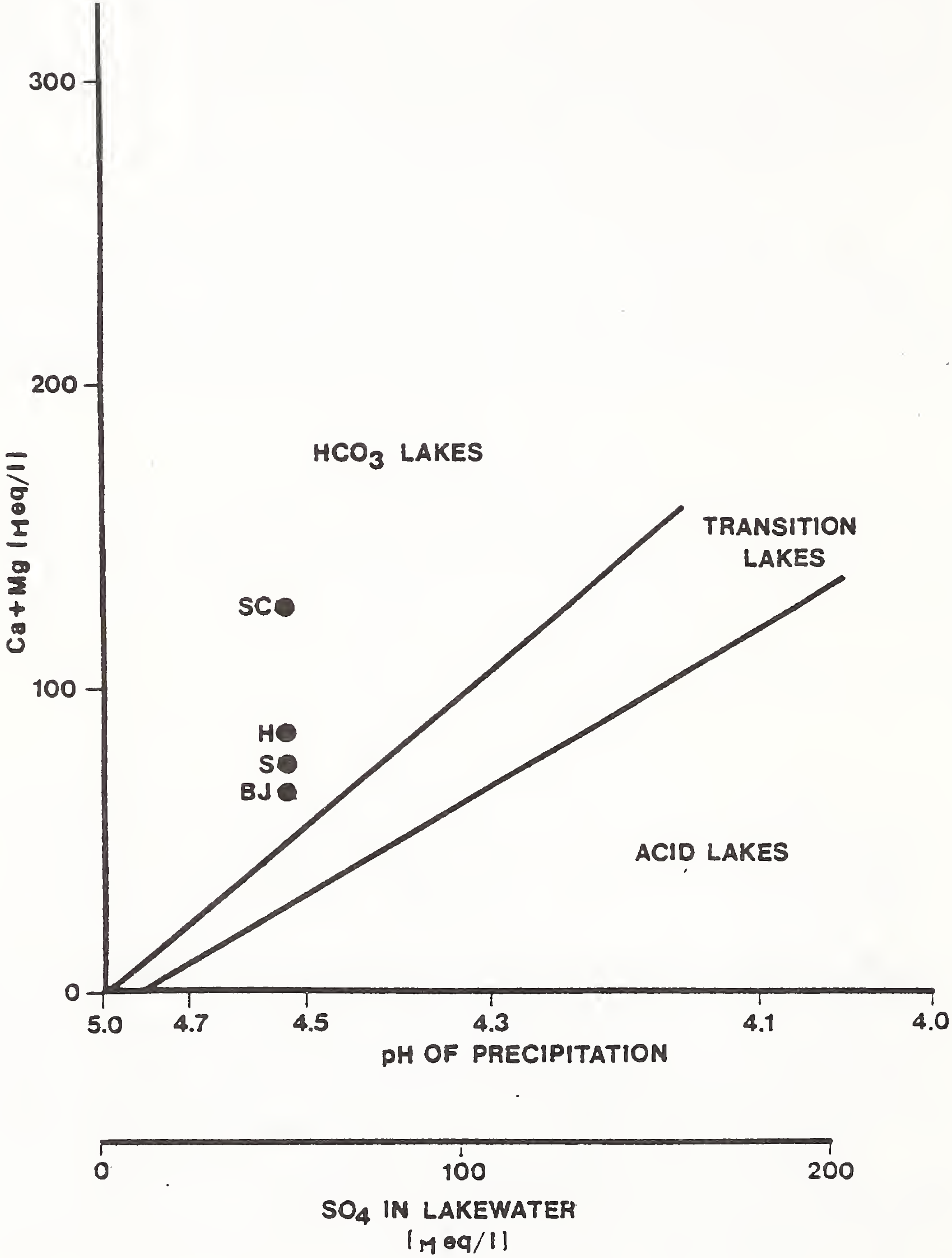
The measured alkalinity can be compared to the calculated, and a measured value lower than the calculated may be due to acidification. This simple approach was applied to all four monitor lakes, with the result in all instances the measured alkalinities were higher than the calculated, as shown in Table 2.

