FLOOD OF OCTOBER 1986 AT SEWARD, ALASKA

U.S.GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 87-4278

Prepared in cooperation with the

STATE OF ALASKA:
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES
DIVISION OF EMERGENCY SERVICES
FEDERAL HIGHWAY ADMINISTRATION
FEDERAL EMERGENCY MANAGEMENT AGENCY
KENAI PENINSULA BOROUGH

Cover photo: Cobbles and gravel deposits at Bridge 1389, Exit Glacier Road, October 13, 1986.

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Anchorage, Alaska
1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

For readers who may prefer to use metric (International System) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	by	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per foot (ft/ft)	0.3048	meter per meter (m/m)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]

Other useful conversion factor for stream channel slope (or gradient):

Multiply	by	To obtain
foot per foot (ft/ft)	5,280	foot per mile (ft/mi)

Sea level:

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

Stream names:

Stream names in parentheses on maps in this report either do not appear on U.S. Geological Survey maps, or indicate local usage.

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ABSTRACT

Broad areas along the lower Resurrection River and Salmon Creek as well as the surfaces of several adjacent alluvial fans in the Seward area were flooded as a result of the intensive rainstorm of October 9-11, 1986. Severe erosion took place through the steep gradient, mountain canyons and near the apex of the fans, while rock and debris were deposited on the distal parts of the fans. In Godwin, Lost, Box Canyon, Japanese, and Spruce Creek basins, and perhaps others, landslides or debris avalanches dammed the streams temporarily. Subsequent failure or overtopping of these dams led to "surge-release" flooding; peak discharge of such a flood at Spruce Creek was 13,600 cubic feet per second, four times as great as any previously known maximum discharge from the basin and 2.5 times as great as the runoff rate upstream from the debris dam.

Flood discharges were determined indirectly -- using the slope-area method -- at ten high-gradient reaches on nine streams. Computed peak discharge for several small basins were the largest since records began in 1963. The largest rainfall-runoff rate unaffected by surge-release was 1,020 cubic feet per second per square mile at Rudolph Creek, which has a drainage area of 1.00 square mile.

The 15.05 inches of rain that fell in one 24-hour period during the storm was assigned a recurrence interval of 100 years or greater. The length of the streamflow record available for most Seward area streams -- 25 years or less -- is inadequate to reliably define flood-frequency relations for recurrence intervals as great as 100 years. However, the slope-area determined discharge of Spruce Creek above the debris avalanche indicates a recurrence interval of 100 years or greater. In addition, conventional flood-frequency analysis techniques are not applicable to peak discharges that are affected by surge-release phenomena. Large, damaging floods have repeatedly caused major damage in the Seward area, and the potential for catastrophic, debris-laden floods is an ever-present threat to areas bordering the many steep mountain streams.

INTRODUCTION

During the period October 9-11, 1986 a large North Pacific storm system moved onshore over southcentral Alaska, where it caused record-setting rainfall that led to widespread, catastrophic flooding and landslides. One of the hardest-hit areas was the coastal community of Seward (fig. 1), which received more than 15 in. of precipitation in one 24-hour period. Broad areas along the Resurrection River and Salmon Creek at the head of Resurrection Bay were inundated (plate 1). The effects of the floodwaters were exacerbated by severe erosion and subsequent deposition of rock and debris along the channels of steep mountain streams. The high sediment discharge, combined with trees, brush and other debris, clogged channels at bridges

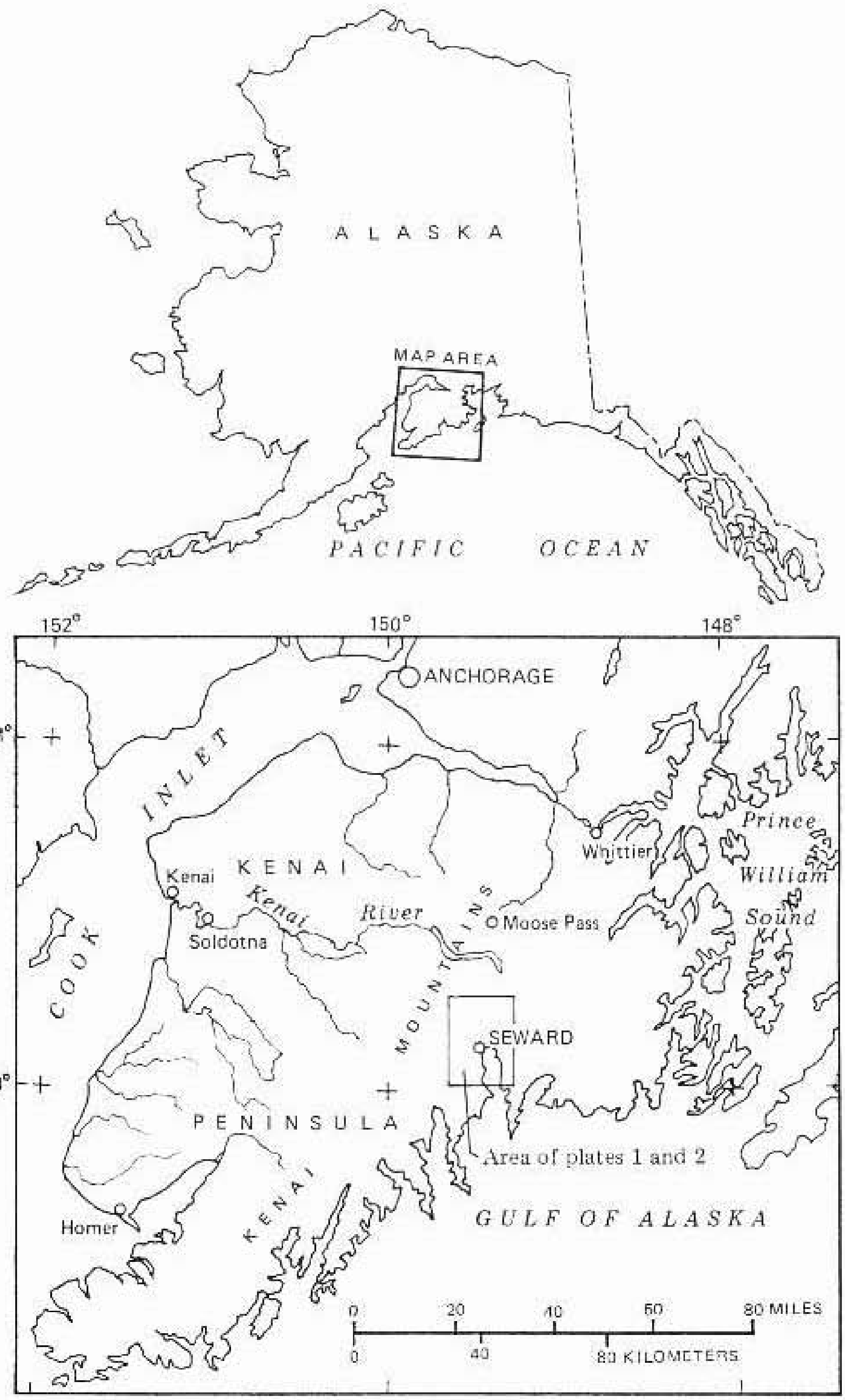


Figure 1.--Location of Seward area in southcentral Alaska.

and culverts, causing overtopping and erosion of bridge approaches and railroad and highway embankments; interruption of highway and rail transportation; and destruction and damage to businesses and residences.

The intense rainfall saturated steep slopes along the mountain streams, inducing landslides, avalanches, and debris flows that contributed material to debris-laden floods and in some instances temporarily dammed stream channels. The sudden failure of these debris dams resulted in mass movement of earth, rock, vegetation, and water. This surge-release flooding produced peak discharges substantially greater than any previously determined flood flows.

Flood data in this report were collected as part of a long-term cooperative program between the U.S. Geological Survey and the State of Alaska, Department of Transportation and Public Facilities (ADOT&PF), and the Federal Highway Administration (FHWA). Additional support for preparation of this report was furnished by the ADOT&PF, Alaska Division of Emergency Services, FHWA, and the Federal Emergency Management Agency (FEMA). The meteorological and rainfall analysis is based on information provided by Gerald Nibler of the National Weather Service.

Purpose and Scope

This report documents the floods of October 1986 at Seward and adjacent areas at the head of Resurrection Bay using information collected and observations made by the U.S. Geological Survey during and after the catastrophic event. Included are descriptions of the mass movement features and processes active in the steep mountainous terrain surrounding Seward, the floods and their effects in each of the affected drainage basins, and a discussion of the hydraulic and statistical analyses of the flood data. A flood inundation map, a discussion of and a map delineating flood-related hazards, and tabulations of hydrologic and hydraulic data on the October 1986 and earlier floods provide a technical basis on which to make flood-plain management decisions. Stream names in parentheses on maps either do not appear on U.S. Geological Survey maps, or indicate local usage.

Acknowledgments

The assistance, cooperation, and information provided by personnel of several agencies and local governments, including the Kenai Peninsula Borough and the City of Seward, are gratefully acknowledged. Helicopter support was provided by the Alaska Army National Guard. Darryl Schaefermeyer and Kerry Martin, City of Seward, and W.F. Barber, Alaska Department of Transportation and Public Facilities, provided valuable technical support and the aerial photographs used to map inundated areas. Finally, the authors thank the people of Seward for granting access to their property to make measurements and observations, and for sharing their knowledge of the present and past floods and flood damage in the area.

PHYSICAL SETTING AND CLIMATE

Seward lies at the head of Resurrection Bay, a deep fiord about 25 mi long on the north shore of the Gulf of Alaska (fig. 1). Near Seward, the bay is 2 to 3 mi wide and about 500 ft deep. The water is deep immediately offshore except at the head of the bay and at the toe of alluvial fan-deltas that have formed at the mouths of steep-gradient streams tributary to the bay. The glaciated Kenai Mountains rise steeply above Resurrection Bay and the valley of the Resurrection River; the highest peaks on the west side of the bay and river reach altitudes of 4,000 to 5,000 ft.

The extreme mountain relief and its effect on the coastal maritime climate cause great local variations in weather in the Resurrection Bay-Seward area. The general circulation of air masses is driven by migrating pressure centers in the Gulf of Alaska. The lifting and cooling of moist air masses at the mountain fronts cause a rapid increase in precipitation with increasing elevations along the windward side of the mountains. Mean annual precipitation ranges from 67 in. at Seward to more than 100 in. in the high-altitude glaciated areas. About 40 percent of the total annual precipitation falls as rain during the period September through November. Beginning in early October, the precipitation above an altitude of 2,100 ft. is usually in the form of snow (D.C. Trabant, U.S. Geological Survey, oral commun., 1987), most of which is stored in mountain and glacier snowpacks.

The upper headwaters of Resurrection River, including the basins of Lost and Grouse Creeks, are in a strong transitional zone between the Harding Icefield, where glaciers are sustained by high precipitation, and the Kenai Mountains, in which precipitation decreases rapidly to the north and west. Mean annual precipitation in this zone decreases rapidly from more than 100 in. in the mountains draining into Resurrection Bay to 40 in. in the Kenai River drainages to the northwest.

GEOLOGY

Alternating units of graywacke and phyllite constitute virtually all the bedrock in the immediate vicinity of Seward. Unconsolidated glacial and fluvial deposits, described in more detail below (from Lemke, 1967, p. 16-24), overlie the bedrock except on the steep, higher slopes. These surficial deposits are generally intermixed in the valley of the Resurrection River (plate 2).

Glacial Deposits

Remnants of lateral moraines flank the main valley of Resurrection River and extend up the sides of tributary valleys to a maximum altitude of about 1,500 ft. The moraines are heavily vegetated in most places, but where exposed consist of rather loose, gray till, composed principally of silt, sand, and gravel, with smaller amounts of clay-sized particles, cobbles, and large boulders. Glaciers in the Seward area have been retreating and thinning in recent years (Field, 1975, p. 523). Continuation of this trend would create and leave additional areas of unconsolidated morainal material subject to accelerated erosion and deposition by streams. Terminal or recessional moraines in mountain glaciated areas may be sufficiently well-preserved so that they dam the stream that replaces the melting glacier (Costa, 1985, p. 31).

Alluvial Fans and Fan-Delta Deposits

Alluvial fans and fan deltas have been deposited at the mouths of most valleys tributary to the head of Resurrection Bay. Deltaic deposits form the distal edges of the fans that extend into the bay. The four largest fans are the broad aprons at Fourth of July, Japanese, Lowell, and Spruce Creeks. The fan deposits, chiefly silt, sand and gravel, range in thickness from about 100 ft to several hundred feet. By definition, alluvial fans are depositional landforms -- formed as a stream channel migrates across the fan surface, changing course primarily during large floods. Because of the process by which alluvial fans are built up, a single flood zone or floodway across the fan cannot be designated or identified. The stream is prone to lateral migration or sudden shifts in course during high runoff events, so that the entire surface of the fan apron is subject to flooding.

Profiles of the stream channels across major alluvial fans at Seward (fig. 2) indicate that gradients near the apex of the fans range from 0.025 to 0.082 ft/ft, whereas gradients near their bases (distal edges) range from 0.010 to 0.052 ft/ft. The presence of steep-walled fan-head trenches indicates that erosion takes place on the upper part of a fan. Deposition begins on the lower part of the fan apron -- typically below a distinct break in slope (fig. 2) -- at gradients less than about 0.052 ft/ft.

The business district and most of the residential sections of the "original" city of Seward are built on the alluvial fan of Lowell Creek. Before the construction in 1940 of a diversion tunnel from Lowell Canyon to the head of Resurrection Bay at the southern edge of the Seward, Lowell Creek flowed in a channel approximately coincident with the present-day Jefferson Street. The channel overflowed periodically, spreading a layer of sand and gravel over much of the fan. By the early 1960's, residential development was beginning on the broad fan of Japanese Creek (Forest Acres area) and in the last two decades has spread to other fan areas, notably those at Lost, Box Canyon, Sawmill, and Spruce Creeks.

