Hydrology, Geomorphology, and Dam-Break Modeling of the July 15, 1982 Lawn Lake Dam and Cascade Lake Dam Failures, Larimer County, Colorado

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1369

Prepared in cooperation with the
Colorado Department of Natural Resources,
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By ROBERT D. JARRETT *and* JOHN E. COSTA

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CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System (SI) units by using the following conversion factors:

Multiply	*By*	*To obtain*
acre	4.047×10^{-3}	square kilometer
acre-foot (acre-ft)	1,233.4	cubic meter
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi$)	1.093×10^{-2}	cubic meter per second per square kilometer
cubic yard (yd^3)	0.7646	cubic meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per second (ft/s)	0.3048	meter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
mile per hour (mi/h)	1.609	kilometer per hour
pound per square inch ($lb/in.^2$)	6,895	pascal
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
ton, short	0.9072	tonne, metric

HYDROLOGY, GEOMORPHOLOGY, AND DAM-BREAK MODELING OF THE JULY 15, 1982, LAWN LAKE DAM AND CASCADE LAKE DAM FAILURES, LARIMER COUNTY, COLORADO

By ROBERT D. JARRETT and JOHN E. COSTA

ABSTRACT

At approximately 0530 Mountain Daylight Time on the morning of July 15, 1982, Lawn Lake dam, a 26-foot-high earthen dam located in Rocky Mountain National Park, Colorado, failed. The dam released 674 acre-feet of water and an estimated peak discharge of 18,000 cubic feet per second down the Roaring River valley. Three people were killed and damages totaled $31 million. The Colorado State Engineer determined that the probable cause of failure was deterioration of lead caulking used for the connection between the outlet pipe and the gate valve. The resulting leak eroded the earthfill, and progressive piping led to failure of the embankment.

Floodwaters from Lawn Lake dam overtopped a second dam, Cascade Lake dam, located 6.7 miles downstream, which also failed. Cascade Lake dam, a 17-foot high concrete gravity dam, 12.1 acre-foot capacity dam, failed by toppling with 4.2 feet of water flowing over its crest. The flood continued down the Fall River into the town of Estes Park, which received extensive damage from the overbank flow.

This report presents the setting, a summary of the causes of the dam failures, the hydrologic data, and geomorphic effects of the flood. Data on dam-breach floods on high-gradient streams are limited. A dam-break computer model was used to evalute the model's capabilities on high-gradient streams, to enhance and provide supplemental hydrologic information, and to evaluate various hypothetical scenarios of dam-breach development and probable impact of the failure of Cascade Lake dam.

Flood data were obtained at two gaging stations (06732500 Fall River at Estes Park and 06733000 Big Thompson River at Estes Park) and five miscellaneous sites downstream from the Lawn Lake dam. Peak discharges were determined using a variety of indirect methods. Because of extensive scour and erosion along the Roaring River, peak discharges were estimated from the dam-break model. Calculated peak discharges for the flood were 18,000 cubic feet per second from Lawn Lake dam, 12,000 cubic feet per second at Horseshoe Falls where Roaring River joins the Fall River, 7,210 cubic feet per second into Cascade Lake dam at the east end of Horseshoe Park, 16,000 cubic feet per second from the failure of Cascade Lake dam, 13,100 cubic feet per second about 1 mile downstream from Cascade Lake dam, 8,520 cubic feet per second just upstream from Estes Park, 6,550 cubic feet per second for gaging station 06732500 Fall River at Estes Park, and 5,500 cubic feet per second for gaging station 06733000 Big Thompson River at Estes Park. Maximum depths ranged from 6.4 to 23.8 feet; maximum widths ranged from 97 to 1,112 feet; and mean velocities ranged from 3.3 to 12.6 feet per second. Traveltimes of the flood were determined from eyewitness accounts. The leading flood wave took 3.28 hours to travel 12.5 miles (average 3.8 miles per hour). Flood peaks were 2.1 to 30 times the 500-year flood for selected locations along the flood path. Geomorphic and sedimentologic evidence suggest that it probably was the largest flood in these basins, at least since the retreat of the glaciers several thousands of years ago.

Geomorphic effects of the flood resulting from the dam failures were profound. Channels were widened tens of feet and scoured from 5 to 50 feet locally. In the Roaring River valley, alternate river reaches were either scoured or filled, depending on valley slope. Generally, reaches steeper than 7 percent were scoured, and reaches less than 7 percent were filled. In the Roaring River, 56 percent of the channel was scoured, some by as much as 50 feet, and 44 percent was filled with coarse sediments, 2 to 8 feet thick.

An alluvial fan of 42.3 acres, containing 364,600 cubic yards of material, was deposited at the mouth of the Roaring River. The fan has a maximum thickness of 44 feet and an average thickness of 5.3 feet. The largest boulder thought to have moved in the flood, 14×17.5×21 feet and weighing an estimated 452 tons, was located on the alluvial fan. Down the flow axis, average particle size changes from 7.5-foot boulders to fine sand and silt in a distance of 1,900 feet. The alluvial fan dammed the Fall River, forming a lake of 17 acres upstream from the fan.

Satisfactory results were obtained from the dam-break model, but not without significant difficulties in proper operation of the model. To calibrate the model, Manning *n*-values between 0.1 and 0.2, or an average of 78 percent greater than field-selected values, were required; subcritical flow was verified. The occurrence of numerous debris dams caused localized backwater, resulting in predominantly subcritical flow. However, when these debris dams broke, flow probably was supercritical for a short distance until another debris dam formed. Without the extensive calibration of the model and the assumption of subcritical flow, results would have been significantly different.

Peak discharges from dam-break modeling reflect water-only discharges; total discharge may have been considerably higher on the Roaring River and on the Fall River immediately downstream from Cascade Lake dam from sediment and debris. At Horseshoe Falls and for a short reach downstream from Cascade Lake dam, geomorphic and sedimentologic evidence indicates the flow temporarily became a turbulent, high-concentration, cohesionless sediment-gravity flow. The sediment and debris may have bulked the peak water flow by 50 to 60 percent. The range of difference of observed and modeled peak discharges varied from -3,200 cubic feet per second to 600 cubic feet per second. The range of difference of observed and modeled maximum flood depth was -1.3 to 2.6 feet and averaged 1.0 foot. The range of difference of observed and modeled leading edge of traveltime was -0.4 and 0.15 hour.

Comparisons were made for hypothetical breach widths of (1) 25 feet and (2) 200 feet. They were compared with model results of the actual breach width of 55 feet:

1. For a breach width of 25 feet, the peak discharge would have been 7,000 cubic feet per second less downstream from Lawn Lake dam to 1,300 cubic feet per second less at Estes Park. Maximum flood

depths would have averaged 0.6 foot lower; the flood wave would have reached Estes Park at the same time. For this hypothetical case, Cascade Lake dam still would have failed.

2. For a breach width of 200 feet, peak discharge would have been 22,600 cubic feet per second greater downstream from Lawn Lake dam to 5,400 cubic feet per second greater at Estes Park. Maximum flood depth would have averaged 2.7 feet higher; the flood wave would have reached Estes Park 0.4 hour earlier. The model also indicated that the outflow peak discharge from the worst-case failure of Lawn Lake dam could have been at least 56,000 cubic feet per second.

If Cascade Lake dam had not failed (or had not been present), peak discharges would have been reduced by 11,300 cubic feet per second immediately downstream from the dam to 500 cubic feet per second less at Estes Park. Maximum flood depths would have averaged 0.6 foot lower, and the flood wave would have reached Lake Estes 0.3 hour later.

INTRODUCTION

Just before sunrise, at about 0530 MDT (Mountain Daylight Time), on the calm, clear morning of Thursday, July 15, 1982, the privately-owned Lawn Lake dam, a 26-ft-high earthen structure, located at an elevation of about 11,000 ft in Rocky Mountain National Park, breached due to a piping failure (Office of the State Engineer, 1983), releasing 674 acre-ft and an estimated peak discharge of 18,000 ft^3/s of water down the Roaring River (fig. 1).

I started to hear a sound like an airplane. Also, there were loud booms. It got louder and louder. I thought it was breaking the sound barrier. I kept looking for a plane, but couldn't see one. I got suspicious and started to look upstream. I saw trees crashing over and a wall of water coming down. I started to run as fast as I could for high ground. There was a deafening roar. I fell and got up and kept running. I stood on high ground and watched it wipe out our campsite. It knocked everything in its path over; Steve didn't stand a chance.

With these words Steven Cashman described his harrowing experience with the flood that swept his camping companion to his death in the Roaring River. Other campers along the Roaring River estimated the wall of water to be 25 to 30 ft high, carrying with it large trees and boulders, so that the water looked like a "wet, brown cloud" and sounded like extremely loud continuous "thunder" or a "freight train."

The flood, attenuated by the relatively flat Horseshoe Park (an old glacial lakebed), continued along the Fall River, where it caused Cascade Lake dam (an approximately 17-ft-high, 12-acre-ft capacity concrete gravity dam) to fail because of tipping over from overtopping. Peak discharge upstream from Cascade Lake dam was 7,210 ft^3/s; however, discharge increased to 16,100 ft^3/s or more as a result of the Cascade Lake dam failure. The flood continued to attenuate in its passage down the Fall River and through the town of Estes Park.

After Cascade Lake dam failed, two campers were swept to their deaths a short distance downstream from the dam. The flood continued down the Fall River, causing extensive damage to homes, motels, businesses, and bridges, particularly in the town of Estes Park. In Estes Park, the flood entered the Big Thompson River for a short distance before entering Lake Estes, which is formed by the U.S. Bureau of Reclamation's Olympus dam. This reservoir contained all the floodwaters. The peak discharge was 5,500 ft^3/s entering Lake Estes, which is about 12.5 mi downstream from Lawn Lake. Peak discharge into Lake Estes occurred approximately 3 hours and 40 minutes after the failure of Lawn Lake dam. In that brief time, three people were killed and approximately $31 million in private and public damages, cleanup, and economic loss was reported. The flood resulted in a Presidential Disaster Declaration for Larimer County on July 22, 1982.

The purpose of this report is to present the setting, a summary of causes of the dam failures, the hydrologic data on the flood, and to document geomorphic effects of the flood. A secondary purpose is to present data obtained from using a dam-break computer model to evaluate that model's capabilities on high-gradient streams, to enhance and provide supplemental hydrologic information, and to evaluate various hypothetical scenarios of dam-breach development and probable impact of the failure of Cascade Lake dam. Documentation and analysis of the flood should provide valuable information on dam-breach floods of small dams on high-gradient streams for future hazard mitigation related to dam failures.

ACKNOWLEDGMENTS

Data and data interpretation in this report are based on the combined efforts of many private individuals, and upon local county, Federal, and State agencies. This assistance is gratefully acknowledged.

Many individuals provided valuable eyewitness information that helped in the understanding of the flood characteristics. Local residents also granted access to their property to the field personnel working in the flooded area. Appreciation also is extended to the officials of the town of Estes Park, of Larimer County, and to National Park Service personnel who cooperated and contributed data during the data-collection period.

Jack Truby, Colorado Division of Disaster Emergency Services, provided estimates of flood damages. Alan Pearson, Colorado Department of Natural Resources, Division of Water Resources, Office of the State Engineer, provided information on the history and causes of failures of the dams. William Stanton, Colorado Department of Natural Resources, Colorado Water

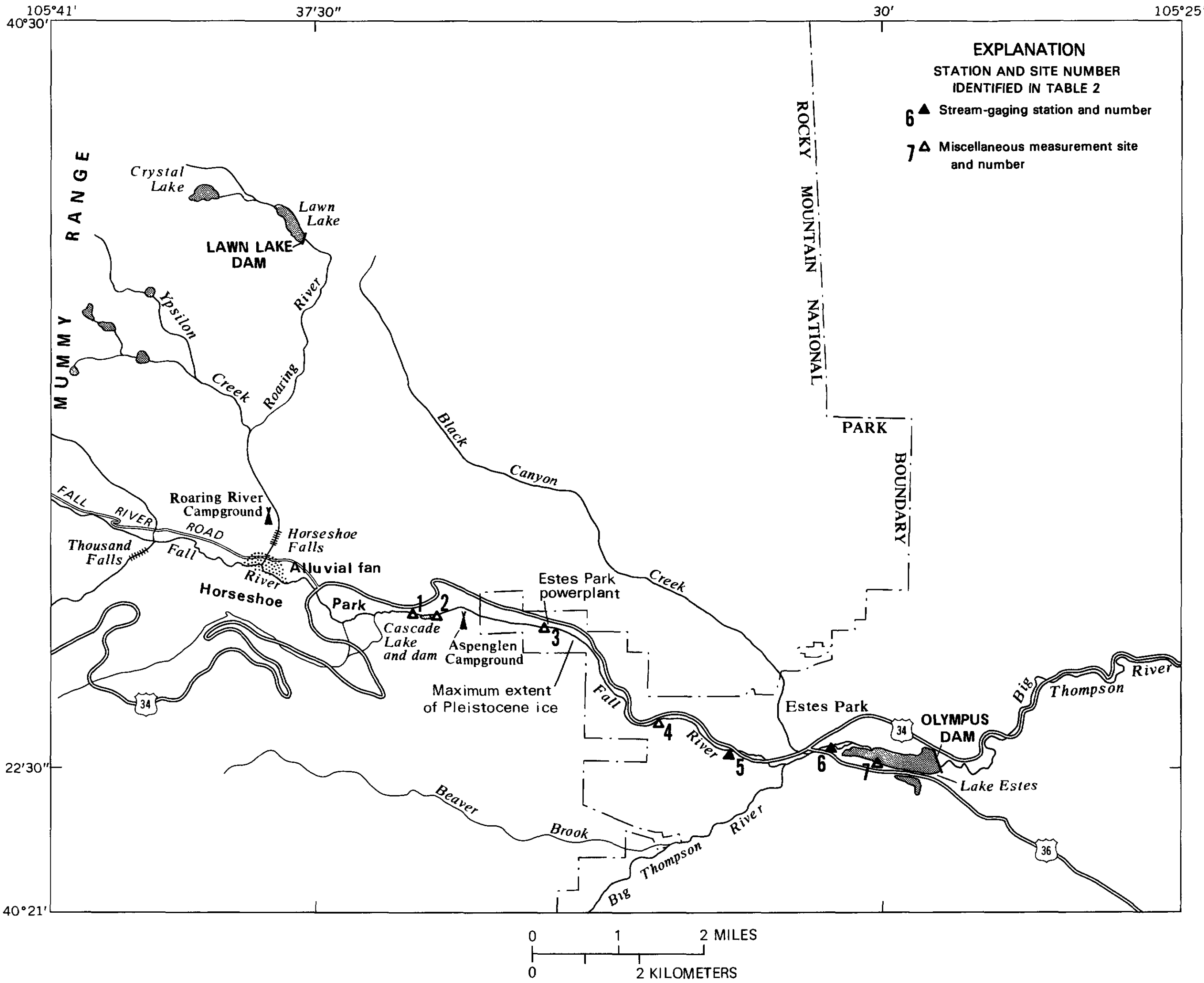

FIGURE 1.—Area between Lawn Lake dam and Lake Estes.

Conservation Board provided historical flood data, flooded area maps, and additional damage data.

The U.S. Bureau of Reclamation, through the Western Area Power Administration, provided helicopter transportation for the collection of data at remote Lawn Lake. Wayne Graham and Curtis Brown of the Bureau of Reclamation provided data on the flood traveltime and warning and response to the flood. Charles Huntley and Zenas Blevins, also of the Bureau of Reclamation, provided computation of the inflow to Lake Estes and hydrologic information.

The U.S. Army Corps of Engineers, Omaha District, provided aerial photographs that were taken 4 hours after the flood and were used to prepare topographic maps of the two lakes. Other valuable photographs in this report were obtained from the town of Estes Park, Federal and State agencies, and from private individuals. These photograph sources are credited in individual figures.

THE SETTING

Lawn Lake is a manmade enlarged natural lake, occupying a moraine-dammed depression on the southeast side of the Mummy Range in Rocky Mountain National Park (Colorado) at an elevation of about 11,000 ft (fig. 1). Local bedrock consists of Precambrian gneisses and schists that are more than 1.7 billion years old (Peterman and others, 1967). Lawn Lake is fed by the Roaring River, which originates upstream from Crystal Lake, a higher cirque lake about 1 mi upstream, at an elevation of about 11,500 ft. Downstream from Crystal Lake, the valley is steep and rugged. The Roaring River descends over a steep cliff into Lawn Lake. Downstream from Lawn Lake, a broad, till-covered valley extends southeast for about 0.5 mi; then the valley turns south. Slopes range from 5 to 26 percent, and average 10 percent along the Roaring River (fig. 2). Mean annual precipitation in the area varies with elevation, ranging from 20 in. at Estes Park to 40 in. or more on the Continental Divide above Lawn Lake.

Downstream from Lawn Lake, the Roaring River descends over a series of steep bedrock falls and through gentle mountain meadows. The Roaring River valley and the Fall River valley were repeatedly glaciated during the Pleistocene Epoch. Landforms and sediments along the course of the flood bear strong imprints of this glacial activity (Jones and Quam, 1944; Richmond, 1960). Lawn Lake is at tree line; along the Roaring River, vegetation consists of spruce, fir, and aspen forests. Where the Roaring River joins the Fall River at an elevation of 8,550 ft in the west end of Horseshoe Park, the Roaring River descends 500 ft in 0.3 mi in a series of rapids known collectively as Horseshoe Falls (fig. 1).

Horseshoe Park is a flat, moraine-rimmed basin that was occupied by a large glacial lake when terminal moraines dammed the Fall River at the east end of the park. The hills surrounding Horseshoe Park are covered with ponderosa and lodgepole pines and aspen forests. The floor of Horseshoe Park is 0.5 mi wide and 3 mi long, and is underlain by ground moraine, outwash, and lacustrine sediments. Valley slope is relatively flat, averaging 0.7 percent. The park is covered by meadow grass; dense willows mark the meandering course of the Fall River through the park. Sinuosity of the Fall River in Horseshoe Park downstream from the Roaring River is 2.2, compared to 1.0 to 1.05 for other steeper mountain streams in Rocky Mountain National Park.

The Fall River flows into Cascade Lake at the east end of Horseshoe Park. Cascade Lake, located about 5.3 mi west of Estes Park, was an artificial lake privately built in 1908 and obtained by Estes Park for power generation in 1945. Downstream from Cascade Lake, the Fall River gradient steepens again to 9 percent as it flows through a series of Pleistocene terminal moraines and into Aspenglen Campground (fig. 2).

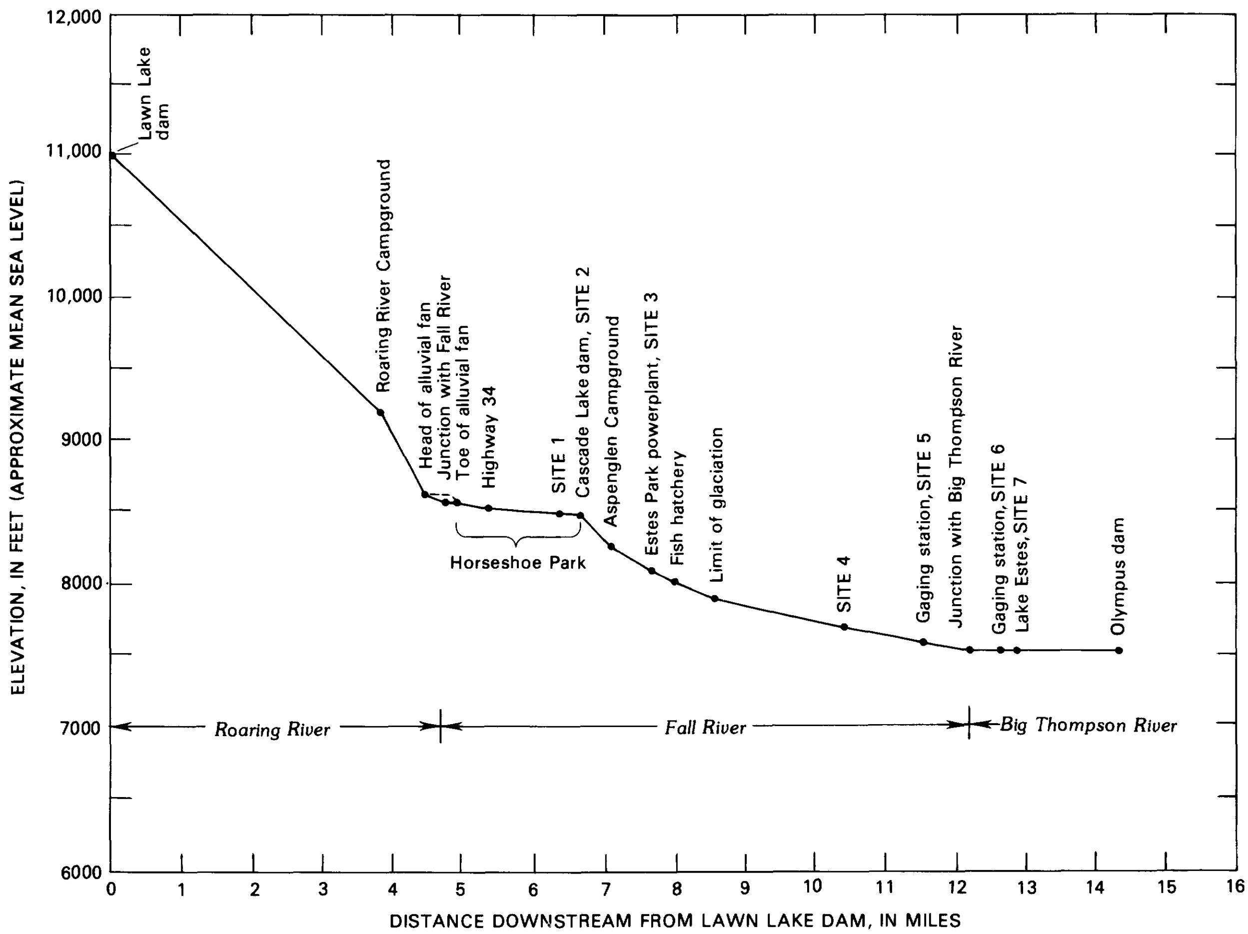

FIGURE 2.—Long profile of flood path of the water from Lawn Lake dam and Cascade Lake dam failures. Vertical exaggeration 10.5 times.

Downstream from the Estes Park powerplant, at an elevation of about 8,000 ft and about 1 mi downstream from Cascade Lake, the Fall River valley narrows noticeably, marking the probable maximum extent of Pleistocene glacial advances (Richmond, 1960; Jones and Quam, 1944). Below 8,000 ft, the Fall River flows down a relatively steep and narrow valley bordered by numerous bedrock outcrops and thin, small, discontinuous flood plains. The Fall River joins the Big Thompson River in Estes Park and then flows 0.7 mi before entering the west end of Lake Estes. Lake Estes is a large reservoir, formed behind Olympus dam, completed as part of the Colorado-Big Thompson project by the U.S. Bureau of Reclamation in 1948.

HISTORY OF THE DAMS

Two dams in Rocky Mountain National Park failed on of July 15, 1982—the Lawn Lake dam and the Cascade Lake dam. A discussion of their histories follows.

LAWN LAKE DAM

Lawn Lake dam was an earthen dam constructed in 1903 by the Farmers Irrigation Ditch and Reservoir Company to impound additional water in an existing mountain lake for irrigation storage (fig. 3). Originally Lawn Lake was a natural moraine-dammed lake with a surface area of 16.4 acres, based on the original map and impoundment plans filed with the Colorado State Engineer's Office (Office of the State Engineer, 1983). The irrigation company's plans called for an earthen dam to be 24 ft high to the spillway crest, which would create a reservoir of 47.1 acres surface area and 811 acre-ft of storage. However, based on several capacity surveys and records of the private irrigation company, the height of the Lawn Lake dam was 20.35 ft to the spillway crest with a reservoir capacity of 611.96 acre-ft, in September of 1907. In September 1931, probably in response to below-average precipitation and dust-bowl conditions on the Colorado High Plains, the dam was enlarged to a height of 24 ft at the spillway and a reservoir capacity of 817.2 acre-ft. This enlargement was never approved by the Colorado State Engineer (Office of the State Engineer, 1983). Postfailure surveys (discussed later) indicated that the dam was 26 ft high (water was 24 ft deep), had a capacity of 674 acre-ft, and was about 560 ft long at the time of failure (figs. 4*A* and 4*B*).

Lawn Lake dam was constructed of heterogeneous local earthfill from the surrounding ground moraine. These glacial deposits have a maximum thickness of about 25 ft in the immediate vicinity of the dam. The underlying Precambrian igneous and metamorphic bedrock is highly fractured and jointed, but fresh. About 4 to 5 ft below the crest of the dam, a 12-in. layer of dark, organic material appeared to cover the entire dam (fig. 5). The origin of this organic horizon is uncertain, but it probably represents a top layer of humus on the 1903 embankment prior to the height enlargement of 4 to 5 ft in 1931.

Earthfill material for the dam is composed primarily of silty and poorly graded sands with varying amounts of fine gravels and considerable amounts of organic material. Geotechnical testing of 20 samples taken from the damfill material following the failure was conducted by the Office of the State Engineer (1983). The tested samples contained 7 to 32 percent nonplastic to high-plasticity fines; they were classified primarily SP-SM and SM in the Unified Soil Classification (U.S. Army Corps of Engineers, 1953). Permeability testing on three samples gave results of 0, 0.7, and 6.6 ft/d. Results of triaxial shear tests on remolded samples are given in table 1. The remolded samples are probably not representative of in situ strength properties.

POSSIBLE CAUSES OF FAILURE

Six possible causes of the failure of the Lawn Lake dam were investigated by the Office of the State Engineer (1983): (1) Overtopping; (2) earthquake shaking; (3) rodent damage; (4) frost penetration; (5) embankment stability; and (6) piping.

Overtopping and earthquake shaking could be dismissed quickly as possible causes of failure. Weather was not a factor in the failure. Rainfall during July 10–15, 1982, in Estes Park totaled 0.11 in., and no large rainstorms occurred in the area during this period. The sky was clear the morning of the dam failure. Snowpack was about normal and runoff slightly below normal in the surrounding region during the winter of 1981–82. However, based on postfailure surveys of the dam and reservoir, the high-water line in the reservoir at the time of failure was about 2 ft below the crest of the dam. The National Earthquake Information Center in Golden, Colo., indicated that no earthquakes were detected at the time of failure; in fact, no earthquake has ever been measured in the area of the dam (Office of the State Engineer, 1983).

The possiblity of failure from rodent damage and frost penetration was more difficult to dismiss. Marmot burrows were observed along the crest and downstream slope of the remaining dam. Through excavation, personnel of the State Engineer's Office determined that the maximum extent of any burrow was 3 to 4 ft, and

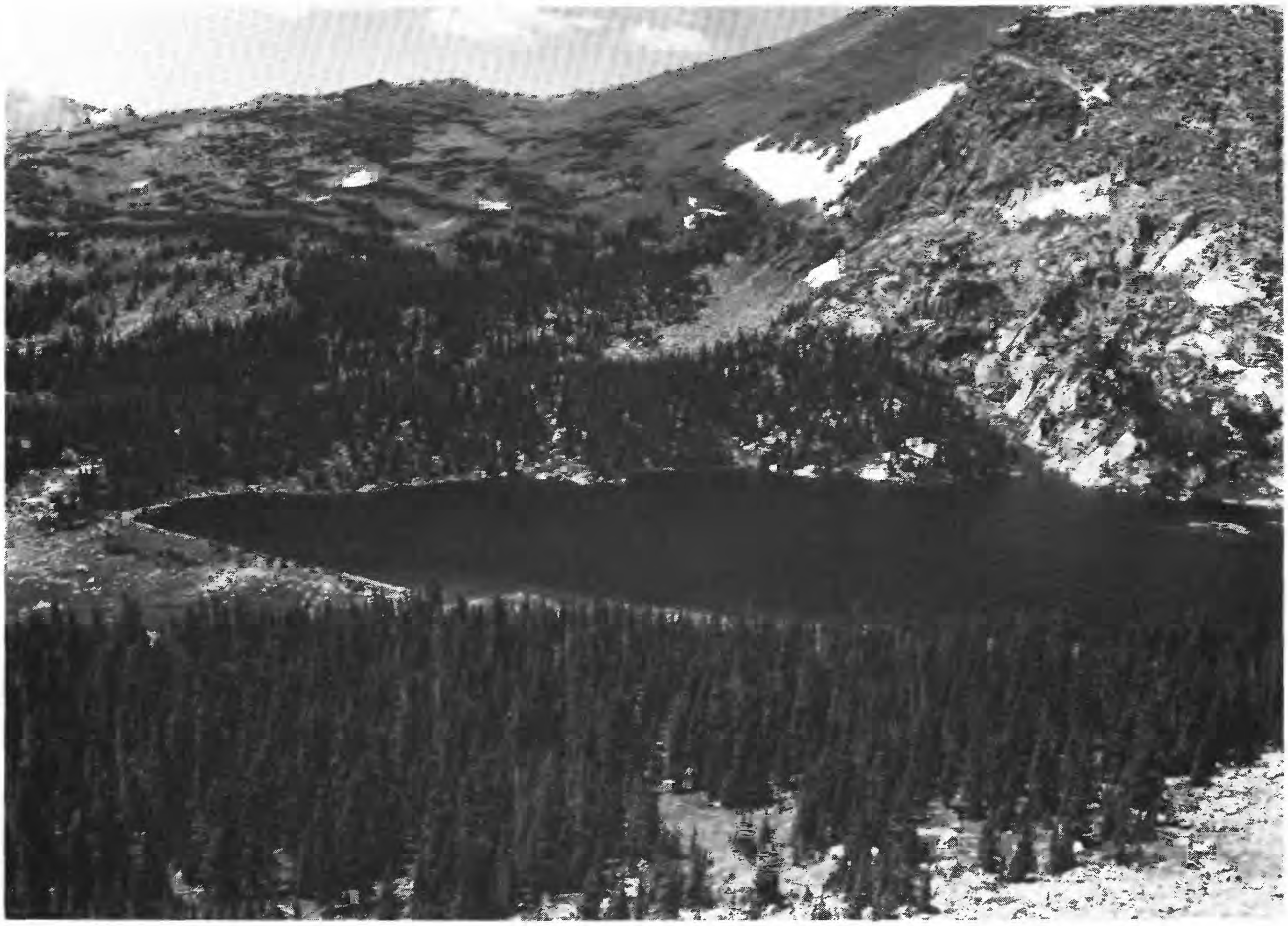

FIGURE 3.—Lawn Lake dam and Reservoir, prior to failure (July 11, 1958) (aerial). Photo courtesy of the National Park Service.

that the dam's interior probably was not extensively burrowed enough to cause failure of the dam.

Earth fill in the dam was sufficiently fine grained to be frost susceptible. Soil-property changes induced by numerous freeze-thaw cycles could have been a possible cause of failure. However, no ice lenses nor frozen ground were found during investigations at the damsite in July 1982; any changed soil characteristics would be reflected in the geotechnical investigations of the fill material.

Results of an undrained embankment-stability analysis by the Office of the State Engineer (1983) indicated a safety factor of only 0.6 existed in the dam for the assumed phreatic conditions. Assumption of an undrained condition, based on the results of permeability tests, is unrealistic. Some type of steady-state drainage must have existed in the dam which kept pore pressures below critical values and prevented the dam from failing.

During investigations at the damsite, numerous pieces of lead caulking that was used to form the seal between the outlet pipe and the gate valve (fig. 6) were found. This lead caulking was corroded and deteriorated to the point that it would be unlikely to form a watertight seal. The use of lead caulking to secure the pipe and valve was not in compliance with original plans and specifications approved by the Colorado State Engineer in 1902, which indicated that the valve would be encased in concrete.

CAUSE OF FAILURE

Data gathered by the Office of the State Engineer (1983) indicated that the most likely cause of the Lawn Lake dam failure was deterioration of the lead caulking used for the connection between the outlet pipe and the gate valve. The resulting leak eroded a pipe-shaped cavity in the earthfill (called piping), creating a void along the outlet pipe. The leak continued to remove easily eroded earthfill and may have reduced the strength and stability of the dam embankment. Such a scenario of leakage, piping, and resulting embankment failure

FIGURE 4.—*A*, The top of Lawn Lake Dam, prior to failure, looking north (July 11, 1958). Photo courtesy of the National Park Service. *B*, The top of Lawn Lake Dam, after failure (July 1982). Man is holding rod at elevation of water at time of failure.

FIGURE 5.—The cross section of Lawn Lake dam following failure. Arrow indicates dark organic layer 4 to 5 ft below top of dam.