Table 2. Comparison of Calculated Vs. Measured Alkalinities, Based Upon Henriksen's Equation.

	ueq/l	
Lake	Calculated	Measured
Black Joe	52	66
Seneca	48	69
Hobbs	66	80
Section Corner	103	125

Another indication of acidification is the balancing of Ca and Mg outflow from a watershed by the retention of H$^+$ within the watersheds (8). Lacking annual budget data, a comparison was made between the snowpack chemistry prior to melt and the epilimnion chemistry after the melt. The thought is that the epilimnion waters should be strongly dominated by the snowpack so that Ca concentration would be expected to be similar if no significant leaching of Ca within the watershed took place. Any excess leaching of Ca could be attributed to exchange with H$^+$. The Ca concentration of the epilimnion water of Hobbs Lake is 60 ueq/l in late spring; whereas the nearby snowcourse at Elkhart had a Ca concentration of 14 ueq/l. There are admittedly other factors than acidification which could explain this difference, and as reported by Wright and Johannessen, (9), this difference may be anticipated in waters with higher pH levels. So for the present, this finding is, at best, suggestive, awaiting more careful mass balance analysis.

Fig. 1. HENRIKSEN NOMOGRAPH



Indicators of Acidification

A further indirect assessment of acidification potential has been made by comparing the annual deposition of sulphate to other regions. There is a lack of agreement as to what constitutes a threshold level. One source (10) reports 20 Kg/HA/yr. below which acidification is unlikely. Another (11) states any deposition above 5 Kg/HA/yr. as likely to lead to long-term acidification. Extrapolating the results for sulphate from Table 1 gives an annual rate of 9.1 Kg/HA/yr. for the Bridger Wilderness - again not conclusive, but enough to dispell complacency on the subject.

Finally, one study (9) has suggested an annual precipitation pH of 4.7 is a threshold for granitic watersheds. Values lower than this threshold may result in increased acidity. As was reported earlier, the average weighted annual pH of wet deposition for the Bridger Wilderness was found to be pH 4.62.

To help assess the present acidification status of lakes and streams within the Wind River Mountains, there are two approaches which have considerable promise. The first is to employ the lakebed sediment core technique (12, 13). Both the community structure of the diatom populations and the metals analysis of the core sample can be used to detect historic shifts in the pH regime of lakes. In cooperation with the National Park Service Water Research group and the University of Maine, we plan to obtain such core analyses of our own monitor lakes next summer. We are particularly interested in the post-World War II history, coinciding within the industrial development in southwestern Wyoming.

Another intriguing possibility involves the examination of the otolith structures in trout taken from lake waters in the Wind River Mountains. As reported by Hultenberg (14) and shown in Figure 2 taken from his article, these otolith structures can give visible signs of exposure to acid waters during the annual and life cycle of the fish. Apparently $CaCO_3$ is not deposited on the otolith during acid water periods leaving an identifiable trace. We plan to follow up this unusual finding in future work. Otolith examination could be an important early warning sign of acid pulses during snowmelt periods.

PREDICTING CHANGES IN LAKE ACIDITY

In this section of the paper we will examine our ability to predict changes in the acidity of the hydrologic system based upon our current information. The Forest Service is required by the Clean Air Act to evaluate effects upon air quality-related values (AQRV), such as the lakes in the Bridger and Fitzpatrick Wildernesses. Should adverse effects be determined, the Clean Air Act requires the Forest Service to take action to protect the AQRV. In order to carry out this legislative mandate the Forest Service must be able to predict changes in advance of any industrial development whose air emissions pose a hazard to AQRV. In dealing with the potential of acid depostion, then, our ability to predict changes in acidity becomes essential.

The map displayed in Figure 3 shows the existing and proposed sources of industrial emissions producing acid precursors in southwestern Wyoming. As

