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WATER-QUALITY EFFECTS ON BAKER LAKE OF RECENT VOLCANIC ACTIVITY AT MOUNT BAKER, WASHINGTON

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ILLUSTRATIONS

		Following page
FIGURE 1.	Map of Mount Baker and vicinity, showing air-temperature and precipitation-data sites--------	7
2.	Map of Mount Baker and Baker Lake---------------------	(In pocket)
3.	Generalized profile along Boulder Creek valley--------	8
3A.	View into Sherman Crater------------------------------	22
4.	Aerial view of Boulder Creek flowing into Baker Lake--	32
5.	Sketch map of central Baker Lake showing cross-section and station locations for lake survey-------	33
6.	Schematic sections showing overflow, underflow, and interflow in a reservoir------------------------	41
7.	Vertical profiles of temperature, specific conductance, and pH at two locations on Baker Lake-----	41
8.	Graph showing capacities of Baker Lake water to buffer Boulder Creek water-------------------------	48

CONVERSIONS

For use of those readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below:

Multiply English unit	By	To obtain metric unit
ft (feet)	3.048×10^{-1}	m (meters)
mi (miles)	1.609	km (kilometers)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
mi^2 (square miles)	2.590	km^2 (square kilometers)
lb (pounds)	0.4536	kg (kilograms)

ABSTRACT

Increased volcanic activity on Mount Baker, which began in March 1975, represents the greatest known activity of a Cascade Range volcano since eruptions at Lassen Peak, Calif. during 1914-17. Emissions of dust and increased emanations of steam, other gases, and heat from the Sherman Crater area of the mountain focused attention on the possibility of hazardous events, including lava flows, pyroclastic eruptions, avalanches, and mudflows. However, the greatest undesirable natural results that have been observed after one year of the increased activity are an increase in local atmospheric pollution and a decrease in the quality of some local water resources, including Baker Lake.

Baker Lake, a hydropower reservoir behind Upper Baker Dam, supports a valuable fishery resource and also is used for recreation. The lake's feedwater is from Baker River and many smaller streams, some of which, like Boulder Creek, drain parts of Mount Baker. Boulder Creek receives water from Sherman Crater, and its channel is a likely route for avalanches or mudflows that might originate in the crater area.

Boulder Creek drains only about 5 percent of the total drainage area of Baker Lake, but during 1975 carried sizeable but variable loads of acid and dissolved minerals into the lake. Sulfurous gases and the fumarole dust from Sherman Crater are the main sources for these materials, which are brought into upper Boulder Creek by meltwater from the crater. In September 1973, before the increased volcanic activity, Boulder Creek near the lake had a pH of 6.0-6.6; after the increase the pH ranged as low as about 3.5. Most nearby streams had pH values near 7. On April 29, in Boulder Creek the dissolved sulfate concentration was 6 to 29 times greater than in nearby creeks or in Baker River; total iron was 18-53 times greater than in nearby creeks; and other major dissolved constituents generally 2 to 7 times greater than in the other streams.

The short-term effects on Baker Lake of the acidic, mineral-rich inflow depend mainly on: (1) the rate of flow and the character of Boulder Creek water at the time; (2) the relative rate of inflow of the feedwater from other streams; and (3) whether the reservoir is temperature-stratified (summer) or homothermal (winter). A distinct layer of Boulder Creek water was found in the lake in September 1975 extending at least 0.3 miles (.5 km) downreservoir. The greatest opportunity for water from Boulder Creek to persist as a layer and extend farthest before mixing with the other reservoir water is when Baker Lake is strongly stratified and Boulder Creek flow rate is large in relation to other feedwater.

Baker Lake probably could assimilate indefinitely the acid loads measured during 1975, by dilution, chemical neutralization, and buffering of the acid-rich Boulder Creek water. Minor elements found in Boulder Creek water included arsenic, selenium, and mercury; however, none of these would reach the limits recommended by the U.S. Environmental Protection Agency for public water supplies unless their concentrations increased to several times the amounts found during this study. Under the prevailing conditions, acid-rich Boulder Creek water apparently cannot accumulate as a pool, or persist as a layer long enough to reach Upper Baker Dam and attack the concrete. However, even if the acid load from Boulder Creek does not greatly increase, occasional light fish mortalities may result near the mouth of the creek. Greater acid and mineral loads, resulting from further increases in volcanic activity or other possible causes, could be more harmful, especially to the fish. Continued monitoring of Boulder Creek flow and water quality is needed to rapidly detect any changes in conditions at Sherman Crater, and to provide warning of possible greater impacts on Baker Lake from any future increases in Mount Baker activity.

INTRODUCTION

On March 10, 1975, volcanic activity on Mount Baker increased dramatically in the form of new or greater emanations of heat, steam and other gases, and dust from an area of fumaroles (vapor vents) high on the mountain. The increased volcanic activity has stimulated great interest and considerable scientific data collection, partly because it affords the first opportunity to observe the heating up of a Cascade Range volcano since eruptions at Lassen Peak, Calif. during 1914-17. Also, because Mount Baker is in the northeastern part of the populous Puget Sound region, the increased volcanic activity has raised much concern and serious questions about hazards to people in the vicinity, adjacent forest and recreation lands, and some of the water resources. The possibilities of hazardous events, including lava flows, pyroclastic (hot explosive) eruptions, avalanches and mudflows--all characteristic of this and similar volcanos--were judged to have increased with the recent heat buildup of Mount Baker. Consequently, some areas on and near the mountain were closed to public access in the spring of 1975. However, by the end of one year of the increased volcanic activity, there were no further indications that an eruption or other catastrophic event was imminent. The greatest undesirable natural results of the increased activity that have been observed during the year are an increase in local atmospheric pollution and a decrease in the quality of some local water resources, including Baker Lake, the subject of this report.

The purpose of this report is to evaluate and describe relationships between the volcanic activity on Mount Baker and the possible impacts on Baker Lake water. Specifically, the report aims to:

1. Present background information on historical and recent events that are known to affect the surface waters draining to Baker Lake or have the potential to do so;
2. Summarize the studies made to date by the U.S. Geological Survey and others that relate to water quality in Baker Lake;
3. Provide a preliminary interpretation~~, based on the data now available,~~ of water-quality changes and possible impacts on Baker Lake;
4. Point out data needs for evaluating any future impact on local water resources; and
5. Provide answers (in part, provisional) to questions raised about water-quality impacts in relation to management of the water and water-related resources.

The senior author participated in the study in cooperation with the Washington Department of Ecology. Valuable data were contributed by that agency, the U.S. Forest Service, University of Washington, Puget Sound Power and Light Company, and Washington Departments of Game and Fisheries.

THE LAKE AND THE MOUNTAIN

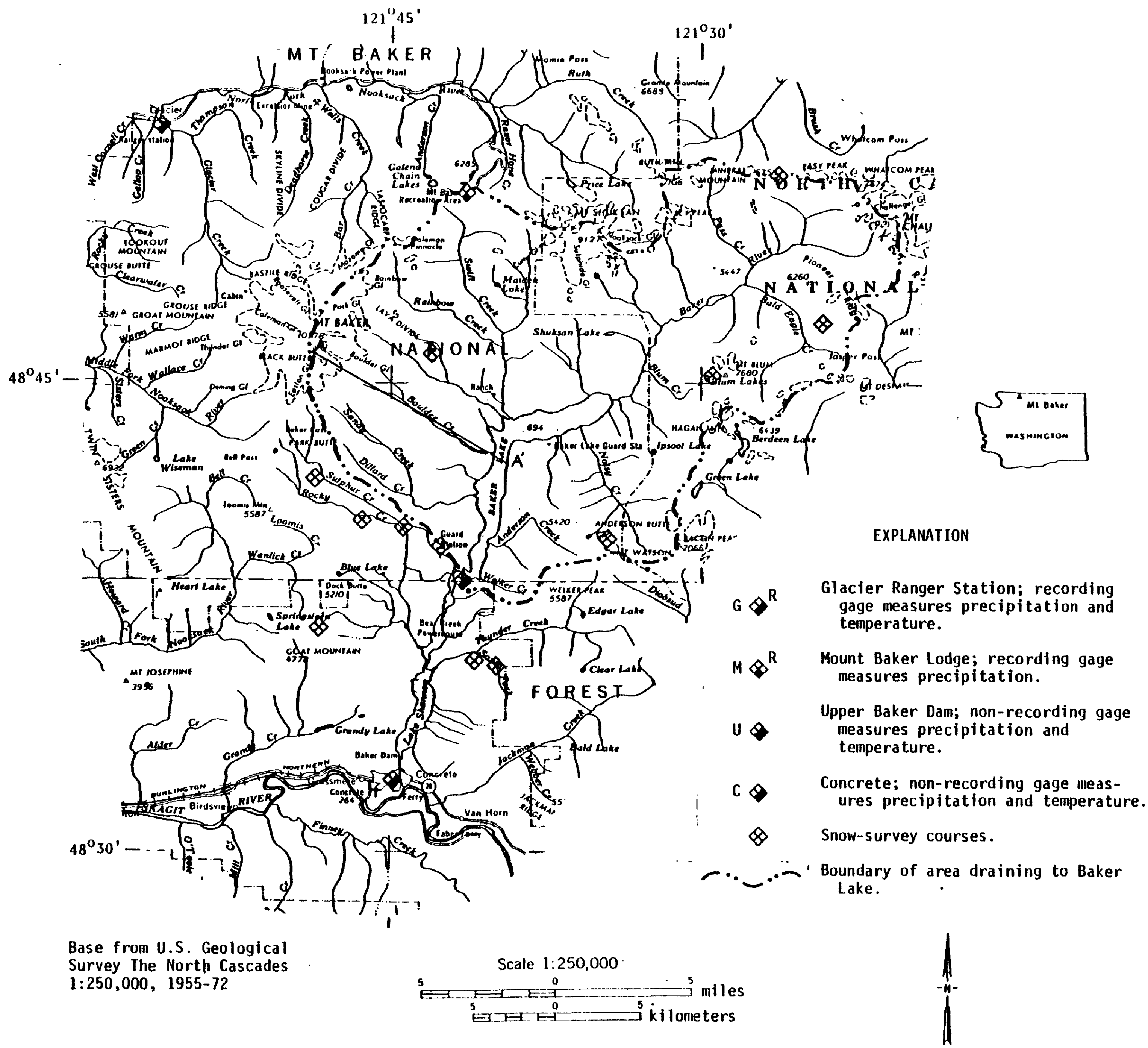
Baker Lake

Baker Lake is a man-enlarged reservoir at the southeastern base of Mount Baker (figs. 1 and 2). The lake is impounded by Upper Baker Dam, located 8 miles (13 kilometers) north of the town of Concrete (fig. 1), at river-mile 9.3 (Km 15) on Baker River. The completion in 1959 of this concrete gravity dam formed Baker Lake, which is operated by Puget Sound Power and Light Company for hydroelectric power generation. The usable storage is 220,000 acre-feet (270 cubic hectometers) between surface altitudes of 724 feet (221 meters) normal full pool and 655 feet (200 m) minimum operating pool . The dead storage in the basin behind the dam is about 65,000 acre-feet (80 hm^3). Filling the reservoir inundated about 8 miles (13 km) of the Baker River as well as the former Baker Lake (1.4 mi, or 2.2 km, long), the old shoreline of which is approximated by the 70-foot (21 m) depth contour on figure 2. The water level in the reservoir may fluctuate 20 to 45 feet (6 to 14 m) during a normal annual operating cycle.

The lake has a drainage area of about 215 square miles (557 km^2). The east shore of the lake borders the previous Baker River channel and drops steeply to the lake surface. The west shore is moderately sloping land formed in part by alluvial fan deposits from tributary streams and by past mudflows originating from the flanks of Mount Baker. The lake is surrounded mostly by National Forest land.

Baker Lake combines a high value as a resource and a high degree of susceptibility to damage from events originating on Mount Baker. Besides its main role in energy generation, the lake is an important recreational resource; several campgrounds and boat-launch sites are located on the west shore. The lake also sustains a valuable fisheries resource as part of the Baker River drainage, which is tributary to the Skagit River (fig. 1).

The main link between Mount Baker volcanic activity and Baker Lake is the channel and valley of Boulder Creek. Several streams that enter the lake drain parts of Mount Baker, but Boulder Creek drains the part of the mountain exhibiting the increased volcanic activity. A generalized profile of the Boulder Creek valley from Sherman Crater on Mount Baker to Baker Lake is shown in figure 3. The stream, where measured (fig. 2) drains an area of 10.7 square miles (27.7 km^2). It heads at Boulder Glacier and receives flow from several smaller streams coming from Boulder Glacier and Talum Glacier (fig. 2). From Sherman Crater, the profile declines steeply for about the first 4 miles (6.4 km), at an average gradient of about 1880 feet per mile (360 m/km). For the remaining 4 miles to the lake the boulder-studded, braided channel of Boulder Creek drops less steeply, at an average gradient of about 320 feet per mile (60 m/km).



Base from U.S. Geological
Survey The North Cascades
1:250,000, 1955-72

Figure 1.--Map of Mount Baker and vicinity, showing sites for collection of air-temperature and precipitation data.

