U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
Alaska Department of Transportation
and Public Facilities

Geomorphology of the Lower Copper River, Alaska

U.S. Geological Survey Professional Paper 1581

USGS
science for a changing world

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may be no longer available.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

Subscriptions to Preliminary Determination of Epicenters can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—2222 West 2300 South
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey office:

- **ROLLA, Missouri**—1400 Independence Rd.

COVER — The lower Copper River near Mile 37, Copper River Highway.

CONTENTS

FIGURES

Geomorphology of the Lower Copper River, Alaska

By TIMOTHY P. BRABETS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1581

Prepared in cooperation with the Alaska Department of Transportation and Public Facilities

1997

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Mark Schaefer, Acting Director

Library of Congress Cataloging in Publications Data

Brabets, Timothy P.
Geomorphology of the lower Copper River, Alaska / by Timothy P. Brabets
p. cm. — (U.S. Geological Survey professional paper ; 1581)
"Prepared in cooperation with the Alaska Department of Transportation and Public Facilities."
Includes bibliographic references (p. –).
ISBN 0–607–87206–3 (pbk.)
1. Geomorphology—Alaska—Copper River Valley. I. Alaska Dept. of Transportation and Public Facilities. II. Title. III. Series.
GB428.A4B7 1997
551.41'09798'7—dc21 97–40451
CIP

ISBN 0-607-87206-3

For sale by U.S. Geological Survey, Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225

TABLES

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	by	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer
ton, short (2,000 lb)	0.9072	megagram
ton per day (ton/d)	0.9072	megagram per day
ton per square mile (ton/mi^2)	0.3503	megagram per square kilometer

Abbreviations used in this report:

mg/L, milligram per liter
mm, millimeter

Sea level:

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

Notes:

In this report, "Kennecott" pertains to mines, mining company, ore deposits, and related topics, and "Kennicott" to geographic and geologic features. The rationale for this dual spelling and usage is as follows: the mining company was named for Robert Kennicott, a pioneer surveyor; somehow, probably inadvertently, an "e" was substituted for the "i" in the company name.

The conversion of the Copper River and Northwestern Railway to the Copper River Highway took place over many years. In 1945, the first 13 miles of the railway— from Cordova to the Cordova Airport—were converted to a highway. Thus, in many of the illustrations in this report showing features from 1945 to the present, the Copper River and Northwestern Railway is referred to as the Copper River Highway.

Geomorphology of the Lower Copper River, Alaska

By Timothy P. Brabets

ABSTRACT

The Copper River, located in southcentral Alaska, drains an area of more than 24,000 square miles. About 30 miles above its mouth, this large river enters Miles Lake, a proglacial lake formed by the retreat of Miles Glacier. Downstream from the outlet of Miles Lake, the Copper River flows past the face of Childs Glacier before it enters a large, broad, alluvial flood plain. The Copper River Highway traverses this flood plain and in 1995, 11 bridges were located along this section of the highway. These bridges cross parts of the Copper River and in recent years, some of these bridges have sustained serious damage due to the changing course of the Copper River.

Although the annual mean discharge of the lower Copper River is 57,400 cubic feet per second, most of the flow occurs during the summer months from snowmelt, rainfall, and glacial melt. Approximately every six years, an outburst flood from Van Cleve Lake, a glacier-dammed lake formed by Miles Glacier, releases approximately 1 million acre-feet of water into the Copper River. When the outflow rate from Van Cleve Lake reaches it peak, the flow of the Copper River will increase between 150,000 to 190,000 cubic feet per second.

Data collected by bedload sampling and continuous seismic reflection indicated that Miles Lake traps virtually all the bedload being transported by the Copper River as it enters the lake from the north. The reservoir-like effect of Miles Lake results in the armoring of the channel of the Copper River downstream from Miles Lake, past Childs Glacier, until it reaches the alluvial flood plain. At this point, bedload transport begins again. The lower Copper River transports 69 million tons per year of suspended sediment, approximately the same quantity as the Yukon River, which drains an area of more than 300,000 square miles.

By correlating concurrent flows from a long-term streamflow-gaging station on the Copper River with a short-term streamflow-gaging station at the outlet of Miles Lake, long-term flow characteristics of the lower Copper River were synthesized. Historical discharge and cross-section data indicate that as late as 1970, most of the flow of the lower Copper River was through the first three bridges of the Copper River Highway as it begins to traverse the alluvial flood plain. In the mid 1980's, a percentage of the flow had shifted away from these three bridges and in 1995, only 51 percent of the flow of the Copper River passed through them.

Eight different years of aerial photography of the lower Copper River were analyzed using Geographical Information System techniques. This analysis indicated that no major channel changes were caused by the 1964 earthquake. However, a flood in 1981 that had a recurrence interval of more than 100 years caused significant channel changes in the lower Copper River.

A probability analysis of the lower Copper River indicated stable areas and the long-term locations of channels. By knowing the number of times a particular area has been occupied by water and the last year an area was occupied by water, areas of instability can be located. A Markov analysis of the lower Copper River indicated that the tendency of the flood plain is to remain in its current state. Large floods of the magnitude of the 1981 event are believed to be the cause of major changes in the lower Copper River.

INTRODUCTION

The Copper River is located in southcentral Alaska and flows into a large, relatively flat, alluvial plain near its mouth (fig. 1). As with many alluvial systems, the banks and streambeds of the lower Copper River are readily erodible and less permanent than most other aspects of the landscape. Numerous braided channels are formed, depending on the quantity and type of available sediment and the quantity and variability of discharge.

The flow of water and sediment in alluvial channels is complex and involves the mutual adjustment of a number of variables such as water discharge, sediment discharge, and slope (Maddock, 1969). However, hydraulics and hydrology are not always the dominant factors (Schumm and Winkley, 1994). Geologic controls such as uplift or subsidence, which may not be included in hydraulic or sediment transport equations, may also influence the alluvial system.

Beginning in Cordova, the Copper River Highway heads east/northeastward for about 48 mi. From mile 27, also known as Flag Point, to about mile 38, the highway crosses the alluvial plain of the lower Copper River. In 1995, 11 bridges were located along this part of the highway (fig. 2). The lengths of the bridges range from 240 to 1,200 ft, and spur dikes are located at some bridges.

Maintaining existing roads or designing structures such as bridges or spur dikes in alluvial channels is not a straightforward process, primarily because the streambed patterns constantly change. The channels located near these structures may scour, fill, or move laterally. Compounding the problem, channel instability is spatially variable, and channel migration may not affect the entire length equally.

In dealing with problems such as bridge scour or flood impacts in an alluvial setting, it is important to view the problem in terms of the larger fluvial system. In this way, it is possible to more fully understand the cause of bridge scour or the impacts from large floods, and to better predict the consequence of proposed mitigation measures. Similarly, prediction can be improved if both the past and present conditions are known, because the historical information allows the record to be extended. When information from the past and the present is combined, it is likely that the ability to predict future changes will be improved.

Significant bridge scour and damage to the Copper River Highway can be directly attributed to the changes in the alluvial system of the lower Copper River. At Bridge 342 (fig. 2), the Alaska Department of Transportation and Public Facilities (ADOT&PF) has made major repairs to both the bridge and the spur dikes. These repairs have cost millions of dollars. The nature of the alluvial system can also cause additional problems, such as encroachment of the river to the highway or scour at other bridges. If a better understanding of the alluvial system could be gained, future problems could be anticipated and thus more cost-effective mitigation measures could be taken.

Purpose and Scope

With this goal of obtaining a better understanding of the alluvial system of the lower Copper River, ADOT&PF and the U.S. Geological Survey (USGS) entered into a cooperative water-resources agreement in April 1991. This report describes the geomorphology of the lower Copper River from the early 1900's to 1995. The scope of the report includes the following: (1) documentation of past geomorphic changes; (2) evaluation of the process or processes that caused these changes; and (3) an assessment of the future changes. In addition to this report, several other reports describe certain aspects of the study such as data collection (Brabets, 1992, 1993), bridge scour (Brabets, 1994), and surface geophysical methods (Brabets, 1995). Parts of these reports are summarized in this report.

Methods of Study

Some of the variables that influence alluvial systems are changes in water discharge, changes in sediment load, movement of the river bed, and lateral shifts of the channels. The methods used in this study were (1) documentation of Van Cleve Lake breakouts and their effects on the flow regime of the Copper River, (2) collection and analysis of geophysical data at Miles Lake, (3) collection and analysis of discharge and sediment data, (4) analysis and interpretation of aerial photography, and (5) statistical procedures for predicting future trends of the Copper River. Each technique is explained in more detail in the following sections.

Acknowledgments

The author gratefully appreciates the assistance of Ray Koleser and Ken Winterberger of the U.S. For-

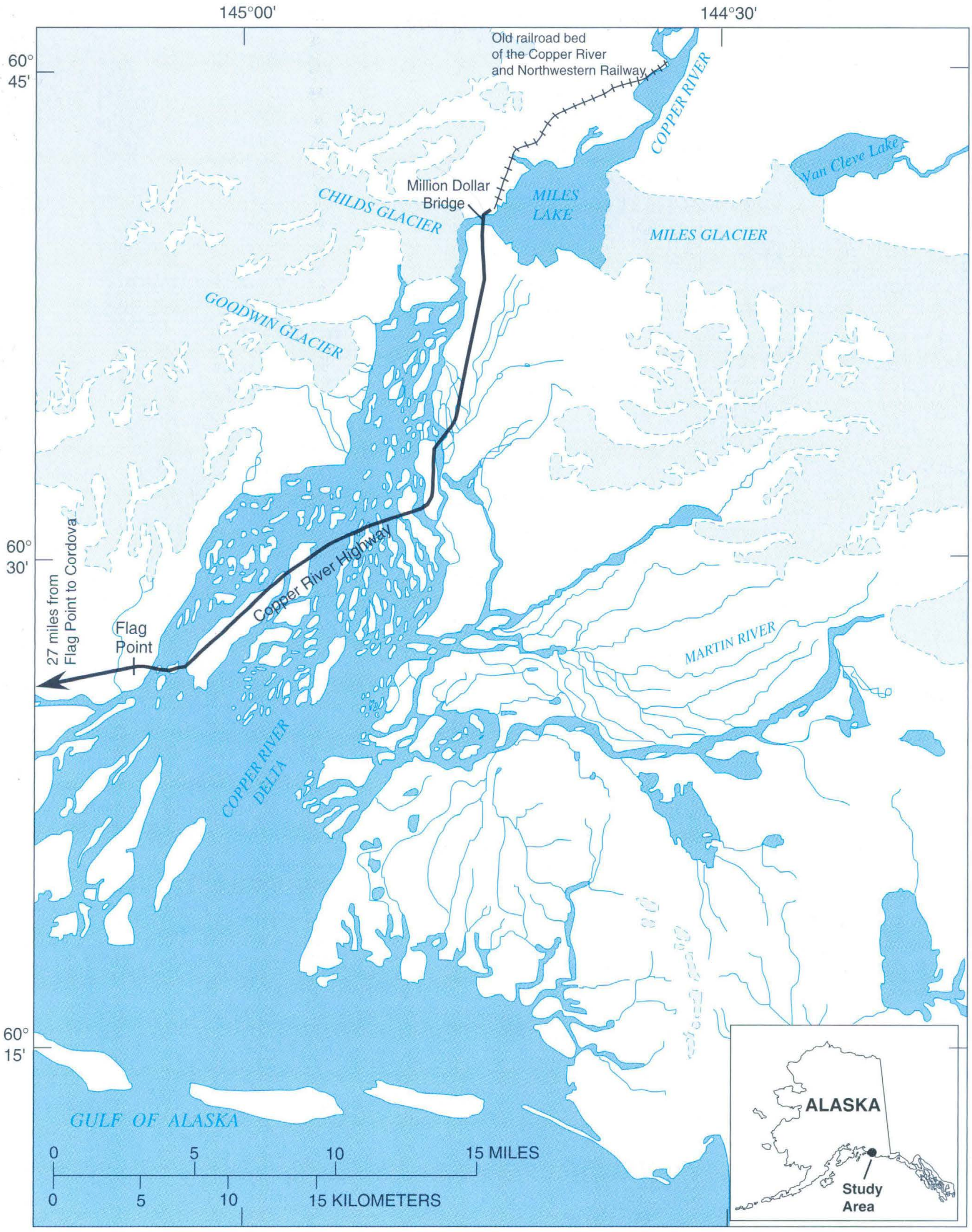

Figure 1. The lower Copper River Delta.

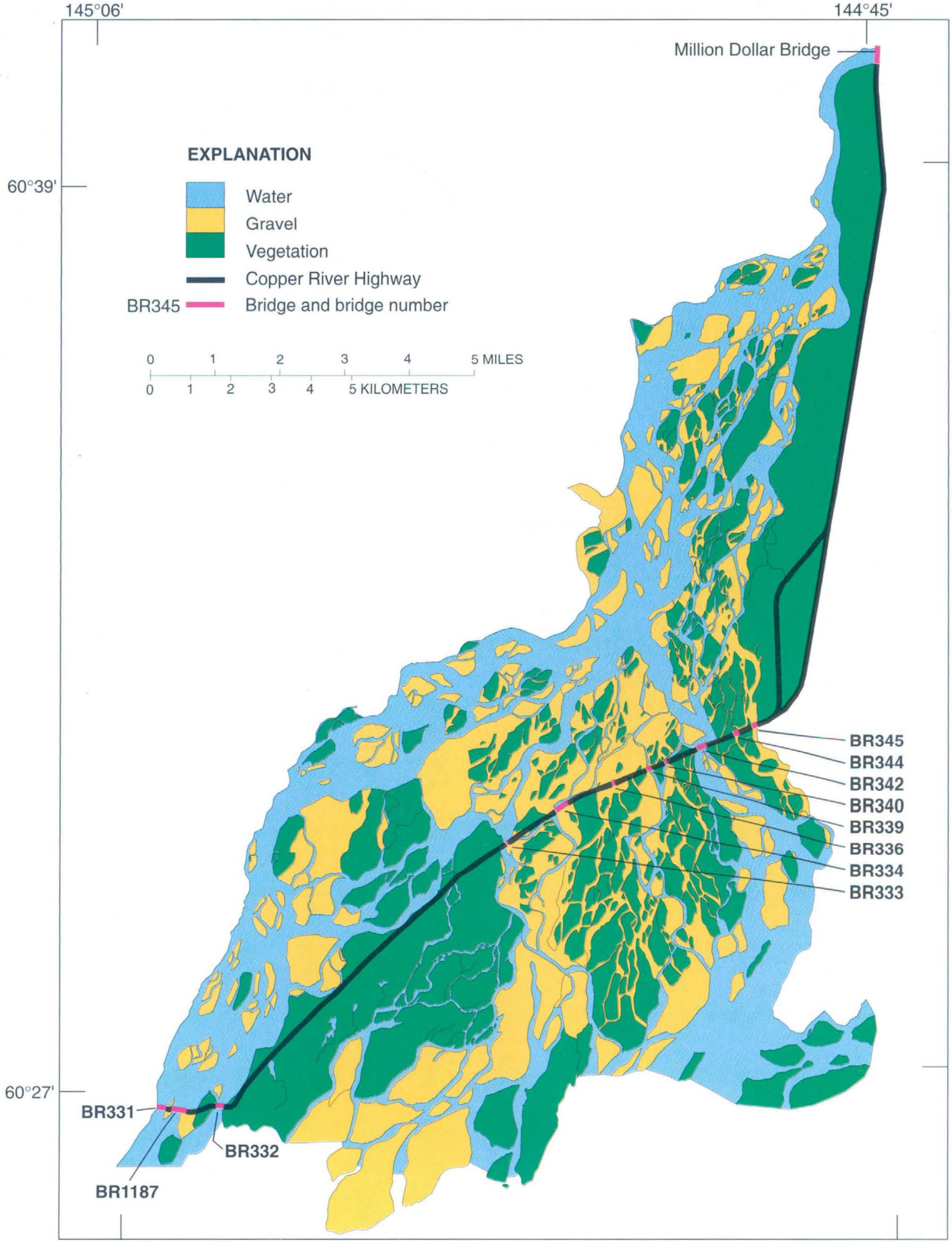

Figure 2. Location of bridges (BR) along the Copper River Highway, 1991.

est Service, Forestry Sciences Lab, in the use of the AP190 analytical stereoplotter and the associated software. Daniel B. Hawkins, professor emeritus, University of Alaska, Fairbanks, provided considerable assistance in the use of the Markov analysis. Finally, special thanks are due to Paul Mulcahy of the Alaska Department of Transportation and Public Facilities for sharing his years of knowledge of the Copper River Highway with the author.

DESCRIPTION AND HISTORY OF THE STUDY AREA

Physical Characteristics

The headwaters of the Copper River lie in the Alaska Range to the north, the Wrangell-St. Elias Mountains to the east, and the Talkeetna Mountains to the west (fig. 3). Along its upper course, the Copper

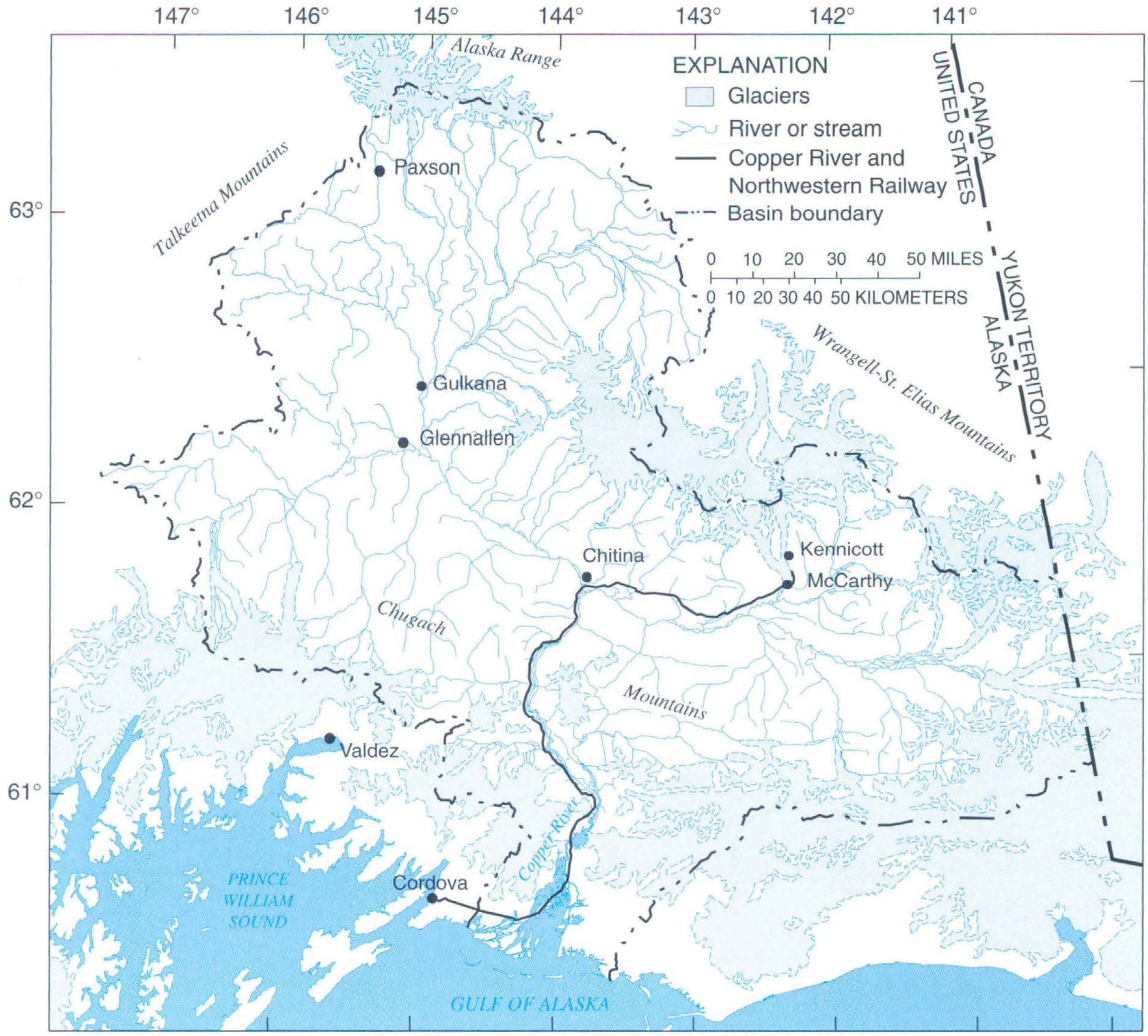

Figure 3. Copper River Basin.

River is fed by many glacial streams from high mountains. The river flows southward to the Gulf of Alaska and is the only river that bisects the Chugach Mountains. The Chugach Mountains effectively divide the climate of the Copper River drainage into two distinct types. The larger part of the basin lies north of the Chugach range within the cold and arid climate of interior Alaska. South of the range, a maritime climate with moderate temperatures and high rainfall exists. The total length of the Copper River is approximately 290 mi, with an average gradient of about 12 ft/mi (Quinn, 1995). For the lower Copper River, the average gradient is about 6 ft/mi.

Most of the valleys of the Copper River and its tributaries are incised in the Copper River Lowlands, a relatively smooth plain that ranges in altitude from approximately 1,000 to 3,000 ft (Wahrhaftig, 1965). Glaciation has been the major force in creating present-day landforms in the basin. Glaciers and glacial lakes have at one time or another covered most of the area. In 1995, approximately 18 percent of the Copper River basin consisted of glaciers.

The Copper River basin is the sixth largest basin in Alaska with an area of 24,200 mi^2 (fig. 4). However, the average discharge of the Copper River, 57,400 ft^3/s, ranks second behind that of the Yukon River. The average discharge per square mile of the Copper River ranks second to that of the Stikine River, which also has a relatively large percentage of its area—10 percent—covered by glaciers.

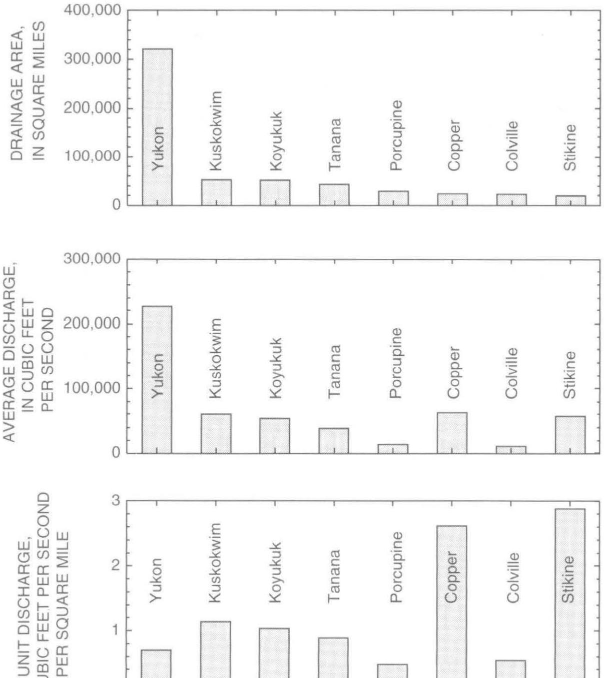

Figure 4. Comparison of drainage area, average discharge, and unit discharge of large river basins in Alaska.

The study area of the lower Copper River consists of the area bounded on the northeast by Van Cleve Lake (fig. 1) and on the south by the Copper River alluvial plain (figs. 1 and 5), approximately 1 mi south of the Copper River Highway. Three principal glaciers are located in the study area: Miles, Childs, and Goodwin (fig. 1). As the Copper River flows past Childs Glacier, the flood plain widens considerably. The river valley is less narrowly confined and is more than three times wider than it is near the terminus of Childs Glacier. In the upper part of the study area near the Million Dollar Bridge (fig. 2), the deposits are primarily glacial—gravel and boulders having diameters up to 3 ft. In the lower part of the alluvial plain, downstream from Childs Glacier, the deposits are fine-grained alluvium. The alluvial plain is dissected by numerous braided and shifting channels.

Early Expeditions

During their occupation of Alaska, Russian explorers made several attempts to ascend the Copper River. Attempts in 1796, 1798, and 1803 failed due to the swift current of the river and the hostility of the Natives. The first successful expedition was made in 1819, but was followed by two unsuccessful attempts in 1843 and 1847.

In the summer of 1884, Lieutenant William Abercrombie started up the Copper River with instructions from General Nelson Miles, to map a route connecting the Copper River with the Yukon River through the unexplored Alaska Range. His party reached a position on the Copper River at latitude 60°41' (near Miles Lake). However, Abercrombie returned from this point, stating that the mountains, glaciers, rapids, and streams to be crossed were too great an obstacle (Abercrombie, 1900).

In 1885, Lieutenant Henry Allen and two other members of the military began another expedition up the Copper River. Allen not only successfully mapped the Copper River basin but also succeeded in mapping the Tanana and Koyukuk Rivers of interior Alaska during the same trip. Perhaps the most notable geologic feature that Allen mapped in the Copper River basin

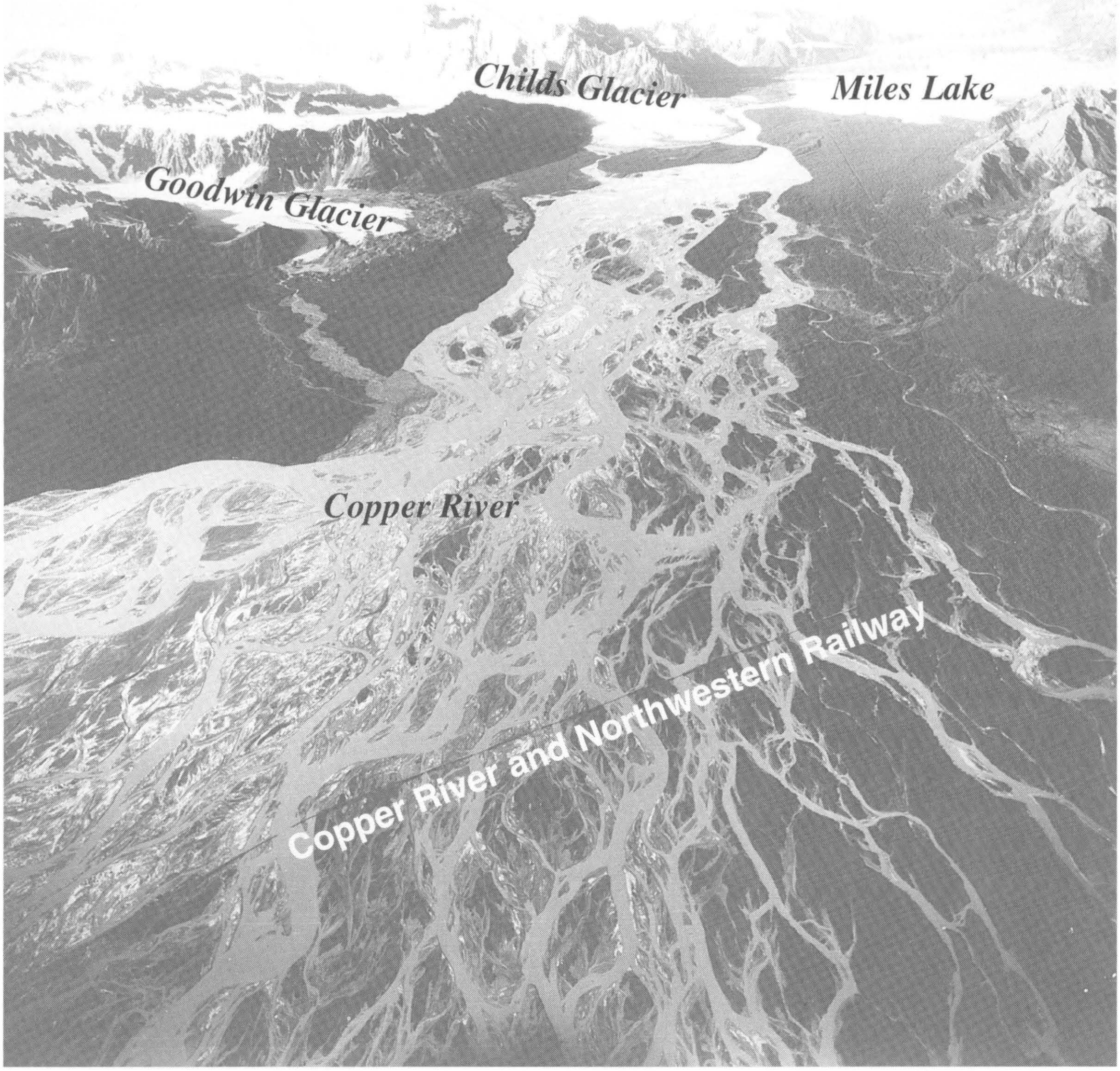

Figure 5. Lower Copper River in 1944. View is looking north from mile 35 of the Copper River and Northwestern Railway.

was an outcrop of nearly pure copper ore near the Chitina River (Allen, 1985). As as result of Allen's successful expedition, additional explorations were made into interior Alaska.