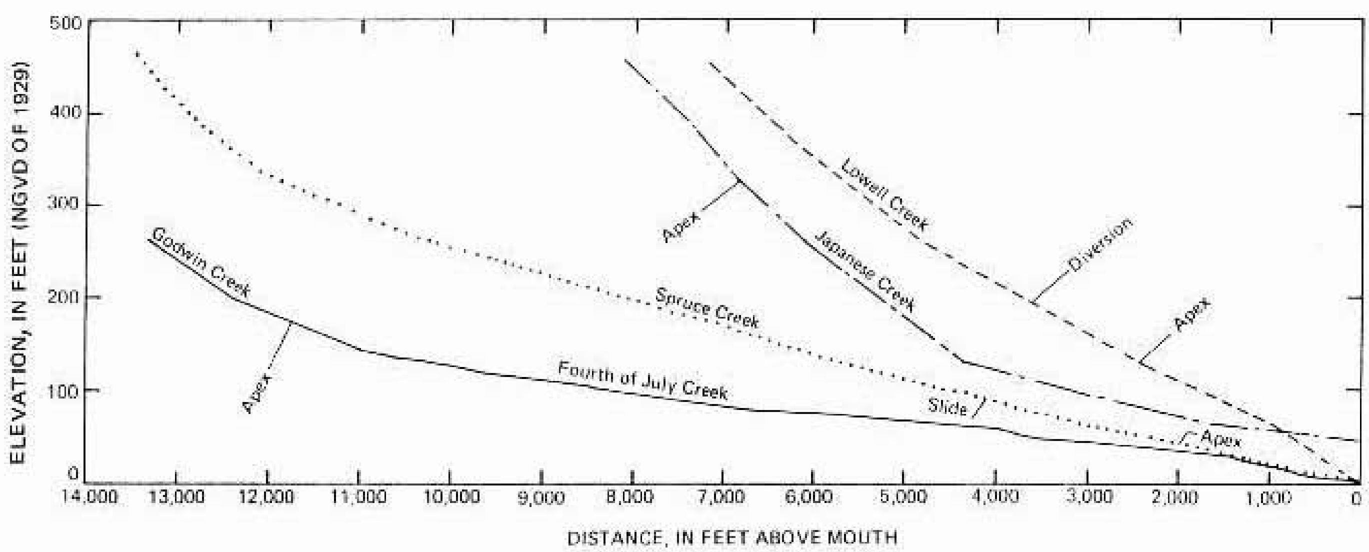


Figure 2.--Longitudinal profile of selected alluvial fan stream channels near Seward.

Valley Alluvium

Resurrection River is a braided stream, within low, vegetated banks, whose channel migrates across a wide flood plain. Its flood-plain deposits consist mainly of sand and fine-to-medium gravel. Coarse gravel and small cobbles armor some of the abandoned stream courses. The alluvium of the lower reach of the Salmon Creek consists chiefly of medium-to-coarse sand and fine gravel, slightly finer than the material along Resurrection River. Over the past 10 years, residential development has encroached onto the flood plain of Salmon Creek, as at Questa Woods and Camelot by the Sea subdivisions, and along Nash Road.

MASS-MOVEMENT FEATURES AND PROCESSES

Saturation of unconsolidated surficial material on steep slopes, including previous landslide deposits, resulted in mobilization of these materials and their incorporation in mass-movement processes variously termed debris avalanches (Swanston, 1970), debris flows (Varnes, 1978; Costa and Jarrett, 1981), and debris floods (Wieczorek and others, 1983). Slope "failure" appeared to take place at the base of granular soils or glacial moraine deposits. After movement of these materials in October 1986, large areas of cracked and scarp-bounded masses remain perched on steep slopes. These masses are now less stable and more likely to be mobilized during heavy rainstorms.

Landslides

Landslide and talus deposits are present on and at the base of slopes along the steep-walled valleys of all small mountain streams near Seward. The 1964 earthquake reactivated some older slides and triggered new ones in these canyons (Lemke, 1967). Old landslides, recent landslides (debris avalanches) triggered by the October 1986 event, and landslide-prone areas are delineated on plate 2.

Debris Avalanches

Debris avalanches, the rapid downhill mass movement of earth, rock, vegetation, and water, are common natural phenomena in coastal, maritime areas of Alaska (Swanston, 1970). The intense rainfall on October 10-11, 1986 caused debris avalanching on the steep, densely vegetated mountain slopes covered by shallow-rooted Sitka spruce trees. The avalanches occurred principally on slopes greater than 32 degrees (0.63 ft/ft) in areas of shallow till soils, a few inches to 2 ft in depth, underlain by bedrock. The steep slopes and increased pore-water pressure in the saturated glacial-till soils were primary factors in the debris avalanching. Other contributing factors were the presence of natural depressions that collected and concentrated the water, the ease with which the soil transmitted water to become rapidly saturated, and the shallow bedrock "sliding surface." Scars of recent debris avalanches are evident on the steep slopes of Spruce and Lost Creeks.

The largest debris avalanche identified in the Seward area in October 1986 occurred on the steep northern slopes of Spruce Creek, 0.8 mi upstream from its mouth. The avalanche scar is about 3,500 ft long, averages 460 ft in width, and is 800 ft wide at its base; the average soil depth was less than 2 ft. The avalanche removed the entire vegetal cover, including the large trees, and bedrock was exposed the entire length of the scar. The amount of material moved was about 3 million ft^3. Several smaller debris avalanches occurred along the northeast-facing slopes at the southern margin of the Japanese Creek alluvial fan. These avalanches were in densely vegetated areas of shallow soils underlain by steeply sloping bedrock surfaces. The avalanche scars were from 300 to 800 ft long and 10 to 25 ft wide.

Several debris avalanches and rockslides occurred on the steep slopes bordering Resurrection Bay along the road between Seward and Lowell Point. The largest such slide, at the base of the mountain front 0.2 mi north of Lowell Point fan, originated from a small, steep, unnamed basin with its headwaters at Bear Mountain. This type of slide usually occurs in V-shaped drainages with slopes greater than about 40 degrees. The boulder-sized material "delivered" by these slides were a source of riprap for post-flood reconstruction.

Debris Flows and Debris-Laden Floods

As landslide and avalanche masses reach stream channels, the material may become mixed with the floodwaters to produce phenomena known as debris flows and debris-laden floods. Debris flows are defined as rapidly moving, gravity-induced slurries of granular solids, water, and air (Varnes, 1978). In October 1986, material from debris avalanches onto the Japanese Creek fan was incorporated in a debris flow and carried some 50 to 150 ft downgrade along the margin of the fan; this debris flow transported at least one moss-covered boulder that was 16 ft long (fig. 3). In debris-laden floods, soil, sediments, and rock with a greater relative proportion of water (than debris flows) are transported by fast-moving floodwaters. Wieczorek and others (1983, p. 3) refer to such water dominated flows as debris floods.

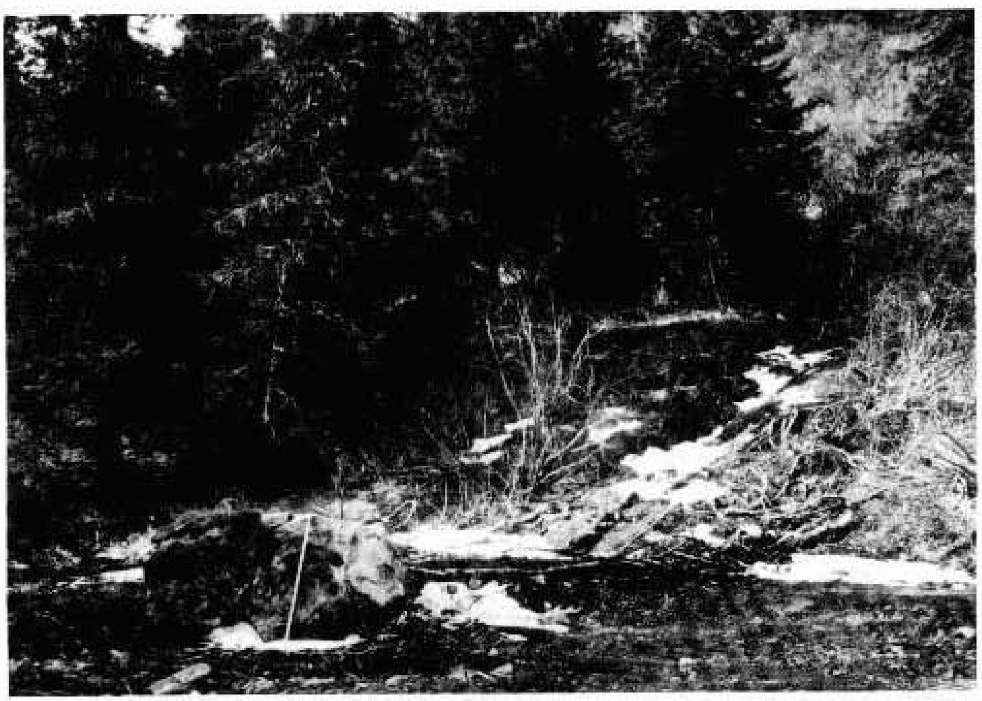


Figure 3.--Debris flow along the west margin in the Japanese Creek alluvial fan. Boulder is 16 feet long.

Surge-Release Flooding

Landslides and avalanches may form a dam across steep, narrow valleys, temporarily storing water that is later released catastrophically as the dams fail or are overtopped (Costa, 1985, p. 34). Such damming and surge-release flooding occurred in October 1986 on Godwin, Lost, Box Canyon, Japanese, and Spruce Creeks. Surge-release floods can also be generated by the sudden release of water stored within or on the surface of a glacier or in depressions on ice-cored moraines.

FLOOD HISTORY AT SEWARD

Seward has a history of the type of flooding and flood damage that occurred in October 1986. The recurrence of heavy and intensive precipitation and the presence of erodible, unconsolidated material on steep slopes have combined several times in the past to produce landslides, debris avalanches and flows, and debris-laden floods, as well as the inundation of wide areas on alluvial fans and the flood plains of valley alluvial streams. The sources and products of these processes are the glacial deposits, alluvial fans, valley alluvium, and other surficial geologic materials mapped by Lemke (1967).

About 90 percent of annual peak discharges from streams that drain the high, glaciated mountain basins occur in the months of August through November. These peak flows are due to intense rainfall rather than to runoff from melting of snow and ice in late spring and early summer. Peak discharges due to snowmelt usually are not excessively large, unless they are accompanied by rainfall. The most severe floods occur when freezing temperatures occur at altitudes higher than those of the surrounding mountains, and precipitation falls as rain rather than snow. The largest floods from glacier-clad basins occur in late summer and fall after snowpacks have melted at lower altitudes but remain saturated on the higher altitude slopes and glaciers.

Flood information for the period 1946-74 has been summarized by the U.S. Army Corps of Engineers (1975, table 2). Additional data on the floods of August 1966 and October 1969 were available from U.S. Geological Survey (1975) and Reid and others (1975). Flood investigations on the Fourth of July Creek fan delta are described by Randall and Humphrey (1984).

FLOOD OF OCTOBER 1986

Meteorological Conditions

by Gerald J. Nibler, National Weather Service

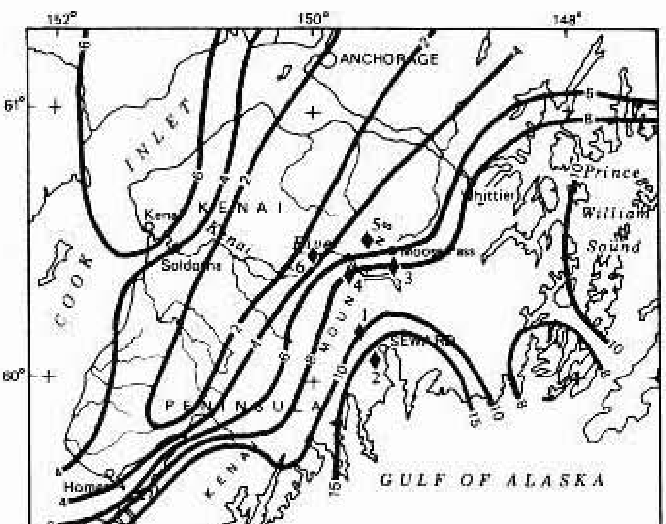
During the period of heaviest precipitation on October 9-11, 1986, the juxtaposition of a surface trough of low pressure along the 155th meridian and a ridge of high pressure along the British Columbia and Southeast Alaska coast produced a southerly jet of warm moist air that centered on the Kenai Peninsula. Normally, flood-producing rains along the coast are caused by the pattern of a strong moist jet, oriented perpendicular to the northern coast of the Gulf of Alaska, which typically remains stationary for 12 to 18 hours resulting in 3 to 6 in. of precipitation. During this storm, however, the jet was stationary for 36 hours and the combined dynamic and orographic uplift produced the long period of intense precipitation in the Seward area. The heaviest rainfall was associated with warm air advection, which forced freezing levels to altitudes higher than the surrounding terrain, so that rain rather than snow fell in the glaciated mountains. Normally, most precipitation in October occurs as snow at these higher altitudes.

Precipitation totals for selected sites near Seward for the 3-day storm period of October 9-11 are summarized in table 1. The isohyetal map in figure 4 shows the location of selected precipitation gages, and that the heaviest precipitation occurred in the Seward area. A graph of cumulative precipitation for selected sites in the Seward area (fig. 5) shows that heavy precipitation began the evening of October 9, and continued into the morning of October 11. Rainfall for the 24-hour period beginning at 4 a.m. (Alaska Daylight Time) on October 10 was 15.05 in. On the basis of U.S. Weather Bureau (1963) data, this 24-hour total has a return period of more than 100 years.

Table 1.--Total precipitation for selected sites near Seward, October 9-11, 1986

[Data from National Weather Service]

Site No. (figure 4)	Station	Rainfall (inches)
1	Seward 9NW	10.14
2	Seward	17.96
3	Lawing	8.10
4	Cooper Lake Project	8.43
5	Moose Pass	4.96
6	Cooper Landing 6W	2.07



EXPLANATION

—2— Line of equal precipitation, in inches; interval 2 inches unless otherwise noted

◆6 Selected precipitation stations in the Seward area (see table 1)

Figure 4.--Total precipitation, October 9-11, 1986, for Seward and Kenai Peninsula area.