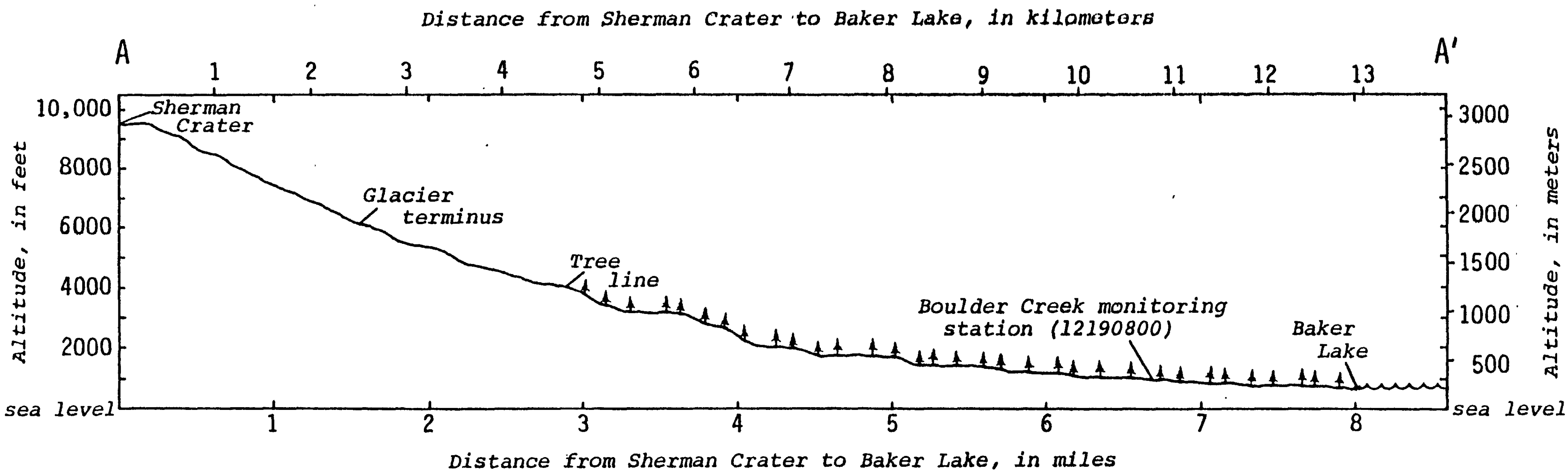


Figure 3.--Generalized profile along Boulder Creek valley (line of profile, A-A', shown in fig. 1).

The Boulder Creek channel would be a likely route for any flood, mudflow or avalanche that might be generated on Mount Baker in association with the increased volcanic activity. If large enough, these movements of water and debris would enter Baker Lake and disturb it by varying degrees depending on the type and amount of material entering the lake and the speed at which it entered. Even at present, without the catastrophic events mentioned above, Boulder Creek is exerting an influence on Baker Lake by bringing unusual quantities of acid- and mineral-rich water into the lake (see beyond).

Mount Baker

Mount Baker is the northernmost of several relatively young volcanos in the Cascade Range of Washington, Oregon, and northern California. Its summit is 10,775 feet (3,284 m) above sea level and about 10,050 feet (3060 m) above adjacent Baker Lake. The mountain is about 16 miles (26 km) south of the Canadian border and well west of the Cascade crest, being only about 32 miles (51 km) east of the salt-water shoreline at the city of Bellingham (not shown). The upper part of the mountain is almost completely covered by glaciers which flow radially from the rounded summit (fig. 2).

Volcanic activity and related hazardous events have been common in the history of Mount Baker, but not during the past several decades. A geologic study by Hyde and Crandell (1975, p. 1) revealed that:

> "Eruptions and other geologic processes at Mount Baker during the last 10,000 years have repeatedly affected adjacent areas, and especially the valleys that head at the volcano.***mudflows from the volcano were caused by massive avalanches of volcanic rock that had been partly altered to clay by steam and other gases.***Small amounts of tephra (airborne rock debris) have been erupted at least four times during the last 10,000 years. ***Eruptions which caused pyroclastic flows (flows of hot rock debris) evidently occurred during only one period***"

From investigation of historical reports, Malone and Frank (1975, p. 680) judged that:

> "***eruptions may have occurred in the 1840's and 1850's but definitely have not occurred in the 20th century."

The emanations beginning in March 1975 probably represent the greatest increase in the mountain's volcanic activity since the turn of the century, at least, and the records also indicate that the discharge of steam and other gases from two fumarole fields have been prevalent throughout the written history of the mountain.

The recent increased volcanic activity is centered at one of these fields, in Sherman Crater, a prominent crater partly filled by a small glacier. The basin of Sherman Crater is nearly 1300 feet (390 m) lower than, and about 2500 feet (760 m) south of, Mount Baker's summit. The east rim of the crater, above the top of Boulder Glacier, has a notch more than 500 feet (150 m) deep, referred to as the east breach. Prior to the increased volcanic activity, the conditions at Sherman Crater were described by Frank and others (1975, p. 83) as follows:

> "A stream fed by snow and ice melt water and thermal springs issues from the crater glacier, flows across the fumarole area, and disappears beneath the avalanche deposit in the east breach. The most impressive feature here is a roaring fumarole on the streambank which forcefully ejects vapor and water 1-10 metres from sulfur-encrusted crevices a few centimetres in diameter in a rock outcrop. Warm ground, boiling pools, and numerous smaller fumaroles cover the remaining area. Small fumaroles also perforate the margins of the avalanche deposit in the east breach***"

The stream referred to is one that flows beneath Boulder Glacier, and contributes to the water in upper Boulder Creek.

PREVIOUS STUDIES AND SOURCES OF DATA

Prior to the increased volcanic activity there had been only a few studies that yielded information directly related to the present investigation. After the increase in activity, several other studies were begun. In addition to the more pertinent earlier studies, described briefly below, basic hydrologic data have been collected at sites shown on figures 1 and 2, including:

(1) Measurements of precipitation or other meterological observations at Glacier Ranger Station, Mount Baker Lodge, Upper Baker Dam, and twelve snow courses (mountain sites for snow measurements), seven of which are located within the Baker Lake drainage basin (all stations continuing at present; see fig. 1). Automatic sensing devices and radiotelemetry equipment broadcast data from four snow courses (Easy Pass, Jasper Pass, Schreibers Meadow, and Marten Lake) including air temperatures, snow-water content, and (at Schreibers Meadow) cumulative water content in a storage-type precipitation gage;

(2) gaging of streamflow in Baker River at Concrete (station 12193500, 1910-15 and 1943-present); Sandy Creek near Concrete (station 12191000, 1953-54); Baker River below Anderson Creek (station 12191500, 1910-25, 1928-31, and 1955-59--site not shown, inundated by Baker Lake); and Sulphur Creek near Concrete (station 12191800, 1963-73);

(3) water-quality sampling and analysis, Baker River at Concrete (station 12193500, 16 measurements during 1961-65); and

(4) recording of the stage of Baker Lake (reservoir) and changes in reservoir volume (station 12191600, 1959-present).

The meteorological data are available in reports by the National Weather Service. The calibration measurements of snow depth and water content are published in a series of seasonal reports by the U.S. Soil Conservation Service (Davis, 1959-76); and the telemetered data are on file at the Tacoma, Wash., office of the Geological Survey. All the other hydrologic and water-quality data are in reports by the U.S. Geological Survey (see "References").

Studies Prior to March 1975

Although there have been several previous studies and many written accounts pertaining to Mount Baker and Baker Lake, only a few are especially significant to the present study.

Surveys of the Mount Baker glaciers by repeated aerial photographs began in 1958 by Austin Post, and in 1964 were made a part of the U.S. Geological Survey's Glaciology Research Project. The earlier photos of the mountain provide excellent background for judgments as to the accelerated melting of snow and ice produced by the increased volcanic activity on the mountain.

In August 1962, a comprehensive limnological study was begun on Baker Lake by the Washington Department of Fisheries as one section of a major investigation of the migration and passage of salmon through hydroelectric reservoirs. The study was based on the distribution of water temperature, conductivity, and dissolved oxygen, observed from top to bottom at a network of stations along nine cross sections. Summary data and descriptions of the water circulation, general hydrography, and environmental conditions in the reservoir were included in the reports (Westley, 1966; Goodwin, 1967). Detailed data are on file with the Washington Department of Fisheries.

During 1972-74, a study was made of the volcanic heat of Mount Baker as part of a cooperative program by the U.S. Geological Survey and the National Aeronautics and Space Administration for thermal surveillance of the Cascade Range volcanos. Additional aerial infrared (heat-sensing) surveys were made over the mountain each year during 1970-73 by the U.S. Forest Service (Frank and others, 1975, p. 77 and 83).

The heat emissions were being evaluated in August 1973 when a large debris avalanche came down Boulder Glacier (fig. 2). This led to a study that related the recurrence of such avalanches to the melting of snow and ice and the alteration (weakening) of rock materials by the heat and gas emanations on the mountain. The report on the study (Frank and others, 1975) includes discussion of the heat emissions prior to 1975, and the "destructive potential in the Boulder Creek valley" from the melting of snow and ice, and accumulation and sudden release of floodwaters from Mount Baker. Baker Lake is the receiving body for any flood or mudflow large enough to travel for the 8-mile (13-km) distance from the crater.

The data collected in 1973 allowed Frank (1975) to describe the temperature and acidic pH[1/] of water draining from the fumarole fields into

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[1/] A pH value (negative logarithm of the hydrogen-ion activity) of 7 is neutral, less than 7 is acidic, and greater than 7 is basic. Surface waters with pH values of about 4.5 or less generally are those receiving certain industrial wastes, or strong acids from volcanic activity, ore bodies, or mine wastes. Natural waters receiving no such acidic inputs normally have pH values within the range 6.5 to 8.5. See also footnote on p. 21.

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upper Boulder Creek, as well as the time of travel of the water beneath Boulder Glacier. Those water-quality data (table 1) are the only data available on the pH of the water flowing into Baker Lake before 1975.

In 1973, a study of the age and origin of eruptions and other geologic events on Mount Baker was begun as part of a project to assess the potential hazards of Cascade volcanos. The study showed that, of the many mudflows that originated on Mount Baker during the last 10,000 years, at least two within the last few centuries moved down Boulder Creek valley more than 7 miles (11 km)--almost the distance between Sherman Crater and Baker Lake (Hyde and Crandell, 1975, table 1).

Studies Since March 1975

A variety of studies and monitoring activities were started as a result of the increased volcanic activity, described by Malone and Frank (1975, p. 679) as follows:

> "In late afternoon on March 10, 1975,***an unusually large dark gray plume of vapor was seen rising above the rim of the Sherman Crater near the top of Mount Baker***. A flurry of aerial observations the following day noted distinct changes from previously known fumarolic activity in the ice-covered crater. New fumaroles, ice pits, semicircular crevasses, and ponded water in the crater had appeared, as well as a thin dusting of gray debris 100 to 300 m outside the crater. The apparently sudden change in the thermal regime of Mount Baker was obvious as well as ominous."

The U.S. Geological Survey and other concerned agencies began ground-based and airborne monitoring activities on an emergency basis for rapid evaluation of the situation. Included were: Aerial and time-lapse photography; airborne infrared surveys; increased seismic monitoring; gravity measurements; gas analysis and temperature measurements; analysis of ejected particulate material (fumarole dust); tilt measurements to detect possible swelling of the mountain; and examination of heat-induced changes within ice caves in Sherman Crater (Malone and Frank, 1975, p. 682-685). Also included, and of special interest for this study, were field measurements of water quality, temperature, and flow of several streams draining Mount Baker, and collection of water samples for comprehensive chemical analyses (see tables 1 and 4).

A joint-agency monitoring program for surveillance of the Boulder Creek-Baker Lake-Baker River system was begun soon after the increase in volcanic activity. U.S. Forest Service personnel measured pH, specific conductance, temperature, and water stage in Boulder Creek about every 3 to 5 days during the summer of 1975.

Also, about every 2 to 3 weeks the Forest Service personnel collected water samples for determination of common dissolved constituents and heavy metals in Boulder Creek and in Baker River below Upper Baker Dam. These and samples from other nearby tributaries draining Mount Baker were analyzed by the U.S. Geological Survey. The results from this monitoring program through December 1975 are included in table 1.

On May 30-31, 1975, biologists of the Washington Department of Fisheries visited Baker Lake to investigate a fish kill. The fish kill is classed as "light", and no cause for it was established. The biologists counted about 200 dead fish, but the actual number was impossible to determine, even roughly. The fact that the dead fish were unmarked and included more than one species suggested that the mortalities probably were related to water conditions. Further, all the dead fish were found downlake from Boulder Creek, mainly in the immediate vicinity (forebay area) of Upper Baker Dam. This evidence raised conjecture that a plume of acidic water from Boulder Creek may have somehow "retained its potency all the way to the dam, where it built up in the forebay area" in temporary lethal concentration (Mark Schuller, Washington Department of Fisheries, written commun., 1975).

Fish kills related to volcanic activity apparently have occurred previously in the area. An early account of a fish kill is provided by George Gibbs (1874, p. 357-358), a geologist with the International Boundary Commission, who reported Indian stories of an eruption of Mount Baker that resulted in volcanic ash, a large forest fire east of the volcano, and a massive fish kill in the Skagit River in 1843.

Concern over possible adverse effects of Boulder Creek water on Baker Lake and its fish life resulted in a reconnaissance of the lake on June 6, 1975, by officials of the U.S. Forest Service and Washington Department of Game. During the visit, water temperature, pH, alkalinity, and acidity measurements were made at the mouths of all tributaries, and at two places in the lake (Curtis Kraemer, Washington Department of Game, written commun.~~ication~~, 1975).

Later during the same month (June 16-17, 1975), the Washington Department of Ecology made a brief survey on Baker Lake (Roger Stanley and Greg Cloud, written commun.~~ication~~, 1975). Measurements were made of temperature, dissolved oxygen, and pH at various lake depths along five cross sections (three near the mouth of Boulder Creek), and in the lower channels of four streams draining Mount Baker (Boulder, Sandy, Park, and Swift Creeks). The biologists concluded that the area of the lake affected by Boulder Creek water (pH 3.8-4.4) was rather small and ran about 225 feet (69 m) north of the creek's mouth, 450 feet (140 m) south, and roughly 300 feet (91 m) east to near the middle of the lake. They observed that the pH values were lowest (that is, acid concentrations were highest) near the deeper water and that the surface water of Baker Lake was relatively unaffected.