In 1899, as a result of the Klondike gold rush, the U.S. Army War Department directed Abercrombie to lead an expedition to explore, survey, and open up a military road from Valdez, through the Interior by way of Copper Center to Eagle, near the Alaska–Canada border. USGS geologists accompanying this expedition contributed valuable information. They noted, studied, and described the geologically important limestone-greenstone contact, the dominant structure along which the copper ore bodies of the Kennecott Mines occur. Prospectors traced the deposits to Bonanza Ridge, which eventually became the incredibly rich Bonanza Mine, one of five mines that supplied copper and silver ore to the Kennecott Mine.

Copper River and Northwestern Railway and the Copper River Highway

The huge potential value of copper ore in interior Alaska created a demand to build a railroad. Many routes were considered (Janson, 1975), but eventually the route along the Copper River from Cordova was chosen. Construction of the Copper River and Northwestern Railway began in 1907 and was completed in 1911.

The main line of the railway was 130.7 mi from Cordova to Chitina (fig. 3). From Chitina, a 65-mile-long branch continued to the Kennecott copper mines. Construction of the Copper River and Northwestern Railway was considered to be a significant engineering feat for its time. Perhaps the most noteworthy accomplishment was the construction of the Million Dollar Bridge across the Copper River between Miles and Childs Glaciers.

The Kennecott mines operated from 1911 until late 1938, when they were permanently closed. Most of the copper ore was mined from the Mother Lode, Jumbo, Erie, and Bonanza Mines. Copper ore worth more than $200 million was extracted from the mines. Silver and other by-products were also mined. Closure of the Kennecott mines in 1938 ended the Copper River and Northwestern Railway.

From 1945 to 1973, the railbed was gradually converted to the Copper River Highway, beginning at Cordova and extending about 25 miles past the Million Dollar Bridge. Most of the bridges from Cordova to mile 51 were reoccupied by the Copper River Highway. Rails were welded together and driven into the riverbed to be used as bridge piles. Decks of most of the bridges were converted to concrete.

Great Alaska Earthquake of 1964

On March 27, 1964, an earthquake of Richter magnitude 9.2 occurred in southcentral Alaska. As a result of the earthquake, the Copper River Delta was raised about 6 ft (Plafker, 1969). In the Cordova area, the tidal regime was significantly altered: large areas of subtidal estuary became intertidal and much of the intertidal wetlands became supertidal.

Seismic shaking caused compaction and subsidence at most of the bridge approaches on the Copper River Highway. During the earthquake, all the bridges supported by piles made of old rails were severely damaged or destroyed because the brittle rail piles were unable to withstand the severe seismic shaking generated by the earthquake (Kachadoorian, 1968). Because of the severe seismic shaking, the 405-foot north span on the north side of the Million Dollar Bridge fell from its pier support to the river bottom where it rests today (fig. 6).

Figure 6. Million Dollar Bridge on the Copper River Highway, 1991.

Reconstruction of the bridges between Flag Point and the Million Dollar Bridge began in 1970. At some locations along the highway where the Copper River had shifted away from the road, bridges were not rebuilt, but rather the bridge opening was filled in. The north span of the Million Dollar Bridge that collapsed during the 1964 earthquake was not raised, but a replacement pier was constructed to stabilize the remaining spans. When reconstruction was completed in 1978, 12 bridges (fig. 2) were located between Flag Point and the Million Dollar Bridge.

GEOMORPHOLOGY OF THE COPPER RIVER

The following discussion of the geomorphology of the lower Copper River begins at the upstream end of the study area, Van Cleve Lake. From this location, the analysis proceeds downstream to Miles Lake, the Million Dollar Bridge, and finally the alluvial fan downstream from Childs Glacier. The analysis ends approximately 1 mi downstream from the Copper River Highway as it crosses the flood plain from Flag Point to Mile 38.

Van Cleve Lake Breakout Floods

As Miles Glacier flows downstream towards the Copper River, it blocks the outlet of the valley where Van Cleve Glacier is located. The meltwater from Van Cleve Glacier, rainfall runoff, and snowmelt runoff are impounded by the ice of Miles Glacier, forming Van Cleve Lake (figs. 1 and 7). Van Cleve Lake fills until it reaches a depth that exceeds about 0.9 times the thickness of the ice dam. When this limit is exceeded, the ice at the dam begins to float, causing the dam to become unstable (Post and Mayo, 1971).

A primary hazard presented by Van Cleve Lake is the catastrophic flooding that might occur when the ice dam fails. Several studies (Desloges and Church, 1992) have suggested that infrequent, high-magnitude

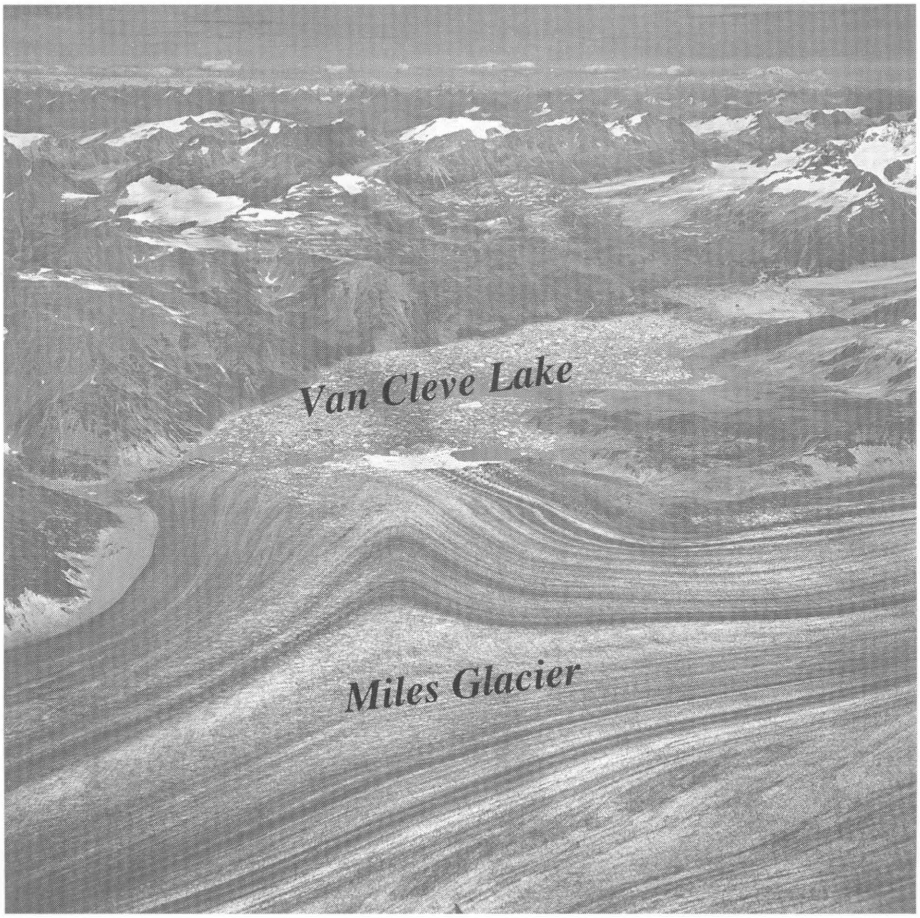

Figure 7. Van Cleve Lake, August 1969. View is to the northeast. Miles Glacier (in foreground) flows from right to left.

floods are the primary cause of major channel changes in alluvial systems. Thus, the effects of breakouts from Van Cleve Lake were investigated for this study.

Past records from the ADOT&PF, the Alaska Department of Fish and Game (ADF&G), and previous work by Post (1967) were examined to develop a chronology of breakouts. Once these dates were determined, efforts were made to estimate possible peak discharges and document channel changes. A breakout of Van Cleve Lake in August 1992 facilitated the analysis, because characteristics such as the quantity of water released and channel changes were documented.

The first recorded breakout of Van Cleve Lake occurred on February 9–17, 1909. Water elevations of the Copper River at the Million Dollar Bridge, recorded by personnel from the Copper River and Northwestern Railway, rose from 21.0 ft on February 9 to 40.0 ft on February 14 (peak elevation) and then declined to 21.5 ft on February 17 (Ellsworth and Davenport, 1915). Tarr and Martin (1914) reported that another breakout occurred on August 16, 1912 and that the water-surface elevation of the Copper River rose 12 ft at the Million Dollar Bridge. The next observation of a breakout was made 50 years later during August 1962 by Post (1967) and was based on aerial observations.

By reviewing files from ADOT&PF and ADF&G, a chronology of the last six breakouts (since 1962) of Van Cleve Lake was constructed (table 1). Six breakouts of Van Cleve Lake have occurred from 1962 to 1992. The average length of time between these breakouts is approximately 6 years and, with the exception of the 1969 breakout, these events have occurred during August.

The 1992 breakout of Van Cleve Lake was the first time continuous water stage (and thus discharge) was recorded. In addition, the water-surface elevation of Van Cleve Lake was surveyed in September 1991 when the lake was nearly full (fig. 8A), and again in September 1992 after the lake had drained (fig. 8B). By collecting this information, the volume of water released by Van Cleve Lake as well as the peak discharge that occurred at the Million Dollar Bridge could be determined accurately.

During the 1992 breakout of Van Cleve Lake, which began on August 4, the water surface of Van Cleve Lake dropped an average 380 ft. The surface area of Van Cleve Lake is 4.4 mi^2, and thus the total volume of water released was slightly over 1 million acre-ft. The Copper River rose approximately 8 ft at the Million Dollar Bridge. Discharge increased from

Table 1. Chronology of Van Cleve Lake breakouts

[Discharge in cubic feet per second]

Date	Source of information	Maximum discharge[1]	Remarks
February 9–17, 1909	CR&NR	190,000	Elevations recorded by railroad personnel
August 16, 1912	Tarr & Martin (1914)	Unknown	Water surface rose 12 feet at Million Dollar Bridge
August 1962	Post (1967)	Unknown	Aerial observation
October 1969	ADOT&PF	160,000	Rating extension
August 1974	ADOT&PF	Unknown	Observed high water marks, debris
August 1979	ADOT&PF	Unknown	
August 2, 1985	ADF&G	155,000	Elevations recorded by ADF&G personnel
August 4–12, 1992	USGS	150,000	Volume of water released determined

[1]Highest discharge from Van Cleve Lake during breakout

A.

B.

Figure 8. Van Cleve Lake. View is to the southwest. A, September 1991; B, September 1992.

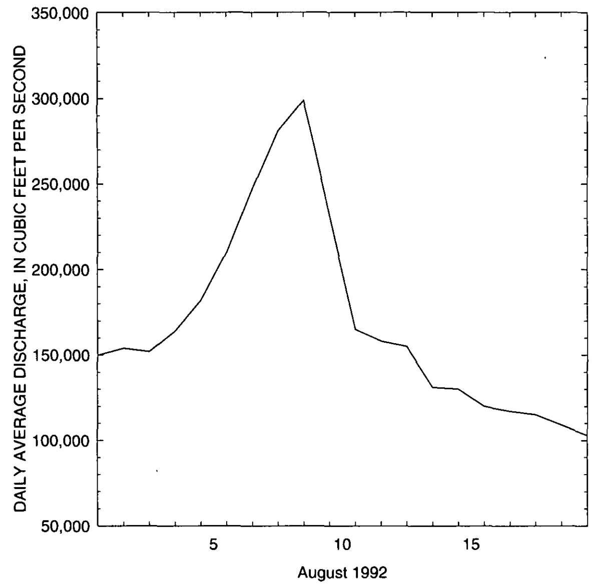

Figure 9. Discharge of the Copper River at the Million Dollar Bridge during the breakout of Van Cleve Lake, August 4-12, 1992.

approximately 150,000 ft^3/s on August 4 to a peak of 300,000 ft^3/s on August 9 (fig. 9). By August 12, flow had decreased to approximately 150,000 ft^3/s. Using 150,000 ft^3/s as baseflow, the area of the hydrograph above 150,000 ft^3/s was computed to determine the volume of water that passed the Million Dollar Bridge from August 4–12. The volume of water calculated was 1.1 million acre-ft, which agrees closely with the volume calculation of Van Cleve Lake.

Efforts were next focused on determining whether other breakouts of Van Cleve Lake exhibited similar characteristics. The 1912, 1962, 1974, and 1979 breakouts were visually observed and no water-surface elevations were recorded. However, the 1909, 1969, and 1985 breakouts have some recorded information. A comparison of the water-surface elevations at the Million Dollar Bridge for the 1909 and 1992 breakouts (fig. 10), indicates similar patterns after the second day. Differences in the first two days of the breakout are expected because of the large differences in baseflow between February and August. The maximum change in stage during 1909 was 19.0 ft. Using the current stage-discharge rating curve for the gaging station at the Million Dollar Bridge, a water stage was estimated for the base-flow discharge before the breakout. On the basis of the stage-discharge rating, the 19-foot rise in stage was equivalent to a discharge of 200,000 ft^3/s. Subtracting the baseflow at the time of the breakout (estimated at 10,000 ft^3/s) indicates that when the outflow rate of Van Cleve Lake was at its highest, flow in the Copper River increased 190,000 ft^3/s.

In 1969, personnel of the ADOT&PF recorded the breakout of Van Cleve Lake in October (Alaska Department of Highways, 1970). Although the actual data are not available, it is likely that an analysis similar to the 1992 breakout was done and ADOT&PF estimated a peak discharge of 160,000 ft^3/s from Van Cleve Lake. In 1985, some water-surface elevations were recorded by personnel from the ADF&G. Correlating these readings with the current stage-discharge rating indicated that on July 31, the discharge of the Copper River was 140,000 ft^3/s and on August 4, the discharge was 295,000 ft^3/s. Thus, at the peak outflow rate, the breakout of Van Cleve Lake increased the flow of the Copper River by 155,000 ft^3/s.

To summarize: the 1909, 1969, 1985, and 1992 breakouts of Van Cleve Lake showed similar characteristics. At the peak outflow rate, the flow of the Copper River was increased from 150,000 to 190,000 ft^3/s. Knowing the discharges and the dates of the breakouts aided in the interpretation of the aerial photography shown later in this report.

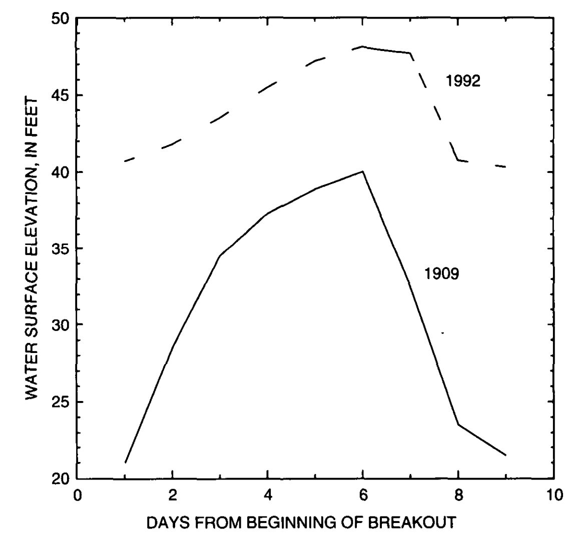

Figure 10. Water-surface elevation of the Copper River at the Million Dollar Bridge during Van Cleve Lake breakouts of 1909 and 1992.

Miles Lake

Miles Lake (fig. 11) formed after the southern lobe of Miles Glacier retreated between 1884 and 1898 (Abercrombie, 1900). At the time of Tarr and Martin's expedition during 1910, the Copper River flowed along the morainal front of Miles Glacier through Abercrombie Rapids and into Miles Lake (fig. 12). Around 1950, the Copper River cut a new channel through the northern stagnant lobe of Miles Glacier, abandoning Abercrombie Rapids (fig. 13). Between 1910 and 1950, the terminus of Miles Glacier retreated approximately 1.7 mi with a loss in area of about 9.3 mi^2. From 1950 to 1991, the terminus of Miles Glacier (fig. 14) retreated approximately 1,400 ft near the center of the glacier; however, the southern lobe of the glacier retreated approximately 1.2 mi. The total loss in area between 1950 and 1991 was about 2.0 mi^2. In 1995, the Copper River flowed southward along the face of Miles Glacier, and then turned westward towards the Million Dollar Bridge.

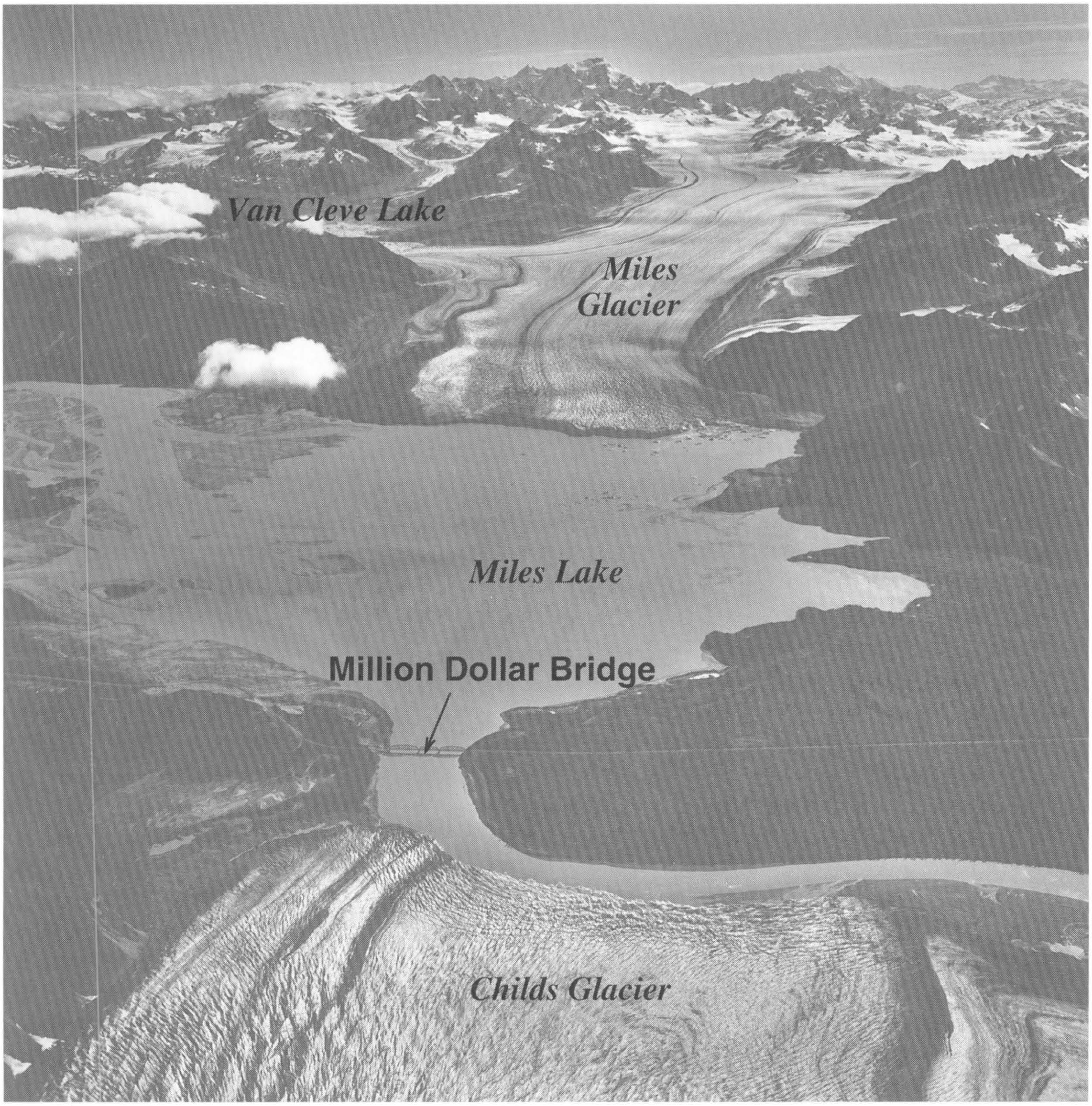

Figure 11. Miles Lake, 1966. View is to the east.

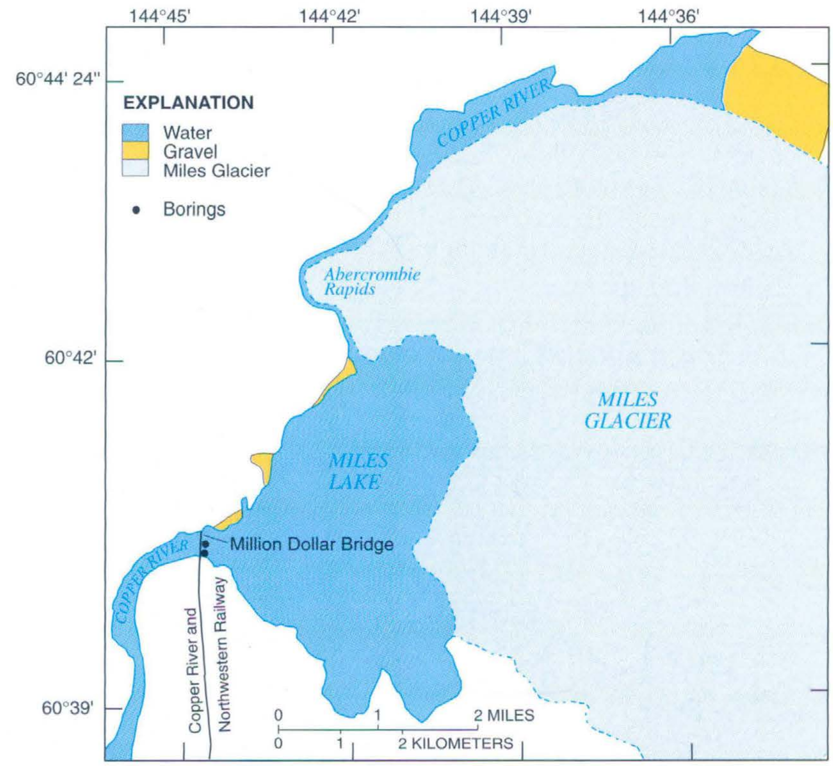

Figure 12. Location of Miles Lake and Miles Glacier, 1910. (See figure 15 for borings.)

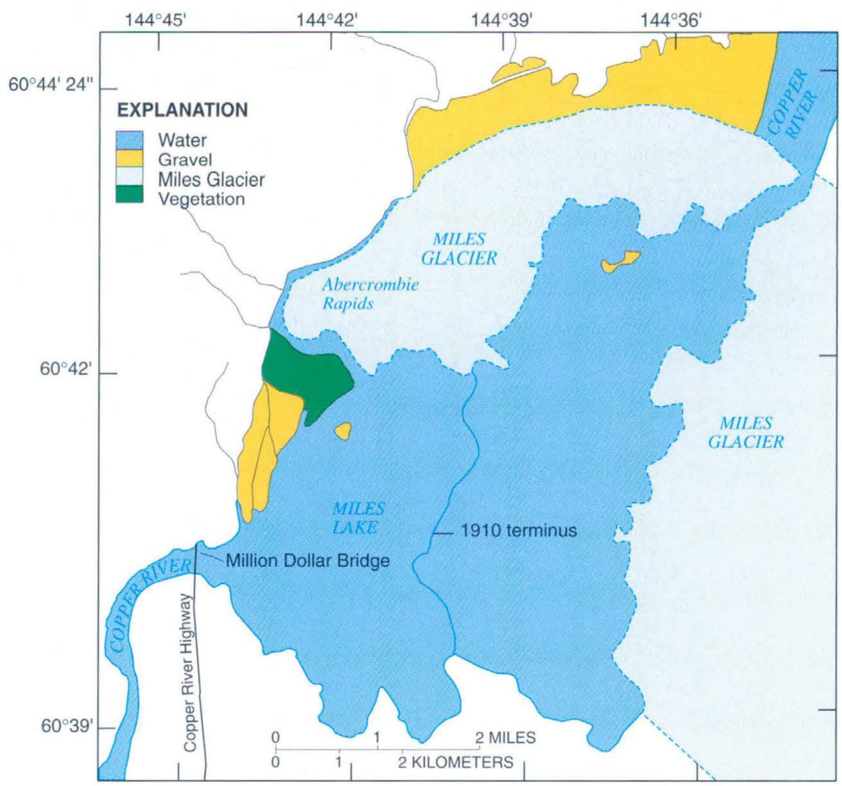

Figure 13. Location of Miles Lake and Miles Glacier, 1950.

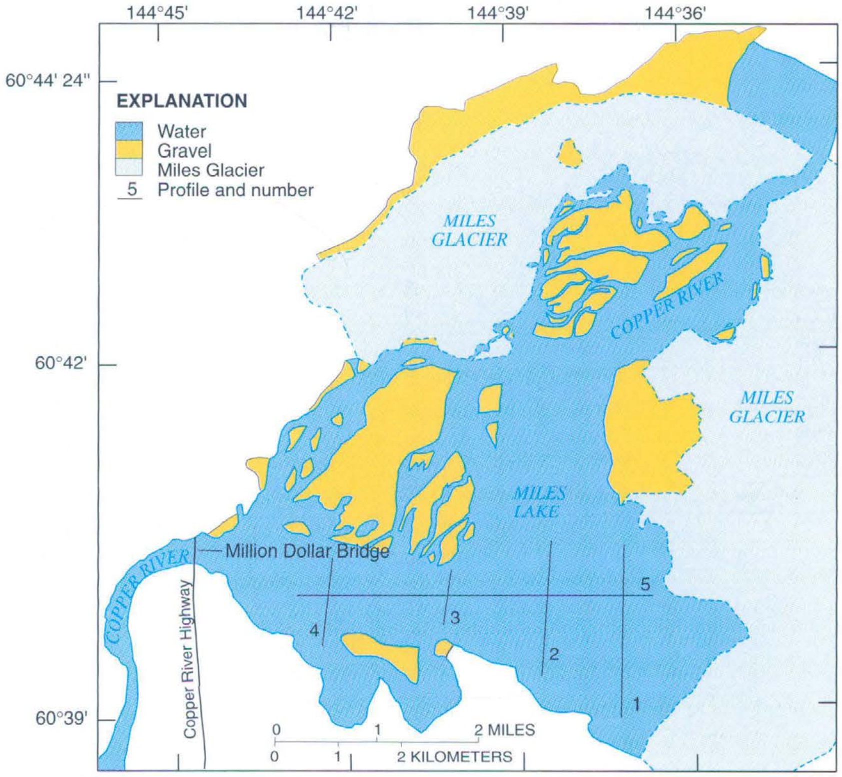

Figure 14. Location of Miles Lake and Miles Glacier, 1991. (See figures 16 and 17 for profiles.)

On the basis of boring logs from the area near the Million Dollar Bridge in 1980 (fig. 15), it was determined that the bottom of Miles Lake probably consists of large boulders, cobbles, and gravel. Also, data collected at the Million Dollar Bridge in 1991 and 1992 indicated that no bedload was being transported past the Million Dollar Bridge (Brabets, 1992, 1993). To determine whether Miles Lake might be a sediment trap for bedload being transported by the Copper River north of Miles Lake, continuous seismic reflection, a geophysical technique, was used in June 1992 to determine the depositional features of the bottom sediments in Miles Lake.