TABLE 1.—*Geotechnical characteristics of the Lawn Lake dam earthfill*

[From the Office of the State Engineer, 1983]

Measured property	Triaxial shear tests (remolded) Sample 2L	Sample 5L	Sample 6L	Ground moraine
Wet density, in pounds per cubic foot	102.1	115.4	99.5	135.0
Dry density, in pounds per cubic foot	87.1	88.9	89.2	-----
Moisture, in percent	17.15	29.8	11.6	-----
Saturation, in percent	52.3	96.1	38.2	-----
Void ratio	.84	.79	.78	-----
Cohesion (effective stress), in pounds per square inch	1.4	0	0	100
Friction angle (effective stress), in degrees	18.4	39.2	32.1	45
Liquid limit, in percent	40	56	no value	-----
Plastic limit, in percent	34	43	nonplastic	-----
Plastic index, in percent	6	13	nonplastic	-----

required the prerequisite conditions of a closed or nearly closed outlet gate and a near-full reservoir, to supply the head necessary for accelerated leakage and subsequent progressive piping through the years. Just prior to failure, the outlet gate was nearly closed and the reservoir was full.

The void created along the outlet pipe would have become enlarged by the internal erosion of embankment

FIGURE 6.—The remains of the outlet valve from Lawn Lake dam. Investigations of this valve led to the conclusion that lead caulking had severely deteriorated.

material. Campers in the vicinity of Lawn Lake the night before the failure reported hearing a noise that sounded like strong winds. This sound indicated that the reservoir may have been discharging through the dam for at least 3 to 4 hours before the hole enlarged sufficiently—or embankment failure occurred—above the outlet pipe, causing a total breach of the dam where the outlet works were located (figs. 7*A*,*B*).

Surveyed breach dimensions are: Depth of 28 ft, top width of 97 ft, and bottom width of 55 ft. Following the complete failure of the dam embankment at about 0530 MDT, the resulting outflow of water reached its peak discharge very quickly (estimated to be within 10 min). The resulting flood peak of 18,000 ft^3/s (see "Dam-Break Modeling") then proceeded down the Roaring River toward Horseshoe Park and the Cascade Lake dam.

CASCADE LAKE DAM

Cascade Lake dam, a concrete gravity dam, was located on the Fall River in Rocky Mountain National Park, 5.3 mi west of Estes Park (fig. 1). A diversion dam was originally constructed at the site in 1908 for a pipeline to a hydropower plant downstream. The powerplant supplied electricity to the Stanley Hotel and the town of Estes Park. The site was at the head of a steep drop with numerous rapids and large boulders in the Fall River, where the stream eroded through several Pleistocene terminal moraines that dammed the Fall River, creating a glacial lake in Horseshoe Park just upstream. Cascade Lake dam consisted of a concrete wall several feet thick, reinforced with a masonry rock buttress on the downstream side. The foundation and abutments were in glacial terminal-moraine sediments; no bedrock is evident in the foundation. A photograph at Cascade Lake dam is shown in figure 8.

The dam was acquired in 1945 by the town of Estes Park, which owned it at the time of failure. Various improvements were made on the structure. It was enlarged to 17 ft high in 1923. The reservoir behind the dam was dredged at least twice since 1945, most recently in November 1981. Postfailure surveys indicated that the water behind Cascade Lake dam was approximately 12 ft deep, and the dam was 143 ft long prior to failure. Because of the sediment accumulation of 5 ft, a height

FIGURE 7.—*A*, The downstream face of Lawn Lake Dam prior to failure, showing the location of the outlet well and pipe (July 11, 1958). Dashed lines on dam face show location of eroded breach. Photo courtesy of the National Park Service. *B*, The front of Lawn Lake Dam following failure, showing the breach width.

FIGURE 8.—Empty Cascade Lake prior to failure. View is toward upstream face of dam (date unknown). Photo courtesy of the National Park Service.

of the dam of 12 ft was used for analysis of the flood hydraulics. Postflood surveys indicated the capacity of the dam was 12.1 acre-ft, corresponding to the top of the dam.

CAUSE OF FAILURE

As early as 0700 MDT on July 15, 1982, a greater than normal inflow into Cascade Lake was observed. By 0715 MDT, water was flowing over the top of the dam. The dam was overtopped for nearly 30 min, to a maximum depth of 4.2 ft of water, before tipping over and failing at 0742 MDT. Hydrostatic pressure of the water on the dam and erosion of the abutments were the probable causes of the dam failure. The topple failure was recorded photographically by residents of nearby summer cottages (figs. 9*A–D*). For comparison, figure 9*E*, taken after the flood shows a view similar to that in figure 9*D*. At the time of failure, inflow into the Cascade Lake dam (Site 1) was approximately 7,210 ft^3/s (determined from a slope-area discharge measurement upstream from the lake), and the reservoir capacity due to the additional depth of water (4.2 ft) above the top of the dam was about 25.1 acre-ft. The toppled dam released a peak flow of 16,000 ft^3/s (see "Dam-Break Modeling") down the Fall River into Aspenglen Campground, about 1/3 mi downstream. Within 5 min after the dam failure, the flood surge had passed the campground.

HYDROLOGIC ANALYSIS OF THE FLOOD

The flood resulting from failures of two relatively small dams was much larger than many engineers would have expected and was catastrophic in its geomorphic effect, due to three primary factors. First, the time of breach development was short for both dams, allowing stored water to be released rapidly. Second, the width of dam breach was large for both dams, allowing the stored water to be released rapidly. Third the slope of the stream (exceeding 20 percent on the Roaring River) and narrow channel limited attenuation of the peak discharge. However, as discussed in "Dam-Break

FIGURE 9.—See caption at end of figure.

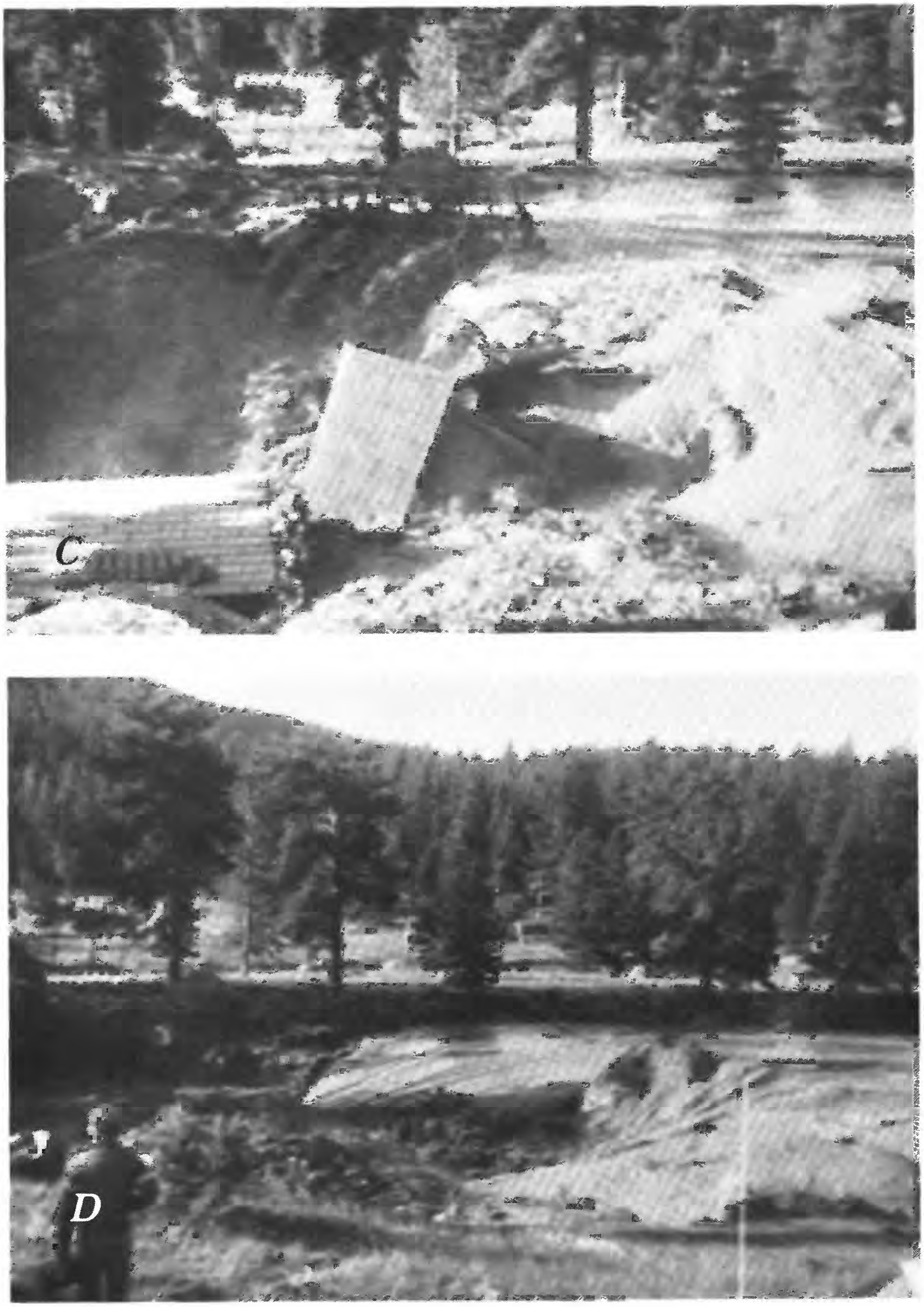

FIGURE 9.—See caption at end of figure.

FIGURE 9.—*A*, Water overtopping Cascade Lake dam. *B*, Cascade Lake Dam in the initial stages of failure. *C*, Cascade Lake Dam taken a few seconds after photograph *B*. *D*, The location of Cascade Lake Dam immediately after total failure. Photos *A–D* courtesy of Grace Davis George and Jennifer D. George. *E*, The location of Cascade Lake Dam following the failure and draining of Cascade Lake. Top of the large boulder on the reservoir floor is shown in *D* and in figure 8.

Modeling," the flood could have had greater peak discharges with more damage for different breach development and hydraulic conditions. The flood occurred during daylight hours in clear weather, and with sufficient numbers of witnesses to photograph and relate their experiences, good documentation of the flood was made. The important hydrologic elements of a flood are peak discharges and depths of flow, traveltimes, volumes, frequency, and flooded areas; these elements are discussed in this section of the report. It is important to document dam-break floods since limited information is available for assessment and hazard mitigation of possible future dam-break floods.

FLOOD DATA

STATION DESCRIPTIONS AND STREAMFLOW DATA

Flood data obtained at two gaging stations and five miscellaneous sites in the affected area are tabulated in downstream order in the section entitled "Gaging Station and Miscellaneous-Site Data." Station descriptions give the location of each site, the method of discharge determination, and peak discharge or peak stage during the flood. Where available, information also is given on gage datum, nature of gage-height records obtained during the flood, and maximum stage and discharge known prior to this flood.

PEAK STAGES AND DISCHARGES

Peak stages and discharges are important in assessing the magnitude of a flood and its associated damages. For the most part, this was true for this flood. Damages were compounded because of the high flow velocities and because of the debris load transported by the flood. As the flood far exceeded the magnitude of previous flows at the two streamflow-gaging stations, and since it peaked very rapidly, direct-discharge measurements could not be made. Peak-flow rates can be computed indirectly using existing methodology with reasonable accuracy following a flood.

Flood discharges were computed at seven locations along the flood path (fig. 1). Several different methods were used, depending on the hydraulic conditions at each site. These methods were the standard U.S. Geological Survey slope-area method (Dalrymple and Benson, 1967), flow over weirs method (Hulsing, 1968), and critical-depth method (Barnes and Davidian, 1978). These techniques, although different in type, are based on similar hydraulic principles. These techniques generally give reasonable results when flow conditions are within the basic assumptions and limitations for which the methods were developed. Flow conditions for this flood did not meet all these limitations; hence, the peak discharges may be less accurate, and the magnitude of errors was difficult to determine. The main factors that affect the accuracy of measurements include unsteady flow, Manning's n-values, high sediment concentrations, and scour and fill that affect the cross-sectional flow area. To varying degrees, these factors influenced peak-discharge measurements. However, until further research is undertaken to improve indirect-discharge measuring techniques under extreme conditions, these methods provide the most accurate results available.

The methods used to compute peak discharge assume steady flow; however, flow is unsteady for dam-failure floods (and flash floods). V. R. Schneider (U.S. Geological Survey, written commun., 1982) indicated that, when the slope-area method was used to determine the peak flow of an unsteady flood wave in a channel, the true discharge was overestimated by as much as 21 percent. Indirect flood measurements could not be made along the Roaring River or on Fall River in Horseshoe Park (fig. 1) because of the highly unsteady flow (described as a "wall of water" in the Roaring River, or as a rapidly attenuating flood wave in Horseshoe Park). The near-instantaneous failure of Cascade Lake dam increased the unsteady nature of the flood wave; however, it rapidly attenuated in a short distance downstream. Indirect discharge measurements were made at locations where unsteady flow was not considered to affect the computed discharges significantly, because the reach lengths generally were less than 200 ft.

Available guidelines on Manning's roughness coefficient n or n-values (Barnes, 1967; Limerinos, 1970) have been made primarily on low-gradient streams. Data collected by Jarrett (1984) indicated that n-values are much greater on high-gradient cobble-and-boulder-bed streams than previously recognized, because of unaccounted turbulence and energy losses. Other factors, such as large amounts of debris, channel obstructions, and irregular banks caused more turbulence and roughness, particularly on high-gradient streams, and therefore resulted in larger n-values. Methods of estimating n-values on high-gradient streams (Jarrett, 1984) were used in the computation of peak discharges; these methods are believed to best represent the energy losses associated with turbulence and roughness in high-gradient streams.

Sediment can alter the fluid characteristics of flowing water by increasing its viscosity and density. Presently, flood-measurement techniques are made by assuming clear-water flow and no sediment in transport. Although sediment data for this flood were not available, eyewitness, photographic, and postflood evidence indicated relatively low sediment loads in all locations where indirect flow measurements were made. Sediment load is assumed not to have affected the computed results significantly, although in local situations downstream from large sediment sources (deeply scoured reaches), geomorphic and sedimentologic evidence indicates sediment loads were temporarily very large.

Scour and fill during the passage of a flood can substantially affect the cross-sectional flow area along a stream and, consequently, peak-discharge computations. The entire length of the Roaring River (fig. 1) was either deeply scoured or filled with sediment (fig. 10; fig. 26), as discussed in the section "Geomorphic Effects of the Flood." Because of scour and fill, high sediment loads, and the unsteady nature of the flood wave, indirect peak-discharge measurements could not be made along the Roaring River. Along the Fall River and the Big Thompson River, scour and fill generally were minor, and sites could be located where scour and fill did not significantly affect the computed peak discharges.

Considering the factors discussed previously, the computed peak discharges shown in table 2 were the best available. Estimated error of the peak discharges, in view of these factors, is about 25 percent. In light of the hydraulic complexities of the flow and channel conditions where these methods were applied to compute peak discharge, results were much better than expected, based on comparisons of peak discharges at the different sites and comparisons with the dam-break modeling results. Peak discharge at Site 6 was supported by flow records (Site 7) of the U.S. Bureau of Reclamation (C. W. Huntley, U.S. Bureau of Reclamation, written commun., 1982) in which the flood hydrograph entering Lake Estes was computed as shown in "Gaging-Station and Miscellaneous-Site Data." Computations of the Big Thompson River inflow to Lake Estes indicated that inflow to the lake peaked during the 5-minute interval from 0910 MDT to 0915 MDT, averaged 5,364 ft^3/s, and had an estimated error of ± 10 percent (C. W. Huntley, U.S. Bureau of Reclamation, written commun., 1983). This value compared well with the indirectly determined instantaneous peak discharge of 5,500 ft^3/s at Site 6. Because sediment plugged the intakes to the gage at Site 6, stage and streamflow hydrographs were not available.

FIGURE 10.—The middle reach (river mile 2.1) of the Roaring River showing the extensive areas of scour and fill along the channel.

Indirect measurements of peak discharges could not be made upstream from Site 1 (fig. 1), but peak discharges estimated from the dam-break model are discussed in the section "Dam-Break Modeling." Channel and hydraulic conditions were such that a peak-discharge measurement could not be made immediately downstream from Cascade Lake dam, but was made 0.9 mi downstream (Site 3). Because of rapid attenuation, the measurement at Site 3 did not reflect the dam-break peak discharge at the dam (see "Dam-Break Modeling" for an estimate of peak discharge). However, the discharge over the top of the dam (fig. 9*A*) at the moment of failure of Cascade Lake dam was computed to be 4,500 ft^3/s. This measurement was made from high-water marks upstream from the dam that were set at the time of failure. Note how the water level dropped 1 to 2 ft on the right (far) bank, in the series of photographs of Cascade Lake dam failing (figs. 9*A–D*), because of failure of the dam.

A peak-discharge profile was constructed from Lawn Lake dam to Olympus dam. Indirect peak-discharge measurements were considered more accurate than dam-break model results; hence, the profile reflects indirect measurements where both were available. The peak-discharge profile (fig. 11) reflects adopted peak discharges and indicates the rapid attenuation of peak flows in the downstream direction. Greatest attenuation probably occurred as the flood traveled through Horseshoe Park. The peak discharge more than doubled as a result of the near-instantaneous failure of Cascade Lake dam.

VOLUME

Since the construction of Lawn Lake dam in 1903, there had been some question as to its storage capacity, particularly the live capacity of the lake. At the time of failure, several capacities were referenced. Minimal information existed on the capacity of Cascade Lake. In District Court for Larimer County, the reservoir was decreed to have a capacity of 759.6 acre-ft, but a 1931 capacity survey indicated 817.2 acre-ft of storage at high water (Office of the State Engineer, 1983). Because of the need for storage-capacity data, land surveys were combined with aerial-photographic mapping techniques to determine pertinent preflood and maximum-flood water-surface levels, develop topographic maps, and determine storage-capacity data of both lakes. These topographic maps are shown on plates 1 and 2 in the

TABLE 2.—*Flood stages and discharges in Larimer County for the flood of July 15, 1982, and during previous maximum floods*

Site number	Station number	Stream and place of determination	Distance downstream from Lawn Lake dam, in miles	Drainage area, in square miles	Maximum floods previously known: Prior to July 1982 Period	Year	Gage height, in feet	Discharge, in cubic feet per second	Flood of July 15, 1982: Hour, mountain daylight time	Gage height, in feet	Discharge in cubic feet per second
1	--------	Fall River above Cascade Lake dam above Estes Park.	6.50	-----	-----	-----	-----	-----	[a]0740	----	7,210
2	--------	Fall River at Cascade Lake dam above Estes Park.	6.67	-----	-----	-----	-----	-----	[a]0745	----	[b]4,500
3	--------	Fall River below Cascade Lake dam above Estes Park.	7.68	-----	-----	-----	-----	-----	[a]0800	----	13,100
4	--------	Fall River above Estes Park.	10.28	-----	-----	-----	-----	-----	[a]0835	----	8,520
5	06732500	Fall River at Estes Park.[c]	11.45	39.5	1947–53 1978–81	1980	8.56	565	[a]0850	11.10	[d]6,550
6	06733000	Big Thompson River at Estes Park.	12.50	137.0	1949–82	1949	[e]3.16	[e]1,660	[a]0905	----	5,500
7	--------	Lake Estes at Estes Park.	12.75	-----	-----	-----	-----	-----	0910 to 0915	----	[f]5,364

[a]Approximate time based on peak time in figure 15.
[b]Discharge at time of dam failure; not the peak discharge.
[c]Destroyed by flood of July 15, 1982.
[d]Estimated from sites 4 and 6.
[e]Site and datum then in use.
[f]Computed by Bureau of Reclamation; discharge is average for 5-minute peak period.

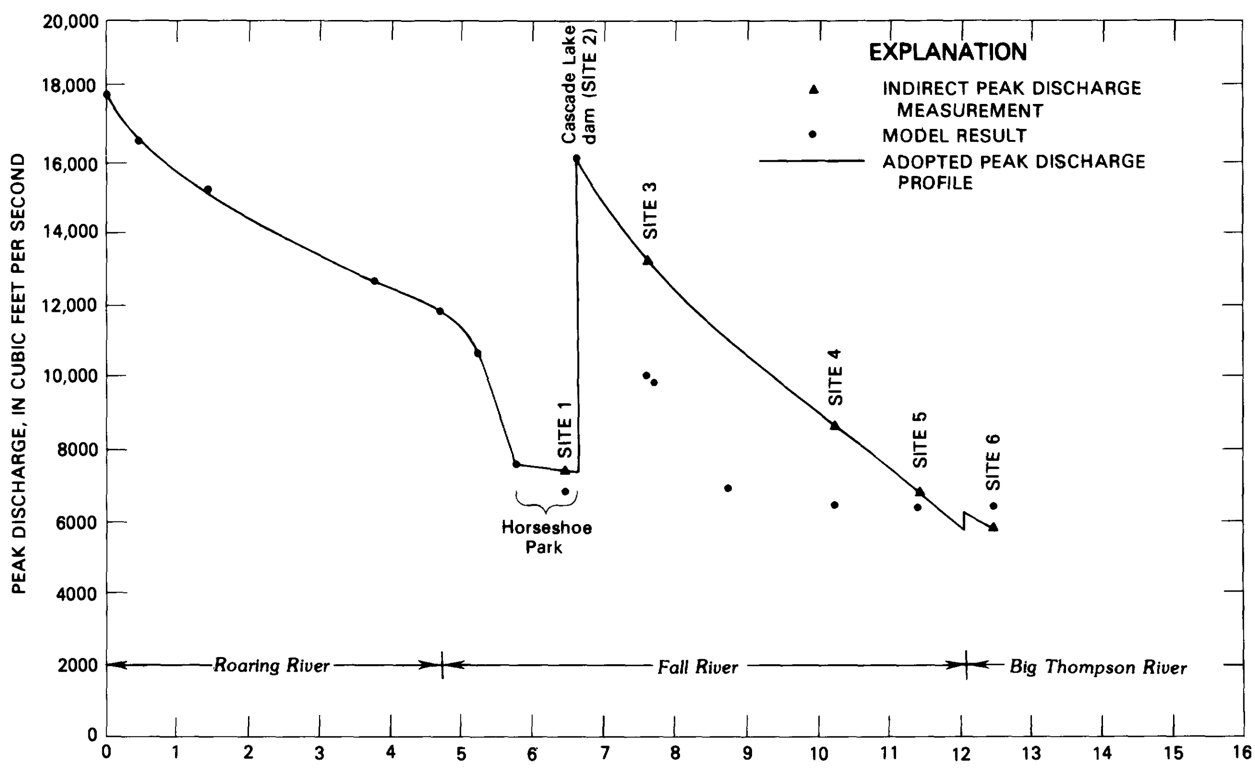

FIGURE 11.—Peak-discharge profile based on indirect peak-discharge measurements and model results. Indirect measurements are believed to be more accurate than dam-break model results.

pocket at the back of the report. Storage-capacity data and other pertinent information for the two lakes are shown in table 3.

The vertical datum for the Lawn Lake topographic maps was approximated from an existing U.S. Geological Survey 7½-min quadrangle map, as the site was so remote from any available accurate vertical control. These surveys indicated that the failure of Lawn Lake dam released 674 acre-ft of water on July 15, 1982. As indicated in figure 12, a substantial amount of water remained as dead capacity, and almost corresponding to the original moraine-dammed mountain lake. Although the lake level at the time of failure was 1 ft deep in the overflow spillway, the water released was considerably less than previously believed to have been stored behind the dam (Office of the State Engineer, 1983). The main reason for this difference appeared to be that the lake bed immediately upstream from the dam embankment was 6.4 ft higher than the inlet elevation of the outlet pipe which was located on bedrock. This outflow control probably had been present since construction of the dam, and was not reflected in earlier lake surveys.

Determination of the capacity of Cascade Lake dam was more difficult, as severe bed erosion (fig. 9*E*) occurred after the dam failure. Postflood surveys indicated that approximately 1.53 acre-ft (table 3) of sediment was removed from the lakebed during the flood. Therefore, field inspections and surveys were made to reconstruct the preflood lakebed. All the evidence indicated that the preflood lakebed was at an elevation of 8,560 ft, plus or minus 1 ft. Contours in plate 2 reflect postflood contours; extensive scour occurred with a maximum of approximately 12 ft. Storage-capacity data and other pertinent data for Cascade Lake, assuming a lakebed elevation of 8,560 ft, are shown in table 3. Cascade Lake contained approximately 12.1 acre-ft of water prior to the flood, and 25.1 acre-ft of water at the time of the Cascade Lake dam failure. The total volume of water released from the failures of the Lawn Lake dam and the Cascade Lake dam was approximately 686 acre-ft.

For the period 0845 MDT on July 15, to 1200 MDT on July 16, C. W. Huntley (U.S. Bureau of Reclamation, written commun., 1982) estimated the inflow to Lake Estes, resulting from the failures of Lawn Lake and Cascade Lake dams, was 663 acre-ft. The difference between the volume released from the two lakes and the volume entering Lake Estes probably was the result of water remaining in valley storage, which had not reached Lake Estes by July 16 at 1200 MDT, and of evapotranspiration and infiltration (particularly in Horseshoe Park). Errors in the methods of determining

TABLE 3.—*Storage capacity and other pertinent information for Lawn Lake and Cascade Lake*

Lawn Lake

Contour[a] elevation, in feet	Surface[b] area, in acres	Storage[b] capacity, in acre-feet	Contour[a] elevation, in feet	Surface[b] area, in acres	Storage[b] capacity, in acre-feet
10,975.69	-----	0.0	10,990	42.29	362.19
10,978	8.93	-----	10,992	45.09	449.55
10,980	23.14	30.96	10,994	47.29	541.92
10,982	27.82	81.85	10,996	49.33	638.53
10,984	31.01	140.66	10,998	50.73	738.59
10,986	35.24	206.86	11,000	52.50	841.81
10,988	38.93	281.00	11,002	54.59	948.89
			11,004	56.57	1,006.40

Cascade Lake

Contour[c] elevation, in feet	Surface area, in acres	Storage capacity, in acre-feet	Contour[c] elevation, in feet	Surface area, in acres	Storage capacity, in acre-feet
8,448	0.0	[d]0.0	8,464	0.70	[e]2.10
8,450	.02	[d].01	8,466	.89	[e]3.69
8,452	.07	[d].09	8,468	1.24	[e]5.81
8,454	.11	[d].27	8,470	1.86	[e]8.89
8,456	.18	[d].56	8,472	2.25	[e]12.99
8,458	.23	[d].97	8,474	2.80	[e]19.56
8,460	.33	[d]1.53/0[e]	8,476	3.41	[e]25.76
8,462	.54	[e].86	8,478	3.84	[e]33.01

[a]Approximate mean sea level; water-surface elevation at failure was 10,996.42 feet.
[b]Above dead storage.
[c]Mean sea level; water-surface elevation at failure was 8,475.80 feet.
[d]Estimated amount below preflood lakebed elevation of 8,460 feet.
[e]Storage capacity above estimated preflood lakebed elevation of 8,460 feet.

FIGURE 12.—Lawn Lake about 1 week after the dam failure, showing the amount of water still remaining in the natural depression forming the original lake (aerial).

the respective volumes (such as surveying and mapping errors) and estimates of nonflood inflow to Lake Estes also may have contributed to these differences.

VELOCITIES, DEPTHS, WIDTHS, AND AREAS

The most destructive components of the flood were high shear stresses and high flow velocities. These high velocities, particularly on the Roaring River and the Fall River immediately below Cascade Lake dam, increased the flood's capacity to erode and transport sediment, resulting in severe channel erosion and transport of debris and streambed material (fig. 10). No direct flow velocities were available; however, average velocities, ranging from 3.3 ft/s to 12.6 ft/s computed by indirect-discharge methods and based on model results, are shown in table 4.

TABLE 4.—*Peak flow data at selected cross sections*

Distance downstream from Lawn Lake dam, in miles	Average velocity,[a] in feet per second	Maximum depth, in feet	Top width, in feet	Cross section area, in square feet
0.55	[b] 8.0	[b]23.8	185	[b]2,070
1.50	[b]11.3	[b]18.6	97	[b]1,340
3.83	[b] 9.9	[b]14.0	348	[b]1,270
5.36	3.6	9.0	927	2,980
5.78	3.3	7.9	1,112	2,250
6.50	4.6	10.1	328	1,560
7.68	[b]11.2	[b]10.8	148	[b]1,170
7.74	12.6	9.9	227	1,020
8.78	12.1	10.6	170	910
10.28	12.0	7.8	175	710
11.45	7.4	6.4	336	880
12.50	6.8	10.5	99	810

[a]Based on the peak discharge profile in figure 11.
[b]Severe channel erosion may have influenced value.

In general, velocities increased in the downsteam direction, except through Horseshoe Park and downstream from river mile 10.28. Maximum depths ranged from 6.4 to 23.8 ft; maximum widths ranged from 97 to 1,112 ft (table 4). Cross-sectional areas ranged from 710 ft^2 to 2,980 ft^2, generally decreasing downstream, except through Horseshoe Park. Cross-sectional data for 14 cross sections and water-surface elevations from which depths, widths, and areas were determined are shown in figures 55 to 70 in the Supplemental Cross-Section Data at the end of the report. These cross sections reflect conditions after the flood. Elevations in most cross sections were surveyed to approximate mean sea level (from topographic maps), unless stated as being mean sea level. Field-estimated Manning's n-values are shown. A question mark follows the values, if conditions (generally scour or debris) indicated a very approximate estimate.

FLOOD PROFILES AND BOUNDARIES

In addition to the indirect-measurement site cross sections, high-water marks were obtained at 12 cross sections from which flood profiles could be determined and are shown in Supplemental Cross-Section Data. Because of the relatively shallow depths of flow and extremely high-channel gradient (fig. 2), flood profiles cannot be shown adequately at a realistic scale. The Colorado Water Conservation Board conducted a study to outline the flood profiles and boundaries downstream from Rocky Mountain National Park to Lake Estes (W. P. Stanton, Colorado Water Conservation Board, written commun., 1982). Flood profiles and boundaries for Estes Park for the July 15, 1982, flood are shown in a report by the Colorado Water Conservation Board (1983).

FLOOD FREQUENCY

It is of interest to know the relative frequency of the occurrence of a flood. Since this flood resulted from dam failures rather than natural causes, flood frequency is not directly applicable. However, knowing the relative frequency can be useful in illustrating the catastrophic nature of this type of flood and its channel-changing processes, related to historic and natural floods of this magnitude. A summary of flood frequencies for the Roaring River and the Big Thompson River is given in table 5.

Floods in the mountainous regions of Colorado generally are from three meteorologic causes: (1) Snowmelt floods, (2) rainfall floods, and (3) rain-on-snow floods. Many times, runoff peaks on a given stream originate from all three causes, but conventional hydrologic

TABLE 5.—*Discharge-frequency summary for the Roaring River at mouth and the Big Thompson River at Estes Park*

Recurrence interval	Discharge, in cubic feet per second	
	Roaring River at alluvial fan[a] (drainage area, 12.0 square miles)	Big Thompson River at Estes Park[b] (drainage area, 137 square miles)
10 year	205	1,540
50 year	287	2,020
100 year	317	2,200
500 year	393	2,620
July 15, 1982	12,000	5,500

[a]Based on regional regression equation (McCain and Jarrett, 1976).
[b]Based on Log-Pearson Type III flood-frequency analysis (Interagency Advisory Committee on Water Data, 1981).

analysis fails to account for the mixed population of runoff peaks contributing to the total population of flood peaks in mixed population flood areas. When snowmelt- and rain-generated peaks are examined separately, flood-frequency analysis shows different trends based on elevation (Jarrett and Costa, 1983). In the Estes Park area above about 7,500 ft, snowmelt dominates, with rainfall generally not contributing to the flood potential for recurrence intervals greater than the 100-year flood. Where rainfall does contribute significantly to flooding above about 7,500 ft, unit discharges are small (generally less than 20 ft^3/s/mi^2) (cubic feet per second per square mile), compared with lower elevation floods resulting from rainfall (which commonly exceed 1,000 ft^3/s/mi^2). Below about 7,500 ft, rainfall-produced floods predominate.

The flood-frequency curve for the Big Thompson River at Estes Park was analyzed for mixed population flows by the methods described in Jarrett and Costa (1983) (fig. 13). Inspection of the plotted rainfall and snowmelt flood-frequency curves indicates that snowmelt flood peaks predominate in the Big Thompson River and tributaries above Estes Park, that is, above an elevation of 7,500 ft. This was consistent with the results of Jarrett and Costa (1983) in which streamflow records of 69 unregulated streams in the South Platte River, the Arkansas River, and the Colorado River basins were examined to separate peak discharges from snowmelt and rainfall runoff during each water year. Above about 7,500 ft, snowmelt is the major cause of flooding, not large, intense rainstorms.