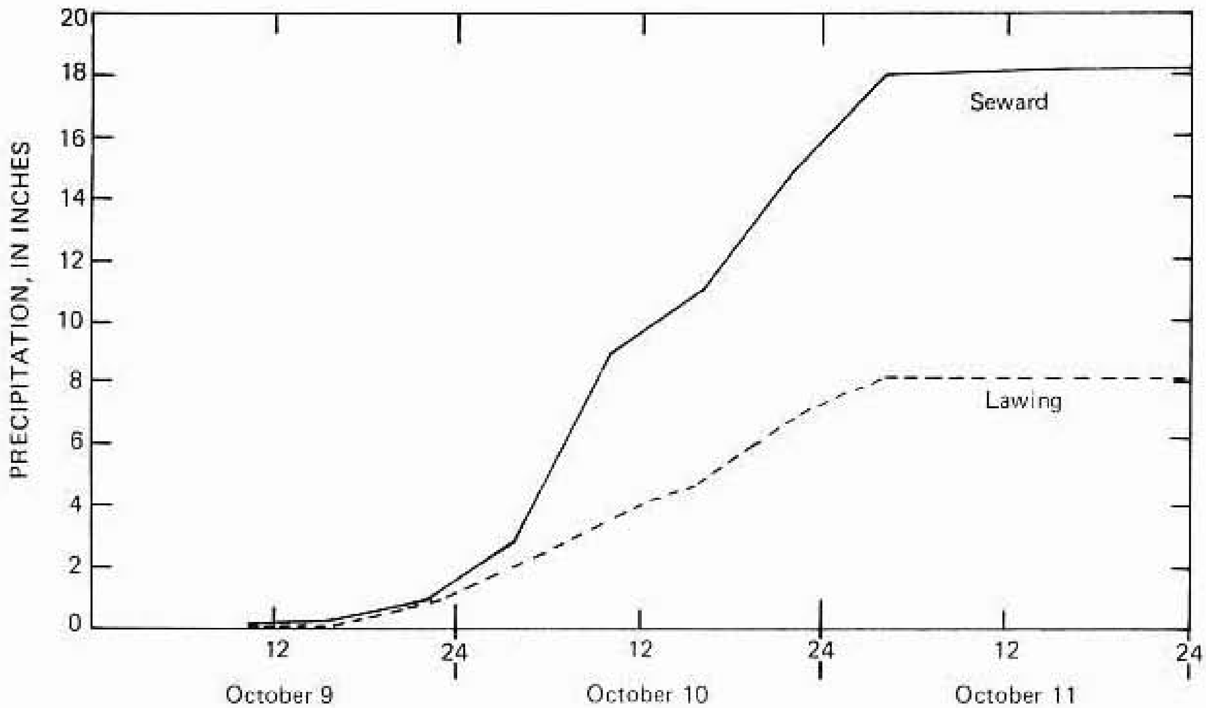


Figure 5.--Cumulative precipitation in Seward area, October 9-11, 1986 (Data from National Weather Service).

Description of Basins and Floods

Fourth of July Creek Basin

A large alluvial fan on the eastern shore of Resurrection Bay opposite the City of Seward has been formed by two glacial-meltwater streams -- Godwin Creek and Fourth of July Creek. The streams are deeply incised in bedrock above the apex of the fan. Prior to the construction of levees, the braided, distributary channels of Fourth of July Creek flowed 3.4 mi from the canyon mouths to Resurrection Bay, meandered across the broad 1.26-square-mile fan and discharged along the 1.5-mile-long base of the fan.

Construction of a new port facility and flood-control levees on the fan of Fourth of July Creek was completed in 1982, and a State prison is now under construction on the lower part of the fan. The levees confine the stream within a gradually constricting channel along the southeast margin of the fan-delta. The surface area of the active fan below the apex of Godwin Creek has thus been effectively reduced 68 percent -- from 1.26 mi^2 to 0.40 mi^2. A flood of September 15-16, 1982 caused extensive damage to the levees. The estimate of peak flow at the levees was approximately 4,700 ft^3/s, with a recurrence interval of 10 to 25 years (Randall and Humphrey, 1984).

Fourth of July Creek drains a 9.40-square-mile basin (38 percent of which is covered by glaciers) above its confluence with Godwin Creek. Immediately downstream from its origin at the termini of three glaciers, the channel slope is 0.055 ft/ft. At a point 1.7 mi below the glaciers, the stream channel slope increases abruptly to 0.17 ft/ft in a steep canyon incised in bedrock.

Godwin Creek, which originates as two stream channels at the terminus of Godwin Glacier, drains a highly glaciated (61 percent ice and snow) basin with steep, rugged peaks rising from sea level to altitudes greater than 5,000 ft. The stream channel above the canyon mouth in the 13.8-square-mile basin (at site 1, plate 1) has a slope of 0.21 ft/ft just downstream from the glacier; the stream flows 1.1 mi through a deeply incised bedrock canyon before discharging across the Fourth of July Creek alluvial fan and delta. Along the meandering fan-head trench near the apex of the fan, the stream channel slope is 0.041 ft/ft. The slope decreases to 0.010 ft/ft as the channel widens in an area of high deposition.

Aerial photographs show evidence of past landslides from lateral moraine deposits perched along the steep-walled canyons of Fourth of July and Godwin Creeks. These landslides have deposited large quantities of material, some containing cobbles and boulders up to 8 ft in diameter, into the stream channels through the canyons. Future damming of the channels poses the potential for debris-laden, surge-release floods and re-deposition of sediment below the canyon mouths.

No evidence of glacier-outburst flooding from Godwin Glacier, either in 1986 or earlier years, has been identified or documented. However, glaciers with no visible lakes or surface depressions may have subglacial stored water that may be released suddenly to cause catastrophic floods (Post and Mayo, 1971).

In October 1986, landslides, slumping and other slope failures in the steep-walled canyon of Godwin Creek formed at least five dams across the channel, which resulted in short-term storage of water and rock debris. Subsequent breaching of the dams by floodwater inflow mobilized a surge-release, debris-laden flood through the canyon and below the canyon mouth. Recent aerial photographs show deposits from such floods scattered over the bedrock in the canyon. The surge release produced a flood whose maximum unit discharge was substantially greater than any previously known flood in Alaska. The peak discharge computed (using slope-area methods) for the canyon 0.1 mi above the fan apex was 30,000 ft^3/s, or 2,200 $(ft^3/s)/mi^2$ (site 1 on plate 1 and table 2). The entrenched channel in the canyon was 170 ft wide and had a mean depth of 12 ft; the bed material in the channel consists almost entirely of boulders, some as large as 8 ft in diameter (figs. 6 and 7). The flood-wave profile had a maximum slope of 0.041 ft/ft, and the average main channel stream velocity was computed at 16 ft/s.

Figure 6.--Godwin Creek, view downstream at flood discharge determination site 1, 0.8 mile below Godwin Glacier. Boulders range from 2 to 8 feet in diameter.

Table 2.--Summary of flood stages and discharges

[Site numbers correspond to those on plate 1; mi², square miles; ft, feet; ft³/s, cubic foot per second; (ft³/s)/mi², cubic foot per second per square mile]

Site No.	Station number	Stream name	Location: Lat	Location: Long	Drainage area (mi²)	Period of record	Maximum flood previously known: Date	Maximum flood previously known: Stage (ft)	Maximum flood previously known: Discharge (ft³/s)	Maximum flood of October 1986: Date	Maximum flood of October 1986: Stage (ft)	Maximum flood of October 1986: Discharge (ft³/s)	Maximum flood of October 1986: Discharge [(ft³/s)/mi²]
1		Godwin Creek near Seward	60°06'06"	149°17'46"	13.8	1986	--	--	--	11	44.10	a30,000	a2,200
2		Sawmill Creek near Seward	60°08'19"	149°21'41"	7.85	1986	--	--	--	11	51.30	b2,800	369
3		Sawmill Creek at Bridge 855 near Seward	60°07'39"	149°22'18"	10.3	1986	--	--	--	11	c29.59	--	--
4		Sawmill Creek at Bridge 854 near Seward	60°07'40"	149°22'18"	.33	1986	--	--	--	11	c32.07	d220	--
5		Resurrection River at Exit Glacier Bridge 1390 near Seward	60°11'42"	149°33'15"	106	1986	--	--	--	11	e353.28	--	--
6		Resurrection River at Bridge 598 near Seward	60°08'30"	149°25'00"	--	1965-67, 86	--	--	--	11	c31.02 cf29.57	d5,800	--
7		Resurrection River at Bridge 597 near Seward	60°08'25"	149°25'03"	--	1965-67, 86	--	--	--	11	c30.47 cg29.50	d7,000	--
8		Resurrection River at Bridge 596 near Seward	60°08'19"	149°25'10"	--	1965-67, 86	--	--	--	11	c30.62 ch29.17	d4,600	--
--	15237700	Resurrection River near Seward (total of sites 6, 7 and 8)	60°08'30"	149°25'00"	169	1965-67, 86	8-21-66	10.58	18,900	11	c31.02	d20,400	120
9	15238000	Lost Creek near Seward	60°12'02"	149°22'57"	8.42	1963-72, 76,86	9-20-76	12.30	920	11	--	a14,000	a1,700
10		Grouse Creek near Seward	60°13'17"	149°21'56"	4.78	1986	--	--	--	11	84.65	i1,890	395
11		Lost Creek at Bridge 600 near Seward	60°10'45"	149°23'35"	23.6	1986	--	--	--	11	c143.00	ad8,300	a360
12		Salmon Creek near Seward	60°10'56"	149°22'05"	7.10	1986	--	--	--	11	50.03	3,910	551
13		Clear Creek at Bridge 599 near Seward	60°09'08"	149°25'06"	--	1986	--	--	--	11	c43.01	d2,800	--
14		Salmon Creek at Nash Rd. at Bridge 853 near Seward	60°08'27"	149°23'58"	36.0	1986	--	--	--	11	c23.44	dj10,300	--
15		Rudolph Creek at Seward	60°07'24"	149°26'43"	1.00	1986	--	--	--	11	--	1,020	1,020
16		Lowell Creek at diversion at Seward	60°06'12"	149°27'00"	4.02	1966,86	8-21-66	(k)	1,200	11	(m)	--	--
17	15238500	Lowell Creek at Seward	60°05'55"	149°26'35"	4.02	1966-68	8-21-66	--	1,200	11	--	--	--
18		Spruce Creek above debris avalanche near Seward	60°04'02"	149°27'30"	8.88	1986	--	--	--	11	--	5,420	608
19	15238600	Spruce Creek near Seward	60°04'10"	149°27'08"	9.26	1966-86	9-15-82	9.46	3,420	11	n14.00	n13,600	n1,500
20	15243900	Snow River near Seward	60°17'11"	149°20'19"	128	1970,74, 77,85,86	8-31-67	42.4	p55,000	11	c480.24	17,500	137
21		Sixteen Mile Creek near Seward	60°18'39"	149°21'28"	3.19	--	--	--	--	11	21.46	2,340	796
22		Snow River at Bridge 603 near Seward	60°19'37"	149°21'27"	--	1970,74 77,85,86	9-20-74	--	2,500	11	--	400	--
23		Snow River at Bridge 605 near Seward	60°20'03"	149°20'57"	--	1970,74 77,85,86	9-20-76	--	24,800	11	--	15,000	--
24	15243950	Porcupine Creek near Primrose	60°21'30"	149°22'15"	16.8	1963-86	9-18-82	13.44	3,430	11	13.03	4,000	288

a Discharge affected by landslide, debris flow or other slope failures causing storage-release flood.
b Includes 140 ft³/s bypassing the slope-area reach.
c National Geodetic Vertical Datum 1929.
d Estimated.
e Federal Highway Administration datum.
f Alaska Railroad bridge milepost 3.3.
g Alaska Railroad bridge milepost 3.2.
h Alaska Railroad bridge milepost 3.0.
i Includes 60 ft³/s bypassing the slope-area reach.
j Includes 2,800 ft³/s from Clear Creek.
k 2 ft below crest of diversion dam.
m 0.7 ft below crest of diversion dam.
n Stage and discharge affected by debris-avalanche release flood.
p Glacier-dammed lake outburst flood.

Figure 7.--View upstream at apex of Godwin Creek alluvial fan.

Boulder fronts and terrace-like boulder berms extending across the flood channels with the coarsest material at or near the surface, similar to those described by Scott and Gravlee (1968), were left by the flood surge (fig. 8). These nearly flat-topped berms extend continuously on both sides of the channel downstream from the fan apex near the canyon mouth. The berm surface is as much as 10 to 15 ft above the present channel although it is below the high-water marks on the valley walls. Scott and Gravlee (1968, p. 19) suggest that very large boulders may be transported in suspension under "macroturbulent" conditions. An alternative explanation for these deposits is that they represent the front of a debris flow (Costa and Jarrett, 1981, p. 314), where they are concentrated by buoyant forces within the flow (Fisher, 1971). Boulders were deposited to a depth as great as 10 ft around the base of mature spruce trees. The trees were scarred 4 to 6 ft above the boulder terraces (figs. 8 and 9), which indicates that a debris-laden flood rather than a debris flow occurred below the canyon. Evidence of mass movement as debris flows below the canyon may have been destroyed or modified by the subsequent debris-laden flood. Trees more than 100 years old growing along the vegetated glacial rock debris deposited over bedrock were scarred and ripped from bedrock crevasses to a height of 15 ft above the bed of the main channel.

The flood of October 10-11, 1986 eroded new channels across the alluvial fan of Fourth of July Creek, and inundated and deposited great quantities of coarse gravel, cobbles, and boulders over the entire surface of the fan upstream from the levees on Fourth of July Creek. Although the levees were severely eroded, and overtopped in places, they did confine most of the flood flow to the leveed channel. High-water marks surveyed along the eroded upstream face of the 650-foot-long diversion levee were 3.1 ft below the levee crest.

Sawmill Creek

The headwaters of Sawmill Creek drain several high-altitude glaciated basins with steep alluvial fans at the mountain front. Below the alluvial fans, the

Figure 8.--Terrace-like boulder berm on Godwin Creek. View downstream, 1.1 mile below Godwin Glacier and near canyon mouth.

Figure 9.--Trees on Godwin Creek fan showing scarring 4 to 6 feet above surface of boulder berm.

stream traverses the valley alluvium in low-banked, braided channels of high gradient (0.032 ft/ft). In the October 1986 flood, many log and debris jams along the stream channel caused considerable lateral bank erosion and diversion of flood waters into abandoned channels. These channels then conveyed water throughout the flood plain. Computations based on data from a slope-area survey at site 2 (plate 1), 0.9 mi upstream from Bridge 855, give a peak flow of 2,900 ft^3/s, or 369 $(ft^3/s)/mi^2$, from an area of 7.85 mi^2. An additional 2.42 mi^2 drains into Sawmill Creek above Nash Road along the east bank between Bridge 855 and the slope-area survey site. During the flood, the water surface rose to 1.0 ft above the low steel (the lowest point of the superstructure of the bridge) of Bridge 855; and 17 ft of the south abutment road was washed out. About 500 ft^3/s of peak discharge overtopped the south rip-rapped dike, bypassed Bridge 855, and flowed south along Nash Road. This bypass flow, combined with runoff from two small, unnamed mountain drainages, flowed over Nash Road at mile 2.4. Bridge 854 (site 4), 0.1 mi north of Bridge 855, carried about 200 ft^3/s of floodwaters -- the combined flow from a small drainage area of 0.33 mi^2 and about 50 ft^3/s overbank flow which had bypassed the slope-area site. Local flooding from small drainages and erosion along gravel roads occurred in residential areas throughout the Sawmill Creek basin. Gravel roads oriented parallel to overflow channels concentrated the floodwaters, thereby reducing damage to structures located on the flood plain.