Continuous seismic reflection is a technique in which a sound wave is generated by a sound source and travels down through the earth. When the sound wave encounters an interface between two materials, and if there is a contrast in the acoustic impedance (the product of the density and acoustic velocity of each material) of the two materials, some of the energy will be reflected. The acoustic source used in this study was a tuned transducer primarily because of its ease of use and because the penetration and resolution characteristics were acceptable. The transducer operated at a frequency of 7.0 kHz.

Four north/south and one east/west continuous seismic reflection profiles of Miles Lake (fig. 14) were obtained. In north/south profile 1 (fig. 16), which was the closest to the face of Miles Glacier, the hyperbolic reflections probably were due to the presence of large boulders on the riverbed. This part of the lake is generally considered an ice marginal or ice proximal fan that consists of very coarse material and is formed from debris washing out from tunnels at the base of the glacier. In addition, the depth of water in this profile was relatively deep.

Profile 2 (fig. 17) was also a north/south profile taken approximately 1 mi downstream from Miles Glacier. In this section, the depth of water was fairly uniform and a distinct layer of fine-grained sediments was present. This layer ranged in thickness from about 2 ft to about 8 ft and overlies a coarser grained deposit, which is most likely the glacier-deposited material.

The remaining downstream profiles of Miles Lake showed similar characteristics of the fine-grained sediments overlying the glacially deposited material. The accumulation of sediment in the lake coupled with the lack of sediment detected during bedload sampling at the Million Dollar Bridge indicates that most, if not all, of the bedload transported by the Copper River is deposited in Miles Lake.

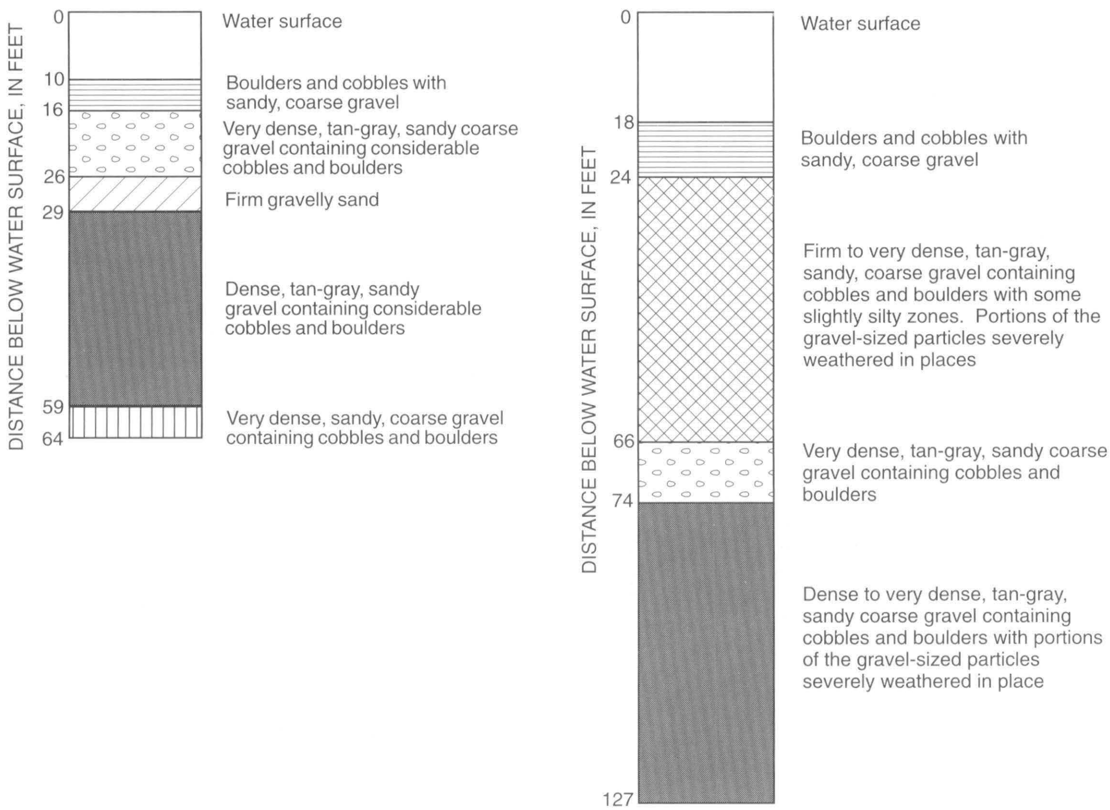

Figure 15. Boring logs from area near the Million Dollar Bridge on the Copper River Highway. (See figure 12 for location.)

According to its past history, Miles Glacier has continued to retreat. No evidence of a surge or advance has been noted since the Copper River and Northwestern Railway was built. However, if Miles Glacier were to advance and occupy Miles Lake, sediment transport and channel characteristics could change in the vicinity of the Million Dollar Bridge.

Discharge

Discharge is one of the most important variables that influences channel form (Lane, 1957). At a given cross section, the width, depth, and velocity of a stream will increase with discharge and the alluvial channel will adjust its hydraulic characteristics such as slope and roughness to transmit the discharge (Leopold and Maddock, 1953). In a given period of time, there are fewer large flows than small or moderate ones. An intermediate range of discharge includes flows that occur frequently and possess sufficient energy to constitute the effective discharge (Wolman and Miller, 1960). During periods of effective discharge, the river can move the material on its bed and in its banks and thus is capable of modifying its shape and pattern.

The USGS has collected continuous daily streamflow information at the Million Dollar Bridge (gaging station No. 15214000) since 1988. Some fragmentary discharge records collected in the early 1900's also exist (Ellsworth and Davenport, 1915). From 1950 to 1990, continuous daily streamflow information was also collected at the Copper River near Chitina (fig. 3) (gaging station No. 15212000), about 65 mi upstream from the Million Dollar Bridge. The drainage area of the Copper River at the Chitina station is 20,600 mi^2 and the drainage area of the Copper River at the Million Dollar Bridge is 24,200 mi^2, about 18 percent larger. In addition, ADOT&PF personnel collected discharge information in 1969–70 and in 1982–85, and ADF&G personnel have measured water-stage elevations at the Million Dollar Bridge from late May until early August since 1982.

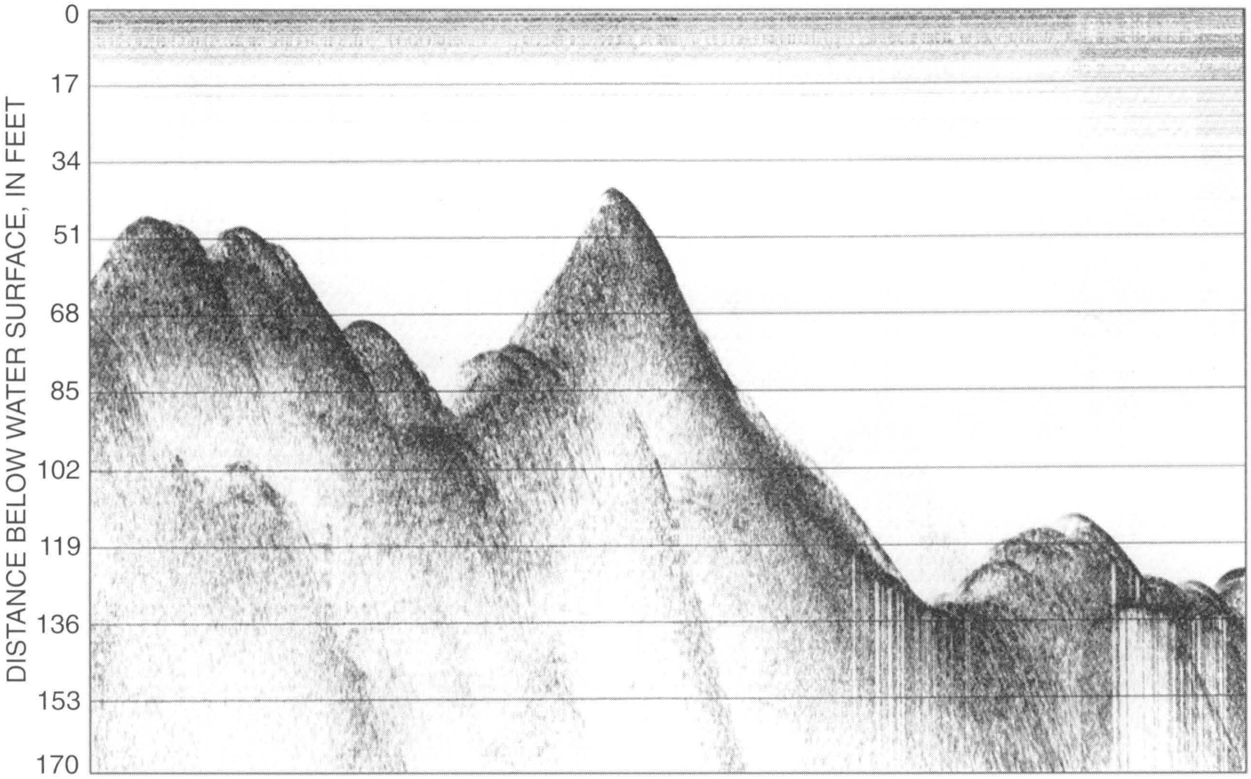

Figure 16. Record of 7.0-kHz continuous seismic reflection cross section from Profile 1 at Miles Lake. (Approximate length of profile is one-half mile; see figure 14 for location.)

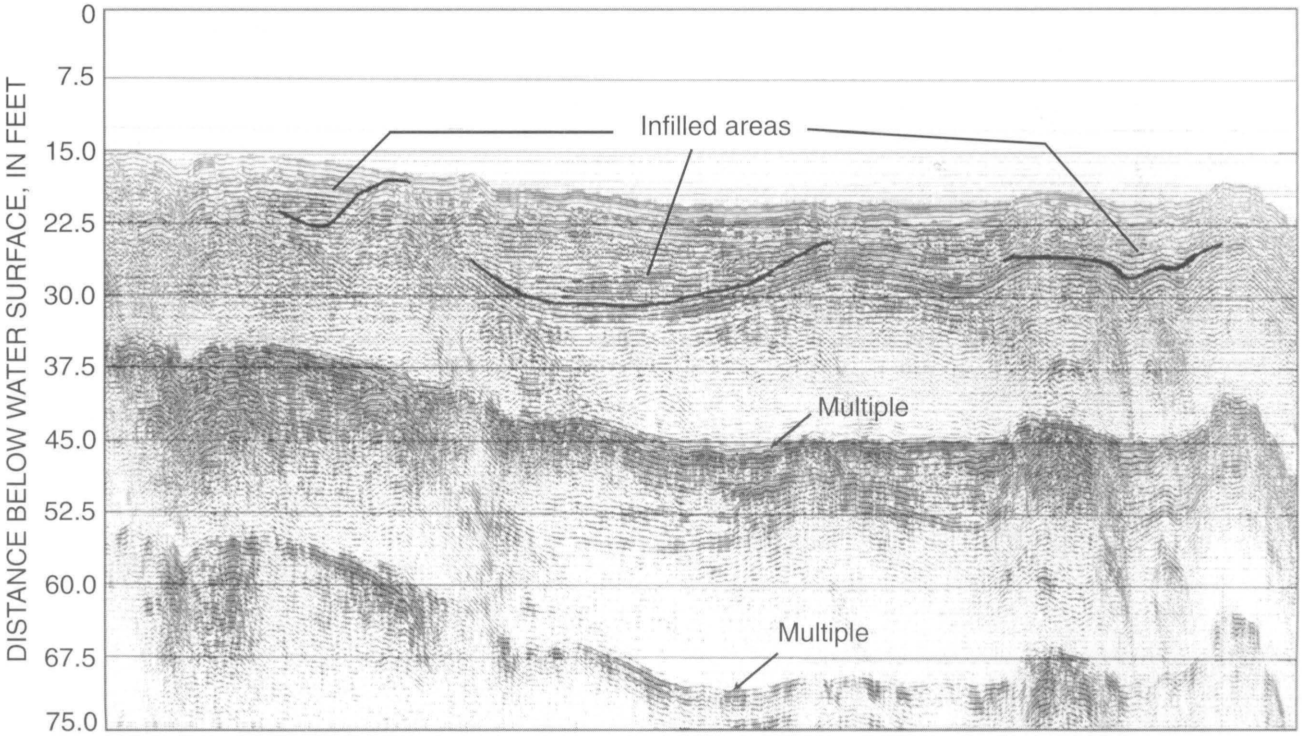

Figure 17. Record of 7.0-kHz continuous seismic reflection cross section from Profile 2 at Miles Lake. (See figure 14 for location.)

The average discharge of the Copper River at the Million Dollar Bridge is about 57,400 ft^3/s; minimum flows occur during winter months and maximum flows occur during summer months (fig. 18). During late May or early June, a high-flow period begins, reflecting snowmelt runoff. Rainfall and glacial melt cause this high-flow period to continue from mid-July through August. Two distinct features are noted for the period of record: the breakout of Van Cleve Lake in August 1992 and the large flood of September 1995.

During the 1991–93 open-water periods (late May–September), discharge measurements were made approximately every 2 weeks at all bridges along the Copper River Highway from Flag Point to mile 38. Because the channel of the Copper River at the Million Dollar Bridge is composed of large stationary boulders, the stage-discharge relation has been stable since the gaging station was installed in 1988. Thus, discharge measurements were made at this site approximately every 6 weeks. During winter periods, discharge measurements were made only at the Million Dollar Bridge.

The discharge information collected at the individual bridges from 1991 to 1993 was analyzed as an indicator of channel changes. Flow that occurred at a particular bridge was compared with the total discharge passing through Bridges 331 to 345. If the percentage of flow at an individual bridge changed, this might indicate that channel change or changes had occurred.

Ordinary least squares (OLS) regression was used to develop a statistical relation between the concurrent streamflow data collected at Chitina and the streamflow data collected at the Million Dollar Bridge. The OLS equation was then modified to develop a line of organic correlation (LOC) using methods outlined by Helsel and Hirsch (1992). By using this technique, flows that occurred at the Million Dollar Bridge between 1950 and 1988 were estimated. This information provided a good, historical perspective of the trends in flow characteristics.

Statistical Analysis

Concurrent daily discharges of the Copper River were available from the Chitina gaging station and the Million Dollar Bridge gaging station from June 1988 to September 1990. Visual analysis (fig. 19) indicated a good correlation between the flow patterns from these two sites. Using the daily discharge from these two sites, a statistical relation was developed to estimate flow at the Million Dollar Bridge based on flow from the Chitina site (fig. 20). The following relation was

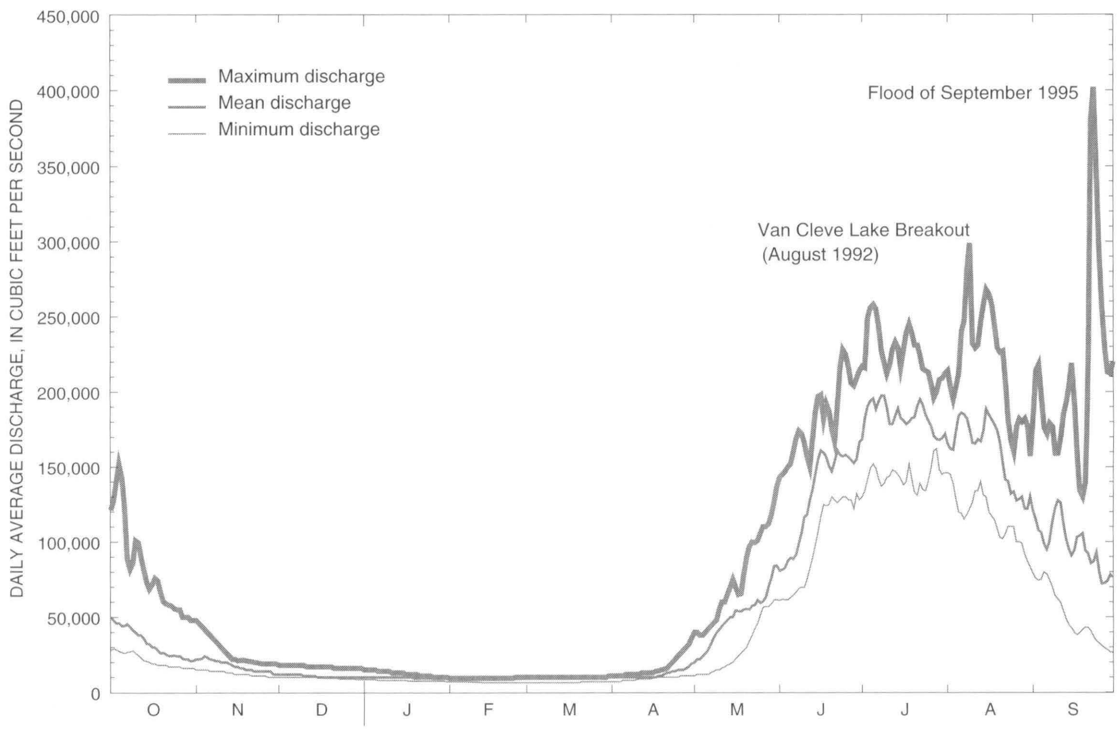

Figure 18. Flow statistics of the Copper River at Million Dollar Bridge, 1988-95.

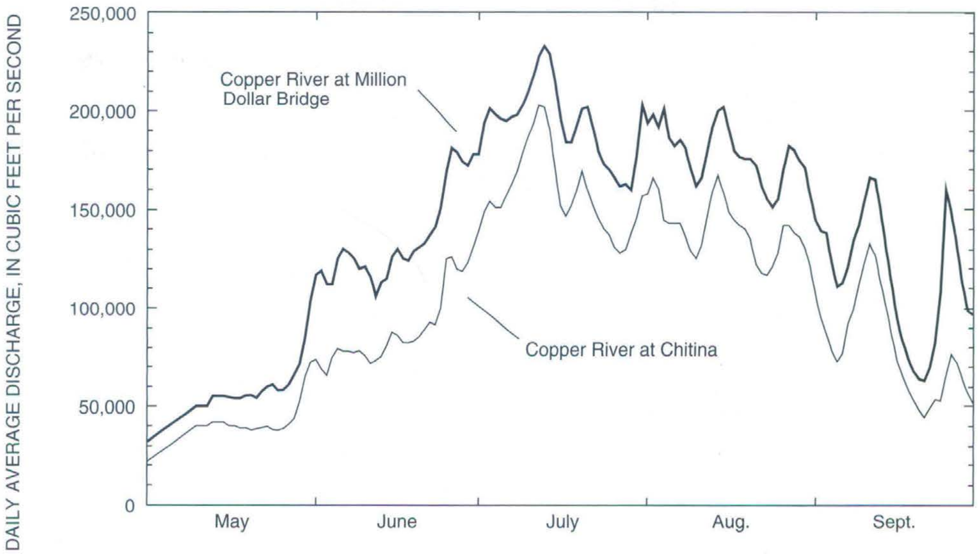

Figure 19. Daily discharge of the Copper River at Chitina and the Copper River at the Million Dollar Bridge, May to September 1989.

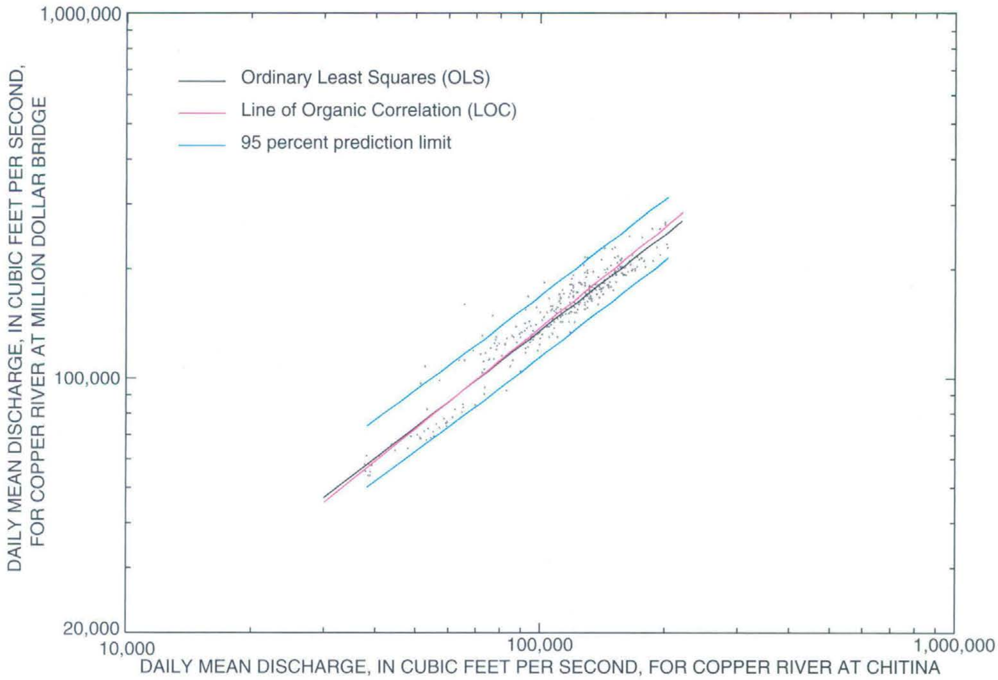

Figure 20. Comparison of concurrent discharges of the Copper River at Chitina and the Copper River at the Million Dollar Bridge.

obtained by ordinary least squares (OLS) regression of the logarithms of the daily flows:

$$Q_M = 5.37\ Q_C^{(0.882)}$$

where

Q_M is discharge of the Copper River at the Million Dollar Bridge, in cubic feet per second, and

Q_C is discharge of the Copper River at Chitina, in cubic feet per second,

Coefficient of determination (R) is 0.92.

Standard error is 9.2 percent.

Number of values is 303.

Mean (X_{ave}) of discharge values at Chitina is 5.029 (in $\log_{10}$ units).

Standard deviation (S_x) of discharge values at Chitina is 0.163 (in $\log_{10}$ units).

Mean (Y_{ave}) of discharge values at Million Dollar Bridge is 5.166 (in $\log_{10}$ units).

Standard deviation (S_y) of discharge values at Million Dollar Bridge is 0.150 (in $\log_{10}$ units).

Helsel and Hirsch (1992) noted that when statistics such as flood frequency recurrence intervals are to be generated from estimated discharges, these statistics depend on the probability distribution of the estimated data. In these instances, the authors recommend using a method known as the line of organic correlation (LOC). The LOC has also been referred to as geometric mean functional regression, reduced major axis, allocation relation, and maintenance of variance-extension (Helsel and Hirsch, 1992). There are three major reasons why LOC is preferable to OLS:

1) The LOC technique minimizes errors in both x and y directions.
2) The LOC produces a unique line, identical regardless of which variable, x or y, is used as the response variable.
3) The technique produces a cumulative distribution function of the predictions, which is a close approximation of the cumulative distribution function of the actual records.

The procedures outlined by Helsel and Hirsch (1992) were used to develop the line of organic correlation:

Slope of the line = (sign of R)(Sy/Sx) = + (0.150)/(0.163) = 0.920

$$\log_{10}(Q_M) = Y_{ave} + (\text{slope of the line})\,[\log_{10}(Q_C) - X_{ave}] = 5.166 + (0.920)[\log_{10}(Q_C) - 5.029]$$

$$\log_{10}(Q_M) = 0.539 + 0.920\,[\log_{10}(Q_C)]$$

$$Q_M = 3.46\ Q_C^{(0.920)} \quad (1)$$

A comparison of the LOC and the OLS equation (fig. 20) indicates that both lines were similar. The LOC is somewhat steeper than the OLS line, which reflects the reduction in variance.

Synthesized Flow Statistics of the Copper River at the Million Dollar Bridge

Using the equation derived from the LOC technique, daily discharges of the Copper River at the Million Dollar Bridge were synthesized from the Chitina record. Because the LOC equation was based on the logarithms of discharge, a bias correction was applied to the computed discharges. The technique used was the minimum variance unbiased estimator (MVUE) or Bradu-Mundlak estimator as outlined by Cohn and others (1989).

From the estimated discharges, the annual mean discharge was computed from 1950 to 1988 (fig. 21A) The annual mean discharge ranged from about 42,000 ft^3/s in 1970 to 71,500 ft^3/s in 1990. Years in which discharges were above the long-term average of 57,400 ft^3/s occurred primarily after 1976.

An analysis of the daily discharge record collected at the Million Dollar Bridge from 1988 to the present indicated that for each water year, the number of days in which the discharge exceeded 200,000 ft^3/s was about 5 percent. Thus, although somewhat arbitrary, this statistic was computed from the synthesized record and used as an indicator of sustained high flows. From 1950 to 1970, relatively few days had discharges exceeding 200,000 ft^3/s (fig. 21B). However, the period from 1970 through 1995 indicates that more sustained, relatively high flows occurred.