The failure of the Lawn Lake dam resulted in a peak flow of 5,500 ft^3/s at streamflow-gaging station 06733000 Big Thompson River at Estes Park (Site 6), just upstream from Lake Estes. Data presented in figure 13 indicate that the 1982 dam-break flood was 2.1 times the 500-year flood for this location. In Estes Park, flood peaks were 2.5 ft above the level of the 500-year flood (Colorado Water Conservation Board, 1983). The

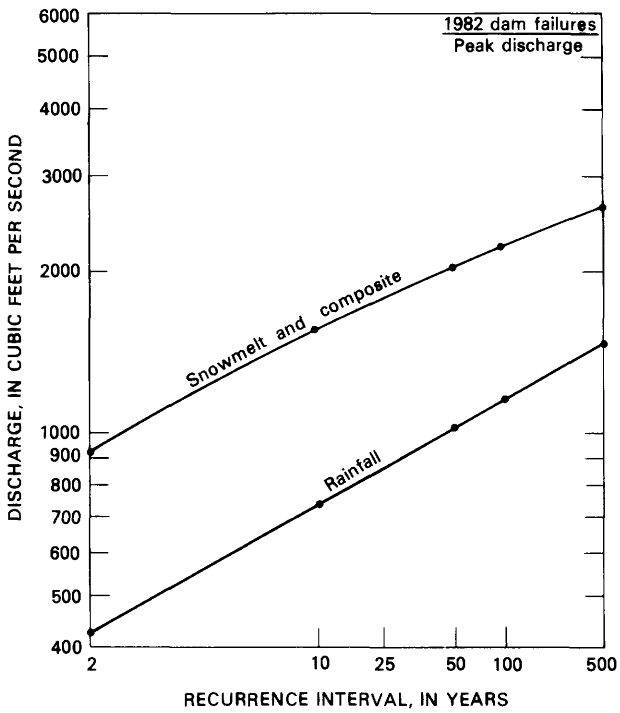

FIGURE 13.—Flood-frequency curves station 06733000 Big Thompson River at Estes Park 1951–77. Annual flood peaks have been separated into rainfall and snowmelt floods, then recombined with conditional probability into a composite flood-frequency curve based on Log-Pearson Type III flood-frequency analysis (Interagency Advisory Committee on Water Data, 1981).

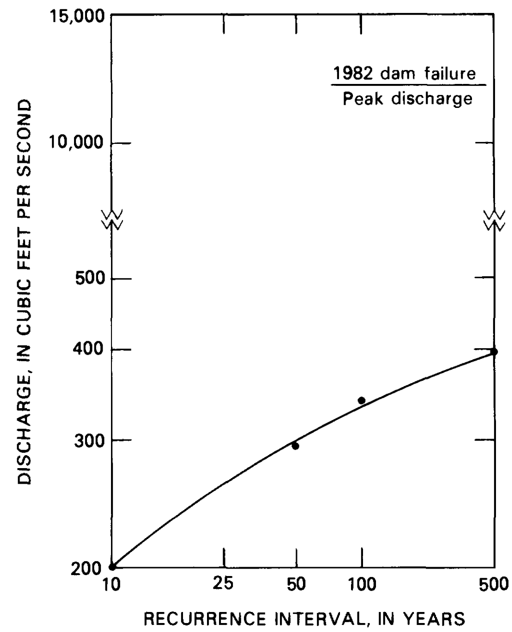

FIGURE 14.—Regional flood-frequency curve for Roaring River at Horseshoe Falls, based on regional regression equation of McCain and Jarrett (1976).

previous flood of record, from a rapidly melted snowpack, was 1,660 ft^3/s in June 1965 (table 2); this flood was estimated from the composite flood-frequency curve in figure 13 to be about a 15-year flood.

Upstream on the Fall River at its confluence with the Roaring River (elevation 8,550 ft), the flood peak (water only) was estimated to have been 12,000 ft^3/s (see "Dam-Break Modeling" results). This represented a unit discharge of 1,000 $ft^3/s/mi^2$, an unprecedented value in historic times for the Colorado Front Range above an elevation of 7,500 ft. A regionalized flood-frequency curve for the mouth of the Roaring River is shown in figure 14, constructed from regional regression equations for mountain areas in Colorado (McCain and Jarrett, 1976). Based on historic flow data under the present climate regime, the estimated 500-year flood for this location on the Roaring River is 400 ft^3/s. The 1982 dam-break flood was 30 times the 500-year flood for this stream; a flow of 12,000 ft^3/s would be very rare.

Along the Roaring River, deposits of Pleistocene ground moraine and outwash were extensively scoured and eroded. A late Pleistocene end moraine at an elevation of 10,900 ft (Richmond, 1960) was overtopped and deeply eroded. In July 1983, extensive field work was conducted in Rocky Mountain National Park to investigate whether or not any stratigraphic or geomorphic evidence existed of comparable large postglacial floods in any of the streams draining into Lake Estes. The sediments and landforms produced by the Lawn Lake dam failure are so distinctive that the evidence of any comparable floodflow in the Holocene should be easy to recognize. No unequivocal evidence of a similar large flood was found in any stream valley that drains into Lake Estes. The dam-break flood of 1982 was very likely the largest flood that has occurred in the Roaring River, Fall River, and Big Thompson River since at least the last glacial retreat, about 10,000 years ago.

Along the Fall River between the Roaring River confluence and Cascade Lake dam, slopes are very gentle, and no extensive modifications occurred. The flood surge of 16,000 ft^3/s from the Cascade Lake dam failure caused a large amount of scour and erosion along the Fall River between the dam and just below Aspenglen Campground. Extensive Pleistocene moraine deposits were scoured and reworked. The flood surge from the Cascade Lake dam failure may have been the largest flow in this stretch of the Fall River since the draining of the glacial lake in Horseshoe Park. This unquestionably was an extremely rare discharge. These estimations of the flood frequencies from the two dam failures in Rocky Mountain National Park are not unprecedented; similar conclusions were reached following the failure of Hell Hole dam on the Rubicon River, Calif., in 1964 (Scott and Gravlee, 1968). Floods of such magnitude from dam failures would be expected to accomplish an enormous amount of geomorphic work, and to cause great modifications to the channels and valleys below the dams (as described in "Geomorphic Effects of the Flood").

TRAVELTIME

Immediately after the flood, personnel of the U.S. Bureau of Reclamation interviewed residents along the flood path and compiled written statements to evaluate the dissemination of and response to the flood warnings. This information, in conjunction with streamflow-gaging station, Lake Estes inflow, and stream mileage data, provided data to compute the traveltime of the flood wave.

Apparently no one observed the failure of Lawn Lake dam, and the time of failure is uncertain. Campers at Lawn Lake reported hearing a roar between 0200 MDT and 0400 MDT, which probably corresponded to increased flows through a partial failure. The amount of water probably was quite small (perhaps less than 100 ft^3/s), because campers along the Roaring River were not affected. Other information supported a small partial failure this early. L. V. Davis, the owner of Cascade Cottages at Cascade Lake dam, reported flow was slightly higher than usual at 0700 MDT, before the main flood wave arrived at the dam at about 0715 MDT. Based on available information, it appears that Lawn Lake dam failure occurred about 0530 MDT, just before sunrise. Because campers along the Roaring River understandably were more concerned with fleeing the wall of water, their estimates of time may be only approximate. Observers along the remainder of the flood path were easily able to distinguish the leading edge of muddy floodwaters from the normally clear streamflow. According to Stephen Gillette, a truck driver for A-1 Trash Services, who was the first to report the flood at 0623 MDT, floodwaters reached Horseshoe Falls at about 0615 MDT and U.S. Highway 34 in Horseshoe Park at 0634 MDT (fig. 1). According to Mr. Davis, floodwaters reached Cascade Lake dam at 0715 MDT, causing its failure at 0742 MDT. Estes Park police reported that floodwaters reached Estes Park a little after 0830 MDT. Floodwaters reached 06733000 Big Thompson River at Estes Park streamflow-gaging station (Site 6) at 0835 MDT, and personnel of the U.S. Bureau of Reclamation reported that water levels started rising in Lake Estes at 0847 MDT.

It was more difficult to determine when the peak was occurring, as no distinctive hydraulic feature existed. Both Rann Schultz and Dan Davis of the National Park Service, as well as Stephen Gillette, provided information to estimate that the peak followed the leading edge by less than 40 min, or about 0700 MDT, at U.S. Highway 34 in Horseshoe Park (fig. 1). As the flood traveled only 0.6 mi through the flatter Horseshoe Park, this estimate appeared quite long, considering that the flood was a "wall of water" in the Roaring River. Based on information provided by Rann Schultz, the peak followed the leading edge by about 25 min, or about 0748 MDT, at the Aspenglen Campground access road, located 0.4 mi downstream from Cascade Lake dam. Dave Thomas, broadcasting the flood's progress from a KSIR radio mobile-transmitter station 1.2 mi upstream from Estes Park, indicated the peak followed the leading edge by 18 min, or at 0830 MDT. Based on a stage hydrograph reconstruction at 06733000 Big Thompson River at Estes Park streamflow-gaging station, just upstream from Lake Estes, the peak followed the leading edge by 30 min or at 0905 MDT. Inflow to Lake Estes peaked between 0910 MDT and 0915 MDT (use 0912 MDT for the peak time), or 25 min after the lake began rising. Unfortunately, because of limited and approximate peak-time data, it is not possible to determine whether the peak was moving faster than the leading edge of the flood wave, as would be expected.

A summary of data related to time of flooding prepared by Graham and Brown (1983) is shown in table 6 and graphically summarized in figure 15. The lower line in figure 15 corresponds to the arrival time of the flood; the upper line in figure 15 corresponds to the peak time of the flood. Traveltimes for the arrival time of the flood were summarized for three channel segments, based on fairly uniform reach traveltimes (fig. 15). The speed of the leading edge of the flood (and probably the peak) averaged 9.1 mi/h (miles per hour) in the Roaring River, 2.1 mi/h in the Fall River through Horseshoe Park, and 4.0 mi/h from Cascade Lake dam on the Fall River to Lake Estes. Overall the speed of the leading edge of the flood averaged 3.8 mi/h. Considering the high-gradient channels, these traveltimes were slow. Apparently, this slowness was because the channels were extremely rough, and tremendous amounts of debris in the water, particularly in the Roaring River, produced the slow speed of the flood wave.

DESCRIPTION OF FLOOD-WAVE CHARACTERISTICS

Specific details of the flood wave are of interest in understanding flow hydraulics. Understanding of flood-wave characteristics is important as they are the major cause of property damages, geomorphic changes, and are a factor in implementing flood warnings. Flood-wave characteristics varied along the flood path; therefore, they are discussed by various segments where characteristics are fairly uniform for that segment. Channel slope is the dominant factor in establishing these segments (fig. 2.)

TABLE 6.—*Time of flooding from the failures of Lawn Lake dam and Cascade Lake dam, July 15, 1982*

[Modified from Graham and Brown, 1983]

Location and distance downstream from Lawn Lake, in miles	Time (mountain daylight time)	Description of occurrence	Source
Lawn Lake Camping area (0)	0200 0400	Campers report hearing roar.	National Park Service witness statements.
	Approximately 500	Campers report normal roar from river.	Rocky Mountain News, July 16, 1982, page 8.
	Shortly before 0530	Dam failure begins.	Rocky Mountain News July 16, 1982, page 8.
	Approximately 0550	Campers heard roar from dam break.	National Park Service witness statements.
	0609	Camper reports roar getting louder.	Rocky Mountain News July 16, 1982, page 8.
Cut Bank (2.41) and Ypsilon Creek Campsites (2.92)	0600 0620	Campers heard thunderous roar and trees breaking; saw wall of water 25 to 30 feet high	National Park Service witness statements.
Endovalley Road (4.54)	Approximately 0615	Water reaches road.	National Park Service witness statements.
	Approximately 0620	Water and debris (logs and limbs) on road.	National Park Service witness statements.
	0627:40	Road completely flooded.	National Park Service dispatch-radio log.
Lawn Lake Trailhead emergency telephone (5.23)	0622:47	Call by Stephen Gillette to park dispatcher.	National Park Service dispatch-radio log and tape recording.
Highway 34 in Horseshoe Park (5.31)	0634	Flood reaches highway.	National Park Service dispatch-radio log.
	0636	Water over bridge.	National Park Service dispatch-radio log.
½ miles west of Cascade Lake dam (6.17)	0657	Water at this location.	National Park Service dispatch-radio log.
Cascade Lake dam (6.67)	0700	Water 4 to 5 inches over Cascade Lake dam (usually 5 inches below top of dam at this time of day and season).	Interview with Cascade Cottages owner (manager).
	0715	Rapid rise in water.	Interview with Cascade Cottages owner (manager).
	0723	Increased water.	National Park Service dispatch-radio log.
	0725	Water going over dam.	National Park Service dispatch-radio log.
	0742	Cascade Lake dam fails.	National Park Service dispatch-radio log.
Aspenglen Campground (7.03)	0731:39	Water over entrance road.	National Park Service dispatch-radio log and tape recording.
	0745	Trees breaking and increase in flood, doubled in size in 30 seconds.	National Park Service dispatch-radio log.
	0747:37	Surge passed.	National Park Service dispatch-radio log.

TABLE 6.—*Continued*

Location and distance downstream from Lawn Lake, in miles	Time (mountain daylight time)	Description of occurrence	Source
Immediately downstream from park boundary (7.48)	0730	Flooding began.	Colorado Water Conservation Board interview with trailer owner.
Fish Hatchery (7.84)	0735 to 0755	Saw rise in river.	Interview with wife of hatchery manager.
Workshire Lodge (8.54)	0745 to 0800	Debris arrived.	Interview with owner (manager).
Fish Hatchery Road (8.58)	0738	½ of road under water.	Estes Park Police Department log.
	0746	Road flooded, bridge in danger of washing out.	Larimer County Sheriff's dispatch tape.
Fall River Trading Post (9.68)	0755 to 0800	Water started rising.	Interview with owner (manager).
Homestead (9.79)	0750	Clock stopped.	Owner of condominium unit.
	0807:45	Water at Homestead.	Larimer County Sheriff's dispatch tape.
	0808	Head of water now east of Homestead.	Tape of KSIR radio broadcast.
	0818	Water over road.	Estes Park Police Department log.
Ponderosa Lodge (9.94)	0745	Water started to rise; could hear flood.	Interview with owner (manager).
	0800	Water really started to hit.	Interview with owner (manager).
	0806	Large volume of water has approached.	Tape of KSIR radio broadcast.
Trails West Cottages (10.11)	0745	Flooding began and was over quickly.	Interview with owner (manager).
Clever Crafters (10.26)	0800	Water hit.	Interview with owner (manager).
Nicky's Motor Lodge (10.49)	0753	Flooding began.	Interview with owner (manager).
Colonial Motel (10.72)	0817:57	"Water one-half way up Colonial Motel; the main thrust has come through."	Larimer County Sheriff's dispatch tape.
	0822	Bridge out.	Estes Park Police Department log.
4 Seasons Motel (10.78)	0812	Remote broadcast from hill opposite motel. A lot of debris first seen coming down the river.	Tape of KSIR radio broadcast.
Downtown Estes Park (11.97)	0836	"The main crest has just come through town, it should be on the east side right now. The water is still rising a little bit. The debris is starting to hit the bridges."	Larimer County Sheriff's dispatch tape.
	0843	Water going right through center of town.	Larimer County Sheriff's dispatch tape.
Big Thompson River near powerplant (12.75)	0846	Rapidly rising water at powerplant.	Tape of KSIR radio broadcast.
Lake Estes (14.19)	0847	Lake begins to rise.	South Platte River Project Office (U.S. Bureau of Reclamation).

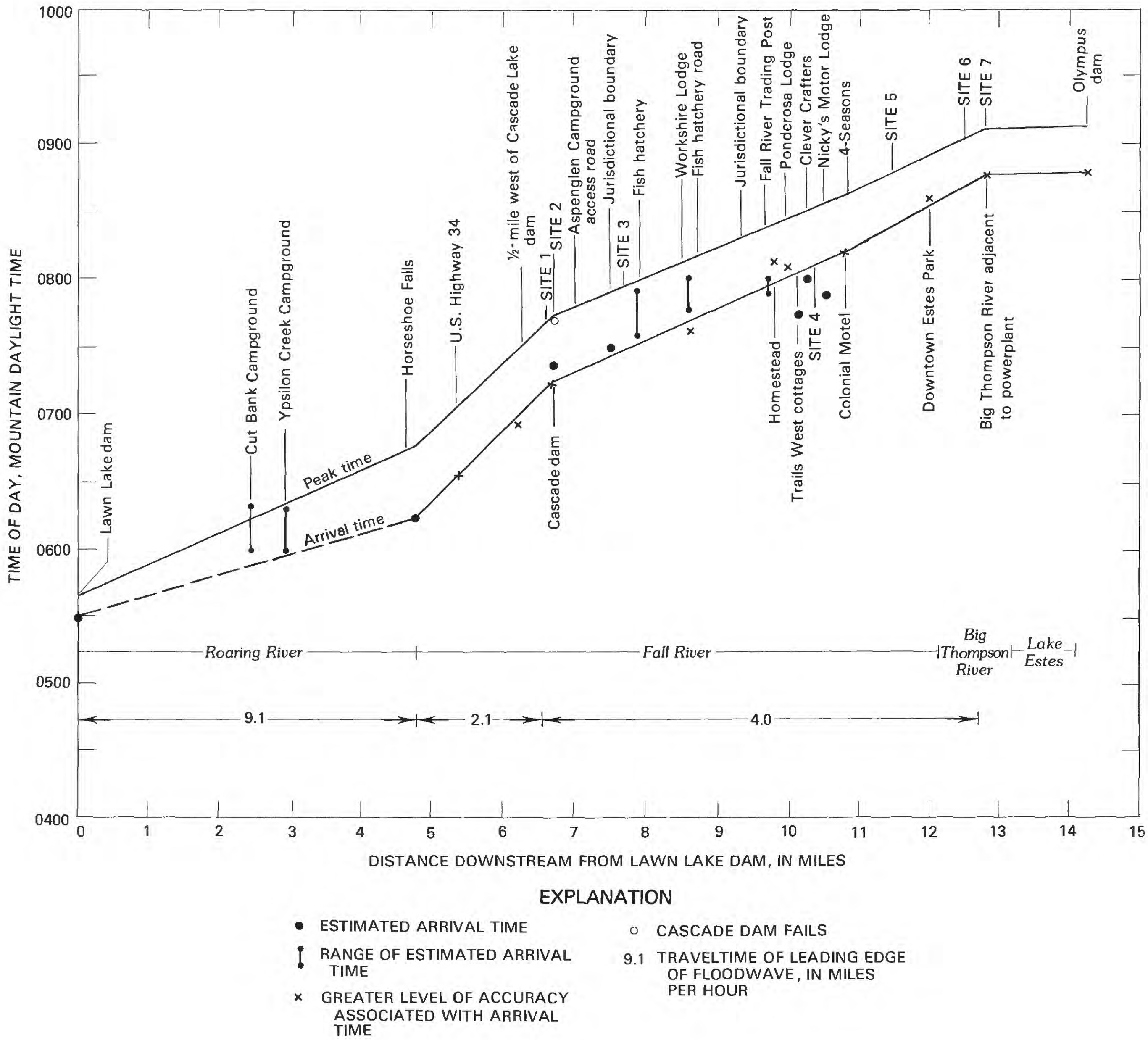

FIGURE 15.—Arrival time, peak time, and traveltime of leading edge of flood wave of July 15, 1982. (Modified from Graham and Brown, 1983).

ROARING RIVER: LAWN LAKE DAM TO HORSESHOE FALLS

As discussed in the early section of this report, "The Setting," the Roaring River is a small, high-gradient stream (fig. 2). A photograph of the mouth of the Roaring River prior to the flood taken in 1978, showing the small, heavily vegetated, high-gradient channel, is shown in figure 16*A*. The Roaring River streamflow prior to the flood probably ranged from 25 to 50 ft^3/s. A photograph taken after the flood at the same location is shown in figure 16*B*. The sudden breach of Lawn Lake dam resulted in a flood wave with a characteristic "wall of water;" in this case, that "wall" was estimated to be 25 to 30 ft high by a number of eyewitnesses. The leading edge of the wave front, although very steep, probably was not a vertical wall of water. This steep wave front probably was accentuated by the large

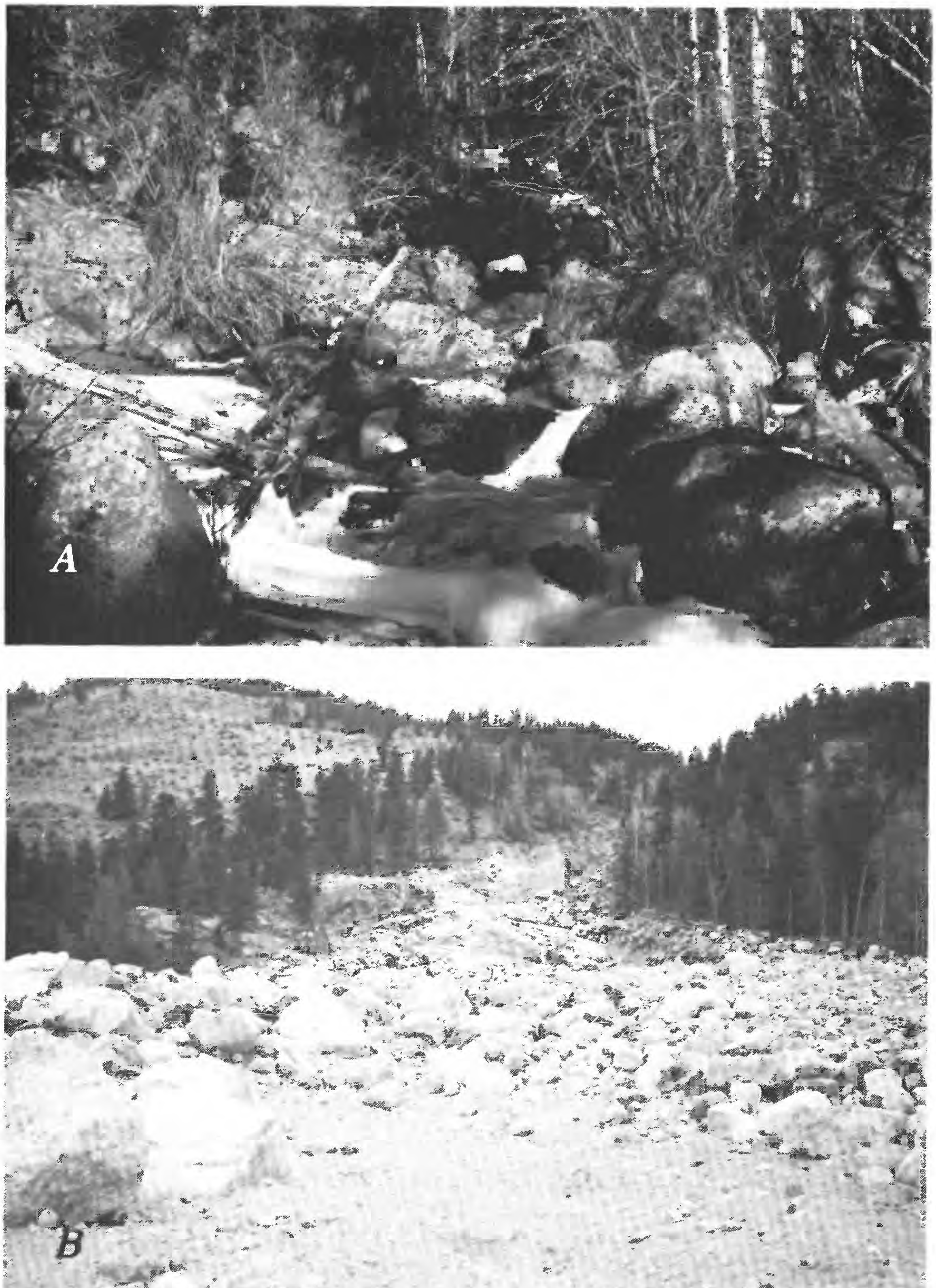

FIGURE 16.—*A*, The Roaring River, looking upstream from the Endovalley Road in 1978. *B*, The Roaring River in 1982, after the flood, from approximately the same location as *A*.

amount of debris. The leading edge of the flood wave was moving at an average of 9.1 mi/h in the Roaring River (fig. 15). The peak probably was very close to the leading edge of the flood wave (see "dam-Break Modeling"). The relatively slow speed of the leading edge was due to retardance by the vegetation and resulting debris dams.

The leading edge probably was very similar to the 1889 flood that resulted from the failure of South Fork dam near Johnstown, Pa., which claimed 2,209 lives. In the 1889 flood, eyewitnesses described the flood as carrying extremely large amounts of debris and traveling much slower than expected.

> From time to time as the flood entered narrow places in the valley, the massed debris acted as a dam and the giant flow seemed to slow and stop; then the front would boil and seethe and huge trees, ejected by overwhelming pressures, would shoot into the air as the flood once more surged ahead. (Clark, 1982, p. 141).

Ample evidence of large debris dams remained in the Roaring River (fig. 17). The 1982 flood also carried large amounts of debris, including very large boulders (fig. 16*B*).

For these conditions, the theory and application of conventional energy and flow-resistance concepts (such as Manning's *n*-values) probably are not applicable. The occurrence of numerous debris dams caused localized backwater, resulting in predominately subcritical flow. However, when these debris dams break, flow probably was supercritical for a short distance until another debris dam formed. Turbulence was extremely high, as observed by Stephen Gillette at Horseshoe Falls, where he saw boulders and trees being thrown into the air.

Across the large alluvial fan formed at the base of Horseshoe Falls, water spread. The depth, width, velocity, or cross-sectional area of flow are unknown. Early in the flood, the flow path was down the major axis of the fan. This was the area of the fan where the largest boulders and thickest sediments were deposited. Soon after the flood wave arrived, the main flow path became plugged with sediment and debris; on the falling limb of the hydrograph, the main flow gradually shifted to the right side of the fan. This migration of the main flow effects from the left to right parts of the alluvial fan is indicated by the distinctly finer-grained deposits on the right side of the fan, flow paths visible on large-scale aerial photographs, and the geographic position of the boulder berms formed during the first few minutes of the flood.

FALL RIVER: HORSESHOE FALLS TO CASCADE LAKE DAM

The confluence of the Roaring River with the Fall River is at the upstream end of Horseshoe Park (fig. 1).

FIGURE 17.—The remains of a large debris dam in the Roaring River valley near river mile 3.21.

The Fall River streamflow prior to the flood was estimated to be about 150 ft^3/s. The channel slope flattened rapidly in Horseshoe Park to 0.7 percent (fig. 2); this decrease in slope dramatically altered the flood-wave characteristics. The combination of the small slope on the prehistoric glacial lakebed, flood-plain widths in excess of 1,000 ft (table 4), and very dense brush (fig. 18) attenuated the flood wave through Horseshoe Park (fig. 11), so that the leading edge was slowed to 2.1 mi/h and was no longer a wall of water (fig. 15). Peak discharge was greatly reduced through Horseshoe Park (fig. 11). The water was very tranquil, as noted by the smooth water surface of the flood near its peak in Horseshoe Park (fig. 19). The flow was subcritical in this segment. Peak discharge decreased from an estimated 18,000 ft^3/s (see "Dam-Break Modeling") at Lawn Lake dam, to 7,210 ft^3/s (Site 1) at the downstream end of Horseshoe Park. The majority of this attenuation probably occurred in Horseshoe Park. A large amount of organic debris from the Roaring River was deposited or trapped by the dense brush at the upstream end of Horseshoe Park, and the majority of the sediment load was deposited in a large alluvial fan at the base of Horseshoe Falls (fig. 1). Little debris or sediment was transported by the flood wave in Horseshoe Park.

It was fortunate for the numerous people in residences and commercial establishments downstream from Horseshoe Park that the park acted as an efficient flood-retarding basin (fig. 19). By slowing the flood wave, the time available for warning and evacuation was increased. Most other Front Range valleys do not have large mountain meadows (that is, former glacial lakebeds) such as Horseshoe Park; without Horseshoe Park, the flood peak and resulting damages would have been much greater downstream.

FALL RIVER: CASCADE LAKE DAM TO ESTES PARK POWERPLANT

Channel slope increased to 8 percent (fig. 2) through Aspenglen Campground to the Estes Park powerplant (fig. 1), resulting in dramatic channel changes. Inflow floodwater to Cascade Lake overtopped the dam. The tremendous forces of the water caused the entire dam to fail (figs. 9A-D). At the time of failure, flood discharge was 4,500 ft^3/s, and water was flowing 4.2 ft over the top of the dam. Failure of the dam released a total of 12.1 acre-ft of stored water in addition to the volume of

FIGURE 18.—Surveyed cross section in Horseshoe Park showing topography of the flat glacial-lake floor. Looking downstream at man standing at cross section at river mile 5.36.

FIGURE 19.—The flood peak in the downstream end of Horseshoe Park. Flow peak is approximately 7,200 cubic feet per second. Photo courtesy of Grace Davis George and Jennifer D. George.

floodwater from Lawn Lake. Because of the near-instantaneous failure and relatively small volume of released water, the resulting flood hydrograph from Cascade Lake dam resembled a "spike"-shaped hydrograph, superimposed on the relatively broad inflow flood hydrograph (fig. 46). The peak discharge of the inflow hydrograph was 7,210 ft^3/s (Site 1), and the dam failed at a discharge of 4,500 ft^3/s (Site 2), indicating that the dam failed just prior to the arrival of the incoming flood peak from Lawn Lake dam. Peak discharge of the Cascade Lake dam failure was extremely difficult to determine because of its inherently unsteady nature. However, a peak discharge of 13,100 ft^3/s was computed 1.0 mi downstream from the dam after considerable attenuation probably had occurred. Dam-break modeling results (discussed later) suggested a peak discharge of 16,000 ft^3/s resulting from the Cascade Lake dam failure.

Flood depths in this high-gradient (8-percent slope), wide flood plain of the Fall River generally were less than 5 ft, as flood conditions resembled overland flow (fig. 20). Several eyewitnesses described the flow as cascading through Aspenglen Campground. The majority of flow probably was subcritical due to shallow depths, the low relative submergence of bed material, energy losses from transporting boulders, and dense vegetation obstructions (fig. 20). Several witnesses at Aspenglen Campground described the flow depths as relatively constant, with a secondary surge that probably corresponded to the "spike" of the flood hydrograph, resulting from the failure of Cascade Lake dam.

The two flood deaths in Aspenglen Campground occurred near the area shown in figure 20. Two campers, having been warned by other campers of an approaching flood, were last seen going into the island campsites.

FALL RIVER AND BIG THOMPSON RIVER: ESTES PARK POWERPLANT TO LAKE ESTES

Channel slope in this part of the flood path gradually decreases from the upstream end of Fall River to the downstream end on the Big Thompson River (fig. 2), with an average slope of 2.3 percent. The channel was relatively narrow in this reach (figs. 21 and 22). Many buildings were located adjacent to the channel on the flood plain (fig. 21); these structures tended to slow the passage of the flood wave. This was particularly true in Estes Park, as shown in the photographs in figures

FIGURE 20.—The entrance to Aspenglen Campground downstream from Cascade Lake dam through the campground area at river mile 7.01. Boulders moved by the relatively wide, shallow flow of water (resembling overland flow).

23 and 24 (taken at about the time of peak flow). Note in figures 23 and 24 that flow was very fast only in the main street of Estes Park (as indicated by the cross waves that imply supercritical flow); the majority of flow being impeded by the buildings was subcritical.

Flood-wave attenuation continued, with peak discharges decreasing from 8,520 ft^3/s (Site 4) at river mile 10.3 to 5,500 ft^3/s (Site 6) at river mile 12.5. Orville Johnson, located about 0.5 mi downstream from the Estes Park powerplant was able to discern two flood surges. However, the surge associated with the failure of Cascade Lake dam rapidly attenuated, and it was not noticed by eyewitnesses farther downstream.

Dave Thomas, observing the flood 1.2 mi upstream from Estes Park, indicated that at first the water was running clear. Then he saw debris and the floodwaters "...coming down the river. It just gradually began to swell—there was no wall of water."

As with the Roaring River, large amounts of debris affected the flow considerably. Bridges and culverts became filled with debris (fig. 49), and energy losses increased, resulting in high-flow resistance. These debris obstructions were noted throughout this channel reach during field work after the flood. Because of these obstructions and the limited channel capacity of the Fall River, the floodwaters went down the main street of Estes Park (figs. 23 and 24).

