HYDROLOGIC HAZARDS ALONG SQUAW CREEK FROM A HYPOTHETICAL FAILURE OF THE GLACIAL MORAINE IMPOUNDING CARVER LAKE NEAR SISTERS, OREGON

By Antonius Laenen, K M. Scott, J. E. Costa, and L. L. Orzol

U.S GEOLOGICAL SURVEY

Open-File Report 87-41

Portland, Oregon
1987

UNITED STATES DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary
GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

Oregon Office Chief
U.S. Geological Survey
847 N.E. 19th Ave., Suite 300
Portland, OR 97232

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Building 41
Box 25425
Denver, CO 80225
(Telephone: (303) 236-7476)

CONTENTS

FRONTISPIECE

Aerial photograph showing Carver Lake

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain metric units
	Length	
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	square kilometer (km^2)
	Volume	
acre foot (acre-ft)	1,233.6	cubic meter (m^3)
cubic yards (yd^3)	0.7646	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

DEFINITION OF TERMS

Debris flow according to Pierson (1982) is considered to be a dense, viscous slurry of poorly sorted gravel, sand, mud, and water sometimes containing organic material. The coarse fragments, suspended in a fluid matrix of silt- and clay-sized particles plus water, are held in suspension by various combinations of friction, buoyant, dispersive, and cohesive forces.

Clearwater flow in this report is considered to have a sediment concentration less than 40 percent by weight.

Hyperconcentration is arbitrarily defined as the sediment concentration between 40 and 80 percent solids by weight (Beverage and Culbertson, 1964). Debris flows are normally from 80 to 90 percent solids by weight.

Lahars are debris flows of volcanic origin. They are heated, especially near the source.

Mudflows are debris flows with larger quantities of silt and clay (less rubble or larger clast material).

Thalweg is the line connecting the lowest or deepest points along a stream bed or valley, whether under water or not.

HYDROLOGIC HAZARDS ALONG SQUAW CREEK FROM A HYPOTHETICAL FAILURE OF THE GLACIAL MORAINE IMPOUNDING CARVER LAKE NEAR SISTERS, OREGON

--

By Antonius Laenen, K. M. Scott,
J. E. Costa, and L. L. Orzol

--

ABSTRACT

A hydrologic hazard exists that could create a large-magnitude, but short-duration, flood in the Squaw Creek drainage and inundate areas in and around the community of Sisters, Oregon. Carver Lake, located at elevation 7,800 feet above sea level on the east slope of South Sister mountain, Oregon, could catastrophically empty. The probability of this lake-breakout flood is estimated to be approximately 1 to 5 percent for any given year. At the U.S. Geological Survey gage (14075000) on Squaw Creek between Carver Lake and Sisters, the magnitude of the breakout flood would be 10 times that of a 1-percent probability meteorological flood. In Sisters, the magnitude of the breakout flood would be about five times that of a 1-percent probability meteorological flood. Meteorological flood occurrences from precipitation and snowmelt are a separate and distinct statistical population from lake-breakout flood occurrences and are only used for comparison purposes.

Several conditions at Carver Lake indicate the potential hazard:

(1) The lake is very deep for its size. The lake contains 740 acre-feet of water and is more than 100 feet in depth.

(2) There is a probability that a large magnitude avalanche and consequent overtopping of the lake could occur. There are steep slopes of unstable volcanic rock and an extensively cravassed glacier located above the lake.

(3) The moraine dam confining the lake is steep-faced, rendering the dam unstable, and unvegetated making it highly erodible.

(4) Large amounts of readily-erodible material available for transport would increase the magnitude of a large flood and keep the flood from attenuating in the steep reaches of the Squaw Creek channel.

(5) Geologically, there is a greater-than-normal possibility for the area to become seismically active. Earthquakes could cause rock and ice to fall into the lake.

A one-dimensional unsteady-state streamflow model was used to route a hypothetical flood down the Squaw Creek drainage. The most extreme scenario considers the lake to be drained almost instantaneously by the displacement of lake water by a rock or ice avalanche. This scenario creates a starting hydrograph with a peak of 180,000 ft^3/s (cubic feet per second). The ensuing hypothetical flood would incorporate readily erodible debris and sediments in the steep canyons, that would increase the total volume of the flood by a factor of two. As the peak emerges from the steeper slopes into a more gently-sloping valley 8 miles from the lake, the peak would attenuate to 47,000 ft^3/s. At the Geological

Survey gage at river mile 26.6, 15.4 miles downstream from the lake (in a valley just upstream of an alluvial fan area), the peak would attenuate to 21,000 ft^3/s. In Sisters on the alluvial fan, at about 20 miles downstream from the lake, the peak would continue to attenuate to 9,800 ft^3/s. Two other scenarios of lesser magnitude were assessed to define the lower range of the hazard.

INTRODUCTION

Background

The Three Sisters area in central Oregon (fig. 1 and 2) has one of the largest concentrations of neoglacial moraine-dammed lakes in the conterminous United States. Floods that resulted from at least three moraine-dam failures in the last 50 years have traveled down the drainages of Soda Creek, Squaw Creek, and White Branch (fig. 3). Recent field work by the U.S. Geological Survey in 1985-86 defined peak flows that reached magnitudes of at least 13,000 ft^3/s and traveled as debris flows as far as 10 miles downstream from the source.

Field work during the past 4 years has been conducted in the Three Sisters area as part of a larger study assessing hydrologic hazards caused by volcanic activity. This work is part of the Geological Survey program known as "Volcanic Hazards Program." Original hydrologic surveys in the Three Sisters Wilderness Area were intended to document channel cross sections for planned computer-simulated modeling of catastrophic volcanic lahars. In assessing the area, it became evident that many flows (debris and hyperconcentrated flows) had resulted from past moraine-lake breakouts, glacial outbursts, and avalanches. Later surveys (fig. 3) documented the flows of glacial origin. Some of the hydraulic information obtained in these later surveys is shown in table 1.

Part of the recent field work in the area documented a flow originating from a moraine-lake breakout that occurred on September 7, 1970 in the upper North Fork Squaw Creek drainage (fig. 4). A volume of approximately 200 acre-ft of water was released from this moraine lake, which drained entirely. This flow reached a magnitude in excess of 10,000 ft^3/s several times during descent from the 7,500-foot elevation. The peak attenuated to 8,000 ft^3/s as it exited from steeply sloping canyons at about elevation 4,400 feet, 7 miles from the source. As the peak flow passed the Geological Survey gage (14075000) approximately 15 miles downstream from the source, it had been drastically reduced to 1,200 ft^3/s (2.5 feet of stage increase at the gage). (For comparison purposes, the highest peak of record since 1909 at the Geological Survey gage was 2,000 ft^3/s, which occurred on December 25, 1980.) At Sisters the peak flow had attenuated even more drastically and passed through as a small muddy-water surge of about 1 foot in height.

Another well documented moraine-lake breakout in the area occurred in the Soda Creek drainage (Nolf, 1966). About 150 acre-ft of water was released, only partially draining Moraine Lake on Broken Top Mountain at elevation 8,000 feet (fig. 5). This moraine-dam failure created a maximum flood peak of about 7,000 ft^3/s at higher elevations and a flood peak of about 2,000 ft^3/s as it inundated the Sparks Lake area, 6 miles downstream. Moraine Lake could breach again in the near future, causing a flood event of similar magnitude. About another 150 acre-ft of water remain in this lake.

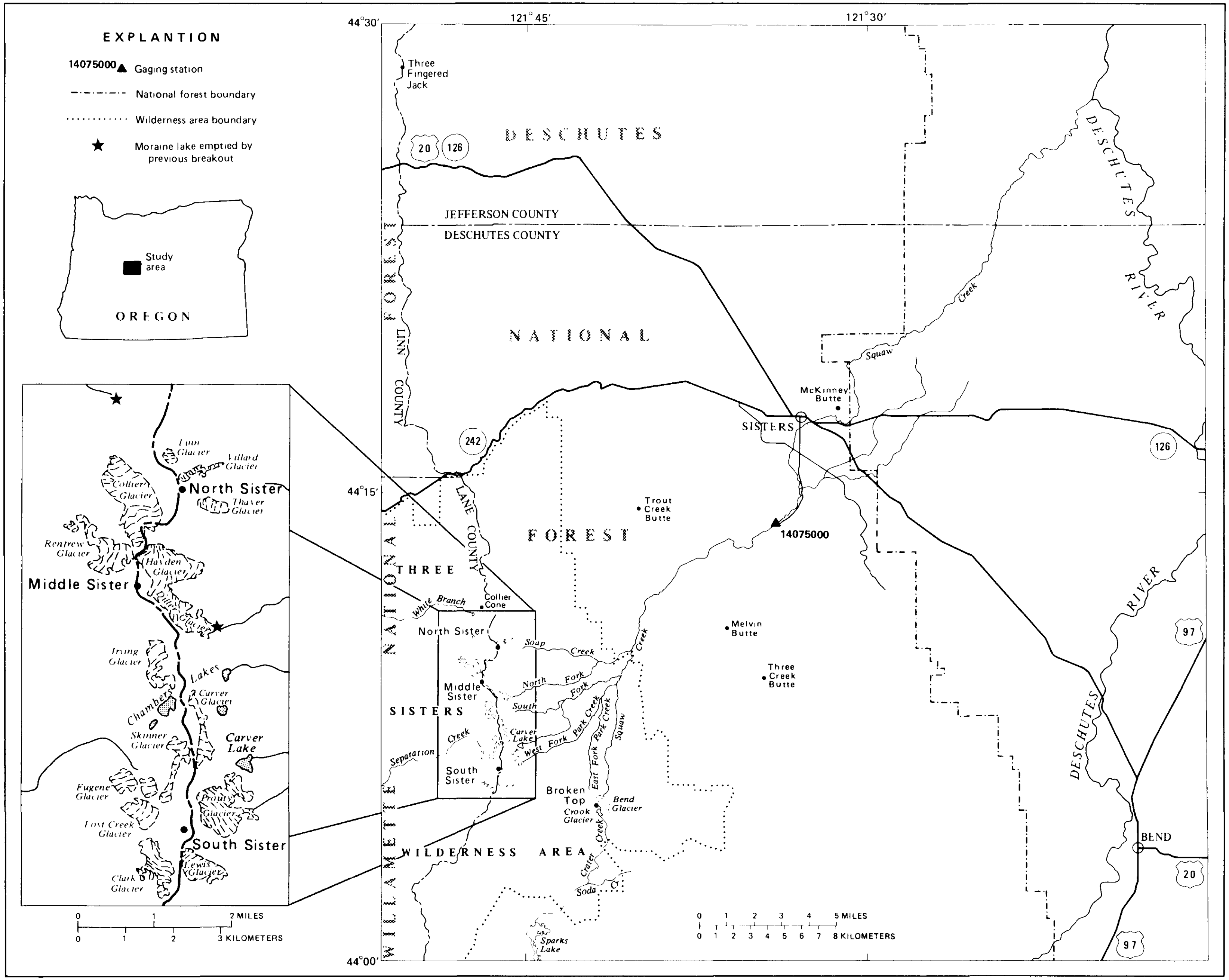
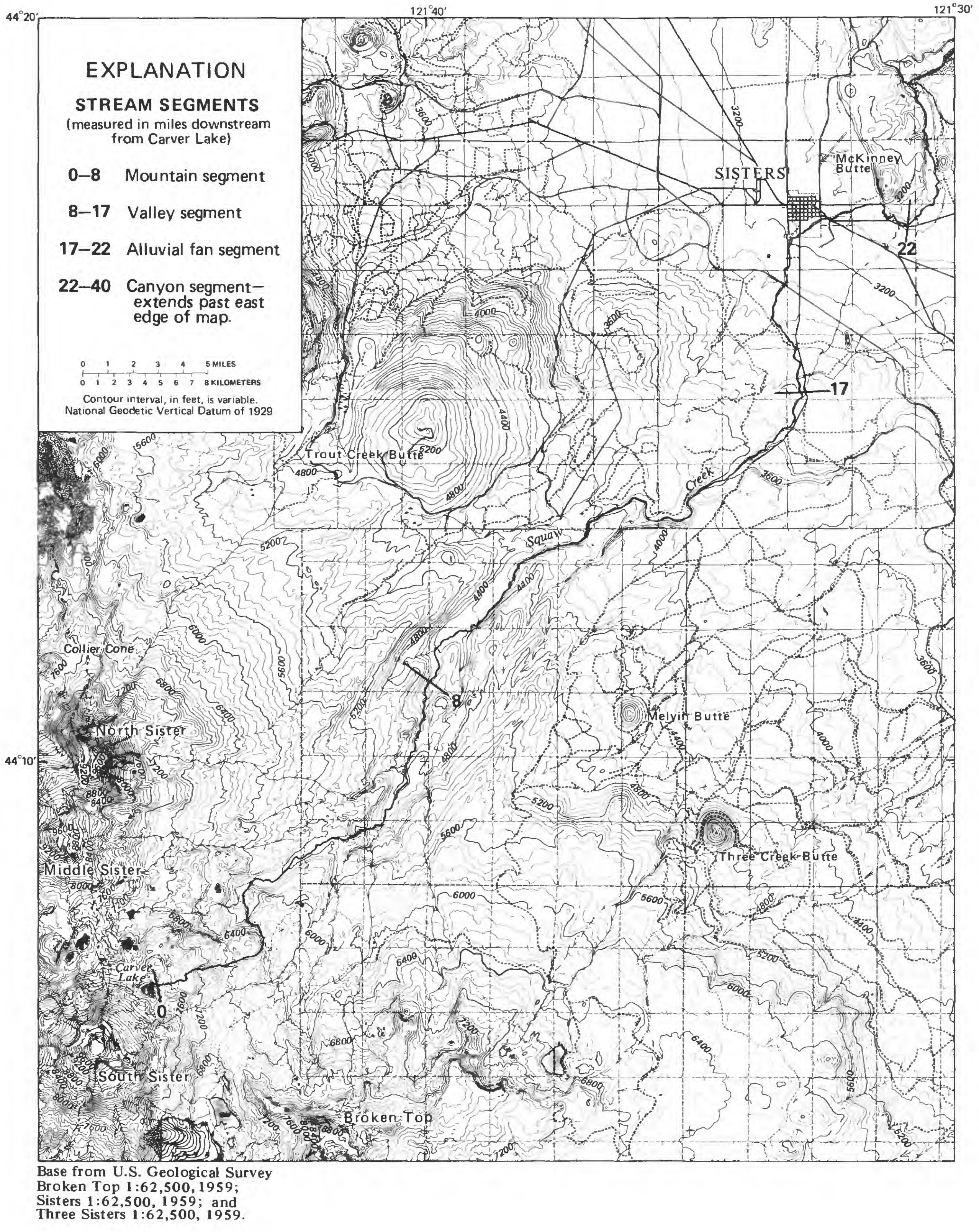


Figure 1. – Location map.



Base from U.S. Geological Survey
Broken Top 1:62,500, 1959;
Sisters 1:62,500, 1959; and
Three Sisters 1:62,500, 1959.

Figure 2. – Topographic map of study area showing Squaw Creek divided into segments dependent on slope and geometry.

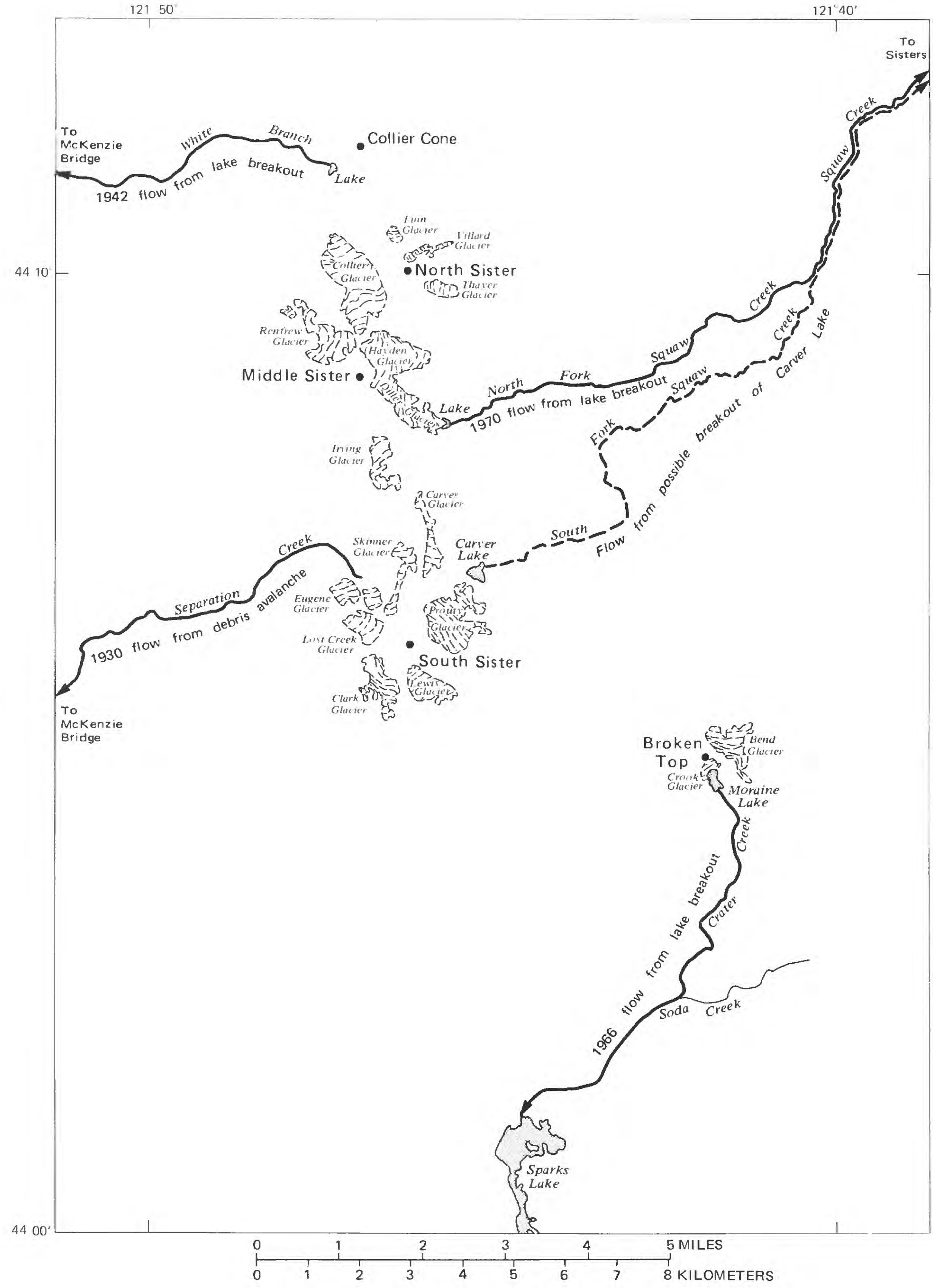


Figure 3. – Generalized flow paths of recent floods of glacial origin.

Table 1.--Hydraulic data for floods from glacial-moraine breakouts in the Three Sisters area, from Geological Survey work done in 1985-1986

Stream	Date of flood	Elevation (ft)	Peak discharge (ft^3/s)	Velocity (ft/s)	Manning's "n" coefficient	Type of survey
Soda Creek	10-07-66	7,200	3,700	14.7	0.076	Superelevation
		6,560	7,300	20.0	.084	Superelevation
		5,520	2,500	13.0	.032	Critical depth
Squaw Creek	9-07-70	6,400	10,500	25.6	.051	Superelevation
		4,720	11,500	31.6	.039	Superelevation
		4,420	8,000	11.9	.020	Slope/area
White Branch	07-42	6,400	12,600	30.9	.086	Superelevation

Figure 4. – Moraine breach in the North Fork Squaw Creek drainage that occurred September 7, 1970 (see arrow). Diller Glacier on Middle Sister is in the background. The lake level dropped 84 feet, completely emptying the lake. This photo shows how moraines are deposited in front of glaciers, August 1986.