There were three concurrent peak discharges for the Copper River at Chitina and at the Million Dollar Bridge. Using the LOC equation, the estimated and observed peak discharges for these three years were as follows (discharge in cubic feet per second):

Year	Chitina peak	Million Dollar Bridge peak	Predicted peak	95 percent prediction level	
				Upper	Lower
1988	186,000	252,000	244,000	281,000	212,000
1989	195,000	236,000	254,000	293,000	220,000
1990	208,000	273,000	270,000	312,000	234,000

The predicted peak discharges were within 10 percent of the observed peak discharges and also within the 95 percent prediction intervals. Thus, the LOC

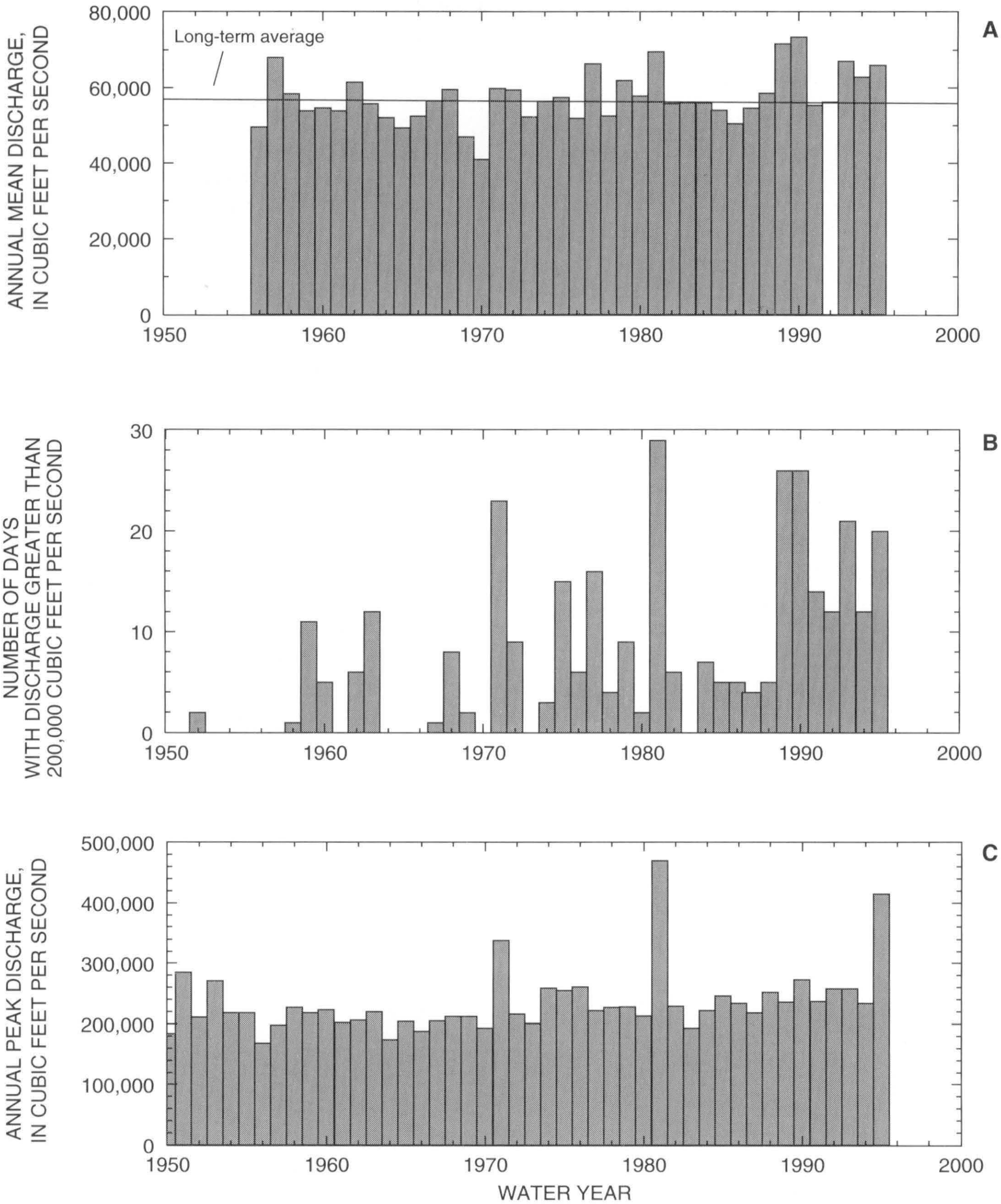

Figure 21. Synthesized flow statistics for the Copper River at the Million Dollar Bridge, 1950 to 1988.

equation was used to estimate the peak discharges of the Copper River at the Million Dollar Bridge from 1950 to 1987 (table 2). These peak discharges were then analyzed using techniques described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). The analysis was done without considering the peak discharges that were caused by the breakout of Van Cleve Lake. On the basis of this analysis, peak discharges that occurred during the period from 1950 to 1970 are considered average annual peaks with a recurrence interval of less than or equal to 2 years (table 2, fig. 21C) with the exception of the 1951, 1953, 1958, and 1960 peaks. The recurrence interval of the 1951 peak discharge was estimated to be 7 years; the 1953

Table 2. Estimated peak discharges and recurrence intervals for the Copper River at Million Dollar Bridge

[Peak discharges computed by line of organic correlation formula; discharge data in cubic feet per second; --, not applicable]

Year	Estimated peak discharge	95 percent prediction interval		Recurrence interval (years)
		Upper	Lower	
1950	184,000	212,000	160,000	<1.25
1951	285,000	329,000	247,000	7
1952	211,000	243,000	183,000	<2
1953	271,000	313,000	235,000	5
1954	218,000	251,000	189,000	<2
1955	218,000	251,000	189,000	<2
1956	168,000	194,000	146,000	<1.25
1957	198,000	228,000	172,000	<1.25
1958	227,000	262,000	197,000	3
1959	218,000	251,000	189,000	<2
1960	223,000	257,000	193,000	3
1961	202,000	233,000	175,000	<2
1962	[a]206,000	238,000	179,000	<2
1963	220,000	254,000	191,000	<2
1964	174,000	201,000	151,000	<1.25
1965	204,000	235,000	177,000	<2
1966	188,000	217,000	163,000	<1.25
1967	205,000	236,000	178,000	<2
1968	212,000	244,000	184,000	<2
1969	[a]212,000	244,000	184,000	<2
1970	193,000	223,000	167,000	<1.25
1971	338,000	390,000	293,000	20
1972	216,000	249,000	187,000	<2
1973	201,000	232,000	174,000	<2
1974	[a]259,000	299,000	224,000	5
1975	255,000	294,000	221,000	5
1976	261,000	301,000	226,000	5
1977	222,000	256,000	192,000	3
1978	227,000	262,000	197,000	3
1979	[a]228,000	263,000	198,000	3
1980	213,000	246,000	185,000	<2
1981	470,000	544,000	406,000	>100
1982	229,000	264,000	199,000	3
1983	193,000	223,000	167,000	<1.25
1984	222,000	256,000	192,000	3
1985	[a]246,000	284,000	213,000	3
1986	234,000	270,000	203,000	<2
1987	218,000	251,000	189,000	4
1988	[b]252,000	--	--	4
1989	[b]236,000	--	--	3
1990	[b]273,000	--	--	7
1991	[b]237,000	--	--	4
1992	[ab]258,000	--	--	5
1993	[b]258,000	--	--	5
1994	[b]234,000	--	--	4
1995	[b]415,000	--	--	65

[a]Van Cleve Lake breakout occurred
[b]Actual discharge, not estimated

peak discharge, 5 years; and the 1958 and 1960 peak discharges, 3 years. During the period 1971 to 1995, the three highest peak discharges for the period of record occurred. The peak discharge of 1981 is estimated to have had a recurrence interval greater than 100 years; the peak discharge of 1995, a 65-year recurrence interval; and the peak discharge of 1971, a 20-year recurrence interval.

The peak discharges that occurred from the breakouts of Van Cleve Lake in 1909, 1969, 1985, and 1992 were as follows:

1909: 200,000 ft^3/s
1969: 160,000 ft^3/s
1985: 295,000 ft^3/s
1992: 300,000 ft^3/s (from USGS gaging-station No. 15214000)

Although the exact dates of the 1962, 1974, and 1979 breakouts are not known, estimates of the peak discharges for these dates were computed as follows:

(1) The average discharge for August 1962, 1974, and 1979 was determined from the discharge records at the streamflow-gaging station at Chitina.

(2) Using the LOC technique, the average discharge for August 1962, 1974, and 1979 for the Copper River at the Million Dollar Bridge was computed.

(3) A discharge of 150,000 ft^3/s was added to the discharge computed by the LOC technique and was used as an estimate of the peak discharge. The results were as follows:

1962: 314,000 ft^3/s
1974: 300,000 ft^3/s
1979: 327,000 ft^3/s

Comparing these discharges with the flood-frequency statistics indicated that the peak discharges in 1909 and 1969 were less than a 2-year recurrence interval. The peak discharges in 1974, 1985, and 1992 are equivalent to approximately an 8- to 10-year recurrence interval. The 1962 peak discharge is equivalent to a 13-year recurrence interval and the 1979 peak is equivalent to a 17-year recurrence interval. From these dates of occurrence and the flood frequencies, it does not appear that breakouts of Van Cleve Lake have created large magnitude floods.

For comparative purposes, a flood-frequency analysis was also done with the peak discharges from Van Cleve Lake included in the analysis. The effect of adding the peak flows caused by Van Cleve Lake was to smooth the upper end of the flood-frequency curve and thus lower the recurrence interval for a given discharge. For example, the recurrence interval of the 1979 peak is lowered to 14 years and the recurrence interval for the 1962 peak is lowered to 10 years. No significant differences were noted for recurrence intervals less than 10 years.

Discharge at Bridges Along the Copper River Highway

From 1991 to 1995, discharge measurements made at bridges along the Copper River Highway indicated that most of the flow occurs at Bridges 331, 1187, 332, and 342 (tables 3–4). The combined flow from these four bridges ranged from 85 percent to 100 percent of the total flow of the Copper River. The percentage of flow at these bridges decreases as the flow in the Copper River increases, indicating that the increased discharge flows into other channels leading to other bridges. During relatively low-flow periods—when flow at the Million Dollar Bridge was less than 100,000 ft^3/s—most, if not all, of the discharge of the Copper River is through these four bridges (table 4). The average percentage of total discharge at Bridges 331, 1187, and 332 for the period was 51 percent and the average percentage of the total discharge at Bridge 342 was 40 percent. From these data, it does not appear that the average percentage of flow through Bridges 331, 1187, 332 and 342 has increased or decreased from 1991 to 1995.

The sum of the discharges measured at each of the bridges along the Copper River Highway equals the flow past the Million Dollar Bridge plus any inflow downstream from the Million Dollar Bridge. The primary inflow between the Million Dollar Bridge and the Copper River Highway is the runoff from Childs Glacier and from Goodwin Glacier. Comparing the discharge at the Million Dollar Bridge with the total measured discharge indicated a good correlation (fig. 22).

Using the data from the 1991–93 field seasons, the following OLS statistical relation was developed:

$$Q_T = 1.56\ Q_M^{(0.97)}$$

where

Q_T is total discharge measured past the Copper River Highway from Bridge 331 to Bridge 345, in cubic feet per second; and

Q_M is discharge measured at the Million Dollar Bridge, in cubic feet per second.

Coefficient of determination (R) is 0.99.
Standard error is 9.2 percent.
Number of values is 26.
Mean (X_{ave}) of Q_T is 5.16 (in $\log_{10}$ units).
Standard deviation (S_x) of Q_T is 0.213 (in $\log_{10}$ units).
Mean (Y_{ave}) of Q_M is 5.10 (in $\log_{10}$ units).
Standard deviation (S_y) of Q_M is 0.218 (in $\log_{10}$ units)

Using the LOC technique the equation was adjusted to:

$$Q_T = 1.45\ Q_M^{0.98} \qquad (2)$$

The OLS and the LOC equations are quite similar (fig. 22) and using either equation would produce approximately the same values, given a discharge value for the Copper River at the Million Dollar Bridge. However, since Q_T is considered a flow statistic, the LOC equation was used in estimating values of Q_T. Similar to computing daily discharges, the bias correction technique (MVUE) was applied to the computed discharges.

Inspection of ADOT&PF files produced flow information that had been collected by ADOT&PF personnel in 1969 and 1970 at Bridges 331, 1187, and 332. Using the daily discharge from the Chitina gaging station for the 1969 and 1970 water years, the discharge at the Million Dollar Bridge was estimated using equation 1. The estimated discharge from the Million Dollar Bridge was then used to estimate the total discharge past the Copper River Highway from Bridge 331 to Bridge 345 (equation 2). The estimated discharges were then compared with the discharges obtained by the ADOT&PF (table 5).

Table 3. Discharge of the Copper River at bridges along the Copper River Highway, 1991 to 1995

[Discharge in cubic feet per second; --, no discharge measurement made; no flow was present at Bridges 336, 344, and 345 from 1991-95]

Date	Flag Point			BR 333	BR 334	BR 339	BR 340	BR 342	Total	Million Dollar
	BR 331	BR 1187	BR 332							
6-7-91	29,000	8,700	7,800	0	0	0	0	37,900	83,400	66,600
6-18-91 to 6-20-91	36,100	16,700	15,000	2,600	1,800	1,200	4,100	64,300	141,800	128,000
7-1-91 to 7-2-91	52,800	35,000	29,400	5,800	12,000	5,400	11,800	91,400	243,600	216,000
7-24-91	44,600	26,100	19,700	4,700	5,000	2,300	6,800	73,900	183,100	159,000
8-13-91 to 8-14-91	48,800	29,500	21,600	5,000	6,000	1,900	7,700	78,600	199,100	158,000
8-28-91 to 8-29-91	35,800	14,400	9,000	2,200	600	600	1,100	45,500	109,200	95,400
9-12-91	38,300	19,000	13,000	2,500	1,000	1,000	1,500	54,400	130,700	108,000
9-23-91	31,700	11,500	7,200	800	400	40	200	40,000	91,800	71,500
5-21-92 to 5-22-92	16,600	0	0	0	0	0	0	26,800	43,400	36,000
6-8-92 to 6-9-92	37,900	18,400	12,200	2,160	620	368	1,140	47,400	120,200	106,000
6-22-92	49,300	30,300	21,800	5,070	5,560	2,240	6,270	69,400	189,900	162,000
7-13-92 to 7-14-92	56,600	38,600	26,900	8,710	13,100	3,700	7,150	78,500	233,300	203,000
7-27-92 to 7-31-92	49,100	31,400	18,000	4,860	5,540	3,200	5,770	69,300	187,200	169,000
8-11-92 to 8-12-92	51,300	30,300	15,000	5,240	8,470	3,800	5,860	64,900	184,900	162,000
8-24-92 to 8-25-92	50,900	30,300	14,700	2,510	3,860	2,160	3,470	64,200	172,100	146,000
9-8-92 to 9-9-92	29,400	11,500	2,280	710	246	425	235	30,200	75,000	67,000
9-18-92	21,600	6,950	367	<100	0	<10	0	13,400	42,400	39,500
5-26-93	38,100	18,930	7,880	2,025	1,660	1,260	1,490	46,800	118,100	110,000
6-9-93	44,400	23,900	13,900	2,770	4,820	2,590	4,150	60,700	157,200	138,000
6-21-93	46,800	24,300	12,600	2,800	5,200	2,600	4,200	65,800	164,300	148,000
7-8-93	45,800	22,000	12,800	2,700	5,000	2,500	4,100	63,100	158,000	145,000
7-19-93	64,600	35,300	23,200	4,940	12,700	9,210	9,040	85,800	244,800	239,000
8-2-93	61,200	29,500	22,500	4,990	10,400	7,530	7,480	85,200	228,800	203,000
8-16-93	73,600	33,400	24,300	7,120	17,600	14,600	10,600	92,100	273,300	246,000
8-30-93	44,200	15,800	9,480	3,280	6,120	4,530	5,470	66,500	155,400	127,000
9-18-93	41,200	14,600	8,750	2,025	1,660	1,260	1,700	66,100	137,300	127,000
6-18-94	--	--	--	--	--	6,590	8,190	83,700	--	188,000
8-21-94	--	--	--	--	--	7,500	10,600	104,400	--	181,000
9-12-95	47,400	25,100	12,600	2,200	5,570	6,590	12,500	106,400	218,400	182,000
9-22-95	--	--	--	--	--	--	24,200	129,000	--	367,000

Table 4. Percentage of total discharge measured at Bridges 331, 1187, 332, and 342, 1991 to 1995

[Discharge in cubic feet per second]

Date	Bridges 331, 1187, and 332		Bridge 342		Total of Bridges 331, 1187, 332, & 342	
	Discharge	Percent	Discharge	Percent	Discharge	Percent
6-7-91	45,500	55	37,900	45	83,400	100
6-18-91 to 6-20-91	67,800	48	64,300	45	141,800	93
7-1-91 to 7-2-91	117,200	48	91,400	37	243,600	85
7-24-91	90,400	49	73,900	40	183,100	89
8-13-91 to 8-14-91	99,900	50	78,600	39	199,100	89
8-28-91 to 8-29-91	59,200	54	45,500	42	109,200	96
9-12-91	70,300	54	54,400	42	130,700	96
9-23-91	50,400	55	40,000	44	91,800	99
5-21-92	16,600	38	26,800	62	43,400	100
6-8-92	68,500	57	47,400	39	120,200	96
6-22-92	101,400	53	69,400	36	189,900	89
7-13-92 to 7-14-92	122,100	52	78,500	34	233,300	86
7-27-92 to 7-31-92	98,500	53	69,300	37	187,200	90
8-11-92 to 8-12-92	96,600	52	64,900	35	184,900	87
8-24-92 to 8-25-92	95,900	56	64,200	37	172,100	93
9-8-92 to 9-9-92	43,200	58	30,200	40	75,000	98
9-18-92	28,900	68	13,400	32	42,300	100
5-26-93	64,900	55	46,800	40	118,100	95
6-9-93	82,200	52	60,700	38	157,900	90
6-21-93	83,700	50	65,800	40	164,300	90
7-8-93	80,600	51	63,100	40	158,100	91
7-19-93	123,100	50	85,700	35	243,900	85
8-2-93	113,200	49	85,200	37	228,800	86
8-16-93	131,300	48	91,900	33	275,700	81
8-30-93	69,500	45	65,800	42	156,400	87
9-18-93	64,600	47	66,400	39	137,300	95
9-12-95	85,100	39	106,400	49	218,400	88
Average		51		40		

Table 5. Comparison of discharges at Bridges 331, 1187, and 332 to estimated total discharge, 1969 to 1970

[Discharge in cubic feet per second]

Date	Estimated discharge at Million Dollar Bridge	95 percent prediction interval		Estimated total discharge from Bridge 331 to Bridge 345	95 percent prediction interval		Discharge at Bridges 331, 1187, and 332	Ratio of discharge at Bridges 331, 1187, and 332 to total discharge
		Upper	Lower		Upper	Lower		
1969								
6-11	95,800	111,000	83,100	110,000	120,000	102,000	118,000	1.07
6-12	113,000	131,000	98,400	130,000	142,000	120,000	130,000	1.00
6-13	126,000	146,000	110,000	145,000	157,000	133,000	158,000	1.09
6-14	150,000	173,000	130,000	172,000	187,000	158,000	190,000	1.10
6-17	200,000	231,000	173,000	227,000	247,000	209,000	195,000	0.86
6-25	175,000	202,000	152,000	200,000	217,000	184,000	172,000	0.86
6-26	175,000	202,000	152,000	200,000	217,000	184,000	171,000	0.86
7-1	175,000	202,000	152,000	200,000	217,000	184,000	173,000	0.87
7-8	170,000	196,000	148,000	194,000	211,000	178,000	179,000	0.92
7-14	175,000	202,000	152,000	200,000	217,000	184,000	188,000	0.94
7-21	163,000	188,000	141,000	186,000	202,000	171,000	172,000	0.92
7-28	129,000	149,000	112,000	148,000	161,000	136,000	166,000	1.12
7-31	138,000	159,000	119,000	158,000	171,000	145,000	156,000	0.99
8-1	138,000	159,000	119,000	158,000	171,000	145,000	158,000	1.00
8-2	125,000	144,000	108,000	143,000	156,000	132,000	161,000	1.13
8-5	138,000	159,000	119,000	158,000	171,000	145,000	170,000	1.08
8-7	150,000	173,000	130,000	172,000	187,000	158,000	177,000	1.03
8-12	72,700	83,900	63,000	84,200	91,800	77,300	113,000	1.34
8-14	64,700	74,700	56,000	75,200	82,000	69,000	99,000	1.32
8-15	55,600	64,200	48,100	64,800	70,700	59,300	91,600	1.41
9-5	48,300	55,800	41,800	56,400	61,700	51,600	82,500	1.46
9-6	48,300	55,800	41,800	56,400	61,700	51,600	82,700	1.47
9-23	39,900	46,200	34,500	46,800	51,300	42,700	65,600	1.40
9-24	38,500	44,500	33,200	45,200	49,500	41,200	59,000	1.31
1970								
6-5	49,300	56,900	42,600	57,500	62,900	52,600	91,600	1.59
6-8	67,400	77,800	58,400	78,300	85,300	71,800	99,000	1.26
6-9	69,000	79,700	59,800	80,100	87,300	73,500	113,000	1.41
6-10	69,800	80,600	60,500	81,000	88,300	74,400	113,000	1.40
6-11	70,000	80,800	60,600	81,200	88,500	74,500	113,000	1.39
6-12	66,900	77,200	57,900	77,700	84,600	71,200	112,000	1.44
6-15	69,700	80,500	60,400	80,900	88,100	74,200	99,000	1.22
6-16	70,400	81,200	61,000	81,600	89,000	74,900	92,000	1.13
6-17	70,500	81,400	61,100	81,800	89,100	75,100	100,000	1.22
6-18	70,500	81,400	61,100	81,800	89,100	75,100	100,000	1.22
6-19	71,900	82,900	62,200	83,300	90,800	76,500	106,000	1.27

Table 5. Comparison of discharges at Bridges 331, 1187, and 332 to estimated total discharge, 1969 to 1970 (Continued)

Date	Estimated discharge at Million Dollar Bridge	95 percent prediction interval		Estimated total discharge from Bridge 331 to Bridge 345	95 percent prediction interval		Discharge at Bridges 331, 1187, and 332	Ratio of discharge at Bridges 331, 1187, and 332 to total discharge
		Upper	Lower		Upper	Lower		
1970								
6-22	76,100	87,900	66,000	88,200	96,000	81,000	113,000	1.28
6-23	76,800	88,600	66,600	88,900	96,800	81,700	115,000	1.29
6-24	79,900	92,200	69,200	92,400	101,000	84,900	116,000	1.26
6-25	84,400	97,300	73,100	97,500	106,000	89,600	116,000	1.19
6-26	85,600	98,700	74,200	98,900	108,000	90,800	116,000	1.17
7-1	97,600	113,000	84,700	113,000	122,000	103,000	118,000	1.04
7-2	105,000	121,000	91,100	121,000	131,000	111,000	118,000	0.98
7-6	121,000	139,000	105,000	139,000	151,000	128,000	140,000	1.01
7-8	115,000	132,000	99,500	132,000	143,000	121,000	140,000	1.06
7-9	111,000	128,000	96,500	128,000	139,000	118,000	135,000	1.05
7-10	109,000	125,000	94,100	125,000	136,000	115,000	130,000	1.04
7-13	105,000	121,000	90,800	120,000	131,000	111,000	140,000	1.17
7-17	96,600	111,000	83,700	111,000	121,000	102,000	120,000	1.08
7-20	95,400	110,000	82,700	110,000	120,000	101,000	120,000	1.09
7-21	94,500	109,000	81,900	109,000	119,000	100,000	120,000	1.10
7-22	97,400	112,000	84,400	112,000	122,000	103,000	120,000	1.07
7-23	106,000	122,000	91,900	122,000	133,000	112,000	120,000	0.98
7-24	107,000	123,000	92,800	123,000	134,000	113,000	130,000	1.06
7-28	165,000	191,000	143,000	189,000	205,000	173,000	170,000	0.90
7-29	179,000	206,000	155,000	204,000	222,000	187,000	177,000	0.87
7-30	189,000	218,000	164,000	215,000	234,000	197,000	179,000	0.83
7-31	180,000	208,000	156,000	205,000	223,000	189,000	179,000	0.87
8-1	165,000	191,000	143,000	189,000	205,000	173,000	180,000	0.95
8-2	169,000	195,000	147,000	193,000	210,000	177,000	177,000	0.92
8-3	148,000	170,000	128,000	169,000	184,000	155,000	177,000	1.05
8-4	129,000	149,000	112,000	148,000	161,000	136,000	160,000	1.08
8-6	123,000	142,000	107,000	141,000	154,000	130,000	140,000	0.99
8-7	120,000	138,000	104,000	138,000	150,000	127,000	140,000	1.01
8-10	120,000	138,000	104,000	137,000	149,000	126,000	135,000	0.99
8-11	112,000	129,000	97,100	129,000	140,000	118,000	130,000	1.01
8-12	111,000	128,000	95,900	127,000	138,000	117,000	125,000	0.98
8-13	114,000	131,000	98,700	131,000	142,000	120,000	125,000	0.95
8-14	115,000	133,000	100,000	132,000	144,000	122,000	125,000	0.95
8-24	84,400	97,300	73,100	97,500	106,000	89,600	120,000	1.23
8-25	81,200	93,700	70,400	93,900	102,000	86,300	116,000	1.24

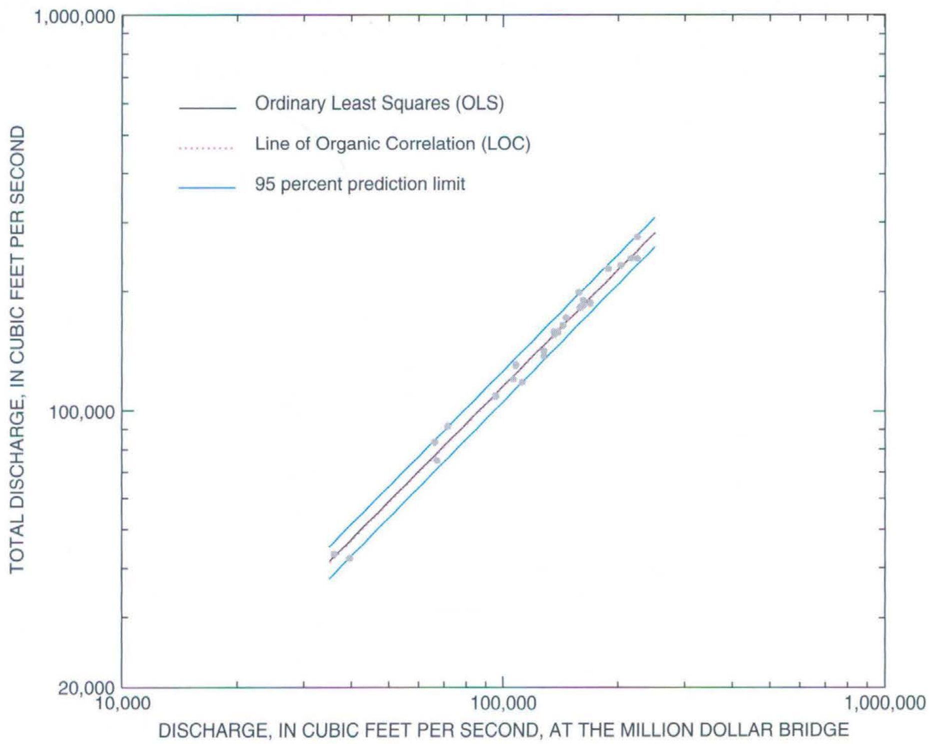

Figure 22. Comparison of discharge of the Copper River at the Million Dollar Bridge with the total measured discharge from Bridges 331 to 345.

There are some limitations to comparing the flows through Bridges 331, 1187, and 332 with the total discharge. Because the flow values for total discharge are based on estimated flow values at the Million Dollar Bridge, two estimating equations were used, each of which has some error. Also, it is uncertain what type of collection methods were used by ADOT&PF to collect the discharge data. However, the comparison does provide some information.

The ratio of the sum of the discharges at Bridges 331, 1187, and 332 to the total discharge ranged from 0.83 to 1.59. However, discounting the discharges less than 100,000 ft^3/s at the Million Dollar Bridge, the ratio ranges from 0.83 to 1.16, which would indicate that most of the flow during 1969 and 1970 that passed through the Million Dollar Bridge also passed through Bridges 331, 1187, and 332. A comparison of the percentage of total flow that passed through these bridges during 1969–70 (table 5) and during 1991–93 (table 4) indicates that the discharge through these bridges has decreased between 1969-70 and 1991-93.

Additional discharge information from ADOT&PF was also available for the period 1982-85. In July and August 1984, discharge measurements were made at all bridges along the Copper River Highway from Bridge 331 to Bridge 345 (table 6). The measured total discharge was within 10 percent of the estimated total discharge. The combined flow of the Copper River at Bridges 331, 1187, and 332 was 36 percent of the total discharge, a lower percentage than either the 1969–70 and 1991–93 periods. The percentage of the total flow at Bridge 342 was 36 percent, about 4 percent lower than the 1991–93 period. However, the percentage of flow at Bridges 334, 339, 340, and 345 changed from 1984 to 1991–93. In 1984, percentages at these bridges ranged from 5 to 10 percent, but in 1991–93 they ranged from no flow (Bridge 345) to only 3 percent (Bridge 340).

Table 6. Discharge of the Copper River at bridges along the Copper River Highway, 1984
[ft³/s, cubic feet per second]

Bridge	July 23-24, 1984		August 4, 1984	
	Discharge (ft³/s)	Percentage of total flow	Discharge (ft³/s)	Percentage of total flow
331	30,800	18	45,200	17
1187	20,500	12	22,400	8
332	10,900	6	17,900	7
333	681	<1	3,800	1
334	12,700	7	21,600	8
336	608	<1	3,800	1
339	13,600	8	28,200	10
340	8,400	5	18,400	7
342	61,600	36	88,300	33
344	377	<1	3,500	1
345	10,000	6	14,000	5
Total	170,200		267,100	
Copper River at Chitina	105,000		162,000	
Estimated discharge and 95 percent prediction interval				
Million Dollar Bridge[1]	144,100		214,700	
—upper limit	166,000		248,000	
—lower limit	125,000		186,000	
Estimated total[2]	165,000		243,500	
— upper limit	179,000		265,000	
—lower limit	152,000		224,000	

[1]From equation 1
[2]From equation 2

Discharge measurements made by ADOT&PF personnel indicate that flow at Bridge 342 ranged from 25 percent to 62 percent of the total discharge from 1982–85 (table 7). Two general observations can be made from the data. First, when the total discharge was less than 100,000 ft³/s, the percentage of flow through Bridge 342 was more than 50 percent. This suggests that a main channel of the Copper River had formed towards this bridge. The second observation is that because most of the flow of the Copper River was through Bridges 331, 1187, and 332 in 1969–70 (table 5), probably only a small percentage of the total discharge passed through Bridge 342. However, because flow at Bridge 342 was at least 25 percent of the total discharge in 1982–85, a decrease in the quantity of flow at Bridges 331, 1187, and 332 probably took place sometime between 1969–70 and 1982–85.