The confluence of the Fall River with the Big Thompson River is in Estes Park (fig. 1). The Big Thompson River streamflow prior to the flood was 385 ft^3/s. Note that the water re-entered the main channel before flowing into Lake Estes (upper right, fig. 24). The 06733000 Big Thompson River at Estes Park streamflow-gaging station (Site 6) is shown at the arrival of the flood in figure 25*A*, and at the peak of the flood in figure 25*B*. Note the approaching muddy water, which supports eyewitness accounts that no wall of water occurred at this location (upper right-hand corner in figure 25*A*). Patrick McLaughlin, located just up-stream from the streamflow-gaging station in Estes Park, described the initial arrival of the floodwaters as a muddy, "jellylike" muck preceding "a surge of water."

GEOMORPHIC EFFECTS OF THE FLOOD

For discussion of geomorphic changes, the flood between the Lawn Lake dam and Estes Park can be

FIGURE 21.—The Fall River valley downstream from Aspenglen Campground (aerial). View is upvalley from about river mile 8.5.

divided into three reaches: (1) The Roaring River from the Lawn Lake dam to Horseshoe Park, (2) the Fall River through Horseshoe Park to the Cascade Lake dam, and (3) the Fall River from the Cascade Lake dam to Lake Estes.

ROARING RIVER: LAWN LAKE DAM TO HORSESHOE FALLS

Geomorphic effects of the dam failure on the Roaring River were catastrophic. The data which follow were from field measurements and aerial photographs of the flood path, taken within 4 hours after the flood, with scales of 1:5,040 to 1:8,400. Prior to the flood, typical dimensions of the Roaring River were 10 to 16 ft wide and 1 to 2 ft deep. The channel was filled with numerous large glacial boulders (fig. 16*A*); in the less steep mountain meadows, the channel followed a sinuous course between finer-grained channel banks of gravelly, coarse sand and silt.

Following the flood, valley bottoms were severely eroded and rearranged. The channel had scoured laterally and vertically into underlying ground moraine. Widths varied from 70 to 500 ft, and the channel was scoured from 5 ft to as much as 50 ft locally (fig. 26). The natural long profile of the Roaring River was a series of steep channel reaches separated by more gentle mountain meadows. Following the flood, these differences became exaggerated. Scour occurred along 11,900 ft of channel, or 56 percent of the length of the Roaring River; deposition occurred along about 9,300 ft in the flatter parts of the valley floor (fig. 27). The average slope of the Roaring River is 10 percent; but locally, reaches are as steep as 26 percent and as low as 5 percent. The threshold slope separating the scoured reaches from the depositional reaches seemed to be about 7 to 9 percent (table 7).

Scoured reaches are steep, and the newly eroded channel is narrow and deep (fig. 28); also see the Roaring River valley cross section at river mile 0.55 (fig. 58) in the Supplemental Cross-Section Data section at the end of the report. In many places, scour removed all overlying glacial material and exposed fresh bedrock in the channel bottom (fig. 27). The flood eroded laterally into glacial sediments, and left steep, overhanging banks, with numerous large boulders half-exposed and ready to fall into the channel below (fig. 26). Thousands of trees in the valley floor were uprooted as their footings were eroded. Little evidence was found of remaining rooted trees having been snapped off or shattered; most trees probably were lost from toppling or undermining and caving of eroding banks during the flood wave. Once incorporated into the floodflow, trees were extensively battered and scarred (fig. 17.

Depositional areas were characterized by more gentle gradients at the breaks in slope below steep reaches. These areas of relatively wide mountain meadows generally had slopes less than 7 to 9 percent. Sediments deposited in the meadow areas were relatively thin, generally no more than 2 to 8 ft thick. Locally, deposits were measured to 10 ft thick (fig. 29). Deposited material in each meadow came from the scoured-valley sides and bottoms of the steep reach upstream. No large boulders or rocks traveled any farther than about 1,000 ft; most probably were moved less than 100 ft. Nearly all the boulders were fresh, with a minimal number of percussion marks, indicating that they did not travel far or very long in the flood.

Some very large boulders (greater than 6-ft diameter) were moved in the floodflow. It was not always immediately evident that a particularly large rock was transported by the flood; in many places along deeply

FIGURE 22.—View downstream at the indirect discharge measurement Site 4 on the Fall River above Estes Park.

FIGURE 23.—The Fall River looking upstream from the western end of Estes Park at river mile 11.9 (aerial). Photo courtesy of Zenas Blevins, U.S. Bureau of Reclamation.

FIGURE 24.—Elkhorn Avenue, Estes Park, looking downstream from river mile 12.0 (aerial). Big Thompson River is along the right side of the photograph; Lake Estes is in the top righthand corner. Photo courtesy of Zenas Blevins, U.S. Bureau of Reclamation.

scoured reaches, very large boulders in ground moraine were undercut and had simply fallen onto the channel floor. The criteria used to establish that a particular boulder did, in fact, move in the flood were: (1) Percussion marks on all sides of the boulder, not just on the upstream side; (2) balanced and wedged smaller rocks, and broken and buried vegetation under larger boulders; and (3) boulder clusters and berms in streamlined depositional forms, with imbricated structure parallel to the flow direction (fig. 30). Some of the largest measured boulders known to have been moved in the Roaring River valley have dimensions of 5.5×8×12.5 ft, 7×12×13 ft, and 3×7×8 ft. Larger boulders were observed in the channel, but minimal or no evidence existed to indicate that they had been moved by the dam-failure flood.

Much less conspicuous, but nevertheless ubiquitous, were sand deposits. Sands were deposited almost continuously, away from the main flood channel, within the edge of the surviving forest and vegetated areas on the valley sides below high-water marks. Some sand deposits were 4 ft thick and had steep wave fronts facing downstream (fig. 31). Sand deposits along the Roaring River are very coarse and massive, or have weak horizontal laminations (fig. 32).

About 400 ft downstream from the Lawn Lake dam, sand splays are extensively developed on the right bank. High-water marks indicated the flood flow was 3.5 ft deep over the top of these splays. Along the edge of the splay next to the deeply eroded channel, backset beds, interpreted to be antidune structures, were preserved (fig. 33). These backset beds were diffuse, curved, and

TABLE 7—*Channel conditions, Roaring River*

Distance downstream from Lawn Lake dam, in miles	Average slope, in percent	Channel condition
Below Lawn Lake dam		
0.00–0.24	7.5	scour
.24– .68	6.9	deposition
.68–1.00	25	scour
1.00–1.16	9.2	deposition
1.16–1.49	23.5	scour
1.49–1.70	5	deposition
1.70–1.95	13.3	scour
1.95–2.23	5.5	deposition
2.23–2.74	7.1	scour
2.74–3.62	5.7	deposition
Horseshoe Falls		
3.62–4.02	26	scour


A

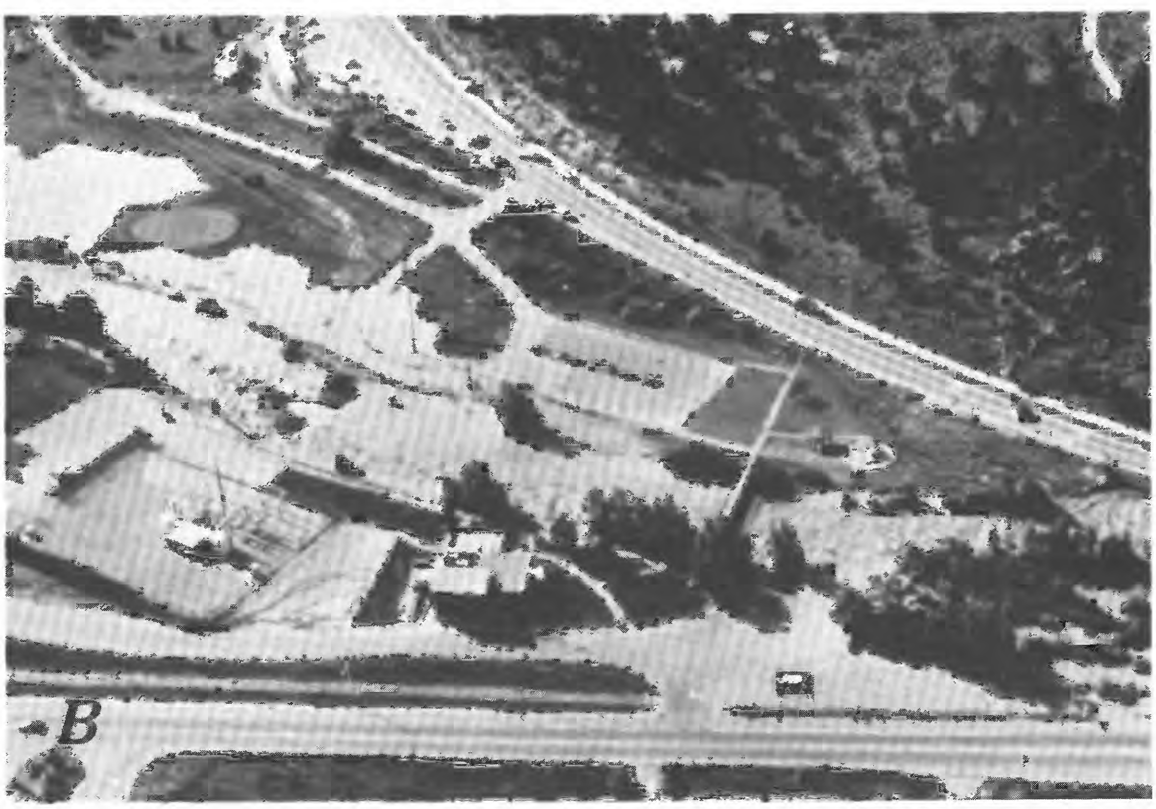
B

FIGURE 26.—Deeply scoured reach in the Roaring River valley below Lawn Lake dam at river mile 0.28. Ground moraine was scoured 35 feet to bedrock. Man (for scale) in right center of photo.

dipping against the flow direction at an angle of 9° to 10°. These beds were nearly identical with those described from flume experiments by Middleton (1965); they indicated upper-flow regime conditions (and perhaps supercritical flow) in the reach immediately below the dam. When the site was visited 1 year later in July 1983, the antidune structures were no longer preserved, probably because of erosion in the exposed location.

ROARING RIVER ALLUVIAL FAN

At the mouth of the Roaring River, a large alluvial fan was deposited on the floor of Horseshoe Park at about 0630 MDT on the morning of the flood (fig. 34). Peak flood discharge at that time was estimated to have been 12,000 ft^3/s (see "Dam-Break Modeling"). Sediments for the fan were derived from the large lateral moraine along the Roaring River and Horseshoe Park, just upstream from and including Horseshoe Falls. Boundaries of the alluvial fan were determined from a vertical aerial photograph taken about 4 hours after the flood peak and enlarged to a scale of 1 in.=96.5 ft. The downstream end of the fan was defined as the location where the Fall River assumed a distinct channel. Upstream from this point, the original stream channel was obliterated and buried by sediments. The area of the alluvial fan is 42.3 acres (0.066 mi^2) (fig. 35).

Volume of sediment in the fan was determined by ground measurements of sediment thickness at 14 points on the fan. Thickness was obtained by digging through the sediment to the original ground surface at 11 sites. At two additional sites, the original ground surface could not be reached by digging, so the depths were minimal estimates. The final site was the highest and thickest point on the alluvial fan. Thickness was

◄ FIGURE 25—*A*, View upstream at the arrival of the floodwaters at the Big Thompson River at Estes Park gaging station (Site 6) (aerial). Muddy water is arriving under the bridge in the upper left-hand corner. *B*, View downstream at the Big Thompson River at Estes Park gaging station (Site 6) during the peak flow (aerial). Photograph taken about one-half hour after photograph in figure 25*A*. Golf green at bottom of figure 25*A* is in upper left-hand corner of photo. Photos courtesy of Zenas Blevins, U.S. Bureau of Reclamation.

FIGURE 27.—The Roaring River valley at river mile 1.14 (aerial); down-valley is to the right. From the left edge of the photo, the channel is scoured to bedrock and very steep; a wide depositional reach is at a mountain meadow; a short, steep-scoured reach is defined by the slope failures on the left bank; and, finally, a flatter depositional reach extends off the right edge of photo.

determined by surveying the height of the deposit above adjacent high-water marks; triangulation of sediment thickness was determined from the slope of the original ground surface beneath the sediments, which produced a maximum thickness of 44 ft in a very small area near the head of the fan. Average thickness of the alluvial fan is only 5.3 ft. A contour map of the sediment thickness of the Roaring River alluvial fan is shown in figure 36.

Volume of sediment in the alluvial fan was calculated two ways; both ways produced approximately the same volume. First, the area between the contour lines shown in figure 36 was measured and multiplied by the average thickness of the bounding contours. Second, a Theissen-Polygon method using the 14 data points was used. The calculated sediment volume, assuming 1/3 porosity, is 364,600 yd^3, which is enough sediment to cover a football field to a height of 205 ft. If a specific gravity of 2.7 is assumed for the granite-gneiss sediments, the unit weight is 168.5 lbs/ft^3. This produced a sediment weight of 829,000 tons, which is approximately 1½ times the sediment load deposited at the mouth of the Mississippi River in 1 day (Milliman and Meade, 1983).

Characteristics of the surface sediments on the Roaring River alluvial fan changed in a downstream direction. The size of the single largest particle in a 3-ft radius, every 50 ft down the major flow axis of the fan, is plotted in figure 37. The particle size changed from 7.5 ft at the head of the fan to 1 ft midway down the fan, where the largest concentrations of big boulders ended, to 0.002 ft at the toe of the fan, overlapping the flood plain of the Fall River. Winter winds during 1982–83 subsequently eroded some of the flood-plain sand and silt, which collected against U.S. Highway 34 road embankment (fig. 1) as dunes with heights of 2 to 3 ft.

The single largest boulder known to have been transported onto the surface of the Roaring River alluvial fan is 14×17.5×21 ft, and weighs an estimated 452 tons (fig. 38). The force of the boulder-charged flow over Horseshoe Falls battered and destroyed most of the vegetation along the main flow path. Some trees still standing after the flood were struck so hard by transported boulders that their tops were snapped off.

The large volume of sediment deposited in the Roaring River alluvial fan dammed the Fall River in Horseshoe Park upstream from the fan, forming a small lake (fig. 35). By July 1983, the lake had established an equilibrium between inflow of the Fall River upstream and outflow along a marginal channel that formed at

FIGURE 28.—View downstream at river mile 0.55 on the Roaring River valley in a scoured reach. Depth of scour is 25 feet; man is holding rod at the level of high-water marks.

FIGURE 29.—View across a mountain meadow at river mile 0.38, showing the accumulation of a thick boulder deposit in a relatively flat reach in the Roaring River valley.

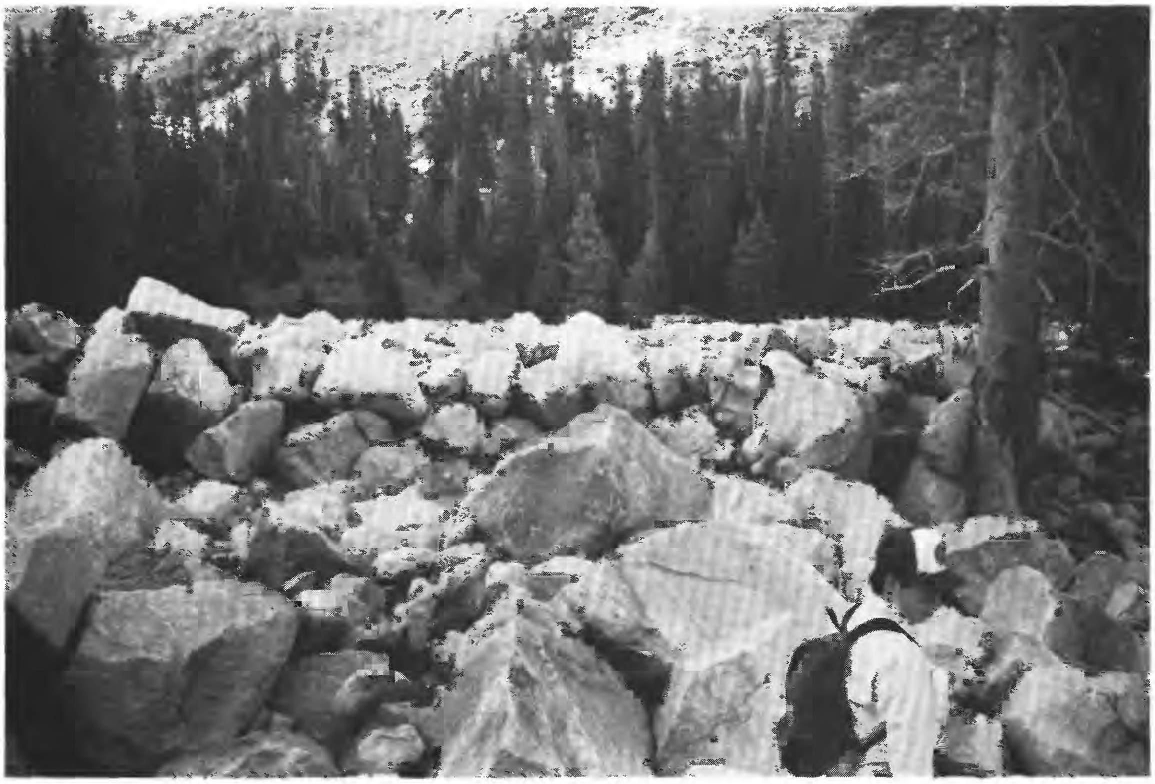

FIGURE 30.—Imbricated structure in boulders deposited in the meadow shown in figure 29. Flow was left to right. Note the near-vertical imbrication of many of the rocks piled behind the tree.

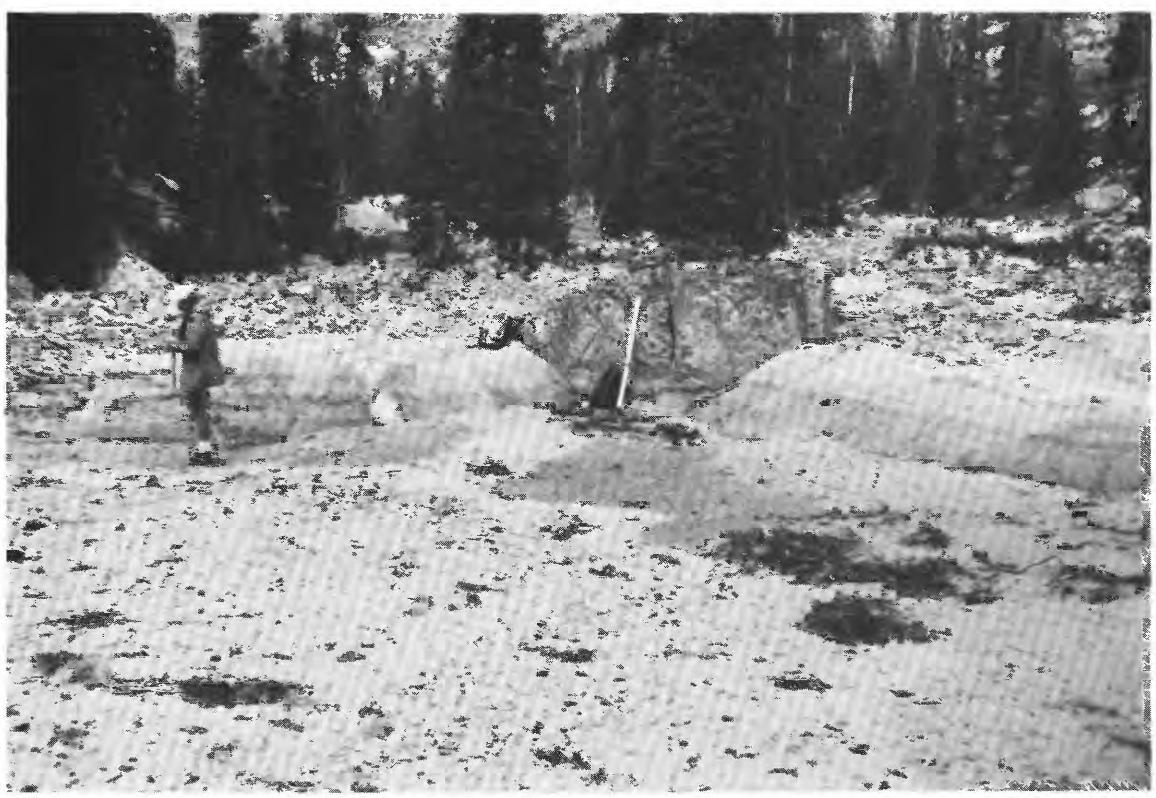

FIGURE 31.—Unusually thick sand waves deposited in the Roaring River valley on the inside of a sharp valley bend at river mile 0.50.

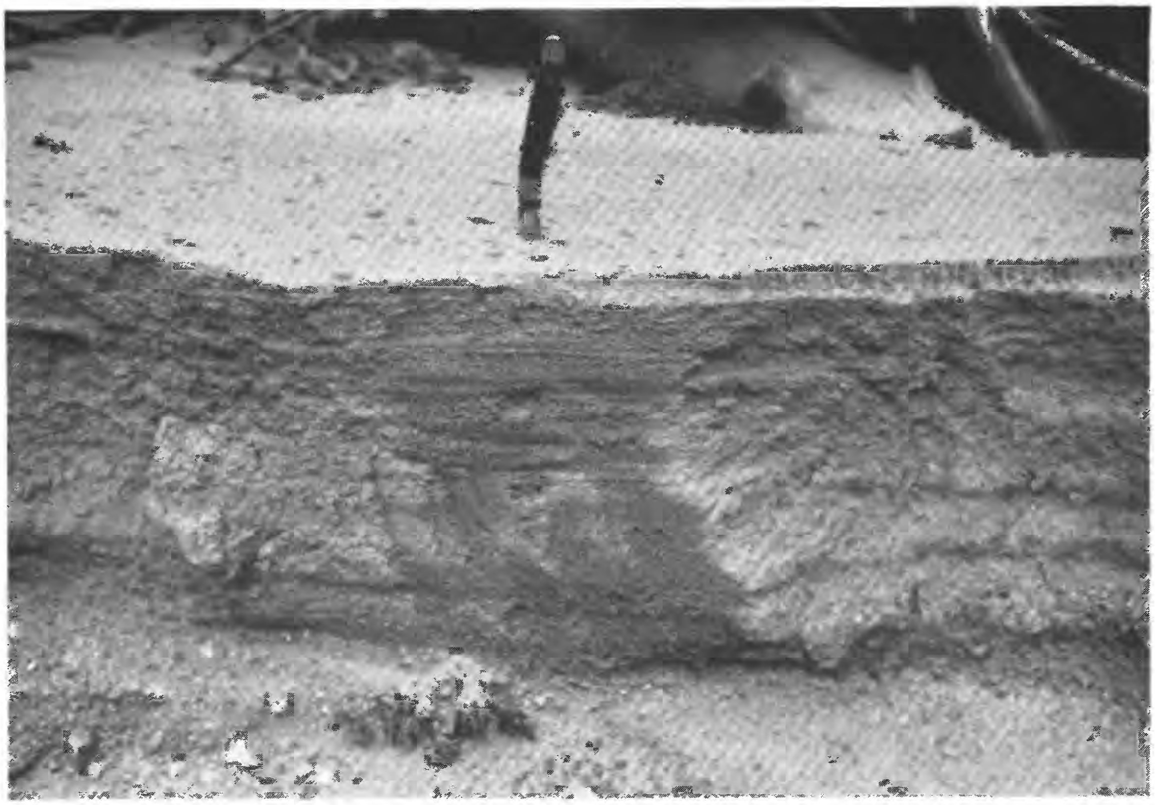

FIGURE 32.—Horizontal laminations in sand deposits at the edge of flow in the Roaring River valley at river mile 3.41.

FIGURE 33.—Gently-inclined backset crossbeds interpreted to be antidune structures in a sand splay 0.25 river mile below Lawn Lake dam. Flow was from right to left; pencil is 5.5 in. long.

FIGURE 34.—The alluvial fan formed at the mouth of the Roaring River. Note the deep scour into the lateral moraine source materials.

FIGURE 35.—Roaring River alluvial fan taken about 4 hours after the flood (vertical aerial). Incipient lake formed from the damming of the Fall River shown in figure 39 is indicated by arrow; dashed lines indicate the outline of the alluvial fan.

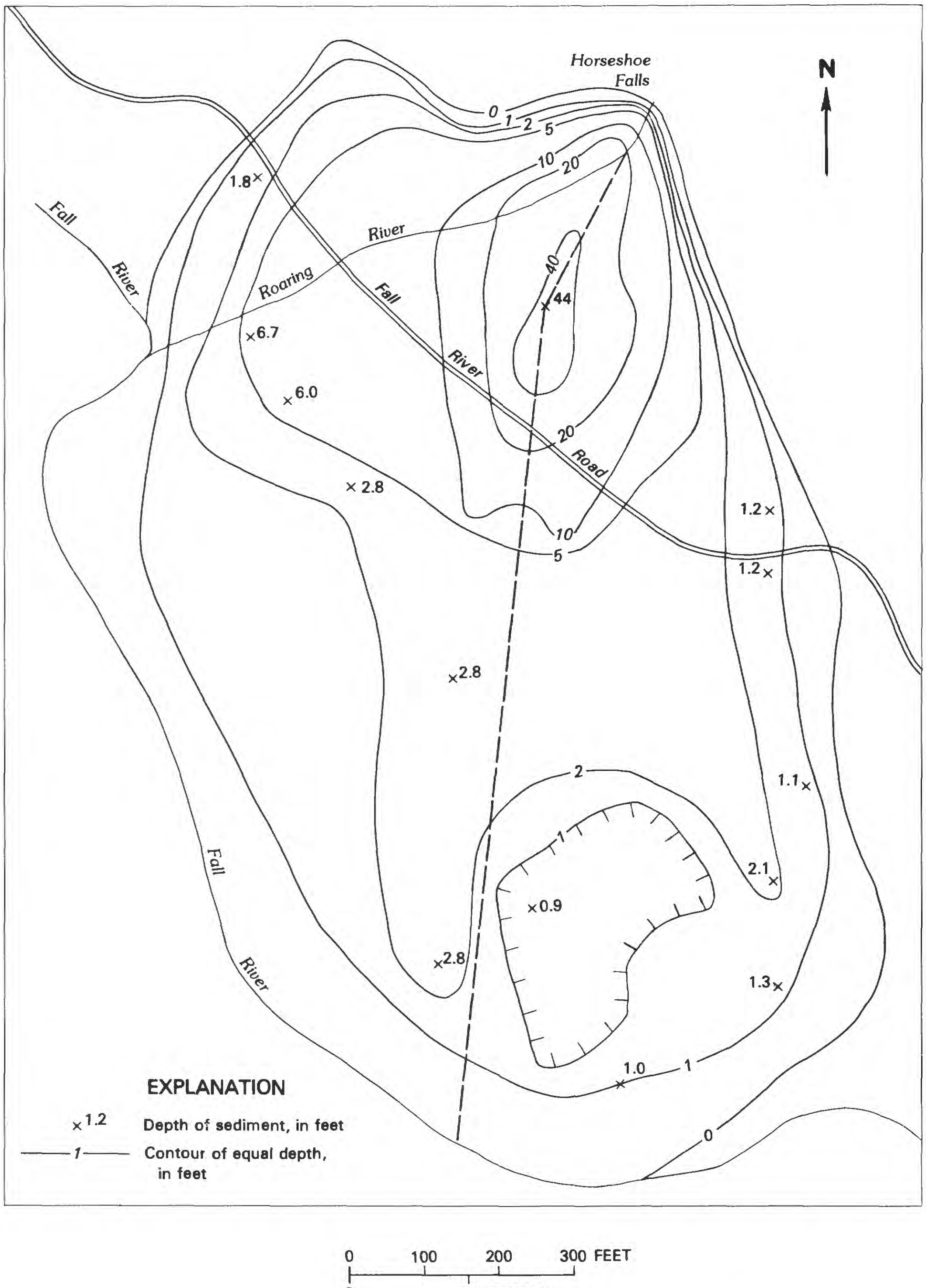

FIGURE 36.—Contours of sediments in the Roaring River alluvial fan. Axis of main flow direction is shown by dashed line. Dashed line also is the path along which particle sizes shown in figure 37 were measured.

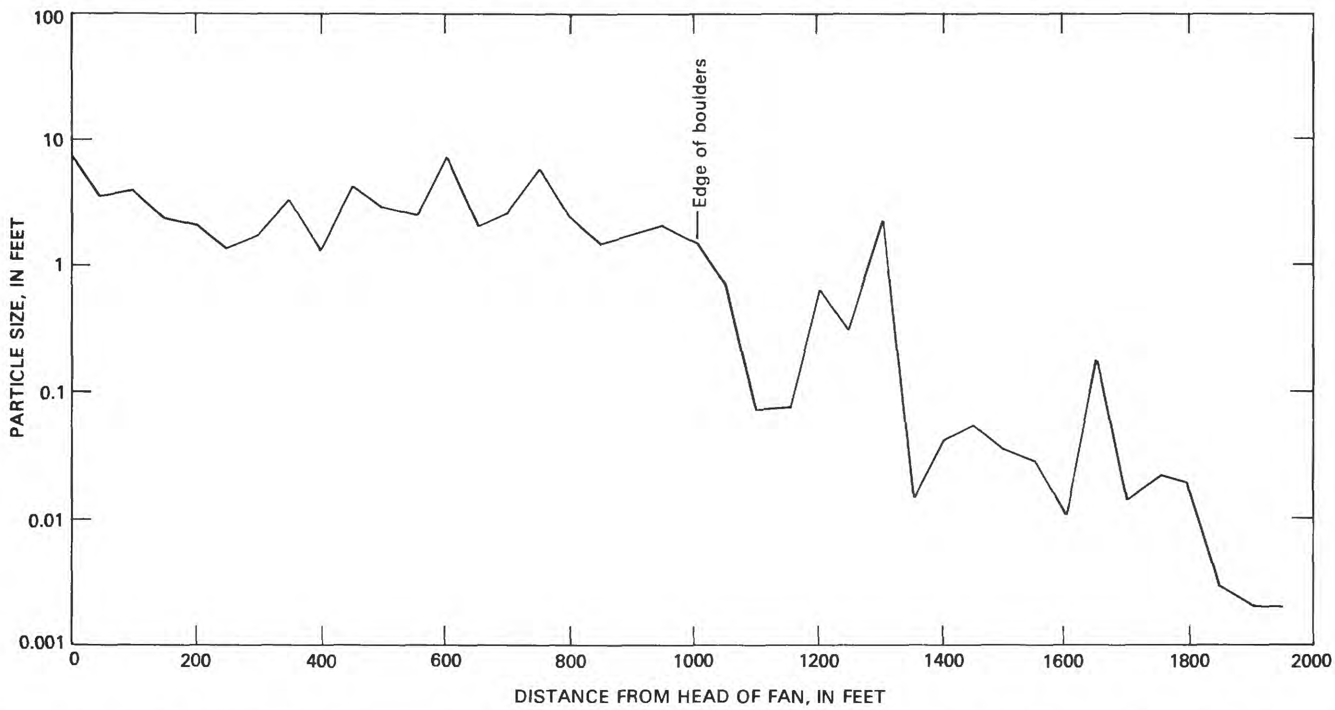

FIGURE 37.—Plot of largest particle measured in 3-foot radius every 50 feet down the major flow axis of the dam-break flood on the Roaring River alluvial fan. Path follows dashed line in figure 36.

FIGURE 38.—The single largest boulder thought to have been moved by the flood onto the Roaring River alluvial fan. Dimensions of the boulder are 14×17.5×21 ft.

FIGURE 39.—The 17-acre lake formed in Horseshoe Park by the damming of the Fall River, taken in August 1983 (aerial). Downstream is to the left.

the edge of the alluvial fan (fig. 39). In July 1983, the lake had a surface area of 17.0 acres (0.0265 mi^2), and appeared to be a permanent hydrologic feature for the foreseeable future.

FALL RIVER: HORSESHOE FALLS TO CASCADE LAKE DAM

The Fall River in Horseshoe Park between the junction with the Roaring River and the downstream limit of Horseshoe Park at Site 1 just upstream from Cascade Lake dam is a sinuous meandering stream that falls 66 ft in 1.8 mi, or a slope of 0.7 percent (fig. 2). A view of Horseshoe Falls and Horseshoe Park is shown in figure 40. Surficial geology in Horseshoe Park consists of cohesive silts and clays deposited on the floor of a late Pleistocene lake. Lawn Lake floodwaters passed over and across the meanders, but the velocity of flow and duration of overbank flows were not sufficient to erode or disrupt the lakebed materials into which the meanders had formed (fig. 41).

In Horseshoe Park maximum flood depth was about 10 ft, and maximum width was 1,300 ft measured on the aerial photograph. Water was out of the banks on the Fall River in Horseshoe Park for less than 4 hours, except for local ponded water. The photograph in figure 41 was taken about a week after the flood; it clearly shows that no immediate visible modification occurred to the meandering channel pattern of the Fall River.