Salmon Creek Basin

Salmon Creek originates at the terminus of Bear Lake Glacier and flows southwesterly for 7 mi to its confluence with the Resurrection River. Below the canyon mouth, Salmon Creek is a braided stream (gradient 0.015 ft/ft) traversing a broad alluvial flood plain bounded on the west by the Alaska Railroad. Lost Creek is the largest tributary to Salmon Creek, with combined flows originating from Lost, Grouse, and Bear Creek drainages. Above its confluence with Salmon Creek, Lost Creek has a total area of 23.6 mi^2 at Seward Highway Bridge 600 (site 11), and accounts for over 65 percent of the total 36.0-square-mile Salmon Creek basin (site 14) (excluding the Clear Creek drainage). Peak flow of Bear Creek was reduced by the effect of storage in Bear Lake, which was at seasonal low stage at the time of the storm.

Grouse Creek

Grouse Creek, which drains a small basin adjacent to the Seward Highway, washed out several sections of a 1-mile stretch of the roadway and flowed over the road upstream of Grouse Lake. Turbulence induced by drop structures in the main channel and small landslides that diverted the flow caused erosion of the highway embankment. Embankment material and landslide debris were deposited farther downstream in Grouse Creek and at the entrance to Grouse Lake. The peak discharge in the canyon of Grouse Creek (site 10) was 1,890 ft^3/s or 395 $(ft^3/s)/mi^2$; the average velocity in the main channel was calculated to be 11 ft/s.

Lost Creek

Lost Creek originates in the high alpine, non-glacial lake basin of Lost Lake (lake area, 0.57 mi^2) and Lower Lost Lake (lake area, 0.05 mi^2), and cascades through a steep-walled bedrock canyon 4.7 mi downstream to the Lost Creek alluvial fan. The drainage area of the basin upstream from the apex of the fan (site 9) is 8.42 mi^2. The stream slope is 0.11 ft/ft through the canyon and 0.039 ft/ft from the apex to the toe of the fan.

Landslides, slumping, and other slope failures along the densely forested steep-walled (32 degrees or greater) canyon of Lost Creek combined with floodwater to cause damming and short-term storage of water and rock debris. Mature spruce trees were eroded from the hillsides, and boulders as large as 8 ft in diameter were deposited along the meandering channel. The channel is incised through deposits of boulders, cobbles, and gravel which are 20 to 25 ft deep and less than 100 ft wide in the canyon. The largest slide formed a debris dam about 1 mi upstream from the apex of the fan. When the dam was breached, the floodwaters mobilized the material as a debris-laden flood, which eroded a meandering, entrenched channel 10 ft deep and 80 ft wide.

The peak discharge of the flood on Lost Creek, computed using data from a slope-area survey at the apex of the fan (site 9), was 14,000 ft^3/s, or 1,700 $(ft^3/s)/mi^2$. The main channel stream velocity averaged 16 ft/s. This estimate of debris-laden peak flow may be too high because of the large amount of sediment in transport, and because the high-water marks may have been left before major channel erosion occurred.

Below the apex, the debris-laden flood eroded new channels of cobbles and gravel and washed out two subdivision road bridges. Deposits of coarse sand, gravel, and cobbles, 2 to 8 ft thick, were distributed randomly across the fan surface, burying buildings, equipment, and vehicles (figs. 10 and 11). Mature Sitka spruce trees on the Lost Creek fan within the Old Mill Subdivision were buried to depths of 2 to 8 ft above the 1986 root level. Many of the trees uprooted by the flood were between 100 and 150 years old. Several large spruce trees in the overbank area showed signs of previous fill. The trees which were found to be about 140 years old, had developed two or three root systems at different heights on the trunk. The lowest of these multiple root systems was 5.5 ft below the 1986 pre-flood land surface.

Figure 10.--Water and debris-laden flood damage to residence on the Lost Creek alluvial fan.

Figure 11.--Flood and debris damage to residence on the Lost Creek alluvial fan.

A large part of the debris-laden flood shifted channels near the old mill at the apex of the Lost Creek fan, and discharged toward the east into Grouse Lake. Below the confluence of Lost and Grouse Creeks, large quantities of sediment and trees were eroded from streambanks, causing the washout of a bridge and flooding of residences northwest of the Seward Highway. Severe flooding and lateral bank erosion also occurred upstream from Seward Highway Bridge 600 (site 11) and the Alaska Railroad bridge at milepost 6.0. Lost Creek reached a peak stage of 143.00 ft at Seward Highway Bridge 600 (site 11) and 142.00 ft at the Alaska Railroad bridge 35 ft downstream from the highway. Logs and other debris lodged on the railroad bridge pilings (fig. 12). This bridge eventually failed. The U.S. Army Corps of Engineers (1975) recognized the possibility that debris buildup on bridges would cause decreased capacity and backwater effects (greater depths) upstream from the structures. The calculated peak discharge at this point was 8,500 ft^3/s. About 500 ft^3/s of this water overflowed the south bank upstream from the highway bridge, eroded 50 ft of streambank, and flooded residences along the west side of Seward Highway.

Salmon Creek

Flooding was severe throughout the Salmon Creek basin. Damage was particularly severe to residential and commercial property in the Questa Woods and Camelot by the Sea subdivisions and near Nash Road.

The peak October 1986 flow of 3,910 ft^3/s from the 7.10-square-mile basin (site 12), 1.2 mi downstream from the steep, glacier-clad headwaters of Salmon Creek, represents a unit runoff of 551 $(ft^3/s)/mi^2$. Severe lateral erosion of 30 ft or more took place along the north bank beginning at the slope-area measurement

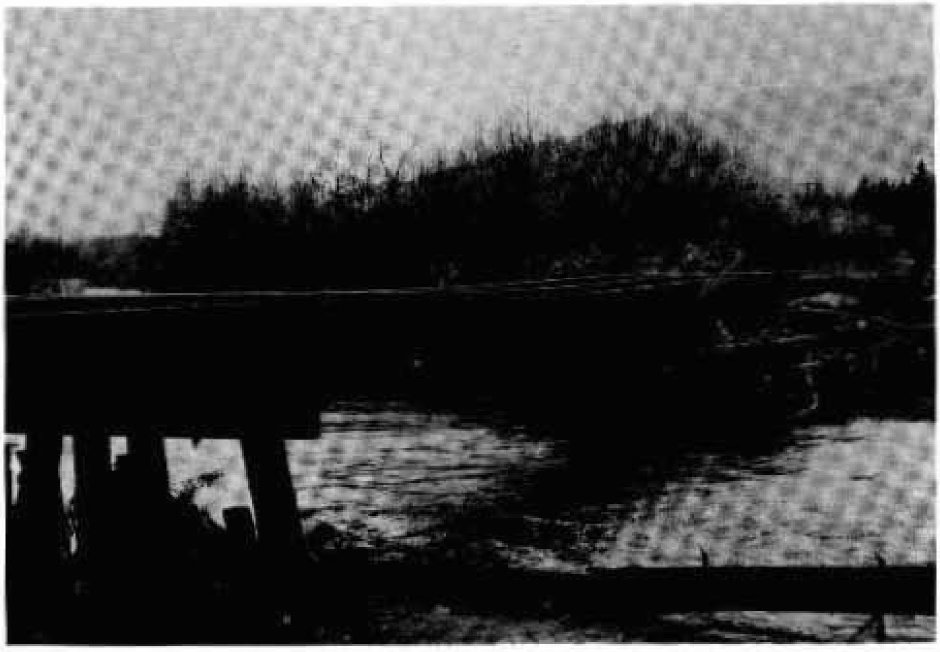


Figure 12.-Flood and floating debris damage to Alaska Railroad bridge at Mile 6.0, Salmon Creek, October 12, 1986.

site and extending 0.8 mi downstream. This accelerated erosion left a vertical cutbank 10 to 15 ft high and contributed to the washout of Questa Woods Subdivision roads, and a bridge 0.4 mi downstream. The erosion by Salmon Creek has left a vertical cutbank within 115 ft of the channel of Bear Creek, which is perched 7 ft above the Salmon Creek streambed. Bear Creek at one time entered Salmon Creek at this point but has been channelized so that it now flows westward to Lost Creek. Continued erosion of the cutbank could eventually lead to the recapture and diversion of the flow of Bear Creek into Salmon Creek.

Farther downstream, debris blocked the Alaska Railroad bridge at milepost 4.8 and diverted water over and around the small spur dike along the south bank at the bridge. The diverted water washed out about 500 ft of track. The potential for debris blockage and flow diversion at this location was also identified by the U.S. Army Corps of Engineers (1975, p. 7 and fig. 6). Some of the overbank flow upstream from the bridge combined with the diverted water and then flowed southward along the railroad embankment. Residential property was extensively flooded and roads in Camelot by the Sea Subdivision were washed out. Gravel roads such as Cemetery Road running parallel to the flow were eroded and became channels of flow. Floating debris also blocked the Alaska Railroad bridge at milepost 3.7; bridge pilings were sheared and 200 ft of track and embankment washed out 800 ft to the south of the bridge. The floodwater came within 2.5 ft of the low steel of the railroad bridge. Bridge 1024 on Cemetery Road was completely inundated.

The 4,000 ft^3/s of Salmon Creek floodwaters that flowed through Bridge 853 at Nash Road (site 14) came within 1.0 ft of low steel. Additionally, about 6,000 ft^3/s of water overflowed a 2,000-foot section of Nash Road with an average water depth of 1.5 ft. About 300 ft^3/s of overflow bypassed Nash Road to the east and washed out 18 ft of the roadway. The sudden release of water impounded by the railroad embankment and accumulated debris at bridges caused temporary increases in peak discharges and consequent accelerated erosion. The combined peak discharge for Salmon Creek at Nash Road was computed to be 10,300 ft^3/s. This total includes about 2,800 ft^3/s of floodflow from Box Canyon Creek, which entered Salmon Creek through Clear Creek at Bridge 599 (site 13). Large quantities of coarse sediment were deposited in the main channel of Salmon Creek below the confluence of Clear Creek due to lower stream gradient and velocity in Salmon Creek.

Resurrection River Basin

Resurrection River drains a 169-square-mile basin (16 percent perennial snow and ice) in which mean annual precipitation is 100 in. In its lower reaches, the Resurrection River is a braided alluvial stream with high velocities and an average gradient of 0.0038 ft/ft below Exit Glacier. The river's low banks are densely vegetated. Runoff from steep, glaciated mountain basins tributary to Resurrection River deposits large quantities of coarse bed material at their mouths, forming large alluvial fans and providing high sediment loads to the river. The steep alluvial channels of Exit Glacier and Paradise Creeks (0.015 ft/ft) deposit most of their coarse bed material at their confluence with Resurrection River.

The Exit Glacier Road traverses the northern edge of the Resurrection River flood plain from the Seward Highway (mile 0.0) to Bridge 1390 (site 5) at mile 7.2 of the road. Although the October storm caused flooding and erosion along Resurrection River adjacent to the Exit Glacier Road, the most destructive erosion and sediment deposition resulted from floodwaters discharging across the steep alluvial fans of several small basins traversed by the road (plate 1). Numerous washouts and overflows occurred along the road.

The coastal mountain barrier effect on precipitation in the Resurrection River basin was pronounced -- total precipitation for October 9-11 decreased from 17.97 in. at Seward, to 10.14 in. at Exit Glacier, to 8.43 in. at the Cooper Lake Project near the headwaters of Resurrection River (table 1). As a consequence, runoff from the 106-square-mile basin of Resurrection River above Bridge 1390 was less than the combined runoff from the several small mountain basins whose streams enter the river downstream from the bridge.

The stage of the October 11 flood peak on Resurrection River at Bridge 1390 was 353.28 ft (Federal Highway Administration datum) -- 3 ft below low steel of the bridge. A comparison of cross-section surveys made prior to the flood and on October 14 shows that about 2-foot general scour occurred in the bridge section.

Bridge 1389, at mile 4.7 of Exit Glacier Road, is on the steep alluvial fan of a stream that drains a 3.11-square-mile basin. The floodwaters deposited streambed material both in the bridge opening and on the bridge deck (figs. 13 and 14). The road was washed out at the east abutment of the bridge and at several other locations across the alluvial fan.

Box Canyon Creek, which crosses Exit Glacier Road through Bridge 1295 at mile 1.7, drains a 12.1-square-mile basin. Landslides have temporarily dammed the entire channel in the past (Lemke, 1967, p. 22) to produce storage-release floods downstream from the canyon. During the intense rainfall of October 10-11, several landslides into the creek contributed to the high sediment load. An old landslide 0.5 mi above the canyon mouth temporarily dammed the stream and subsequently

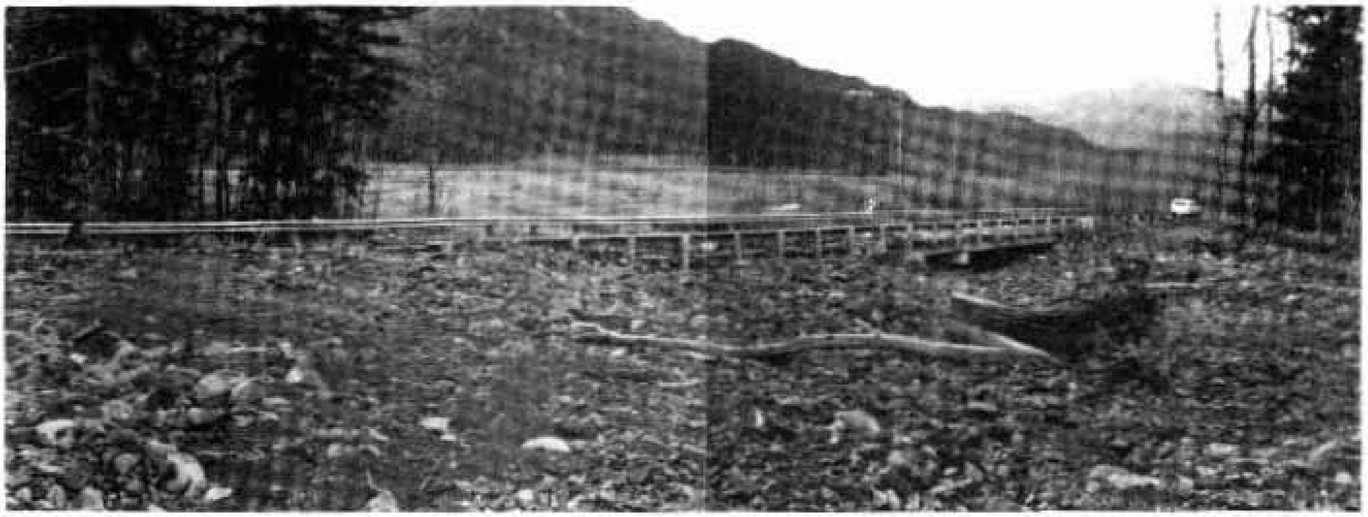


Figure 13.--Cobble and gravel deposits at Bridge 1389, mile 4.7 Exit Glacier Road. View downstream on October 13, 1986.