Sediment Transport

The sediment particle size determines to a large extent whether a stream carries the load as suspended load or as bedload. Knowledge of the quantity and particle size of suspended sediment that is transported can aid in determining scour or fill characteristics. Similarly, knowing the size of bed material and the size and quantity of sediment being moved as bedload may indicate if a channel is stable or unstable.

Suspended-sediment samples were collected at the bridges from Flag Point to the Million Dollar Bridge using techniques outlined by Edwards and Glysson (1988). At five bridges—331, 1187, 332, 342, and the Million Dollar—bedload samples were collected using a sampler (Helley and Smith, 1971) designed for collecting coarse material (medium sand to 76.2 square millimeters) and using techniques outlined by Emmett (1980). In 1992, bed-material samples were collected at Bridges 331, 1187, 332, and 342. These samples were collected during a low-water period from exposed sand and gravel bars downstream from these bridges. Bed-material samples were also collected at several locations throughout the study area in 1994 and analyzed with the bed-material samples collected at the bridge sites to determine the spatial size distribution of the bed material.

Table 7. Discharge of the Copper River at Bridge 342, 1982 to 1985
[ft³/s, cubic feet per second]

Date	Bridge 342 discharge (ft³/s)	Estimated total discharge (ft³/s)	95 percent prediction interval		Percentage of total discharge
			Upper	Lower	
7-15-82	42,900	172,000	187,000	158,000	25
8-13-82	52,000	158,000	171,000	145,000	33
9-17-82	53,400	121,000	131,000	111,000	44
6-1-83	37,600	65,900	71,900	60,400	57
7-27-83	60,000	196,000	213,000	180,000	31
8-23-83	53,200	120,000	131,000	111,000	44
5-10-84	19,200	35,300	38,800	32,100	54
7-23-84	61,600	165,000	179,000	152,000	37
8-4-84	88,300	243,500	265,000	224,000	36
7-11-85	70,800	198,000	216,000	182,000	36
8-6-85	72,400	183,000	199,000	168,000	40
9-10-85	59,500	100,000	109,000	92,000	60
10-08-85	31,500	50,800	55,600	46,400	62

Analytical techniques developed by Cohn and others (1989) were used to compute the annual suspended-sediment discharge of the Copper River at the Million Dollar Bridge. Suspended-sediment discharges at the Million Dollar Bridge were compared with the total suspended sediment discharges at Bridges 331–345 to determine if sediment was being deposited in the study area. Bedload data were analyzed to determine the size and quantity of material moving on the riverbed

Suspended Sediment

Virtually all the sediment transported by the Copper River in a given year occurs during the open-water season. In the spring, as snowmelt enters the Copper River, a corresponding increase in streamflow and suspended sediment occurs. Flow and sediment transport are maintained throughout the summer as glacial meltwater and rainfall runoff enter the river. In the fall, glacial melt ceases, streamflow declines, and less sediment is transported.

The concentrations of suspended-sediment samples collected at each bridge usually increased with a corresponding higher discharge (appendix 1). Most of the sediment is finer than sand (<0.062 mm) or composed of silt and clay (appendix 1). A particle-size analysis on a selected number of samples (appendix 2) indicated that the composition of the sediment ranged from about 20 to 50 percent clay (less than 0.004 mm) and the remaining sediment consisted of silt (0.004 to 0.062 mm) and sand (>0.062 mm). On the average, the sand fraction is about 10 percent of the suspended load.

Boxplots of the suspended-sediment concentrations (fig. 23) indicate that the range of concentrations at each bridge is similar. As a further check on this distribution, a Kruskal-Wallis test was done (Helsel and Hirsch, 1992). The Kruskal-Wallis test is appropriate because the data did not exhibit a normal distribution. For the Kruskal-Wallis test, the following hypothesis was tested:

H_0: The means of the nine distributions are equal (the null hypothesis);

H_a: Not all of the means of the nine distributions are the same (the alternative hypothesis).

Results of the Kruskal-Wallis test (table 8) indicated no significant difference among the mean suspended-sediment concentrations. Thus, the suspended-sediment concentrations at the Million Dollar Bridge and at Bridges 331–342 are considered to be similar.

Table 8. Results of Kruskal-Wallis test on suspended-sediment concentrations at bridges along the Copper River Highway

1) All observations ranked from 1 to N, smallest to largest.

2) Within each group, the average group rank, R_j is computed:

$$R_j = \frac{R_{ij}}{n_j}$$

Bridge	Count	Mean rank
331	21	97.7
1187	21	92.1
332	20	92.8
333	17	80.1
334	17	74.6
339	17	79.8
340	18	78.6
342	21	79.4
Million Dollar	20	98.2

3) The average group rank, R_j is compared to the overall average rank, $R = \frac{N+1}{2}$ squaring and weighting by sample size, to form the test statistic K:

$$K = \left(\frac{12}{N(N+1)}\right)\sum_{j=1}^{k} n_j\left[R_j - \frac{N+1}{2}\right]^2$$

$$K = 5.182$$

4) Determine the Chi-Square value for the number of degrees of freedom at the .05 level. Degrees of freedom equals 9-1 = 8. The Chi-Square value = 15.51.

5) Since K is less than the Chi-Square value we do not reject the null hypothesis.

Because continuous daily-discharge data were available for the Copper River at the Million Dollar Bridge, the annual suspended-sediment load was computed. In computing the suspended-sediment load, a relation between the instantaneous values of sediment discharge and streamflow (fig. 24) was used. However, it is not always correct to assume that the relation between the instantaneous values is the same for the daily values. Thus, the MVUE techniques were used to apply a bias correction to each daily sediment discharge.

The total suspended-sediment load for the Copper River at the Million Dollar Bridge computed by this method for the 1991–93 water years ranged from 63 to 78 million tons per year with a 3-year average of 69 million tons. The annual suspended-sediment load for other large rivers in Alaska was also computed as a

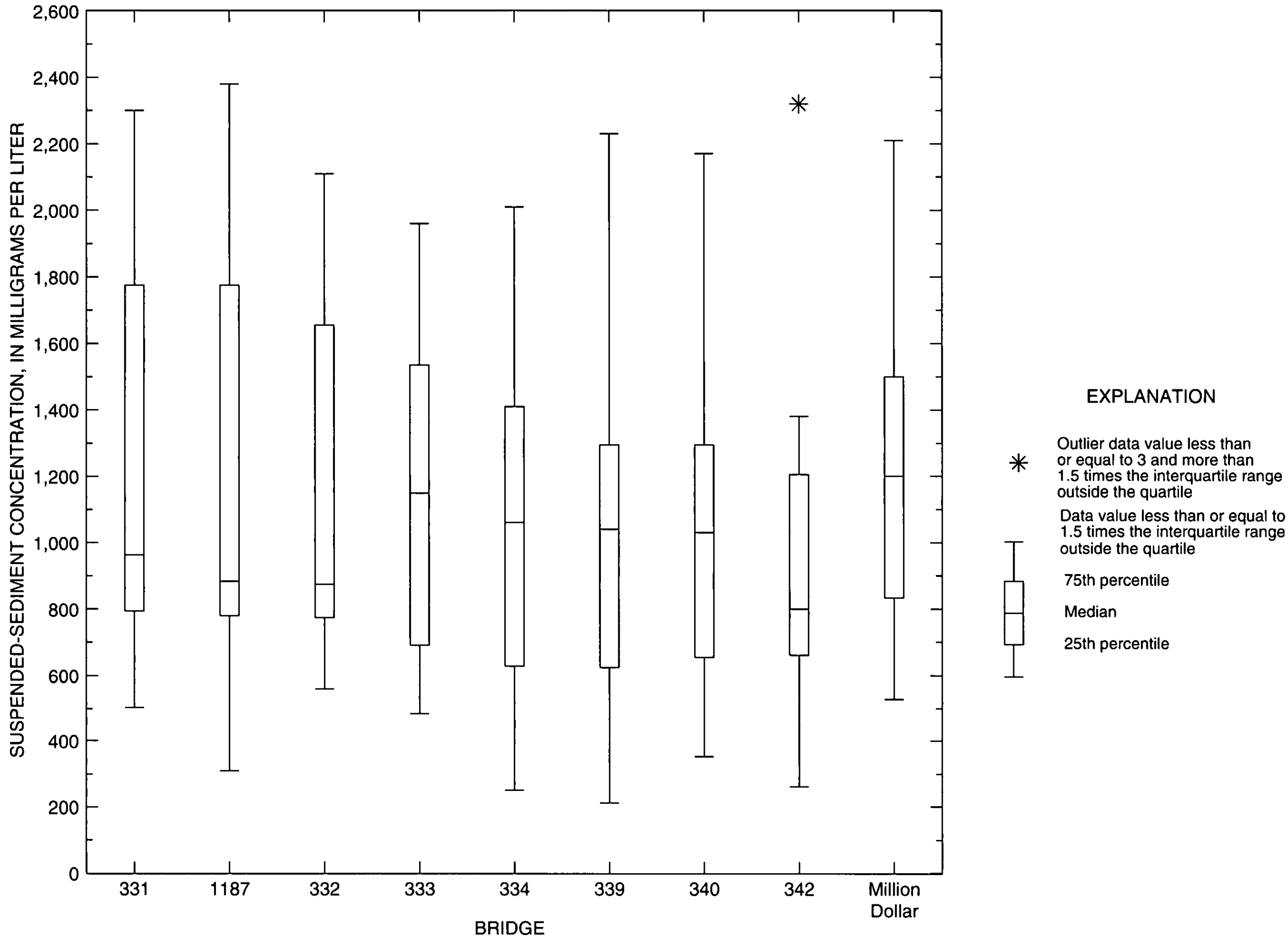

Figure 23. Suspended-sediment concentrations of the Copper River at bridges along the Copper River Highway.

comparison (fig. 25). On a total load basis, the Copper River transports approximately the same quantity of suspended sediment as the Yukon River does. However, on a yield basis (tons per square mile), the Copper River exceeds the other rivers in Alaska by more than a factor of 2.

For a given sampling period, most of the suspended-sediment samples at the bridges along the Copper River Highway were collected over a 2- or 3-day period. Although precise comparisons of suspended-sediment discharges cannot be made, the sediment discharges were compared for these 2- or 3-day sampling periods to determine if any trends were evident between the suspended-sediment discharge at the Million Dollar Bridge and the combined suspended sediment discharge from Bridges 331 to 342.

Comparison of the suspended-sediment discharges (table 9) indicates that more suspended sediment is being transported past Bridges 331 to 342 than is being transported past the Million Dollar Bridge at discharges greater than 100,000 ft^3/s. At discharges below 100,000 ft^3/s, less sediment is being transported past Bridges 331 to 342 than is being transported past the Million Dollar Bridge, and some deposition may be taking place.

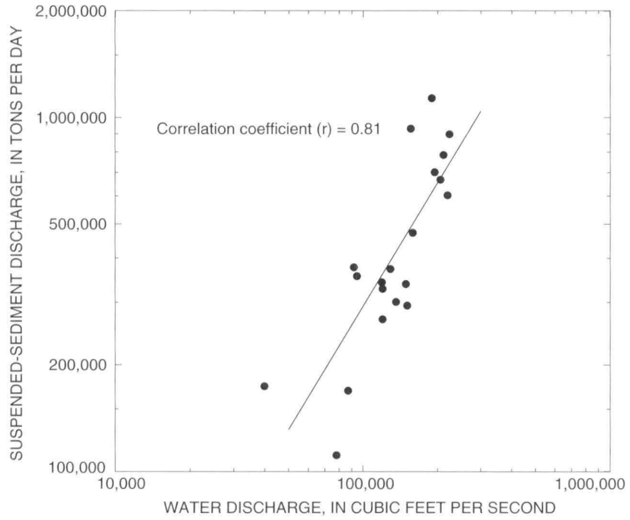

Figure 24. Suspended-sediment transport curve for the Copper River at the Million Dollar Bridge.

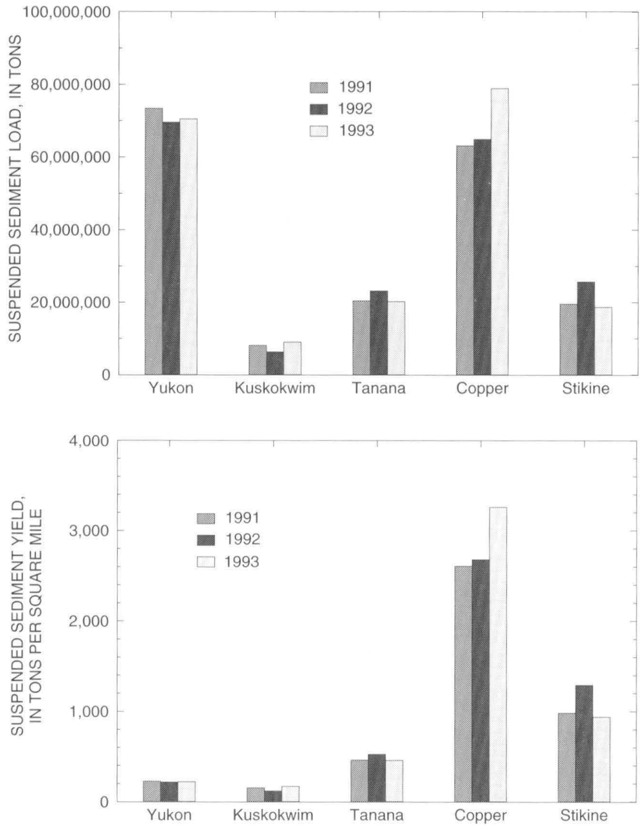

Figure 25. Suspended-sediment load characteristics of major rivers in Alaska.

Table 9. Comparison of suspended-sediment discharges of the Copper River at the Million Dollar Bridge and the Copper River from Bridges 331 to 342

[ft³/s, cubic feet per second; ton/d, tons per day]

Date[1]	Million Dollar Bridge water discharge[2] (ft^3/s)	Suspended-sediment discharge (ton/d)		
		At Million Dollar Bridge	Sum at Bridges 331 to 342	Difference
7-02-91	216,000	[3]713,000	983,000	270,000
7-24-91	162,000	[3]511,000	600,000	89,000
8-14-91	170,000	[3]541,000	909,000	368,000
8-28-91	95,400	349,000	217,000	-132,000
9-11-91	116,000	269,000	293,000	24,000
9-23-91	73,200	111,000	146,000	35,000
7-10-92	197,000	599,000	725,000	126,000
7-29-92	165,000	432,000	472,000	40,000
8-12-92	156,000	945,000	1,114,000	169,000
8-26-92	168,000	441,000	763,000	322,000
9-04-92	78,500	[3]221,000	136,000	-85,000
9-22-92	40,600	174,000	86,500	-87,500
6-08-93	153,000	341,000	365,000	24,000
6-18-93	152,000	353,000	326,000	-27,000
7-20-93	231,000	927,000	1,051,000	124,000
8-17-93	199,000	658,000	1,163,000	505,000
9-01-93	184,000	[3]592,000	836,000	244,000
9-15-93	101,000	193,000	251,000	58,000

[1]Starting date of sample collection, which lasted 2-3 days

[2]Average discharge for sampling period

[3]No samples collected at Million Dollar Bridge. Suspended-sediment discharge estimated from suspended-sediment curve (fig. 24)

Bedload

Bedload sampling at the Million Dollar Bridge indicated no presence of bedload (appendix 3). This is not unexpected because the smaller size material that might be transported is trapped by Miles Lake as the Copper River flows into it from the north. At the Million Dollar Bridge, the Copper River does not produce the required shear stress to transport the particle sizes found in the riverbed. Thus, bedload transport begins downstream from Childs Glacier as the Copper River enters the alluvial plain.

Bedload transport most likely occurs along the entire distance from Childs Glacier downstream to the Copper River Highway. No samples were collected in this area due to the swift currents of the Copper River and consequent difficulty of collecting samples from a boat. The bedload samples collected at Bridges 331, 1187, 332, and 342, which currently pass most of the flow of the Copper River, give some indication of bedload transport characteristics at these locations along the Copper River Highway.

From the median diameter of the bedload material, D_{50}, the composition of the bedload at Bridges 331, 1187, 332, and 342 could be classified as coarse sand to medium gravel (appendix 4). However, there are some differences between bridges. At Bridge 331, the D_{50} ranged from 0.4 to 6.0 mm (coarse sand to fine gravel). The D_{50} at Bridge 1187 ranged from 0.4 to 1.8 mm (coarse to very coarse sand). For Bridge 332, the D_{50} ranged from 0.5 to 0.9 mm, (coarse sand), which is considered a narrow range. This particular channel is composed primarily of fine to very fine sand. At Bridge 342, the D_{50} ranged from 0.8 to 16.0 mm (coarse sand to medium gravel).

The ranges of bedload discharge at Bridges 331, 1187, and 332 (Flag Point) were similar (fig. 26). A Kruskal-Wallis test on the means of the bedload discharges (table 10) indicated no significant differences.

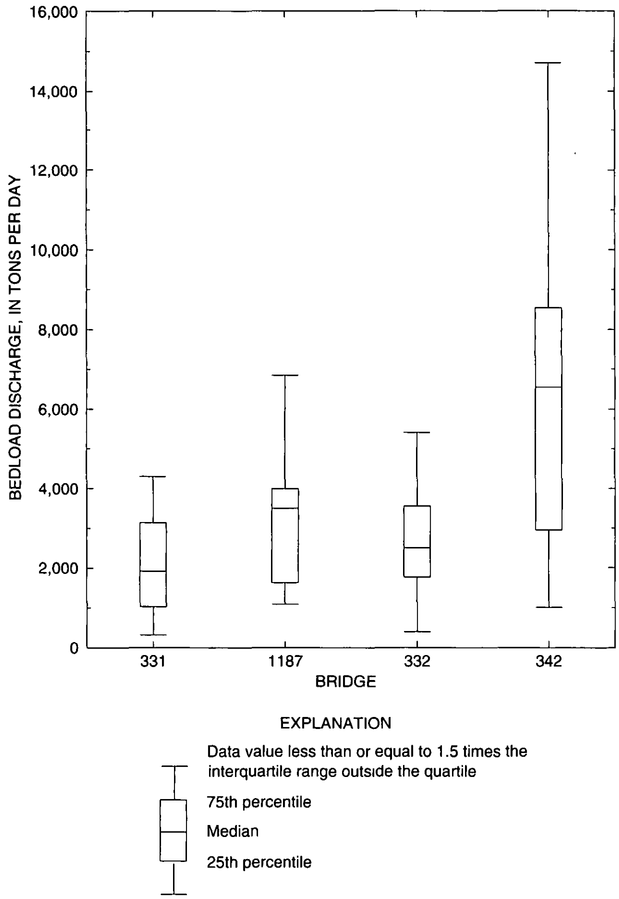

Figure 26. Bedload discharge of the Copper River at Bridges 331, 1187, 332, and 342.

Table 10. Results of Kruskal-Wallis test on bedload discharges at Bridges 331, 1187, and 332 along the Copper River Highway

1) All observations ranked from 1 to N, smallest to largest.

2) Within each group, the average group rank, R_j is computed:

$$R_j = \frac{R_{ij}}{n_j}$$

Bridge	Count	Mean rank
331	16	18.6
1187	15	27.9
332	15	24.3

3) The average group rank, R_j is compared to the overall average rank, $R = \frac{N+1}{2}$ squaring and weighting by sample size, to form the test statistic K:

$$K = \left(\frac{12}{N(N+1)}\right)\sum_{j=1}^{k} n_j\left[R_j - \frac{N+1}{2}\right]^2$$

$$K = 3.745$$

4) Determine the Chi-Square value for the number of degrees of freedom at the .05 level. Degrees of freedom equals 3-1 = 2. The Chi-Square value = 5.99.

5) Since K is less than the Chi-Square value we do not reject the null hypothesis.

Bedload discharge as a function of the total sediment load was generally less than 5 percent of the total at Bridges 331 and 1187 and generally less than 10 percent of the total at Bridge 332 (appendix 4). Bedload discharge at Bridge 342 ranged from 1,000 to 14,700 ton/d (fig. 26). Similar to Bridges 331, 1187, and 332, bedload discharge as a function of the total sediment load was less than 5 percent.

Transport of bedload begins at a particular discharge, sometimes referred to as the incipient motion discharge (W.W. Emmett, U.S. Geological Survey, written commun., 1996). From the incipient motion to the bankfull discharge, the relation of bedload discharge to water discharge is very steep. At Bridges 331, 1187, 332, and 342, this type of relation was not apparent between these two variables (fig. 27). The lack of a relation between bedload discharge to water discharge may be due to the non-uniform distribution of transportable sediment in the lower Copper River.

The bedload data were further analyzed to determine if some type of relation exists between bedload discharge and water discharge. In reaches where the supply of transportable sediment is not uniformly distributed, a pattern of bedload transport has been described by Klingeman and Emmett (1982). During a runoff period, the sediment supply at a sampling site downstream from an area in which large quantities of transportable sediment are stored is depleted during the rising stage of storm runoff. This depletion in supply results in reduced bedload discharges for a given water discharge. During the recession stage of storm runoff, the supply of transportable sediment at the sampling site is replaced by sediment scoured from the upstream storage area and bedload discharges increases. In comparing the bedload collected during a rising stage or a falling stage (fig. 27), this type of pattern appears to be evident at Bridge 342. More bedload was being transported during a falling stage or when discharge was decreasing. However, at Bridges 1187 and 332, the pattern appears to be reversed; more bedload was being transported during a rising stage when discharge was increasing.

Bed Material

Samples of bed material of the Copper River were collected at several locations throughout the study area (fig. 28). Five of the sites—1, 6, 9, 10, and 11—represent samples collected at the Million Dollar Bridge, and Bridges 342, 331, 1187, and 332, respectively. The remaining samples were collected either from the riverbed or from nearby gravel bars. A particle-size distribution was determined for each sample. These distributions were then analyzed in order to detect any trends.

A foundation report by the ADOT&PF (1981) characterized the bed material of the Copper River at the Million Dollar Bridge as boulders and cobbles with lesser quantities of sand and gravel. According to Guy (1969), this type of material has a D_{50} ranging from 128 mm to greater than 256 mm. Progressing downstream, the D_{50} of samples from sites 2 to 6 ranged from 17 to 65 mm (fig. 29). This type of material is classified as coarse gravel to very coarse gravel. At site 7, approximately 4 mi downstream from Bridge 342, the material is composed primarily of fine sand.

The type of bed material from sites 8–11 downstream towards Flag Point ranged from medium sand to fine or medium gravel. Thus, there appears to be a general trend of decreasing size of bed material from the Million Dollar Bridge downstream to the Copper River Highway. This decline in size downstream from the Million Dollar Bridge is probably due to the reservoir-like effect of Miles Lake. Miles Lake cuts off the supply of bed material that can be moved and the resulting effect is to armor the channel downstream from the lake outlet. As one proceeds downstream, the effect is diminished.

Cross Sections of the Copper River

Most alluvial channels will adjust during the passage of a flood. The width, mean depth, and mean velocity all increase as power functions with increasing discharge (Leopold and Maddock, 1953). Shear stress on the bed increases, and bed elevation changes due to either scour or fill. On the falling stage, competence of the flow to transport sediment is changed, and bed elevation again changes, most commonly back to the approximate level as that which existed before the flood. By surveying cross sections of a river at a particular point over time, trends—either aggradational or degradational—can be detected.

A common datum was established in the study area in 1991 by use of Global Positioning System (GPS) techniques (Brabets, 1992, 1993). At each bridge, at least one monument was established. When discharge measurements were made, the water-surface elevation was referenced to this datum. In this way, streambed elevations could be determined from depth soundings. At bridge sites where no flow was present, the ground elevation was surveyed in 1993. By comparing the cross sections, the quantity of scour or fill at a particular bridge site in a given year could be determined.

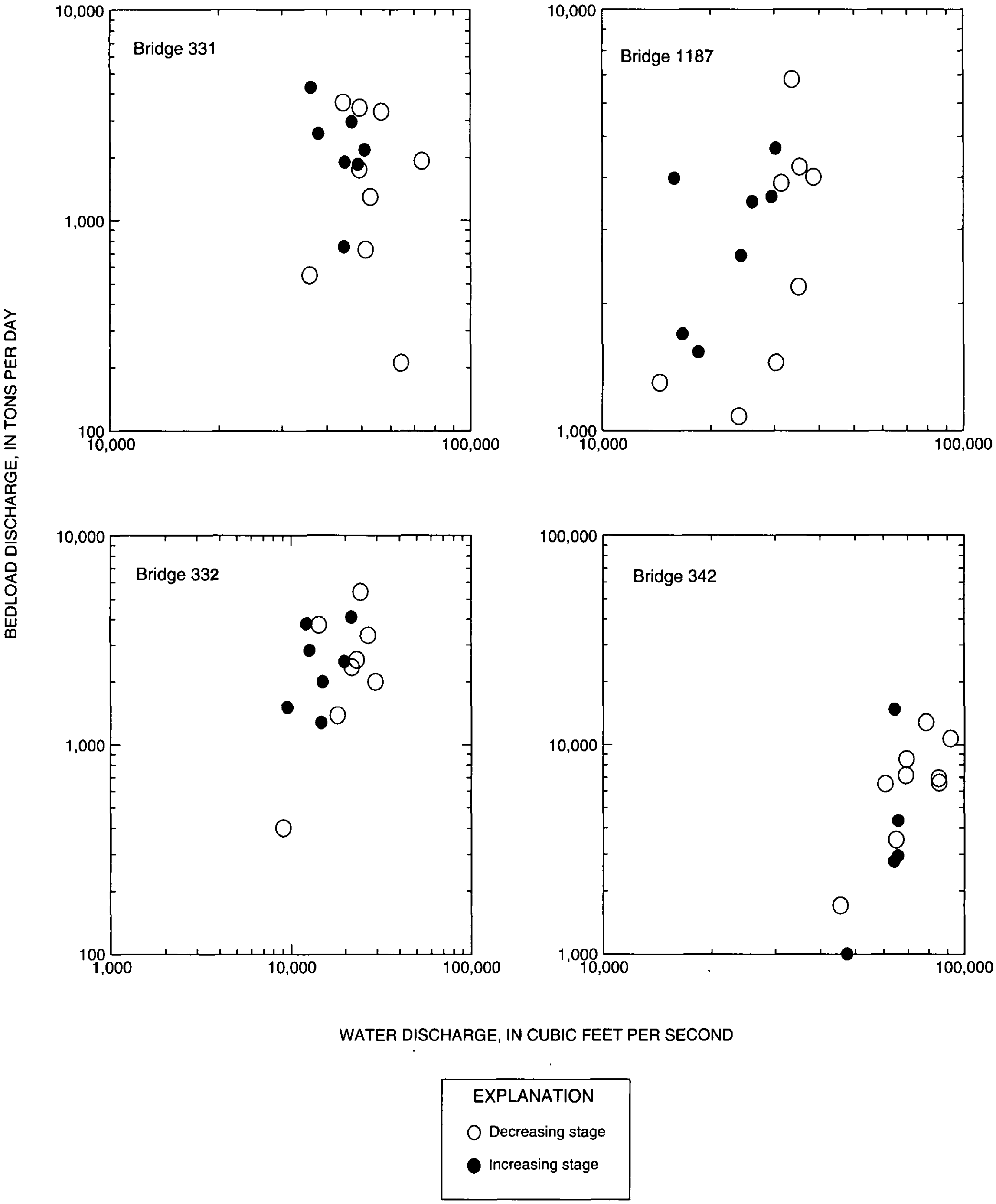

Figure 27. Bedload discharge and water discharge for the Copper River at Bridges 331, 1187, 332, and 342.