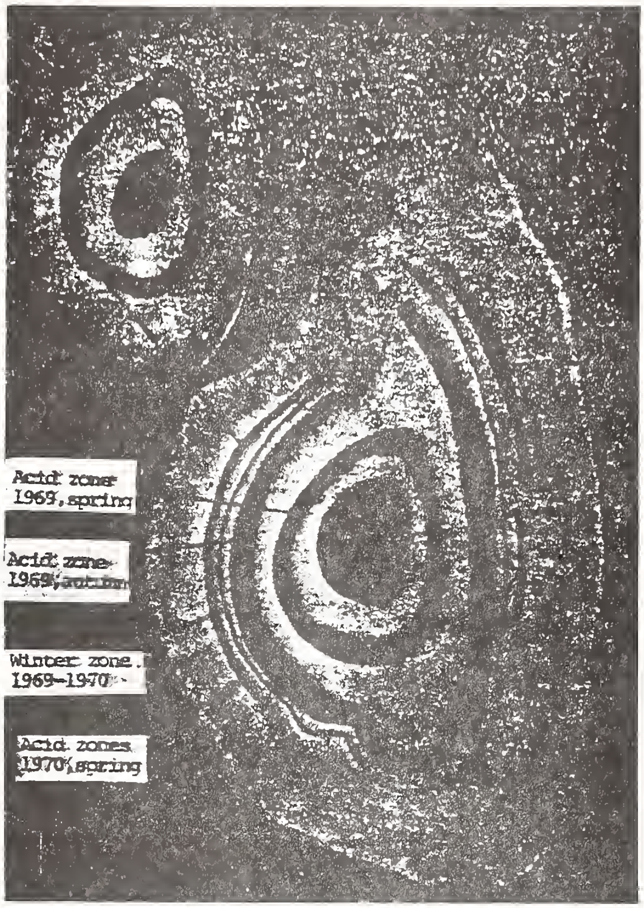


Fig.2.

These biological disorders brought about by thermally stratified acid water in late winter lead to oligotrophication which in turn accelerates the acidification process.