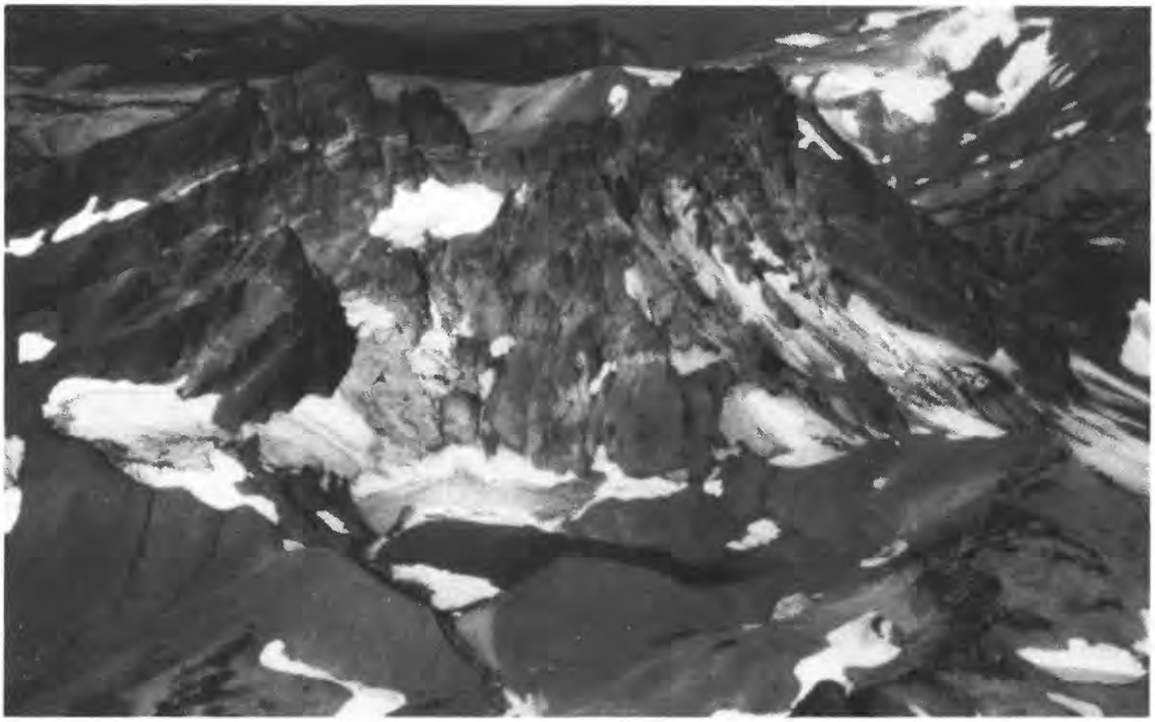


Figure 5. – Moraine lake with Broken Top in the background. The moraine breach occurred on October 7, 1966, causing a flood in the Soda Creek drainage. (Photo courtesy of U.S. Forest Service, 9/3/86)

Recent field work also has revealed a significant hydrologic-hazard potential at Carver Lake in the Squaw Creek basin at elevation 7,800 feet on the east flank of the South Sister (fig. 1). The following factors indicate that the lake is a particular hazard:

(1) Carver Lake is large and deep. It has a maximum depth of 101 feet and contains approximately 740 acre-ft of water (about five times the volume of the moraine lake that breached in 1970). Most lakes in the area are relatively shallow compared to Carver Lake.

(2) The moraine dam is unstable. The material in the moraine generally consists of sand- and gravel-size particles that are loosely consolidated. The moraine-dam face is at a slope of 42 degrees, is steeper than the angle of repose, and is unvegetated. The outlet channel of the lake is not significantly armored with boulder-size material and is thereby potentially erodible in the event of an overtopping wave of water.

(3) Avalanches of rock and ice that could cause the lake to overtop the moraine are highly probable. In August of 1930, a large avalanche occurred on the west side of South Sister (fig. 3). Large volumes of potentially unstable rock rise with vertical slopes above the headwaters of the lake. The steeply sloping and heavily crevassed Prouty Glacier also is located almost immediately above the lake.

(4) Large amounts of readily erodible material are available for transport in the channel below the lake. Debris-flows attenuate differently than clearwater flood flows because debris flows increase in volume by picking up sediment and debris where channel slopes are steep. A larger breakout than that which occurred in 1970 would mobilize more material and create a larger magnitude flood. Once channel slopes become more gentle, however, debris flows generally attenuate more quickly than clearwater flows.

(5) Although the area is not now seismically active, earthquakes could be generated with renewed volcanic activity in the Three Sisters area. Basaltic eruptions in the area occurred as recently as 400 years ago, when Collier Cone was created (Taylor, 1965). Tremors would increase the probability for avalanches to occur.

Purpose and Scope

The purpose of this report is to alert State and Federal agencies and the public of the hydrologic hazard associated with a potential breakout of Carver Lake. The report identifies specific flood hazards, based on reasonable scientific assumptions and computations for a hypothetical flooding down Squaw Creek and through the community of Sisters in the event of a catastrophic breakout of Carver Lake. Computer models were used to simulate a starting flood hydrograph at the moraine dam and route the flow downstream. Three failure scenarios were addressed: (1) most extreme, which assumes total displacement of the lake by avalanche material; (2) next extreme, which assumes the moraine dam to breach to a maximum lake depth in 3 minutes; and (3) least extreme, which assumes only the upper 25 feet of the lake to drain with a maximum breach in 3 minutes. We assumed that the simulated floods would increase in volume by two times from sediments and debris incorporated in the flow in the steep upper reaches of the channel.

NEOGLACIAL MORAINE DAMS

Many moraine dams occur throughout the world, but the most dangerous of these are restricted to alpine regions affected by the advances and retreats of valley glaciers in steep mountain areas. A globally synchronous readvance of glaciers during the last few centuries has been documented (Grove, 1979); this readvance has been referred to as the Little Ice Age (Matthes, 1939) or neoglacial time (Porter and Denton, 1967). More recent local glacial oscillations also have created moraine-dammed lakes. Neoglacial ice advances in mountain areas north of the Three Sisters area have been documented by Scott (1977). In the last 50 years, mountain glaciers have retreated significantly (Porter and Denton, 1967), leaving behind many moraine-dammed lakes.

Neoglacial moraine-dammed lakes are hazards because (1) they are sufficiently young and located at such high elevations that ground vegetation has not completely stabilized their slopes, so that that they are highly erodible; (2) slopes are steep, and some are greater than the angle of repose; (3) thermal degradation may have melted an ice or snow core in some moraines, rendering them unstable; and (4) these dams are close to the ice front and adjacent to steep, rock-walled valleys. Extensive meltwater or ice and (or) rock falls into the lakes may precipitate breaching failure of these dams.

Comprehensive descriptions of the failure of morainal dams are rare (table 2) because such failures occur primarily in remote areas. Moraine-dam failures in the Cordillera Blanca and Cordillera Huayhuash of north-central Peru are an exception. This highly populated region has an especially large number of moraines enclosing narrow, steep valleys. Nearly all glaciers of the Cordillera Blanca lie behind large push moraines of neoglacial age and contain lakes (Lliboutry and others, 1977). In 1941, Laguna Cohup, a proglacial moraine-dammed lake, drained rapidly when the moraine dam failed. The resulting flood of mud and water (known in Spanish as "alluvion") destroyed almost half of the town of Huaraz and killed more than 6,000 people (Ericksen and others, 1970; Eisbacher, 1982). This disaster led to a major effort toward control and lowering of lake levels in dangerous moraine-dammed lakes in Peru (Lliboutry and others, 1977).

The most comprehensive description of the failure of a morainal dam known to us, as reported by Blown and Church (1985), is the failure of the morainal dam of Nostetuko Lake, British Columbia, Canada (fig. 6). On July 19, 1983, Nostetuko Lake, dammed by the neoglacial moraine of Cumberland Glacier in the Coast Mountains of British Columbia, partly drained and sent a large flood of water and debris down the Nostetuko River. The lake was lowered by 126 feet as 5,200 acre-ft of water was released. The breach of the moraine dam was initiated when glacial ice collapsed into the lake, forming a single large wave that translated across the lake to the outlet channel across the top of the moraine. The wave augmented flow in the outlet channel, initiating erosion that permitted increased flow from the lake as it began to drain.

Most of the textural data from morainal dams indicates that the moraine material is silty, sandy, bouldery till, with very little clay (less than 5 percent). Lake levels are controlled by seepage through the barrier and open overflow channels across the top of the moraine. The moraines may or may not have ice cores but have ground water that probably is frozen at depth for most of the year.

Table 2.--Examples of moraine dams that have failed

Lake or site name	Location	Date failed	Change in lake level (ft)	Volume discharged (acre-ft)	Flood peak (ft^3/s)	Failure mechanism	Reference
Jancarurish	Peru	1950	21	4,800-8,000	240,000-280,000	Collapse of undercut glacier	Lliboutry and others, 1977
Soda Creek	Oregon, USA	10-07-66	4.6	150	3,700	Ice fall	Nolf, 1966
Squaw Creek	Oregon, USA	9-07-70	25.6	200	10,500	--	
Safuna Alta	Peru	1970	38	3,900 (stored in lake)	--	Earthquake-induced piping	Lliboutry and others, 1977
Klattasine	British Columbia, Canada	June 1971-Sept. 1973	13	1,400	35,000	--	Clague and others, 1985
Moraine #13	Soviet Union	8-03-77	5.2	70	7,500	Melting of frozen soil	Yesenov and Degovets, 1979
Nostetuko	British Columbia, Canada	7-19-83	38.4	5,200	380,000	Ice fall	Blown and Church, 1985
Langmoche glacier	Nepal	8-04-85	--	1,600	--	Ice fall	Galey, 1985; V. S. Williams, written commun., 1986

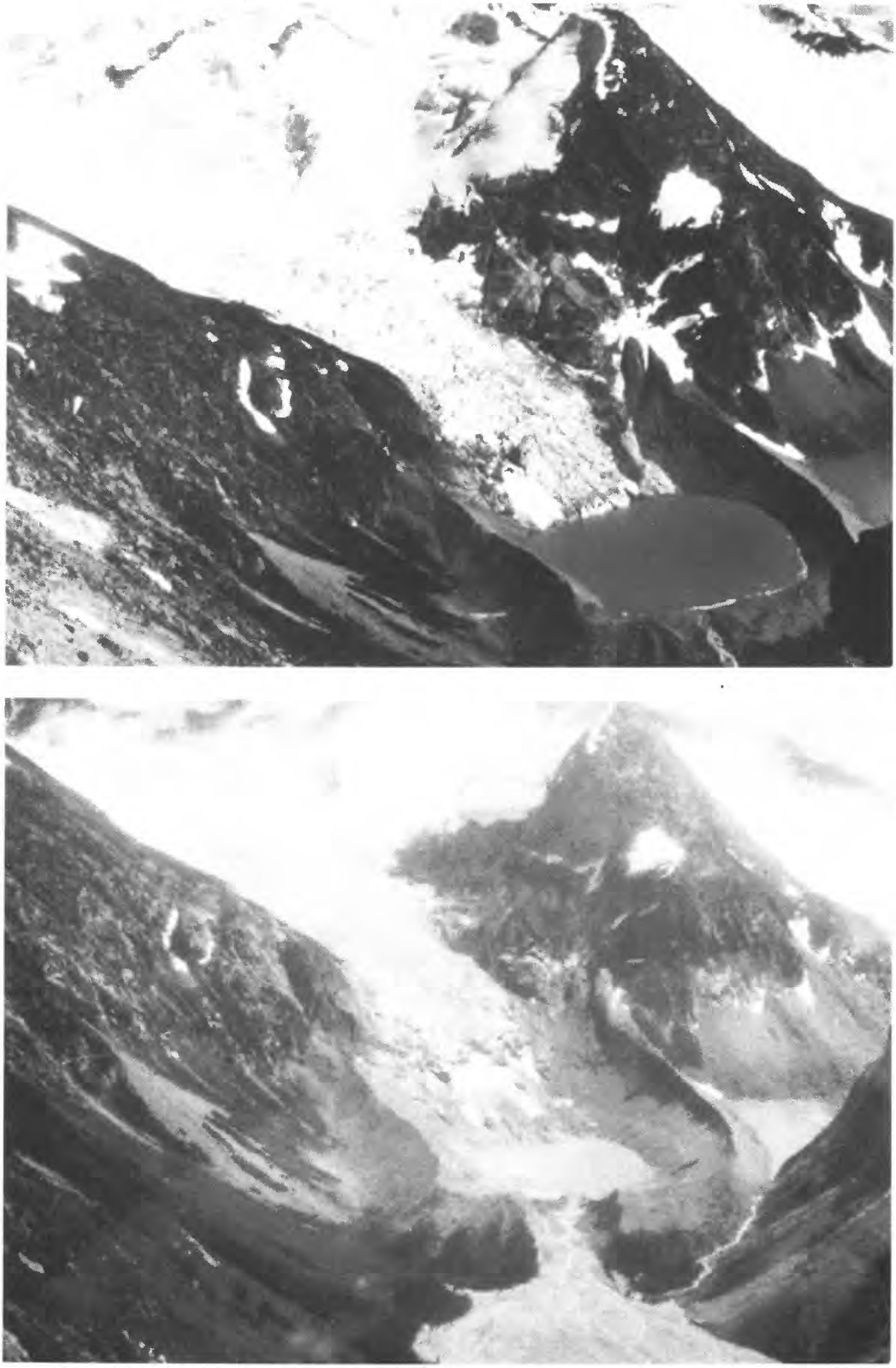


Figure 6. – Before and after views of Nostetuko Lake, British Columbia, Canada. The moraine breached in 1983. (Photos courtesy of J.M. Ryder and Michael Church)

The most commonly reported failure mechanism of moraine dams is overtopping by a wave or series of waves generated by icefalls or rockfalls or by snow or rock avalanches into the lake basin (six examples, Costa, 1985). The wave overtops the barrier, initiating erosion that is propagated by the downcutting and release of additional lake water. Settlement and subsequent failure of moraine dams accompanying earthquakes is another potential failure mechanism (one example, Costa, 1985). The large Peruvian earthquake of May 1970 resulted in the release of at least two moraine-dammed lakes in the Cordillera Blanca. The natural drainage for the moraine lake at Satuna Alta, Peru, was seepage through the barrier. Following the earthquake, the moraine dam settled and moved. Springs at the toe turned muddy and increased in discharge, implying piping. When the lake had lowered to 125 feet, the piping ceased (Lliboutry and others, 1977). Although no documented cases are known, the failure of an ice-cored moraine dam from ice-melt also is a distinct possibility.

The question of the longevity and stability of moraine dams is complex. All of the known moraine dams that have failed in the last century are of neoglacial (Little Ice Age) or younger origin. These moraine dams, formed in the last 300 years, were fresh and steep, may have been unvegetated, and were potentially unstable. They were formed in mountainous regions, where steep valley walls surround dammed lakes and the proximity of glacial ice presents the potential for excessive meltwater and mass movements into the lakes and the formation of dam-breaching waves. Ice-cored moraines or moraines of frozen soil may thaw over centuries and then may reach critical levels of instability (Ostrem, 1964; Andrews, 1975).

POTENTIAL HYDROLOGIC HAZARD

Moraine Failure

The moraine that contains Carver Lake is a push type terminal moraine of neoglacial origin. The texture of the moraine material is a silty, sandy, bouldery till with very little clay (less than 5 percent). Morainal material completely encircles the lake (fig. 7; see also cover and frontispiece). A terminal moraine curves gently around the downstream side of the lake. Another terminal moraine abuts the upstream end of the lake, and lateral moraines form the remaining sides.

The downstream terminal moraine shows the remains of a previous breach. A bouldery field that was laid downstream as a result of this breach is shown in figure 8. The stream that now runs in the bottom of the breach travels level for about 200 feet and then plummets down the steep face of the moraine, incising a channel (figs. 7 and 9). Because the moraine is 200 feet wide at the present lake level, smaller avalanches probably would not trigger downcutting of the moraine. However, the downcutting of the small stream on the face of the moraine continues to gradually reduce moraine stability. Also, the stability of the moraine probably is dependent on the proximity to the surface of a frozen ice or ground-water core. Techniques for identifying ice interfaces in moraines involving geophysical investigations have been developed by Haeberli (1986), but were not used in this study. The use of ground penetrating radar also may help to identify any ice interface.

Figure 7. – View of Carver Lake from the northeast showing encircling moraines September 3, 1986. (Photo courtesy U.S. Forest Service)

Figure 8.– Boulder plain downstream of Carver Lake with outlet channel and moraine in the foreground, August 31, 1986. (Photo courtesy U.S. Forest Service)

Figure 9. – Carver Lake outlet channel flowing down steep face of moraine, August 31, 1986. (Photo courtesy U.S. Forest Service)

An avalanche of ice and (or) rock into a moraine lake is the usual trigger causing the moraine-dam failure. Vertical outcrops of highly fractured volcanic rock are observed above Carver Lake (see cover photo). Prouty Glacier, directly above the lake (but not directly connected because of a second terminal moraine; refer to frontispiece), is highly cravassed, probably because of the steep slope and recent hydrothermal alteration. Sections of ice could calve from above.

Many Cascade peaks have had catastrophic avalanche-caused debris flows originating from fractured rocks such as those found above Carver Lake (for example, the Mount Tom, Lake George, and Little Tahoma Peak avalanches on Mount Rainier). The Little Tahoma Peak avalanche is a well documented example of a rapid failure and resulting flood (Crandell and Fahnesstock, 1965). In August of 1930, an avalanche of rock, snow, and ice on the west flank of South Sister created a debris flow that was channeled down the Separation Creek drainage and was noticed 25 miles downstream at McKenzie Bridge (see fig. 3). In the last 50 years, three known moraine dams in the Three Sisters area have breached and caused large-magnitude floods. Because of this recent evidence and the inference of other undocumented events in the last century, the frequency of breakouts of moraine-impounded lakes in the Three Sisters area can be considered to be greater than about one every 15 to 20 years (an annual probability of at least 5 to 6 percent) until moraine lakes in the area no longer exist).

A standard frequency analysis is not possible in the determination of the probability of Carver Lake breaching, because a large enough statistical sample was not available. However, at least five lakes in the area (Upper Chambers Lake, Moraine Lake on Broken Top, unnamed lake on South Fork Squaw Creek, Carver Lake, and unnamed lake near Three Fingered Jack) are known to have a potential for breaching. Although many lakes with this potential probably exist, few have been studied. A crude estimate of probability might be obtained by the following method. Given the number of breakouts that have occurred in the area for a given period (3), divided by the number of potential lakes times the period of time in years (5 x 50), it is assumed that the probability of any given lake failing to be approximately 1 percent a year.

Time of year may affect the probability statistics. All the recorded avalanches and lake-breakouts appear to have occurred from June through October. It is highly probable that this is the window of time when another lake-breakout will occur. This fact, combined with the fact that the last 50 years have seen a general retreat of glaciers that took 800 years to advance (Porter and Denton, 1967), indicates that the probability for a Carver Lake breakout could be higher than 1 percent. The most objective estimate of the probability of occurrence would then range from 1 to 5 percent. This estimate suggests that Carver Lake could have a 1-to-5 chance in 100 of being breached in any given year.

The hazard represented by the failure of Carver Lake, a probability of 1 percent per year, is larger (the magnitude will be higher) than a typical design hydrologic event with a recurrence frequency of 100 years (equivalent to an annual probability of 1 percent). The topographic setting of the lake at the base of steep unstable masses of ice, snow, and rock, as well as the complete drainage of other moraine-dammed lakes in the area, clearly indicate that Carver Lake dam could fail catastrophically. A worst-case event is the most appropriate design analysis for planning possible mitigating measures.

A survey of Carver Lake showed the maximum depth to be 101 feet. A bathymetric map made from this survey is shown in figure 10. The lake has a surface area of 15.4 acres and a volume of 740 acre-ft. The crew making the survey, while on the lake, experienced the thrill of riding a 6-inch wave created from snow calving from the adjacent field (fig. 11). This minor surge probably created an instantaneous peak of about 10 ft^3/s at the outlet. Assuming that a large section of rock or ice were to "splash" into the lake and create a 10-foot wave, the instantaneous peak would then be about 4,000 ft^3/s--a discharge sufficiently large to begin erosion of the channel and breach the moraine.

The National Weather Service model DAMBRK by Fread (1980) was used to simulate a number of breach scenarios to identify the sensitivity of the authors' assumptions. For all scenarios, a breach side slope of 1:1 with a bottom width of 10 feet was assumed. How the outflow peak discharge varied with time of breach development over the maximum depth of breach (assumed to be 80 feet) is shown in figure 12. Figure 13 shows how different breach depths affected the peak discharge for a 3-minute time-to-maximum breach. Breach volumes were included with the volume of the lake for simulation purposes. The maximum breach volume totaled less than 10 percent of the total volume.

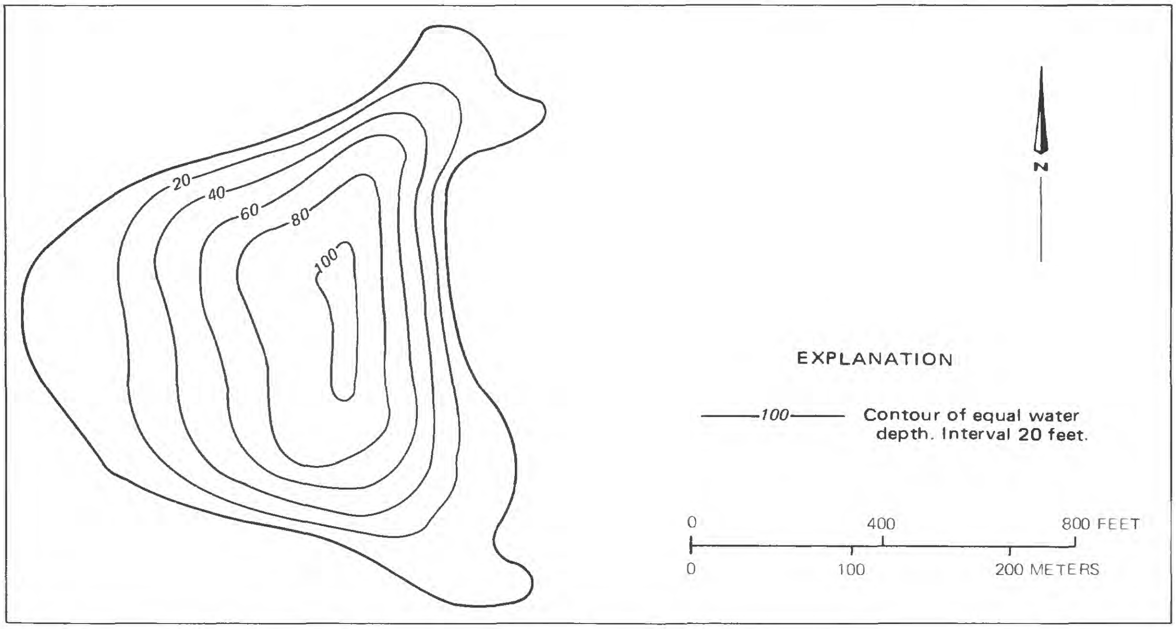


Figure 10. – Bathymetric map of Carver Lake, August 12, 1986.