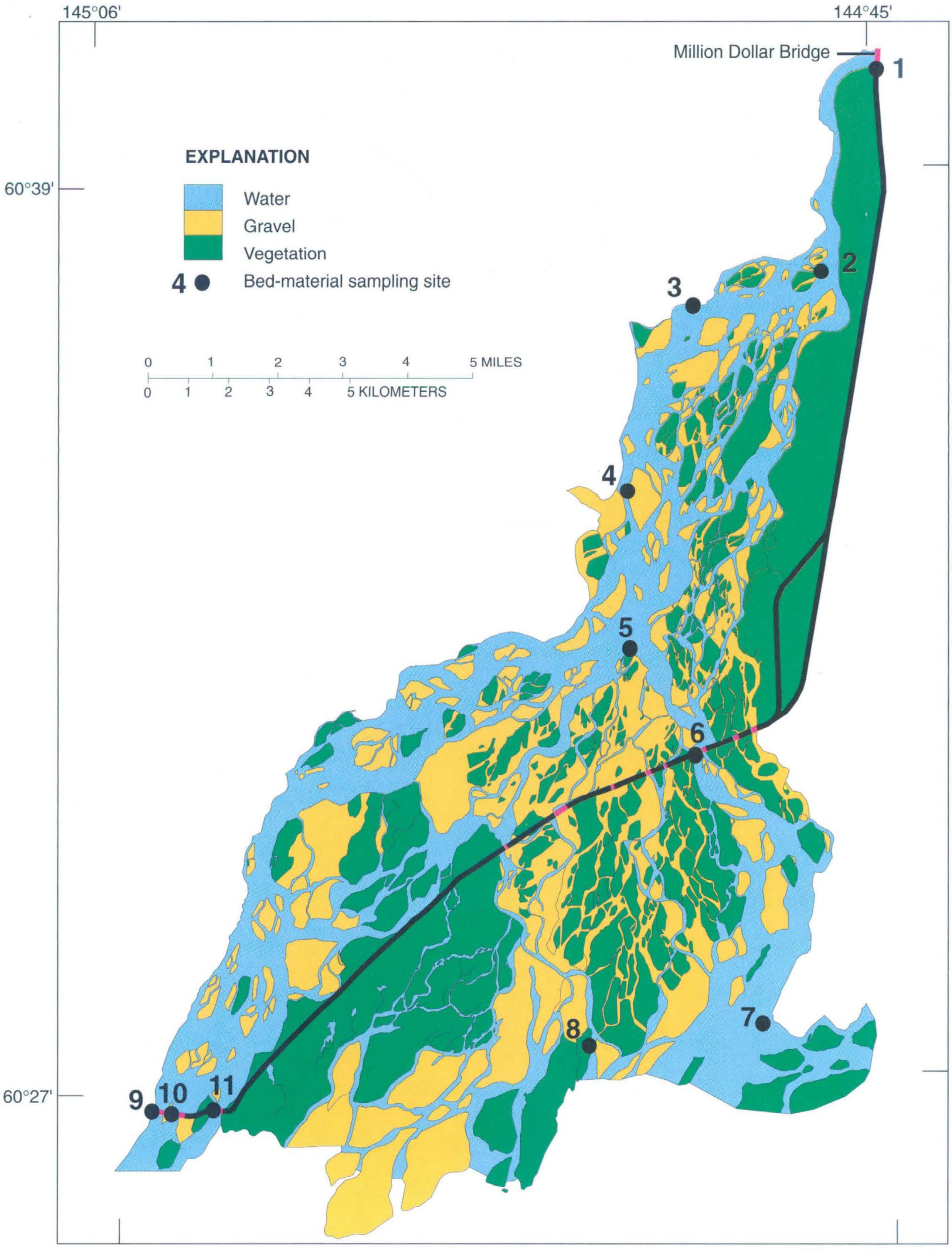

Figure 28. Location of sampling sites for bed material along the Copper River.

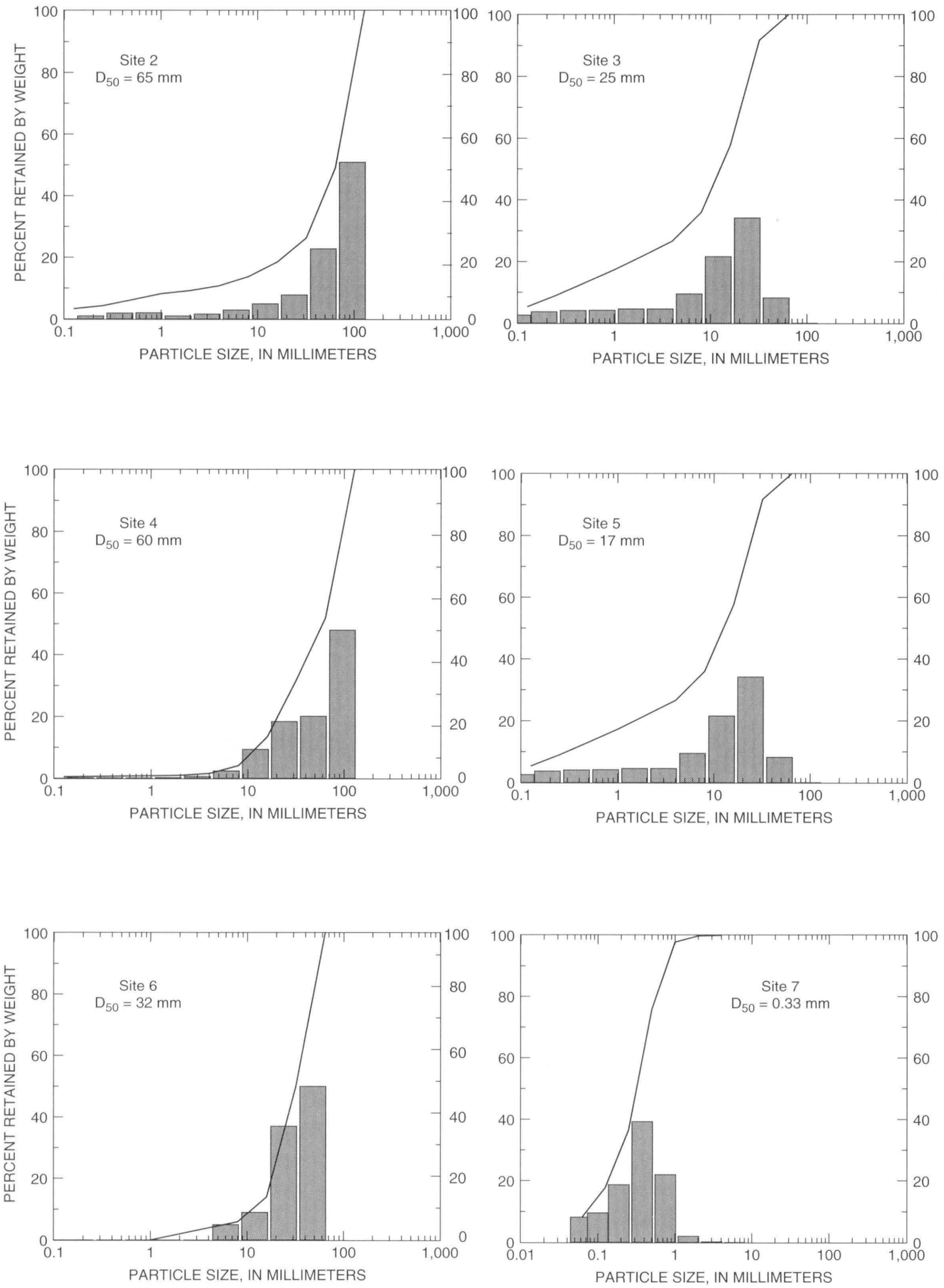

Figure 29. Particle-size distribution and median diameter of bed-material samples of the Copper River (see figure 28 for locations of sampling sites).

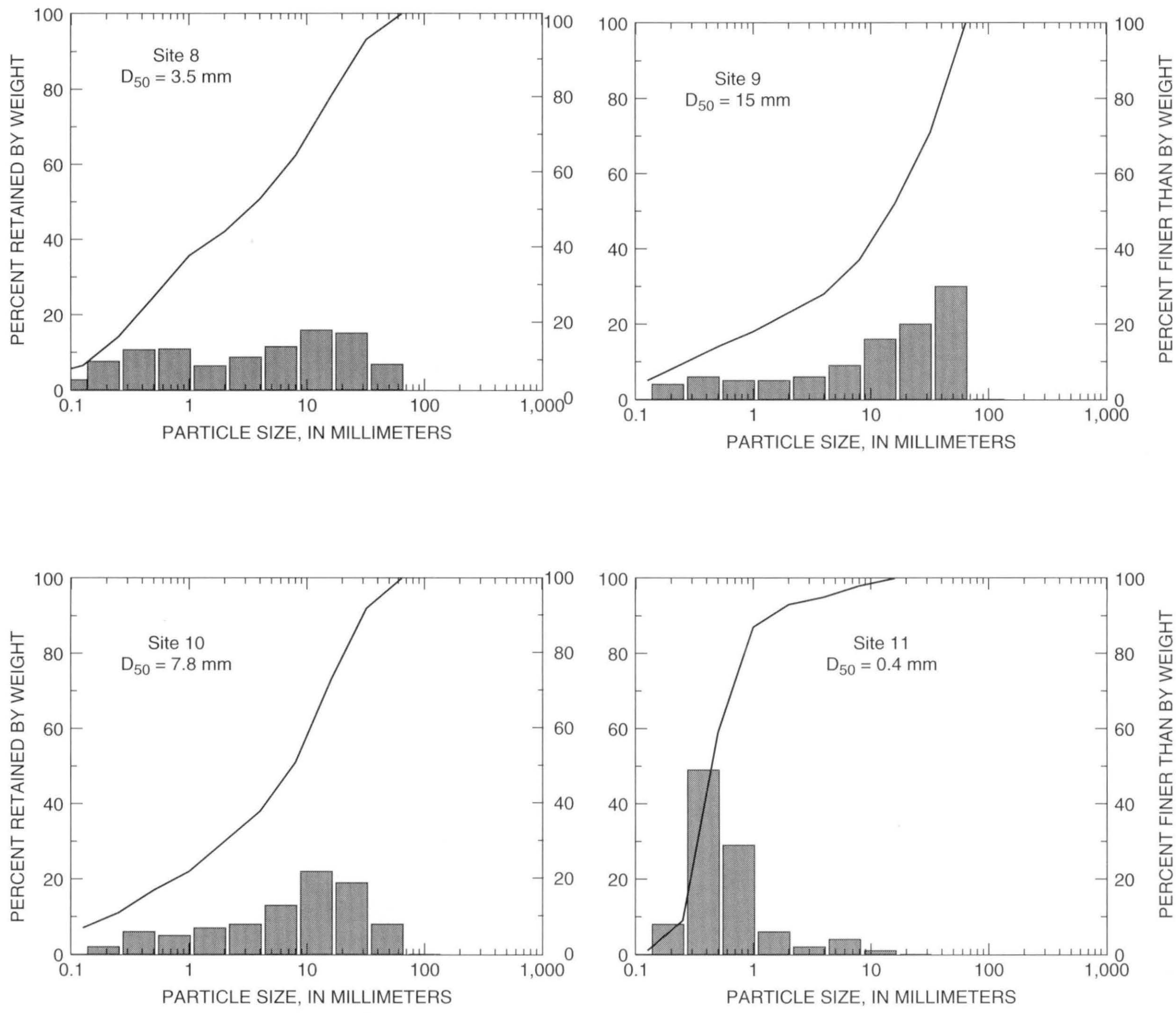

Figure 29. Continued.

In addition to the bridge survey data collected in 1991 and 1992, survey data were also available from ADOT&PF files and from the original 1908 survey of the Copper River and Northwestern Railway. Where possible, the survey data were adjusted to the 1991 datum. Thus, long-term trends in aggradation or degradation at the bridges located along the Copper River Highway could be determined by comparing the cross sections over time.

Cross sections of the Copper River between the Million Dollar Bridge and the Copper River Highway were surveyed in 1993. The objectives of this surveying were threefold: (1) to determine the slope of the Copper River between the Million Dollar Bridge and the Copper River Highway, (2) to determine the main channel(s) or thalweg of the river, and (3) to determine locations along the Copper River where the channel is constantly changing.

Historical Data

The earliest known cross sections of the Copper River were surveyed in 1908 during construction of the Copper River and Northwestern Railway (data available at Cordova Museum, Cordova, Alaska). Although the datum that was used in May 1908 could not be adjusted to the currently used datum, these cross sections still provide some information on the probable locations of the main channels of the Copper River in 1908. These cross sections were surveyed in May, which is a relatively low-flow period of the Copper River.

Using the survey data and corresponding water-surface elevation, the cross-sectional area at each bridge was determined. The cross-sectional areas (table 11) and inspection of the cross sections (fig. 30) indicated that probably the main channels—and thus most of the discharge—passed through Bridges 331, 1187, 332, and 334. Most likely, smaller channels carrying less flow passed through the remaining bridges.

The cross-sectional areas of the bridges in 1908 were compared with cross-sectional areas of the bridges measured in May 1993. Assuming that flows, water-surface elevations, and water velocities were rel-

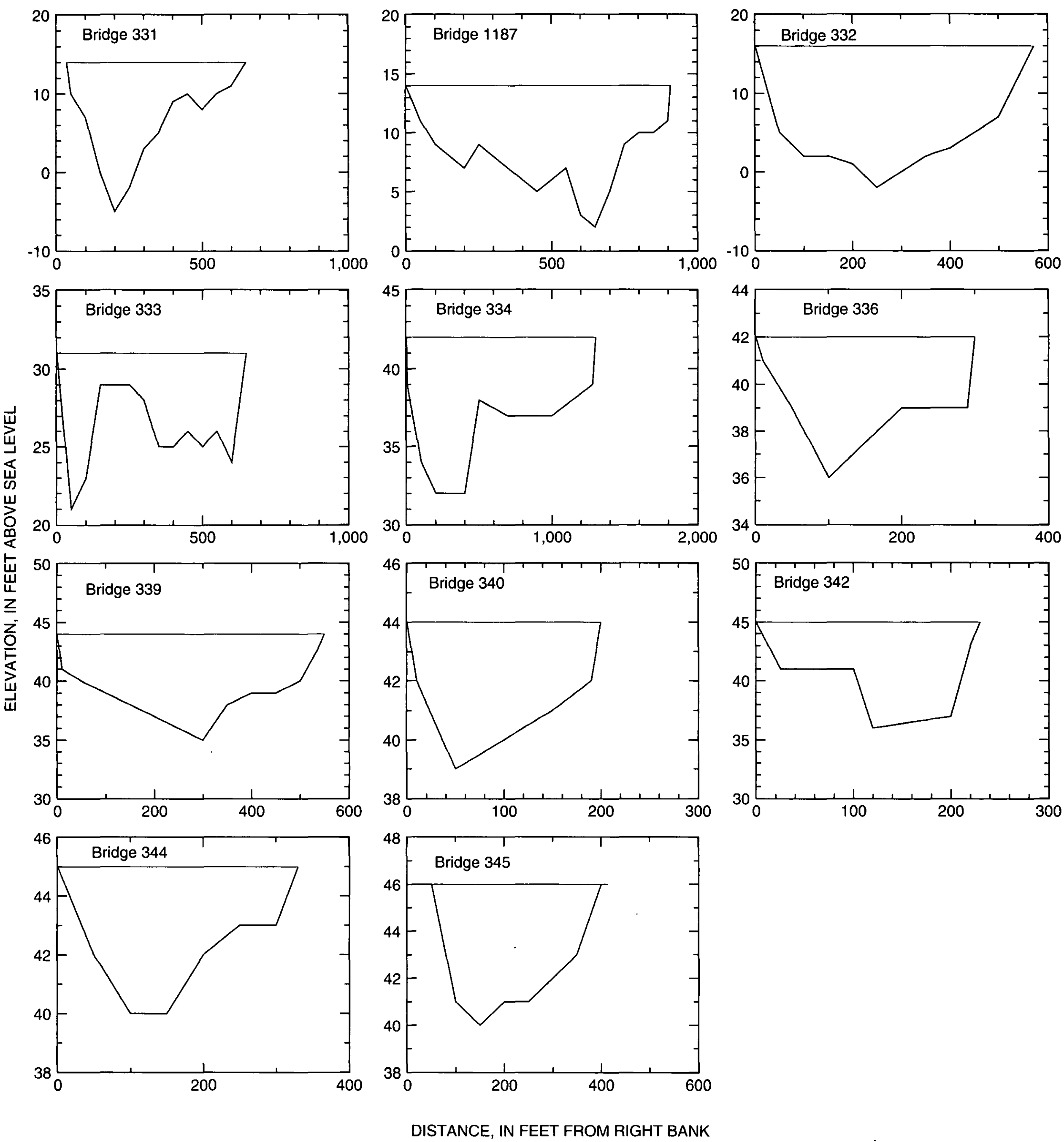

Figure 30. Cross sections of the Copper River at bridges along the Copper River and Northwestern Railway, 1908.

Table 11. Comparison of cross-sectional areas at bridges along the Copper River Highway, 1908 and 1993

Bridge	Area, in square feet	
	1908	1993
331	5,050	6,880
1187	. 5,800	5,690
332	6,870	3,100
333	3,100	1,650
334	7,500	2,040
336	1,200	0
339	1,400	820
340	800	1,290
342	1,200	12,300
344	975	0
345	1,325	0

atively similar in May 1908 and May 1993, differences in areas exist (table 11). The most significant is the magnitude of increase in cross-sectional area at Bridge 342, which indicates that flow patterns of the Copper River have changed over time. The reduction in cross-sectional area at Bridges 334, 344, and 345 also indicates that less flow or no flow is passing through these bridges.

The next known cross sections of the Copper River at the bridges along the Copper River Highway were surveyed in 1968. Between that time and 1993, significant changes took place at some bridges (fig. 31). Two distinct channels formed at Bridge 331, whereas the channel at Bridge 1187 remained relatively unchanged. At Bridge 332, there appears to be continual scour and fill, although the channel has not changed significantly since 1968. Bridges 333, 334, 336, 339, and 340 all have distinct channels that formed since 1968 and did not change significantly between 1991 and 1993.

From 1908 to 1968, no significant channel changes appear to have taken place at Bridge 342 (fig. 30 and fig. 32). The channel at the bridge in 1968 was 280 ft wide and when the replacement bridge was constructed in 1976–78, the channel was cleaned out to a width of 400 ft. Three years later, during the 1981 flood, the Copper River cut a channel through the road at the approach to the bridge (Cordova Times, 1983).

Beginning in 1982, the ADOT&PF began to monitor the streambed at Bridge 342 on a regular basis. Because of the increased flow through the bridge, contraction scour occurred. The channel continually scoured and filled, and as much as 54 ft of scour occurred from 1968 to 1985 at one point in the channel (fig. 32). From 1982 to 1987, the mean bed elevation of the channel decreased from 36.6 ft to 22.0 ft (table 12). Concern for the safety and integrity of the bridge led ADOT&PF to make major repairs to the structure in 1987. These repairs consisted of lengthening the bridge at each end by 240 ft (480 ft total) and constructing spur dikes at the left and right upstream abutments. Construction was completed in November 1988.

After construction, the first cross section at Bridge 342 was obtained in August 1989. The mean bed elevation was 46.3 ft. High water of 1989 overtopped and destroyed the left bank upstream spur dike. The flow of the Copper River was directed at the highway embankment and then flowed westward under the bridge. This resulting change in flow direction caused considerable scour on the right side of the channel (fig. 32) and lowered the mean bed elevation to 34.9 ft. In 1990–91, the spur dikes were rebuilt to a higher elevation. Since that time, the channel has continued to shift. In 1991, the tip of a gravel bar upstream from the bridge was about 300 ft from the tip of the rebuilt spur

Table 12. Changes in mean bed elevation of the Copper River at Bridge 342, 1968 to 1992

[All values in feet]

Date	Mean bed elevation	Change in mean bed elevation[1]	Minimum bed elevation
1968	48.0	--	43.0
7-15-82	36.6	-11.4	26.0
7-27-83	28.4	-8.2	4.0
7-22-84	30.7	+2.3	9.0
8-6-85	22.4	-8.3	-11.0
7-7-86	24.0	+1.6	4.0
7-29-87	22.0	-2.0	-5.0
After bridge lengthening			
8-89	46.3	--	32.0
5-10-90	39.6	-6.7	26.0
6-15-90	34.9	-4.7	14.0
After new spur dike			
6-7-91	37.5	+2.6	27.5
9-12-91	41.3	+3.8	20.3
9-18-92	32.5	-8.8	20.7

[1]Mean bed elevation is based on a width of 400 ft before August 1989 and a width of 880 ft from August 1989 to September 1992

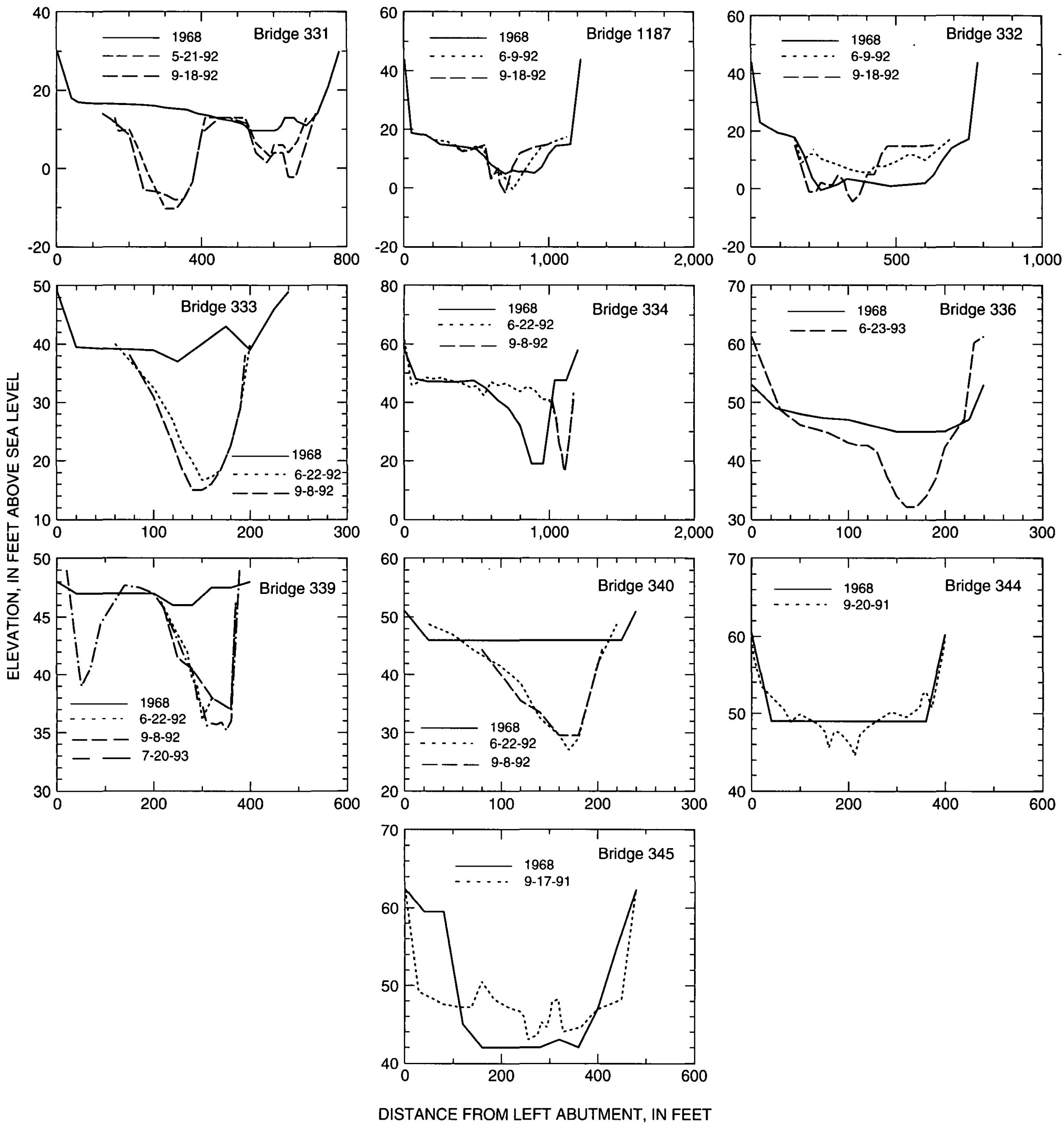

Figure 31. Cross sections of the Copper River at bridges along the Copper River Highway, 1968 to 1993.

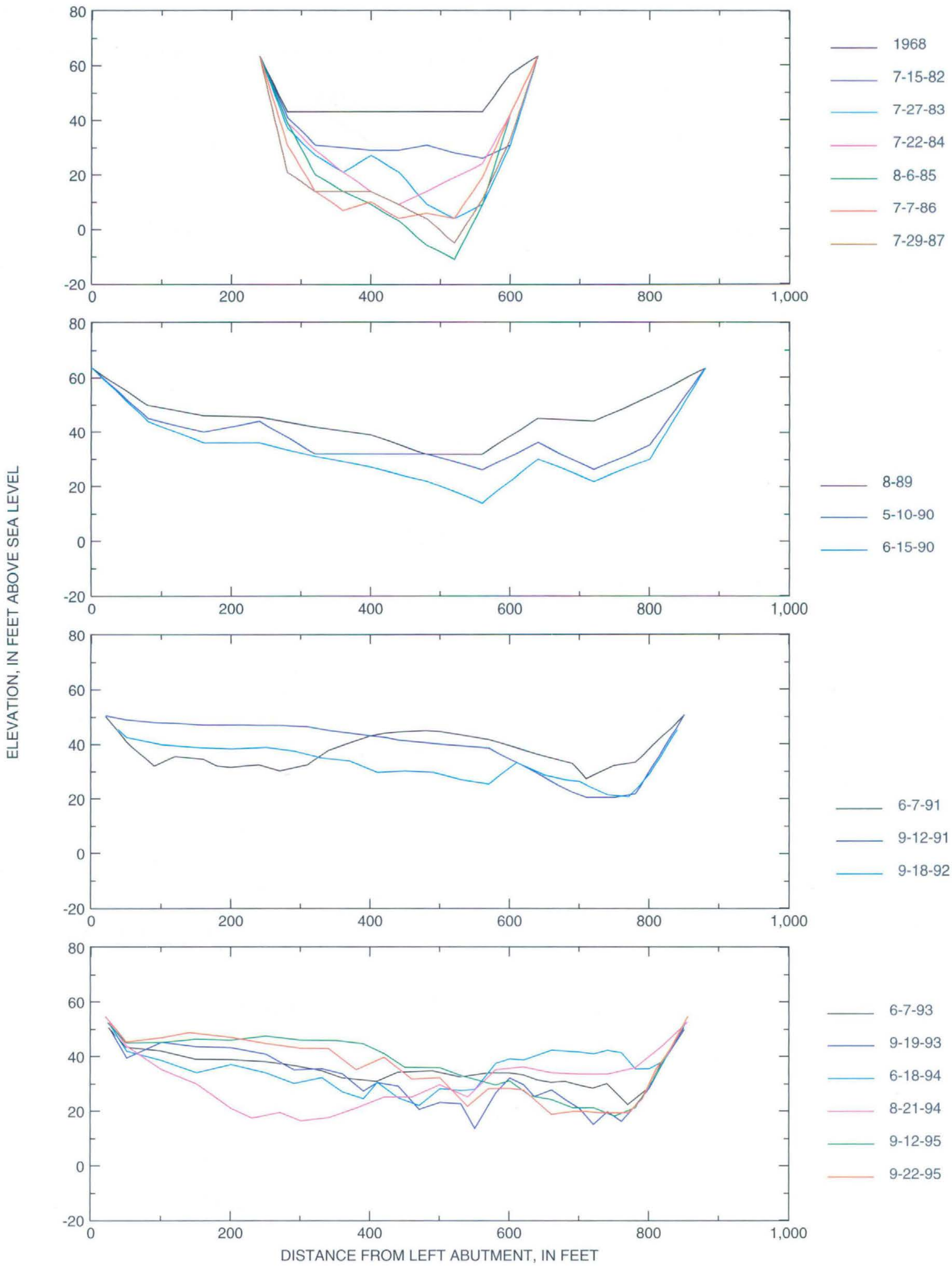

Figure 32. Cross sections of the Copper River at Bridge 342, 1968 to 1995.

dike (fig. 33–34). From 1991 to 1993, surveys showed the gradual erosion of the gravel bar and the gradual realignment of the channel. In 1991, the angle of flow to Bridge 342 was approximately 70 degrees. By 1994, visual observations indicated that most of the gravel bar had eroded and that the angle of flow to the bridge was nearly 90 degrees. This realignment most likely caused the scour on the left side of the channel (fig. 32). In 1995, visual observation indicated that the gravel bar had reappeared and the angle of flow had returned to about 70 degrees. This change in flow direction most likely caused fill to occur in the left side of the channel.