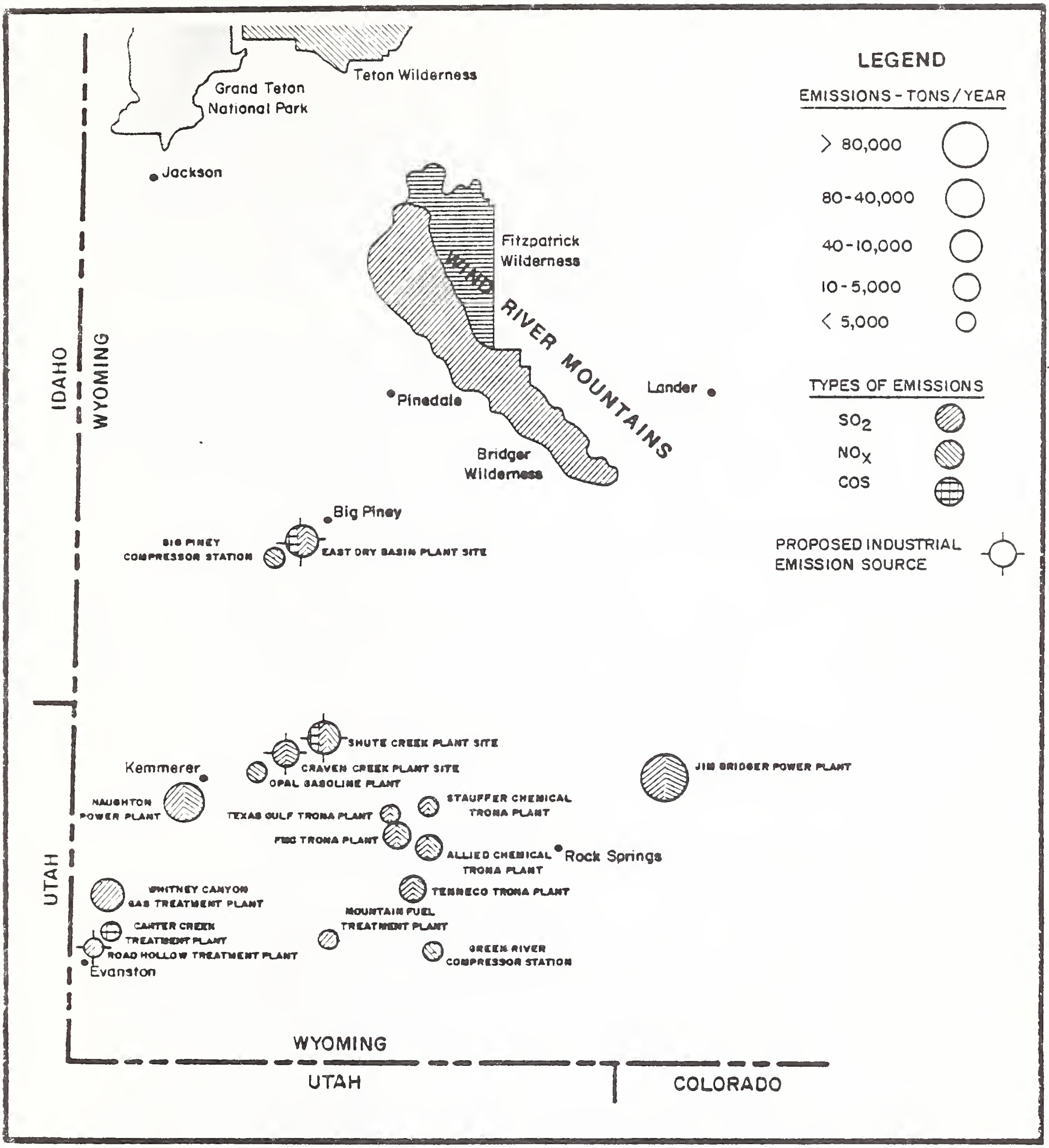


Fig.3. EXISTING AND PROPOSED SOURCES OF ACID PRECURSORS

has been discussed elsewhere in the workshop, the prevailing wind pattern is out of the southwest so that the Bridger and Fitzpatrick Wildernesses are downwind of these sources. It is of more than casual interest to realize that the combined potential emissions of the industrial sources shown in Figure 3 at full output is greater than 150,000 tons/year of SO_2 and NO_x - 42% and 58% respectively (15). The effect of increased emissions by the proposed "sweetening" plants or any unknown future development in this region is now governed by the Clean Air Act and its PSD regulations, discussed previously by Dennis Haddow. Viewed in this perspective, the need to develop a predictive capability becomes readily apparent.

Up to the time of this workshop there have been two initial attempts to predict changes in the acidity of lakes in the Bridger Wilderness; one took place as part of the Environmental Impact Statement for the Riley Ridge project; the other as supporting information in the PSD application by EXXON, Incorporated, for the Shute Creek site. In both instances due to the lack of specific and sufficient field measurements a "worst case" type of prediction was attempted. These worst case predictions were based upon several assumptions such as:

1. All SO_2 and NO_x emissions are converted to the acid form.

2. Complete mixing of the lakes by snowmelt water takes place.

3. A lake with the lowest initial alkalinity or pH was chosen for analysis.

4. No buffering capacity is assumed for the watershed, i.e., soil, vegetation, etc.

5. No buffering within the snowpack is assumed.

6. The lake volume and snowpack volume of water are assumed to be equal.

7. Winter and summer conditions, processes, and flowpaths are treated as being the same.

With the possible exceptions of Numbers 3 and 5, none of these assumptions bear much resemblance to the actual hydrologic processes which control the lake chemistry. This being the case, it was decided to explore an improved prediction method. The remainder of this paper will develop the framework for a more realistic prediction, and present a very approximate attempt to predict the change in lake acidity due to the well documented acid pulse effect of snowmelt. Furthermore, the prediction will be based upon field measurements as much as possible.

To begin with the differences between the snowmelt season, the growing season, and the winter season, in terms of hydrology and limnology are large enough to require separate attention. During snowmelt, the flow paths and relative amounts in each are greater than at any other time of year. The rates of flow are obviously the greatest during snowmelt, and therefore the opportunity for buffering enroute to the lake is reduced. Considerably more acid deposition apparently takes place during the growing season, probably due to the higher atmospheric temperatures at that season (16). Our first-year data indicates the deposition of H^+ to be at least three times greater during the growing season than the remainder of the year. Evapotranspiration comes into play during the growing season and regulates the soil water system allowing for longer residence times for water in the soil. Increased soil temperatures provide for greater weathering and production of alkaline species during the growing season. In the mid- to late- fall our lakes experience a major overturn, or mixing, which may carry through the winter season. Gas exchange in the lakes is restricted by ice formation and during the winter the possibility for anoxic conditions to develop is the greatest. All of these seasonal changes may be important in predicting both short-term as well as long-term changes in lake acidity.

The Snowmelt Season

In those areas where the snowpack has been acidified to some degree by atmospheric deposition an abrupt and often dramatic increase in meltwater acidity has been observed (7). Generally this increase in meltwater acidity is transmitted to the headwater lakes, although at a concentration lower than that found in the snowpack (8). This increase in acidity can persist from two to six weeks (18) before dilution takes place from the relatively acid-free remainder of the meltwater. The SNSF Norwegian study reports that 90% of the acid in the snowpack is contained in the first 30% of the melt (8). These features of the snowmelt season are shown on Figure 4, which illustrates a snowmelt hydrograph typical for the Wind River Mountains and the corresponding H^+ hydrograph which could result from an acid snowpack. The graph of H^+ demonstrates the rapid increase in concentration associated with the first meltwaters, which, due to the freezing point depression effect, would be the most highly concentrated. The duration of the low pH period no doubt is governed by the amount of acid deposited in the snowpack and the type of melt season, whether prolonged or shortened by weather conditions.