Figure 11. – Snowfield on southwest shore of Carver Lake. Note icefall at lower right of photo, August 31, 1986. (Photo courtesy U.S. Forest Service)

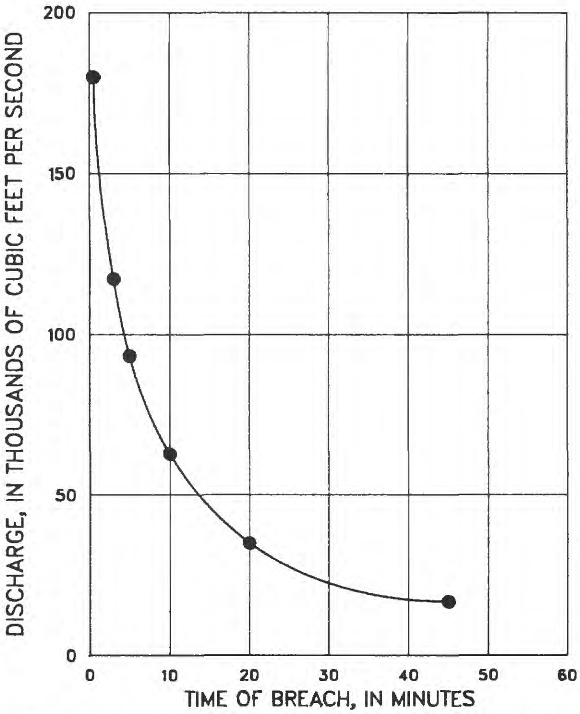


Figure 12. – Peak discharges from hypothetical breach for various times to maximum breach (for a breach geometry with 1:1 side slopes and 10 foot bottom width).

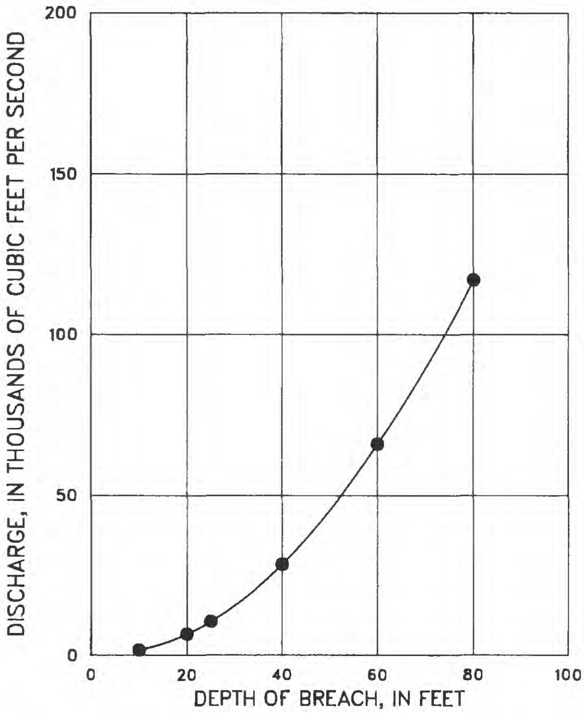


Figure 13. – Peak discharges from hypothetical breach for various depths in a maximum breach time of three minutes (for a geometry breach with 1:1 side slopes and 10 foot bottom width).

In analyzing with DAMBRK, moraine-dam failures that occurred in the Soda Creek and North Fork Squaw Creek drainages, the time to maximum breach would have to be 3 and 10 minutes, respectively. Discharges for these events are found on table 1. Moraine Lake in the Soda Creek drainage was only partially drained, whereas the lake in the North Fork Squaw Creek drainage was drained completely. Carver Lake has drained partially in post-neoglacial times, while the lake at the foot of Collier Glacier (in White Branch drainage) was drained completely in 1942. At present, there is no way to determine if Carver Lake will drain partially or completely. The chances are that a small avalanche would not have enough potential force and volume to start a breach, and that a large avalanche would not only start a breach but continue it until the lake was completely (or nearly completely) drained.

The most extreme scenario for hypothetical failure therefore would be the total and almost instantaneous evacuation of the lake, caused by a large avalanche displacing all lake water. For this scenario, we can estimate 80 feet of head in a broad-crested trapezoidal-notch breach, with a 10-foot-wide bottom width and can calculate an instantaneous peak flow of about 180,000 ft^3/s. Another extreme scenario, might also assume that the entire lake drains quickly (with a time to maximum breach of 3 minutes), with a peak discharge of 120,000 ft^3/s (fig. 12). Finally, a least extreme scenario would call for a partial draining of the lake (estimate the top 25 feet); the resulting peak would be 11,000 ft^3/s (fig. 13). Should a new breach completely empty the lake, approximately 170,000 yd^3 of material in the moraine dam would be removed.

Bulking and Debulking

Debris and hyperconcentrated flows do not attenuate as do clearwater flows, as evidenced in past flows resulting from lake breakouts (Scott, 1986). Flows from historic lake breakouts on Mount St. Helens have increased in magnitude and volume as they entrained erodible material. Scott has estimated instantaneous peak magnitudes in excess of 10,000,000 ft^3/s (the flood flow on the Amazon River) for an ancient lake breakout of Spirit Lake on Mount St. Helens in Washington (the lake volume there is 30 times that of Carver Lake).

On the basis of the behavior of the previous flows in Squaw Creek, White Branch, and Soda Creek, the flood wave would bulk continuously for about 8 miles. Variations in that trend would occur, but the overall trend would be the net addition of eroded sediment to the flood wave. Boulder fields 6 feet in depth would be formed below the breach but would represent only a minor part of the volume, as would aggradation in the minor valley "flats" in the bulking reach. A deposit thickness of about 6 feet would occur locally outside of the main channel area in valley "flats" but would be offset partially by erosion along the main channel. This thickness estimate is based on the deposits of previous breakout flood waves in Squaw and Soda Creeks.

Previous breakout flood waves from moraine-dammed lakes, such as the drained lake in the upper North Fork Squaw Creek basin, have remained high in the hyperconcentrated flow range (40-80 percent sediment by weight), as evidenced by the presence of a transition facies (Scott, 1985, figs. 10, 39, and 42) at a comparable point in the Squaw Creek channel.

An ending sediment concentration for the bulking reach (the first 8 miles of flow) of 50 percent is likely, thereby doubling the volume of the clearwater peak released from the breach (but not the peak discharge). This value is based on the stratigraphic evidence of earlier moraine-dam failures in the area; it is based on quantitative comparisons of the textures of downstream Squaw Creek deposits with those resulting from flows with known sediment concentrations in the Toutle River, Mount St. Helens, Washington. Clay content, mean size, and sorting of the deposits are all comparable.

Debris flow, if not attained at the breach, would not be attained downstream. Debris flow probably would not occur because of the noncohesive nature of the morainal deposits (less than 5 percent clay). The probable nature of the flow deposits from the previous breakout of Carver Lake also suggests that debris flow deposits in lower Squaw Creek, resulting from such a moraine-lake failure, would not occur.

The same bulking scenario is used with confidence for all three of the modeled flood waves: most-extreme case, next extreme, and least extreme. The examples of completely drained lakes in upper White Branch and North Fork Squaw Creek drainages are proof of the very real possibility of the worst-case event at Carver Lake.

The Carver Lake flood wave would debulk continuously downstream from the end of the bulking reach. At Mount St. Helens, the median thickness of lahar-runout flow deposits on flood plains in the Toutle River system is about 2 feet. A general discussion of the formation, but not quantities, of hyperconcentrated flood flows is found in reports by Scott (1985a, b). The flood wave would be a hyperconcentrated flow, based on the bulking criteria discussed above. The following debulking criteria, are based on the experience at Mount St. Helens:

(a) If flow depth is greater than 6 feet, volume of sediment on flood plain surfaces, in feet = 0.7 x (inundated area minus area of active channel); or

(b) If flow depth is less than 6 feet, volume of sediment on flood-plain surfaces, in feet = 0.35 x depth x (inundated area minus area of active channel).

As flow spreads out in the debulking interval and encounters greater roughness on the fan surface,

(c) Case (a) becomes = [1.0 + (0.1 x flow depth greater than 6 feet)] x (inundated area minus area of active channel); and

(d) Case (b) becomes = 0.50 x depth x (inundated area minus area of active channel).

The energy of the peak created by catastrophic breaching would mobilize additional material (bulk up) as it progressed downstream through steeply sloping canyons. In areas where canyons open to wider valleys and the channel slope decreases, the flow would begin to deposit what it had picked up (debulk). The evidence in this area shows that, in most cases (one exception: the debris flow down White Branch in 1942), flows did not bulked up past hyperconcentration. Therefore, by the time the peak reaches the exit of the mountain area (fig. 2), it is assumed that the flow would have doubled in volume to 1,480 acre-ft and would reach an approximate sediment concentration of 50 percent by volume.

Debulking would begin to occur when the channel slope decreases at the end of the mountain segment; it would begin at approximately 8 miles from the breach and would occur rapidly. Debulking would be confined to the valley and alluvial fan segments (fig. 2). The magnitude of the event at the exit of the mountain segment would determine the length of the major depositional reach. At the exit of the valley segment, at mile 16, the flow would become so wide that deposition would occur very rapidly. The flow probably would be out of the hyperconcentrated range, and would become a water-dominated flood flow by the time it traveled 3 miles into the alluvial fan segment.

Peak Routing

The DeLong (1984) one-dimensional, unsteady-state streamflow model HYDRAUX was used to route the breach hydrograph downstream. Assuming that the event would occur sometime from June to October, the baseflow used was a maximum of 230 ft^3/s (Friday and Miller, 1984). The flow of the model was periodically interrupted to bulk the system with estimated volumes of sediment and debris. An algorithm to simulate the debulking process (as described in the previous section) was used from mile 8 on downstream. No attempt was made to factor in viscosity changes due to increased sediment and debris concentrations. Considering all the other unknowns, it is not likely that this inclusion would significantly improve our assessment.

Concentration and viscosity changes are reflected in the Manning roughness coefficient(s) assigned at each cross section. This Manning's "n" was determined from values defined by past flows in the area (table 1) and from other data obtained in the Mount St. Helens area (Laenen and Hansen, 1986). Geological Survey cross sections surveyed for the "Volcanic Hazards Study" were used to depict channel geometry above the Geological Survey gage at river mile 15.4. The Portland District Army Corps of Engineers (COE) supplied cross-section data from the Geological Survey gage to the town of Sisters and downstream. The COE data are from a report of the area detailing flood inundation from meteorological events (1978).

Carver Lake flows into an unnamed tributary of South Fork Squaw Creek. It flows for 3.1 miles in this tributary before it reaches the confluence of the South Fork Squaw Creek. In the South Fork Squaw Creek it flows for 2.5 more miles before it reaches the main stem of Squaw Creek at River Mile 36.3 (fig. 1).

The channel from Carver Lake to the mouth of Squaw Creek, a total distance of 42 miles, was analysed in four segments: (1) a mountain segment, with an average channel slope of 380 ft/mi (feet per mile) and some canyon slopes of 800 ft/mi; (2) a valley segment, with an average channel slope of 110 ft/mi and average valley widths of 500 ft; (3) an alluvial fan, with one major and two minor channels and an average channel slope of 50 ft/mi; and (4) a canyon segment, with an average channel slope of 50 ft/mi. In all segments, three possible breach scenarios (described in a previous section) were routed downstream. Discharge hydrographs at specific cross sections in the channel for the most extreme scenario are shown in figure 14. From figure 14, flood-wave and peak arrivals, as well as flood-peak magnitude, can be determined along the entire route from the lake to the confluence with the Deschutes River. Table 3 is a summary of peak discharge, stage, time of peak, and Mannings "n" values at all input cross sections for all scenarios.

Mountain Segment, River Mile 0.0 to 8.0

For the most extreme scenario, a peak discharge of 180,000 ft^3/s, with a volume of 810 acre-ft, is used as the starting hydrograph. The model was stopped and additional volumes added to simulate bulking at river miles 0.5, 1.6, 4.2, and 7.9, on the rising limb and on one-third of the receding limb of the hydrograph. The total lake volume of 740 acre-ft was doubled by mile 8. By the end of this segment, the peak had increased in volume but had attenuated to 53,000 ft^3/s (fig. 14). The peak had taken 0.9 hours to reach this location. For the next extreme scenario, a peak discharge of 120,000 ft^3/s, with a volume of 810 acre-ft, was used as the starting hydrograph. Similar bulking techniques were applied, and the resulting peak downstream attenuated to 43,000 ft^3/s, arriving in 1.0 hours. For the least extreme scenario, a peak discharge of 11,000 ft^3/s, with a volume of 750 acre-ft, was used to define a downstream hydrograph with a peak of 25,000 ft^3/s in 1.3 hours. (If these assumptions are reasonable, bulking actually increased the least extreme scenario peak to a discharge larger than the starting peak discharge.)

Flows in this segment of stream, for those scenarios presented, could overflow into other channels. For example, from mile 0 to mile 2 it would not be difficult for a flow with stages up to 40 feet above the streambed to spill over to the Park Creek drainage (fig. 1). This spillage would not significantly affect the flood volume downstream, but would cause some attenuation of the magnitude.

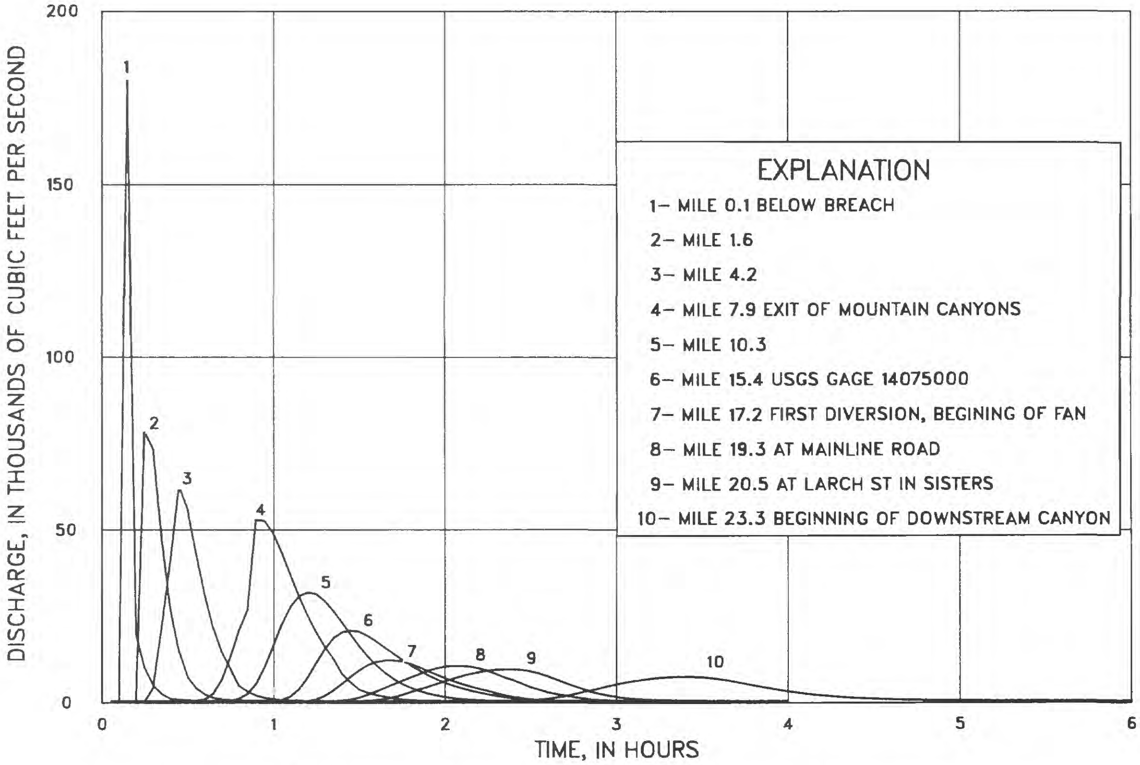


Figure 14. – Hypothetical discharge hydrographs at selected cross sections on Squaw Creek showing progression of flood downstream.

Table 3.--Summary of peak discharge, stage, time, and Manning's "n" for three hypothetical moraine-failure scenarios at input cross sections

[SF = South Fork Squaw Creek, CL = Carver Lake Tributary, SQ = main stem Squaw Creek; elevation, in feet, refers to distance above sea level]

		Model scenarios											
		Most extreme (total lake depletion)			Next extreme (total depletion in 3 minutes)			Least extreme (25 ft lake level drop in 3 minutes)			Manning's "n" values used at cross section		
Downstream mile	River mile	Peak discharge (ft^3/s)	Elevation (ft)	Time 1/ (hrs)	Peak discharge (ft^3/s)	Elevation (ft)	Time 1/ (hrs)	Peak discharge (ft^3/s)	Elevation (ft)	Time 1/ (hrs)	Sub area	Main channel	Sub area
CL 0.0	CL 3.1	180,000	7,816	0.00	120,000	7,812	0.05	11,000	7,794	0.05	0.095	0.085	0.095
CL 0.4	CL 2.7	147,000	7,750		89,000	7,747		10,200	7,743		.090	.080	.090
CL 0.5	CL 2.6	137,000	7,492		83,000	7,490		9,900	7,484		.085	.075	.085
CL 1.0	CL 2.1	104,000	6,989		70,000	6,986		11,500	6,981		.080	.070	.080
CL 1.6	CL 1.5	78,000	6,661		60,000	6,657		13,300	6,646		.075	.065	.075
CL 2.6	CL 0.5	69,000	6,188		56,000	6,185		16,100	6,175		.070	.060	.070
SF 4.2	SF 1.5	63,000	5,534		53,000	5,532		20,000	5,528		.090	.055	.090
SQ 6.6	SQ 35.4	59,000	4,807		51,000	4,805		24,000	4,798		.080	.050	.090
SQ 7.9	SQ 34.1	53,000	4,443	0.90	50,000	4,442	1.00	26,000	4,438	1.30	.090	.045	.090
SQ 9.2	SQ 32.8	44,000	4,279		41,000	4,278		23,000	4,274		.085	.040	.090
SQ 10.3	SQ 31.7	32,000	4,196		28,000	4,195		20,000	4,192		.090	.045	.080
SQ 13.0	SQ 29.0	24,000	3,787		21,000	3,786		14,800	3,783		.080	.040	.085
SQ 15.4	SQ 26.6	21,000	3,513	1.65	17,900	3,511	1.70	10,500	3,509	2.05	.075	.035	.085
SQ 17.2	SQ 24.9	12,400	3,389		11,400	3,386		7,500	3,384		.060	.032	.060/.080
SQ 17.3	SQ 24.8	12,300	3,378		11,300	3,376		7,300	3,374		.085	.030	.065/.080
SQ 19.1	SQ 23.0	10,900	3,258		10,000	3,257		4,400	3,255		.085	.030	.065/.085
SQ 19.3	SQ 22.8	10,800	3,249		9,900	3,248		4,200	3,246		.085	.028	.085
SQ 20.1	SQ 22.0	10,000	3,203		9,400	3,202		4,100	3,199		.085	.028	.085
SQ 20.5	SQ 21.5	9,800	3,184	2.35	9,200	3,184	2.40	3,900	3,183	2.70	.085	.028	.085
SQ 20.8	SQ 21.3	9,400	3,176		8,900	3,176		3,700	3,174		.085	.028	.085
SQ 21.3	SQ 20.8	9,100	3,153		8,500	3,153		3,500	3,150		.085	.032	.085
SQ 22.0	SQ 20.1	8,600	3,125		7,800	3,125		3,200	3,121		.085	.035	.085
SQ 23.3	SQ 18.8	7,600	3,069		7,200	3,069		3,100	3,063		.085	.038	.085
SQ 28.1	SQ 14.0	7,000	2,852		6,600	2,852		2,800	2,846			.040	
SQ 32.3	SQ 9.8	6,500	2,671		6,200	2,671		2,500	2,665			.045	
SQ 36.4	SQ 5.6	6,300	2,495		6,000	2,495		2,400	2,489		.060	.045	
SQ 39.1	SQ 3.0	6,000	2,374		5,700	2,374		2,300	2,368			.045	
SQ 41.9	SQ 0.2	5,700	2,193	5.50	5,400	2,193	5.60	2,200	2,188	6.70		.045	

1/ Time to peak from start of moraine breach.

Valley Segment, River Mile 8.0 to 17.0

For the most extreme scenario, the peak discharge at the Geological Survey gage at 15.4 miles from the lake would arrive in 1.65 hours and have a magnitude of 21,000 ft^3/s. This magnitude can be compared with 2,000 ft^3/s, the 100-year frequency meteorological event at this location. A comparison could also be made with the stages at this location (see cross section in Appendix I). Modeled values for the most extreme scenario showed a stage 13 feet above the thalweg and 8 feet higher than the COE 100-year flood elevation. For the next extreme scenario, the peak discharge at the Geological Survey gage location was 18,000 ft^3/s, arriving in 1.7 hours. For the least extreme scenario, the peak would be 10,500 ft^3/s in 2.05 hours.

Alluvial Fan Segment, River Mile 17.0 to 22.0

As the flood enters an alluvial fan (or fanhead valley), most flow would follow the principal channel (Squaw Creek), but some would follow distributary channels (an abandoned channel and Squaw Creek Ditch). It is also a distinct possibility that some new channels could be eroded on the fan because of the high stream velocities associated with the estimated flows. Certainly, flows would be overbank in this area and, if localized damming occurs, almost any location on the fan could be susceptible to flooding.