Comparison of cross sections taken at the Million Dollar Bridge in 1978, 1991, and 1992 (fig. 35) indicates that only about 2 ft of scour and fill has taken place. Some of these differences may be due to the inaccuracies of the various surveys. Although the precise datum of the 1913 cross section is unknown, comparing this cross section with the later cross sections indicates that the two main channels present in the 1978, 1991, and 1992 cross sections were also present in 1913. Further evidence that the channel at the Million Dollar Bridge is stable is the cross section obtained in October 1995, after the large flood in September. No significant changes were noted. The area between pier 1 and pier 2 and the area near pier 3 may not have scoured, because the 1913 cross section is the only one measured at the upstream side of the bridge.

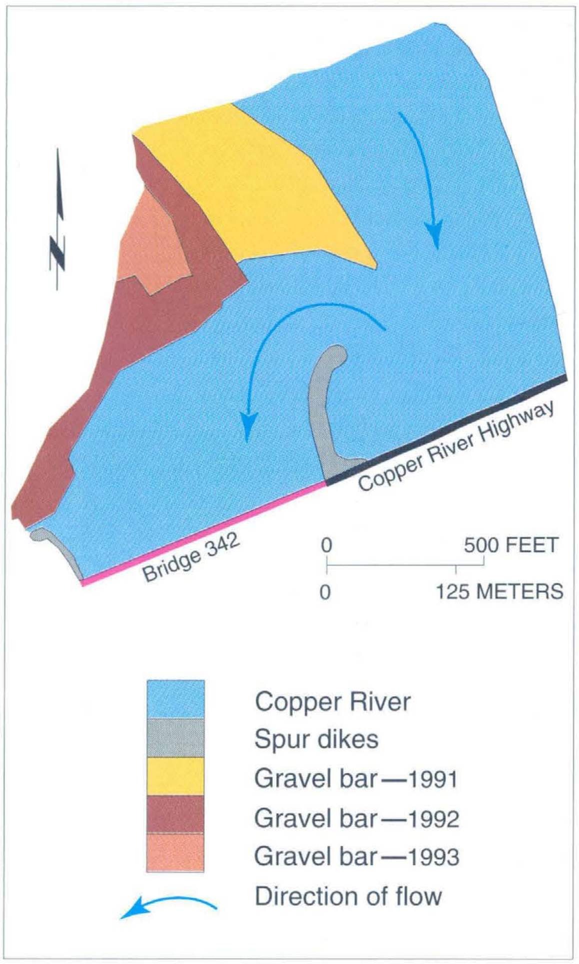

Figure 33. Location of gravel bar upstream from Bridge 342, 1991 to 1993.

1993 Data

A number of cross sections at various locations along the Copper River between the Million Dollar Bridge and the Copper River Highway were surveyed in 1993 (fig. 36–37). Some of the cross sections were surveyed twice in order to determine the relative stability of the channel. It should be noted that there is some error associated with the surveying, primarily due to the difficulty of surveying from a boat situated in high water velocities.

Cross section 1 (fig. 37) is located just downstream from Childs Glacier. The bed material at this site is composed of large cobbles and boulders, similar to the characteristics found at the Million Dollar Bridge. The section is uniform and deep and not likely to change because of the type of material. The remaining cross sections are located within the alluvial plain and are expected to change.

Sections 2, 3, and 5 define the main channel of the Copper River. The channel widens from approximately 1,500 ft to more than 2,500 ft along this reach of the river. Each section is characterized by a relatively deep subarea. Velocities along this reach at the time of surveying were estimated to be about 8 ft/s.

Section 4 was surveyed to define the characteristics of a bend of the Copper River downstream from section 2. Surveying was difficult in this area but generally, the deepest part of the river is at the outside or left edge of the bend. Section 6 defines a channel downstream from this bend and was uniform and deep, and approximately 1,000 ft wide. Because the width is shorter in this reach than it is in the reach defined by sections 1, 2, 3, and 5, this reach is considered a secondary channel.

Figure 34. Bridge 342, spur dike, and gravel bar: top, September 1991; bottom, September 1992. View is looking upstream from the bridge.

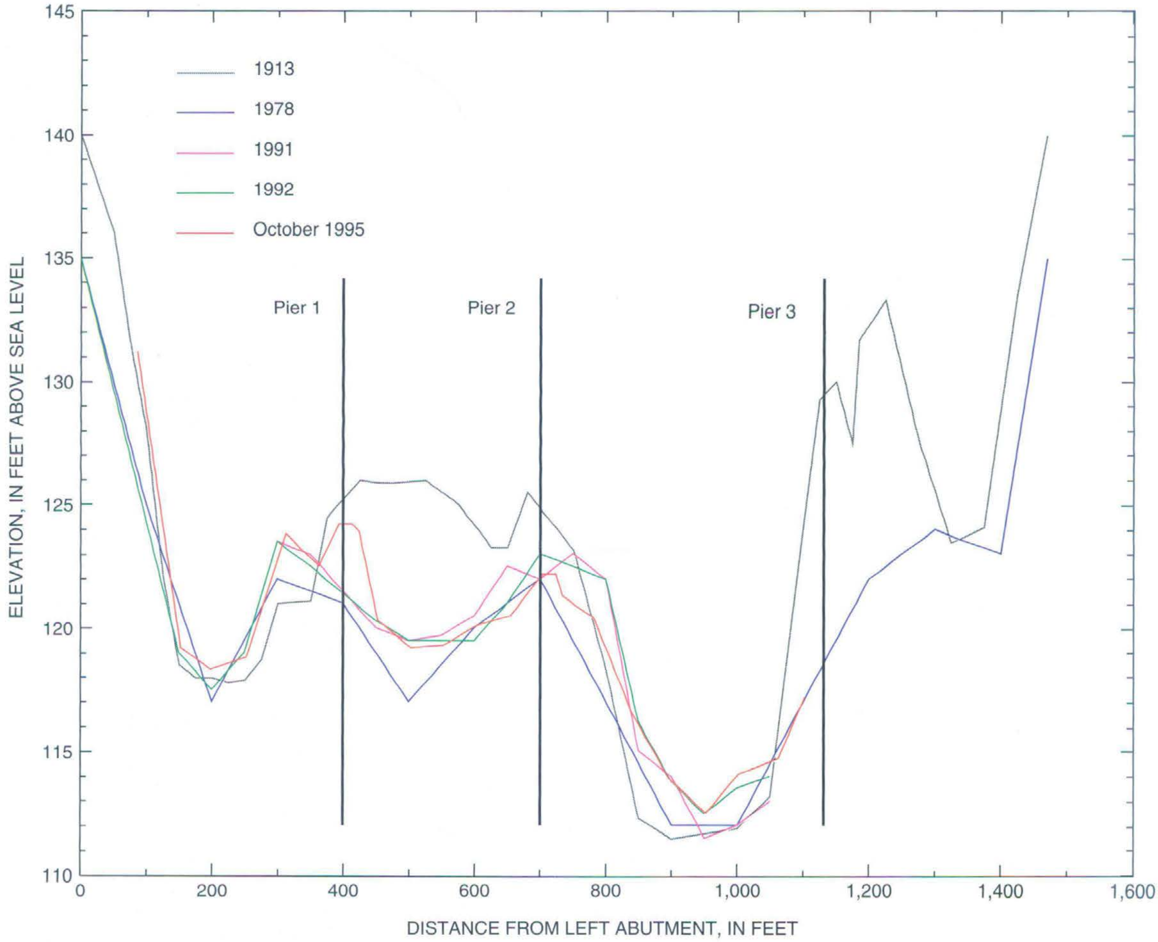

Figure 35. Cross sections of the Copper River at the Million Dollar Bridge, 1913 to 1995. (Vertical lines indicate locations of piers.)

Cross section 7 is more than 5,000 ft wide and represents most, if not all, of the flow of the Copper River. The main channel of the Copper River is located approximately 1,500 ft from the left monument and is more than 30 ft deep. Sections 8 and 9 confirm that the main channel of the Copper River is located along the left side. Section 10, located at the entrance channel to Bridge 342, scoured considerably in 1993. The scouring may indicate that additional flow is entering this channel.

Cross sections 11–12 define the channel towards Bridge 342, whereas cross sections 13–18, define the channel towards Flag Point. Cross sections 10–12 indicate that the channel towards Bridge 342 is constantly shifting. Sections 13–18 indicated that most of the flow in this reach of the Copper River flows near the right bank.

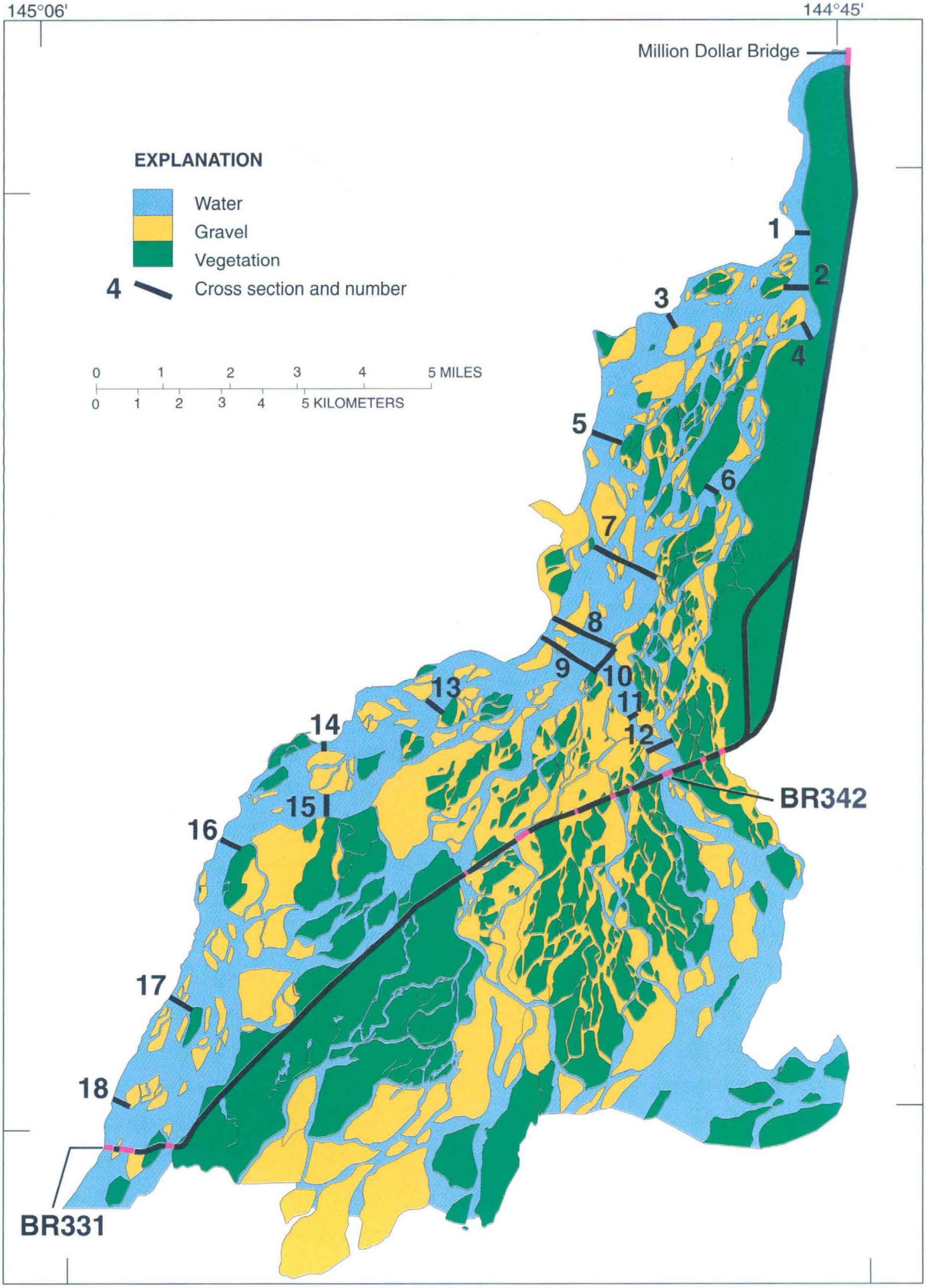

Figure 36. Locations of cross sections along the Copper River.

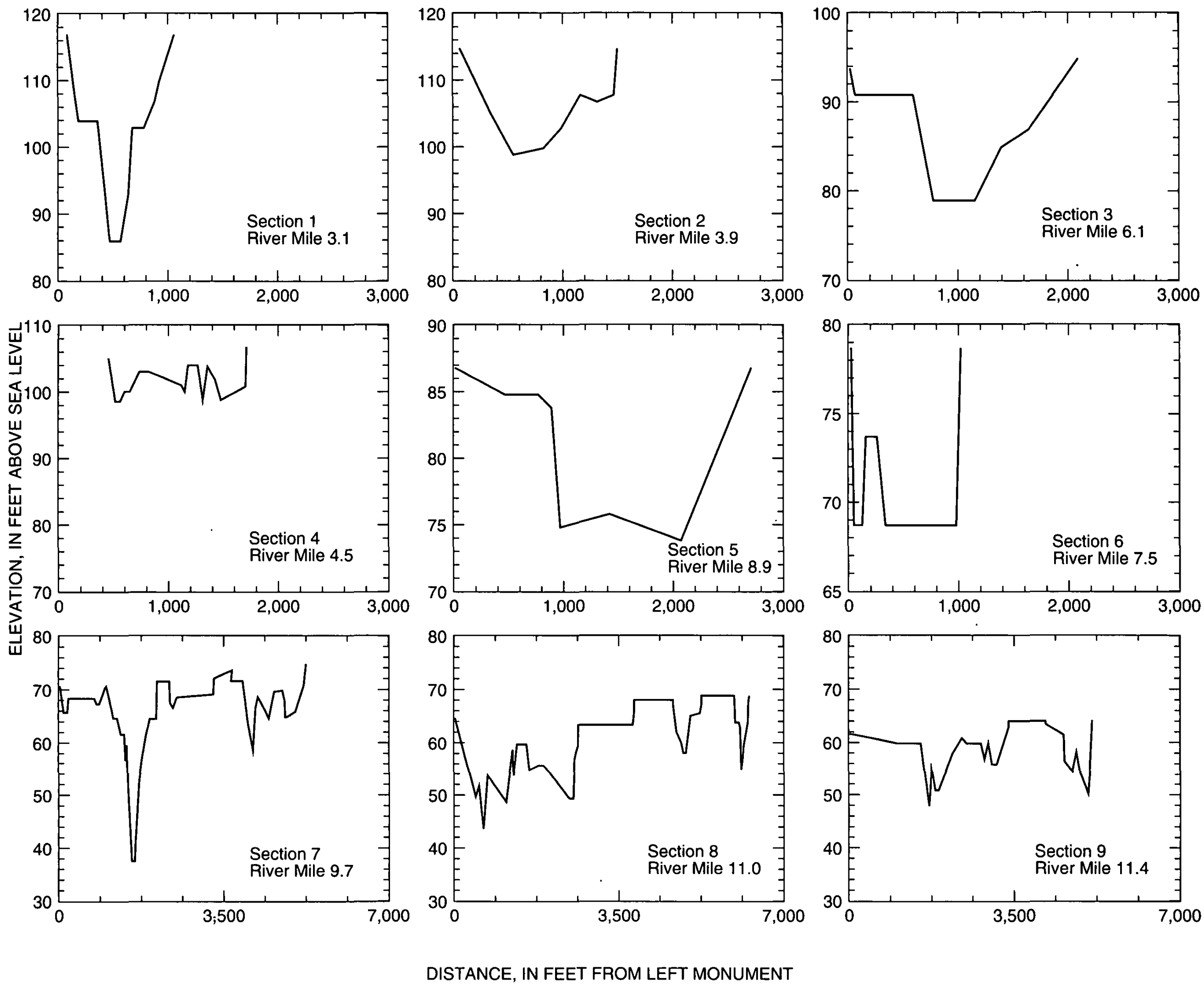

Figure 37. Cross sections of the Copper River, 1993 (see figure 36 for cross-section locations).

Water-Surface Profiles

Water-surface profiles of the Copper River from Miles Lake to Bridge 342 and from Miles Lake to Bridge 331 were developed from the surveyed cross-section data (fig. 38). From these profiles several observations can be made. The water surface is relatively flat from Miles Lake to the Million Dollar Bridge. From this point downstream to Bridge 342, a distance of 13.1 mi, the water-surface elevation decreases 88.5 ft for an average slope of 0.0013. From the Million Dollar Bridge to Flag Point, a distance of 22.7 mi, the water-surface elevation decreases 120 ft for an average slope of 0.0010. A slight change in gradient is noticeable at approximately mile 20.

Entrainment of Bed Material

The power or ability of moving water to transport bed material is commonly referred to as competence or the ability to entrain sediment. Entrainment has been expressed in terms of the intermediate diameter of the largest particle that can be transported at a given flow velocity (Scott and Gravlee, 1968). Entrainment has also been expressed as tractive force or related to boundary shear (Fahnestock, 1963). Regardless of the terms and units used to describe entrainment, the concept of a critical flow strength at which particles begin to move on a riverbed is central to sediment transport theory.

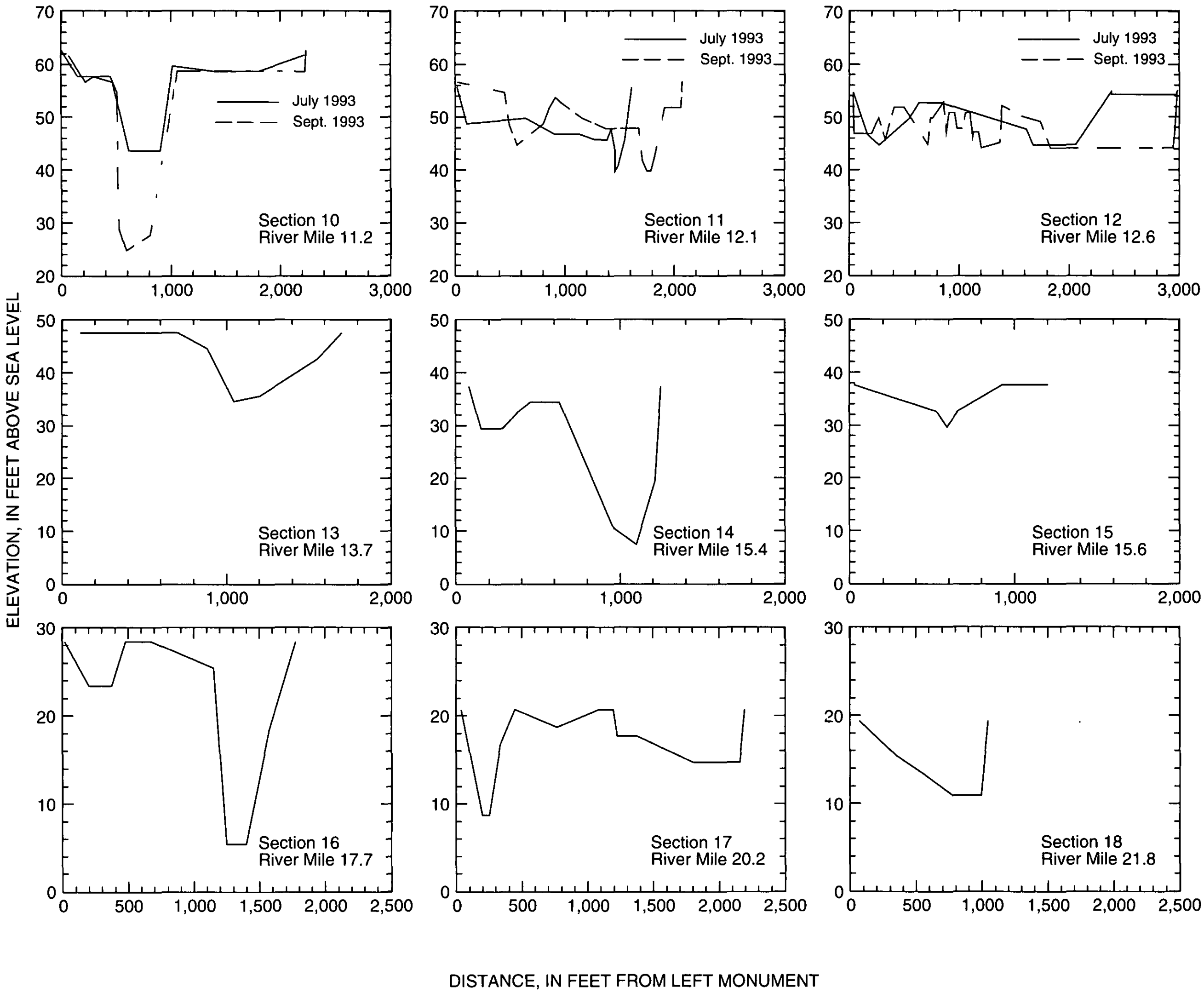

Figure 37. Continued

The processes of selective grain entrainment are not completely understood. Factors such as a particle's exposure to flow, its pivoting angle over another particle, and frictional forces still require additional study. However, in general terms, with the passage of a flood, the lift and drag forces acting on a particle increase. When these forces exceed the restraining forces of weight and friction, bedload transport commences, which subsequently can lead to channel changes.

In most natural gravel-bed rivers, the bed material is immobile in ordinary flow conditions and moves only during floods. The critical flow condition for entrainment is therefore of interest. Perhaps the most common means of predicting the threshold of motion is the computation of the shear stress:

$$\tau = \rho g d S$$

where τ is shear stress,
ρ is density of water,
g is acceleration due to gravity,
d is mean water depth, and
S is water surface slope.

Previous works by Andrews and Smith (1992) and Neill (1968) have shown that occasional motion of bed particles begins at a dimensionless shear stress as small as about 0.020. Only those particles resting in the shallowest bed pockets, however, can be moved under these conditions. As the dimensionless shear stress increases, the number of bed particles in transport increases rapidly, and at a shear stress of about 0.060 most of the particles on the bed surface are in motion.

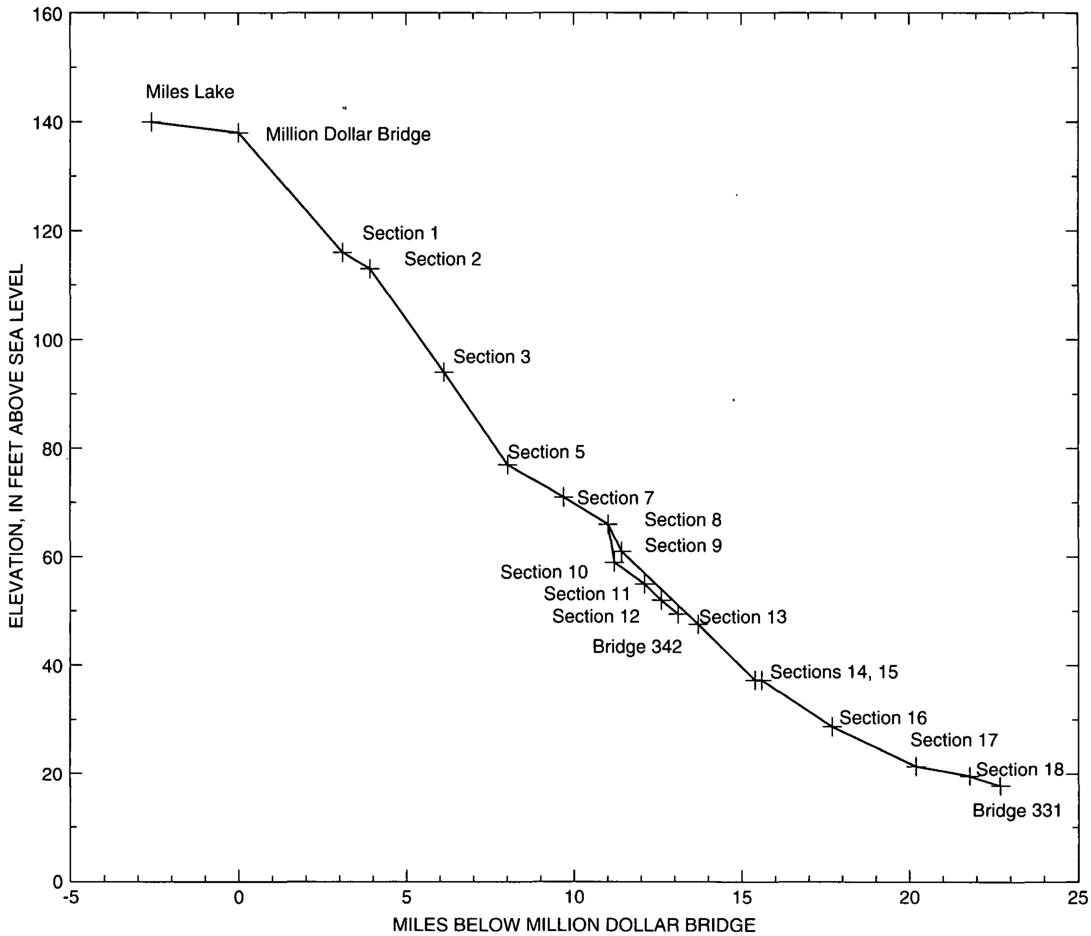

Figure 38. Water-surface elevations at locations along the Copper River.

Because shear stress is not routinely monitored, efforts have been directed towards developing an entrainment criterion in the form of a critical discharge. For example, Komar (1989) undertook comparisons between entrainment formulas and empirical relationships based on selective-entrainment measurements. He concluded that unit-width discharge equations for determining the entrainment of bed material developed by Bathurst and others (1987) were compatible with shear stress measurements.

Ferguson (1994) has continued this type of research and has recently developed a critical discharge equation for entrainment, which was used in this study. Although there are some limitations and assumptions of Ferguson's equation, it was used to establish a range of entrainment discharges at various locations along the Copper River. The past history of flows in the Copper River could then be compared with the entrainment discharges to determine if these flows would have been of sufficient magnitude to cause entrainment of the bed material.

Ferguson (1994) related the entrainment discharge of a certain particle size to slope and D_{50} as follows:

$$Q_{ci} = \frac{0.134(D_{50})^{1.5}\left(\frac{D_i}{D_{50}}\right)^{0.19}}{S^{1.37}}$$

where

Q_{ci} is discharge per unit width, in square meters per second;

D_{50} is median diameter of bed material, in meters;

D_i is diameter of bed material of interest, in meters; and

S is slope.

The constant, 0.134 is dependent on the value of the τ_{c50}, the dimensionless shear stress required to move a particle of diameter D_{50}, and m, which is a value dependent on the roughness height and D_{50}. For the above equation, Ferguson used a value for τ_{c50} of 0.06 and a value for m of 1.14 to determine the constant of 0.134. The exponent, 1.37, used for S is dependent on the type of flow resistance law, and can range from 1.17 to 1.37, which does not significantly influence the value of critical discharge. The exponent of 0.19 is dependent on a hiding factor which can range from 0 to 1. A hiding factor of 0 indicates that the particle will move only when its critical shear stress is exceeded, whereas a value of 1 indicates that the movement of the particle is dependent on the ambient size of other particles. For the above equation, Ferguson used a hiding factor of 0.9 to determine the value of 0.19.