In order to predict the magnitude and the relative duration of the pH depression, several characteristics which may be watershed specific need to be known. In the discussion to follow, the major factors used to make a prediction for one of our monitor lakes, Black Joe, will be analyzed. In the first place, it is possible to make predictions at differing levels of approximation. For example, in Figure 5 four such predictions are demonstrated. The curve is a titration curve constructed from a Gran titration of Black Joe Lake water. The general shape of the curve indicates that even at a moderately neutral pH of 6.5 the drop in pH can be rather rapid in this low buffered lake - alkalinities ranging from 55-75 ueq/l. Some have suggested a lake is analagous to a titration flask and that the snowmelt in effect titrates the lake water. Applying this approach, a rather absurd value of pH 6.22 was calculated. At the other extreme it has been reported that meltwaters can produce H^+ concentrations 10 times that of the snowpack (8). So by taking the snowpack concentration, in our case, pH 4.96, and assuming that the snowmelt will replace the lake water with virtually no buffering taking place, a prediction of pH 3.96 could be made. The assumption of no buffering enroute to the lake and no exchange between snowmelt and lake water is certainly not born out by the research (19). A slightly more realistic approach is to consider the snowmelt water to replace the lakewater, that is the epilimnion (the subject of stratification will be amplified later). When this is calculated, a pH of 4.53 is obtained. Again the assumption of no buffering is made.