Biologists of the Washington Department of Game returned to Baker Lake on July 18, 1975 and measured water temperature and pH at the lake surface and at depth in various places along the former channels of Boulder Creek and Baker River, which are now inundated by the reservoir water. The measurements led to the conclusions that the Boulder Creek water was being diluted and buffered by the Baker Lake water, and that the high acidity of Boulder Creek was then causing little problem to the fish life in Baker Lake (Curtis Kraemer, Washington Department of Game, written communication, 1975).

Periodic measurements of water quality and flow of Boulder Creek continued throughout the latter part of 1975, and in January 1976 a radio-telemetering monitor was installed on Boulder Creek to warn of sudden changes in the character or amount of streamflow, which may be early indicators of changing conditions at Sherman Crater. The monitor measures water stage, pH, temperature, specific conductance, and dissolved oxygen. The water-quality part of the monitor has been operational since April 23, 1976, and the flow gage for a longer time. The data are relayed hourly by radio-telemetry to the Tacoma, Wash. office of the Geological Survey. This Boulder Creek monitoring station (12190800) is located about 200 feet (60 m) upstream from the highway bridge crossing, which was the site for previous flow measurements and sample collections. The station is 6.6 miles (11 km) downstream from the crater, and about 1.4 miles (2.2 km) upstream from the lake.

QUALITY OF SURFACE WATERS DRAINING TO BAKER LAKE

Water in Sherman Crater

The increased volcanic activity during 1975-76 has produced a number of specific changes in Sherman Crater that affect the surface waters draining to Baker Lake or have the potential to do so. These include: (1) Increased heat, which accelerated the melt rate of snow and ice in and immediately outside Sherman Crater; (2) increased gaseous emanations; and (3) spewing out of fumarole dust. The dust particles and gases are the main sources of the acidity of the Sherman Crater water.

A large circular depression formed in the ice fill near the center of the crater and was enlarged considerably by the steam activity during March 1975. In April the depression collapsed and a highly acidic lake was exposed at the bottom of a 130-foot (40 m) deep ice pit. On June 11, 1975, a water sample from this central lake had a pH of 2.5 (table 1) and an acidity[2/] of 15 mg/liter as H^+ (milligrams per liter as hydrogen ion). The pH of the crater water on that date was not much lower (not much more acid) than pH values measured during 1973 and 1974 in the stream that flows through the east breach. Those earlier values ranged from 2.8 to 3.5 pH units (table 1). However, the flow of water through the east breach probably was greater during the June 11 (1975) measurement than it had been during the earlier measurements, making the total acid discharge greater, also.

[2/] Acidity is closely related to pH, but not the same. It is the measured capacity of a water or other solution to react with hydroxyl (OH^-) ions to reach an arbitrarily designated pH. Usually, the selected endpoint (equivalence point) is pH 8.3, which represents complete neutralization of strong mineral acids (if present) plus virtually complete neutralization of all reactive weak acids. See also footnote on p. 15.

As the 1975 summer progressed, previously unobserved fumaroles appeared as the unusually widespread melting continued (fig. 3A). Whether the overall area of fumaroles gradually continued to increase after March 10 or had existed previously and was merely uncovered was not entirely clear according to Malone and Frank (1975, p. 682). If new fumaroles continued to open up, they presumably would represent increased opportunity for emanations of heat, gases, and fumarole dust.

On August 8, 1975 a water sample from the central lake in the crater had a pH of 2.4 and an acidity of 11 mg/liter as H^+ (table 1). Although this is very acidic for a natural water, it is about 3,200 times less in hydrogen-ion concentration than a standard solution of concentrated laboratory sulfuric acid, for example. The mineralized nature of the crater water is shown by the analysis of the August 8 sample, which had a specific conductance of 2400 µmhos/ (micromhos per centimeter), dissolved sulfate content of 960 mg/liter, total iron content of 19,000 µg/liter (micrograms per liter), total aluminum content of 38,000 µg/liter, and boron content of 2,500 µg/liter (table 1).

Figure 3A.--View on July 3, 1975 looking west-northwest into Sherman Crater, showing major fumaroles (steam areas) and deposits of fumarole dust (a) on the snow and ice in the crater. Central ice pit and warm lake (b), and enlarged former warm lake (c), are visible among steam plumes. Meltwater from the crater flows toward viewer through the east breach (d), and passes beneath Boulder Glacier (lower right edge of photograph) to reach upper Boulder Creek (not shown). Sherman Peak (e) and Lahar Lookout (f) are identified on figure 2. (Photo by Austin Post, U.S. Geological Survey)

Fumarole gases bubbling through the water and, possibly, a warm lake bed kept the central lake heated to a temperature of 34°C (Celsius) on June 11 and 26°C on August 8, 1975. The increased heating of the crater outflow is indicated by before-and-after temperatures of the stream that flow through the east breach (table 1):

Date		Temperature (deg. C)
May 28, 1974	(before increased	7.0
August 17, 1974	activity)	8.0
September 19, 1975	(after increase began)	21.2

Sulfur in the fumarole dust deposits described by Frank and others (1976, table 6), and aerosol and gas measurements made in the vicinity of Mount Baker by the University of Washington Cloud Physics Group (Radke and others, 1976), indicate appreciable emissions of particulate and gaseous sulfur from the fumaroles. Measurements of sulfur (assumed to be gaseous hydrogen sulfide) were made by aircraft during a series of traverses of the plume downwind of the mountain. The sulfur emissions were estimated to be 0.77 pounds per second, or 0.35 kilograms per second (kg/s) on March 27 and 2.9 pounds per second (1.3 kg/s) on June 30, 1975, respectively (Radke and others, 1976, p. 93). Thus, the reported emission was 3.7 times greater during the second flight than during the first. The emission rates of gaseous sulfur on June 30 were comparable to the largest single industrial source of sulfur in the Pacific Northwest (Radke and others, 1976, p. 93). The gaseous sulfur concentrations observed along flight lines downwind from the mountain reportedly were too low to constitute a hazard from hydrogen sulfide toxicity, but concentrations encountered above the crater may have reached the maximum limit for short-time exposure of humans. Very small aerosol particles also were found in the plume effluents; those greater than about 1 micrometer in diameter consisted predominantly of silicon, aluminum, sulfur, potassium, and calcium (Radke and others, 1976, p. 94

The long-range atmospheric impact of the airborne particles and sulfurous gases is not known, but if these materials are sufficiently abundant they presumably could cause the rainfall to be more acidic than normal (Cogbill and Likens, 1974, p. 1133). In addition, if aerosols containing heavy-metal compounds are sufficiently concentrated in streams (particularly ions of metals such as iron and aluminum), they may hydrolyze in water to release additional acidity. However, the water-quality data from local streams other than Boulder Creek (Park, Sandy, Sulphur, and Rocky Creeks) that drain Mount Baker indicated no unusually low pH values during 1975 (table 1), suggesting that these processes were not producing measurable amounts of acid.

Boulder Creek and Other Streams

Prior to 1975, little was known about the flow or character of the water in Boulder Creek and other small streams that bring water to Baker Lake from Mount Baker. Frank (1975) had proven by dye-tracer studies that water flowing from Sherman Crater passed beneath Boulder Glacier and surfaced in Boulder Creek at the glacier terminus. Frank also provided the only available water-quality measurements and samples of Boulder Creek at the glacier terminus (1973 and 1974), and 1973 pH measurements in Park Creek and in Boulder Creek near the present monitoring station (fig. 2). Unfortunately, no data are available on the flow of the creeks at those times, which would be needed to estimate the load of acid or other dissolved constituents formerly reaching the lake.

The pre-1975 pH data for Boulder Creek, summarized from table 1, are included in table 2. As table 2 shows, in the summer of 1973 acidic water from Sherman Crater (pH 3.5) had been traced to the head of Boulder Creek (pH 3.8), at the lower end of Boulder Glacier. At that time, however, the pH of Boulder Creek water increased considerably before the water reached Baker Lake, as less-acid water from other parts of the creek's drainage area diluted and buffered the acidic water from the crater. Corresponding pH measurements in lower Boulder Creek, near the present station, showed that the water there had a pH of about 6 to 6.6, only slightly more acidic than water in nearby Park Creek (pH 6.8; table 1). However, field measurements soon after the increase in volcanic activity showed an obvious acid condition (and possible slight increase in temperature) of the water in lower Boulder Creek, indicating that the crater water was more dominant even 6.6 miles (11 km) downvalley from the crater. Also, during some early sampling visits, the lower Boulder Creek water had a "rotten egg" odor typical of hydrogen-sulfide gas.

Table 2.--Temperature, specific conductance, pH, and acidity of waters in Sherman Crater and in Boulder Creek (summarized from table 1, with additions).

Date	Temperature (°C)	Specific conductance (micromhos per centimeter at 25°C	pH (units)	Total acidity (milligrams per liter as hydrogen ion	Remarks
Sherman Crater (sampling sites as listed)					
9-03-73	--	--	3.5	--	Creek near outlet of crater (site BW-3).
5-28-74	7.0	1400	2.8	4.9	Do.
8-17-74	8.0	1360	3.2	8.2	Do.
6-11-75	34.0	3840	2.5	15	Lake in central pit (site BW-5).
8-08-75	26.0	2400	2.4	11	Do.
9-05-75	--	2200	2.6	--	Creek at site 98 feet (30 m) upstream from BW-3.
9-19-75	18.0	1980	3.0	12	Do.
9-30-75	14.7	1760	2.8	--	Do.
Boulder Creek (sta 12190800, fig. 2, unless otherwise noted)					
9-02-73	--	--	6.6	--	
9-03-73	--	--	3.8	--	Boulder Creek at terminus of Boulder Glacier.
9-04-73	--	--	6.0	--	
5-28-74	2.0	380	3.5	1.0	Boulder Creek 0.75 mi (1.2 km) downstream from terminus of Boulder Glacier
7-22-74	--	--	4.7	--	
3-20-75	--	--	3.7	1.6	
4-09-75	--	560	3.4	1.7	
5-04-75	--	--	4.3	1.4	
5-28-75	8.4	200	4.1	0.8	
7-28-75	6.1	185	4.1	0.7	
9-26-75	7.2	320	4.1	1.3	
10-22-75	5.6	156	4.9	0.3	
11-13-75	4.2	169	5.5	0.4	
12-22-75	3.3	200	5.6	0.2	
4-07-76	--	135	5.2	--	Boulder Creek at mouth.
4-23-76	5.0	140	5.2	0.2	

Sampling and water-quality measurements since March 10, 1975 show the amount of pH decrease in lower Boulder Creek that resulted from the increased volcanic activity. The frequent monitoring of lower Boulder Creek also has revealed significant changes in its water quality since that date. A pH measurement on March 20 was 3.7, and throughout most of the summer the pH in Boulder Creek ranged from 3.4 to 4.8, with a median value of 3.9. One of the lowest pH values measured (3.4) was, suprisingly, during August, a time of high streamflow in Boulder Creek from high-elevation snowmelt (table 1). For the pH to remain so low at higher rates of flow, the supply of acid from the crater area had to increase significantly; if not, the acid would have been diluted more by melt water from adjacent areas. Although the water-quality data for the sampling sites on the mountain are meager, the pH of the Sherman Crater water remained low (pH 2.4-2.6) even while the rates of melting in the crater were unusually high.

Translating the pH values into acid load, Boulder Creek supplied an estimated equivalent of 1200 to 2400 pounds of concentrated sulfuric acid per day (560 to 1090 kg/day) to Baker Lake during March through June 1975. During June through August, the creek supplied an estimated equivalent of 7600 to 27,400 pounds of sulfuric acid per day (3400 to 12,400 kg/day).

During the late fall of 1975 and throughout the winter rainy season, the pH of Boulder Creek rose to about 5.0 or higher. Likewise, the acidities ranged from 0.4 to 3.8 mg/liter as H^+ during spring to early fall and dropped to 0.1 to 0.4 mg/liter as H^+ by late fall and winter. On October 22, 1975, the estimated acid load decreased to an equivalent of about 220 pounds of sulfuric acid per day (98 kg/day). The trend of higher pH and lower acidities has continued into the early spring of 1976. For example, Boulder Creek water had a pH of 5.2, on both April 7 and April 23, 1976 (table 2). The higher pH and lower acidities during the winter months and early spring of 1976 may be due to: (1) Decreased acidity related to a change in volcanic activity; (2) a temporary decrease in discharge of acid water due to damming near the crater; (3) runoff and storage of precipitation in patterns different from those earlier in 1975; or (4) the solution (or suspension), by melt water, of acidic material derived from the initial "clearing out" of the fumaroles--most likely the fumarole dust (fig. 3A) that spewed out abundantly during spring and early summer of 1975, but which has diminished since that time.

During 1975, while median summertime pH in Boulder Creek was 3.9, the pH in nearby streams ranged from 6.3 to 8.3, with most values near pH 7.0. Immediately downstream from Baker Dam the median pH of Baker River was 6.9 during 1975. The concentration of dissolved constituents of Boulder Creek, indicated by specific conductance measurements, was quite high in relation to nearby streams. In 1975, the average specific conductance was about 240 µmhos/cm in Boulder Creek compared to about 50 µmhos/cm in nearby streams and in Baker River below Baker Dam.