In the spring of 1983, about 1 year after the Lawn Lake flood, numerous sandy point bars had formed in the Fall River channel in Horseshoe Park. Large amounts of sandy bedload, produced from a high spring runoff eroding bare and exposed channel banks along the Roaring River, and from the alluvial fan area, had moved into Horseshoe Park. Bedload and channel measurements by John Pitlick (1985) indicated that parts of the Fall River channel have been completely filled with sandy sediment.

After the flood passed, much of the flood plain of Horseshoe Park was covered with a thin veneer of fine-grained silt and sand. No mineral sediments coarser than very coarse sand were transported through Horseshoe Park, although some vegetal debris was trapped in the willows lining the channel. Sediment thickness varied from about 1 ft in locally protected places near the channel at the upstream end of Horseshoe Park, to thin drapes at the edges of the flow.

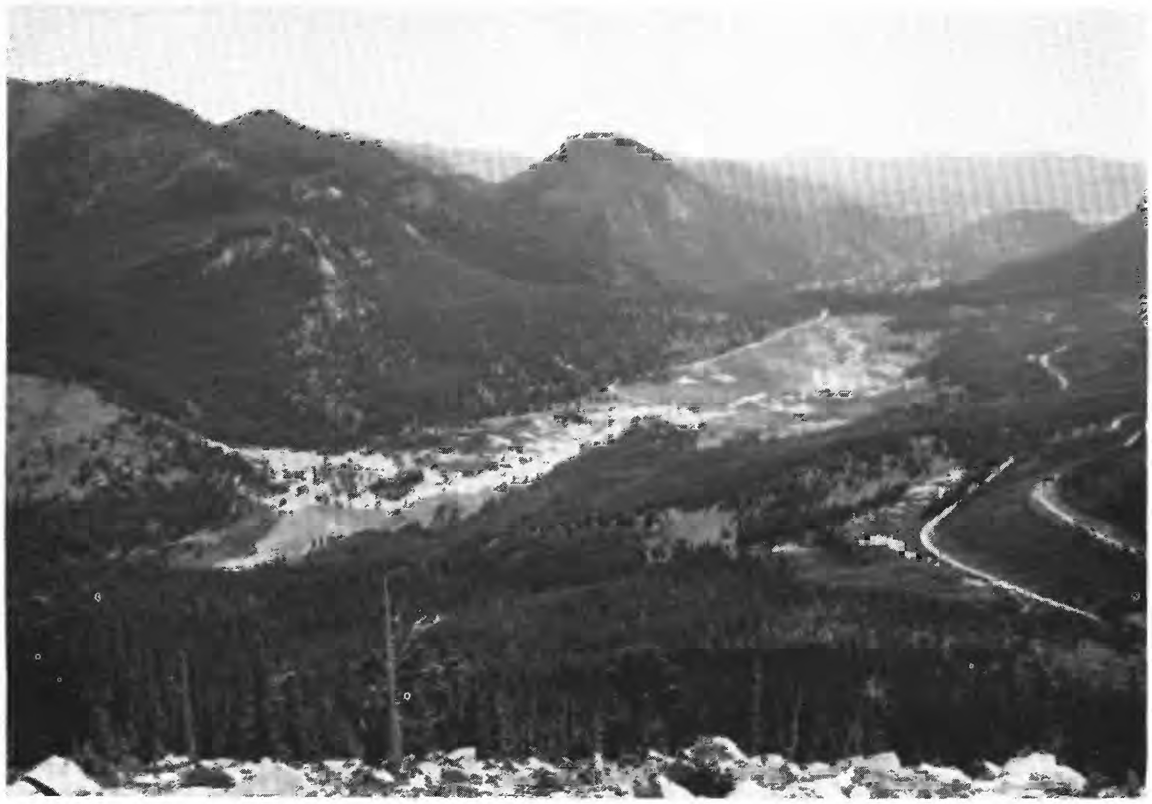

FIGURE 40.—Horseshoe Park and the Fall River valley, looking down-valley. Roaring River alluvial fan is in left-center of photo.

FIGURE 41.—Horseshoe Park taken 1 week after the flood, looking upstream from river mile 6.5 (aerial). The tight meanders of the Fall River were unaffected by the floodwaters.

FIGURE 42.—The Fall River channel about 0.3 mile below Cascade Lake dam, showing extensive channel scour. View is upstream.

FALL RIVER: CASCADE LAKE DAM TO ESTES PARK POWERPLANT

The distance from the Cascade Lake dam to the Estes Park powerplant is about 0.9 mi, and the Fall River drops about 400 ft; average slope is about 8 percent. The slope of the Fall River steepens abruptly below the Cascade Lake dam (fig. 2), because the Fall River flows over the Pleistocene terminal moraines that dammed the river in glacial times. Fall River follows three well-defined separate channels that course through the morainal sediments. Immediately below the Cascade Lake dam, above the Aspenglen Campground, the floodwaters scoured the glacial sediments as much as 30 ft (fig. 42). The bed material is extremely coarse, bouldery gravel. Some of the largest boulders believed to have moved were 5.8×6.4×8.4 ft; 3.8×10.2×14.7 ft; 5.3×5.8×6.5 ft; and 4.2×4.8×8 ft. Many trees in the flood path were either broken, undercut and toppled, or severely scarred and stripped of bark.

CATASTROPHIC FLOOD FEATURES

Two types of sedimentary features were especially well developed during this flood—boulder berms and step-pool long profiles. On the west side of Roaring River alluvial fan, and below Cascade Lake dam above the Aspenglen Campground, boulder berms similar to those described from other catastrophic floods in steep mountain channels (Scott and Gravlee, 1968, p. M13–M14) were well-developed (fig. 43*A*). These boulder berms are boulder levees deposited by floodwaters in the two locations where sufficient sediment was entrained in the flow to temporarily produce an inertial granular flow (Pierson and Costa, 1986). These conditions existed for only two short reaches where (1) the Roaring River eroded through the high lateral moraine at Horseshoe Falls, and (2) the Fall River deeply eroded Pleistocene terminal moraine sediments below Cascade Lake dam.

An inertial granular flow is a special type of sediment gravity flow in which (1) large amounts of coarse debris and organic matter are being transported down steep channels, (2) the flow is noncohesive because of the relatively small percentage of silt and clay, and (3) the flow is highly turbulent. Flows of this type have been described by Church and DeSloges (1984).

Particle-size analysis of a sample of matrix material from the right boulder berm or debris-torrent levee at the Roaring River alluvial fan is shown in figure 43*B*. The median particle size is 0.118 in., and the matrix contains only 0.5 percent clay. The berm ends with a steep front

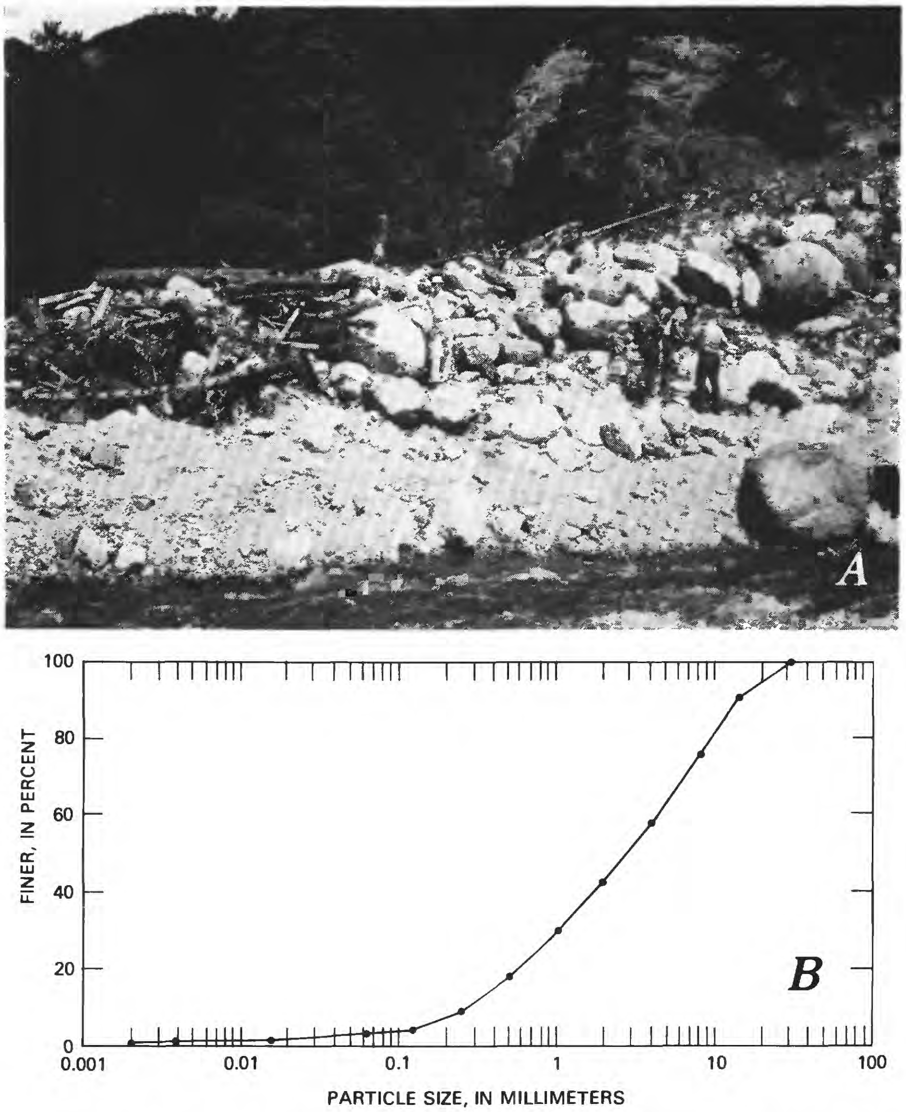

FIGURE 43.—*A*, A well-developed boulder berm along the right bank of the Roaring River on the large alluvial fan at river mile 4.73, showing the concentration of organic material in the front of the berm. View is upslope on the surface of Roaring River alluvial fan. *B*, Partical-size analysis of matrix from Roaring River alluvial fan boulder berm.

that includes numerous large shattered tree trunks and other organic material as well as large boulders. Upslope, there is no organic material and the berm consists of very coarse boulders and a coarse, noncohesive matrix deposited directly on ground moraine with little or no erosion. The coarse texture of the matrix and the small clay content are characteristic of such flows (Church and Desloges, 1984).

Some of the coarsest boulders are at or near the surface of the berms, and the top of the berm is well above adjacent high-water marks on the valley side (assuming a level water surface). The boulders have a pronounced imbricated structure, with their long axes perpendicular to the flow direction and their intermediate axes dipping steeply at 30° to 90°. There are nine criteria that are characteristic of boulder berms formed by inertial gravity flows:

1. They form below rapidly expanding reaches.
2. They may not form on both sides of the channel.
3. They are short, but continuous; lengths range from 6 to more than 30 ft.
4. They form below reaches with large sources of debris, such as deep scour or landslides.
5. They are mostly grain-supported with little matrix. The matrix is coarse and usually contains less than 4 to 5 percent silt and clay.
6. Boulders have steep imbrication angles, commonly greater than 60°.

7. Long axes are perpendicular to the flow direction.
8. Some of the coarsest rocks are on the top of the berms.
9. The tops of the berms may be above high-water marks on valley sides.

Step-pool long profiles are a common feature in high-gradient mountain streams, where more shallow-gradient, deep pools of water are separated by abrupt, steep steps or falls in the channel. Each step consists of a cluster of very coarse boulders extending across the channel. Water flows over the steps or concentrations of large boulders and into pools, where much of the fluid energy is dissipated. The origin of step-pool features in mountain channels has been much debated; Whittaker and Jaeggi (1982) reviewed the proposed origins. They concluded that step-pool features form in high gradient mountain streams with heterogeneous bed material sizes during high intensity, low-frequency floods. These are extremely stable forms during more frequent lower flows.

Four well-developed steps ranging in height from 4 to 9 ft were formed within a distance of 110 ft in the Fall River just upstream from Aspenglen Campground. One step-pool bedform in boulder deposits in the Fall River is shown in figure 44. Average sizes of the 10 largest boulders exposed in the front of each of the steps were 3.4 ft, 3.5 ft, 4.0 ft, and 4.4 ft. The steps formed downstream from Cascade Lake dam probably were analogous to the steppool forms so common in coarse-boulder steep channels, and support the belief that they originate as bedforms under catastrophic flood conditions, probably collecting under hydraulic jumps formed near the peak of the flood.

FALL RIVER AND BIG THOMPSON RIVER: ESTES PARK POWERPLANT TO LAKE ESTES

Between the Estes Park powerplant just below the Aspenglen Campground and the confluence of the Fall River with the Big Thompson River in Estes Park, the stream slope averages 2.3 percent. Water was 3.0 to 6.0 ft deep in the overbank areas. Flood width varied with the valley morphology, but typically was 200 ft wide (table 4).

Scour and channel widening were not as pronounced as they were along other steeper parts of the flood path. Estimates of channel scour from exposed channel banks and tree roots were in the range of 0.5 to 2.0 ft, except immediately downstream from the powerplant, where scour approached 30 ft. Sediments were deposited in the channel and on the flood plains. Channel deposits were predominantly coarse, bouldery gravel bars and sand bars. Flood-plain deposits consisted of sand splays in

FIGURE 44.—The front of one step-pool bedform in boulder deposits in the Fall River upstream from Aspenglen Campground at river mile 7.01.

protected sites, such as inside sharp channel meanders, and in wide valley cross sections. Maximum thickness measured was a deposit of coarse sand and gravel about 2 ft thick.

Where the Fall River entered the west end of Estes Park at river mile 11.5, at an elevation of 7,550 ft, the stream passed under a narrow bridge opening and followed a channelized path along the south end of town, before joining the Big Thompson River near the eastern end of Estes Park. The majority of the flood water left the channel of the Fall River at the narrow bridge crossing and overflowed down Elkhorn Avenue, the main street in Estes Park (figs. 23, 24). No significant amounts of scour or deposition occurred in this short reach between Estes Park and the streamflow-gaging station (06733000 Big Thompson River at Estes Park).

SEDIMENT IN LAKE ESTES

There were no accurate measurements taken of the sediment and debris deposited in Lake Estes by the flood. However, the U.S. Bureau of Reclamation spent approximately $80,000 for heavy debris and sediment removal following the flood. Periodic sediment surveys have not been performed at Lake Estes because sedimentation was not considered a problem prior to this flood. A major volume of sediment was deposited in Lake Estes during the spring of 1983, 1 year after the flood. This accumulation was moved into the reservoir by the sustained high spring snowmelt flood. The source of sediment was primarily from erosion of exposed river banks and channels that had lost their protective covers of vegetation and rock armor during the big flood. Subsequent work in and near the channel by adjacent property owners also created some streambed instability.

Zenas Blevins (U.S. Bureau of Reclamation, oral commun., 1983) estimated that there was at least 10 times more sediment deposited in Lake Estes during the spring runoff of 1983 than was deposited by the Lawn Lake flood. The unstable sand and gravel deposits along the Roaring River, Fall River, and Big Thompson River indicates that the river is not yet stabilized and will continue to transport large amounts of sediment into Lake Estes for several years. Water quality problems are expected each spring during the next several years. The river banks across the glacial moraine deposits are still very steep and unstable and will continue to slough for many years.

DAM-BREAK MODELING

Hazard mitigation of floods resulting from dam failure requires documentation of historic dam failures to understand the processes involved. Future hazard mitigation also requires analysis of past dam-failure floods to estimate potential flood discharges, depths, boundaries, and traveltime. These analyses of dam-break floods are often made with deterministic digital-computer models. However, most of the documentation and analyses of dam-failure floods generally have been made on relatively low-gradient streams (Land, 1980; Chen and Armbruster, 1979); whereas, the Lawn Lake dam and Cascade Lake dam failures flood occurred on very high-gradient streams (fig. 2). Some aspects of the documentation of this flood could not be made because of hydraulic problems previously discussed. Questions also need to be answered concerning various scenarios of possible dam-failure floods of this type. Therefore, dam-break computer modeling was undertaken to evaluate the model's capabilities on high-gradient streams, to enhance and provide supplemental hydrologic information, to evaluate various hypothetical scenarios of dam-break development, and to assess probable impacts of the failure of Cascade Lake dam, as well as impacts of other situations. These analyses provide the range of possible flow characteristics from the actual conditions as well as other possible conditions. The following section of this report provides a summary of the dam-break model analysis.

DAM-BREAK MODEL

The selected dam-break flood model was formulated, developed, and documented by Fread (1977) and modified and documented to meet U.S. Geological Survey needs by Land (1981). The model was selected because of its general purpose formulation. Studies by Land (1980) indicate that it is the most accurate, economical, flexible, numerically stable, and easiest to apply of four models tested on three documented dam-failure floods. The model formulation is based on the two one-dimensional open-channel flow equations (Saint Venant) of continuity and momentum for shallow depth and unsteady conditions. The numerical analysis technique used is a nonlinear implicit finite-difference method. Minor modifications to the dam-break model by Land (1981) were made to meet the objectives of a general purpose model for the needs of the U.S. Geological Survey. These included eliminating the multiple dam-failure option, altering the computation of the time step, reorganizing data entry and printout formats, preventing the model from switching from one state of flow to the other (subcritical to supercritical) in a given subreach, and allowing for tributary inflow.

The model is designed to simulate a dam-break flood in one computer run; however, the simulation is done in two distinct parts. The first part is to route an incoming flood through the reservoir and compute an outflow breach hydrograph. The dam breach develops when the water level at the dam reaches a preselected elevation. The outflow hydrograph is computed with a hydrologic (storage-continuity) method, or with a hydraulic method used for streamflow routing. Instantaneous flow through the breach is approximated by broad-crested weir equations for triangular, rectangular, or trapezoid shapes. The breach develops during a specified time period and progressively takes one of these shapes to a specified maximum breach bottom width and elevation. The broad-crested weir equation is used to compute spillway and gate outflow. A discharge through outlet pipes also can be specified. The second part is routing the outflow hydrograph through the stream. The routing is mathematically accomplished with the Saint Venant flow equations and a nonlinear implicit finite-difference method. If the stream has segments where the state of flow is different, then the flood wave is completely routed through one segment before being routed through the next. To accurately represent the conveyance and storage areas of a cross section, the cross-section subareas can be specified as being active or inactive flow areas.

DATA REQUIREMENTS AND ASSUMPTIONS

The model requires initial and boundary conditions, as well as a physical description of the lakes, dams, and stream-channel reach. The model layout shown in figure 45 indicates the location of the segment numbers, cross sections, and computational nodes. Computational nodes, or nodes, refer to the location where discharge and water-surface elevations are computed inside the model. These data can be either measured or estimated. For this study, most of the data were available, particularly for calibrating the model with observed data to evaluate its capabilities on high-gradient streams.

Hydraulic routing of the dam-break hydrograph through the stream channel requires a physical description of the channel and other flow characteristics. The geometry of the channel was defined by 12 cross sections (Supplemental Cross-Section Data). The channel was subdivided into segments to allow for an evaluation of subcritical or supercritical flow in each segment, primarily based on channel slope (fig. 2). Generally, if the average slope of the segment was less than about 5 percent,

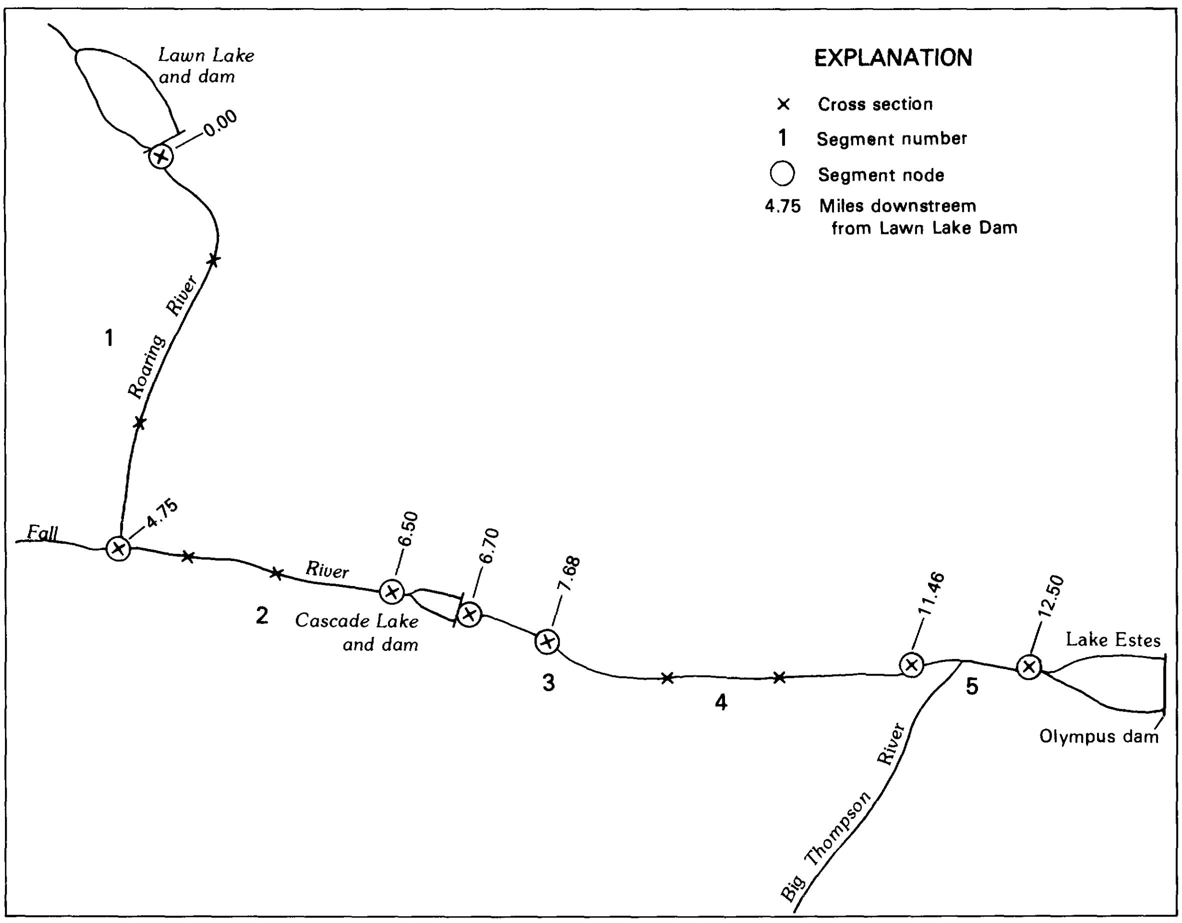

FIGURE 45.—Dam-break model layout for the lakes-stream system.

subcritical flow was assumed. Computational cross sections were spaced at intervals that ranged from 0.02 mi to 0.6 mi, depending on the segment of channel. Immediately downstream from each dam, computational cross sections were closely spaced to produce better results where the flood hydrograph was changing rapidly.

The time step of the computations was computed automatically; therefore, it was not directly controlled. Generally, the time step varied by the position of the flood wave. That is, during gradual changes in stage, the time step was longest (a maximum of 15 min), and during the maximum development of the breach and near the peak flow when stages are changing rapidly the time step was shortest (3 seconds). Base flow used to start the model ranged from 250 ft^3/s for reaches downstream from Lawn Lake dam to 400 ft^3/s for reaches downstream from Cascade Lake dam. These base flows were higher than actual conditions, but were required by the model for computational purposes. Estimated tributary inflows were 150 ft^3/s for the Fall River and 385 ft^3/s for the Big Thompson River. These inflows reflected estimated base flows of these rivers and other minor tributary base flows. The initial water-surface elevation at each cross section (surveyed and computational) was computed by the normal depth method by the model. The model's computational cross-section smoothing option was not used.

The hydrologic routing method was used for each dam to compute the dam-breach hydrographs. Storage-capacity data and elevation of water surface at the time of breach are shown in table 3 for each dam. Since Lawn Lake dam probably failed from piping, the initial water surface was set at 0.01 ft below the water surface at time of failure. The initial water-surface elevation for Lawn Lake dam was 10,996.41 ft. It was assumed that the trapezoidal breach function in the model (an overtopping failure) would adequately model a piping failure, since the piping breach developed so rapidly. An inflow discharge of 350 ft^3/s was used to raise the water surface sufficiently to cause the Lawn Lake dam to fail by overtopping (although the actual inflow probably was about 25 ft^3/s). An average side slope of the breach (Lawn Lake dam=0.84; Cascade Lake dam=2.77), elevation of breach crest (Lawn Lake dam=10,975 ft; Cascade Lake dam=8,460 ft) and bottom breach width at end of failure (Lawn Lake dam=55 ft; Cascade Lake dam=80 ft) were obtained from the cross-section data in the Supplemental Cross-Section Data section at the end of the report; these characteristics are shown in those supplemental data for each dam.

To operate the model in the Roaring River (discussed later), an outlet discharge of 250 ft^3/s was used. Probably less than 5 ft^3/s flowed out the overflow. An outlet discharge of 400 ft^3/s was used for Cascade Lake dam. Artificially high base flow in a reach of river is often required to operate the hydraulic routing component due to computational difficulties when flow depths are shallow (Cunge and others, 1980, p. 176). These high base flows are small in relation to the observed peaks and do not affect the flood-wave hydraulics. Elevations of the crests of the dams used in the model were 10,996.42 ft (actual water level at time of failure) for Lawn Lake dam and 8,471.55 ft for Cascade Lake dam. The duration of breach development, based on available data and judgment, was 10 min for Lawn Lake dam and 1 min for Cascade Lake dam. Although Lawn Lake dam may have allowed a small rate of water to escape for several hours prior to 0530 MDT, it was felt that the erosion of the embankment to full breach width took about 10 min. Cascade Lake dam toppled instantaneously due to overtopping, but it was estimated it took about 1 min for the water to move the remains of the dam and allow the water to escape freely. The duration of model simulation was 5 hours, which covered the passage of most of the flood wave.

Over one-half the length of the Roaring River channel was extensively scoured, and the flood wave contained large amounts of debris and boulders. Rapid channel changes occurred during the flood passage, and the cross sections probably do not reflect these conditions. Similarly, high-water marks probably were set before the majority of scour; therefore, flood depths computed from these data were not accurate. The postflood surveyed cross sections shown in Supplemental Cross-Section Data were used in the hydraulic routing. Debris and boulders had an unknown effect on the flow characteristics (particularly in the Roaring River), but certainly did not meet the model assumption of clear waterflow. These problems were recognized, but accurate solutions, if possible, are very complex. Therefore, the objective of modeling flow in the Roaring River was to develop a breach hydrograph and route it downstream to give reasonable results based on the observed traveltime and documented peak discharges farther downstream. Small bridges and culverts in the flood path were assumed to have negligible effects on flow conditions.

MODEL CALIBRATION

Model calibration was made to obtain the best fit, based on observed peak discharges (table 2), flow depths (table 4), and traveltime (table 6). Parameters available for calibration in the model were Manning's roughness coefficient (*n*-values), expansion and contraction coefficients, and designation of cross-section active and inactive flow areas. As described in the section "Peak Stage and Discharge," the selection of *n*-values was extremely difficult. Field selected *n*-values (see Supplemental Cross-Section Data section at the end of the report) ranged from an estimated 0.15 on the Roaring River to 0.035 along the lower reach of the Fall River and the Big Thompson River. Composite *n*-values used in the model are listed by reach in table 8. Initially, expansion coefficients were -0.5, and the contraction coefficients were 0.5. Cross sections were assumed to contain only active-flow area based on flood and postflood field observations.

The first model runs would not compute, as the flow regime alternated between subcritical and supercritical flow, depending on the flow rate. Therefore, runs were made by increasing or decreasing *n*-values to maintain subcritical flow or supercritical flow in various segments, based on slopes (as previously discussed). When flow was assumed to be supercritical, that is lower *n*-values, the model peak discharges were too large; water depths were too shallow; and traveltimes were too fast. Therefore, *n*-values were increased to 0.2 along the Roaring River and to 0.1 on the lower reaches of the Fall River and the Big Thompson River to maintain subcritical flow in all segments, which provided the best results. This substantiates that subcritical flow predominated in the river reaches studied. These modified or calibrated model *n*-values averaged 78 percent larger than field-selected *n*-values; they are listed by segment in table 8. These *n*-values were reasonable since Leutheusser and Chisholm (1973) measured an *n*-value of 0.225 in a heavily vegetated channel; flow also was subcritical. The use of the inactive flow area did not improve model results. Results of the model calibration of observed and computed peak discharges, flow depths, traveltimes of the leading edge of the flood wave, and percent differences for selected locations are shown in table 9. Peak discharges also are shown as a peak-discharge profile in figure 11. The peak-discharge profile was based on indirect peak-discharge measurements and model results. Selected modeled flood hydrographs and the observed hydrograph at Lake Estes are shown in figure 46. Flood profiles are not shown because of the extremely high-gradient slopes and shallow depths of flow.

Results of the calibration phase indicated that the model has the potential to simulate dam-break floods in high-gradient stream channels. The range in difference of observed and modeled peak discharges varied from -3,200 ft^3/s to 600 ft^3/s. At worst, the model underpredicted peak discharge by 27 percent 3.6 mi downstream from Cascade Lake dam (Site 3). Results were quite reasonable, considering the dynamics of the breach development. The range of difference of observed and modeled maximum flood depth was -1.3 to 2.6 ft; the range averaged 1.0 ft. The range of difference of observed and modeled leading edge of traveltime was -0.4 to 0.05 hour. Considering the complex problems previously discussed, the model reasonably simulated this dam-break flood and demonstrated that the model could be used to provide supplementary hydrologic information that could not be obtained otherwise. However, it must be emphasized that model results would have been significantly different without the extensive calibration and the assumptions made to allow the model to operate.

TABLE 8.—*Field selected- and calibrated model-composite Manning's* n-*values*

Model segment[a]	Distance downstream from Lawn Lake dam, in miles	*n*-values	
		Field selected	Calibrated model
1	0.00- 4.74	0.125	0.20
2	4.74- 6.50	.075	.11
3	6.67- 7.78	.055	.10
4	7.78-11.46	.055	.10
5	11.46-12.52	.035	.10

[a]See figure 45 for segment location.

MODEL SIMULATIONS

Selected hypothetical scenarios of dam-breach development and the probable impact of the failure of Cascade Lake dam were made. Analyses of the scenarios were made to indicate the range in possible flood conditions resulting from the failure of Lawn Lake dam. Factors that could result in the greatest range of peak discharge from the failure of a dam appeared to be the time and width of breach development. Shorter time and greater widths of breach development resulted in larger peak discharges for a given volume of stored water. This particularly applied to Lawn Lake dam where the embankment was narrow and long. Conversely, the embankment of Cascade Lake dam was narrow and short and probably would have failed in the same manner, regardless of the magnitude of the inflow-flood hydrograph from the failure of Lawn Lake dam. However, it is important to understand what the flood hydrology would have been if Cascade Lake dam had not been present, or if Cascade Lake dam had not failed. These two general scenarios are discussed separately to provide information on the range of flood conditions that could have occurred.

VARIATIONS OF LAWN LAKE DAM BREACH WIDTH AND TIMING

Accuracy of the modeled peak discharges was lowest immediately downstream from Lawn Lake and Cascade Lake dams, primarily because of the uncertain aspects of length of time of full breach development, as well as

TABLE 9.—*Summary of dam-break model simulation*

[First line is observed; second line is model value]

Distance downstream from Lawn Lake dam, in miles	Peak discharge, in cubic feet per second	Difference from observed peak discharge, in cubic feet per second	Percent difference from observed peak discharge	Average flood elevation, in feet	Minimum ground elevation, in feet	Maximum flood depth, in feet	Difference from observed maximum flood depth, in feet	Percent difference from observed maximum flood depth	Leading flood-wave time, in hours	Difference from observed leading flood-wave time, in hours	Percent difference from observed leading flood-wave time, in hours
0.0	--	--	--	--	--	--	--	--	[a]0	--	--
	18,000								[a]0		
.55	--	--	--	(b)	(b)	(b)	(b)	(b)	--	--	--
	16,600			(b)		(b)					
1.50	--	--	--	(b)	(b)	(b)	(b)	(b)	--	--	--
	15,200			(b)		(b)					
3.83	--	--	--	(b)	(b)	(b)	(b)	(b)	--	--	--
	12,600			(b)		(b)					
[c]4.73	--	--	--	--	--	--	--	--	0.75	0.05	-6.7
	11,800			8,556.1					.80		
5.36	--	--	--	8,513.0	8,504.9	8.1	2.6	32.1	--	--	--
	10,600			8,515.6		10.7					
5.78	--	--	--	8,509.9	8,501.0	8.9	1.3	14.6	--	--	--
	7,500			8,511.2		10.2					
[d]6.50	7,210	510	-6.9	8,492.6	8,482.6	10.0	.6	6.0	--	--	--
	6,700			8,493.2		10.6					
[e]6.67	--	--	--	--	--	--	--	--	1.75	-0.15	-8.6
	16,000								1.60		
[f]7.68	13,100	-3,200	-24.4	8,056.2	8,045.0	11.2	-1.3	-11.6	--	--	--
	9,900			8,054.9			9.9				
7.74	--	--	--	8,041.9	8,032.0	9.9	1.1	11.1	--	--	--
	9,700			8,043.0		11.0					
8.78	--	--	--	7,862.1	7,852.0	10.1	.7	6.9	--	--	--
	6,700			7,862.8		10.8					
[g]10.28	8,500	-2,300	-27.0	7,696.9	7,689.0	7.9	1.7	21.5	--	--	--
	6,200			7,698.6		9.6					
[h]11.45	6,550	-450	-6.9	7,579.1	7,573.0	6.1	1.2	19.3	--	--	--
	6,100			7,580.3		7.3					
[i]12.50	5,500	600	10.9	7,502.9	7,492.5	10.4	.7	6.7	3.25	-.42	-12.9
	6,100			7,503.6		11.1			2.83		

Average difference from observed maximum flood depth, in feet=1.0.