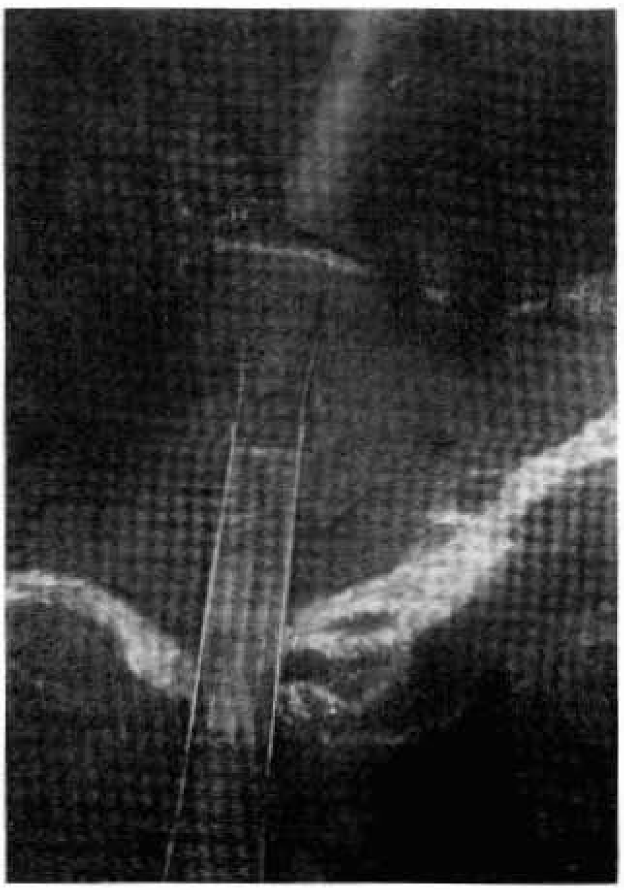


Figure 14.- Aerial view looking east at Bridge 1389, mile 4.7 Exit Glacier Road, October 13, 1986.

released a debris-laden flood that caused a major channel shift at the canyon mouth. Downstream, the flood breached a manmade levee of streambed material on the southeast bank, spread over the entire alluvial fan surface, and washed out Exit Glacier Road between miles 0.8 and 1.7. The debris-laden water was concentrated in an abandoned channel at mile 1.2, where erosion exposed multiple-root systems (like those described along Lost Creek) on 150-year-old Sitka spruce trees to a depth of 7 ft below the pre-1986 flood fan surface and uncovered buried tree stumps cut during construction of the Alaska Railroad 65 years ago (Dr. Robert V. Kesling, Alaska Vocational and Technical School, oral commun., 1987). Near the apex of the Box Canyon alluvial fan, the active channel is artificially leveed at an elevation about 8 ft higher than the abandoned channel. Breaching of the levee by future floods would again result in diversion of flow to the abandoned channel and the inundation and erosion of Exit Glacier Road.

About 2,800 ft^3/s of floodwaters from Box Canyon Creek were diverted into Salmon Creek through Clear Creek at Bridge 599 (site 13) at mile 3.9 Seward Highway. Most of the water from Box Canyon Creek bypassed Bridge 1295 and left it unaffected by either erosion or deposition of material. However, the water eroded and inundated the approaches to Bridge 1295 and came within 3 ft of the bridge low steel. The remaining flood waters from Box Canyon Creek flowed southward along the embankment of the Seward Highway, flooding residential and commercial property and finally entering Resurrection River at Bridge 598.

Flood-peak stage and discharge data were collected at the Seward Highway (site 6) during the period 1965-67. The National Weather Service has operated a flood-stage warning station at Seward Highway Bridge 598 since 1977. The stage hydrograph for the October 1986 flood on Resurrection River at Bridge 598 (site 6) is shown in figure 15; stage and discharge data for other sites on the river are summarized in table 2.

The combined Resurrection River flow (20,400 ft^3/s) at the three highway bridges, and a flow of 10,000 ft^3/s from Salmon Creek caused extensive flooding and damage to residential and commercial property downstream from the Seward Highway. The extent of damage by inundation and erosion along both streams was intensified when trees and other debris were carried downstream to lodge at bridge piers and other obstructions (fig. 16).

Japanese Creek

Japanese Creek (U.S Geological Survey, 1983, p. 226) originates in a high altitude, glaciated basin that drains through canyon walls that have been greatly over-steepened by glacial erosion. The main stream channel through the 3.48-square-mile basin above the canyon mouth has a slope of 0.19 ft/ft. At the canyon mouth, a broad fan 1.5 mi long and 1 mi wide extends to the valley alluvium of Resurrection River. The slope of the stream channel is 0.082 ft/ft downstream from the fan apex and decreases to 0.020 ft/ft as the active stream channel widens in an area of high deposition farther down the fan apron.

As in other alpine basins in the Seward area, retreating glaciers have left lateral moraines perched on steep slopes in the upper basin of Japanese Creek. A large landslide 0.1 mi above the canyon mouth, identified by Lemke (1967), was reactivated by the intense rainfall of October 10-11 and deposited rock and

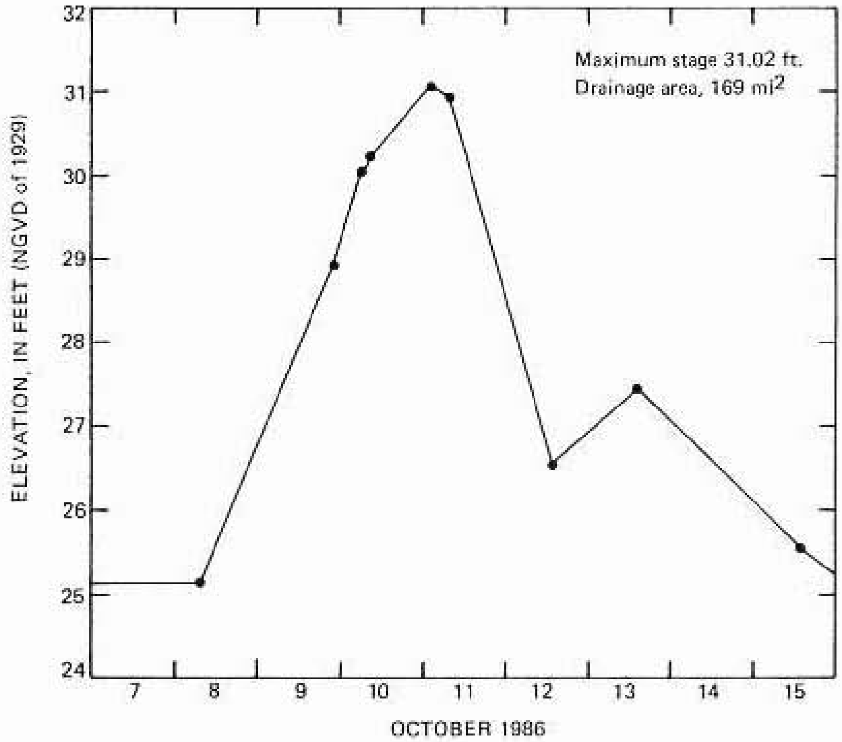


Figure 15.--Stage hydrograph of Resurrection River at Bridge 598 (site 6) October 7-15, 1986. (National Weather Service)

Figure 16.--Debris lodged on bridge pilings, Resurrection River.

boulders as large as 6 ft in diameter in the stream channel. When the resulting debris dam failed, the flood washed out a manmade levee along the southeast stream bank at the apex of the fan and inundated and eroded abandoned channels to the south and east. Similar flooding and erosion occurred at this site in August 1966 (fig. 17). The entrenched channel at the apex of the fan, about 25 ft deep and 100 ft wide with a slope of 0.082 ft/ft, meanders across the 300-foot-wide apex. The flood-fighting efforts of Seward bulldozer operators, working continuously through the night of October 10-11, contained Japanese Creek within this most recent fanhead trench (Frank Diekgraeff, METCO, oral commun., 1986).

Debris-laden floods on Japanese Creek in August 1966, October 1969, September 1976, September 1982, and again in October 1986 document the frequent recurrence of stream damming and surge-release flooding of sufficient volume to be transported past the canyon mouth to affect the lower portion of the alluvial fan. The fanhead trench conveyed sediment-laden water to the lower portion of the fan where the active stream channel widens, the slope decreases to 0.020 ft/ft, and rapid deposition occurs. In October 1986, the flood flow migrated laterally, inundating and eroding subdivision roads west of Forest Acres Subdivision.

Rudolph Creek

Rudolph Creek drains a high-altitude, glaciated basin of 1.00 mi^2 above the canyon mouth (site 15) at the southern edge of the Japanese Creek fan. Below its origin at the base of an ice-cored moraine, the main channel slope is 0.14 ft/ft. About 0.5 mi below the moraine, the stream enters a steep canyon, incised in bedrock, with an abrupt increase in slope to 0.38 ft/ft. The lack of recent landslide and debris-flow activity along Rudolph Creek downstream from ice-cored moraine is indicated by the absence of a distinctive alluvial fan at its canyon mouth. If the glacier and ice-cored moraine continue to melt, however, readily erodible material will become available and the main channel could be dammed by mass-movement phenomena. In addition to the surge-release flooding potential from such debris dams, floods are also possible from the sudden breaching of small lakes on ice-cored moraines (plate 2).

The peak discharge at the Rudolph Creek canyon mouth (channel slope of 0.083 ft/ft) on October 11 was determined to be 1,020 ft^3/s, or 1,020 $(ft^3/s)/mi^2$; calculated mean velocity was 11 ft/s. This was the maximum rainfall-runoff flood (unaffected by surge-release flooding) calculated for the small mountain basins near Seward. Farther downstream, the flood washed out culverts and roads, inundated and eroded channels across the base of the Japanese Creek fan, and deposited coarse sediment in a lagoon upstream from Third Avenue. The rapid runoff from Rudolph Creek and several other small mountain streams combined to cause extensive flooding along Third and Fourth Avenues. Road overflow from the lagoon bordering Third Avenue eroded the saturated artificial fill along Fourth Avenue and deposited sediment in the small boat harbor (inset B, plate 1).

Lowell Creek

The original townsite and older parts of Seward are built on the fan at the mouth of Lowell Creek canyon. The fan is 1.2 mi long and 0.5 mi wide, and rises at an average gradient of 0.052 ft/ft from sea level to an altitude of 130 ft at the mouth of the canyon. Following repeated flooding and damaging erosion and (or)

Figure 17.--Views upstream at apex of Japanese Creek alluvial fan.

a. After flood of August 1966

b. After flood of October 1986

deposition within the townsite, a diversion levee and a 2,000-foot long, 10-foot diameter tunnel were constructed in 1940 to divert Lowell Creek into Resurrection Bay at the southern edge of the city. Subsequently, debris-laden floods through the tunnel have deposited large quantities of sediment over the road and Bridge 1136 repetitively -- in August 1966, September 1967, October 1969, September 1976, and again in October 1986.

During a flood in August 1966, high-water marks were 2 ft below the crest of the upstream end of the Lowell Creek diversion levee, which angles across the stream (site 16); in October 1986 the water came within 0.7 ft of the crest at this point (fig. 18). During the night of October 10-11, debris from small landslides above the tunnel entrance, at the downstream end of the levee, temporarily obstructed the entrance, and the water level surged to within a few feet of the crest of the levee. Blockage of the tunnel entrance or breaching of the levee dam would have caused flooding, erosion, and deposition through the city of Seward downstream from the canyon mouth.

Spruce Creek

Spruce Creek drains a 9.26-square-mile steep mountain basin upstream from the U.S. Geological Survey's stream-gaging station (site 19); mean annual precipitation in the basin is 112 in. and 8 percent is glacier-covered. Spruce Creek originates at a small glacier and cascades 3.5 mi through a steep-walled, bedrock canyon in which landsliding and rock and snow avalanches occur frequently. About 2.5 mi above its mouth the stream gradient decreases abruptly to 0.025 ft/ft and continues in a meandering alluvial channel 300 ft wide and bounded by densely vegetated bedrock slopes. A small lake formed by perennial snow within the headwaters of Spruce Creek (plate 1) presents a potential for surge-release flooding. The Lowell Point fan-delta at the mouth of Spruce Creek canyon extends 0.5 mi into Resurrection Bay with a gentle stream channel slope of 0.021 ft/ft. The braided, distributary channels of lower Spruce Creek are evidence of random shifting of stream courses that takes place on the distal parts of an alluvial fan (fig. 19).

The intense rainfall on October 10-11, 1986 triggered a massive debris avalanche (described earlier) on the steep northern slope of Spruce Creek 0.8 mi above its mouth (fig. 20 and 21). The mass of debris deposited in the channel was 1,000 ft long and 200 ft wide, which caused the damming and short-term storage of water, earth, rock and trees (fig. 22). The breaching of the dam released a water-debris slurry which was rapidly transported downstream. All the debris avalanche material at the base of the slope was removed by the ensuing flood. The catastrophic release of the stored water and debris eroded a new channel below the dam. Prior to the October 1986 storm, the stream channel at the gaging station had remained relatively stable over a 21-year period and there was no historical evidence of storage-release flooding within the basin. In 1986, however, the former channel through the densely vegetated flood plain along the left bank was eroded to a width of 40 to 45 ft and a depth of 3 ft below the pre-1986 flood-plain level (figs. 23 and 24). An estimated 20,000 ft^3 of material was eroded from the channel extending from the debris dam to the apex of the alluvial fan 1,500 ft downstream. Farther downstream, trees from the avalanche and the streambanks became jammed in the channel along the right (south) side of the alluvial fan, diverting the debris-laden water northward and away from the sewage treatment plant. Residential and commercial property was damaged, power lines were severed, and Bridge 1783 was washed out. In September 1982, severe scour and lateral erosion by Spruce Creek caused damage to the main sewer line buried across the fan-delta.