For comparison purposes, concentrations of dissolved constituents in one set of samples, collected April 29, 1975 from several sources, are shown on table 3. The sampled waters included tributary streams draining to Baker Lake (Boulder, Park, and Sandy Creeks); Sulphur and Rocky Creeks, which drain into Lake Shannon; and Baker River below Baker Dam (fig. 2). As table 3 shows, concentrations of all the listed constituents, dissolved silica, calcium, magnesium, sodium, potassium, chloride, and fluoride, were higher in Boulder Creek than in nearby streams or in Baker River. The concentrations of the major constituents, except for total iron and dissolved sulfate, were generally 2 to 7 times greater in Boulder Creek than the other streams; sulfate concentration in Boulder Creek was 6 to 29 times greater. The few available data on flow rates at the times when samples were collected (table 1) suggest that the sulfate load in Boulder Creek during March 28-June 30, 1975 was about 40,000-46,000 pounds (18,000-21,000 kg) per day. In contrast, the sulfate load in Park Creek was on the order of 3800 to 6700 pounds (1700-3000 kg) per day during the period.

Table 3.--Concentrations of common constituents and heavy metals in streams draining to Baker Lake and Baker River on April 29, 1975 (sampling sites shown on fig. 2; data from Table 1).

Stream	Milligrams per liter								Micrograms per liter			
	Dis. silica (SiO_2) [1]	Dis. calcium (Ca)	Dis. magnesium (Mg)	Dis. sodium (Na)	Dis. potassium (K)	Dis. sulfate (SO_4)	Dis. chloride (Cl)	Dis. fluoride (F)	Total iron (Fe)	Total arsenic (As)	Total boron (B)	Total selenium (Se)
Boulder Creek (sta 12190800)	35 (23) [2]	35 (17)	5.5 (2.4)	10.0 (4.7)	1.6 (1.4)	150 (110)	3.1 (1.8)	0.7 (.4)	530 (3700)	11 (6)	280 (120)	1 (1)
Park Creek (sta 12190720)	8.4	11	2.1	2.7	.8	15	1.1	.1	30	1	60	0
Sandy Creek (sta 12191000)	12	6.1	1.0	2.0	.6	5.2	1.3	.1	0	0	50	0
Sulphur Creek (sta 12191820)	21	12	3.6	5.2	1.5	24	1.9	.1	10	0	70	0
Rocky Creek (sta 12191900)	6.4	9.2	.9	1.4	.3	6.4	.8	.1	30	1	40	0
Baker River (sta 12191700)	8.9 (6.8)	9.3 (6.8)	1.5 (1.1)	2.2 (1.5)	.6 (.5)	14 (9.1)	1.5 (.9)	.1 (.1)	430 (550)	2 (0)	50 (40)	0 (0)

[1] Dissolved.
[2] Numbers in parentheses are median concentrations for 1975 (19 or fewer samples).

Table 3 shows that the total iron concentration of the Boulder Creek sample was about 18-53 times greater than that of the other small streams, but only 1.2 times the concentration in the Baker River samples. In 1975, the median iron concentration of Boulder Creek was 3700 μg/liter, which is about 12 times higher than the recommended limit for public water supplies (300 μg/liter). With the exception of total iron, the common constituents and heavy metals in Baker River water below Baker Dam were at normal background concentrations detected in other streams draining to Baker Lake (other than Boulder Creek). The concentrations of total iron in Baker River below Baker Lake ranged from 430 to 1200 μg/liter throughout 1975, in contrast to a background of 0 to 30 μg/liter for Park, Sandy, Sulphur, and Rocky Creeks. During a previous sampling period (1961-65), fairly high total iron concentrations had been observed in Baker River at Concrete (station 12193500) below Lake Shannon. At that station (not shown on fig. 2), total iron in 15 samples ranged from 90 to 810 μg/liter, and the mean was 250 μg/liter. Unfortunately, no comparable iron-concentration data are available for either upstream parts of Baker River or for lower Boulder Creek prior to the increased volcanic activity. However, a total-iron concentration of 3200 μg/liter in a May 1974 sample of Boulder Creek at the terminus of Boulder Glacier (table 1), as well as obvious iron-oxide coatings on rocks along the lower Boulder Creek channel, indicate that the creek characteristically had high concentrations of iron. The data are not adequate to indicate how much of the iron content of Baker River is attributable to Boulder Creek.

WATER-QUALITY IMPACT ON BAKER LAKE

September 1975 Lake Survey

For the present study, a preliminary survey on Baker Lake was made in September 1975 by G.C. Bortleson and colleagues in the U.S. Geological Survey. The study was made, in cooperation with the Washington Department of Ecology, to measure various water-quality characteristics in the lake, especially near the inflow of Boulder Creek. Specific conductance, pH, temperature, and dissolved-oxygen measurements were made near the water surface and lake bottom, and in vertical profiles at two stations. The measurements were made from a small boat using a Martek (Mark II) water-quality monitor[3/], which was calibrated before and after the field measurements.

[3/] The use of the brand name in this report is for identification purposes and does not imply endorsement by the U.S. Geological Survey.

At the time of the survey, Boulder Creek entered Baker Lake mainly from two channels (three channels at higher flows, fig. 4). The southern channel carried most of the flow. The turbidity of Boulder Creek water produced a murky gray color in the lake for a distance of about 50-75 feet (15-23 m) offshore (fig. 4). A slight hydrogen-sulfide odor was detected in the air near the mouth of the creek. On September 3, the first day of the lake survey, water at the mouth of Boulder Creek had a temperature of 10.0°C, specific conductance of 260 umhos/cm, and pH of 3.8. The estimated discharge from Boulder Creek was 75 cubic feet per second (2.1 m^3/s).

Figure 4.--Aerial view of Boulder Creek flowing into Baker Lake on August 13, 1975. Light-colored water areas are sediment-laden creek water. (Photo by Roger Stanley, Washington Department of Ecology.)

To determine the effect of the acid-rich water of Boulder Creek on Baker Lake, 88 water-quality stations (on seven cross sections) were located near Boulder Creek (fig. 5). Six cross sections were established approximately perpendicular to Boulder Creek channels (or plumes of Boulder Creek water in the lake) and following roughly along bottom contours. The other cross section was perpendicular to the old (now inundated) Baker River channel about 1.1 miles (1.8 km) downlake from the southernmost channel of Boulder Creek. It should be noted that, at the time of the study, Baker Lake was drawn down to a water-surface altitude of 706 feet (215 m), considerably lower than normal pool altitude of 724 feet (221 m).

Data from three cross sections (total of 22 stations) in the lake less than 150 feet (46 m) offshore from the channels of Boulder Creek showed a pH range of 3.8-6.3 near the surface and 4.0-6.3 near the bottom. Close to shore, where stream inflow and reservoir water were mixing, the pH values varied from station to station but slightly more than half the values (both near-surface and bottom) had pH values less than 5.0 (table 4).

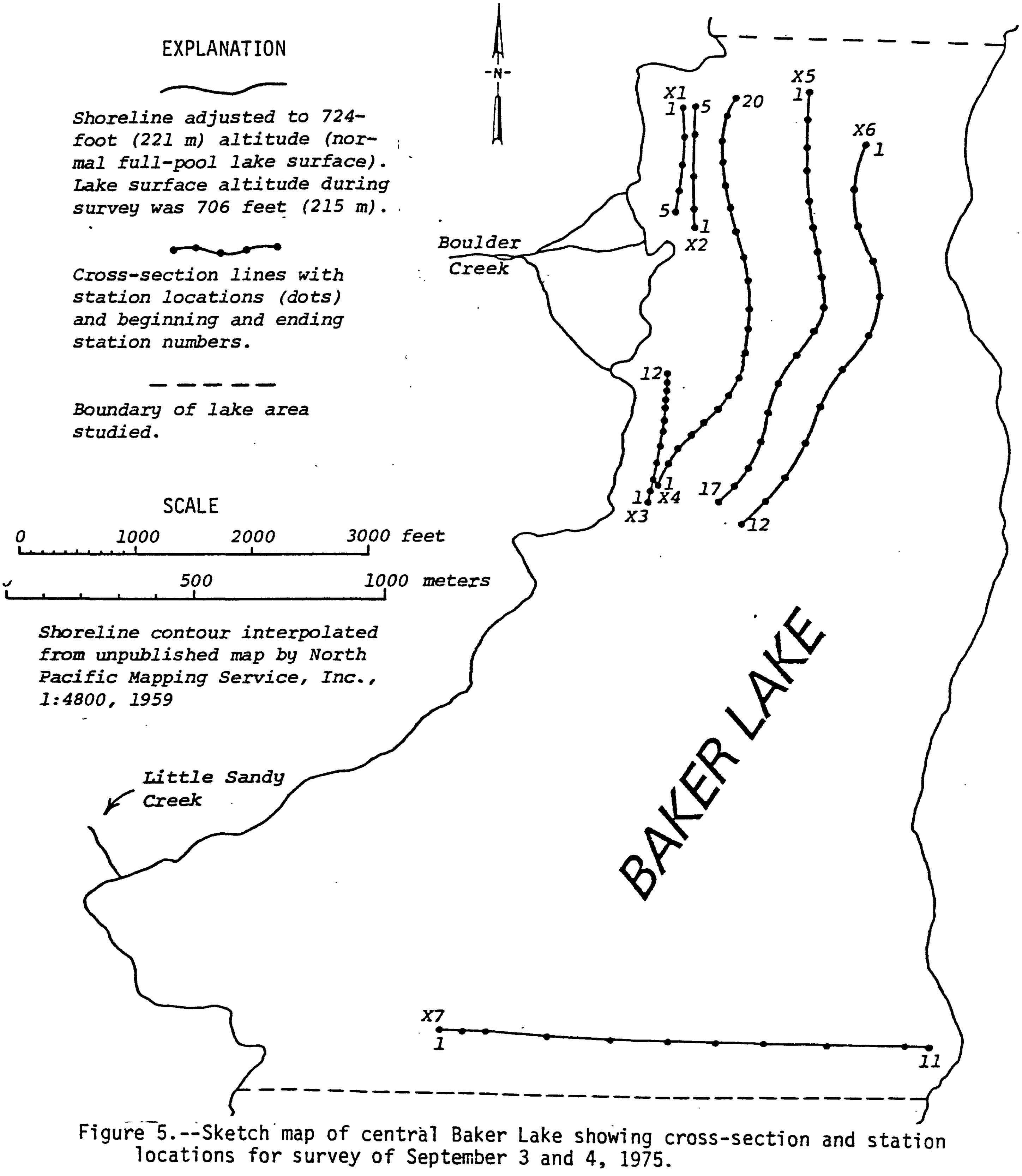


Figure 5.--Sketch map of central Baker Lake showing cross-section and station locations for survey of September 3 and 4, 1975.

Table 4.--Specific conductance, pH, temperature, and dissolved-oxygen measurements in Baker Lake, Sept. 3-4, 1975.

Locations: Transect and station locations are shown on figure 5.
Depths: Measurement depth and sounding depth (total depth to lake bottom) are given in feet below the lake surface (altitude 706 feet during this survey).

Water data: Values of specific conductance, pH, temperature, and dissolved oxygen are field measurements made with Martek (Mark II) water-quality monitor. Specific conductance values are in micromhos per centimeter at 25°C, dissolved oxygen in milligrams per liter.

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 3	X1	1	1	1	220	3.8	12.8	10.1
3...	X1	2	1	2	158	4.1	12.0	10.1
3...	X1	3	3	5	98	4.4	15.0	10.1
3...	X1	3	1	5	100	4.8	15.0	10.1
3...	X1	4	1	5	104	4.7	15.0	10.1
3...	X1	5	1	4	119	4.5	14.9	10.1
3...	X2	1	1	7	121	4.5	14.8	10.2
3...	X2	1	4	7	167	4.0	13.2	10.4
3...	X2	2	1	7	98	4.7	14.2	10.2
3...	X2	2	4	7	123	4.3	14.1	10.2
3...	X2	3	1	7	67	5.3	14.7	10.2
3...	X2	3	4	7	103	4.6	14.3	10.2
3...	X2	4	1	9	73	5.2	14.7	10.0
3...	X2	4	4	9	100	4.8	14.5	10.2
3...	X2	5	1	4	82	5.1	14.7	10.1
3...	X2	5	2	4	82	5.1	14.7	10.1

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 3...	X3	1	1	12	57	6.2	14.1	10.4
3...	X3	1	10	12	76	5.3	14.0	10.3
3...	X3	2	1	13	60	5.9	14.0	10.2
3...	X3	2	10	13	60	6.0	14.0	10.1
3...	X3	3	1	18	60	6.0	14.0	10.1
3...	X3	3	15	18	85	4.6	12.9	10.4
3...	X3	4	1	12	58	6.1	14.0	10.0
3...	X3	4	10	12	60	5.9	14.0	10.1
3...	X3	5	1	7	76	4.8	13.8	10.4
3...	X3	5	4	7	97	4.6	12.1	10.3
3...	X3	6	1	4	50	6.2	14.0	10.0
3...	X3	6	3	4	50	6.3	14.2	10.0
Sept. 4...	X3	7	1	4	50	6.3	14.2	10.0
4...	X3	7	2	4	51	6.2	14.2	10.0
4...	X3	8	1	4	71	4.4	14.0	10.2
4...	X3	8	2	4	118	4.2	12.2	10.4
4...	X3	9	1	5	53	6.0	14.2	10.0
4...	X3	9	3	5	113	4.3	13.1	10.4
4...	X3	10	1	2	55	5.0	14.0	10.0
4...	X3	11	1	6	53	6.3	14.2	10.0
4...	X3	12	5	6	56	5.4	14.0	10.0