At mile 17.2, an old diversion set in the channel diverts flow down an abandoned stream channel (fig. 15). At this location, flow in Squaw Creek follows a tight curve to the left; considerable flow could conceivably be diverted down the abandoned channel. For modeling purposes, a maximum estimate is assumed for each route: a maximum of 75 percent of the flow is assumed as a worse case, to follow the Squaw Creek channel and a maximum of 50 percent (assumed worse case) to be diverted towards the abandoned channel. It was also assumed that the flows would never coalesce. At mile 17.9 along the abandoned channel, the flow again has alternatives: across Squaw Creek Ditch or down the Ditch. Because the Ditch follows a side slope, the left bank over the levee is downhill. Therefore, the flow in the ditch was limited to full capacity (approximately 1,000 ft^3/s) and the remainder of the flow was allowed to follow the approximate path of the abandoned channel. Because the abandoned channel has a small capacity, flows would diffuse and coalesce on the debris fan and would attenuate rapidly.

For Squaw Creek, the most extreme scenario would have a magnitude of 9,800 ft^3/s at mile 20.5 in the town of Sisters. The flow wave would first arrive in Sisters in about 1.8 hours, with the peak arriving at about 2.4 hours. This peak again can be compared to the estimated meteorological peak for the 100-year frequency event. Stage at this location is about 10 feet above the thalweg and 3 feet higher than the 100-year event. For flows in the abandoned channel and other routes at Mainline Road, the magnitude would be about 2,000 ft^3/s and would attenuate rapidly. For Squaw Creek, the next extreme scenario would have an estimated peak of about 9,200 ft^3/s at mile 20.5 in Sisters. The estimated peak for the least extreme scenario would be 3,900 ft^3/s in Sisters. For all scenarios, the peak elevation at mile 20.5 is approximately the same.

Figure 15. – Squaw Creek channel at 17.2 miles downstream of Carver Lake. A large magnitude flood could easily flow straight ahead through the ponderosa pines (just right of vehicle) in an old abandoned stream channel, October 1986.

Canyon Segment, River Mile 22.0 to 42.0

For the most extreme scenario, the peak would arrive at the mouth of Squaw Creek in 5.5 hours with a magnitude of 5,700 ft^3/s. Because flow has been confined to a canyon, the peak would not have much attenuation. The next extreme scenario would have a peak magnitude of 5,400 ft^3/s arriving in 5.6 hours, while the least extreme scenario would have a peak of 2,200 ft^3/s and arrive in 6.7 hours.

Model Sensitivity

It was beyond the scope of this study to do a detailed model-sensitivity study. Prior work done by Laenen and Hansen (1986) did such an analysis for modeled flows in the Mount St. Helens area. However, for the current study, model sensitivity was tested for Mannings's "n." An average increase of 0.020 for all base values shown in table 3 yielded an average peak magnitude decrease of 15 percent (at the Geological Survey gage and at Sisters), and an average decrease of 0.020 yielded an average peak magnitude increase of 20 percent.

An item not considered in model simulation was loss of water to the streambed and streambanks in a dry weather situation. All model scenarios done in the analysis assumed a saturated condition as a worse case. Modeling of the 1970 breakout over simulated observed peak flows at the Geological Survey gage and at Sisters was overestimated by approximately 2,000 ft^3/s. The 1970 flow model simulation did, however, closely approximate field-estimated peak flows in the upper basin (the first 8 miles).

Inundation

For all hypothetical scenarios, flow generally has been confined to the channel area in the first 17 miles downstream of the lake breakout. Up to this point, there has been some flooding and deposition in mountain valley "flats" and some flooding with appreciable deposition in the last 9 miles of valley (approximately 0.6×10^6 yd^3 as indicated by the debulking algorithm in the model).

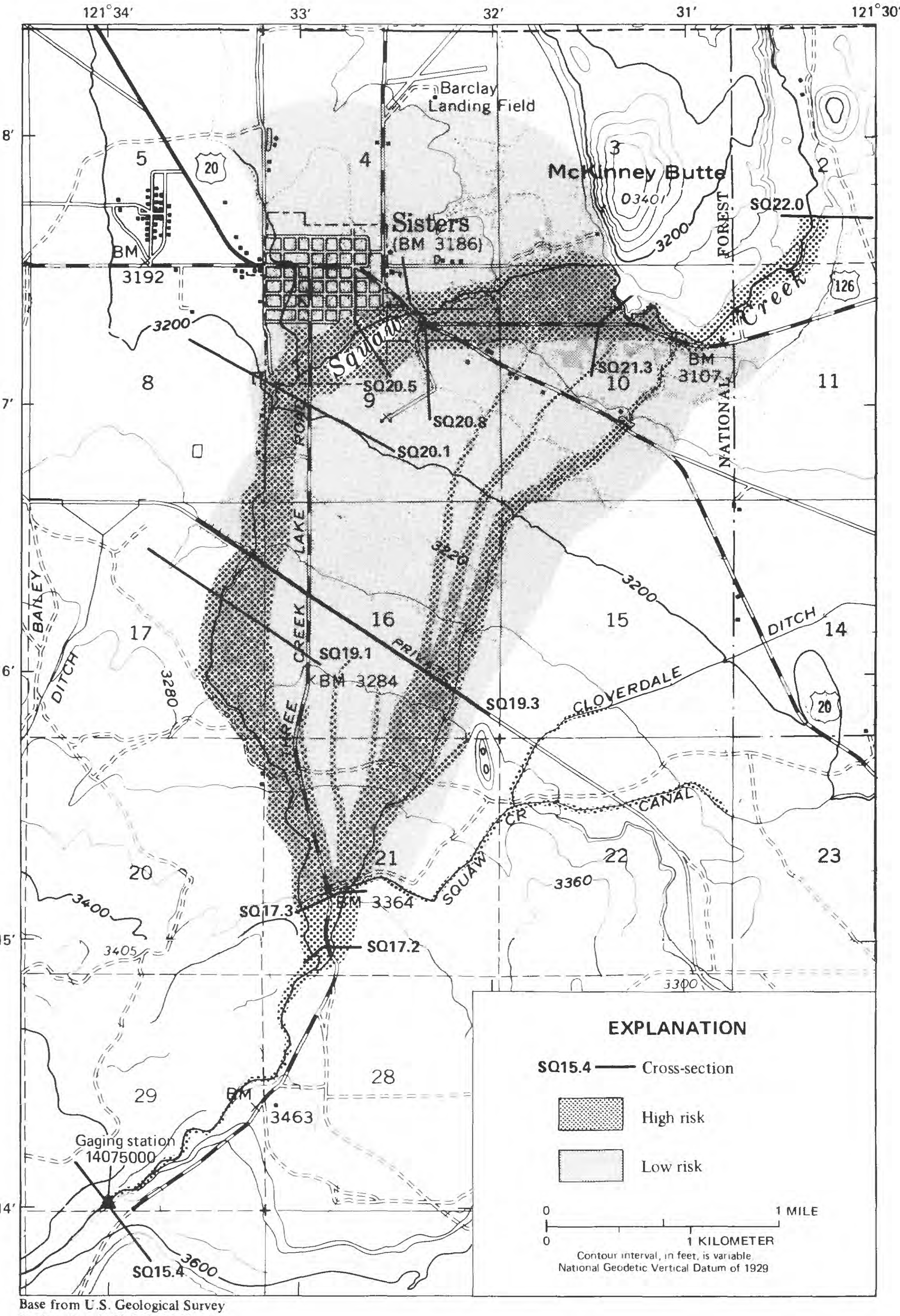
Appendix I is an index to cross-section location, and cross-sections used in the model.

At mile 17, the confining valley begins to open into a wide alluvial fan (fig. 16). A one-dimensional model was used with discretion to analyze the channel sections on the debris fan. All two-dimensional interpretations were made objectively from field observations. The topographic information available was too coarse and the time available too short to try to develop a two-dimensional analysis.

At the beginning of the alluvial fan, modeled flows indicate peak velocities of approximately 20 ft/s at mile 17. Coincidentally at this location, the main channel makes a sharp curve. Considerable flow would surge straight ahead (fig. 15) along an old abandoned channel, uprooting Ponderosa pines and eroding a channel through Three Creek Lake Road. The flow next would encounter Squaw Creek Ditch levees and easily would erode through these barriers. The ditch would flow full capacity, with any overflow spilling downhill. The flow continuing along the path of the abandoned channel would spread to about 1,000 feet in width in the pine and sage and would begin to create many distributary channels. Because of all the vegetation and the loosely consolidated soils, the flow would quickly attenuate and little of it would find a way back to the main channel. Figure 16 shows one interpretation of what might occur. Flow velocities at the peak are great enough, and the alluvial fan is flat enough, to have a channel begin almost anywhere on the surface.

By about 19 miles downstream of the lake, almost all the major debulking would have taken place. Downstream from this point, the flood water would continue to erode and entrain whatever sediments the stream velocities will allow, but when velocities subside, the volume of deposition in overflow sections would not be nearly as great as in the first 19 miles.

If no damming occurs along the main stem, inundation along Squaw Creek in the alluvial fan area would be somewhat (but not appreciably) greater than the 500-year frequency meteorological flood predicted by the COE (1978). Damming at any of the ditch diversion structures (fig. 17), road crossings, or sharp stream bends could cause local flooding beyond what is shown in figure 16 as most probable flooding. As the hypothetical extreme peak flow reaches Sisters, velocities would still be high (maximum 14 ft/s) and would be more than enough to create new channels beyond the most probable flow route. This is especially likely at mile 20.2, where a small distributary diverts water along Ash Street in Sisters. Figures 18 and 19 are photographs from a COE 1978 report. The probable flood elevations from the most extreme moraine-dam failures scenario are shown in comparison to probable 100- and 500-year- frequency events.



Base from U.S. Geological Survey
Broken Top 1:62,500, 1959 and
Sisters, 1:62,500, 1959

Figure 16. – Inundated area near Sisters from hypothetical breakout (most extreme scenario) showing high and low risk areas.

Figure 17. – Squaw Creek at Squaw Creek ditch diversion. A possible place for damming because of constriction. Note the flat topography beyond the channel incision, October 1986.

CONCLUSION

A high potential exists for failure of the moraine dam that impounds Carver Lake. During the last 50 years, at least three moraine dams have breached in the Three Sisters Wilderness Area, and the resulting floods have traveled down the White Branch, Soda, and Squaw Creek drainages. The probability of a failure for Carver Lake is estimated to be 1 to 5 percent for any given year and would be expected to occur from June to October. The moraine that dams Carver Lake is steep, unvegetated, noncohesive, and loosely consolidated. Small avalanches of ice and rock occur frequently, and it is only a matter of time before a major avalanche will trigger the mechanism to cause a catastrophic lake breakout.

A dam-break computer model was used to simulate a hypothetical breach of the moraine dam. The three failure scenarios used to define the initial flood at the elevation of the lake are as follows:

(1) Most extreme -- Total displacement of the lake water by avalanche material that would almost instantaneously result in an initial peak discharge of 180,000 ft^3/s.

(2) Next extreme -- A breach occurring within 3 minutes that drains the upper 80 feet of the lake and results in an initial peak discharge of 120,000 ft^3/s.

(3) Least extreme -- A breach occurring within 3 minutes, that drains the upper 25 feet of the lake and results in an initial peak discharge of 10,000 ft^3/s.

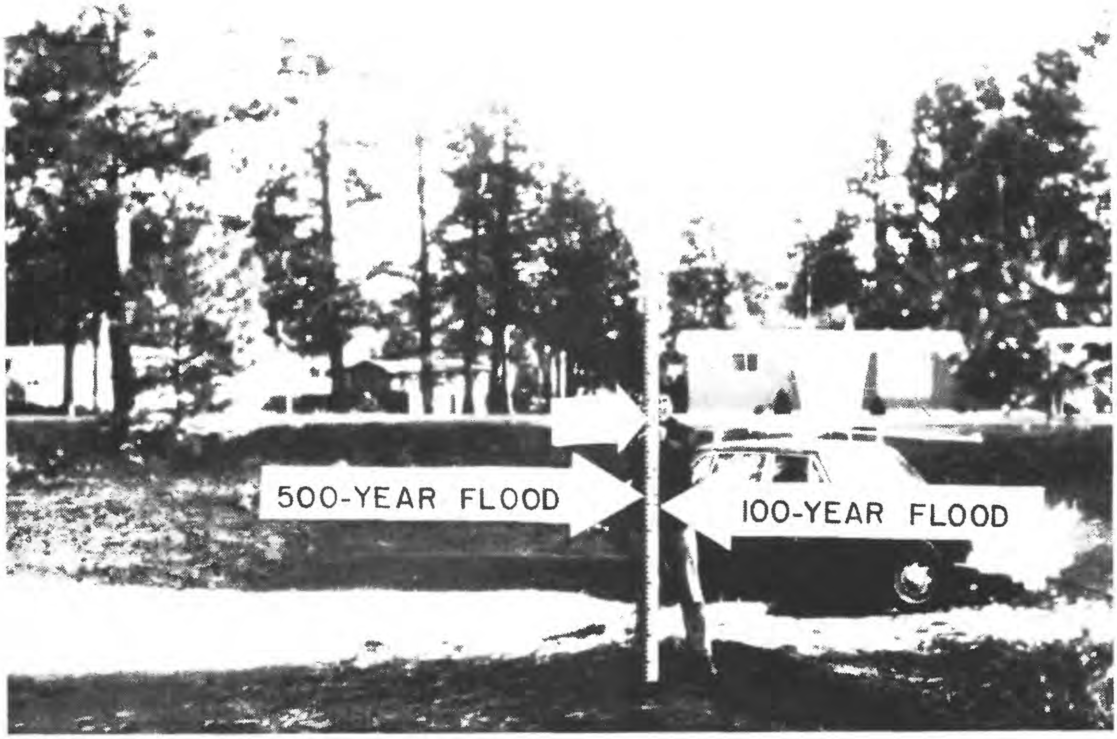


Figure 18. – Potential flood elevations in Sisters near Elm Street (Three Creek Lake Road) bridge. Small arrow shows estimated elevation of most extreme flood caused by Carver Lake breakout. The 100- and 500-year flood elevations are from U.S. Army Corps of Engineers (1978).

Figure 19. – Potential flood elevation in Sisters City Park. Small arrow shows estimated elevation of most extreme flood caused by Carver Lake breakout. The 100- and 500-year flood elevations are from the U.S. Army Corps of Engineers (1978).

For all hypothetical scenarios, it is assumed that the flow would bulk up to a sediment concentration of 50 percent by volume (hyperconcentration) in the section between the breach and the end of the steeply sloping canyons, a distance of 8 miles. Debulking of the flood is assumed to occur in overflow sections of valley and debris-fan segments. Initial flood hydrographs were routed downstream using a one-dimensional unsteady-state streamflow model that incorporated field determinations of Manning's "n" coefficients to allow for hyperconcentrated flow. In the vicinity of the Geological Survey gage (15.4 miles downstream from the lake), routing of the three failure scenarios simulated estimated flood peak discharges of 21,000, 18,000, and 10,000 ft^3/s. In comparison, all simulated flood peak discharges were greater than that of a 100-year frequency-of-occurrence flood from high precipitation or snowmelt. The 100-year frequency-of-occurrence flood is used for comparison of peak magnitude only; the probability of occurrence is from a different statistical population.

Three potential channels of flow were defined for the alluvial fan where the community of Sisters is located. Flow could occur almost anywhere on the alluvial fan because of channel shifting that accompanies local scour and damming. It was assumed that about 75 percent of the total flow would be diverted in the main channel of Squaw Creek towards Sisters. The three hypothetical-flood scenarios resulted in estimated discharges of 9,800, 9,200, and 3,900 ft^3/s, at mile 20.5 in Sisters along the main channel. In the remaining channels about 3,000 and 1,000 ft^3/s, respectively, would start to flow down Squaw Creek Ditch, an abandoned channel (now used as a ditch), and down Squaw Creek Canal; but these flows probably would attenuate rapidly.

The community of Sisters would begin to experience rising flood water about 1.8 hours after the dam breach; the flood peak would arrive about 30 minutes later. The lesser amplitude scenarios would have later arrival times. Because of the increase in flood volume from the bulking process downstream of the lake and localized backwater in the channel in Sisters, regardless of the scenario referenced, the peak stage in Sisters is approximately the same. The probability of a flood from any breakout of Carver Lake has an estimated 1-to-5 percent chance of occurring in any given year and would likely occur in the next century. In Sisters, locally high velocities, damming, erosion, and sediment deposition could cause considerable property damage and possible loss of life. The stream would be especially dangerous at road crossings where bridges may fail or sections wash away.

ADDITIONAL STUDIES AND NEEDS

This report raised difficult questions about the likelihood of a potential dam break of the moraine confining Carver Lake and the resulting hydrologic hazards in the downstream area. Answers provided in this report are qualified as being the best estimates based on current assumptions and available data.

Additional data is needed to more accurately estimate the probability of occurrence of moraine-lake breakout floods. This additional data could be obtained by cataloging the existing moraine lakes of a region (or worldwide). This activity wold not require much time or effort and would benefit others by locating lakes with hazard potential similar to Carver Lake. The next step would be to identify breached lakes, determine peak discharge, and date the occurrence of breach.

To more accurately determine the probable magnitude of the Carver Lake breakout, both avalanche potential and moraine stability need to be investigated. Geotechnical surveys of the volcanic rock, glacier, and moraine need to be made. A survey of the moraine material alone may indicate the depth to subsequent breaching.

Regardless of future investigative studies, some early warning, zoning, and planning studies are needed to prevent loss of life and property damage in areas downstream of the lake. In the town of Sisters, the potential breakout of Carver Lake represents several times the magnitude flood that county and city governments presently plan for. The flood would occur with little or no warning and could occur when climatological conditions may be fair.

REFERENCES

Andrews, J. T., 1975, Glacial systems: Duxbury Press, North Scituate, Mass., 191 p.

Beverage, J. P., and Culbertson, J. K., 1964, Hyperconcentrations of suspended sediment: Journal of Hydraulics Division, American Society of Civil Engineers, v. 90, HY-6, p. 117-128.

Blown, I. G., and Church, Michael, 1985, Catastrophic lake drainage within the Homathko River basin, British Columbia: Canadian Geotechnical Journal, v. 22, no. 4, p. 551-563.

Clague, J. J., Evans, S. G., and Blown, I. G., 1985, A debris flow triggered by the breaching of a moraine-dammed lake, Klattasine Creek, British Columbia: Canadian Journal of Earth Sciences, v. 22, p. 1492-1502.

Costa, J. E., 1985, Floods from dam failures: U.S. Geological Survey Open-File Report 85-560, 54 p.

Crandell, D. R., and Fahnestock, R. K., 1965, Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington: U.S. Geological Survey Bulletin 1221-A, 30 p.

DeLong, L. L., 1984, Extension of the unsteady one-dimensional open-channel flow equations for flow simulation in meandering channels with flood plains, in Meyer, E. L., ed, Selected papers in the hydrologic sciences: U.S. Geological Survey Water Supply Paper 2270, p. 101-105.

Eisbacker, G. H., 1982, Mountain torrents and debris flows: Episodes, v. 1982, no. 4, p. 12-17.

Ericksen, G. E., Plafker, George, and Concha, J. F., 1970, Preliminary report on the geologic events associated with the May 31, 1970, Peru earthquake: U.S. Geological Survey Circular 639, 25 p.

Fread, D. L., 1980, DAMBRK--The dam-break flood forecasting model: Silver Spring, Maryland, National Weather Service, Office of Hydrology, Maryland, 37 p.

Friday, John, and Miller, S. J., 1984, Statistical summaries of streamflow data in Oregon, volume 1, eastern Oregon: U.S. Geological Survey Open-File Report 84-454, 150 p.

Grove, J. M., 1979, The glacial history of the Holocene: Progress in Physical Geography, v. 3, p. 1-54.

Haeberli, W., and Epifani, F., 1986, Mapping the distribution of buried glacier ice--an example from Lago Delle Locee, Monte Rose, Italian Alps: Annals of Glaciology, no. 8, International Glaciology Society, p. 78-81.

Laenen, Antonius, and Hansen, R. P., 1986, Simulation of three lahars in the Mount St. Helens, Washington area, using a one-dimensional, unsteady-state streamflow model, Unpublished data on file in Portland, Oregon office of U.S. Geological Survey, 28p.

Lliboutry, Louis, Arnao, B. M., Pautre, Andre, and Schneider, Bernard, 1977, Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention: Journal of Glaciology, v. 18, p. 239-254.

Matthes, F. E., 1939, Report of committee on glaciers: Transactions, American Geophysical Union, v. 20, p. 518-523.

Nolf, Bruce, 1966, Broken Top breaks: Flood released by erosion of glacial moraine, October 1966 issue: The Ore Bin, v. 28, no. 10, Oregon State Department of Geology and Mineral Industries, p. 182-188.

Ostrem, G., 1964, Ice-cored moraines in Scandanavia: Geografiska Annaler, v. 46, p. 282-337.

Pierson, T. C., 1982, Flow behavior of two major lahars triggered by the May 18, 1980 eruption of Mount St. Helens, Washington: Proceedings of the symposium on erosion control in volcanic areas: Public Works Research Instituet, Ministry of Construction, Japan, Vancouver, WA, July 6-9, 1982, p. 99-129.