[a]Clock time is 0530 Mountain Daylight Time.
[b]Severe channel erosion; computations and comparisons are not applicable.
[c]Synthetic cross section based on cross section at river mile 5.36.
[d]Site 1.
[e]Cascade Lake dam and Site 2.
[f]Site 3.
[g]Site 4.
[h]Site 5.
[i]Site 6; possible backwater from flume.

dimensions of the breach at the time of the peak. For the actual breach dimensions, the model was able to evaluate the variation of time of full breach development on the magnitude of outflow discharges from the dams. Outflow discharge for various times to full breach development for both dams is shown in figure 47. This analysis indicates less change of discharge with time occurred for the failure of Lawn Lake dam, and available information indicated a full breach-development time of 10 min, with a probable range of 5 to 20 min. Hence, discharge from Lawn Lake dam probably ranged from 20,000 ft^3/s to 16,000 ft^3/s in that time frame. However, for Cascade Lake dam, the rate of change in peak discharge was much greater in the probable time of full breach development of 30 s to 5 min (1 min was assumed). The range of peak discharge from Cascade Lake dam could have been 23,000 ft^3/s to 9,000 ft^3/s in that time frame. As the modeling demonstrated, because of the smaller capacity of Cascade Lake, greater attenuation occurred downstream.

After the hydraulic-routing part of the model had been calibrated, different simulation runs of conditions

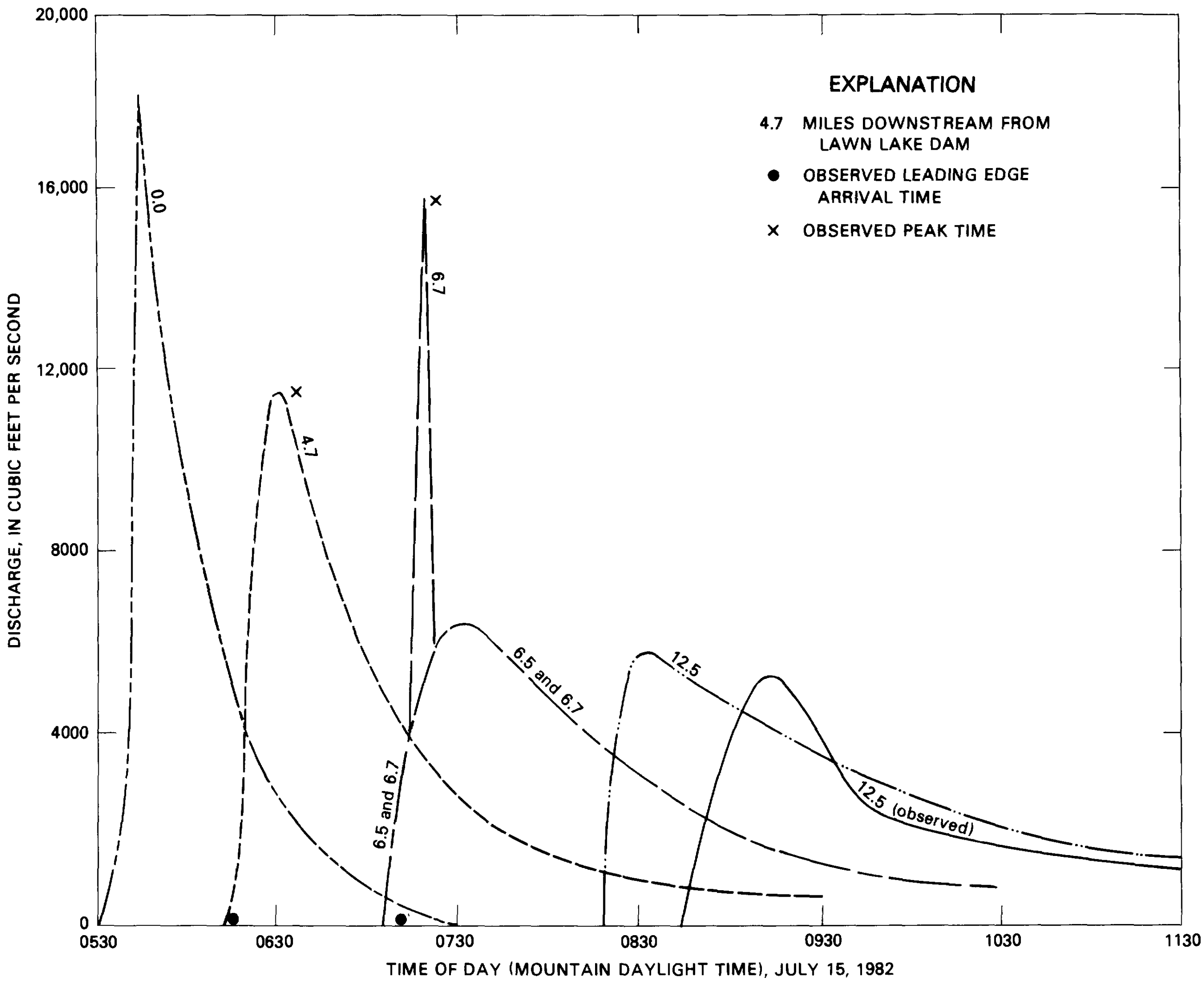

FIGURE 46.—Selected modeled and observed hydrographs.

of breach width were made for Lawn Lake dam. Hypothetical breach (bottom) widths of 25 ft and 200 ft were compared with model results of the actual breach width of 55 ft. For consistency, these scenarios were compared to the calibrated model results. This range in breach widths was suggested by McMahon (1981). Outflow discharges for hypothetical breach widths for a time of failure of 10 min for Lawn Lake dam are shown in figure 48. This figure demonstrates how much greater discharge could have been. Results of these model simulations are summarized in table 10 for a breach width of 25 ft, and in table 11 for a breach width of 200 ft.

Data in table 10 indicate that, for a breach width of 25 ft, peak discharges would have been 7,000 ft^3/s less downstream from Lawn Lake dam, to 1,300 ft^3/s less at the downstream end of the study reach at mile 12.5. Maximum flood depths averaged 0.6 ft lower. Flood wave traveltime was the same. Model results also indicated that, even with this hypothetical breach width of 25 ft, the resulting flood would have overtopped Cascade Lake dam by 4.2 ft and would have resulted in the failure of the dam.

For a breach width of 200 ft, peak discharges would have been 22,600 ft^3/s greater downstream from Lawn Lake dam, to 5,400 ft^3/s greater at the downstream end of the study at mile 12.5 (table 11). Maximum flood depths averaged 2.7 ft higher. The flood wave would have reached Estes Park 0.4 hour earlier. Model results (tables 10 and 11) indicate that hydraulic differences as a result of breach-width size decrease in the downstream direction, and with sufficient distance, would converge to similar flood hydrographs.

The model also was used to evaluate a worst-case scenario for the failure of Lawn Lake dam that would reflect a very abrupt and almost complete breach of the

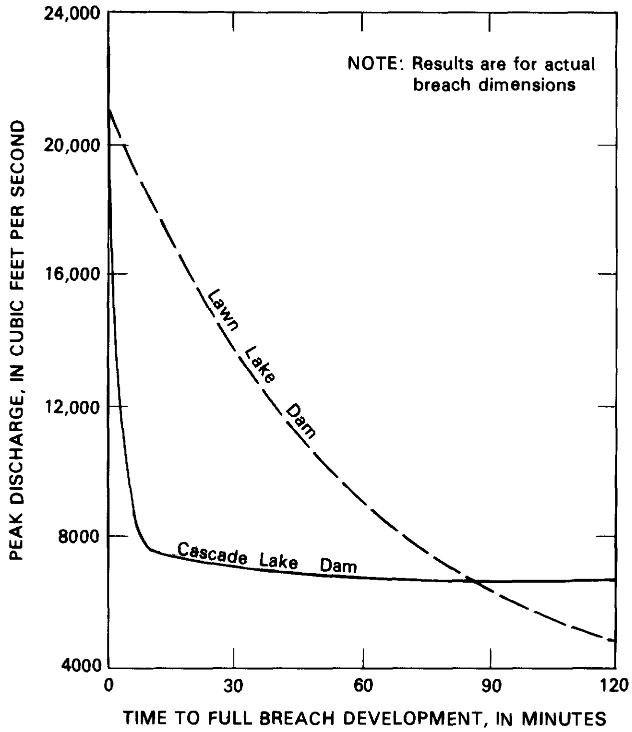

FIGURE 47.—Outflow discharge for various times of breach development for Lawn Lake dam and Cascade Lake dam.

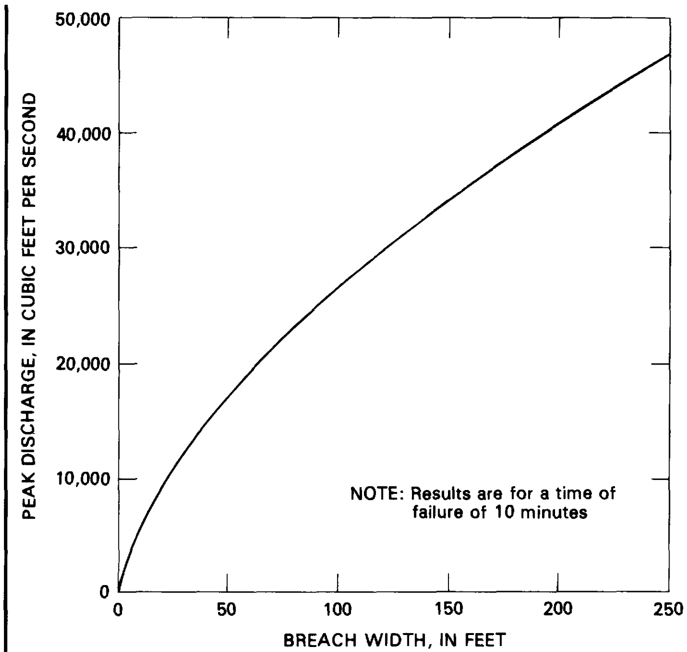

FIGURE 48.—Outflow discharge for hypothetical breach width for Lawn Lake dam, assuming 10-minute time of failure.

TABLE 10.—*Comparison of model results of a hypothetical breach width of 25 feet to the actual breach width of 55 feet*

Distance down-stream from Lawn Lake dam, in miles	Peak discharge, in cubic feet per second	Difference in peak discharge from model with failure, in cubic feet per second	Flood elevation, in feet	Maximum flood depth, in feet	Difference from maximum flood depth of 55-foot width, in feet
0.0	11,000	-7,000	----	----	----
.55	10,000	-6,600	(a)	(a)	(a)
1.50	9,400	-5,800	(a)	(a)	(a)
3.83	8,500	-4,100	(a)	(a)	(a)
[b] 4.73	8,400	-3,400	(a)	(a)	(a)
5.36	7,500	-3,400	8,514.7	9.8	-.9
5.78	5,600	-1,900	8,510.3	9.3	-.9
[c] 6.50	5,200	-1,500	8,492.3	9.7	-.9
[d] 6.67	15,500	-500	----	----	----
[e] 7.68	9,500	-400	8,054.8	9.8	-.1
7.74	9,300	-400	8,042.8	10.8	-.2
8.78	6,700	0	7,862.7	10.7	-.1
[f] 10.28	6,200	-1,400	7,697.9	8.9	-.7
[g] 11.45	4,800	-1,300	7,579.8	6.8	-.5
[h] 12.50	4,800	-1,300	7,502.3	9.8	-1.3

Average difference from maximum flood depth of 55-foot width, in feet=-.6

[a]Severe channel erosion; computations and comparisons are not applicable.
[b]Synthetic cross section based on cross section at river mile 5.36.
[c]Site 1.
[d]Cascade Lake dam and Site 2.
[e]Site 3.
[f]Site 4.
[g]Site 5.
[h]Site 6.

TABLE 11.—*Comparison of model results of a hypothetical breach width of 200 feet to the actual breach width of 55 feet*

Distance downstream from Lawn Lake dam, in miles	Peak discharge, in cubic feet per second	Difference from peak discharge of 200-foot width, in cubic feet per second	Flood elevation, in feet	Maximum flood depth, in feet	Difference from maximum flood depth of 200-foot width, in feet
0.0	40,600	22,600			
.55	38,300	21,700	(a)	(a)	(a)
1.50	35,600	20,400	(a)	(a)	(a)
3.83	30,400	17,800	(a)	(a)	(a)
[b] 4.73	29,100	17,300	(a)	(a)	(a)
5.36	24,100	13,500	8,518.5	13.6	2.9
5.78	17,000	9,500	8,513.4	12.4	2.2
[c] 6.50	13,700	7,000	8,496.0	12.4	1.8
[d] 6.67	25,600	9,600	----	----	----
[e] 7.68	18,400	8,500	8,057.7	12.7	2.8
7.74	18,200	8,500	8,045.4	13.4	2.4
8.78	14,700	8,000	7,866.1	14.1	3.3
[f] 10.28	12,700	6,500	7,701.5	12.5	2.9
[g] 11.45	12,100	6,000	7,582.9	9.9	2.6
[h] 12.50	11,500	5,400	7,507.4	14.9	3.8

Average difference from maximum flood depth of 200-foot width, in feet=2.7

[a] Severe channel erosion; computations and comparisons are not applicable.
[b] Synthetic cross section based on cross section at river mile 5.36.
[c] Cascade Lake dam.
[d] Cascade Lake dam and Site 2.
[e] Site 3.
[f] Site 4.
[g] Site 5.
[h] Site 6.

dam embankment in a short span of time. Outflow peak discharges could have been as high as 56,000 ft^3/s for a time of full breach development of 10 min (or a greater peak discharge for a shorter breach time), and a breach width of 550 ft, for these extreme conditions.

EFFECTS OF CASCADE LAKE DAM FAILURE

The dam-break model also was used to assess the flood wave downstream from Cascade Lake dam if the dam had not failed or was not present. This scenario was important for assessing the magnitude of damages. Observed and modeled data indicate that the failure of Cascade Lake dam probably doubled the peak discharge immediately downstream from the dam and increased the flood stage by an average of 0.6 ft (table 12).

The model also was run with the calibrated river hydraulics, except Cascade Lake dam was not allowed to fail. Hence, the inflow flood hydrograph to Cascade Lake dam was simply routed over the top of the dam. Similarly, since the dam was small, these results reflected the hypothetical condition of Cascade Lake dam not being in the river system. A comparison of model results with and without the failure of Cascade Lake dam is shown in table 12. Peak discharges would have been 11,300 ft^3/s less immediately downstream from the dam, to 500 ft^3/s less at mile 12.5, without the failure of Cascade Lake dam. Maximum flood depths would have averaged 0.6 ft lower. The flood wave without failure would have reached mile 12.5, 0.3 hour later.

DISCUSSION OF RESULTS

Computer modeling provided a means to enhance and supplement the observed data, to evaluate the use of the model on high-gradient streams, to evaluate the relative accuracy of the results, and to evaluate various alternative dam-breach scenarios. The model, properly calibrated, worked well in high-gradient streams compared to the observed data . It is important to note that there also were errors associated with the indirect peak-discharge measurements and flood-wave traveltimes (particularly in the Roaring River). Problems of operating the model in such complex high-gradient channels were overcome by minor changes to the preflood base flows, and with major increases of n-values.

The state of flow was very important in hydraulic routing. Subcritical flows from the extremely large flow

TABLE 12.—*Comparison of model results with and without the failure of Cascade Lake dam*

Distance downstream from Lawn Lake dam, in miles	Peak discharge, without failure, in cubic feet per second	Difference in peak discharge from model with failure, in cubic feet per second	Flood elevation without Cascade Lake dam failure, in feet	Maximum flood depth, in feet	Difference in maximum depth from model with failure, in feet
[a] 6.67	6,700	11,300	----	----	----
[b] 7.68	6,300	3,600	8,054.1	9.4	-0.8
7.74	6,200	3,500	8,042.3	10.3	-.7
8.78	5,800	900	7,863.0	11.0	-.8
[c]10.28	5,700	500	7,699.1	10.1	-.5
[d]11.45	5,600	500	7,580.7	7.7	-.4
[e]12.50	5,600	500	7,504.3	11.8	-.7
Average difference in maximum flood depth from model with failure, in feet=0.6					

[a]Cascade Lake dam.
[b]Site 3.
[c]Site 4.
[d]Site 5.
[e]Site 6.

resistance appeared reasonable and provided the best comparison with the observed data.

As table 8 indicates, field-selected n-values had to be increased by an average of 78 percent for high-flow resistance and energy losses. Calibration with n-values meant a tradeoff in minimizing the differences of peak discharge, traveltime, and water-surface elevations. As n-values were reduced, peak discharges were increased, but traveltime was faster and water-surface elevations were lower. Conversely, as n-values were increased, peak discharges were decreased, but traveltime was slower and water-surface elevations were increased.

Flow conditions were unknown in the Roaring River, and the effects of debris and channel changes were unknown; the model assumed clear water. However, in the Roaring River and on the Fall River immediately downstream from Cascade Lake dam, total water and debris discharge probably was much greater than the model indicated. Geomorphic and sedimentologic evidence at Horseshoe Falls and downstream from Cascade Lake dam indicates that at these two locations the water flood bulked up with enough sediment and debris to temporarily create a noncohesive, coarse-grained, turbulent, sediment gravity flow. For these boulder berms to have formed, sediment loads must have been at least 50 to 60 percent of the flood flow, by volume (Costa, 1984). Model results indicated moderate flood-wave attenuations in the Roaring River; however, probably little attenuation occurred in this steep reach. The model appeared to have difficulty reproducing results immediately downstream from Cascade Lake dam, a very small-capacity dam. Although the model reasonably reproduced the Cascade Lake dam peak outflow, the hydraulic routing component attenuated peak flows too much (table 9). All modeling results indicated that the effects of different breach scenarios decreased with distance downstream.

THE FLOOD AFTERMATH

Since 1890, 130 known dam failures have occurred in Colorado (Colorado Water Conservation Board, 1983). Floods from these failures have resulted in small loss of life, but large property losses. Because of the relatively small volume of water released from Lawn Lake and Cascade Lake dams, and because Lake Estes impounded the flood, flooding lasted only a few hours. However, impacts were severe. Surprisingly few fatalities occurred as a result of the flood, because of several positive factors related to the flood warning. The number of people at risk upstream from Cascade Lake dam at the time of failure was limited to about 25 to 30 camped along the Roaring River, and probably fewer than 20 people in Horseshoe Park. Therefore, in the first 6.75 mi downstream from Lawn Lake, probably fewer than 50 people were at risk. Because it is National Park property, few structures existed in the flood plain. However, the National Park Service indicated about 275 people were camped in Aspenglen Campground downstream from Cascade Lake dam. The Estes Park Chief of Police estimated that 4,000 to 5,000 residents and tourists were in the flood plain; they could have been potential flood victims in the reach from Cascade Lake dam to Lake Estes (fig. 1).

This section of the report summarizes the human element and the damages resulting from the flood.

FIGURE 49.—Flood warning sign at the downstream entrance to the Big Thompson River Canyon near Loveland, Colo.

It also summarizes studies by Graham and Brown (1983) and Jack Truby (Colorado Division of Disaster Emergency Services, written commun., 1983).

THE HUMAN ELEMENT

There were three fatalities; all three victims, whose ages ranged from 21 to 36 years, lived outside Colorado. One victim, while sleeping at a Roaring River campsite, did not survive the "wall of water" and debris. Two other campers at Aspenglen Campground died from the flooding, although they had been warned of an approaching flood (but not a dam failure) by fellow campers. Apparently, these two campers misjudged the magnitude of the flooding when they walked back into the flood area to retrieve camping gear.

Several factors kept the number of fatalities low. The time of day, as well as the clear and dry weather, was nearly optimal for minimal loss of life. Had the dam failed during the night, the public would not have been able to respond as quickly to the warnings. Although the flood had traveled 4.5 mi before being detected by Stephen Gillette at Horseshoe Falls, a rapid dissemination of warning was made within minutes by National Park Service, Larimer County Sheriff, Estes Park police, and KSIR radio. The warning also spread rapidly because of the clustering of motels, businesses, and homes that had access to major roads. The majority of the public responded quickly to the flood warning. This was possibly because of their previous experience with the 1976 flash flood in the nearby Big Thompson River canyon (McCain and others, 1979) which killed at least 139 people and resulted in $35 million in damages, and because of warning signs placed along the river canyons in Colorado (fig. 49). Also, the flood wave traveled relatively slowly (an average of 3.9 mi/h), aided by the retarding effect of Horseshoe Park, enabling most people who did not receive a warning but heard the loud noise, or saw the leading edge of the flood, to walk or run to higher ground.

THE DAMAGE

The Colorado Division of Disaster Emergency Services estimated total damages to be approximately $30.7 million. A summary of damage estimates is given in table 13, including public and private losses to structures, cleanup of debris, and economic losses. Business, physical damage, and economic injury losses of almost

TABLE 13.—*Damage estimates for the July 15, 1982, flood*
[From Colorado Division of Disaster Emergency Services Data]

Breakdown	Dollar estimate
Rocky Mountain National Park	$ 4,978,000
Home and personal property	1,569,500
Business physical damage and economic injury	17,180,000
Private and public utilities	365,000
City and County public utilities	3,335,900
Federal and State facilities	659,900
Agriculture	2,550,000
Total	$30,638,300

$17.2 million accounted for the majority of the total damages. The flooding destroyed 18 bridges, damaged road systems (particularly Fall River Road), inundated 177 businesses (75 percent of Estes Park's commercial activity), and damaged 108 private residences. Most businesses reported 3 to 4 ft of water, and as much as 1 to 2 ft of mud in their establishments. The flood occurred during the 3 summer months when businesses depend on tourism to generate a major part of their income. Fortunately, the majority of businesses were able to reopen within a few days of the flood as a result of community involvement in cleanup. Other major damaged structures included Lawn Lake dam, Cascade Lake dam, campsite and trail facilities along the Roaring River, a U.S. Highway 34 bridge, Aspenglen Campground, Estes Park powerplant, State Fish Hatchery, utility lines, and two streamflow-gaging stations (sites 5 and 6 in fig. 1).

Selected photographs of damages and debris are shown in figures 50, 51, 52, and 53. The Ponderosa Lodge at river mile 9.9 on the Fall River, which was reconstructed above the 500-yr flood level, was totally destroyed (fig. 51*A*); however, the lodge was rebuilt in the same location as shown in figure 51*B*. Farther downstream, damages were prevented when the floodwaters were contained in Lake Estes (fig. 54).

SUMMARY AND CONCLUSIONS

Early on the morning of July 15, 1982, Lawn Lake dam, a 26-ft-high earthen dam, located at 11,000 ft in Rocky Mountain National Park, Colorado, failed. Full-breach development was estimated to have taken 10 min. The dam released 674 acre-ft of water, and an estimated peak discharge of 18,000 ft^3/s down the Roaring River valley. In the Roaring River, the flood wave was described as a wall of water 25 to 30 ft high. Three people were killed, and damages totaled $31

FIGURE 50.—About 0900 MDT on July 15, 1982, looking upstream at washed-out U.S. Highway 34 bridge in Rocky Mountain National Park at river mile 5.3. Photo courtesy of Zenas Blevins, U.S. Bureau of Reclamation.

FIGURE 51.—*A,* The Ponderosa Lodge, which was destroyed by the flood, at river mile 9.9 on the Fall River. Note the structure was rotated almost 90° off its foundation. *B,* The Ponderosa Lodge, as rebuilt after the flood, from the same perspective as *A*. The structure is above the 100-year flood elevation.

FIGURE 52.—Debris jam on the upstream side of Elkhorn Avenue at river mile 11.8 along the Fall River in Estes Park.

FIGURE 53.—High-water lines on buildings along the Fall River at Estes Park.

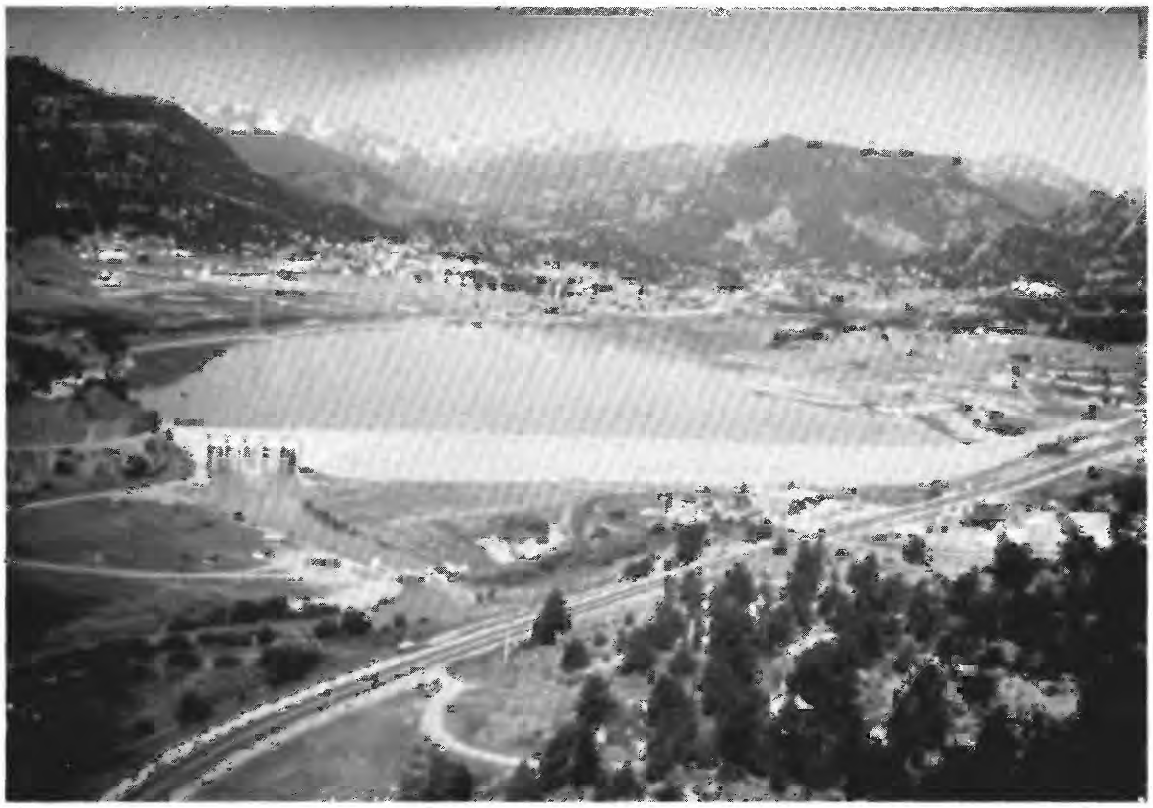

FIGURE 54.—View upstream from Olympus dam and Lake Estes, containing the floodwaters (aerial).

million. The Colorado State Engineer determined that the cause of failure was deterioration of lead caulking used for the connection between the outlet pipe and the gate valve. The resulting leak eroded the earthfill, and progressive piping led to failure of the embankment.

Floodwaters from Lawn Lake dam overtopped a second dam, Cascade Lake dam, located 6.7 mi downstream, which also failed. Cascade Lake dam was a 17-ft-high, 12.1 acre-ft capacity concrete gravity dam, which failed with 4.2 ft of water flowing over the top, corresponding to a discharge of 4,500 ft^3/s. Full-breach development was estimated to have taken 1 min. The resulting surge of water (16,000 ft^3/s) swept into Aspenglen Campground, only 1/3 mi downstream, and claimed the lives of two of the three victims. The flood, no longer a wall of water, continued down the Fall River into the town of Estes Park, which received extensive damage from the overbank flow. The flood resulting from the failures of the two relatively small dams was much larger than expected, and was catastrophic in its geomorphic effects.

Flood data were obtained at two gaging stations and five miscellaneous sites downstream from the Lawn Lake dam. Peak discharges were determined from the slope-area method, from flow over weirs and through a flume, and from the critical-depth method. Because of extensive scour and erosion along the Roaring River, peak discharges were estimated from a dam-break model. Calculated peak discharges for the flood were 18,000 ft^3/s from Lawn Lake dam (dam-break model), 12,000 ft^3/s at Horseshoe Falls where Roaring River joined the Fall River (dam-break model), 7,210 ft^3/s into Cascade Lake dam at the east end of Horseshoe Park (slope-area measurement), 16,000 ft^3/s from the failure of Cascade Lake dam (dam-break model), 13,100 ft^3/s about 1 mi downstream from Cascade Lake dam (critical-depth measurement), 8,520 ft^3/s just upstream from Estes Park (slope-area measurement), 6,550 ft^3/s for gaging station 06732500 Fall River at Estes Park (estimated), and 5,500 ft^3/s for gaging station 06733000 Big Thompson River at Estes Park (weir and flume measurement). Maximum depths ranged from 6.4 to 23.8 ft; maximum widths ranged from 97 to 1,112 ft; and mean velocities ranged from 3.3 to 12.6 ft/s.

The flood peak at the mouth of the Roaring River (12,000 ft^3/s) was 30 times the estimated 500-yr flood for that site. In Estes Park, flood depths were 2.5 ft above the level of the estimated 500-yr flood. At the gaging station on the Big Thompson River at Estes

Park, the flood peak was 2.1 times the 500-yr flood. Geomorphic and sedimentologic evidence suggest this was probably the largest flood in these basins since at least the retreat of the glaciers about 10,000 years ago.

Traveltimes of the flood wave were determined from eyewitness accounts. The leading flood wave took 3.28 hours to travel 12.5 mi (average 3.8 mi/h). This slow traveltime was attributed to the extreme valley roughness and damming of the flow by large amounts of debris in the Roaring River, and to the long, flat, glacial lake valley of Horseshoe Park, which attenuated the flood.

Because of the steep channel, debris-laden flows, and unusual and poorly understood characteristics of unsteady flash floods, the theory and application of conventional energy and flow-resistance concepts probably are not applicable for these conditions. When hydraulic analyses are made on these floods, the effects of unsteady flow, Manning's n-values, high sediment concentrations, and scour and fill that affect the cross-sectional flow area need to be analyzed. To varying degrees these factors may influence hydraulic computations, particularly indirectly determined peak discharges.

Geomorphic effects of the dam-failure flood were catastrophic. Channels were widened tens of feet and scoured from 5 to 50 ft locally. In the Roaring River valley, alternate river reaches were either scoured or filled, depending on valley slope. Generally, reaches steeper than 7 percent were scoured, and reaches less than 7 percent were filled. In the Roaring River, 56 percent of the channel was scoured as much as 50 ft, and 44 percent was filled with coarse sediments 2 to 8 ft thick.

Antidune backset beds were preserved in a sand splay 700 ft downstream from the dam; horizontal stratified coarse sand at the flow margins all along the Fall River indicated upper-flow regime conditions. An alluvial fan of 42.3 acres, containing 364,600 yd^3 of material, was deposited at the mouth of the Roaring River. The fan had a maximum thickness of 44 ft and an average thickness of 5.3 ft. The largest boulder known to have moved in the flood, $14 \times 17.5 \times 21$ ft and weighing an estimated 452 tons, was located on the alluvial fan. Areas of sediment deposition shifted from the east to the west side of the fan during the flood. Down the flow axis, average particle size changed from 7.5-ft boulders to fine sand and silt in a distance of 1,900 ft. The alluvial fan dammed the Fall River, forming a lake of 17 acres upstream from the fan.

On the west side of the Roaring River alluvial fan, below Cascade Lake dam and upstream from the Aspenglen Campground, boulder berms similar to those described from other catastrophic floods in steep mountain channels were well-developed. They are believed to have originated from non-cohesive, turbulent, coarse sediment-gravity flows. Upstream from Aspenglen Campground, floodwaters formed large-scale concentrations of boulders across a part of the channel, forming a step-pool profile. Downstream on the Fall River, channel scour and sediment deposition were much less significant than downstream from Cascade Lake dam.