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 4...	X4	1	1	20	43	6.7	14.8	10.0
4...	X4	1	18	20	54	5.9	13.2	10.2
4...	X4	2	1	20	42	6.7	14.9	10.2
4...	X4	2	18	20	54	5.9	13.8	10.0
4...	X4	3	1	20	43	6.7	14.8	10.0
4...	X4	3	18	20	56	5.8	13.5	10.0
4...	X4	4	1	20	43	6.7	14.9	10.0
4...	X4	4	18	20	55	5.8	13.5	10.0
4...	X4	5	1	19	43	6.7	14.9	9.9
4...	X4	5	18	19	55	5.9	13.3	10.2
4...	X4	6	1	19	42	6.7	14.9	10.0
4...	X4	6	18	19	69	4.9	13.0	10.0
4...	X4	7	1	20	42	6.6	14.9	10.0
4...	X4	7	18	20	68	5.2	13.1	10.1
4...	X4	8	1	19	43	6.6	14.8	9.9
4...	X4	8	17	19	64	5.2	13.1	9.9
4...	X4	9	1	19	42	6.7	14.9	9.8
4...	X4	9	18	19	56	5.8	13.9	10.0
4...	X4	10	1	18	42	6.7	15.0	9.8
4...	X4	10	17	18	54	5.7	14.0	10.0
4...	X4	11	1	18	42	6.7	15.0	9.7
4...	X4	11	17	18	58	5.5	13.8	9.8
4...	X4	12	1	18	41	6.7	15.1	--
4...	X4	12	17	18	51	5.6	13.9	10.0
4...	X4	13	1	19	43	6.6	15.1	9.8
4...	X4	13	17	19	52	6.0	14.0	9.8
4...	X4	14	1	20	41	6.6	15.2	9.4
4...	X4	14	18	20	53	5.9	15.7	9.6
4...	X4	15	1	18	39	6.7	15.2	9.6
4...	X4	15	17	18	48	5.9	14.0	9.8

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 4...	X4	16	1	19	42	6.7	15.5	9.8
4...	X4	16	17	19	61	5.4	13.7	10.1
4...	X4	17	1	19	40	6.6	15.5	9.8
4...	X4	17	17	19	56	5.7	13.9	9.9
4...	X4	18	1	13	39	6.6	15.4	9.7
4...	X4	18	12	13	40	5.8	14.8	9.7
4...	X4	19	1	19	40	6.7	15.3	9.2
4...	X4	19	17	19	44	6.3	13.9	9.7
4...	X4	20	1	19	42	6.6	15.4	9.3
4...	X4	20	17	19	46	6.0	13.8	9.5
4...	X5	1	1	40	40	6.7	15.5	9.6
4...	X5	1	38	40	37	6.8	12.2	9.8
4...	X5	2	1	40	40	6.7	15.7	9.6
4...	X5	2	38	40	34	6.8	12.1	10.0
4...	X5	3	1	39	40	6.7	15.6	9.6
4...	X5	3	33	39	34	6.8	12.3	10.0
4...	X5	4	1	38	39	6.7	15.3	9.3
4...	X5	4	35	38	36	6.7	12.4	10.0
4...	X5	5	1	38	39	6.7	15.2	9.8
4...	X5	5	35	38	36	6.8	12.7	10.0
4...	X5	6	1	40	39	6.8	15.5	9.5
4...	X5	6	38	40	37	6.7	12.8	10.0
4...	X5	7	1	38	39	6.7	16.0	9.6
4...	X5	7	35	38	69	5.1	13.0	10.0
4...	X5	8	1	40	39	6.7	15.2	9.8
4...	X5	8	38	40	43	6.5	12.2	10.0
4...	X5	9	1	37	42	6.7	15.5	9.8
4...	X5	9	17	37	55	5.8	13.7	--
4...	X5	9	35	37	53	5.9	12.9	9.9

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 4...	X5	10	1	40	41	6.7	15.6	9.6
4...	X5	10	17	40	50	6.0	14.0	--
4...	X5	10	35	40	44	6.1	12.9	9.8
4...	X5	11	1	40	41	6.7	16.2	9.6
4...	X5	11	17	40	47	6.3	14.1	9.9
4...	X5	11	37	40	46	6.2	12.9	10.0
4...	X5	12	1	40	41	6.7	15.6	9.8
4...	X5	12	32	40	53	5.5	13.0	--
4...	X5	12	37	40	55	5.8	12.9	10.0
4..	X5	13	1	39	42	6.7	16.0	9.6
4...	X5	13	20	39	64	5.3	13.6	--
4...	X5	13	37	39	57	6.2	12.9	10.0
4...	X5	14	1	40	39	6.7	15.8	9.8
4...	X5	14	37	40	89	4.7	13.1	10.2
4...	X5	15	1	39	43	6.7	16.1	9.6
4...	X5	15	21	39	56	5.7	13.5	10.0
4...	X5	15	37	39	77	4.8	13.0	10.2
4...	X5	16	1	39	39	6.6	15.7	9.6
4...	X5	16	37	39	58	5.3	13.0	10.0
4...	X5	17	1	38	40	6.6	17.0	9.6
4...	X5	17	35	38	45	6.1	13.0	9.8
4...	X6	1	1	50	41	6.7	17.0	10.4
4...	X6	1	48	50	34	6.7	12.0	10.6
4...	X6	2	1	50	41	6.7	17.0	9.6
4...	X6	2	48	50	34	6.7	12.0	10.6
4...	X6	3	1	50	41	6.7	17.0	9.8
4...	X6	3	18	50	46	6.2	13.0	10.4
4...	X6	3	48	50	33	6.6	12.0	10.5

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 4...	X6	4	1	50	41	6.7	16.5	9.8
4...	X6	4	15	50	46	6.2	13.2	10.0
4...	X6	4	48	50	34	6.7	12.4	10.4
4...	X6	5	1	50	41	6.7	16.6	9.8
4...	X6	5	18	50	41	6.3	13.2	10.0
4...	X6	5	48	50	36	6.5	12.5	10.2
4...	X6	6	1	48	39	6.7	16.5	9.8
4...	X6	6	17	48	50	5.9	13.5	10.0
4...	X6	6	45	48	37	6.3	12.8	10.0
4...	X6	7	1	50	36	6.6	16.6	9.9
4...	X6	7	17	50	51	5.9	13.5	--
4...	X6	7	48	50	41	6.2	12.8	10.2
4...	X6	8	1	50	27	6.6	16.5	9.6
4...	X6	8	18	50	59	5.5	13.5	10.1
4...	X6	8	48	50	37	6.1	12.8	--
4...	X6	9	1	50	38	6.6	17.0	9.6
4...	X6	9	18	50	94	4.6	13.8	10.2
4...	X6	9	48	50	45	5.9	12.7	10.1
4...	X6	10	1	50	38	6.5	16.8	9.8
4...	X6	10	35	50	59	5.4	13.0	10.1
4...	X6	11	1	50	38	6.6	16.5	10.0
4...	X6	11	18	50	60	5.4	13.5	10.0
4...	X6	11	48	50	65	5.0	12.5	10.2
4...	X6	12	1	51	37	6.5	16.5	9.8
4...	X6	12	18	51	53	5.8	13.5	10.1
4...	X6	12	48	51	50	5.6	12.8	10.1

Table 4 (cont.)

Date	Transect No.	Station No.	Measurement depth (ft)	Sounding depth (ft)	Specific conductance (micromhos)	pH (units)	Temperature (deg C)	Dissolved oxygen (mg/l)
Sept. 4...	X7	1	1	27	35	6.6	17.0	9.5
4...	X7	1	25	27	38	6.3	14.0	10.0
4...	X7	2	1	51	35	6.6	17.0	9.5
4...	X7	2	47	51	36	6.4	13.0	10.0
4...	X7	3	1	50	32	6.6	17.0	9.5
4...	X7	3	47	50	36	6.4	13.0	10.0
4...	X7	4	1	50	37	6.4	17.0	9.8
4...	X7	4	47	50	32	6.4	12.8	10.1
4...	X7	5	1	69	25	6.6	16.0	9.8
4...	X7	5	66	69	31	6.4	12.1	10.0
4...	X7	6	1	88	36	6.5	16.0	9.8
4...	X7	6	85	88	29	6.6	11.9	9.5
4...	X7	7	1	90	36	6.6	16.0	9.7
4...	X7	7	85	90	30	6.4	12.0	10.0
4...	X7	8	1	92	35	6.6	16.0	10.0
4...	X7	8	90	92	26	6.4	11.9	10.1
4...	X7	9	1	97	35	6.6	16.0	9.9
4...	X7	9	94	97	25	6.6	11.5	10.0
4...	X7	10	1	84	35	6.6	16.0	9.7
4...	X7	10	80	84	30	6.6	12.0	10.1
4...	X7	11	1	58	35	6.5	17.0	9.6
4...	X7	11	55	58	31	6.4	12.3	10.0

Even though the temperature, pH, and specific conductance values were unstable in the mixing zone or shoreward region of the lake, the stations located at deeper depths showed definite patterns. In general, when stream water at a certain temperature enters impounded water, the stream water not only begins mixing with the resident water, but also tends to flow to a depth interval at which the stream water has the same density as the resident water. Depending on the density difference between incoming water and the reservoir water (mainly related to temperatures), either overflow, underflow, or interflow could result. These flow patterns are shown schematically in figure 6. Boulder Creek inflow water was colder than the surface water of Baker Lake during the September survey and consequently showed a pattern of spreading as an underflow or interflow depending on water depth in the lake. The underflow and interflow patterns are shown clearly in figure 7 where Boulder Creek water with its high specific conductance and low pH was traced as an underflow (fig. 7B) in 16 feet (5 m) of water or interflow (fig. 7A) in 32 feet (10 m) of water. Generally the water from Boulder Creek moved close to the bottom in the shallower part of the lake until it reached deeper waters of the same density, at which depth it moved as interflow.

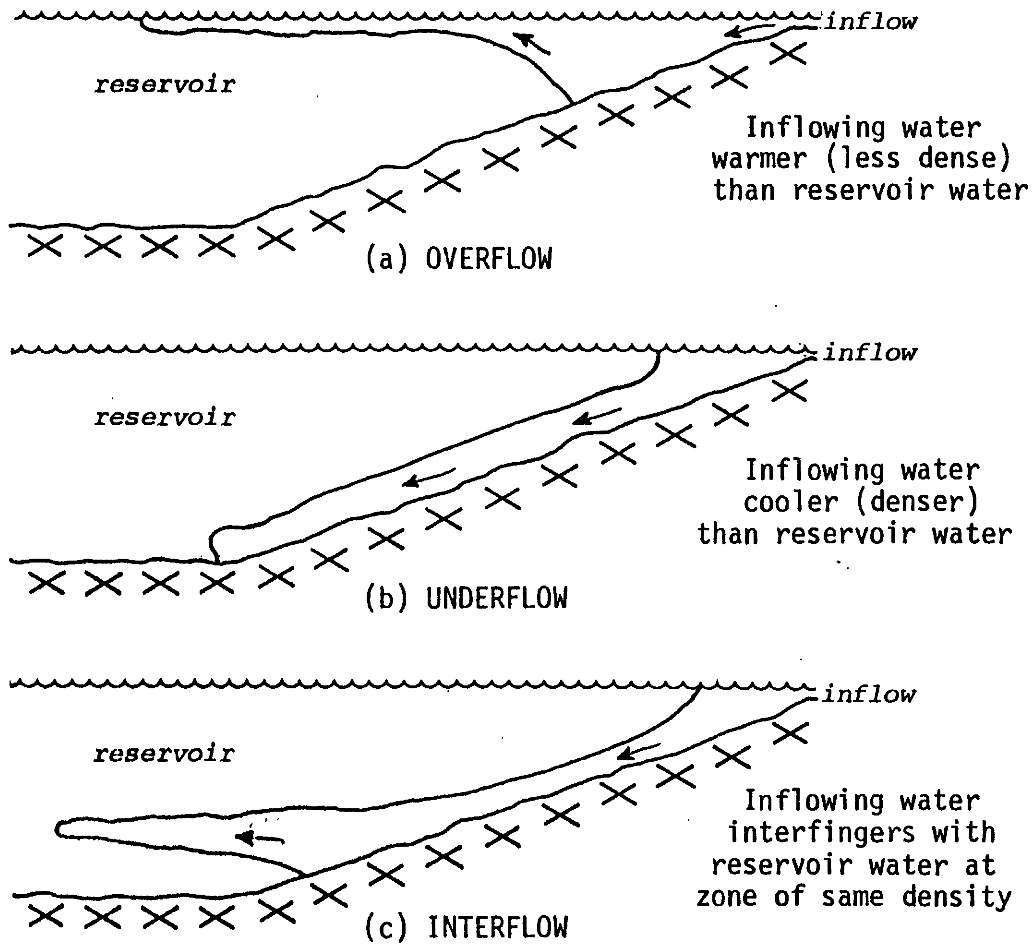


Figure 6.--Schematic sections showing overflow, underflow, and interflow in a reservoir from incoming stream water.