Porter, S. C., and Denton, G. H., 1967, Chronology of neoglaciation in the North American Cordillera: American Journal of Science, v. 267, p. 177-210.

Scott, K. M., 1985a, Lahars and Lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington--origins, behavior, and sedimentology: U.S. Geological Survey Professional Paper 1447-A, 202 p.

_____1986b, Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington--origins, behavior, and sedimentology: U.S. Geological Survey Professional Paper 1447-B, 92 p.

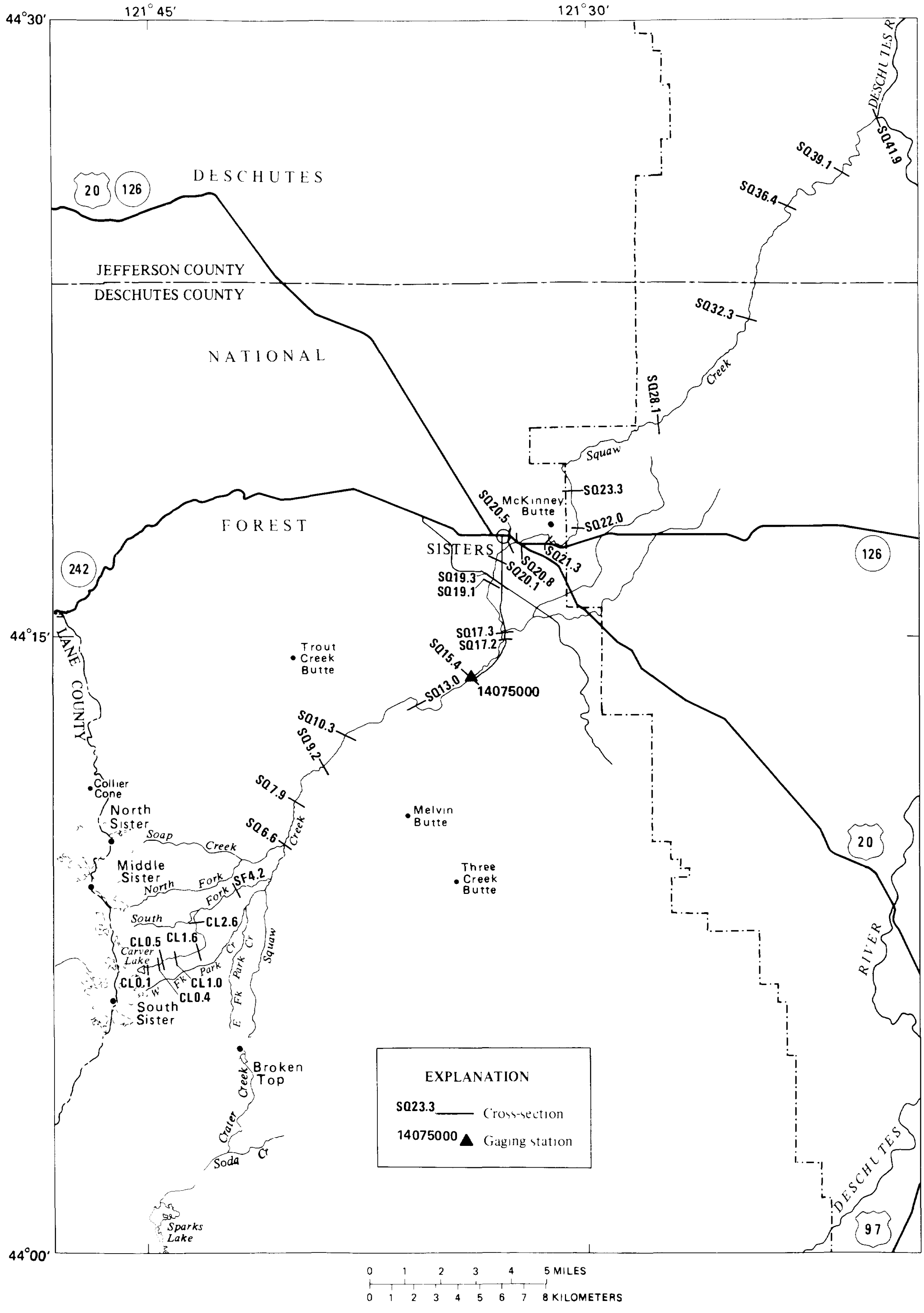
Scott, W. E., 1977, Quaternary glaciation and volcanism, Metolius River area, Oregon: Geological Society of America Bulletin, v. 88, January 1977, Document no. 70113, p. 113-124.

Taylor, E. M., 1965, Recent volcanism between Three Fingered Jack and North Sister, Oregon Cascade Range: The Ore Bin, v. 27, no. 7, Oregon State Department of Geology and Mineral Industries, p. 121-148.

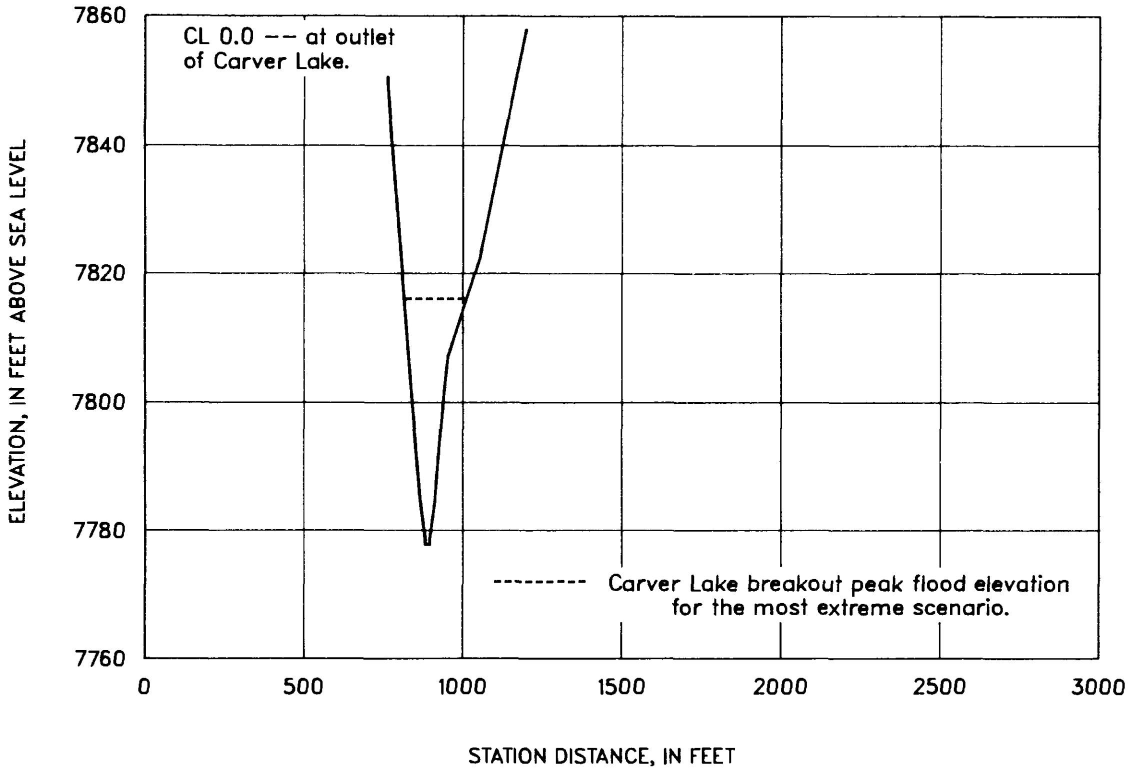
Yesenov, U. Y., and Degovets, A. S., 1979, Catastrophic mudflow on the Bol'shaya Almatinka River in 1977: Soviet Hydrology, v. 18, p. 158-160.

U.S. Army Corps of Engineers, 1978, Flood plain information, Squaw Creek, Sisters, Oregon: Department of the Army, Portland District Corps of Engineers, 50 p.

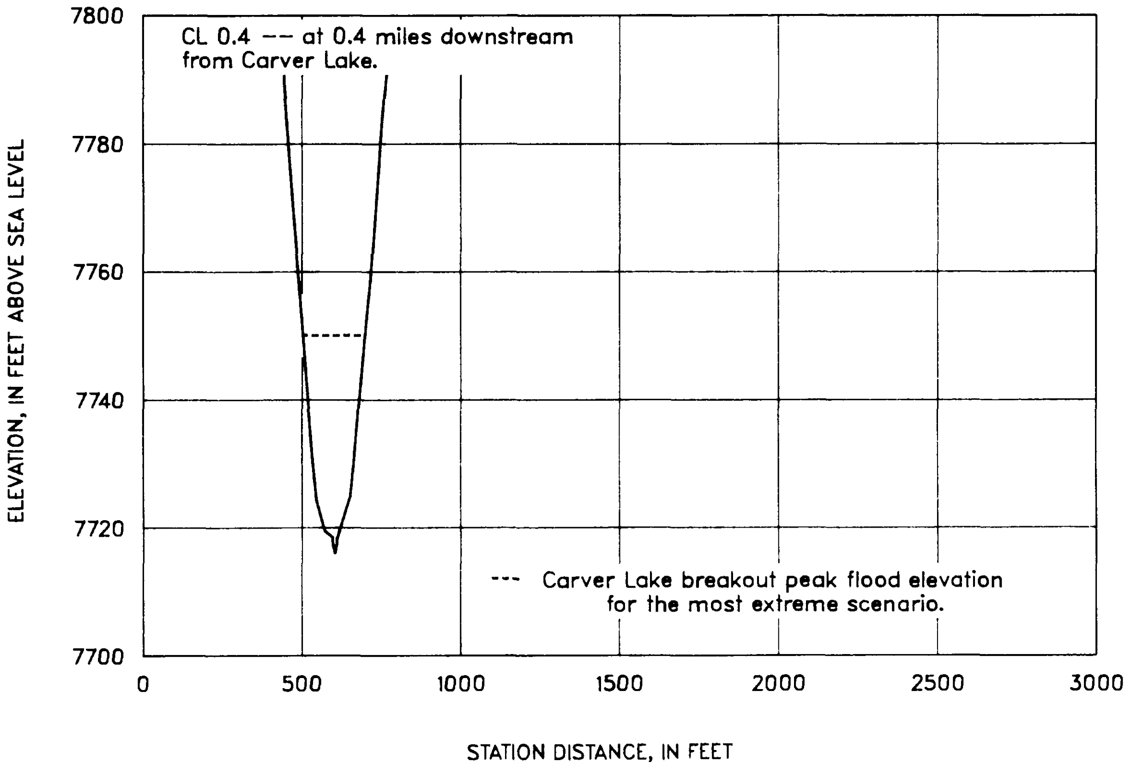
APPENDIX I: CHANNEL LOCATION AND CROSS-SECTIONAL PROFILES FOR SELECTED SITES IN THE STUDY AREA



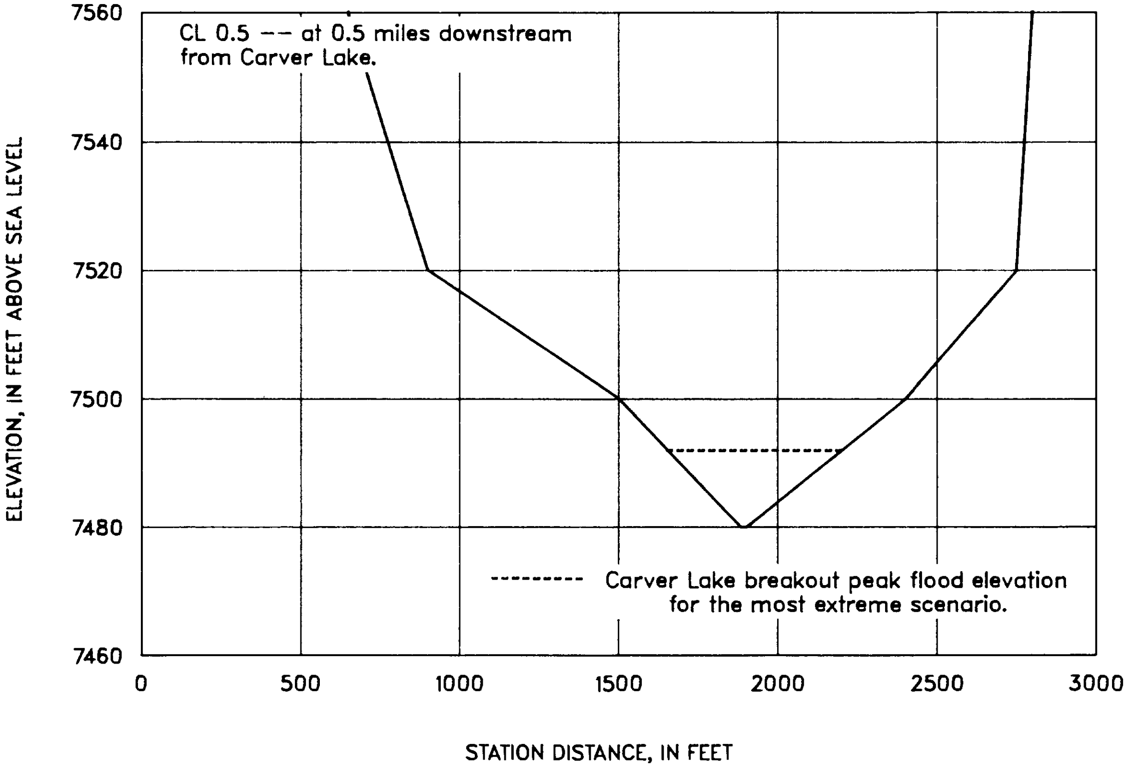
Locations of cross-sections downstream of Carver Lake.

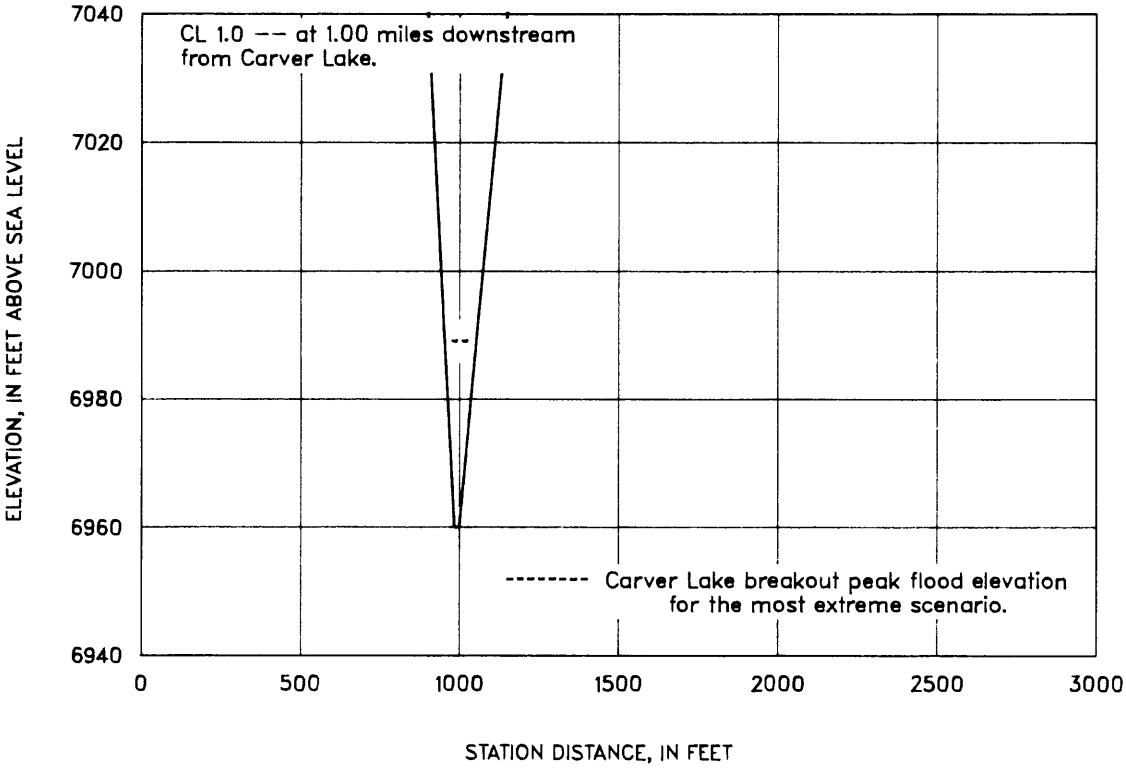


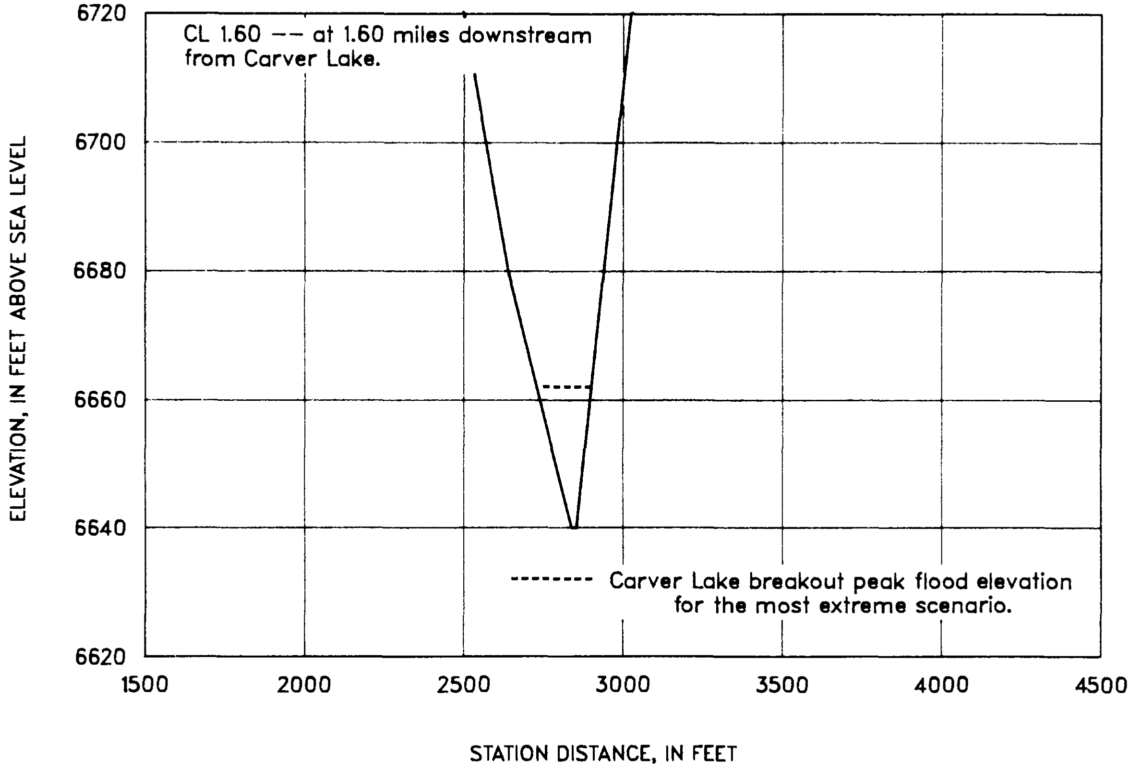
CL 0.0 -- at outlet of Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
ELEVATION, IN FEET ABOVE SEA LEVEL
7860
7840
7820
7800
7780
7760
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