The U.S. Bureau of Reclamation spent $80,000 for debris removal in Lake Estes following the flood, but estimated at least 10 times more sediment was deposited in the lake during high spring runoff in 1983. The source of the sediment was primarily from erosion of exposed river banks. The channels of the Roaring River, Fall River, and Big Thompson River are not yet stabilized and will continue to transport large amounts of sediment into Lake Estes for some time in the future.

A dam-break flood model was used to evaluate the model's performance on high-gradient streams, to provide supplemental hydrologic information, particularly peak flows for these dam failures, and to evaluate various scenarios of dam-breach development and the probable impact of the failure of Cascade Lake dam. Satisfactory results were obtained, but not without significant difficulties in getting the model to run properly. To calibrate the model, Manning n-values between 0.1 and 0.2, or an average of 78 percent greater than field-selected values, were required, and subcritical flow was assumed and substantiated. Locally, very short reaches of supercritical flow occurred. Model results would have been significantly different without calibration.

Results of the calibration phase indicated that the model had the potential to simulate dam-break floods in high-gradient stream channels. Peak discharges from dam-break modeling reflected water-only discharges; total discharge may have been considerably higher on the Roaring River from sediment and debris. The range of difference of observed and modeled peak discharges varied from $-3,200$ ft^3/s to 600 ft^3/s. At worst, the model underpredicted peak discharge by 27 percent 3.61 mi downstream from Cascade Lake dam. Considering the dynamics of the breach development and errors in the indirect measurements of peak discharge, the results were quite reasonable. The range of difference of the observed and modeled maximum flood depth was -1.3 to 2.6 ft; it averaged 1.0 ft. The range of difference of the observed and modeled leading edge of traveltime was -0.4 and 0.05 hour.

Comparisons were made for hypothetical breach widths of 25 ft and 200 ft, which were compared with model results of the actual breach width of 55 ft. or a breach width of 25 ft, the peak discharge would have been 7,000 ft^3/s less downstream from Lawn Lake dam to 1,300 ft^3/s less at river mile 12.5. Maximum flood depths averaged 0.6 ft lower, and the flood wave would have reached Estes Park at the same time. For this hypothetical case, Cascade Lake dam still would have failed. For a breach width of 200 ft, peak discharge would have been 22,600 ft^3/s greater downstream from Lawn Lake dam to 5,400 ft^3/s greater at river mile 12.5. Maximum flood depth averaged 2.7 ft higher, and the flood wave would have reached Estes Park 0.4 h earlier. The model indicated that outflow peak discharge from a worst-case failure of Lawn Lake dam could have been at least 56,000 ft^3/s.

If Cascade Lake dam had not failed (or had not been present), peak discharges would have been 11,300 ft^3/s less immediately downstream from the dam, to 500 ft^3/s less just upstream from Lake Estes. Maximum flood depths would have averaged 0.6 ft lower, and the flood wave would have reached Lake Estes 0.3 hour later.

GAGING-STATION AND MISCELLANEOUS-SITE DATA PLATTE RIVER BASIN

Site 1: Fall River above Cascade Lake dam above Estes, Park, Colo. (Miscellaneous site)

Location.—Lat 40°24'05", long 105°36'18", in SW¼ NW¼ sec. 17, T. 5 N., R. 73 W., Rocky Mountain National Park, Larimer County. Site located at downstream end of Horseshoe Park, 6.50 mi downstream from Lawn Lake dam, 900 ft upstream from Cascade Lake dam, and 5.47 mi upstream from State Highway 66 bridge in Estes Park.

Discharge record.—Peak discharge determined by slope-area method.

Maximum.—July 15, 1982: Discharge, 7,210 ft^3/s.

Site 2: Fall River at Cascade dam above Estes Park, Colo. (Miscellaneous site)

Location.—Lat 40°24'03", long 105°36'08", in NE¼ SW¼ sec. 17, T. 5 N., R. 73 W., Rocky Mountain National Park, Larimer County. Site located 6.67 mi downstream from Lawn Lake dam and 5.30 mi upstream from State Highway 66 bridge in Estes Park.

Discharge record.—Discharge, at time of dam failure, determined by critical-depth method.

Value.—July 15, 1982: Discharge, 4,500 ft^3/s.

Site 3: Fall River below Cascade Lake dam above Estes Park, Colo. (Miscellaneous site)

Location.—Lat 40°23'59", long 105°35'05", in NW¼ SW¼ sec. 16, T. 5 N., R. 73 W., Estes Park, Larimer County. Site located at 12-ft concrete drop structure, 7.68 mi downstream from Lawn Lake dam, 1.01 mi downstream from Cascade Lake dam, 500 ft downstream from Estes Park powerplant, and 4.29 mi upstream from State Highway 66 bridge in Estes Park.

Discharge record.—Peak discharge determined by critical-depth method.

Maximum.—July 15, 1982: Discharge, 13,100 ft^3/s.

Site 4: Fall River above Estes Park, Colo. (Miscellaneous site)

Location.—Lat 40°23'01", long 105°32'58", in SW¼ SW¼ sec. 23, T. 5 N., R. 73 W., Larimer County. Site is located 1.17 mi upstream from gage (site 5) and 1.70 mi upstream from State Highway 66 bridge in Estes Park.

Discharge record.—Peak discharge determined by slope-area method.

Maximum.—July 15, 1982: Discharge, 8,520 ft^3/s.

Site 5: 06732500 Fall River at Estes Park, Colo.

Location.—Lat 40°22'40", long 105°31'56", in NW¼ NW¼ sec. 25, T. 5 N., R. 73 W., Larimer County on left bank 100 ft upstream from U.S. Highway 34 bridge and 0.7 mi upstream from mouth.

Drainage area.—39.5 mi^2.

Gage-height record.—1947 to 1953: Water-stage recorder approximately 2,000 ft downstream from present site. Datum of gage was 7,547.06 ft above mean sea level (levels by U.S. Bureau of Reclamation). 1978 to present: Crest-stage gage. Arbitrary datum.

Discharge record.—Stage discharge relationship defined by current meter measurement to 350 ft^3/s. Peak discharge for July 15, 1982, determined by linear interpolation by stream distance of peak discharge at sites 4 and 6.

Maxima.—July 15, 1982: Discharge 6,550 ft^3/s (gage height, 11.10 ft). 1947 to 1953: Discharge, 476 ft^3/s, June 14, 1953 (gage height, 2.69 ft, site and datum then in use). 1978 to 1981: Discharge, 565 ft^3/s 1980 (gage height, 8.56 ft).

Site 6: 06733000 Big Thompson River at Estes Park, Colo.

Location.—Lat 40°22'42", long 105°30'48", in NW¼ NW¼ sec. 30, T. 5 N., R. 72 W., Larimer County, on right bank in Estes Park, 600 ft downstream from bridge on State Highways 7 and 66, 900 ft downstream from Black Canyon Creek, and 0.3 mi northeast of Estes Park powerplant. Station is upstream from Lake Estes.

Drainage area.—137 mi^2.

Gage-height record.—Water-stage recorder graph furnished by Colorado Division of Water Resources.

Datum of gage is 7,492.5 ft above mean sea level (levels by U.S. Bureau of Reclamation). Stage records unusable from 0835 MDT to 1200 MDT, July 15, 1982, because gage intakes were plugged by sediment.

Discharge record.—Stage-discharge relation defined by current-meter measurement below 1,500 ft³/s. Peak discharge for July 15, 1982, determined by flow through Parshall flume and flow over weir.

Maxima.—July 15, 1982: Discharge, 5,500 ft³/s (gage height not determined). 1949 to 1982: Discharge, 1,660 ft³/s June 18, 1949 (gage height 3.16 ft, site and datum then in use).

Site 7: Lake Estes at Estes Park, Colo. (Miscellaneous site)

Location.—Lat 40°22'32", long 105°29'13", in NE¼ sec. 29, T. 5 N., R. 72 W., Larimer County. Gage located at Olympus dam on the Big Thompson River, 2.22 mi downstream from State Highway 66 bridge in Estes Park.

Gage-height record.—Water-surface elevations obtained at selected time intervals by Bureau of Reclamation personnel as well as telemetered reservoir levels at the dam. The lake level began rising at 0847 MDT.

Discharge record.—Discharge based on change in storage and accounting of inflow and outflow. Values given are reconstructed Big Thompson River inflows.

Maximum.—July 15, 1982: 5-minute average peak discharge, 5,364 ft³/s, which occurred from 0910 to 0915 MDT.

DISCHARGE AT INDICATED TIME, 1982

[ft³/s, cubic feet per second]

Time	Discharge (ft³/s)	Time	Discharge (ft³/s)	Time	Discharge (ft³/s)
July 15					
0845	[a]387	1000	2,046	2200	431
0850	1,279	1015	1,699	2300	431
0855	2,876	1030	1,792	2400	427
0900	4,039	1045	1,545		
0905	4,768	1100	1,458	July 16	
0910	5,066	1200	1,106	0100	389
0915	5,364	1300	766	0200	383
0920	3,628	1400	718	0300	387
0925	4,356	1500	671	0400	421
0930	3,632	1600	533	0500	431
0935	3,782	1700	479	0600	429
0940	3,495	1800	439	0700	427
0945	2,625	1900	418	0800	416
0950	3,351	2000	401	0900	412
0955	2,192	2100	418	1000	385
				1100	385
				1200	363
		Total Big Thompson River inflow volume			1,500 acre-ft
		Big Thompson River inflow volume			- 837 acre-ft
		Lawn Lake flood volume			663 acre-ft

[a]Big Thompson River average inflow was approximately 371 ft³/s during time period.

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SUPPLEMENTAL CROSS-SECTION DATA

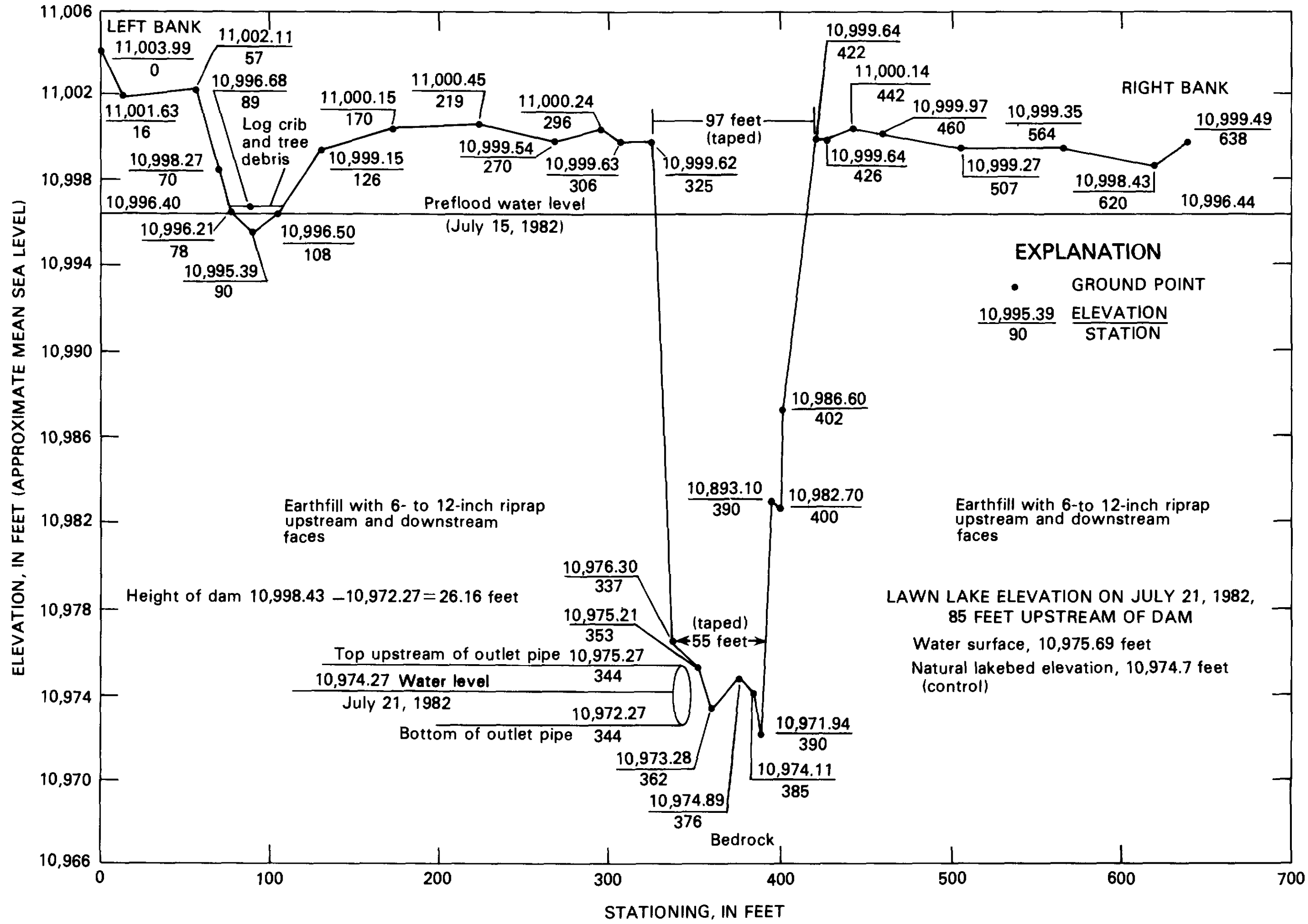

FIGURE 55.—Lawn Lake dam embankment cross section on the Roaring River at river mile 0.0.

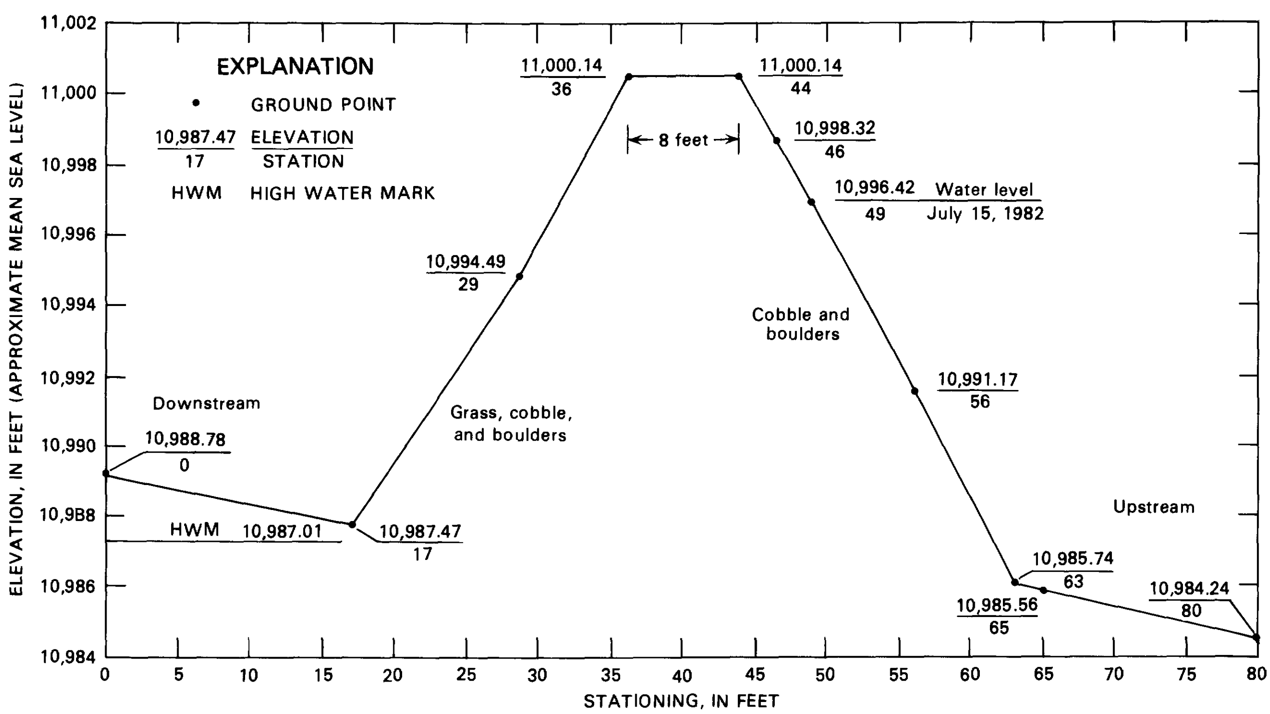

FIGURE 56.—Lawn Lake dam cross section of breach (right side) on the Roaring River at river mile 0.0

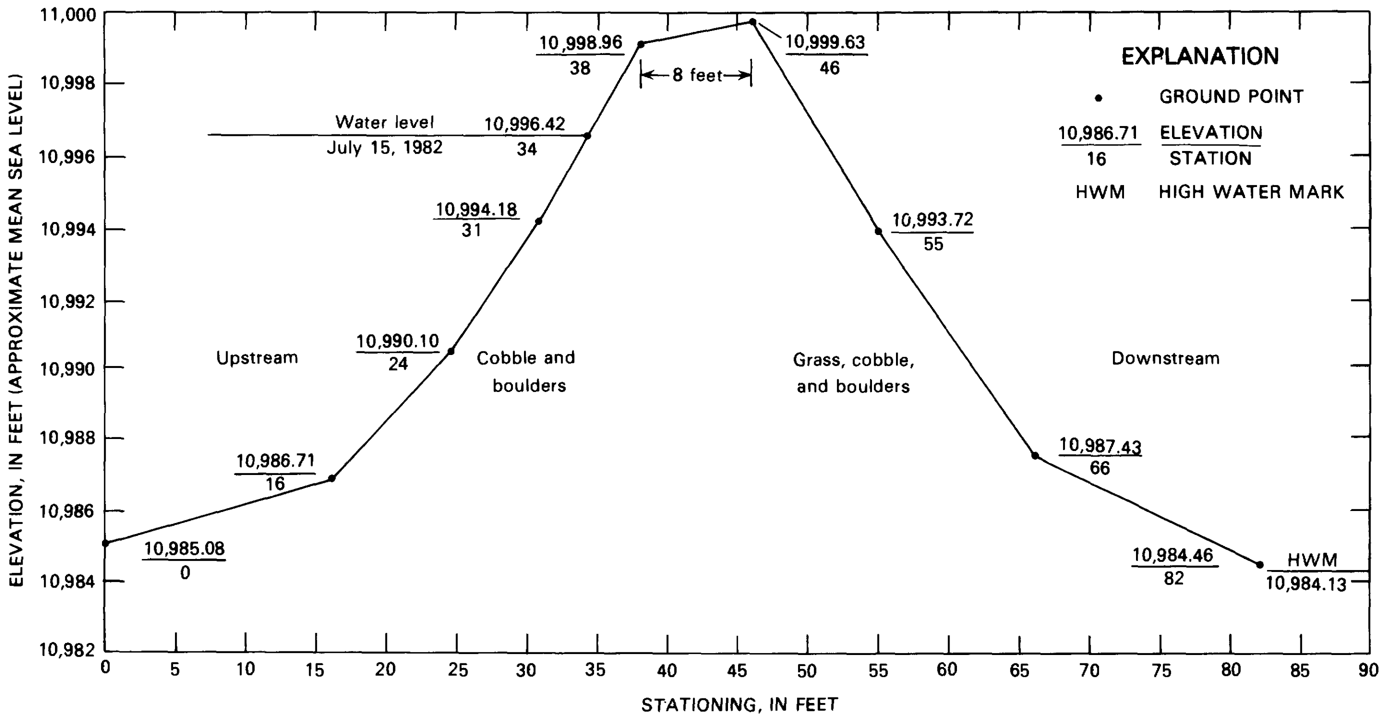

FIGURE 57.—Lawn Lake dam cross section of breach (left side) on the Roaring River at river mile 0.0.

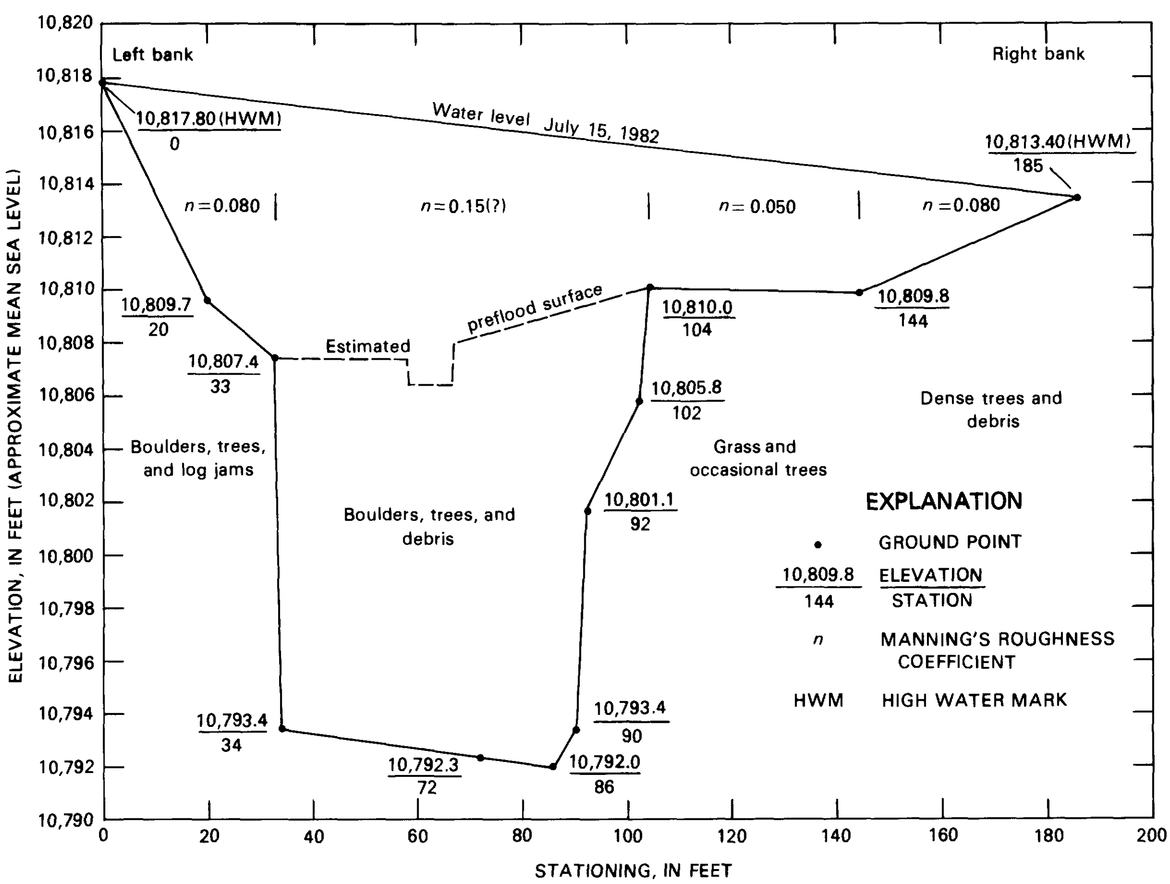

FIGURE 58.—Roaring River cross section at river mile 0.55.

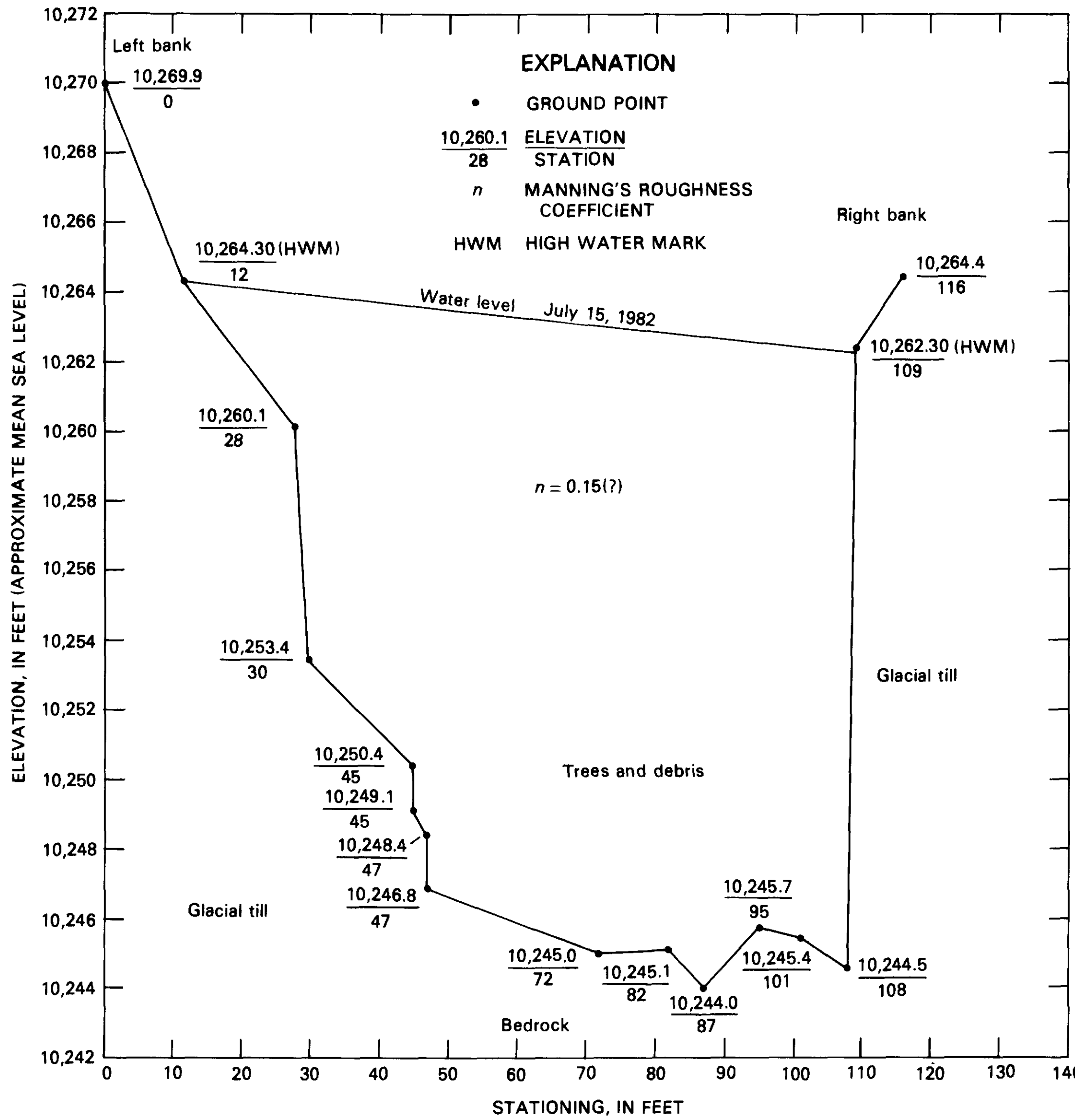

FIGURE 59.—Roaring River cross section at river mile 1.50.

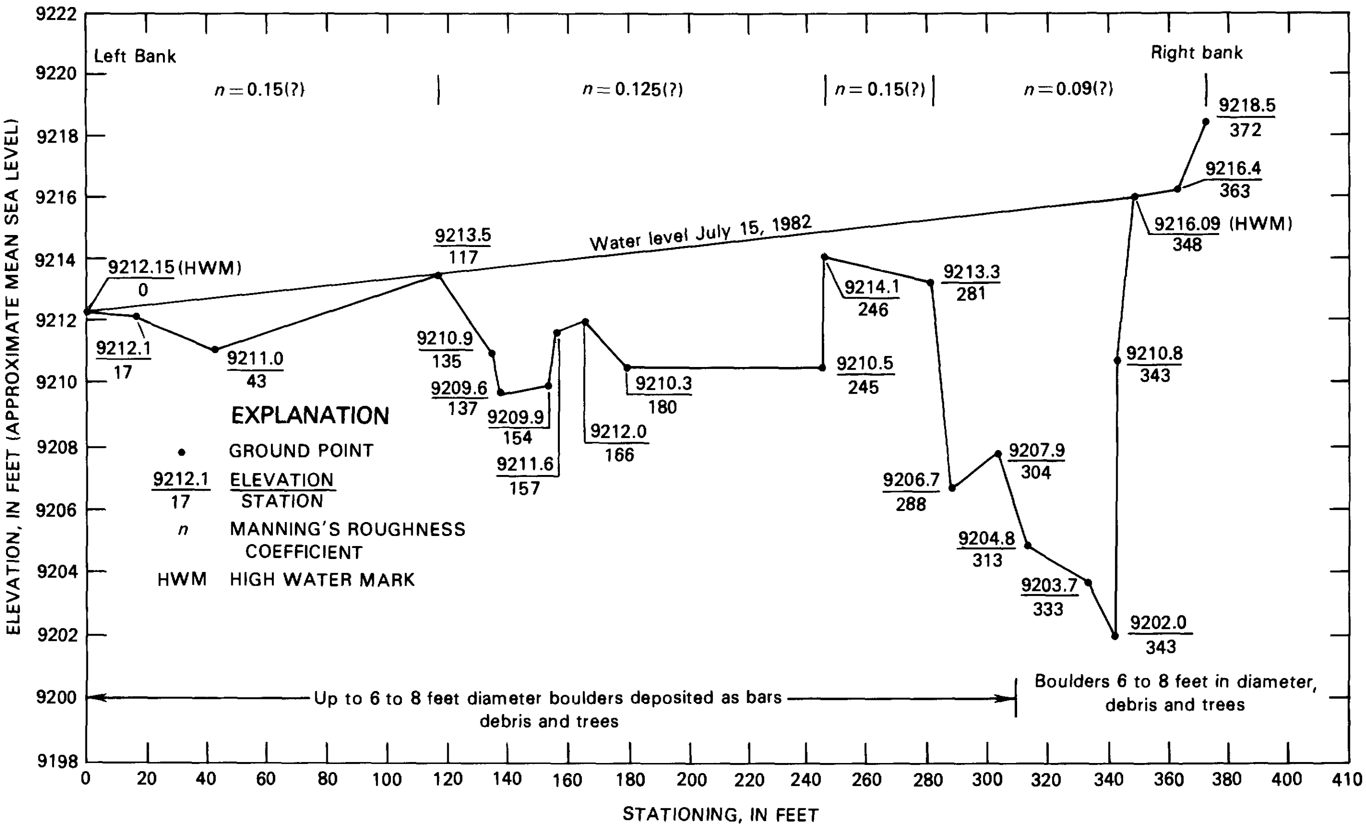

FIGURE 60.—Roaring River cross section at river mile 3.83.

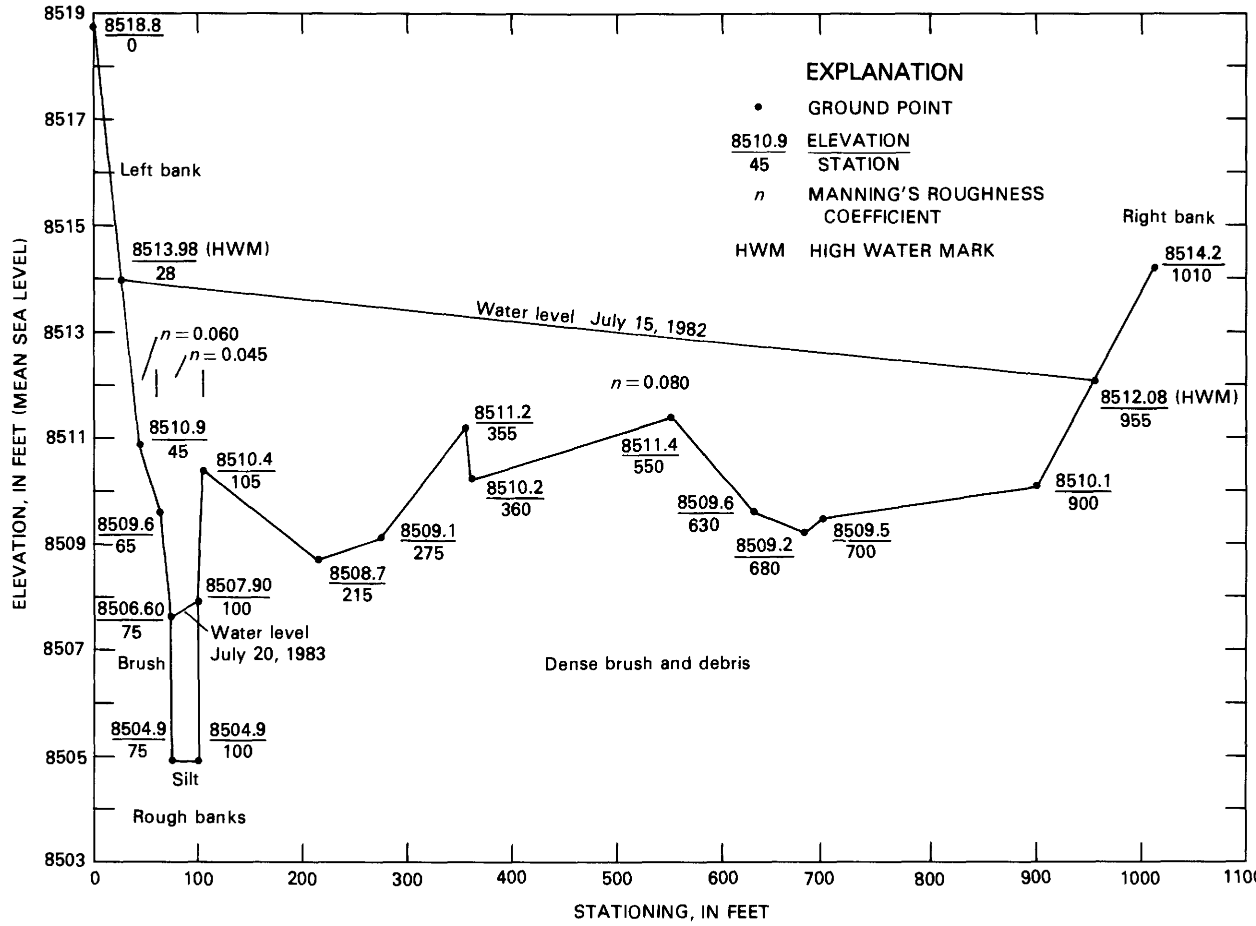

FIGURE 61.—Fall River cross section at river mile 5.36.