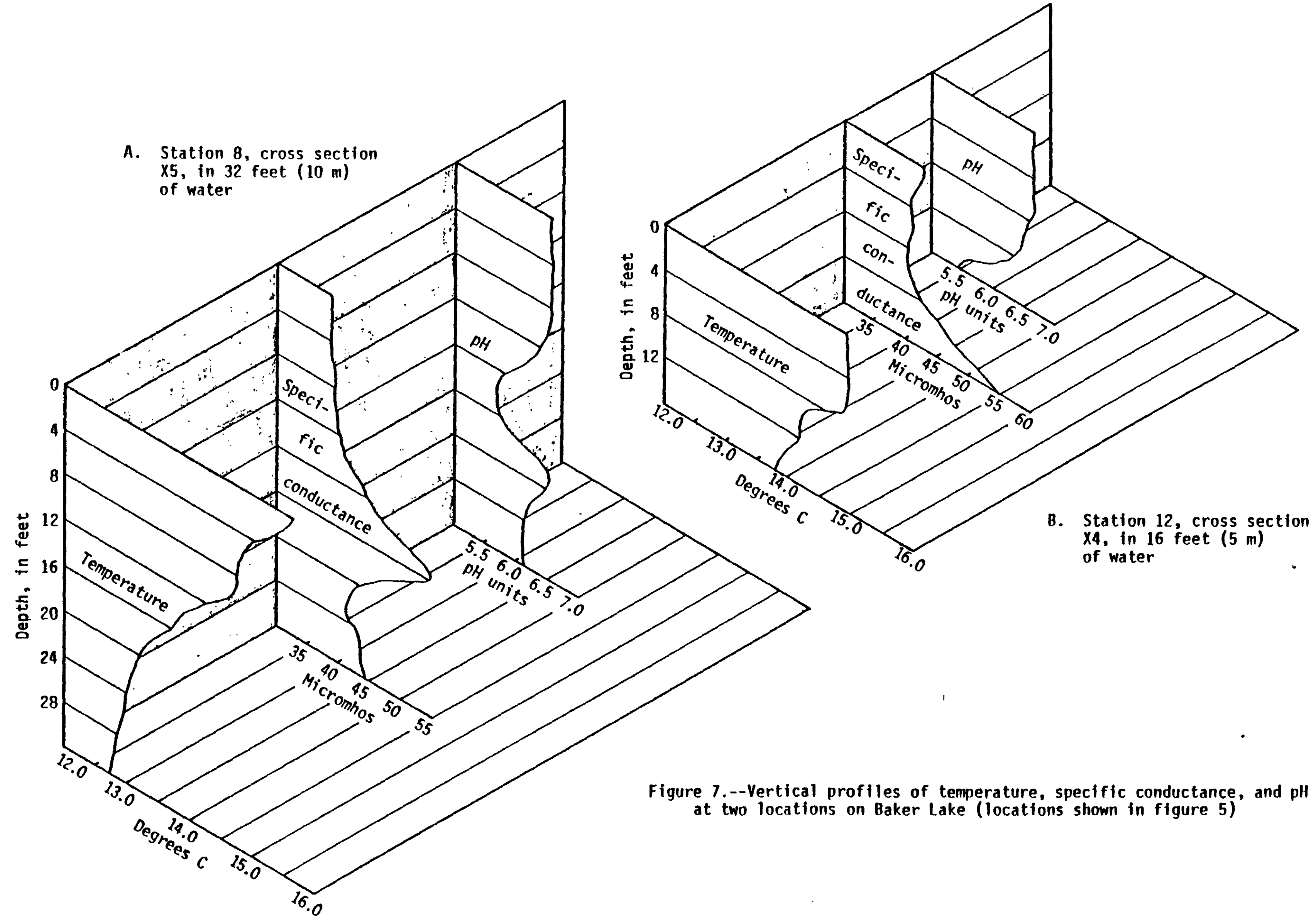


Figure 7.--Vertical profiles of temperature, specific conductance, and pH at two locations on Baker Lake (locations shown in figure 5)

The upper layer of water in that part of the lake remained nearly unchanged in terms of pH and specific conductance. For example, the upper layer of water depicted in figure 7 had about the same quality as the lake water upstream of Boulder Creek (pH 6.7, specific conductance 35). Normal background pH and specific conductance values are shown for the upper waters at all stations in cross sections X4 to X7 of the September 1975 survey (table 4). In contrast, where Boulder Creek water was flowing as underflow in X4, the median nearbottom pH was 5.8 and specific conductance 55 μmhos/cm (table 4). In general, for the greater lake depths in the vicinity of Boulder Creek (deeper than 16 ft or 5 m), the pH was lower by 0.5 to 1.5 units and specific conductance higher by 5 to 20 μmhos/cm from normal background values. However, the dissolved oxygen concentration in the lake did not appear to be affected by Boulder Creek. Dissolved oxygen concentrations were at or near saturation at all depths and stations checked, including those close to shore near the mouth of Boulder Creek (table 4).

The detectable plume of acid-rich water from Boulder Creek, moving as a density current, dissipated as it moved downreservoir. Although the exact areal extent of Boulder Creek interflow is not known, it did not extend beyond the sampling cross section (X7) located about 1.1 miles (1.8 km) south of Boulder Creek. All stations of cross section X7 showed normal background pH and specific conductance values (table 4). The low-pH water was not pooled in large quantities on the bottom.

The results from the September 1975 survey and from the previous studies of Baker Lake provide a general understanding of the persistence or dispersal of Boulder Creek water in the reservoir.

The extent of characteristic Boulder Creek water downreservoir depends upon the dilution and buffering provided in the reservoir; these processes, in turn, depend greatly on temperature and volume of other stream waters entering the reservoir. Boulder Creek drains only about 5 percent of the total drainage area for Baker Lake, and most of the total drainage area (79 percent) is upstream from the creek. Therefore, as Boulder Creek water moves downreservoir it is diluted by water from upstream tributaries moving in the same direction, as well as by the resident reservoir water. The stream water (feedwater) flows through the reservoir as a discernable mass (moving layer) when the reservoir has a temperature stratification (warmest at top, coldest at bottom). Conversely, when the reservoir is about the same temperature throughout (homothermal) there is no distinct moving layer--the entire volume of reservoir water moves as a body. Water from Boulder Creek is most likely to persist as a layer or plume at times when it enters the reservoir as interflow or underflow (fig. 6) and joins a distinct moving layer in its course downreservoir.

The moving layer of stream water is most distinct, and tends to have the least volume, when the temperature stratification is greatest. The stratification usually begins in March and is well underway by May. In summer Baker Lake is moderately stratified. For example, Goodwin (1967, p. 50) measured a $10^{o}C$ difference in water temperature ($18^{o}C$-$8^{o}C$) between the lake's surface and bottom waters (at most depths) in August 1974. During summer the moving layer constitutes the smallest percentage of the reservoir volume; it was only 14 percent of the volume in August 1973, according to Goodwin (1967, p. 31). By December, the reservoir usually loses all stratification (Goodwin, 1967, p. 14). Therefore, during the winter months the acid-rich water from Boulder Creek is likely to mix quickly with the reservoir water, become diluted and buffered, and move with the entire reservoir volume.

The volume of upstream feedwater is important in determining the time required to flush out Boulder Creek water--that is, the speed of its flow through the reservoir. Water-residence time is the time necessary to displace the water in the lake with inflowing water, the rate of which can be estimated by the mean annual outflow. If a mixed (homothermal) water mass, normal pool altitude, and mean annual outflow are assumed, the theoretical average water-residence time for Baker Lake is 0.2 year--meaning that the lake is flushed 5 times a year. The actual water-renewal time for any given time of the year may vary considerably, depending mainly on the flow of the tributaries, total volume of reservoir that is actively engaged in transport of water, and the withdrawal of water from the reservoir. Generally, a reservoir such as Baker Lake, draining a large river system, has a much shorter water-residence time, and can flush a pollution load much faster, than most natural lakes which receive much less inflow.

In summary, three important factors in assessing possible adverse effects of acid-rich water entering Baker Lake are: (1) The flow rate and concentration of acid in Boulder Creek, (2) the degree to which the acidic inflow remains segregated from the other lake water, and (3) the volume of upstream feedwater that dilutes Boulder Creek water.

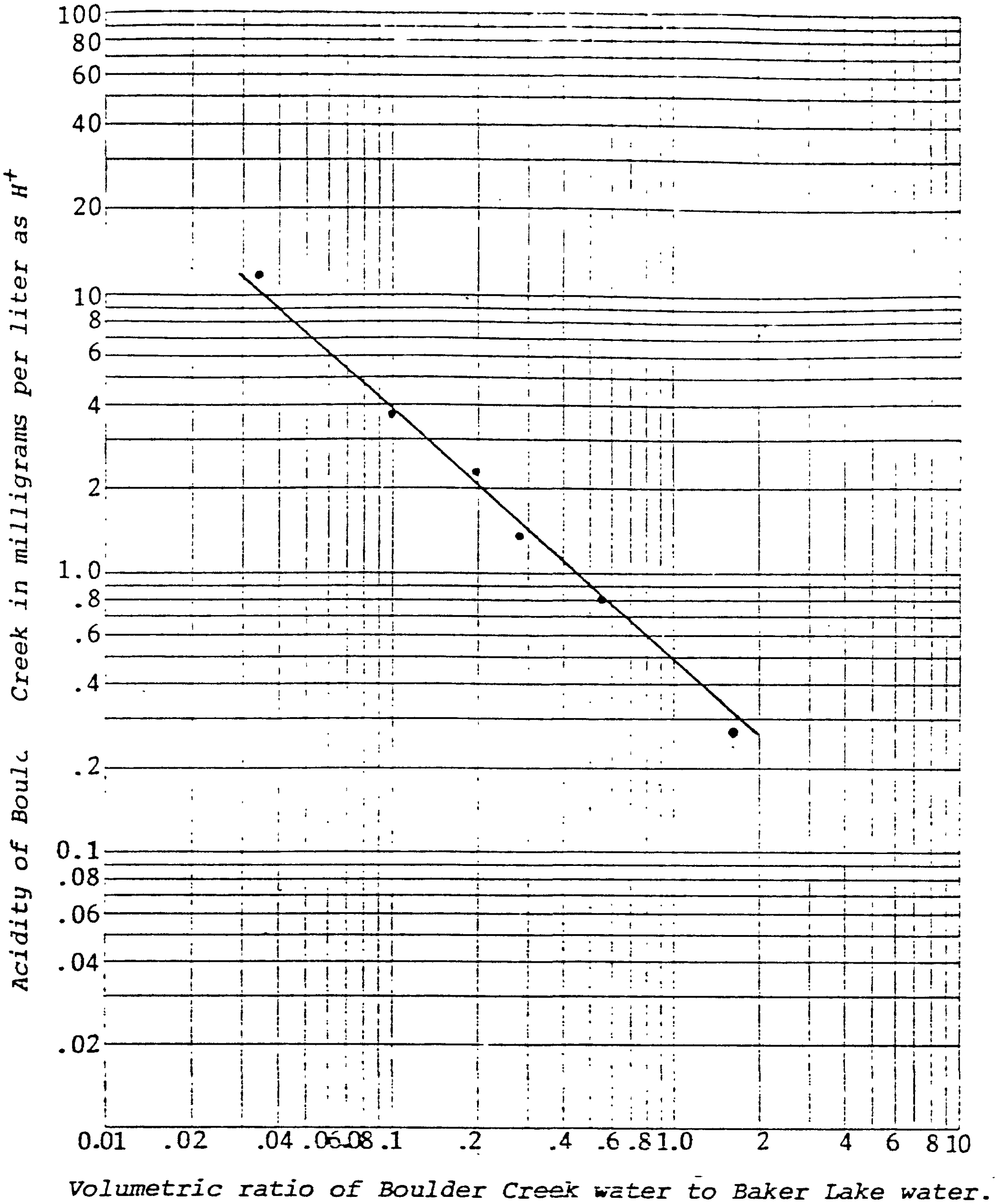
Lake Alkalinity and Acid Buffering Capacity

Another important factor in assessing the possible effects of acid-rich inflow is the ability of the lake to chemically neutralize or buffer the acid. A buffer is a substance or mixture of substances that, in solution, is capable of neutralizing both acids and bases within limits, and thus acts to maintain the original hydrogen-ion concentration (pH) of the solution. Natural buffering action maintains the pH between 6.5 and 8.5 in most open lakes. Lakes in igneous-rock areas, such as Baker Lake, are often not well-buffered, and have low alkalinity values.

The buffering mechanism for Baker Lake is primarily due to the equilibrium between carbon dioxide (CO_2) in the air and bicarbonate ion (HCO_3) in the water. If a few drops of acid are added to a liter of Baker Lake water, little or no change occurs in pH. The bicarbonate ions present, in effect, take up enough of the added hydrogen ions from the acid so that the amount of free hydrogen ions in the solution is not greatly increased. The maintenance of pH by buffering, of course, is possible only within limits. When enough acid has been added to a buffered solution to significantly change the ratio of acid to bicarbonate, the buffer loses its effectiveness; the pH is lowered and responds directly to additions of hydrogen ion.

The capacity of a water to chemically neutralize acid is measured by its "alkalinity", which is a standard way of designating the bicarbonate (HCO_3) and carbonate (CO_3) concentrations in the water. Alkalinity is equivalent to the amount of concentrated sulfuric acid (laboratory standard) needed to neutralize the CO_3 and HCO_3 ions in a liter of water. For Baker Lake water, the completion of the reaction (termed the equivalence point) occurred when the pH was lowered to about pH 5.2-5.5. The alkalinity of Baker Lake water in 1975 was observed to range ~~vary~~ from 14 to 20 mg/liter as calcium carbonate.