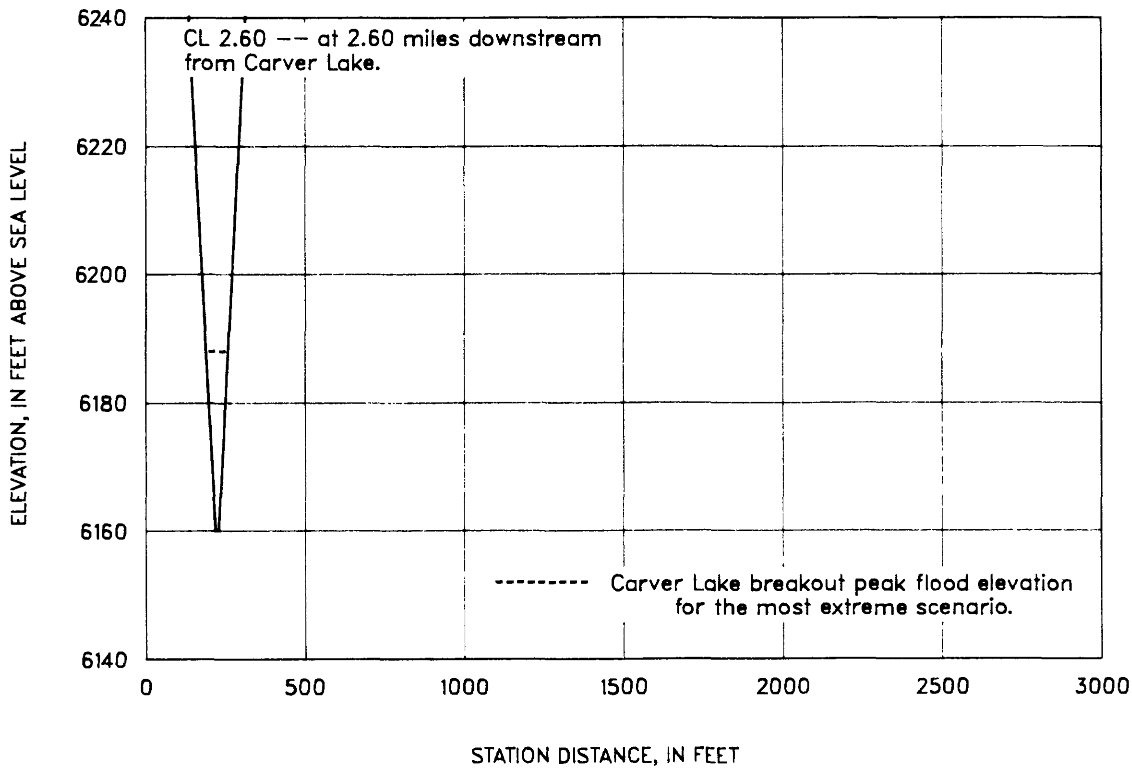


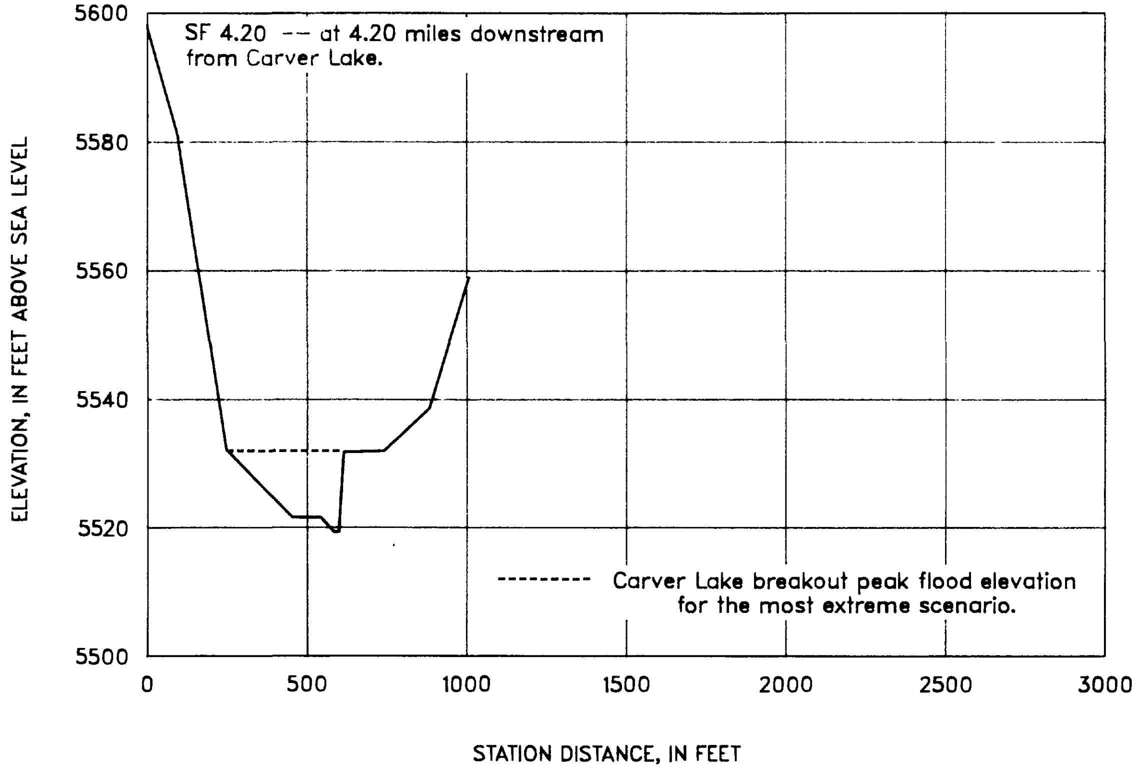
CL 0.4 -- at 0.4 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
ELEVATION, IN FEET ABOVE SEA LEVEL
7800
7780
7760
7740
7720
7700
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

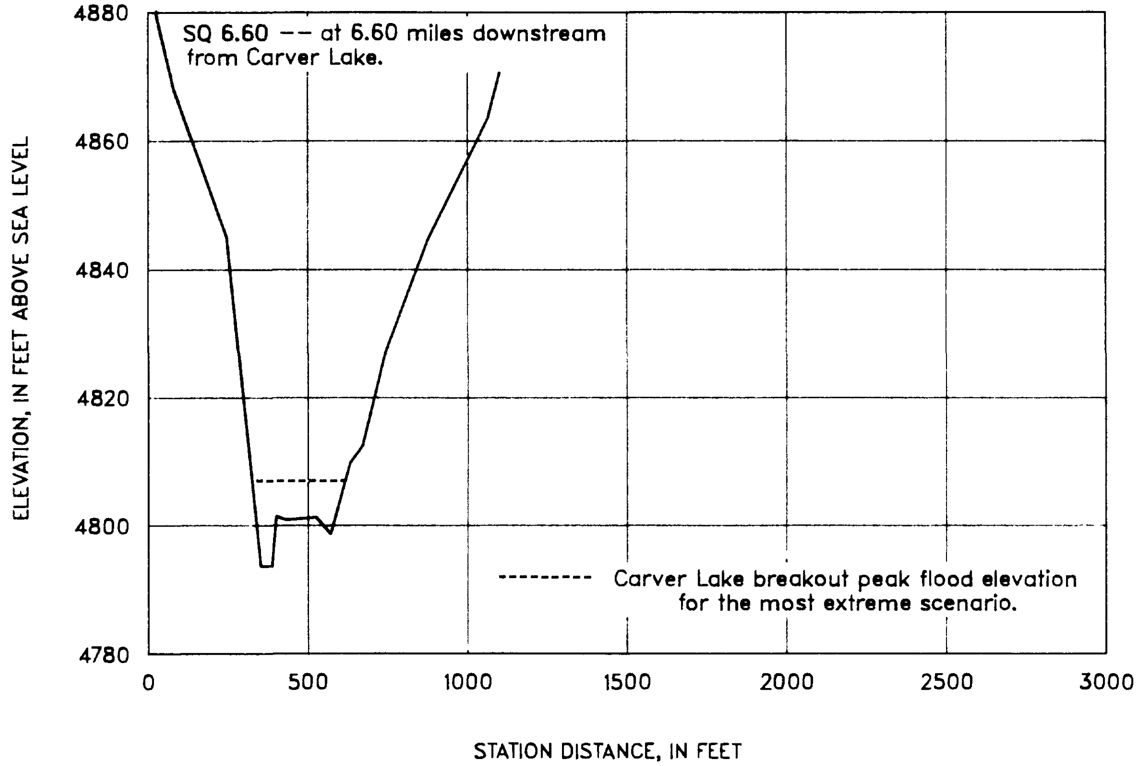

7560
7540
7520
7500
7480
7460
ELEVATION, IN FEET ABOVE SEA LEVEL
CL 0.5 -- at 0.5 miles downstream
from Carver Lake.
--------- Carver Lake breakout peak flood elevation
for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

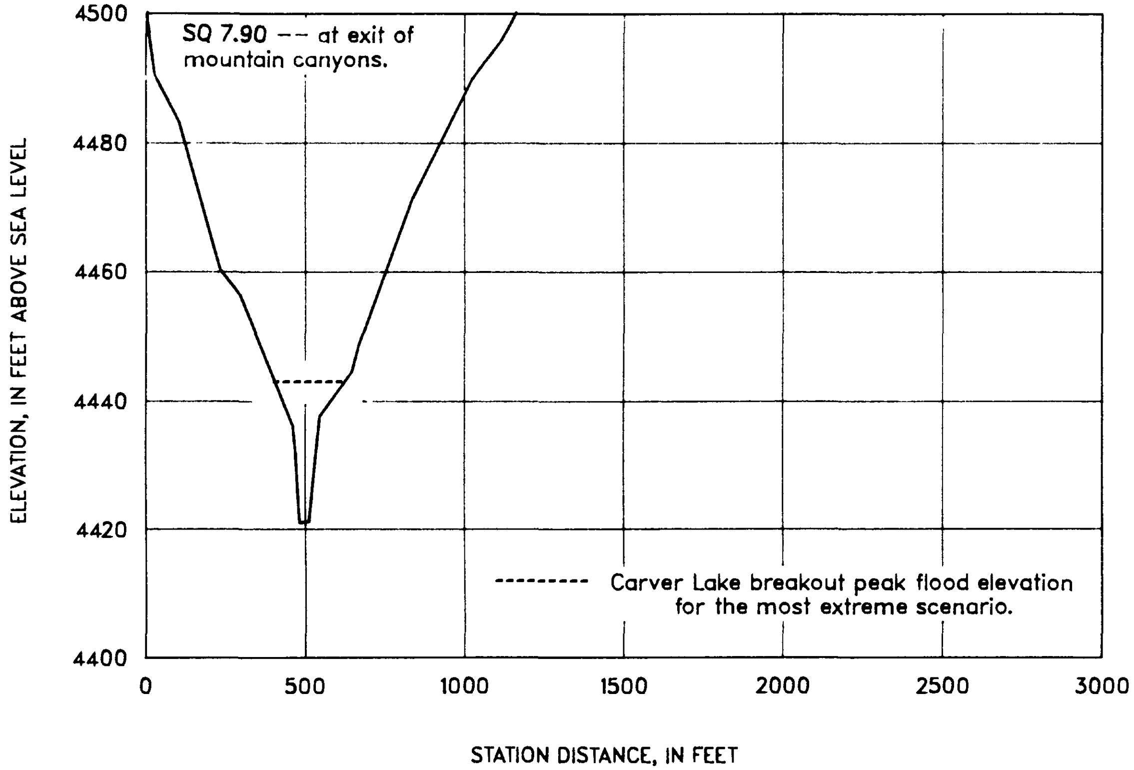

7040
7020
7000
6980
6960
6940
ELEVATION, IN FEET ABOVE SEA LEVEL
CL 1.0 -- at 1.00 miles downstream
from Carver Lake.
-------- Carver Lake breakout peak flood elevation
for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

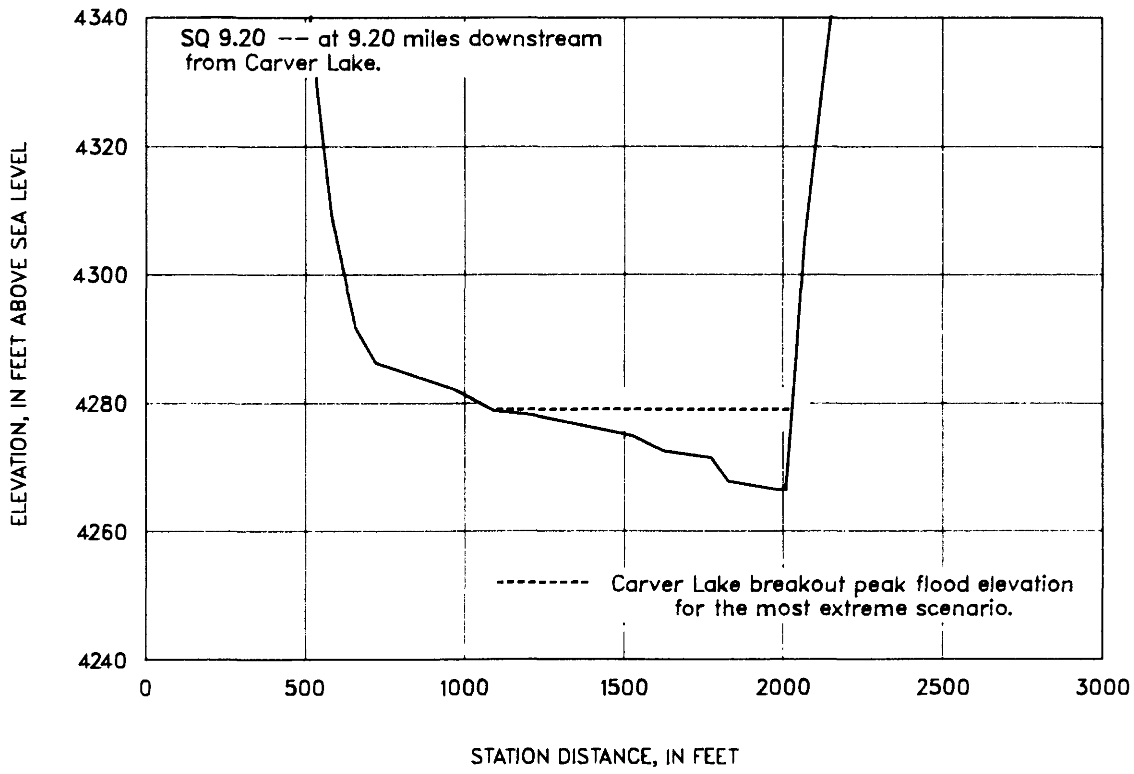

CL 1.60 -- at 1.60 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
6720
6700
6680
6660
6640
6620
1500
2000
2500
3000
3500
4000
4500
STATION DISTANCE, IN FEET
-------- Carver Lake breakout peak flood elevation for the most extreme scenario.

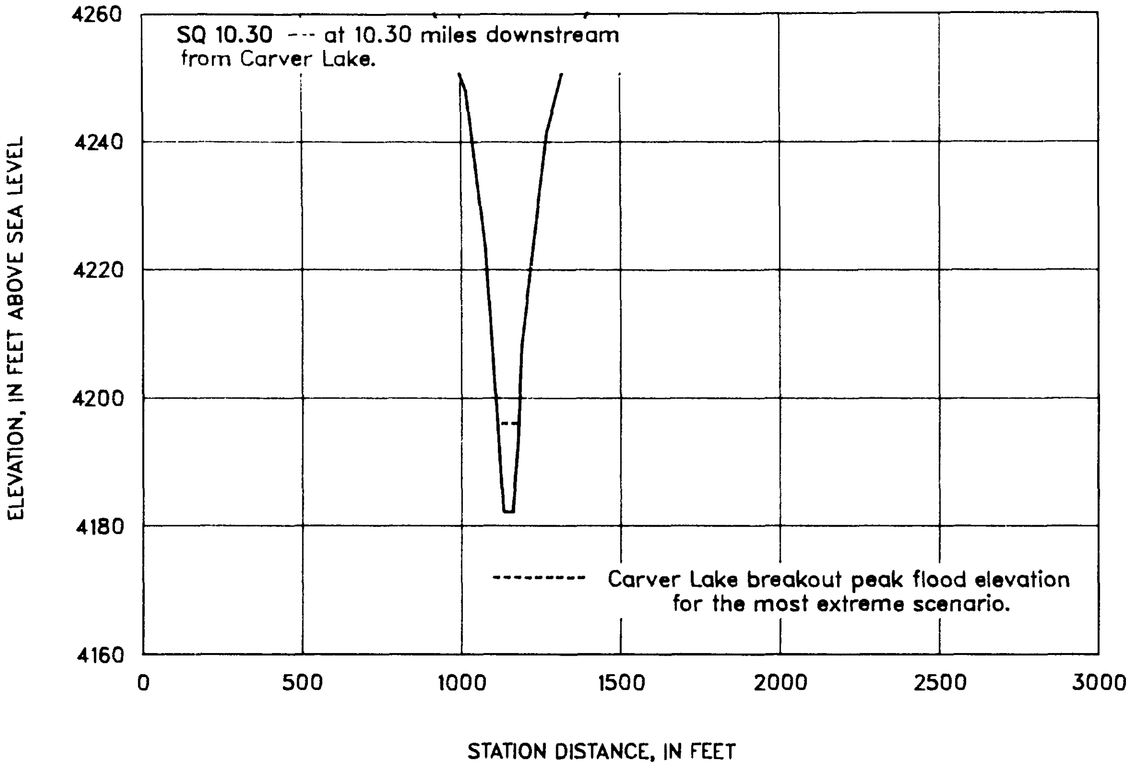

CL 2.60 -- at 2.60 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
6240
6220
6200
6180
6160
6140
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.

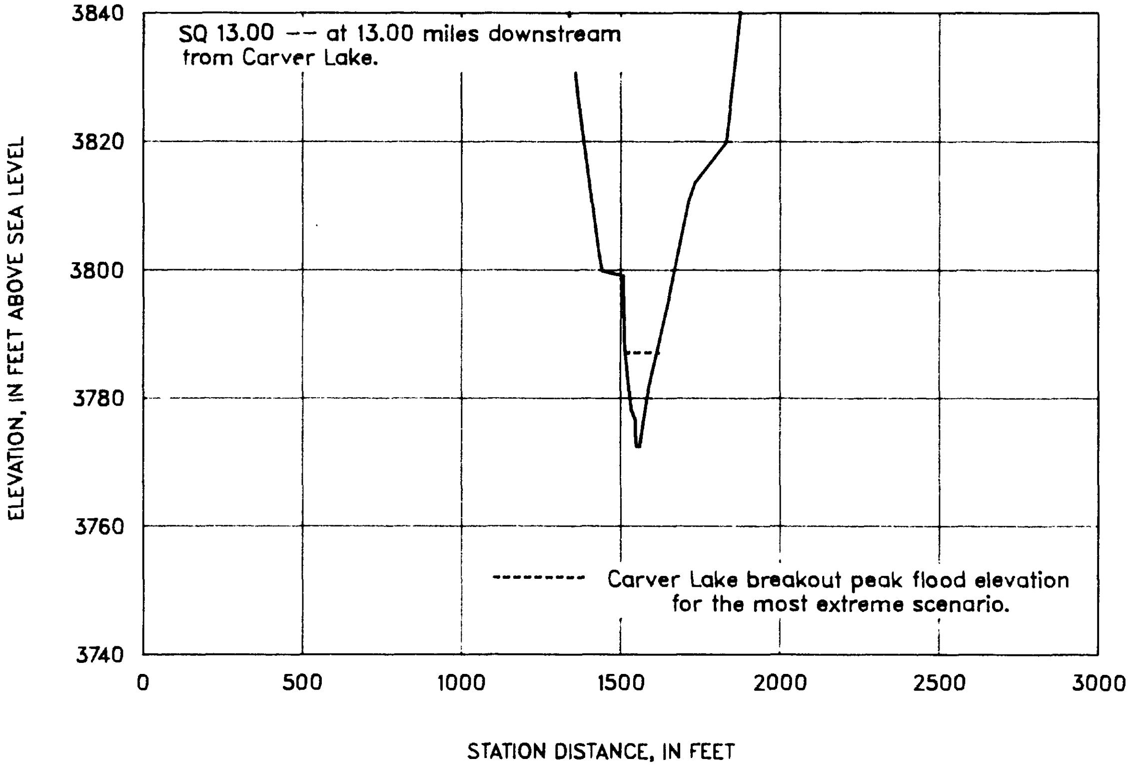

SF 4.20 -- at 4.20 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
5600
5580
5560
5540
5520
5500
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation for the most extreme scenario.

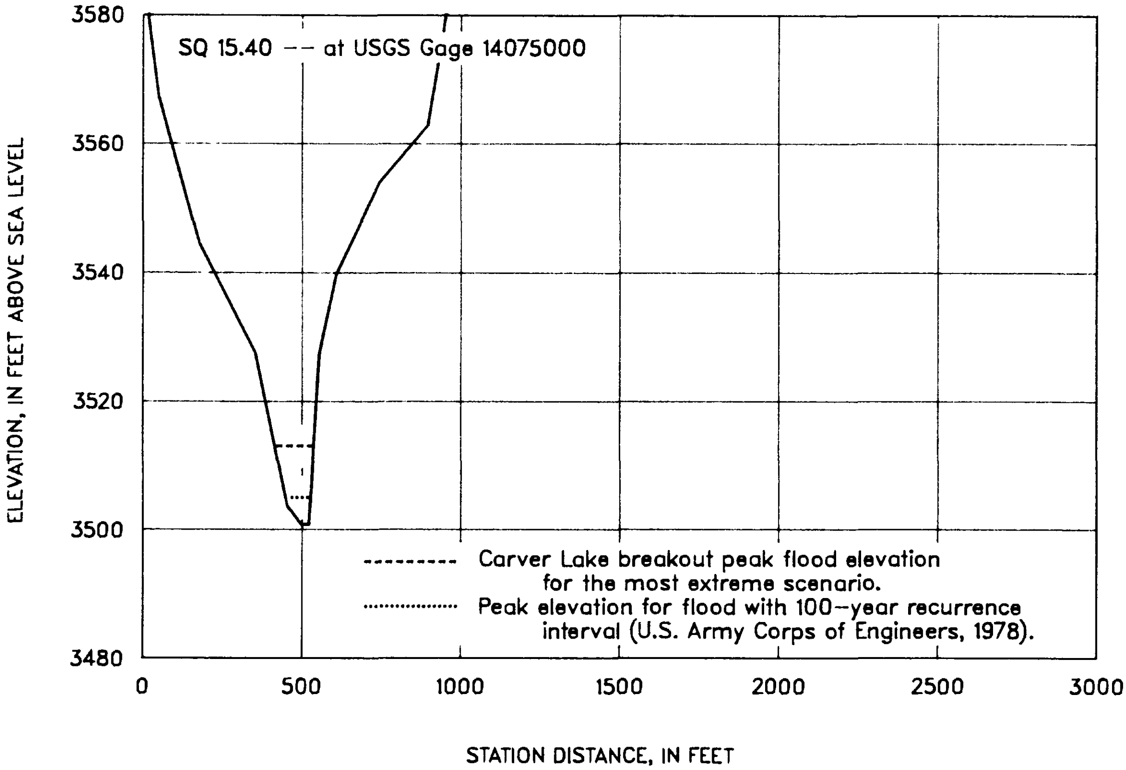

SQ 6.60 -- at 6.60 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
4880
4860
4840
4820
4800
4780
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation for the most extreme scenario.