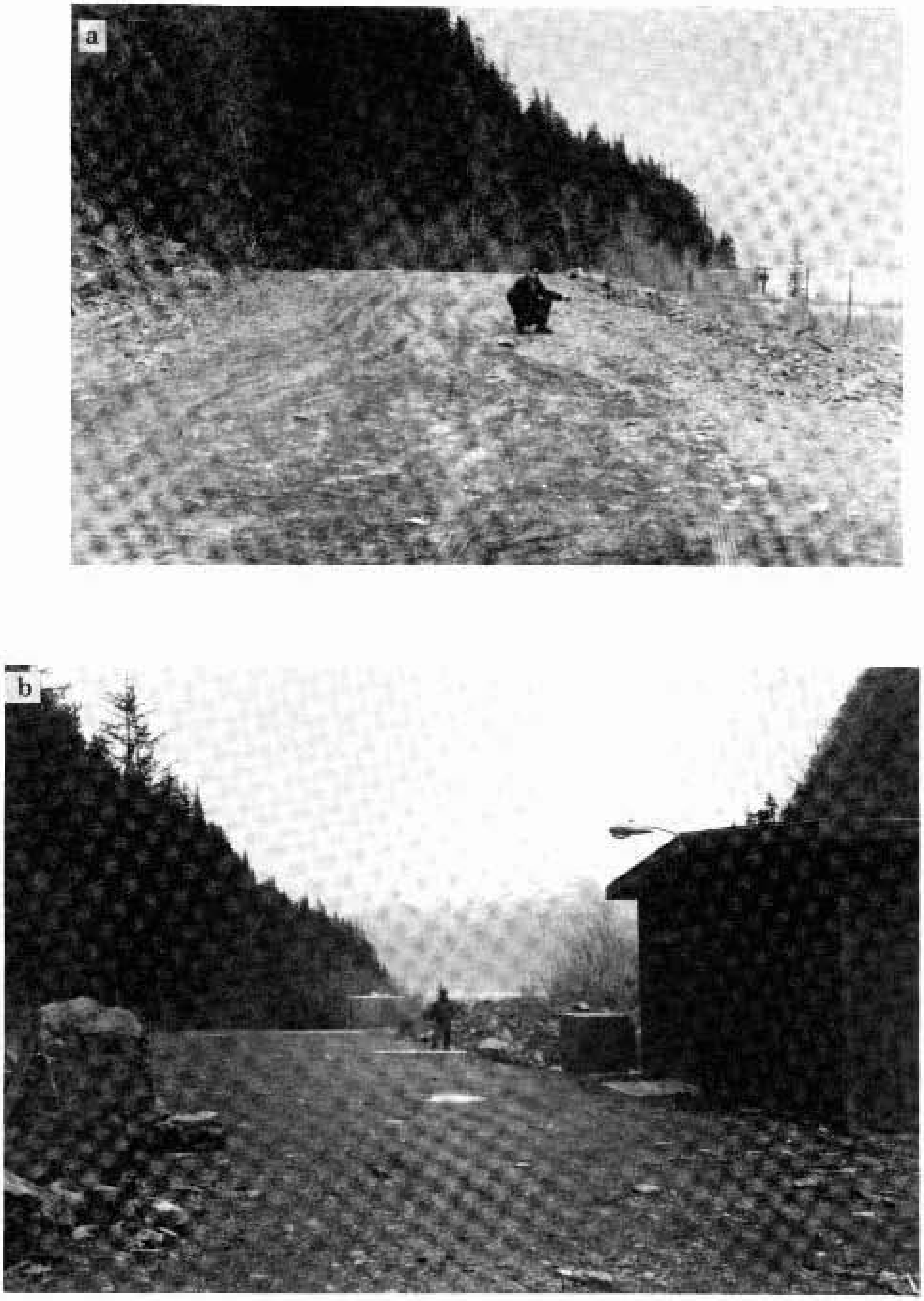


Figure 18.--Highwater marks (HWM) on upstream side of Lowell Creek diversion levee.

a. Flood of August 1966, HWM = 2 feet below crest

b. Flood of October 1986, HWM = 0.7 feet below crest

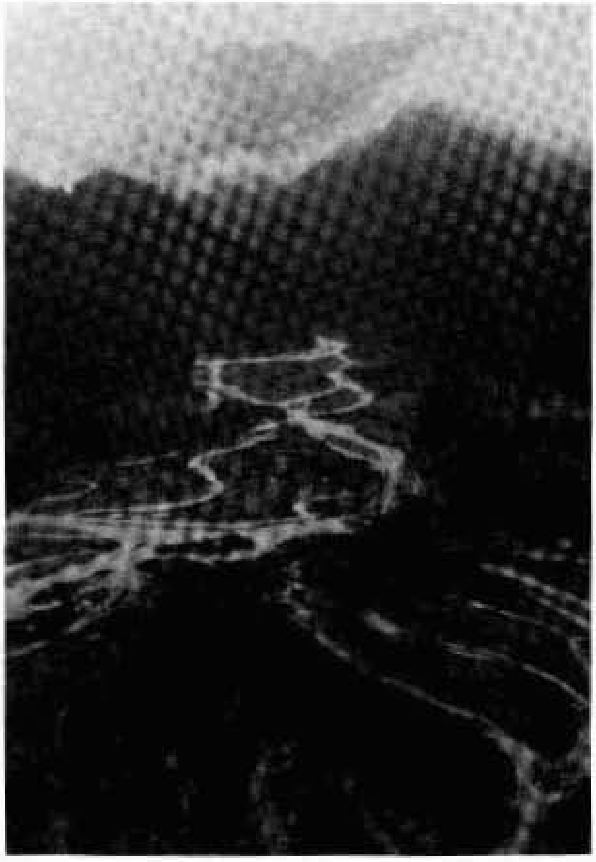


Figure 19.--Spruce Creek alluvial fan, October 14, 1986.

Figure 20.--Debris-avalanche scar on Spruce Creek, October 12, 1986.

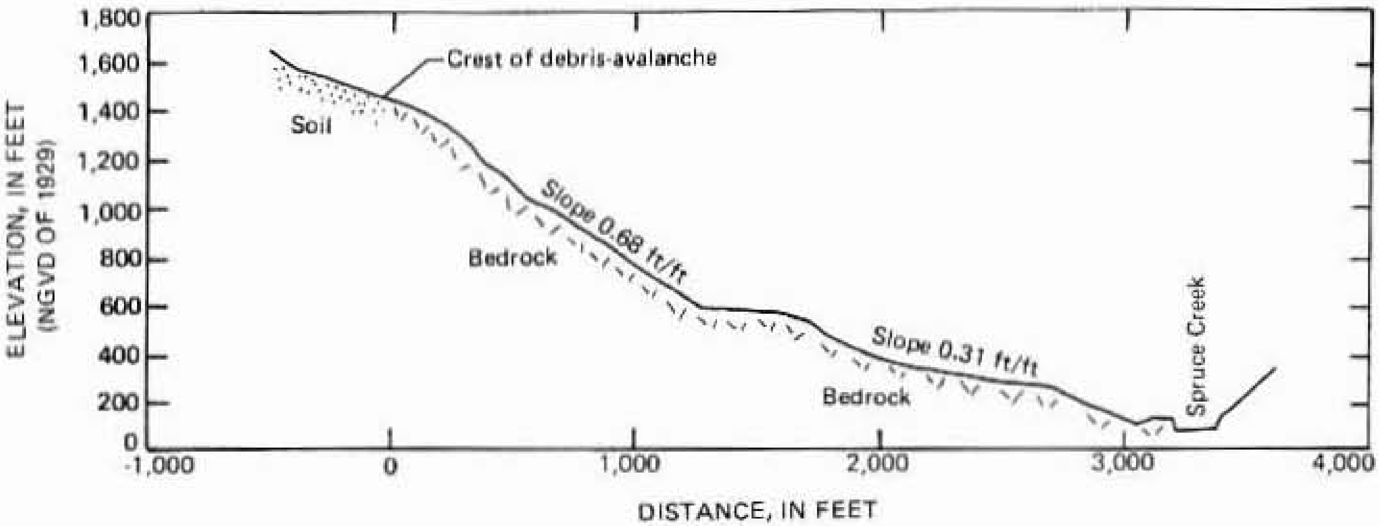


Figure 21.--Longitudinal profile of Spruce Creek debris-avalanche scar

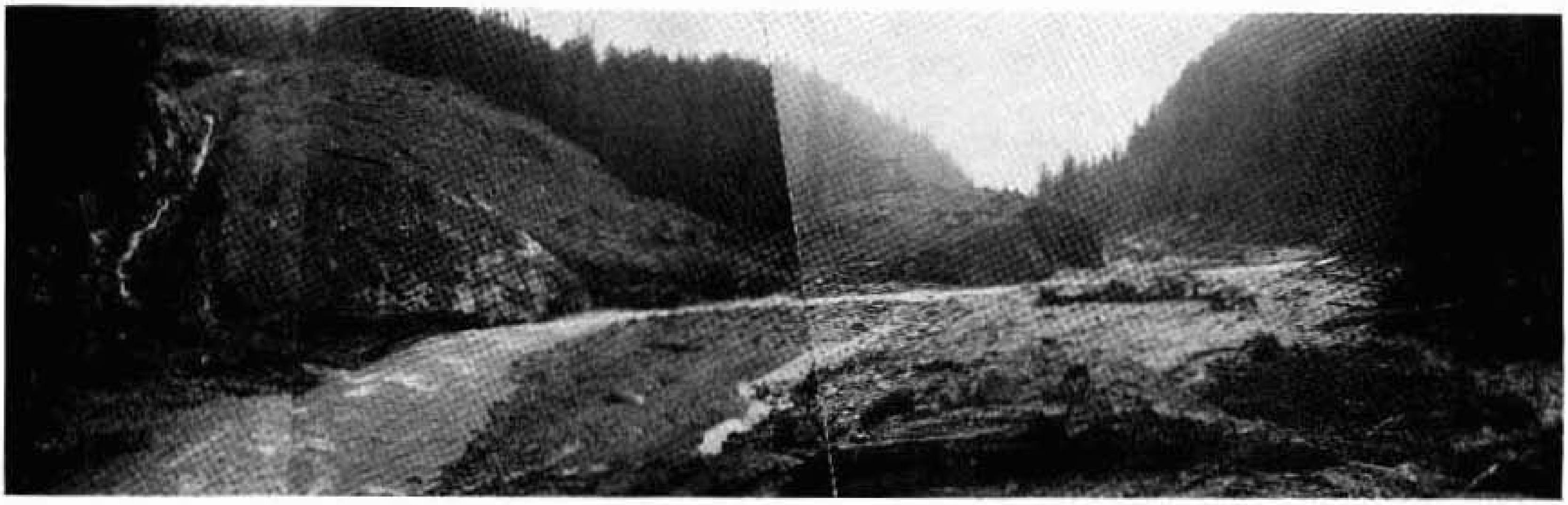


Figure 22.--Spruce Creek debris-avalanche scar and location of debris dam.

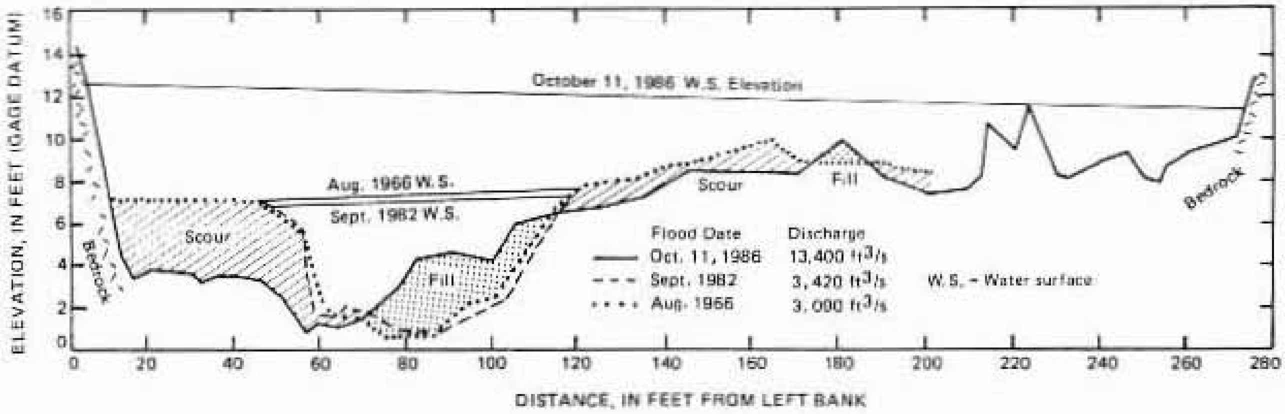


Figure 23.--Channel cross sections at Spruce Creek gaging station (site 19).

The peak discharge 1,000 ft upstream from the debris avalanche (site 18), computed using slope-area methods, was 5,420 ft^3/s, 608 $(ft^3/s)/mi^2$. This discharge was not affected by the formation and breaching of the debris dam. However, the peak discharge of the debris-laden flood surge, determined at the gaging station (site 19), was 13,600 ft^3/s, which is equivalent to a unit runoff of 1,500 $(ft^3/s)/mi^2$. The average velocity in the main channel through the slope-area reach was calculated to have been 16 ft/s, with a slope of 0.017 ft/ft. The flood stage at the gaging station, 1,000 ft downstream from the debris dam, was 4.5 ft higher than any previously known flood and the discharge was four times the previous maximum.

Hydraulic and Statistical Analyses

Evaluation of Flood Measurements

The slope-area method (Dalrymple and Benson, 1967) was used to estimate peak discharges at ten high-gradient reaches (friction slopes ranging from 0.0097 to 0.0828) on nine streams. The hydraulic properties used in the computations for each reach are listed in table 3. Estimates of peak discharge using the slope-area method for unstable, steep-gradient streams are subject to large errors (Jarrett, 1984; Randall and Humphrey, 1984), and are generally too large if highwater marks were deposited before major channel erosion occurred. To minimize such errors in indirect determinations of discharges for the October 1986 flood, the surveys were made, where possible, in the bedrock canyons above the fan apex where flows were confined and only the streambed is subject to scour and fill.

Peak discharges for the ten reaches were also calculated using methods described by Riggs (1976) and by Jarrett (1984). Results of these calculations are compared with the slope-area determined values (table 4). A rating of "poor" is assigned if the measurement error is considered to be larger than 25 percent. Peak discharges determined using the slope-area method, with field-selected Manning roughness coefficients, averaged 30 percent higher than values computed using Jarrett's method and averaged 7 percent higher than values computed using Riggs' method. The largest difference for a slope-area determined peak discharge was that for Lost Creek, which was 49 percent higher than the value computed using Jarrett's methods.