To determine the effect of mixing Boulder Creek water with Baker Lake water, laboratory tests similar to alkalinity determinations were made, using acid-rich Boulder Creek water instead of a standard laboratory acid. As in an alkalinity test, the mixing of the two waters produced a neutralization reaction, resulting in the removal from the Baker Lake water of all CO_3 and HCO_3 ions. With the addition of Boulder Creek water to a sample of Baker Lake water, the pH changed very little at first, slowly declined as the buffering capacity was depleted, then changed rapidly and reached the equivalence point at about pH 5.5. The volumetric mixing ratio of Boulder Creek to Baker Lake water at pH 5.5, plotted against Boulder Creek acidity, is shown in the graph of figure 8. Six tests (called titrations) were performed, for Boulder Creek acidities ranging from 0.27 to 12 mg/liter as H^+. The upper leftmost point on the graph (12 mg/liter as H^+) represents a sample taken from a creek in Sherman Crater on September 19, 1975, and the lower rightmost point (0.27 mg/liter as H^+) represents a sample taken at the Boulder Creek station on October 22, 1975. Thus, the ranges on the graph define the approximate upper and lower acidity values observed in 1975. If the acidity of Boulder Creek at a specific time is known, the graph can be used to estimate the relative amount of Boulder Creek water, expressed as a volumetric ratio, required to lower the normal pH of a volume of Baker Lake water to pH 5.5. For example, the graph shows that, in order to lower the pH of Baker Lake water from its normal value to pH 5.5, [50 liters of Boulder Creek water at] an acidity of 0.9 mg/liter as H^+ would need to be added to 100 liters of Baker Lake water. In contrast, only 4 liters of Sherman Crater water at an acidity of 9 mg/liter as H^+ would produce the same neutralizing effect. Experimental titration data (not shown by fig. 8) indicate that at acidity values of 0.1 mg/liter as H^+ or less, the lake could assimilate Boulder Creek water indefinitely, at flows observed in 1975, without lowering the pH of Baker Lake water below 6.0. Furthermore, at a creek-water acidity of 0.5 mg/liter as H^+ (fig. 8), a volume of Boulder Creek water greater than [less than] Baker Lake water would be required to lower the pH of the mixture to 5.5.



EXPLANATION FOR FIGURE 8

For a known acidity of Boulder Creek water, this graph can be used to estimate the relative volume of Baker Lake water needed to buffer the acid as the waters mix. For example, when Boulder Creek water has an acidity of 4 mg/liter as H^+ (represented by horizontal line in upper part of graph) 10 liters of Baker Lake water would buffer about 1 liter of Boulder Creek water (0.1 volumetric ratio) to pH 5.5 in the resultant mixture. Derivation of the graph is discussed in the text.

Figure 8.--Graph showing experimental volumetric capacities of Baker Lake water to buffer Boulder Creek water of various acidities to pH 5.5.

The graph in figure 8 is useful to estimate the buffering capacity of Baker Lake attributable to dissolved buffer components in the water. However, it should be considered as only an approximate relationship because the lake's buffering capacity also may depend on such things as: (1) Ion-exchange processes or buffering by bottom and suspended sediments, (2) biochemical processes, and (3) rates at which buffering reactions take place (Stumm and Morgan, 1970, p. 152).

CURRENT MONITORING ACTIVITIES

Despite the continued steaming of Mount Baker, the Geological Survey's monitoring activities from March 1975 to April 1976 have been unable to detect definite geological warning signals usually associated with impending eruptions. For this reason, and because of the lack of evidence for an imminent steam explosion or some other volcanic event that could trigger a large avalanche or mudflow, the U.S. Forest Service and the Puget Sound Power and Light Co. re-opened Baker Lake, its lakeshore, and nearby campgrounds to public use. The Geological Survey has reduced its level of surveillance but plans to continue, in cooperation with other agencies, periodic visual observations and some seismic and ground-deformation measurements.

For water-resources monitoring, current plans are to continue surveillance of the Boulder Creek-Baker Lake-Baker River system to provide additional background data on water-quality conditions and flow of Boulder Creek, and to detect any significant changes in these conditions. Specifically, the objectives of this program are to:

1. Maintain the radiotelemetry monitor on Boulder Creek to provide hourly ~~instantaneous~~ data on streamflow, pH, stream temperature, and specific conductance. The radiotelemetry capability will allow early detection of any major changes in the flow or water conditions in Boulder Creek that might indicate significant events on Mount Baker related to volcanic activity. Possible events include (a) blockage of the east breach by an avalanche, thereby reducing outflow to upper Boulder Creek and impounding more water in Sherman Crater; (b) changes in the heat emission in the crater, which would tend to increase or decrease melting of snow and ice and the outflow to upper Boulder Creek; or (c) changes in the character or amount of the acidic fluid discharge from vents in and around the crater. These changes might be detected in the pH, specific conductance, temperature, or flow of Boulder Creek water.

    In addition, a continuous record of streamflow and the other characteristics of Boulder Creek will provide background data for: (a) computations of the loads of acid and some mineral constituents reaching Baker Lake from Boulder Creek; (b) computations of percentage contribution of Boulder Creek flow to the total flow through the lake; and (c) assessment of long-term changes in streamflow and water quality corresponding to increased or decreased volcanic activity.

2. Continue periodic sampling of Boulder Creek, Baker Lake, and Baker River for analyses of acidity, heavy metals, and other selected constituents. These data will allow determination of the extent and intensity of water-quality differences and changes within the Boulder Creek-Baker Lake-Baker River system.
3. Monitor water-quality in selected nearby streams by periodically sampling them for determination of acidity and other selected characteristics. The resulting data will define water-quality conditions of adjacent streams that do not head in Sherman Crater. The data will be useful for background comparison to Boulder Creek water and also for assessing the impact of aerosol drift and possible acid rainfall caused by the volcano.

CONCLUSIONS, QUESTIONS, AND SOME ANSWERS

The increased volcanic activity on Mount Baker has sharpened the scientific insight to the dynamic processes of Cascade volcanos, and has provided an impetus to developing a better understanding of possible impacts of volcanic activity, including effects on the water resources. Many questions about water-quality impacts have been raised in relation to management of the water and water-related resources. The data available at present allow answers (in part, provisional) to some of these questions; the monitoring activities and studies now under way are expected to furnish additional answers. Several of the more obvious questions are listed below along with the answers indicated by the available data:

1. Question--Are the waters of Baker Lake and Boulder Creek safe for drinking and other human contact?

   Answer--Water near the surface of Baker Lake, except perhaps near the mouths of Boulder Creek, apparently is not much different from its condition prior to March 1975; therefore, it is of generally excellent chemical quality. Boulder Creek water, however, has always been silty at times; its present acidity, high iron concentration, and slight rotten-egg (hydrogen-sulfide) odor make it even less desirable for drinking and other uses. Although the water in the lower reaches of Boulder Creek, under the conditions so far measured, should not be harmful in normal skin contact, the drinking of this or any other natural water, including Baker Lake, without treatment is not recommended because of the possible presence of bacterial contaminants.

2. Question--Are dangerous constituents being emitted and finding their way into the streams and lake?

Answer--The water analyses made to data included determinations of eight constituents usually considered minor or trace elements, or substances that typically occur in concentrations less than 1 mg/liter. These elements included total lithium, mercury, manganese, aluminum, iron, arsenic, boron, and selenium (tables 1, 2, and 3). Arsenic, selenium, and mercury can be considered "dangerous" to animal life in minor amounts. Using the concentrations of arsenic and selenium shown in table 3 for comparison, the limits recommended by the U.S. Environmental Protection Agency (1973) for public water supplies would not be exceeded unless arsenic concentrations in Boulder Creek increased 9 times, or selenium about 10 times, the concentrations in the April 29, 1975 sample. For mercury (table 1) the highest concentration was 0.2 μg/liter in a Boulder Creek sample--about 10 times less than the recommended limit for public water supplies (U.S. Environmental Protection Agency, 1973, p. 72); however, no mercury was detected in 7 out of 10 samples from Boulder Creek in 1975.

Lithium is present in most natural waters in minor amounts but thermal waters may contain higher lithium levels. In 1975, three samples of Boulder Creek water that were analyzed for lithium showed no detectable concentrations of that element (table 1). Another measured trace element, boron, is toxic to plants in small concentrations. However, even sensitive plants probably would not be harmed by water from Boulder Creek unless boron concentrations more than tripled the amount shown in table 3 (U.S. Environmental Protection Agency, 1973, p. 341). The concentrations of iron (table 3) and manganese (table 1) observed in Boulder Creek exceed the recommended limits for public water supply (Environmental Protection Agency, 1973, p. 69, 71); however, these limits are based on water-user preference rather than toxicity to plants and animals. Low concentrations of aluminum are common to waters at near-neutral pH, but aluminum may occur at higher concentrations in low-pH water. The concentrations of aluminum in the low-pH Boulder Creek water ranged from 440 to 22,000 μg/liter in 1975 (table 1), considerably higher than most natural waters. Although no public water-supply limit has been recommended for aluminum, the presence of ionic aluminum in concentrations greater than 100 μg/liter would be deleterious to growth and survival of fish (U.S. Environmental Protection Agency, 1973, p. 179).

In the analyses of samples from the other streams, little arsenic and no detectable selenium or mercury was found, indicating that the source of these trace elements in Boulder Creek is the drainage from Mount Baker, rather than fallout such as fumarole dust or contaminated precipitation. Although other trace elements may exist in Boulder Creek water in amounts detectable in the laboratory, it is unlikely that any are present in dangerous amounts. However, a broader spectrum of analyses would be required to make certain, and is planned.

3. Question--Are pools or layers of acidic water likely to accumulate in the lake?

Answer--As previously stated, the degree to which inflowing Boulder Creek water remains as a distinct layer, unmixed with the receiving water of Baker Lake, depends mainly on the seasonal temperature stratification in the lake. During the September 1975 survey, when the lake water was temperature-stratified, an identifiable layer of Boulder Creek water was found to extend beyond 0.3 miles (.5 km) from the mouths of the creek (beyond cross section X6) but not as far as 1.1 miles (1.8 km) downreservoir (to cross section X7). The acidity of the inflowing creek water, of course, depends on the acid load received from Sherman Crater and the rate of flow of the creek. Any identifiable layers of acidic water can only accumulate during periods of stratification, which are temporary. Mixing with other lake water goes on continuously, and is especially rapid during the late fall and winter seasons when there is little or no stratification in the lake.

4. Question--Is the acidic water likely to weaken the concrete of Baker Dam?

Answer--Data from the September 1975 survey indicate that the layer of acidic water from Boulder Creek had dissipated before it moved one-third of the distance downlake from the creek to the dam; thus, it appears unlikely that acidic water would pool behind the dam unless Boulder Creek increased greatly in flow and acid load. Acidic waters are generally regarded as damaging to concrete if their pH values are lower than 6 (Czernin, 1962, p. 88), and for lower pH values the corrosion of concrete becomes appreciably more severe (Biczók, 1964, p. 246). Sulfate ions in sufficient concentration also are damaging to concrete. Depending on local conditions, the critical sulfate concentration at which damage would begin may differ widely even for the same type of cement or concrete, but special methods of protecting concrete against corrosion are generally considered necessary when water in contact with the concrete has sulfate concentrations exceeding about 400 mg/liter in still water (Biczók, 1964, p. 187-188). However, according to Czerin (1962, p. 91), a moving water might prove dangerous to concrete while containing no more than 180 mg/liter of sulfate, a concentration that was exceeded in Boulder Creek samples only during March and April 1975.

Therefore, even if Boulder Creek water somehow reached the dam in an undiluted condition, the sulfate concentration, under conditions measured to date, probably would not be great enough to weaken the concrete of the dam, although the hydrogen-ion concentration (pH) apparently would be sufficient to attack the concrete to some degree.

5. <u>Question</u>--Will the acidity of Baker Lake gradually build up?

<u>Answer</u>--As previously stated, the acid in the inflowing Boulder Creek water apparently is being neutralized by natural buffering agents in the lake water (including, perhaps, sediment). Buffering agents are being continually added by inflowing water in Baker River and the many other streams. Under conditions that prevailed in winter 1975, the lake water probably could assimilate the flow of Boulder Creek almost indefinitely without increasing measurably the average acidity of the lake. However, the buffering ability of the lake depends largely on the acid load from Boulder Creek in relation to the inflow from other sources and on the rate of outflow at Upper Baker Dam. If Boulder Creek were to bring in water of the same acidity at a much greater rate of flow, or if the acidity of that or other creeks were to increase greatly, then much more lake water would be needed to buffer and neutralize the greater acidic inflow.

6. Question--Can acid waters from Boulder Creek be expected to cause fish kills in the future?

Answer--Past research has revealed that pH levels of less than 5.0 are lethal to eggs and fry of salmon, whereas waters with a pH in the range of 6.0-6.5 are unlikely to be toxic to fish unless free carbon dioxide is present in excess of 100 mg/liter (U.S. Environmental Protection Agency, 1973, p. 141). Conditions during the September 1975 survey suggest that, when the lake is well stratified, not much increase in acid load would be required to produce a pH of 5 or less near the mouth of Boulder Creek. Therefore, even if the acid load from Boulder Creek does not greatly increase in the future, occasional light fish mortalities would not be surprising--particularly, because hydrogen sulfide toxicity to fish is greatly increased in acidic conditions. However, according to Bell (1973, chap. 10, p. 1), the ultimate effects of low pH on fisheries may depend on many factors such as temperature, dissolved oxygen, concentrations of various other dissolved constituents, and prior acclimatization of the fish to acid water. The timing of acid infusion to a lake also may be important. Sudden drops in pH at the time fish are spawning or eggs are hatching may cause malformation and death to developing fish, even at acidity levels lower (pH levels higher) than those normally harmful to adult fish (Chemical and Engineering News, 1976, p. 15).

If the volcanic activity should increase greatly, the load of acid reaching Baker Lake would likely increase, and the chance of acid-related fish kills could increase accordingly. Also, of course, fish mortalities might occur at any time from other unrelated causes. Since the acidic potency of Boulder Creek is locally increased during the summer, it is during this period of the year that the greatest biological impact may occur, such as fish kills--especially if the Boulder Creek acid load became greater than that in September 1975.