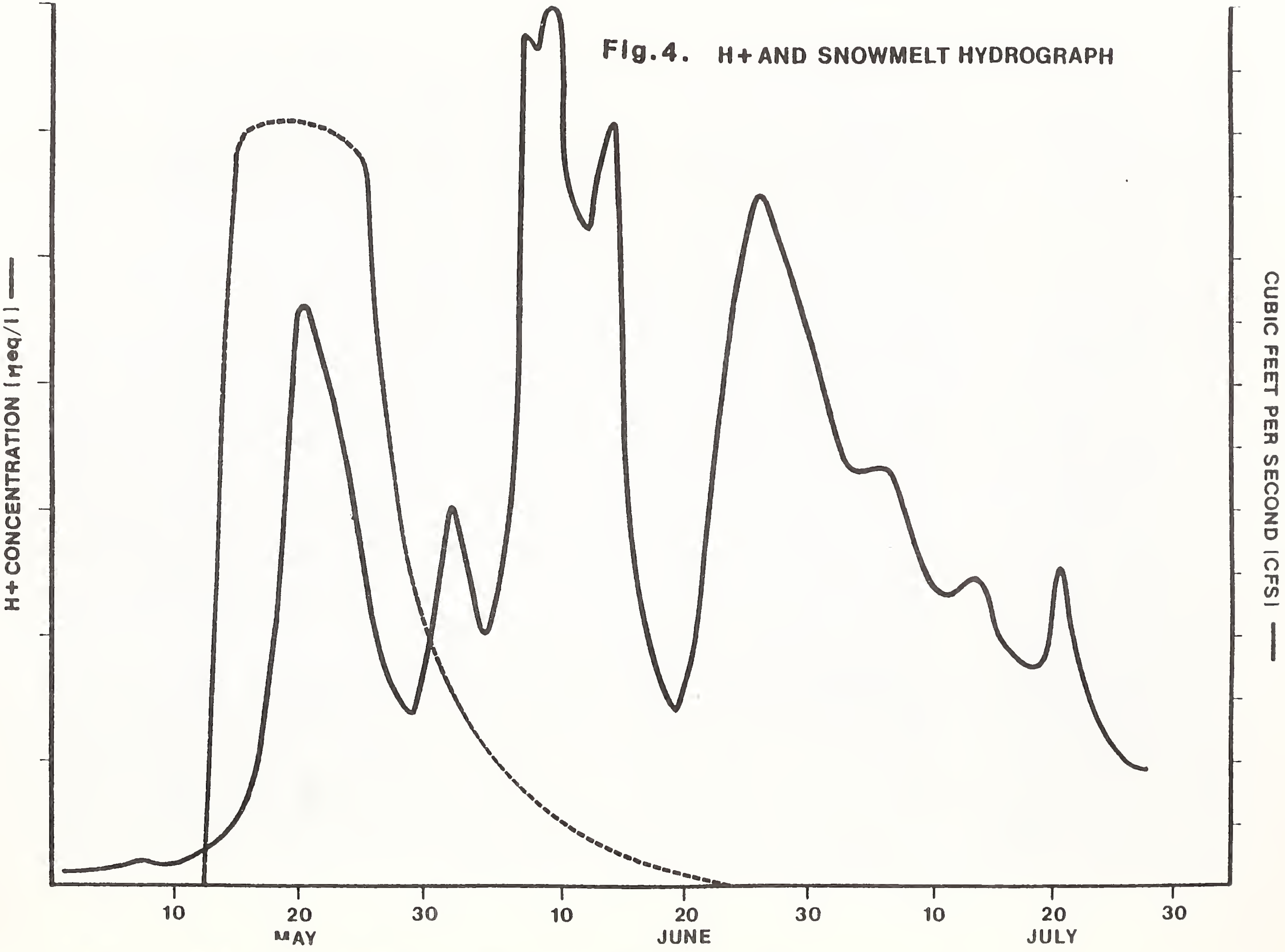
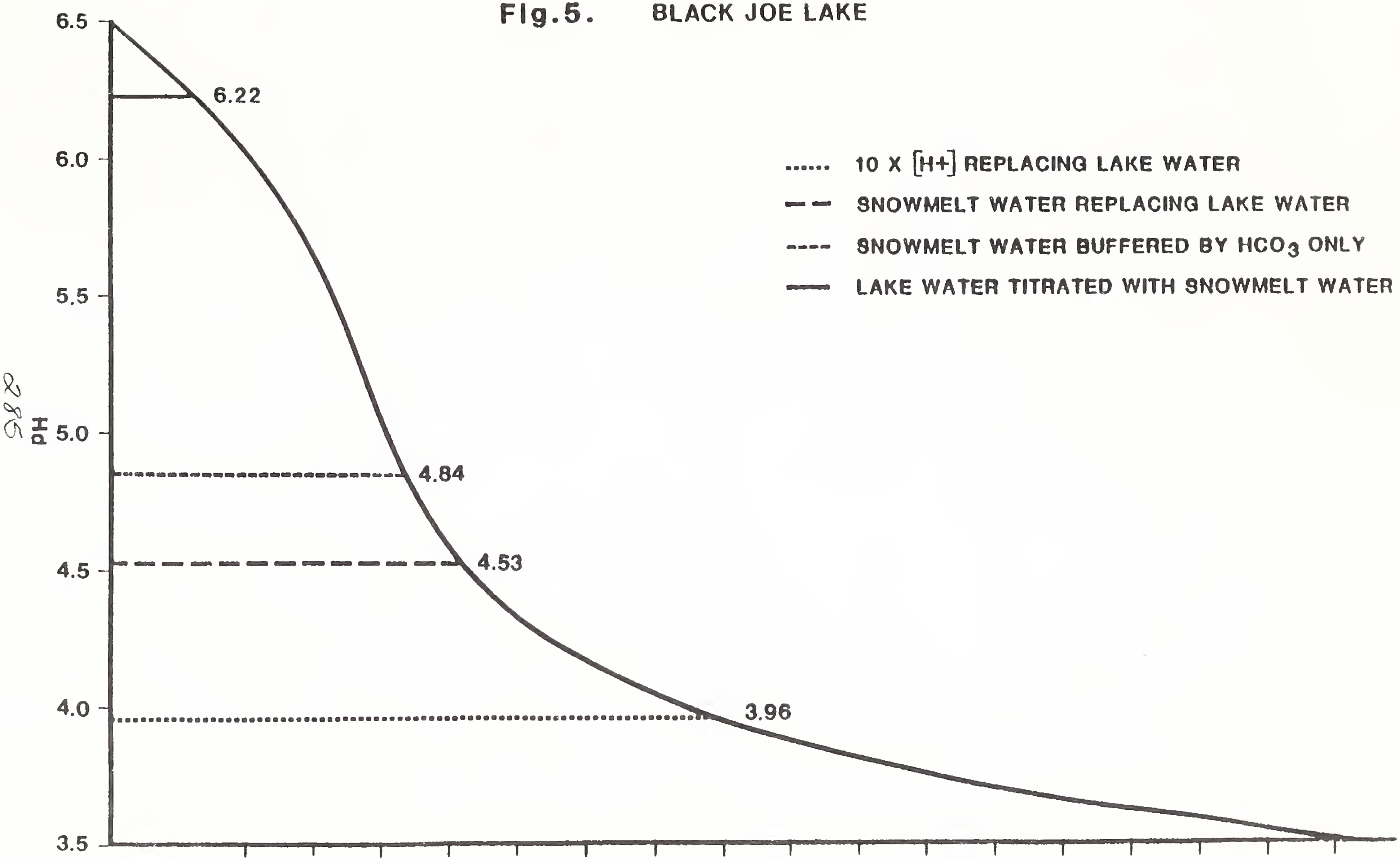