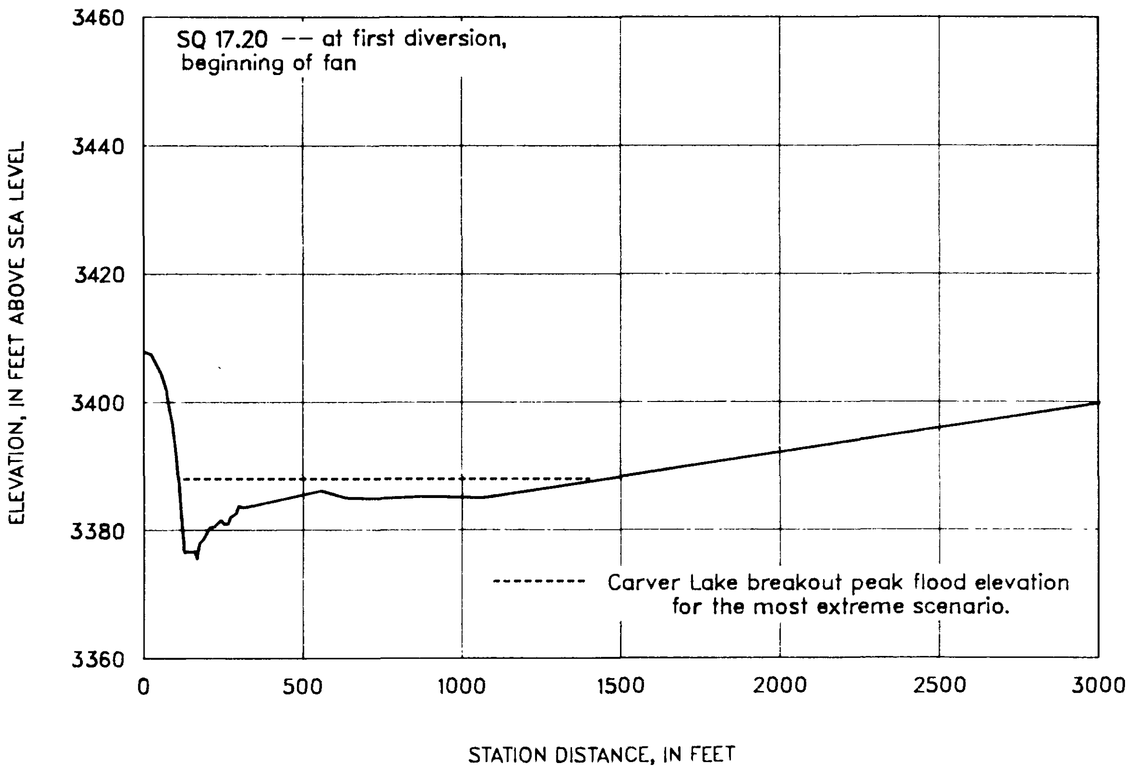

SQ 7.90 -- at exit of mountain canyons.
ELEVATION, IN FEET ABOVE SEA LEVEL
4500
4480
4460
4440
4420
4400
0
500
1000
1500
2000
2500
3000
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.
STATION DISTANCE, IN FEET

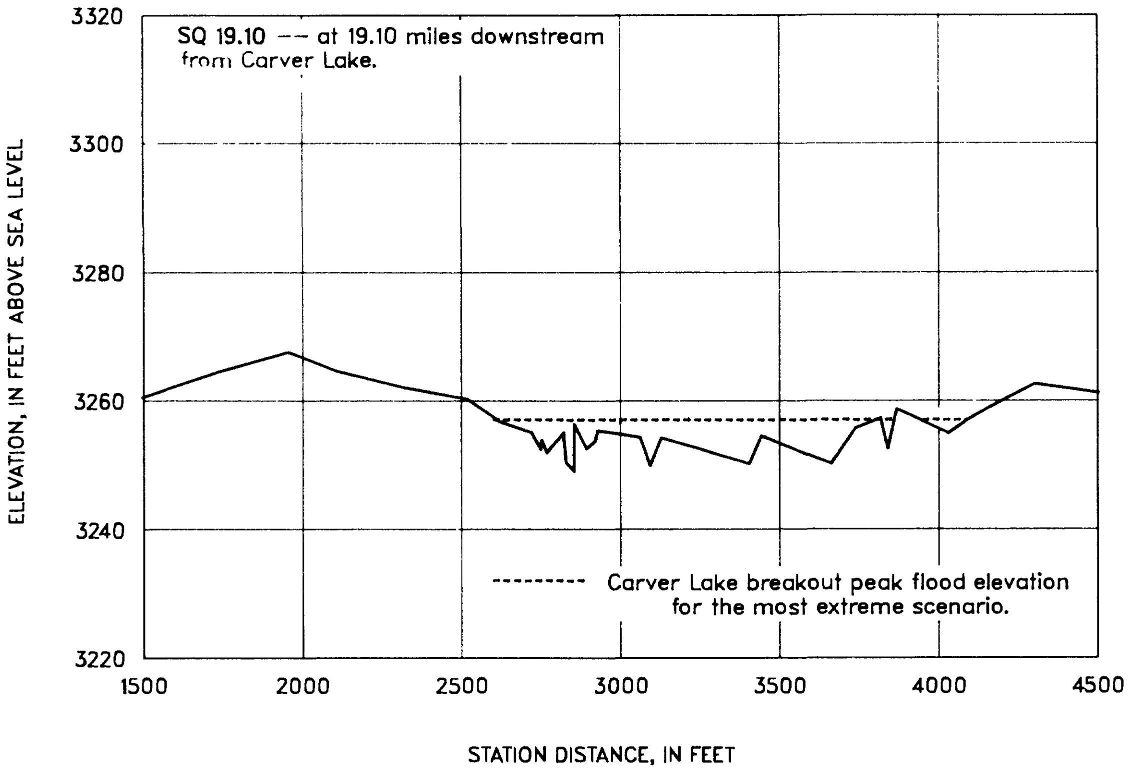

SQ 9.20 -- at 9.20 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
4340
4320
4300
4280
4260
4240
0
500
1000
1500
2000
2500
3000
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.
STATION DISTANCE, IN FEET

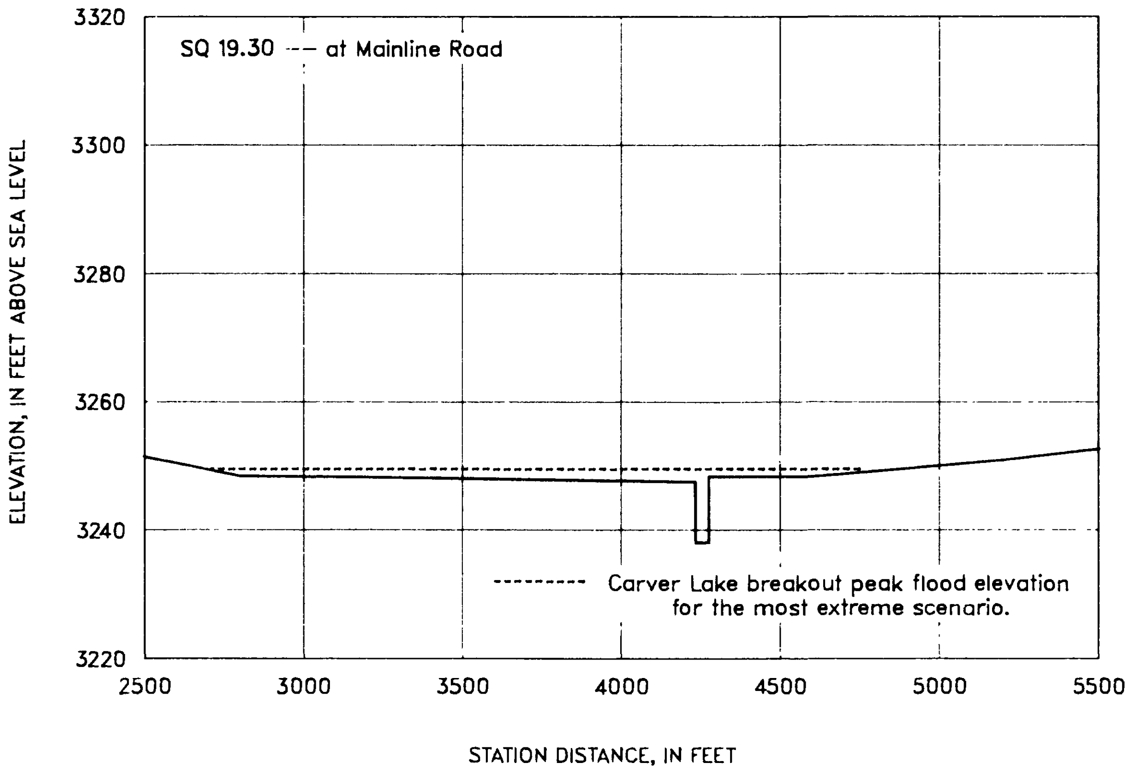

4260
4240
4220
4200
4180
4160
ELEVATION, IN FEET ABOVE SEA LEVEL
SQ 10.30 --- at 10.30 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

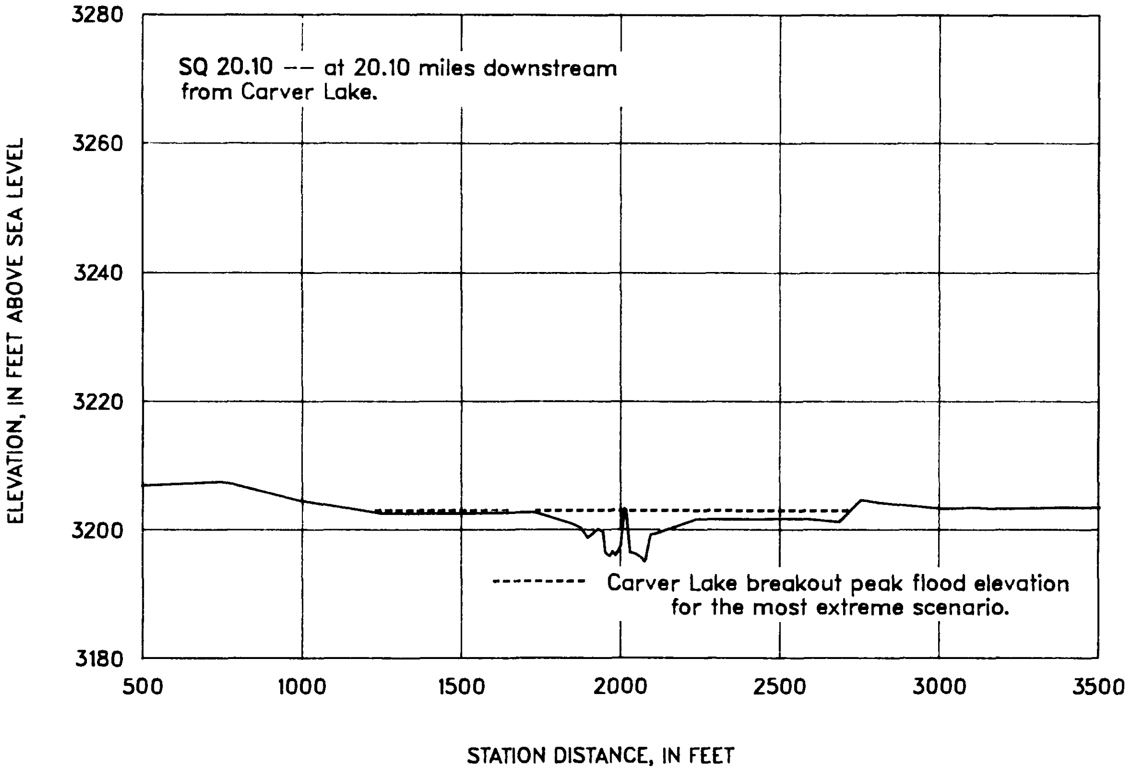

3840
3820
3800
3780
3760
3740
ELEVATION, IN FEET ABOVE SEA LEVEL
SQ 13.00 -- at 13.00 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

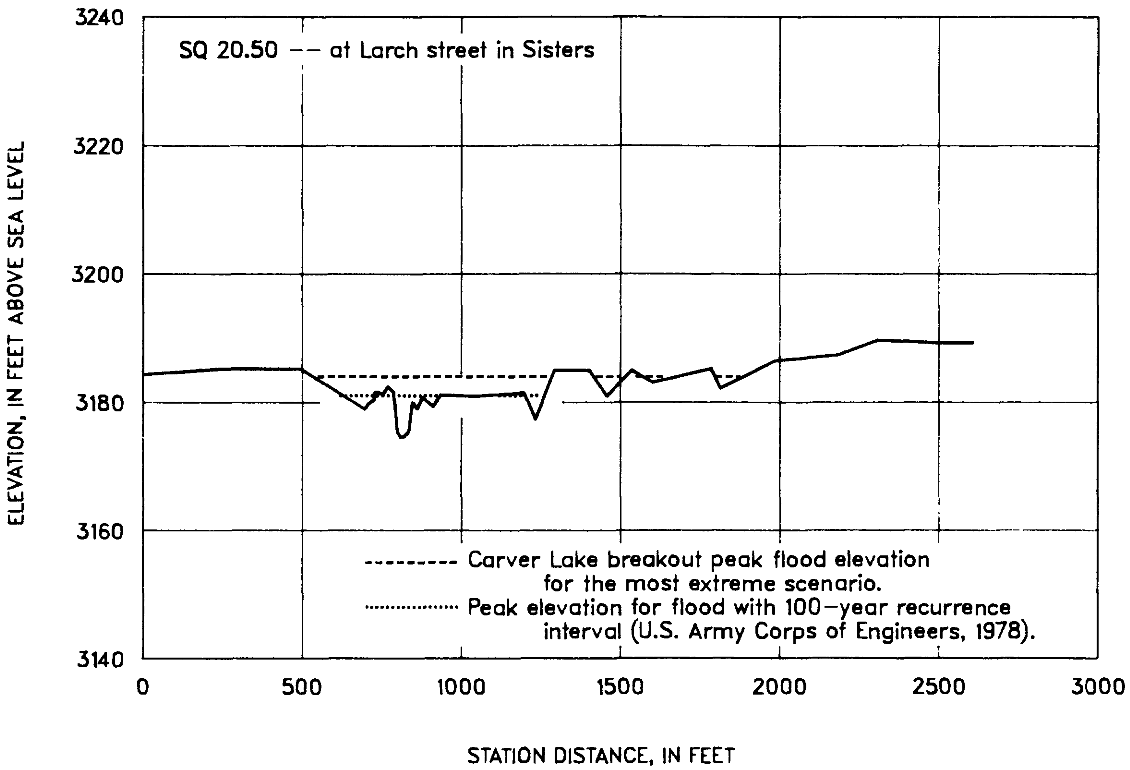

SQ 15.40 -- at USGS Gage 14075000
ELEVATION, IN FEET ABOVE SEA LEVEL
3580
3560
3540
3520
3500
3480
Carver Lake breakout peak flood elevation for the most extreme scenario.
Peak elevation for flood with 100-year recurrence interval (U.S. Army Corps of Engineers, 1978).
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

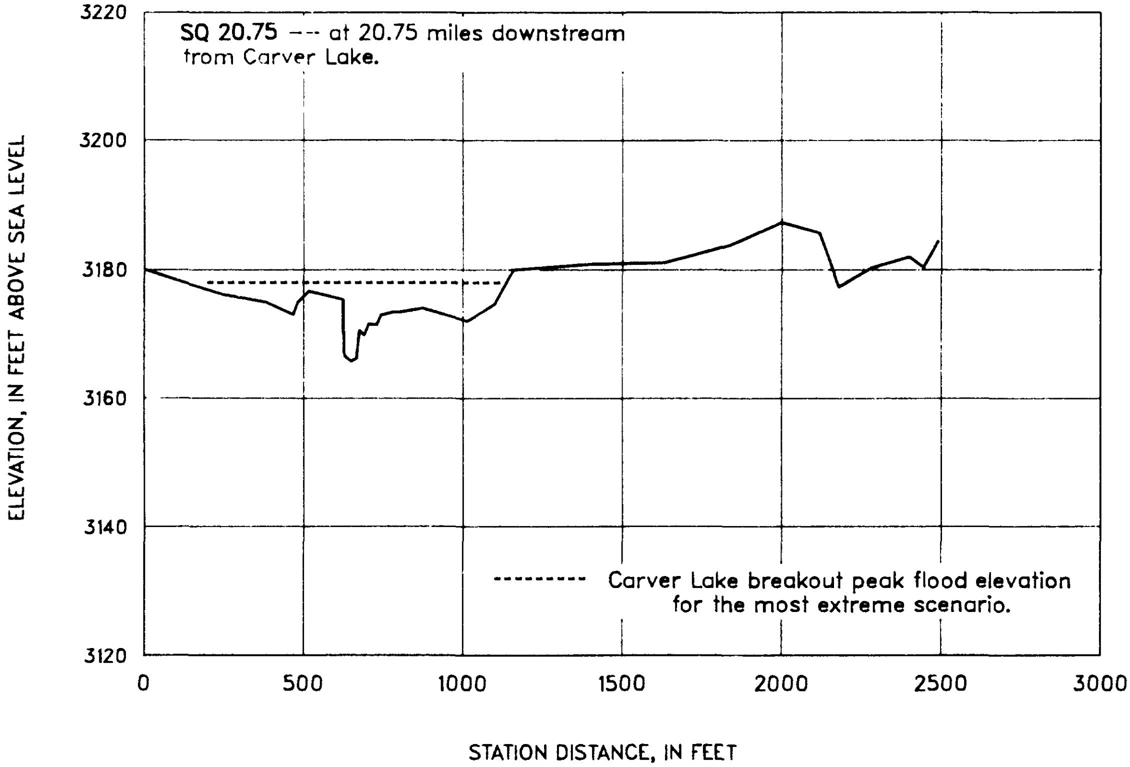

SQ 17.20 -- at first diversion, beginning of fan
ELEVATION, IN FEET ABOVE SEA LEVEL
3460
3440
3420
3400
3380
3360
Carver Lake breakout peak flood elevation for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

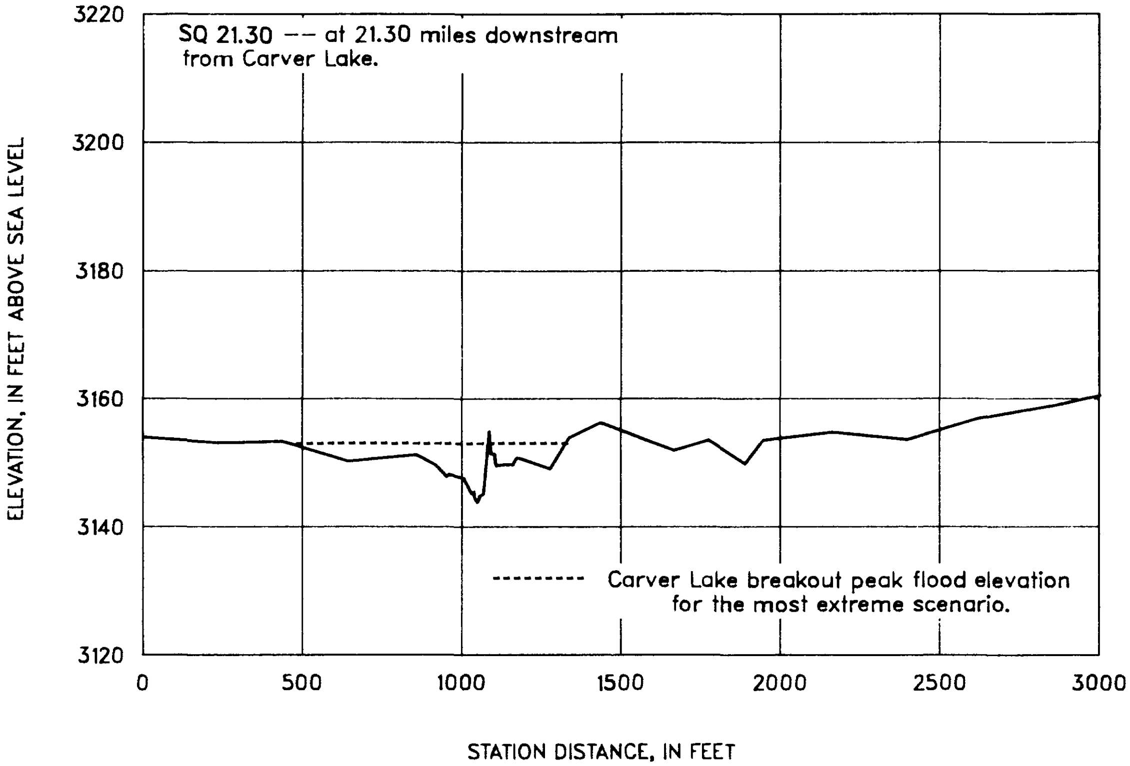

SQ 19.10 -- at 19.10 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
3320
3300
3280
3260
3240
3220
1500
2000
2500
3000
3500
4000
4500
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation for the most extreme scenario.