In conclusion, the greatest level of volcanic activity observed during 1975 undoubtedly caused increased inflow of acidity and dissolved constituents to Baker Lake by way of Boulder Creek, but the inflowing creek water apparently had no major deleterious effect on the lake, its fisheries, or Upper Baker Dam. However, the available data indicate that the same array of acid or other mineral input, in somewhat greater concentrations or at greater rates, could be more serious. The greater input could occur in at least three ways: (1) Temporary blockage of the east breach of Sherman Crater, with accumulation and subsequent sudden release of a slug of the more potent Sherman Crater water; (2) greater volcanic activity, with corresponding increase in the load of acidity and other constituents in Boulder Creek water; or (3) increases in the acidity or concentration of troublesome dissolved constituents in other streams draining from Mount Baker to Baker Lake.

Despite the monitoring experiments and observation programs, it is uncertain whether the mountain's activity will continue and lead to an eruption, mudflow, or additional impact on local water resources, or whether current activity eventually will die away until some future time. This uncertainty, and the magnitude of the possible effects on Baker Lake, make continued monitoring of Mount Baker and the affected water resources very desirable.

REFERENCES

Bell, M. C., 1973, Fisheries handbook of engineering requirements and biological criteria: U.S. Army Corps of Engineers, Fisheries Research Program, chap. 10, p. 1-3.

Biczók, Imre, 1964, Concrete Corrosion--Concrete Protection: Budapest, Hungarian Acad. Sci., 543 p.

Chemical and Engineering News, 1976, Norway: Victim of other nations' pollution: Chemical and Engineering News, v. 54, no. 25, p. 15-16.

Cogbill, C.V., and Likens, G.E., 1974, Acid precipitation in the northeastern United States: Water Resources Research, v. 10, no. 6, p. 1133-1137.

Czernin, Wolfgang, 1962, Cement Chemistry and Physics for Civil Engineers: New York, Chemical Publishing Co., 139 p.

Davis, R.M., 1959-76, Water supply outlook for Washington: Portland, Oreg., U.S. Soil Conservation Service, dupl. rept. (published monthly during Jan.-June for years indicated).

Frank, David, 1975, Subglacial transfer of geothermal fluids in Boulder Glacier, Washington (abs): Amer. Geophys. Union Trans., v. 56, no. 8, p. 532.

Frank, David, Post, Austin, and Friedman, J.D., 1975, Recurrent geothermally induced debris avalanches on Boulder Glacier, Mount Baker, Washington: U.S. Geol. Survey Jour. Research, v. 3, no. 1, p. 77-87.

Frank, David, Meier, M.F., and Swanson, D.A., 1976, Assessment of increased thermal activity at Mount Baker, Washington, March 1976-March 1977: U.S. Geol. Survey Professional Paper ___ (in preparation).

Gibbs, George, 1874, Physical geography of the northwestern boundary of the United States: Jour. Amer. Geog. Soc. of New York, v. 4, p. 298-392.

Goodwin, C.L., 1967, Comparative physical limnology of seven hydroelectric reservoirs in the western United States: State of Washington Dept. of Fisheries Summary Rept., 74 p.

Hyde, J.H., and Crandell, D.R., 1975, Origin and age of postglacial deposits and assessment of potential hazards from future eruptions of Mount Baker, Washington: U.S. Geol. Survey Open-File Rept. 75-286, 22 p.

Malone, S.D., and Frank, David, 1975, Increased heat emission from Mount Baker, Washington: Amer. Geophys. Union, v. 56, no. 10, p. 679-685.

Radke, L.F., Hobbs, P.V., and Stith, J.L., 1976, Airborne gases and aerosols from volcanic vents on Mt. Baker: Geophys. Research Letters, v. 3, no. 2, p. 93-96.

Stumm, Werner, and Morgan, J.J., 1970, Aquatic chemistry: New York, Wiley-Interscience, 583 p.

U.S. Environmental Protection Agency, 1973, Water Quality Criteria, 1972: Ecological Research Series, EPA-R3-73-033, 594 p.

U.S. Geological Survey, 1955, Compilation of records of surface waters of the United States through September 1950, Pt. 12, Pacific Slope basins in Washington and upper Columbia River basin: U.S. Geol. Survey Water-Supply Paper 1316, 592 p.

——— 1961, Quality of surface waters of the United States, Pts. 9-14, Colorado River basin to Pacific Slope basins in Oregon and lower Columbia River basin: U.S. Geol. Survey Water-Supply Paper 1885, 677 p.

——— 1962, Quality of surface waters of the United States, Pts. 9-14, Colorado River basin to Pacific Slope basins in Oregon and lower Columbia River basin: U.S. Geol. Survey Water-Supply Paper 1945, 691 p.

——— 1963, Quality of surface waters of the United States, Pts. 9-14, Colorado River basin to Pacific Slope basins in Oregon and lower Columbia River basin: U.S. Geol. Survey Water-Supply Paper 1951, 781 p.

——— 1964, Compilation of records of surface waters of the United States, October 1950 to September 1960, Pt. 12, Pacific Slope basins in Washington and upper Columbia River basin: U.S. Geol. Survey Water-Supply Paper 1736, 415 p.

——— 1965, Water quality records in Washington, 1964: Tacoma, Washington (annual reports of a series).

——— 1966, Water resources data for Washington, 1965, Pt. 2, water quality records: Tacoma, Washington (annual reports of a series).

——— 1971, Surface water supply of the United States 1961-65, Pt. 12, Pacific Slope basins in Washington: U.S. Geol. Survey Water-Supply Paper 1932, v. 1, 679 p.

——— 1972-75, Water resources data for Washington, Pt. 1, surface water records, 1971-74: Tacoma, Washington (annual reports published for years indicated).

——— 1974, Surface water supply of the United States, 1966-70, Pt. 12, Pacific Slope basins in Washington: U.S. Geol. Survey Water-Supply Paper 2132, v. 1, 640 p.

Westley, R.E., 1966, Limnological study of Merwin, Upper Baker, and Lower Baker Reservoirs: State of Washington Dept. of Fisheries Summary Rept., 206 p.

Wilson, R.T., and Fretwell, M.O., 1976, Table of data on quality of surface waters and of snowpack draining to Baker River from Mount Baker, Washington: U.S. Geol. Survey open-file rept. (unnumbered), 4 p.

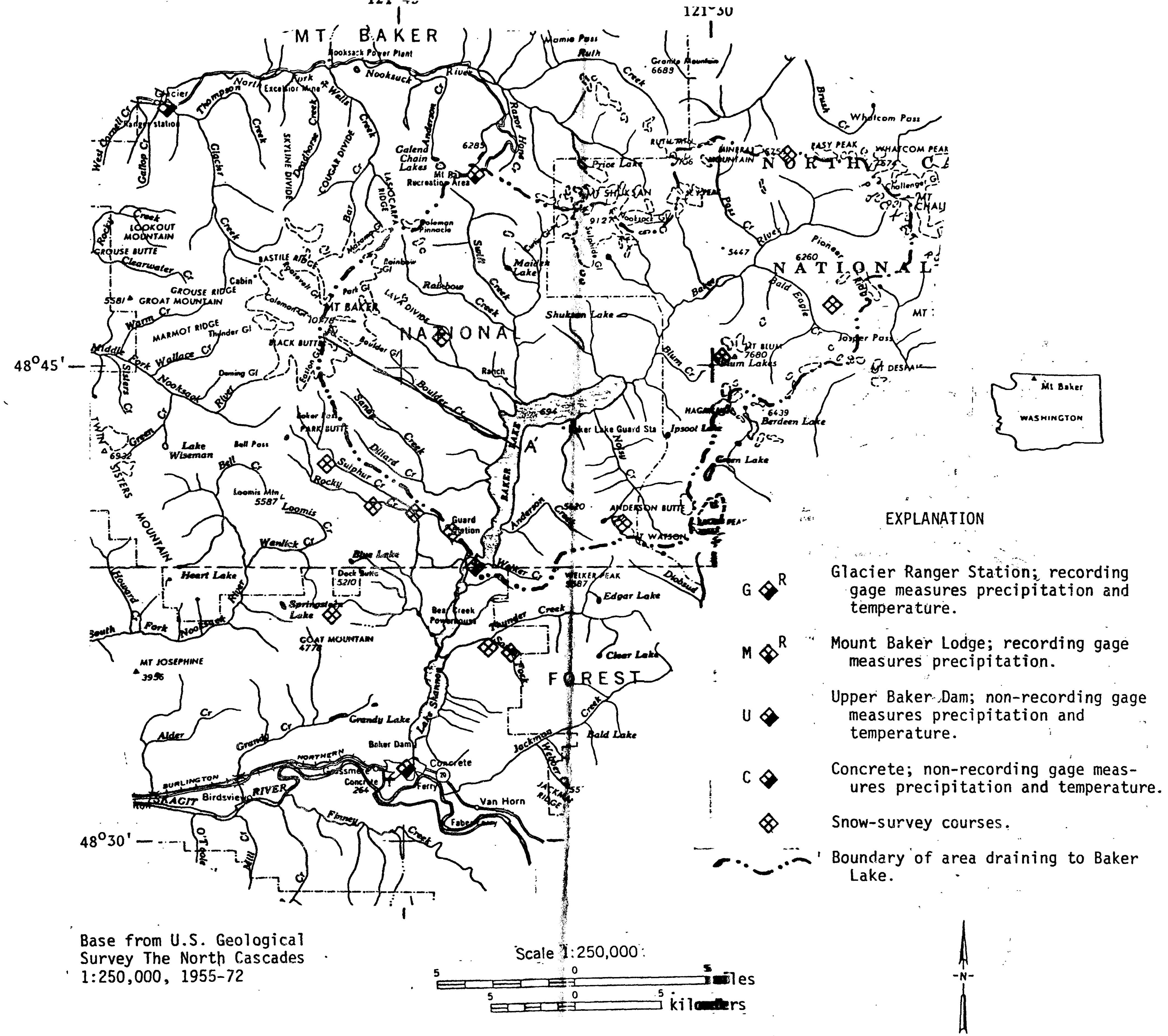


Figure 1.--Map of Mount Baker and vicinity, showing sites for collection of air-temperature and precipitation data.

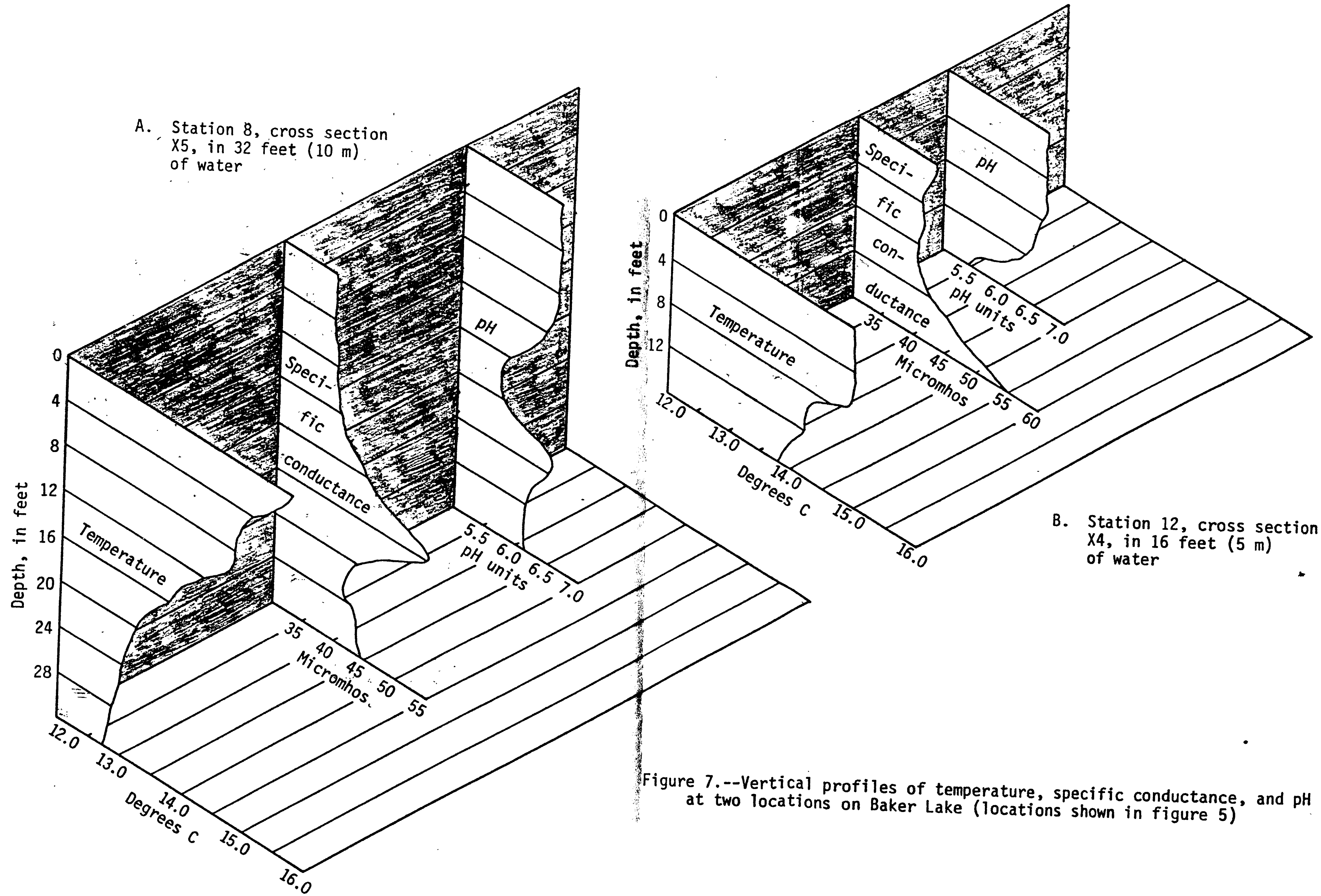


Figure 7.--Vertical profiles of temperature, specific conductance, and pH at two locations on Baker Lake (locations shown in figure 5)