Fig.4. H+ AND SNOWMELT HYDROGRAPH

Fig.5. BLACK JOE LAKE



Another possibility is to assume complete mixing of the pre-melt epilimnion and meltwater, thereby allowing the alkalinity of the epilimnion to neutralize the incoming acid contained in the meltwater. This prediction results in a pH of 4.84 for Black Joe Lake at some time during the early-melt period. No buffering enroute to the lake is assumed. The limited value of these somewhat off-the-wall predictions perhaps is that a range is established. In this instance it would appear highly unlikely that the pH of the lake could fall below pH 3.96, given the pre-melt acidity of the snowpack. Lower snowmelt depressions of pH have been reported, however (20). Likewise, it seems virtually certain that some pH depression will occur and at a value lower than the pH 6.22 of the titration approach. The intermediate predictions of pH 4.52 and 4.84 would suggest that a measured change is likely to be greater than pH 4.53 since the published research invariably shows lakewater pH higher than the precipitation pH, thereby indicating some buffering within the watershed (8).

The question to be answered by a prediction based upon processes operating within the watershed is how much buffering or acid neutralizing capacity, ANC, probably a preferred term, is available. To answer this question it is necessary to look at the possible sites where the meltwater could come in contact with acid neutralizing reactions. The first site would be within the snowpack. There is the possibility of alkaline dust deposition within the snowpack of the Wind River Mountains. The possibility has also been raised that fly ash from the trona plants could supply some acid neutralization capacity, ANC, as well. At any rate, assuming migration of the acid to the lowest level of the snowpack by the onset of melt, the measured snowpack pH in April or May should reflect the end result of any ANC within the snowpack.

Exposure to the surface vegetation or bedrock which outcrops in the watershed is another possible source of ANC. The type of vegetation is important in determining what the effect will be, whether to neutralize or acidify (21). Regardless of vegetation type the ANC is likely to be minimal during the melt season since the vegetation has been buried under snow throughout the winter. What little work that has been done on bare rock surface does not suggest a very significant ANC (8).

The most promising area for ANC appears to be within the soil. The collodial surface within most soils has abundant exchange capacity relative to the amount of annual atmospheric deposition. The critical characteristics of the soil are the pH level and associated base saturation in determining the ANC. A word should also be mentioned here about the possibility of groundwater flow. It is generally believed that little groundwater flow occurs in granitic mountain ranges such as the Wind River Range. If groundwater was found to be an important pathway, then a certain amount of ANC could be expected from this source, depending upon the minerology and geochemistry involved.

It is possible that some ANC could take place during stream flow. Given the low biological activity, high flows, and low water temperature during snowmelt, it seems improbable that much ANC can be expected from this flow path.

Finally, there is the potential for the pre-melt alkalinity of the lake water to be a source of ANC. This could be a sizeable amount of ANC if the total lake volume were available for mixing. This does not appear to be the case, however, since studies conducted elsewhere (14, 22) and results from our work and others in Wind River Mountain lakes strongly suggest that the lake will stratify during the initial phase of melting, due to density differences between the incoming meltwater at 0 -0.5° C and the lake water, closer to 4° C. The stratification is well developed in our monitor lakes shortly after ice-out and persists and intensifies until the fall turnover. For this reason, we are making the assumption that little mixing of the meltwater with lakewater takes place. To be certain, there will be turbulent mixing along a shallow zone between the presumably lower lying lakewater and the overriding meltwater. But it appears reasonable to assume minimal mixing at this stage of our investigation. As this is a critical assumption in any prediction of snowmelt effect upon lake pH, field verification is imperative.

Our prediction of snowmelt effect upon lake pH is based upon these assumptions concerning the site and relative magnitude of ANC as the meltwater passes from the snowpack to the lake. In order to make the prediction it was necessary to subdivide the Black Joe watershed into separate flow paths as different amounts of ANC could be expected, depending upon the flow path. We did not make any allowance for groundwater during the snowmelt. The primary flow paths which were derived from aerial photo examination were as follows in Table 3.