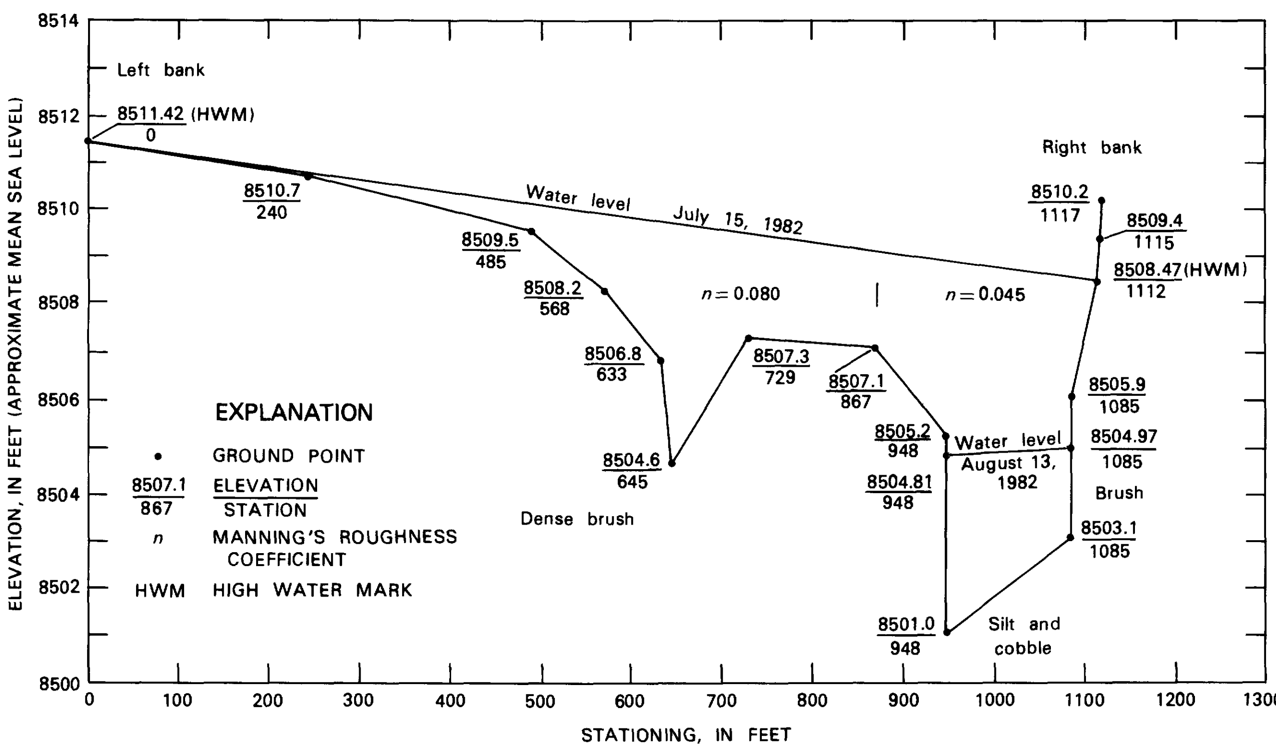

FIGURE 62.—Fall River cross section at river mile 5.78.

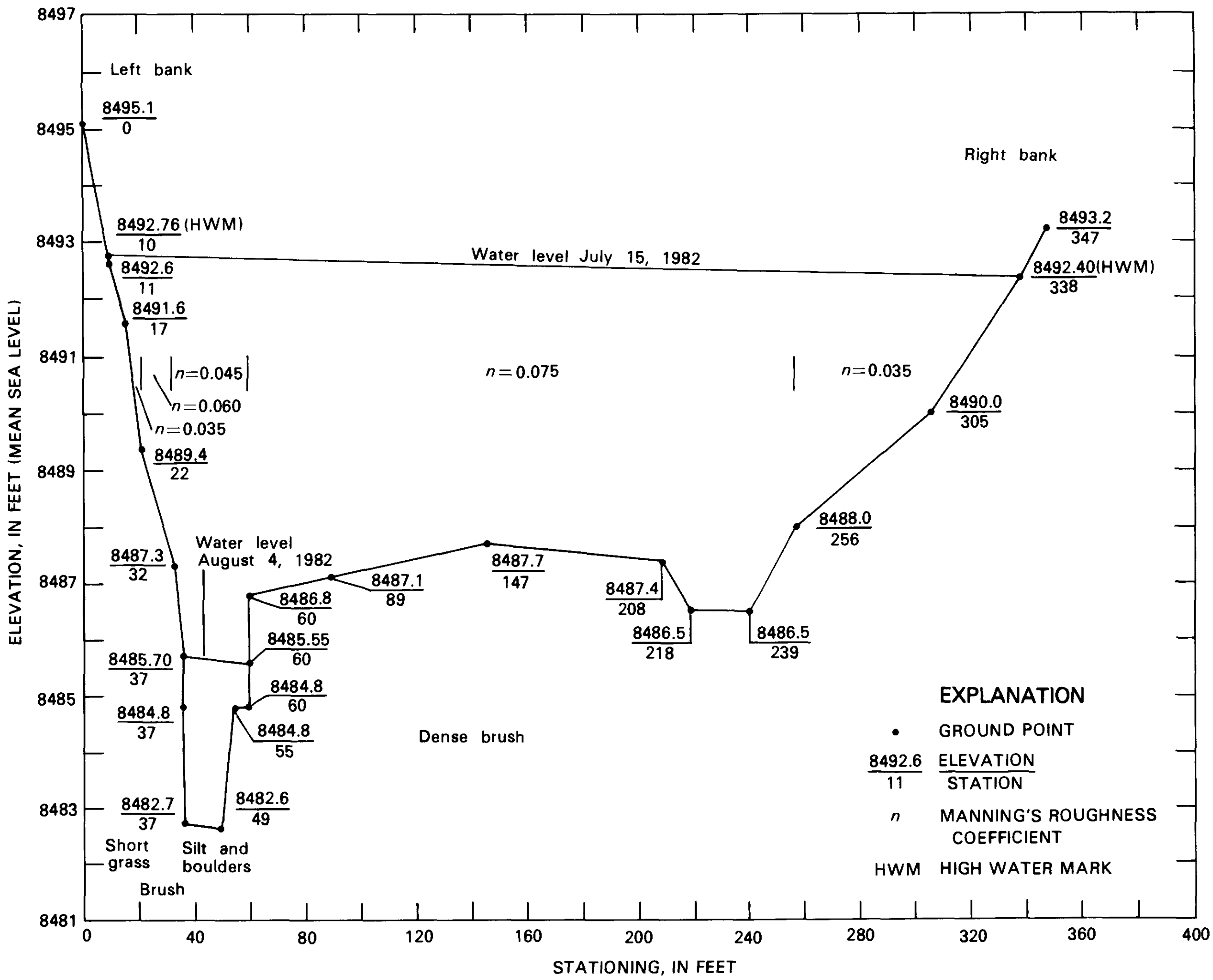

FIGURE 63.—Fall River cross section at river mile 6.50 (site 1).

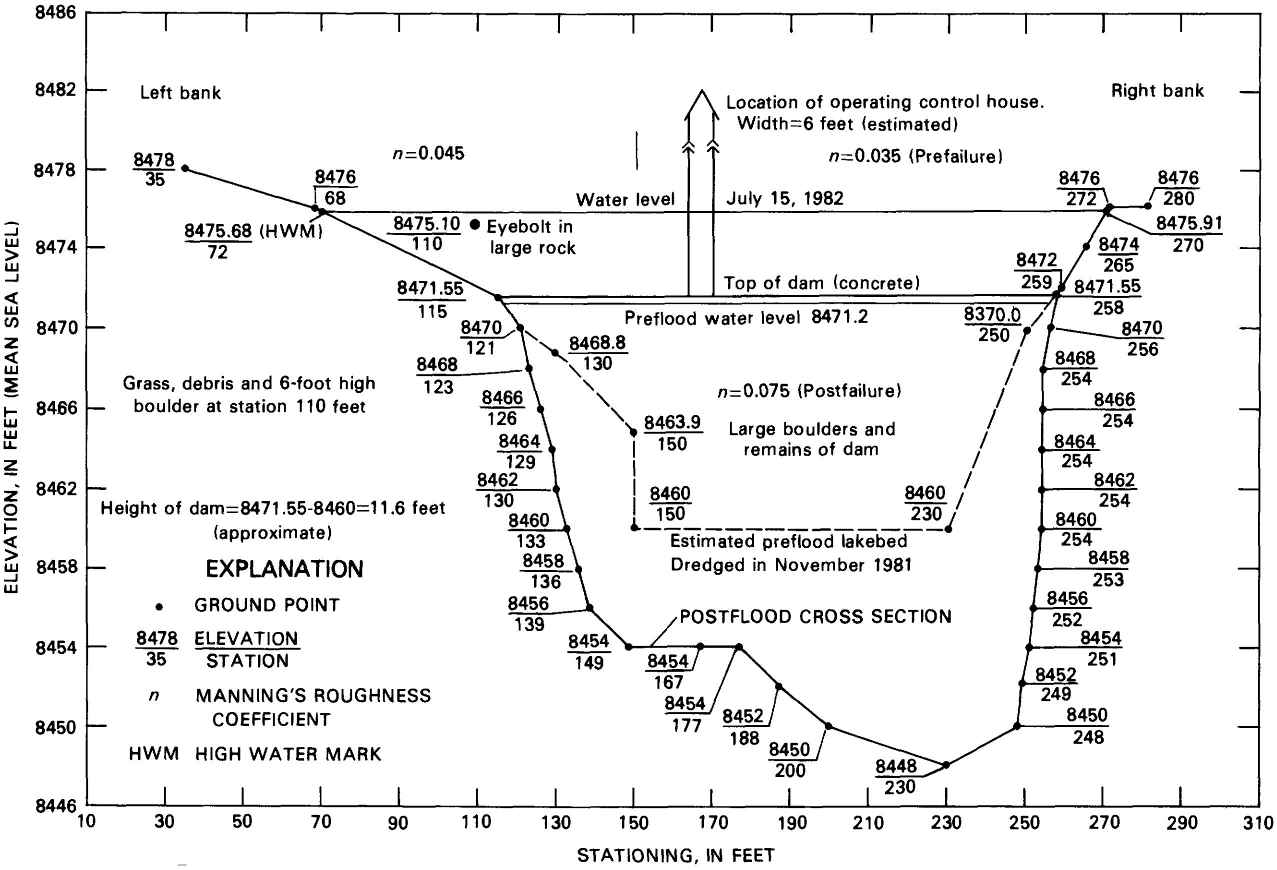

FIGURE 64.—Cascade Lake dam cross sections on the Fall River at river mile 6.67 (site 2).

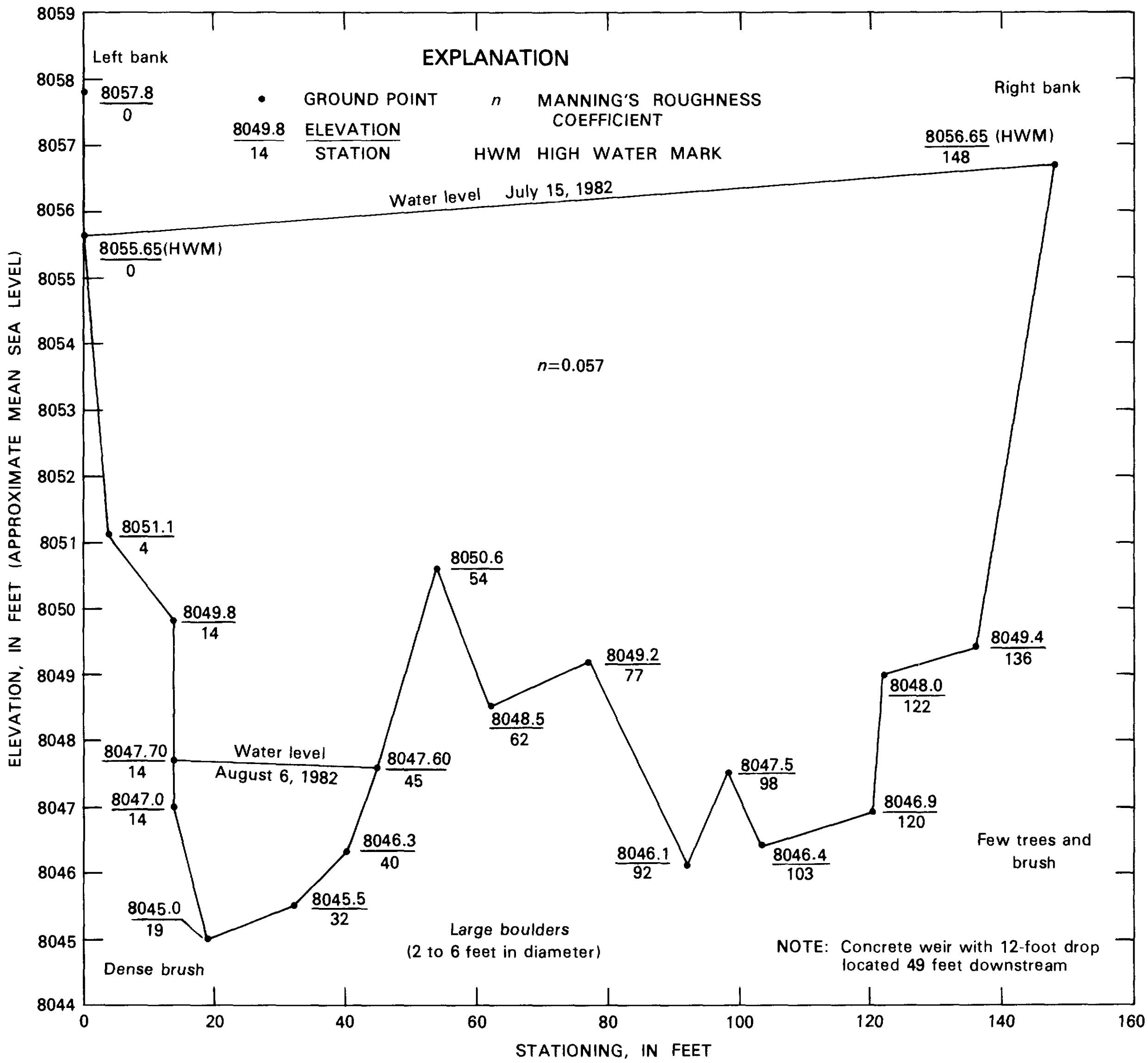

FIGURE 65.—Fall River cross section at river mile 7.68 (site 3).

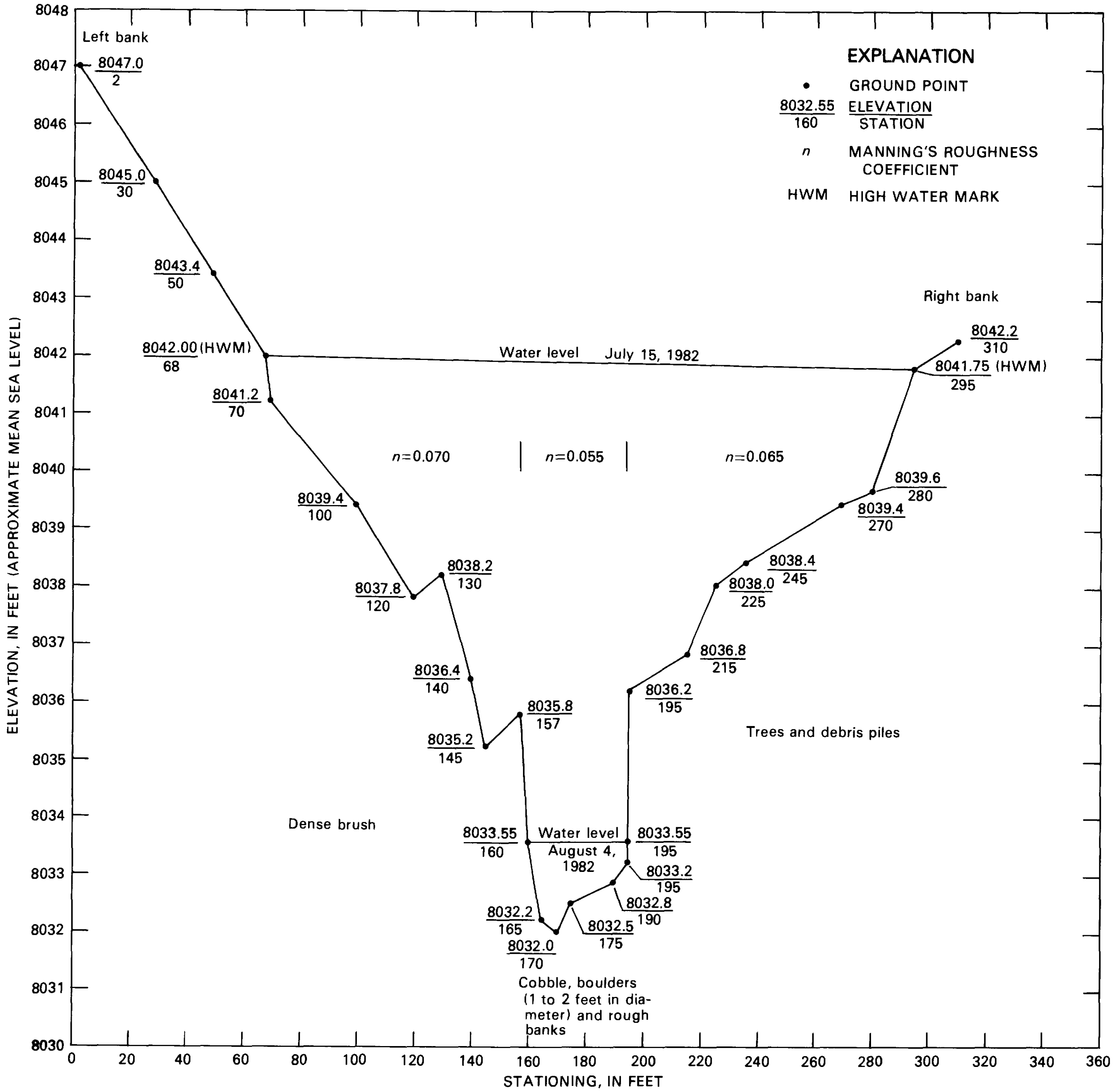

FIGURE 66.—Fall River cross section at river mile 7.74.

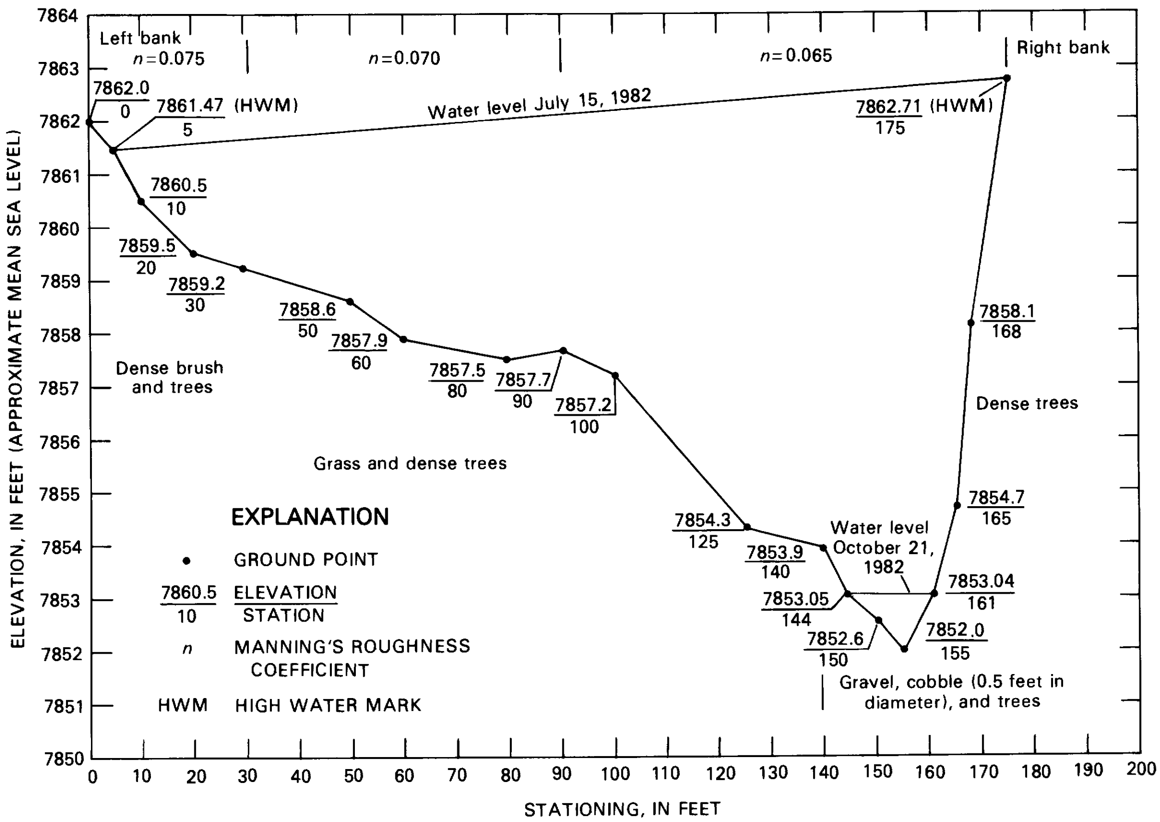

FIGURE 67.—Fall River cross section at river mile 8.78.

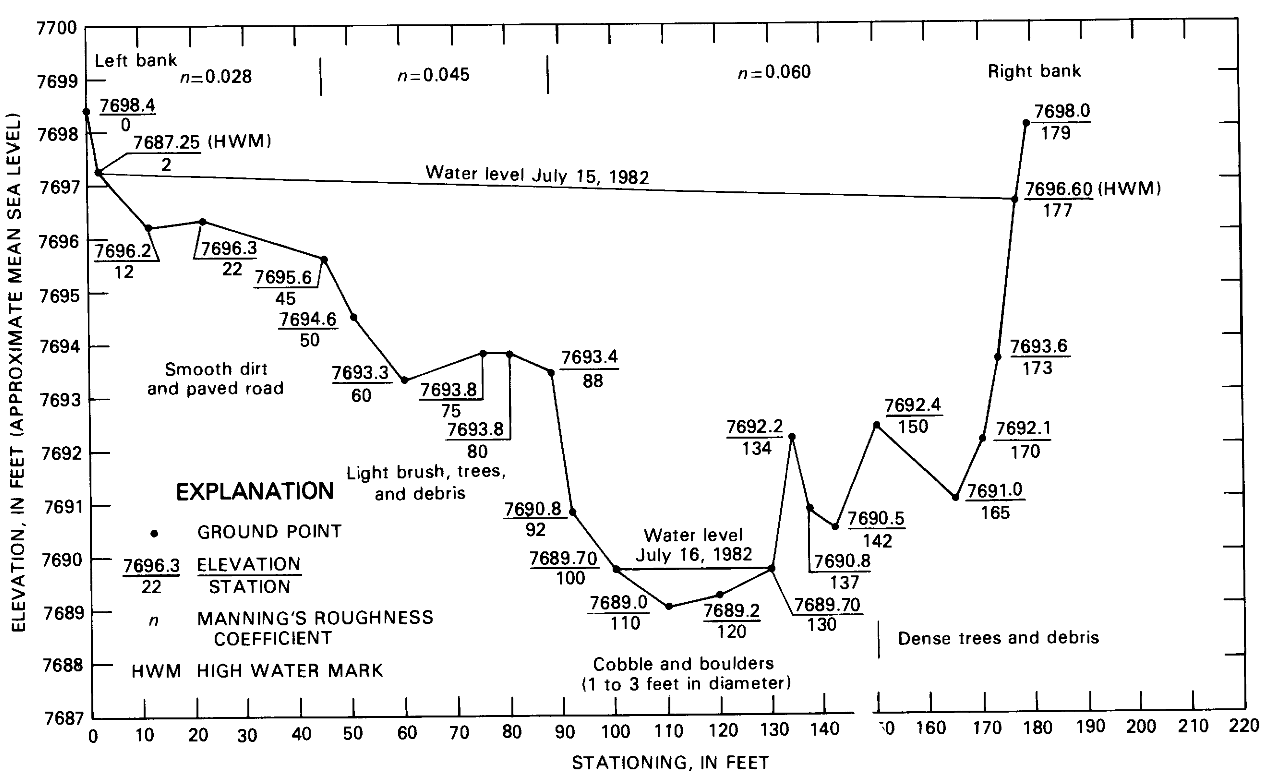

FIGURE 68.—Fall River cross section at river mile 10.28 (site 4).

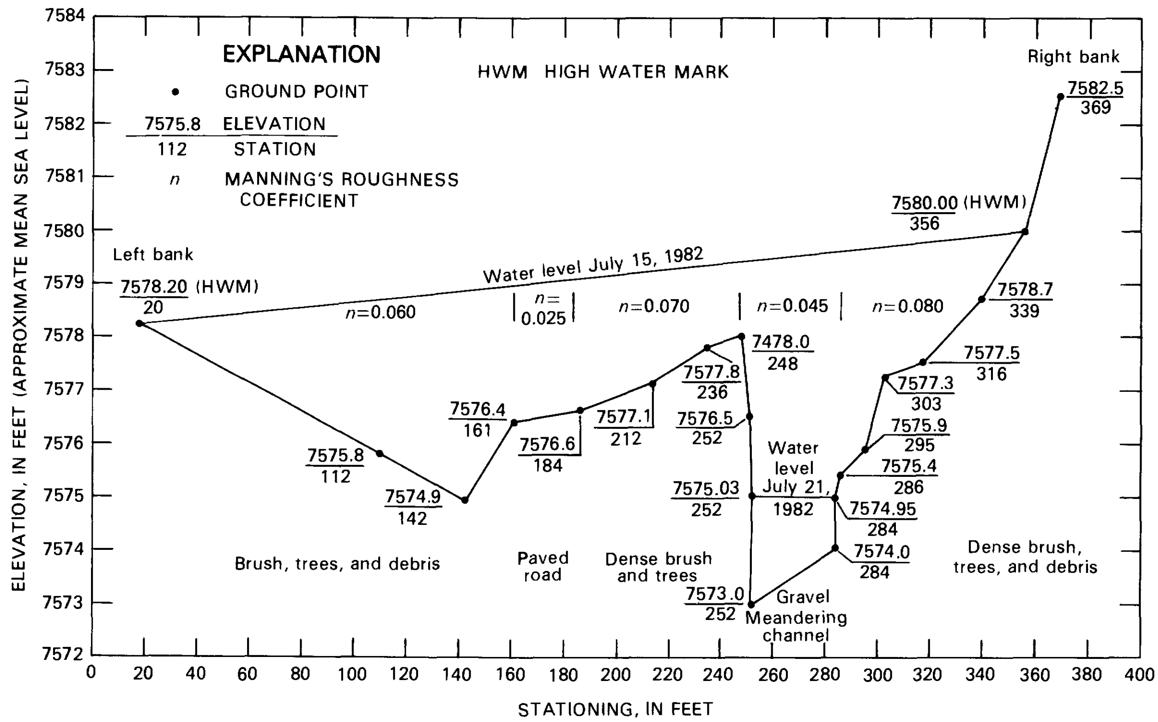

FIGURE 69.—Fall River cross section at river mile 11.45 (site 5).

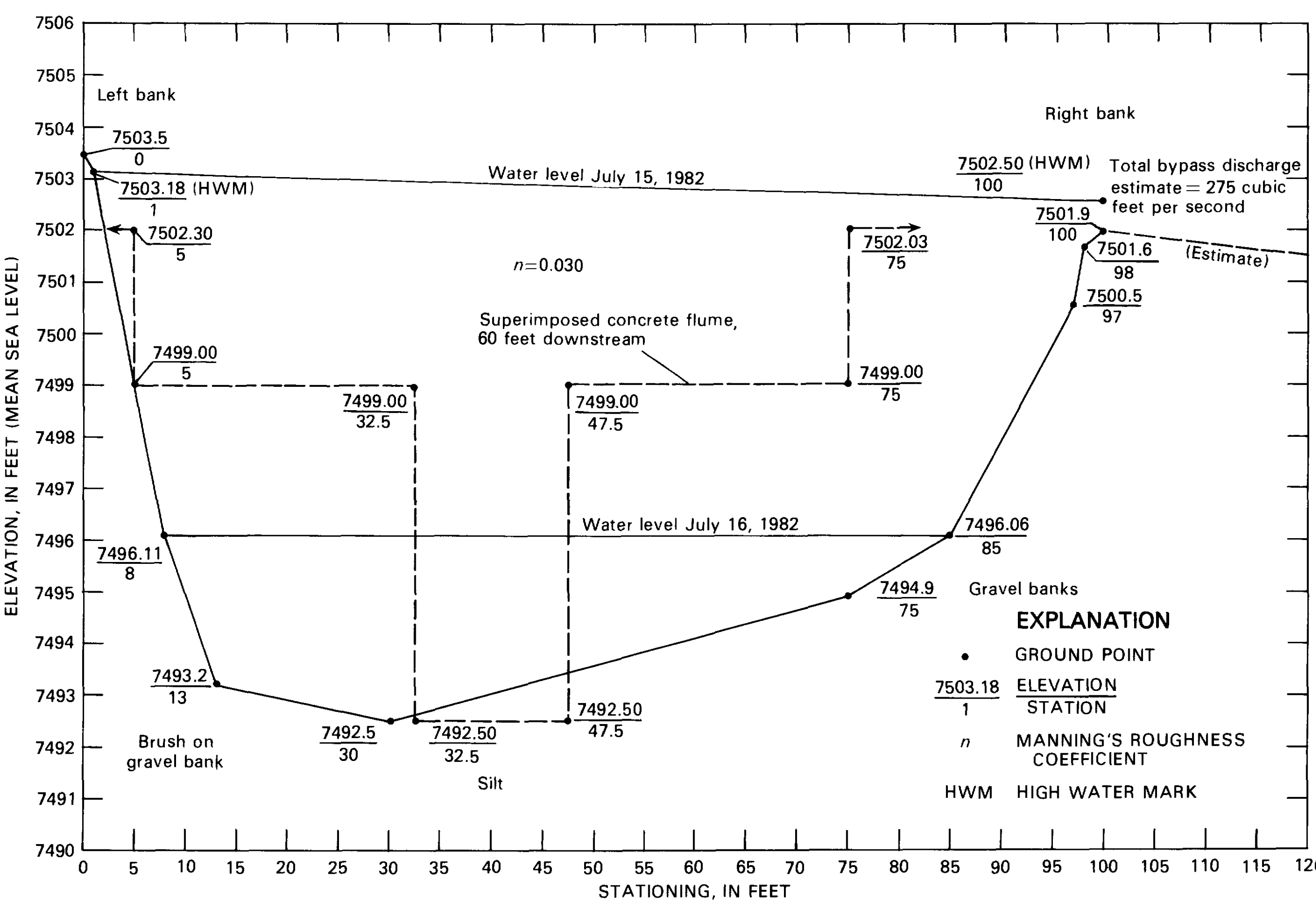

FIGURE 70.—Big Thompson River cross section at river mile 12.5 (site 6).

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