Figure 24.--Views downstream from Spruce Creek streamgaging station (site 19).
a. September 1967
b. October 12, 1986

Table 3.--Summary of hydraulic properties for slope-area discharge determinations for selected streams at Seward, October 1986

[Site numbers correspond to those on plate 1]

			Average main channel									
Site No.	Stream	Peak discharge (ft^3/s)	Manning roughness coefficient, n (field selected)	Velocity (ft/s)	Cross-sectional area (ft^2)	Width (ft)	Depth (ft)	Hydraulic radius, R	Friction slope (ft/ft)	Velocity head coefficient	Froude number, F	Accuracy of peak discharge
1	Godwin Creek	30,000	0.070	16.1	1,870	228	8.20	8.07	0.0414	1.00 - 1.018	0.91 - 1.07	Poor
2	Sawmill Creek	2,760	.048	8.47	326	103	3.17	2.99	.0324	1.00	.62 - 1.28	Poor
9	Lost Creek	14,000	.035	16.1	864	204	4.25	4.03	.0398	1.22 - 1.78	1.27 - 1.33	Poor
10	Grouse Creek	1,830	.035	10.3	175	35	5.00	4.40	.0097	1.00	.80 - .86	Good
12	Salmon Creek	3,910	.046	8.96	439	134	3.28	3.38	.0147	1.00	.72 - 1.16	Poor
15	Rudolph Creek	1,020	.060	10.8	98	39	2.51	2.35	.0828	1.00	.90 - 1.45	Fair
18	Spruce Creek	5,420	.050	8.44	642	155	4.14	3.99	.0161	1.34 - 2.97	.62 - .97	Fair
19	Spruce Creek	13,600	.045	12.7	1,098	226	4.87	4.61	.0170	1.31 - 1.91	.77 - 1.16	Poor
21	Sixteen Mile Creek	2,540	.060	15.4	170	30	5.67	4.18	.0501	1.00	.86 - 1.38	Poor
24	Porcupine Creek	4,000	.042 - .049	10.4	386	80	4.82	4.34	.0148	1.00 - 1.07	.75 - 1.32	Poor

Table 4.--Comparison of peak discharge determinations, using selected indirect methods, for October 1986 floods at Seward

[Site numbers correspond to those on plate 1; S/A, slope-area; ft/ft, foot per foot; ft^3/s, cubic foot per second]

			Estimated peak discharge					
Site No.	Stream	Slope (ft/ft)	S/A[1/] method (ft^3/s)	Jarrett[2/] method (ft^3/s)	Differs from S/A (percent)	Riggs[3/] method (ft^3/s)	Differs from S/A (percent)	S/A accuracy rating
1	Godwin Creek	0.0414	a30,000	27,500	-8	34,800	+16	Poor
2	Sawmill Creek	.0324	2,760	2,040	-26	3,200	+16	Poor
9	Lost Creek	.0398	a14,000	7,100	-49	12,400	-11	Poor
10	Grouse Creek	.0097	1,830	1,310	-28	1,050	-43	Good
12	Salmon Creek	.0147	3,910	2,770	-29	4,000	+2	Poor
15	Rudolph Creek	.0828	1,020	560	-45	790	-23	Fair
18	Spruce Creek	.0161	5,420	4,600	-15	6,700	+24	Fair
19	Spruce Creek	.0170	a13,600	9,100	-33	14,000	+3	Poor
21	Sixteen Mile Creek	.0501	2,540	1,480	-42	1,500	-41	Poor
24	Porcupine Creek	.0148	4,000	3,100	-22	3,400	-15	Poor

1/Dalrymple, and Benson (1967)
2/Jarrett (1984)
3/Riggs (1976)
a Discharge affected by surge-release flood

Debris-laden flows associated with the surge-release flooding on Godwin, Lost, and Spruce Creeks caused unsteady flow and increased the viscosity and density of the water flood. The effects of the unsteady flow, large sediment concentrations, and scour and fill introduce large errors in calculated peak discharges when using conventional energy and flow concepts, and may overestimate peak discharges (Jarrett, 1987). Although peak discharges determined by indirect methods may be in error, the survey data document channel changes and the computed sediment-laden discharges assist in determining whether surge-release flooding has occurred in the basin.

Flood Magnitude

The October 1986 peak discharges from small basins near Seward were the largest recorded since crest-stage gage stations were established in 1963. Comparison of the 1986 peak discharges with previous maximums shows that this flood had the largest unit runoff rates in the maritime area of southcentral Alaska. Figure 25, which relates flood discharge rates to corresponding drainage area, shows that peak discharge rates were greatest on basins of less than 50 mi^2; peak rates from the larger basins, such as Resurrection River, were not as outstanding. The maximum rainfall-runoff rate (unaffected by surge-release flooding) determined for a small mountain stream was 1,020 ft^3/s from a 1.00-square-mile drainage basin. The envelope curve A of figure 25, defined by the greatest discharge rates during the October 1986 flood, provides a guide for estimating potential maximum flood flows for maritime southcentral Alaska. Sites 1, 9, and 19 (triangles in fig. 25), whose discharge values are above envelope curve A, were affected by surge-release flooding from temporarily impounded waters. These surge-release debris-laden flows produced peaks substantially greater than previously determined water floods.

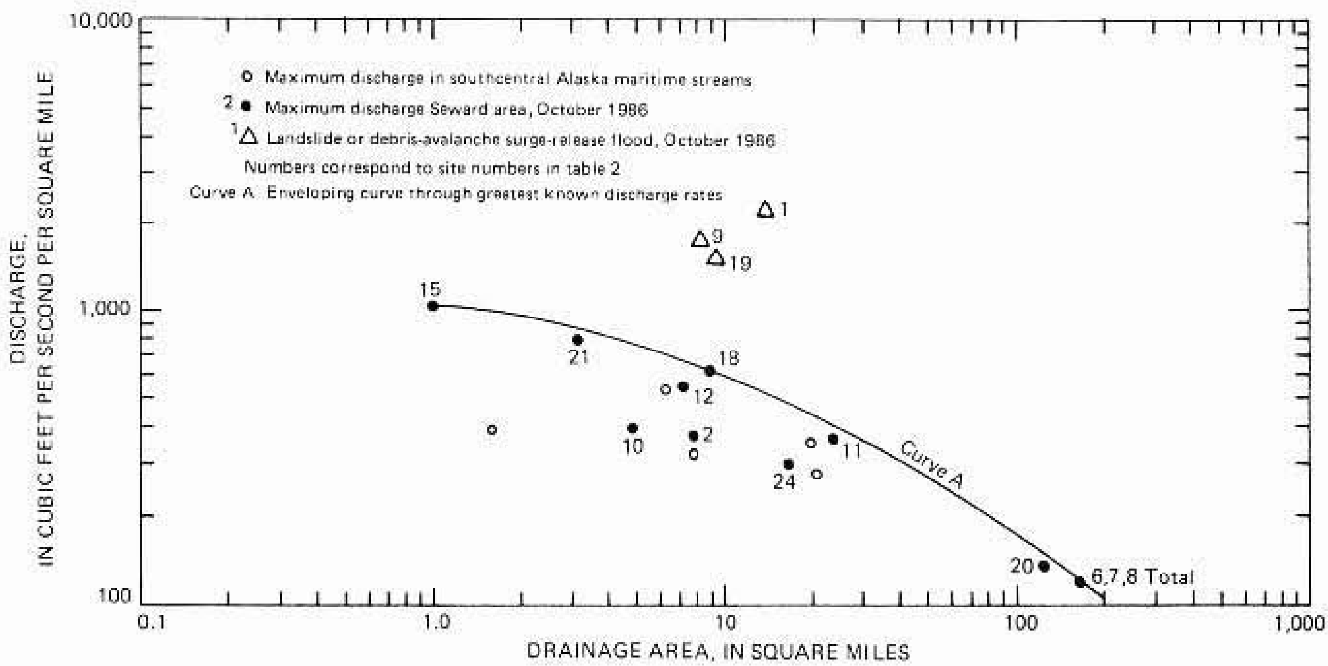


Figure 25.--Comparison of October 1986 peak discharge with maximum known flood peaks for southcentral Alaska maritime streams.

Flood Frequency

Flood-frequency analysis is the basis for the design of adequate flood-plain structures and for making management decisions about flood-plain land use. Recurrence interval, as applied to flood events, is the average number of years within which a given flood peak will be equalled or exceeded once. The frequency of a flood flow may also be stated in terms of its probability of occurrence, which for large floods is the reciprocal of the recurrence interval. Thus, a flood with a 100-year recurrence interval would have a 0.01 probability or a 1 percent chance of being exceeded in any given year. Recurrence intervals are average figures -- so that the occurrence of a major flood in one year does not reduce the probability of that flood being equaled or exceeded in the following year, or even later in the same year. All frequencies, or recurrence intervals, were estimated from station data using log-Pearson Type III frequency analysis procedures described by the Interagency Advisory Committee on Water Data (1981). Station frequency curves were developed using skew and standard deviation statistics determined by Lamke (1978).

For the area of this report, the length of available streamflow records -- 25 years -- is inadequate to reliably define flood-frequency relations for recurrence intervals as great as 100 years. Thus the extreme flood of October 1986 is difficult to evaluate by conventional flood-frequency analysis methods. Only three crest-stage stations on small drainage basins have been operated in the Seward area. A flood-frequency determination could not be made for the October 1986 peak at Lost Creek because the peak was affected by surge-release type flooding. A mixed population of instantaneous peak discharges was analyzed using a method described by Crippen (1978), in which peaks resulting from snowmelt as well as those generated by either rainfall alone or rain on snow are combined. The resulting composite log-Pearson Type III frequency distribution of instantaneous peak discharges for Spruce Creek upstream from the debris avalanche (site 18), unaffected by surge-release flooding, gives a recurrence interval of 100 years or greater, or about a 1 percent chance of being equalled or exceeded in any given year. Analysis of peak discharge data for Porcupine Creek near Primrose (site 24), also unaffected by surge-release flooding, gives a recurrence interval of 80 years, or a slightly greater than 1 percent chance of being either equalled or exceeded in any given year.

The frequency analysis presented in this report applies only to events in which runoff was not affected by surge-release flooding. Small streams draining steep mountain basins near Seward may have a higher probability of flooding due to debris dam formation and release than to "normal" rainfall- and snowmelt-runoff events. The magnitude and frequency of past catastrophic floods at Seward might also be evaluated using one or more of the geologic and dendrochronologic dating techniques described by Costa (1978) and by Costa and Jarrett (1981).

The maximum 24-hour precipitation at Seward for October 10-11, 1986 was 15.05 in., the highest recorded since 1908. Seventy-four years of annual maximum daily precipitation data for Seward (periods 1908-24, 1929-37, and 1939-86) were analyzed using the Pearson Type III distribution with log transformed data (Interagency Advisory Committee on Water Data, 1981). No adjustments were made for missing record or for changes in location of the gage. A precipitation station skew coefficient of 1.65 was used, and the high outliers of December 1934 and October 1986 were retained as part of the systematic record. This analysis suggests that the precipitation total for the October 1986 storm has a recurrence interval of greater than 100 years (fig. 26), and agrees with Nibler's (1986) determination based on the U.S. Weather Bureau's Technical Paper 47 (1963).

The Pearson Type III distribution was also used to make separate analyses of data for rainstorms which occurred principally during the months of April through October, and data for "winter" storms (November through March). These separate distributions were used to compute a combined distribution described by Crippen (1978). The resulting composite curve indicated no substantial improvement in the overall accuracy of estimate of the frequency distribution of precipitation.

Area Inundated and Flood Damage

The extent of flooding in and near Seward in October 1986 is delineated on plate 1. Because of the limitations of map scale, some local topographic features or small areas within the flood boundaries that were not inundated may not be shown. The elevation of high-water marks along streams was determined by level

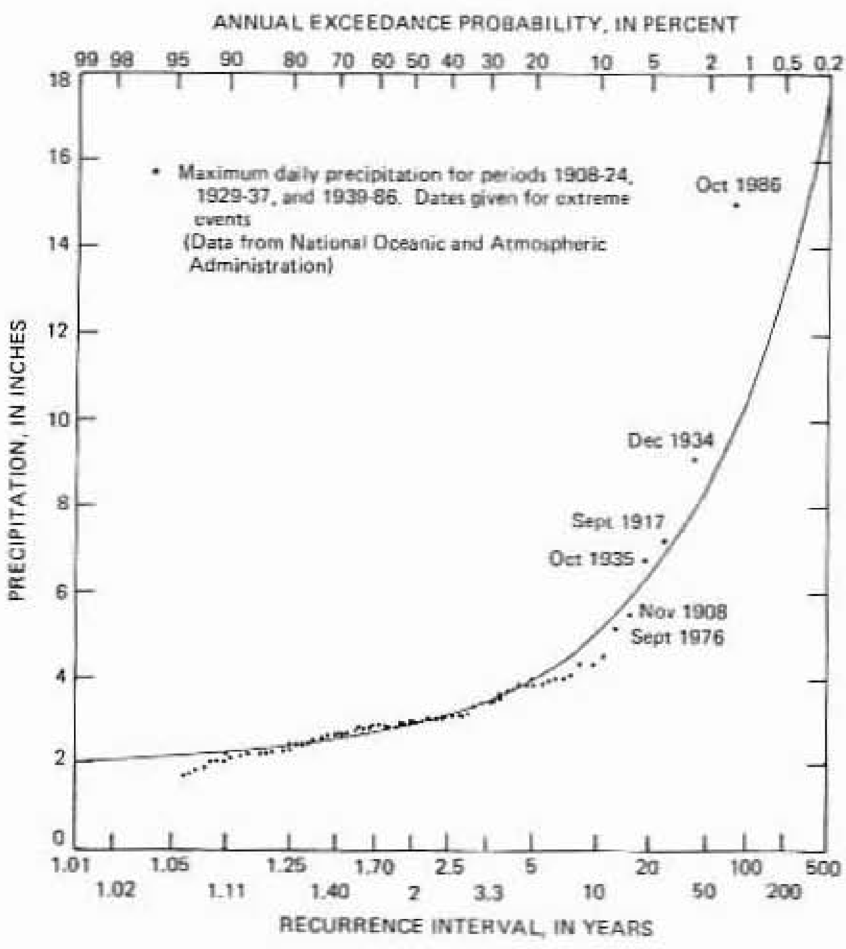


Figure 26.–Pearson Type III frequency distribution for maximum daily total precipitation at Seward.

surveys to the marks identified and flagged during or immediately following the flood. These elevations have not been plotted on the map because of their large variability, particularly on alluvial fans where severe local scour (erosion) or fill (deposition) took place. Elevations of high-water marks at selected bridges are shown in the "stage" column of table 2. Additional data on elevation of high-water marks and profiles of the flood crests may be obtained from the U.S. Geological Survey, U.S. Army Corps of Engineers, and the Kenai Peninsula Borough.