Table 3. Flow paths for Black Joe watershed

Flow Path	%
1. Snow - stream or lake	5
2. Snow - rock - stream or lake	42
3. Snow - soil - rock - stream or lake (the soil - rock order could be reversed)	29
4. Snow - surface vegetation - soil - stream or lake	24

As we did not have sufficient information on the surface vegetation, and as there was so little in the Black Joe watershed, we combined categories 3 and 4. With this combination the distribution of these flow paths on the watershed is as shown under the % column. The amount of ANC in each flow path was derived as follows: For the snow - stream or lake flow path no ANC was assumed and the measured pH of the snowpack in April near the Wilderness boundary was used to calculate the amount of H^+ which would be added to the lake. For the snow - rock - stream or lake a minimal amount of ANC, 1 eq/l was assigned. For the remaining combined flow path, the properties of the watershed soils supplied by Dr. Larry Munn had to be taken into account.

The first calculation involved determining the amount of soil water retained in the soil near saturated conditions which would be expelled at the early stage of snowmelt. This soil water was assumed to have come into chemical equilibrium with the exchange complex in the soil and accordingly was given an H^+ concentration of pH 5.2, measured in the soils of the Black Joe watershed.

Next, the amount of H^+ exchange from the meltwater percolating through the soil was addressed. In the absence of results from soil core studies which will be conducted, and in order to test what the maximum ANC effect might be, it was decided to calculate the H^+ of the meltwater leaving the soil as that of the soil pH, 5.2 again. No adjustment of the soil pH during the exchange process was made. For this prediction the assumption was also made that all the meltwater percolated through the soil.

When these various assumptions were applied, the prediction gave the resulting lake pH as 4.77 by making the additional assumption that the epilimnion would attain the pH of the incoming meltwater from the three principal pathways. This prediction of pH 4.77 can be compared with the earlier prediction of pH 4.53 which did not allow for any soil buffering. By and large, this analysis confirms our suspicion that for most of these high elevation, granitic, alpine lakes, with conifer vegetation being most dominant, soil ANC might be limited. Making the prediction more realistic by allowing one-half of the snowmelt to come off as surface runoff (23) without the opportunity of soil ANC, changes pH to 4.64.

By applying the assumption of replacing the pre-melt epilimnion by snowmelt water, the duration of the pH depression can also be estimated. In the case of assuming that a two-meter zone of mixing with pre-melt epilimnion water by snowmelt water occurs, the duration of the pH depression is calculated at 5 days. Without the mixing assumption, the duration could extend to 25 days.

We have not taken the analysis any farther at this time. A more complete prediction will have to take into account the more complex processes operating during the growing season. An estimate of dry acid deposition from the measurement of wet deposition would be needed for this season. The chlorine method (9) of estimating dry deposition requires a measurement of outflow of chlorine and other constituents from a watershed to compare with measured amounts of atmospheric deposition. Currently outflow measurements throughout the year are not available to us. Another important series of measurements which needs to be made is the over-winter status of the lake chemistry, particularly the ANC. This measurement will shed some light on the annual cycle of ANC and the ability of the watershed to renew ANC.

CONCLUSIONS

From the foregoing it is possible to make the following conclusions:

1. The lakes and streams of the Bridger and Fitzpatric Wildernesses are highly sensitive to acid deposition.

2. If the rate of acid deposition as indicated by snowpack and NADP site pH measurements is borne out by subsequent years' results, the amount of acid deposition being experienced in the Wind River Mountains may be approaching one-half that of the Adirondack Mountain area where acidification of granitic basin lakes has already taken place.

3. The possibility of substantial watershed buffering of acid deposition appears unlikely for the headwater, cirque basin lakes in the Wind River Mountains.

4. Water balance analysis requiring continuous outflow measurements in addition to precipitation, wet and dry, measurements will be needed to determine the present status and future trend of watershed alkalinity or buffering capacity.

5. In the final analysis the possibility of lake acidification in the Wind River Mountains may turn on the combination of atmospheric deposition of alkaline substances plus the geochemical production of alkaline species. When and if the atmospheric deposition of strong acid exceeds these two sources of ANC, then it seems highly likely the lakes will acidify to a level governed primarily by the chemistry of the annual precipitation.

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