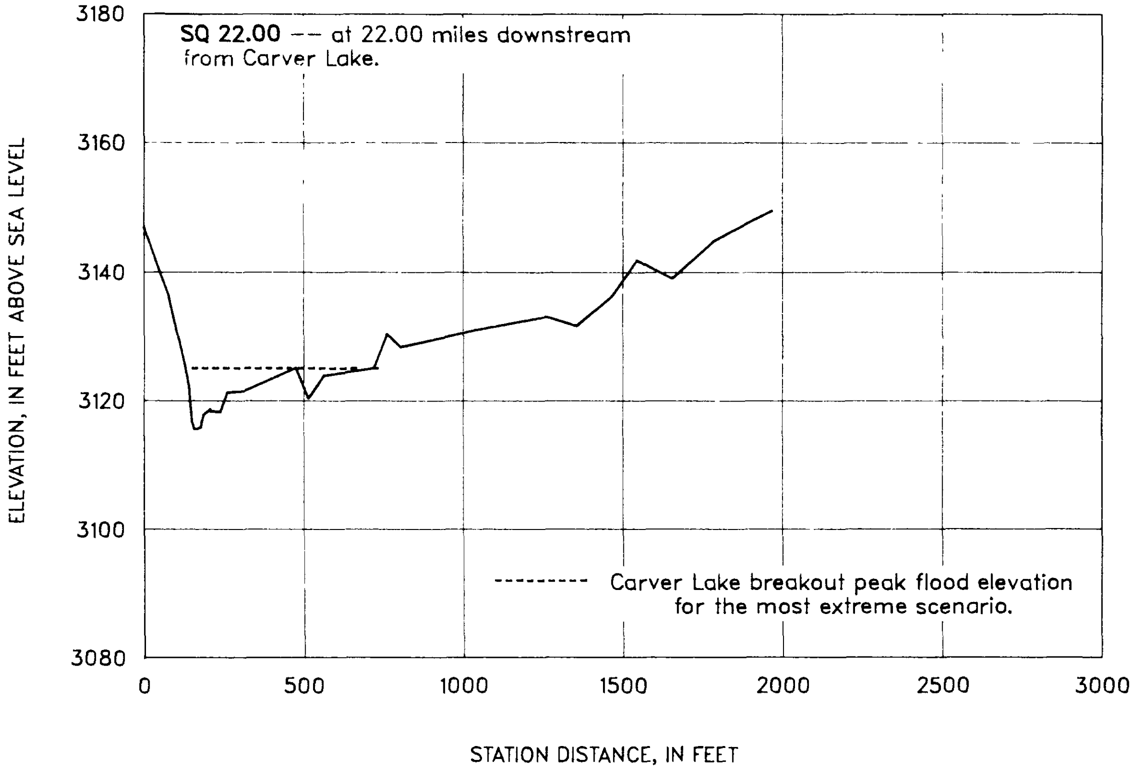

SQ 19.30 -- at Mainline Road
ELEVATION, IN FEET ABOVE SEA LEVEL
3320
3300
3280
3260
3240
3220
2500
3000
3500
4000
4500
5000
5500
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation for the most extreme scenario.

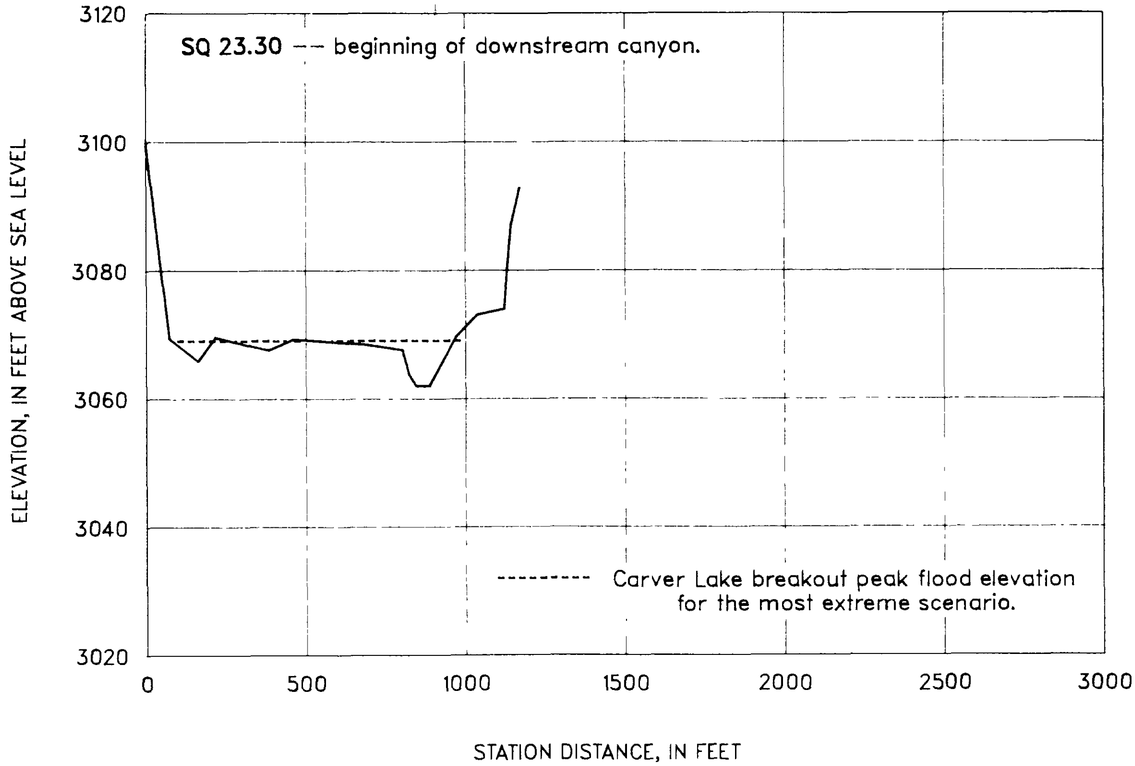

SQ 20.10 -- at 20.10 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
ELEVATION, IN FEET ABOVE SEA LEVEL
3280
3260
3240
3220
3200
3180
500
1000
1500
2000
2500
3000
3500
STATION DISTANCE, IN FEET

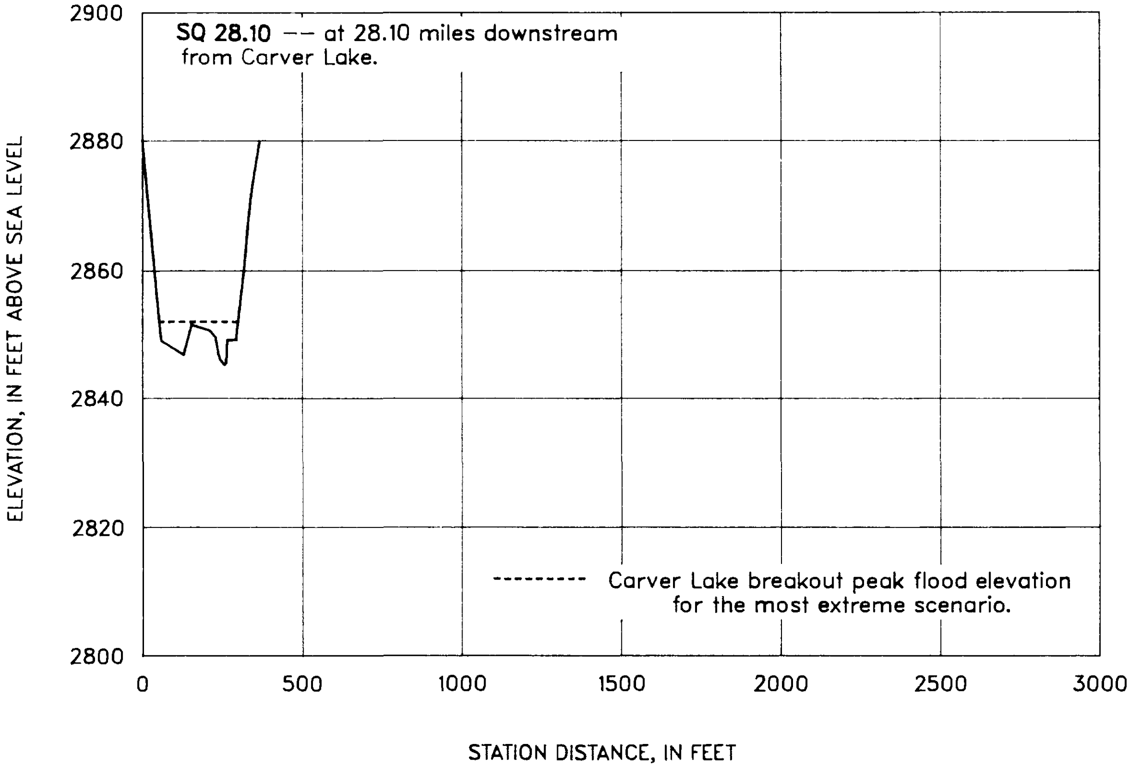

SQ 20.50 -- at Larch street in Sisters
Carver Lake breakout peak flood elevation for the most extreme scenario.
Peak elevation for flood with 100-year recurrence interval (U.S. Army Corps of Engineers, 1978).
ELEVATION, IN FEET ABOVE SEA LEVEL
3240
3220
3200
3180
3160
3140
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

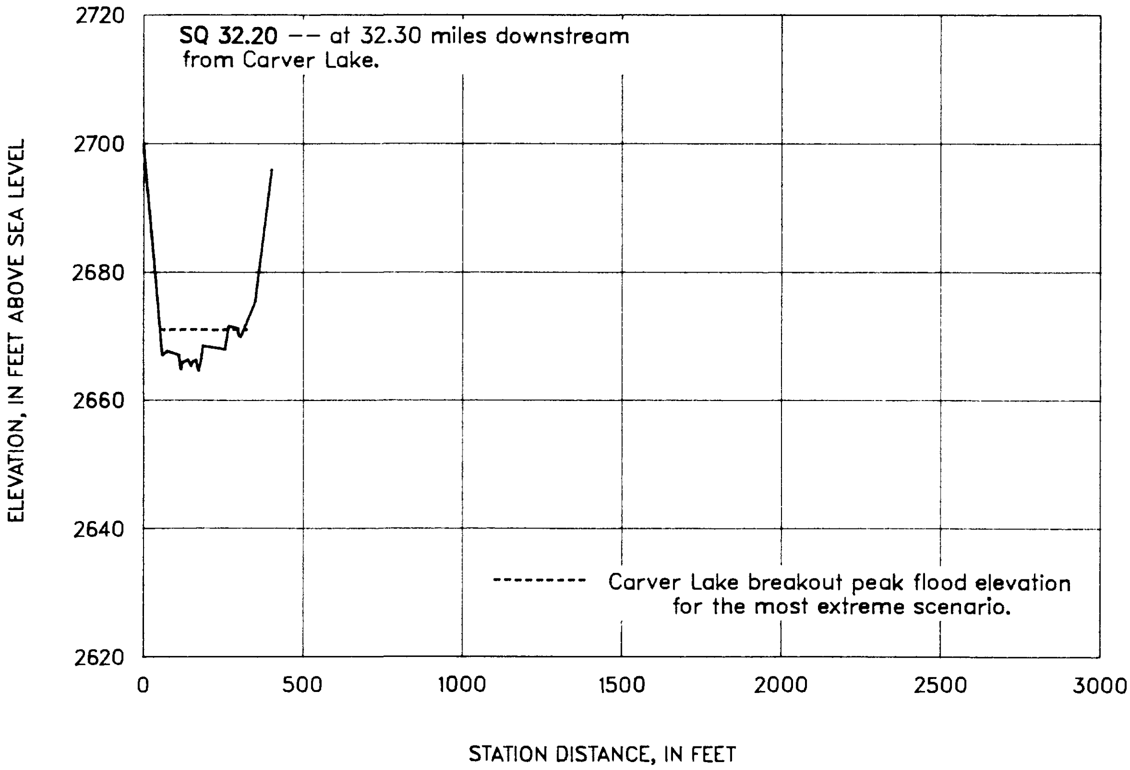

SQ 20.75 -- at 20.75 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
ELEVATION, IN FEET ABOVE SEA LEVEL
3220
3200
3180
3160
3140
3120
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

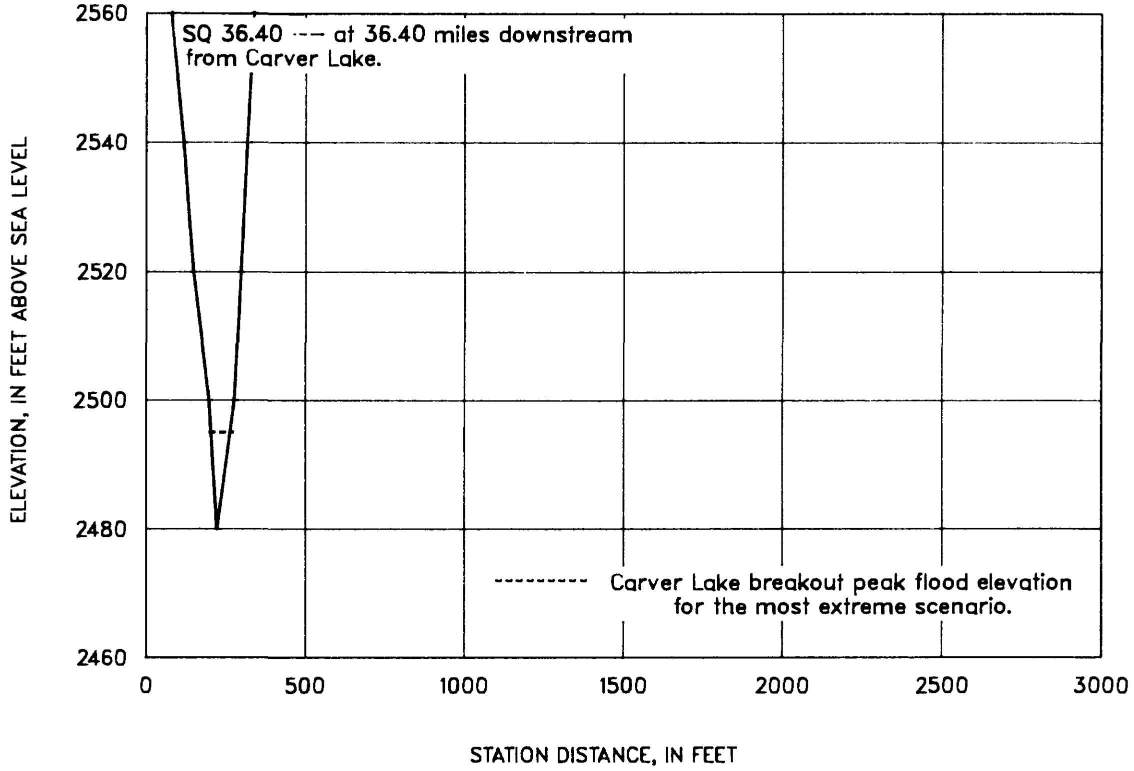

SQ 21.30 -- at 21.30 miles downstream from Carver Lake.
Carver Lake breakout peak flood elevation for the most extreme scenario.
ELEVATION, IN FEET ABOVE SEA LEVEL
3220
3200
3180
3160
3140
3120
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET

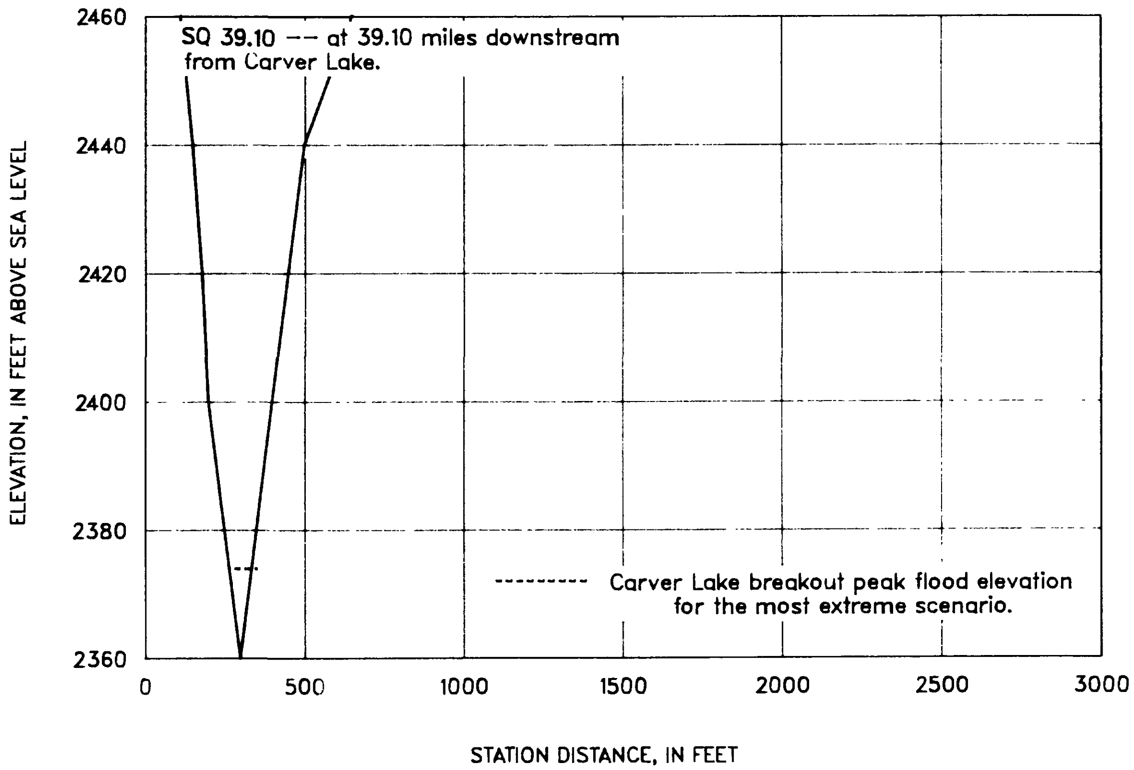

SQ 22.00 -- at 22.00 miles downstream
from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
3180
3160
3140
3120
3100
3080
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation
for the most extreme scenario.

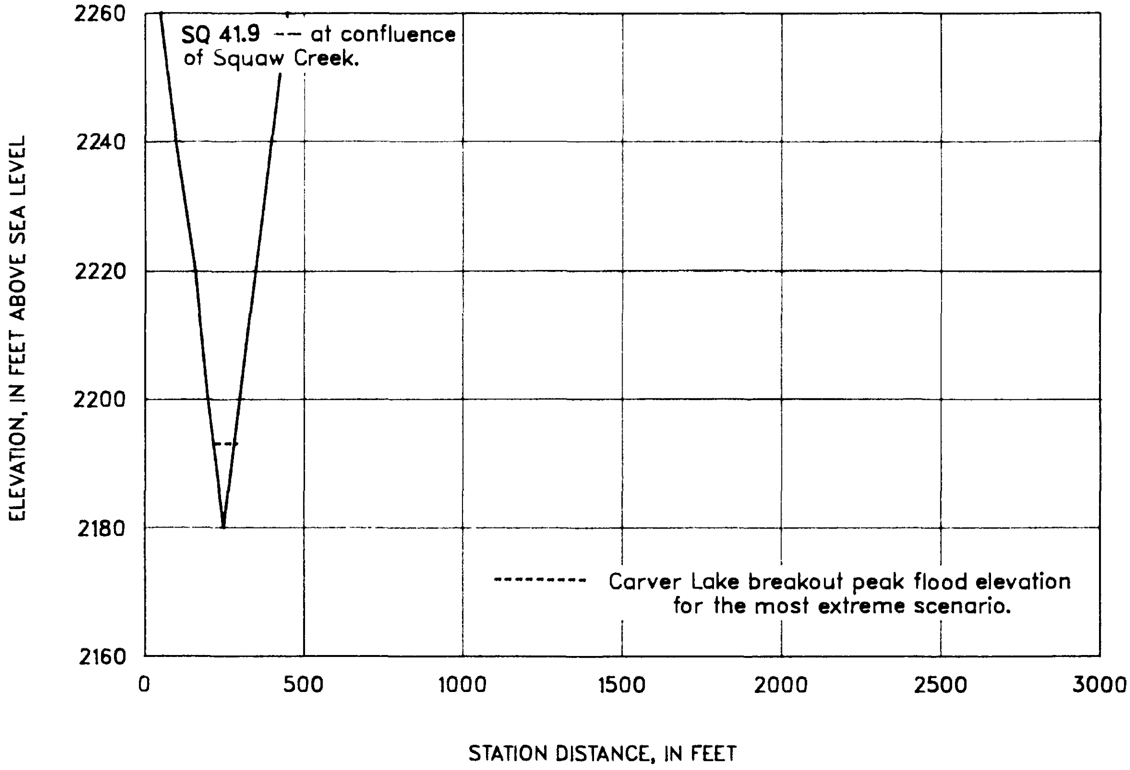

SQ 23.30 -- beginning of downstream canyon.
ELEVATION, IN FEET ABOVE SEA LEVEL
3120
3100
3080
3060
3040
3020
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
Carver Lake breakout peak flood elevation
for the most extreme scenario.


SQ 28.10 -- at 28.10 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
2900
2880
2860
2840
2820
2800
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.


SQ 32.20 -- at 32.30 miles downstream from Carver Lake.
ELEVATION, IN FEET ABOVE SEA LEVEL
2720
2700
2680
2660
2640
2620
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.


2560
2540
2520
2500
2480
2460
ELEVATION, IN FEET ABOVE SEA LEVEL
SQ 36.40 -- at 36.40 miles downstream from Carver Lake.
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET


2460
2440
2420
2400
2380
2360
ELEVATION, IN FEET ABOVE SEA LEVEL
SQ 39.10 -- at 39.10 miles downstream from Carver Lake.
--------- Carver Lake breakout peak flood elevation for the most extreme scenario.
0
500
1000
1500
2000
2500
3000
STATION DISTANCE, IN FEET



☆ U.S. GOVERNMENT PRINTING OFFICE:1987- 792-958/60078