On October 27, 1986 the flooded portions of the Kenai Peninsula Borough were declared disaster areas, thereby qualifying them for Federal funds for relief and recovery efforts (Federal Emergency Management Agency, 1986). The Seward Highway was washed out and flooded, as were embankments and bridges of the Alaska Railroad. Highway travel to and from Seward was curtailed for 1 day, and rail service was interrupted for nearly 2 weeks. The City of Seward suffered extensive damage to its electric utility, many roads, bank protection works at the small boat harbor at the Fourth of July Creek levee, and the destruction of two city bridges. The principal damage to properties located on the alluvial fans was the erosion and subsequent deposition associated with the high velocities of the debris-laden floodwaters. Many subdivision roads, bridges, and residences on the fan surfaces were destroyed.

Ground-Water Fluctuations

Ground-water levels within the valley alluvium and on the alluvial fans rose very rapidly to record high levels. Water levels in an observation well at Fort Raymond (fig. 27) were influenced by intense local precipitation as well as by direct infiltration of flood waters traversing the alluvial fan of Japanese Creek about 3,000 ft upstream from the well. Water level in the well rose 20 ft to within 2 ft of the land surface. The ground water flooded basements and structures located below ground surface, particularly on the fans of Japanese and Lowell Creeks. Ground-water levels rose to the land surface on the Fourth of July Creek fan and also discharged as surface runoff along the base of the fan. Such elevated ground-water levels decrease the stability of the fans and mountain slopes, and increase the potential for mass movement of the unconsolidated materials. The gradual decline of the water level in the Fort Raymond well from October 13-23 (fig. 27) reflects the slow return to normal levels from the saturated condition of the area's alluvial fans.

FLOOD AND FLOOD-RELATED HAZARDS

Since the beginning of man's presence in the Seward area, floods and the occurrence and effects of associated mass-movement phenomena have repeatedly caused major damage to bridges, roads, private property, and public facilities. Determination of the statistical probability (also expressed as frequency or recurrence interval) of future flooding in the area is hampered by the paucity of streamflow records for the area, but the fact that large, damaging floods have affected Seward is well documented as well as being within the memory of long-term residents.

Because of the steep, rugged terrain surrounding Seward, recent urban expansion has been concentrated on the slopes of the area's alluvial fans. Abundant precipitation, frequently as intense rainstorms, coupled with a plentiful supply of unconsolidated landslide and glacial deposits, make these fan areas

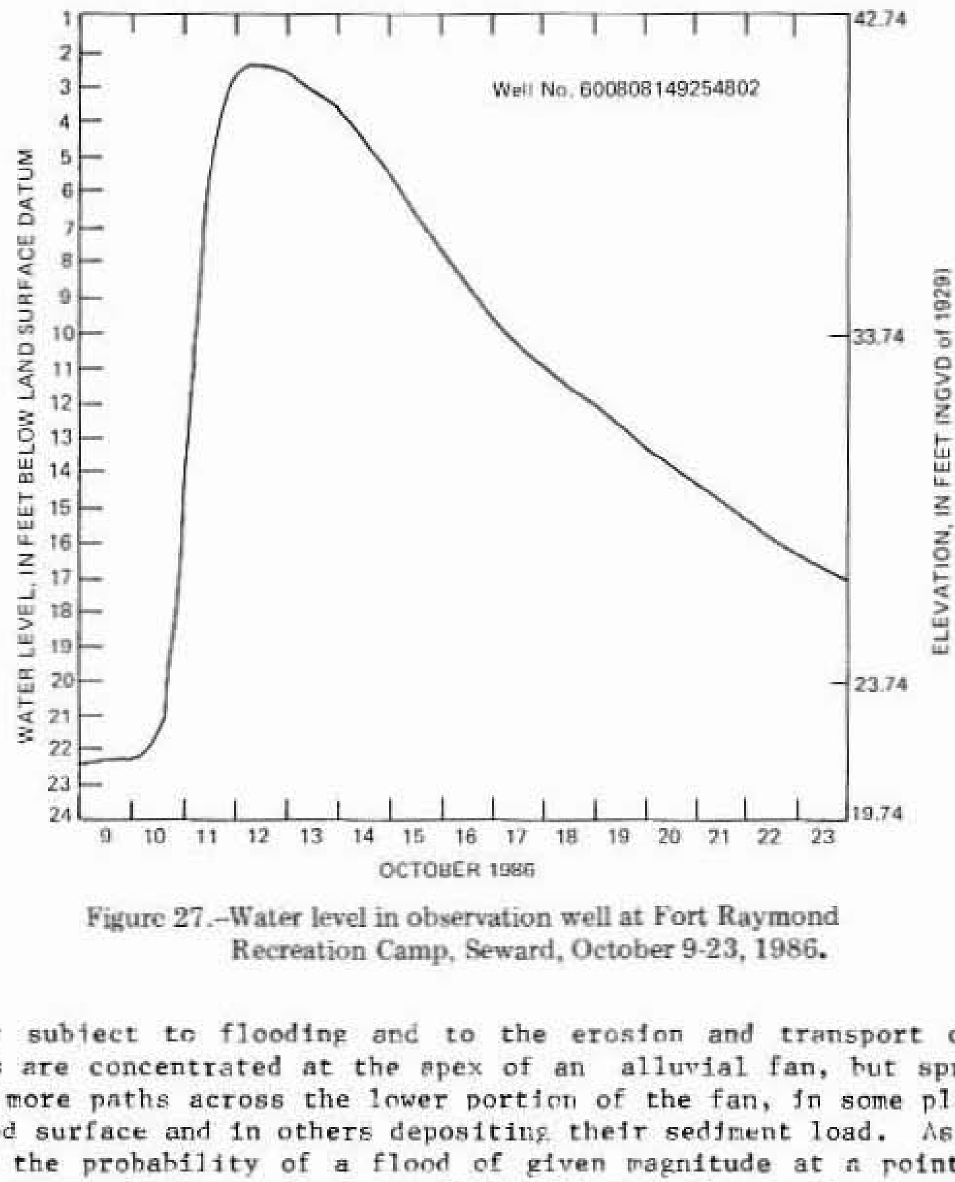


Figure 27.--Water level in observation well at Fort Raymond Recreation Camp, Seward, October 9-23, 1986.

particularly subject to flooding and to the erosion and transport of material. Flood waters are concentrated at the apex of an alluvial fan, but spread out and take one or more paths across the lower portion of the fan, in some places eroding the pre-flood surface and in others depositing their sediment load. As an alluvial fan widens, the probability of a flood of given magnitude at a point should, in general, decrease. However, flood magnitudes determined near the apex of a fan may not be indicative of magnitudes that can occur at any point further downstream on the fan surface (Dawdy, 1979, p. 1408).

Braided reaches of streams within wide flood plains and across alluvial fans are areas of very active vertical scour, lateral erosion, and constant channel migration. As these streams traverse forested areas, bank erosion causes trees and clumps of brush to fall into the stream. During the flood of October 1986, much debris was transported downstream, where it accumulated at natural channel constrictions, bridges, and culverts. Such accumulations of debris at bridges in the Seward area caused backwater, diversion or flow along road and railroad embankments, and flooding and erosion at points some distance from the normal channel. In some instances, the temporarily dammed water exerted stresses that resulted in damage to or failure of the structures.

One or more debris-laden or surge-release floods or debris avalanches that have occurred since 1964 have been identified or documented in several Seward-area stream basins. These historical and the most recent (October 1986) events were evaluated to develop a rating of the relative potential for occurrence of such mass-movement phenomena (plate 2 and table 5). The assignment of potential for debris-laden and surge-release floods was based on known past events; assignment of potential for landslides or avalanches was based on work by Lemke (1967), field reconnaissance in October 1986, and analysis of historical aerial photographs.

Table 5.--Known and potential occurrences of water-related mass-movement phenomena in steep mountain basins in the Seward area

[Relative potential for occurrence: A, high; B, moderate; C, low. See plate 2 for designated hazard areas.]

Drainage basin	Landslide/debris avalanches		Debris-laden floods		Surge-release floods		
						Potential	
	Known	Potential	Known	Potential	Known	Landslide dam	Ice or moraine dam
Fourth of July Creek	1986	A	a1982,86	A	---	A	A
Godwin Creek	1986	A	a1982,86	A	1986	A	A
Resurrection Bay tributary	---	B	1986	B	---	C	C
Sawmill Creek tributary (south)	---	B	---	B	---	C	C
Sawmill Creek	---	A	1976,86	A	---	B	C
Sawmill Creek tributary (north)	---	B	---	B	---	C	C
Glacier Creek (from Bear Lake Glacier)	---	B	1986	A	---	B	B
Grouse Creek	1986	C	1986	C	---	C	C
Lost Creek	1986	A	1969,76,86	A	1986	A	C
Lost Creek tributary	---	C	1986	A	---	C	C
Box Canyon Creek	1964,86	A	1986	A	1986	A	C
Japanese Creek	1964,66,76,86	A	1966,69	A	1966	A	C
Rudolph Creek	---	C	1986	C	---	C	A
Lowell Creek	---	A	1966,67,69,76, 86	A	---	A	C
Spruce Creek	1986	A	1966,76,82, 86	B	1986	A	A

a from Randell and Humphrey (1984)

SUGGESTIONS FOR FUTURE STUDIES

Identification and evaluation of various flood and mass-movement phenomena at Seward in October 1986 suggest several topics for future study:

1. Landslides and debris avalanches

    a. Prepare landslide susceptibility maps, in which factors of slope, soil, and geology are considered, and areas at risk are identified (National Research Council, 1985, p. 14).

    b. Assess stability of "partly detached", landslide-prone material(identified by scarps left as result of previous slides).

    c. Develop relations between rainfall, soil saturation (shallow ground-water levels), and landslide movement.

    d. Develop techniques to monitor landslide-prone slopes.

2. Floods on alluvial fans

    a. Apply alternative and recently developed methods, which take into account geomorphic, stratigraphic, and dendrochronologic evidence, to improve flood-frequency estimates for alluvial fan areas.

    b. Estimate the quantity of debris that would be transported by a particular stream in storms of various magnitude.

    c. Develop techniques for delineating areas of potential erosion and deposition on alluvial fans.

    d. Apply and evaluate special alluvial fan flood-mapping methods described by Dawdy (1979) and Magura and Wood (1980).

3. Surge-release floods

    a. Assess conditions and determine what mechanism could trigger release of stored water, e.g. thawing of ice-cored moraine or overtopping of depression on glacier or moraine.

    b. Develop techniques to monitor streams identified as having either documented or high potential for surge-release type flooding (for example, Godwin, Lost, and Box Canyon Creeks).

4. Assess effect of flood-mitigating structures (levees, bridges, etc.) and land-use regulations (avoidance, design, and control and stabilization) (National Research Council, 1985, p. 14-15) located within alluvial channels by documenting erosion and (or) deposition through time, especially following any future floods.

SUMMARY

Record-setting rainfall -- as much as 15 in. in 24 hours -- caused flooding in the Seward area, Alaska, during the period October 9-11, 1986. Broad areas along Salmon Creek and the lower Resurrection River were inundated, while the effects of the floodwaters were exacerbated by severe erosion and deposition of sediment and debris along steep-gradient mountain streams and the surfaces of alluvial fans at their canyon mouths.

Seward lies at the head of Resurrection Bay, which is bordered by the glaciated Kenai Mountains. Unconsolidated deposits, principally of glacial origin, overlie bedrock on all but the highest slopes. These deposits provide material, occasionally as landslides and avalanches, to the steep mountain streams which have built alluvial fans at their canyon mouths.

The flood of early October 1986 was not a new experience to the residents of Seward. Major floods and the accompanying damage have affected the area several times in recent history. The most severe and damaging floods have been due primarily to intensive rainfall in the months of August through November rather than to runoff from melting snow and glacier ice in late spring and early summer.

The original townsite of Seward and the present-day central business district are built on the broad alluvial fan of Lowell Creek. North of the fan, considerable development has occurred on the flood plains of the Resurrection River and Salmon Creek. More recent construction has taken place on other alluvial fan areas. Floodwaters, erosion of streambeds and banks, and the subsequent deposition of sediment and debris caused extensive damage in October 1986 along both the large, braided streams and their steep-gradient tributaries. The latter streams, however, pose the greater flood hazard due to:

1. The potential for temporary damming by landslides and debris flows within their steep canyon reaches, and the subsequent failure of those dams and resulting catastrophic "surge-release" flooding. Several such surge-release floods, whose peak flows far exceeded any previously known peaks, were documented in October 1986.

2. The potential for such streams to abruptly shift course at the apex of their alluvial fans during high runoff events, so that a single floodway or corridor at risk cannot be identified. Neither can the probable magnitude of a flood at a given point on the surface of an alluvial fan be reliably estimated.

Estimates of peak flood discharge in October 1986 were made for nine streams using indirect (slope-area) methods. Because such estimates for unstable-channel steep-gradient streams may be too large, flood peaks also were estimated using two other computation methods and the resulting values compared with those obtained by slope-area methods.

The surge-release-affected peak discharge of the flood at Spruce Creek (south of the city) was determined to be 13,600 ft^3/s, or 1,500 $(ft^3/s)/mi^2$ from the 9.26 square-mile basin. The maximum rainfall-runoff rate (unaffected by surge-release flooding) determined was that for Rudolph Creek -- 1,020 $(ft^3/s)mi^2$ for a 1.00-square-mile drainage area.

Although the intense rainfall total of 15 in. in a 24-hour period was calculated to have a recurrence interval of 100 years, the length of streamflow records for the Seward area -- 25 years or less -- is considered inadequate to reliably define flood-frequency relations for intervals as long as 100 years. However, the slope-area determined discharge of Spruce Creek above the debris avalanche indicates a recurrence interval of 100 years or greater. Flood-frequency relations cannot be defined by conventional methods for streams subject to surge-release flooding.

Water-level measurements in at least one well, reports of flooded basements, and observations on the alluvial fan of Fourth of July Creek, indicated the rapid rise of ground-water levels during the flood. Such elevated ground-water levels decrease the stability of materials on fans and slopes, increasing the potential for mass movement of the unconsolidated material.

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