As Ferguson's assumptions were considered reasonable, his equation was used at several cross sections where bed material, slope, and channel width data were available. The intent of using Ferguson's equation was to establish a range of discharges which could indicate that entrainment of bed material would occur.

The discharge values needed for entrainment of selected particle sizes using Ferguson's equation are realistic (table 13). The range of entrainment discharges which were computed do occur in the Copper River. One noteworthy feature is the range of flows required to move material near Bridge 342. These discharges occur frequently at Bridge 342. The fact that the cross sections are constantly changing confirms that considerable bed material is being transported past the bridge.

Table 13. Discharge estimates for bed entrainment at various locations along the Copper River

[Ferguson's (1994) equation uses units of meters and square meters per second per meter of width. All calculations were done in metric units and then converted to inch-pound units.]

Location	Width (feet)	D_{50} (mm)	Slope	Discharge, in cubic feet per second					
				Particle size, in millimeters					
				4.0	8.0	16.0	32.0	64.0	128
Cross section 3	800	25	0.0014	26,100	29,800	34,000	39,000	44,200	50,500
Cross section 4	1,200	65	0.0015	41,300	47,300	54,200	61,500	70,600	80,000
Cross section 10	2,000	17	0.0008	85,200	97,000	110,500	126,500	144,200	164,400
Bridge 342	830	32	0.00095	64,000	73,000	83,300	95,100	108,500	123,700

Aerial Photography

Analysis of aerial photography obtained at different time periods is perhaps one of the best techniques to document channel changes. For many years, this type of analysis was done using a zoom transfer scope. With a zoom transfer scope, an aerial photograph can be viewed in superposition with a map, and information from the photo can be readily transferred onto the map by direct tracing. In recent years, digital computer techniques have been developed that allow information from photographs to be stored electronically. The significance of the digital methods is that one can build a model that removes the photo distortion.

Aerial photography of the study area is available for 8 years: 1950, 1965, 1971, 1974, 1978, 1982, 1985, and 1991. The scale of the photography (table 14) ranged from 1:12,000 to 1:60,000. With the exception of the 1974 and 1982 photography, photo coverage of the study area was complete. Interpretation of the aerial photography was done by the use of an AP190 analytical stereoplotter. This stereoplotter has a 10–15 micrometer measurement capability and is coupled to a desktop computer. The computer software developed for the AP190 is based on established photogrammetry equations and includes programs for interior, relative, and absolute orientation of stereographic models. After a set of stereo models was registered, SIMBA (SIMultaneous Block Adjustment), a software program developed by the USGS, was then used to link the stereo models together. SIMBA is an aerial triangulation program for the ground adjustment of independent models as single models, strips, or blocks. The program adjusts a block of photogrammetric units (such as stereo models) to each other and to ground control in two or three dimensions.

Table 14. Aerial photography obtained for the lower Copper River

Date	Type	Scale
8-01-50	Black and white	1:50,000
7-07-65	Black and white	1:12,000
7-09-71	Color	1:40,000
7-17-74	Color	1:18,000
8-18-78	Color infrared	1:60,000
7-27-82	Color infrared	1:60,000
8-27-85	Color infrared	1:60,000
8-07-91	Color	1:30,000

As the AP190 measures photo coordinates on a stereo model, the computer software converts and stores the coordinates in a specified datum. In this study the Universal Transverse Mercator (UTM), North American Datum of 1927 (NAD27) was used. For each stereo model, features such as edge of water, vegetated bars or islands, and gravel bars were digitized. Some subjectivity was involved in determining the number of gravel bars to digitize, because digitizing is very time consuming. Thus, the procedure for determining the number of gravel bars to be digitized was one of digitizing data until it appeared that the photography was accurately represented.

The digitized data were entered into a Geographical Information System (GIS) database. The GIS of the study area provided a means to compare the aerial photography easily and at a common scale. Using GIS techniques, each year of aerial photography was analyzed to document significant features such as the main channel(s) or large gravel bars. Beginning with the 1965 aerial photography, comparisons were made with the previous aerial photography (for example 1965/1950, 1971/1965 etc.) in order to document features such as channel changes or loss of vegetation.

Another aspect of the photographic interpretation was to determine if effects caused by uplift from the 1964 earthquake could be detected in the study area. Uplift is an important consideration because it may have resulted in some channel changes in the lower Copper River. No survey data—before and after the earthquake—exist to determine how much uplift occurred in the study area. However, if significant uplift had occurred in the study area, characteristics such as large sediment deposits and channel changes, would be seen readily from the aerial photographs obtained after 1964.

For each year of aerial photography, the discharge of the Copper River was determined using equation 1. Then, using the stage-discharge rating curve from the gaging station at the Million Dollar Bridge, the water-surface elevation was determined. Thus, when comparing successive years of photography, knowing the difference in discharge between the two years assisted in the interpretation of features such as gravel bars. In addition, throughout this discussion, the flow characteristics given in figure 21 are used to determine if any relation(s) between flow and channel changes existed.

1950 to 1965

The period from 1950 to 1965 can be classified as a quiescent period. Average discharge was below the long-term average in 7 of the 10 years for which daily flow records were available (fig. 21A). The highest estimated peak discharge during this period was 285,000 ft^3/s, which is estimated to have a recurrence interval of approximately 10 years. Only 6 years had flow periods where discharge exceeded 200,000 ft^3/s.

In 1950, the Copper River flowed in a south/southwestward direction towards Flag Point (fig. 39). The alluvial fan at the south side of Goodwin Glacier did not protrude significantly into the main channel of the Copper River. A secondary channel flowed primarily southward toward Bridge 345. Past the Goodwin Glacier fan, the main channel turned toward the southwest, with most of the flow toward Flag Point and Bridge 334.

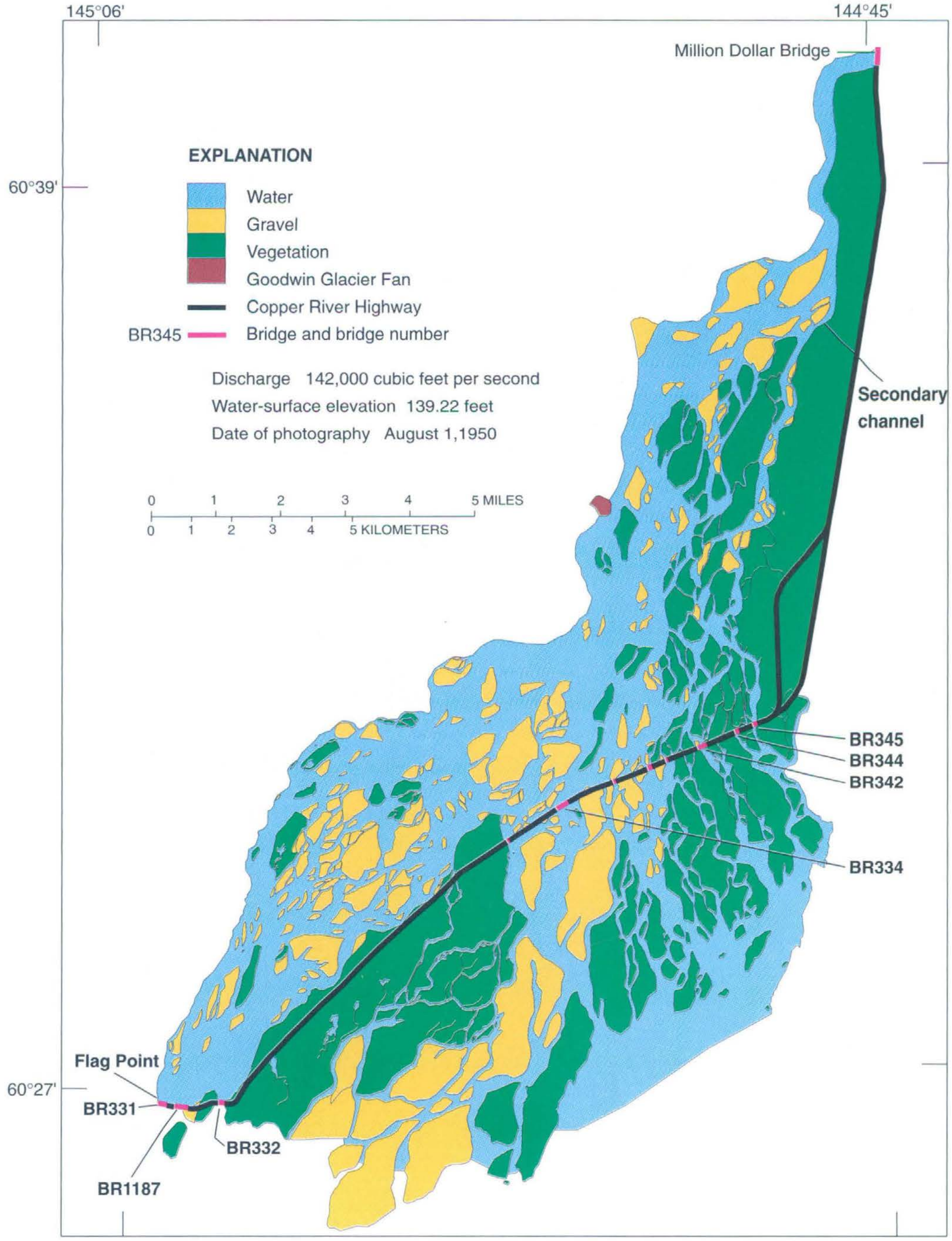

Figure 39. The lower Copper River based on aerial photographs taken in 1950.

The flow patterns of the lower Copper River in 1965 (fig. 40) are similar to the 1950 flow patterns. There was no significant advance of the Goodwin Glacier fan and most of the flow was toward Flag Point and Bridge 334. Although a larger quantity of gravel is present near Bridge 334, it is most likely attributed to the lower water-surface elevation when the 1965 photography was obtained. Three notable features of the 1965 photography are (1) the appearance of vegetated bars in the lower part of the Copper River, which indicates that distinct channels had formed in this area; (2) the absence of dramatic channel shifts caused by the 1964 earthquake; and (3) no major channel changes from the 1962 breakout of Van Cleve Lake.

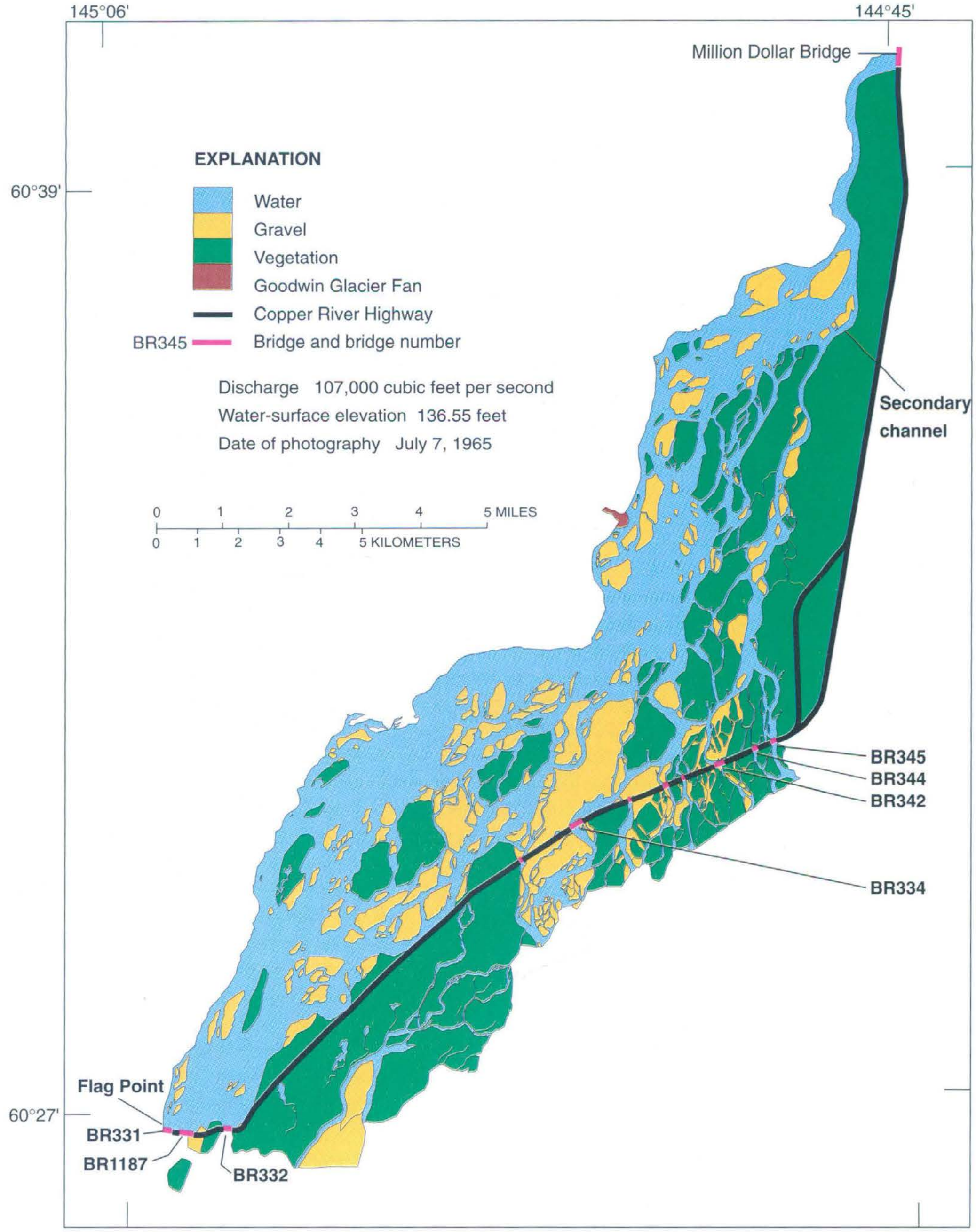

Figure 40. The lower Copper River based on aerial photographs taken in 1965.

The overlay of the 1965 map on the 1950 map indicates few trends (fig. 41). No advance of the fan near Goodwin Glacier is apparent and only a small amount of vegetated area changed to water. A considerable amount of water area changed to gravel. However, this is not unexpected, because the photography of 1965 was obtained at a lower water surface. Some areas of the lower part near Flag Point that were gravel changed to water. This indicates some channel shifting in these areas. A substantial amount of gravel upstream and downstream from Bridge 334 turned into vegetated area, indicating that no channel shifting had occurred in this area.

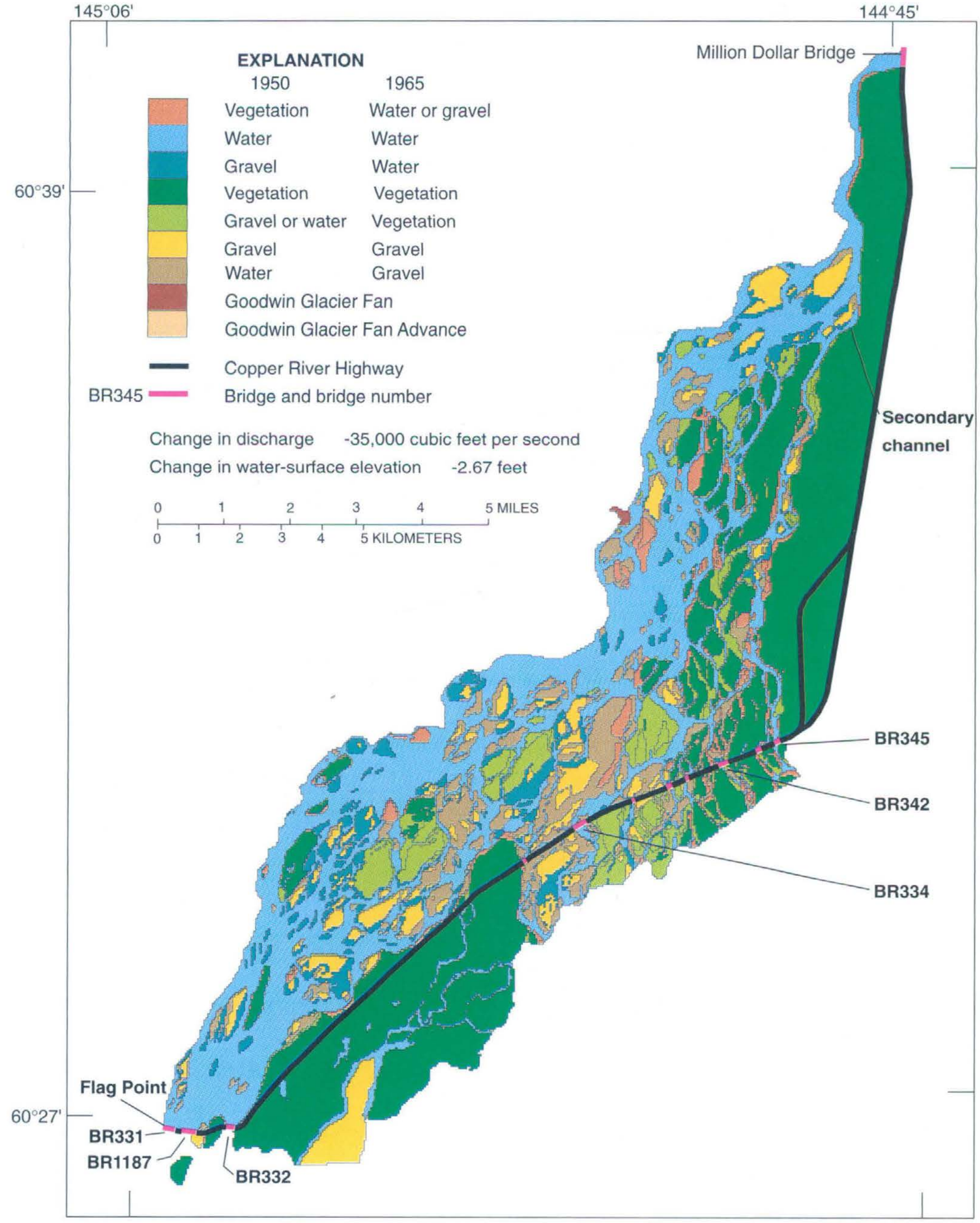

Figure 41. Comparison of the lower Copper River, 1950 to 1965.

1965 to 1971

Between 1965 and 1971 three notable hydrologic events occurred. A breakout of Van Cleve Lake occurred in 1969. In 1970, the average discharge for the Copper River was approximately 41,000 ft^3/s, the lowest average discharge for the period of record (fig. 21A). In 1971, a peak discharge of 338,000 ft^3/s occurred, equivalent to a 20-year recurrence interval.

The 1971 photography of the lower Copper River (fig. 42) was obtained on July 9, 1971, six days before the peak discharge. The water-surface elevation at the time of the 1971 photography was 3.69 ft higher than it was at the time of the 1965 photography. Thus, a number of gravel areas are covered by water. The discharge data collected by the ADOT&PF personnel in 1969 and 1970 confirmed that most of the discharge of the Copper River flowed through the bridges at Flag

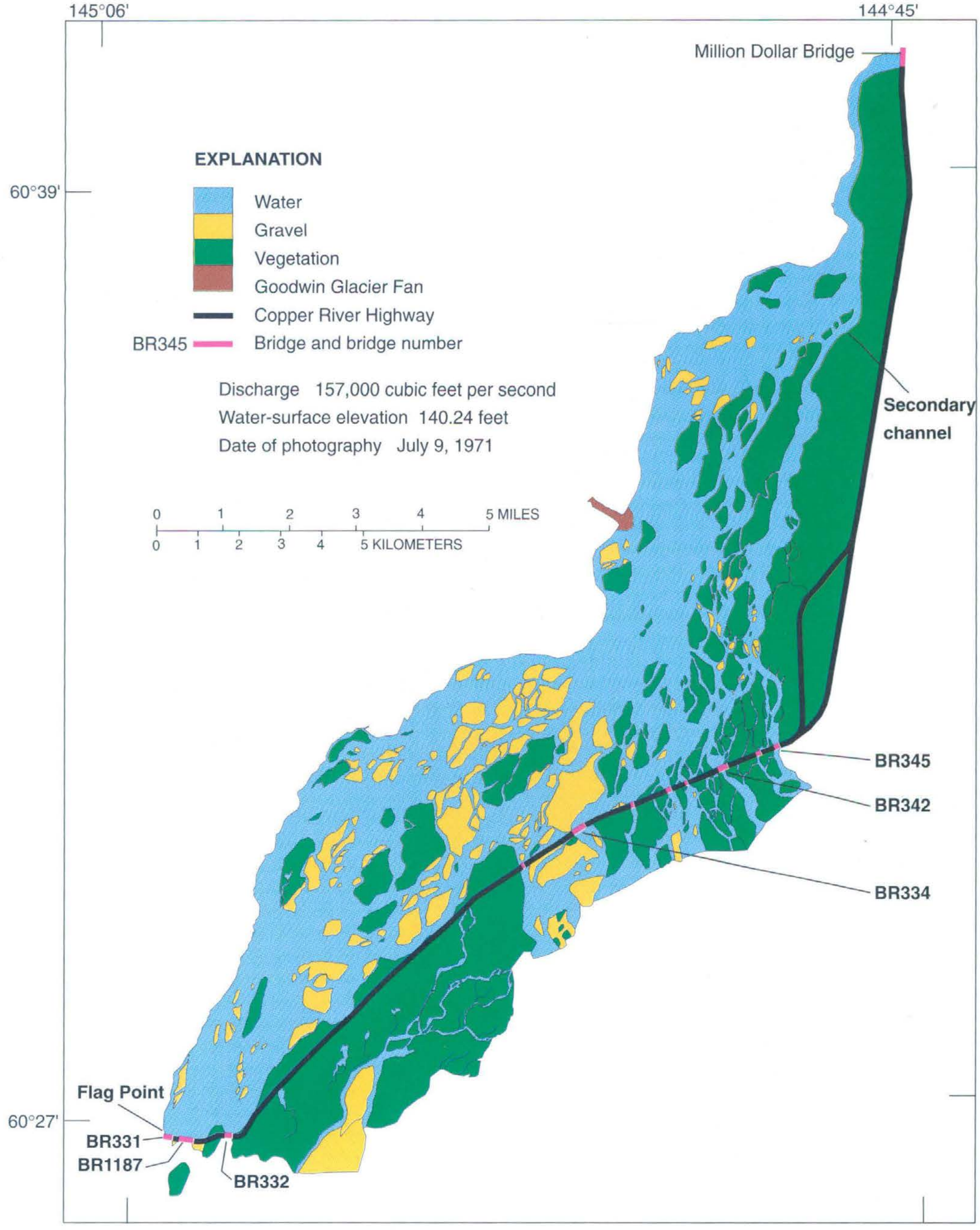

Figure 42. The lower Copper River based on aerial photographs taken in 1971.

Point. This trend is still apparent in the 1971 photography. No channel changes attributed to the 1964 earthquake or the 1969 breakout of Van Cleve Lake are evident.

Comparison of the 1965 and 1971 photography indicates several features (fig. 43). In the upper part of the study reach, some vegetated area in the secondary channel was eroded into water or gravel indicating that perhaps more flow was entering this channel. The number of areas where gravel changed to water is not considered significant because of the differences in discharge at the time the photography was obtained. In the area near Bridge 342, vegetated areas did change to water or gravel, indicating some channel change or channel widening in this area. Finally, a slight advance of the Goodwin Glacier fan is noted.

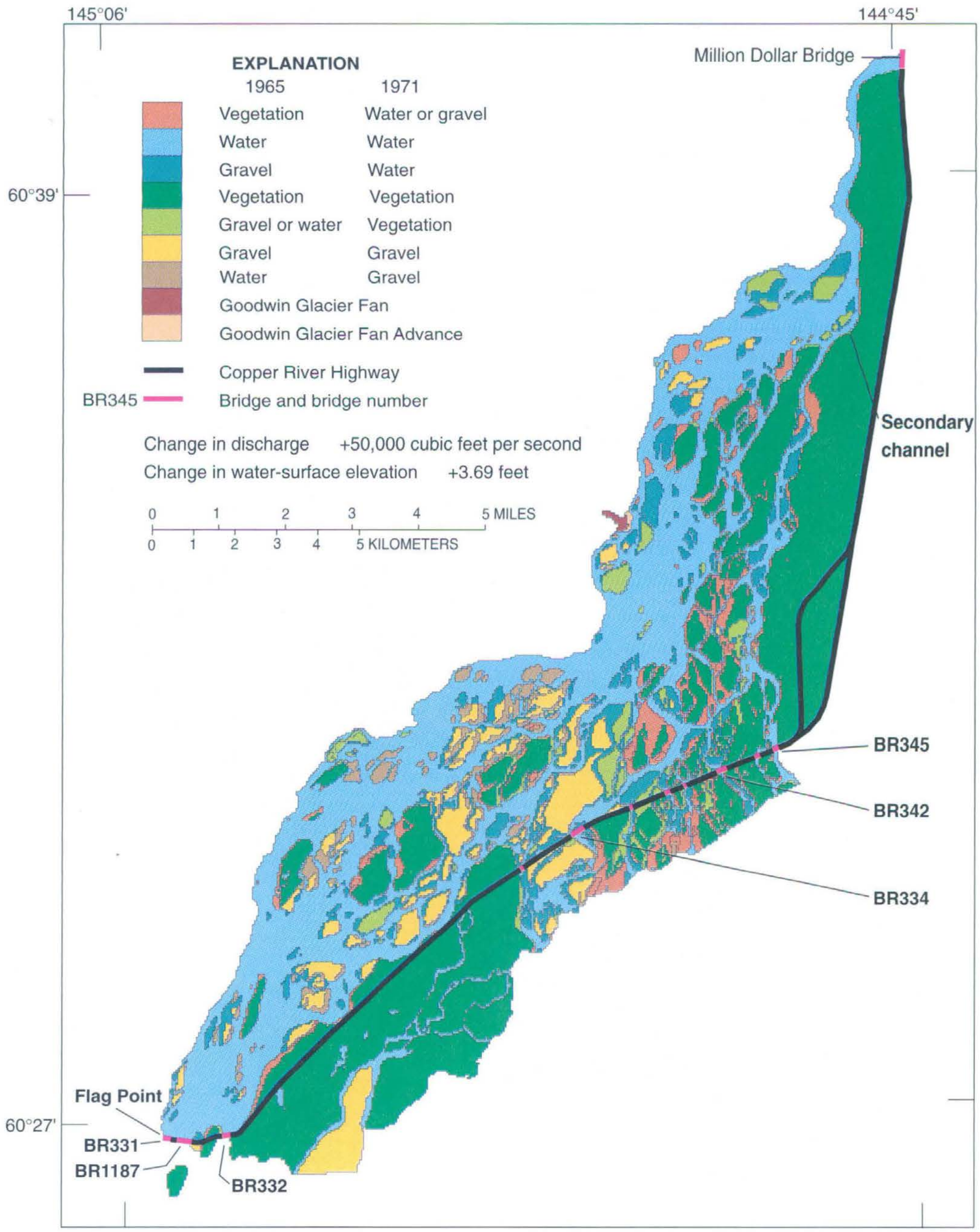

Figure 43. Comparison of the lower Copper River, 1965 to 1971.

1971 to 1974

With the exception of the high discharges in 1971, the peak discharges in 1972–74 were all less than a 5-year recurrence interval. Average discharge for this period was near the long-term average (fig. 21A). The number of days in which discharge exceeded 200,000 ft^3/s was insignificant. The 1974 breakout of Van Cleve Lake occurred after the photography was obtained.

The 1974 photography (fig. 44) shows the progression of the alluvial fan near Goodwin Glacier. Post (1967) noted a number of rock avalanches that had occurred on glaciers near the Copper River as a result of the 1964 earthquake. An inspection of aerial photographs taken by Post indicated that a rock avalanche had occurred on Goodwin Glacier. Movement and melting of the glacier as well as precipitation had most likely moved this material into the Copper River by 1971.

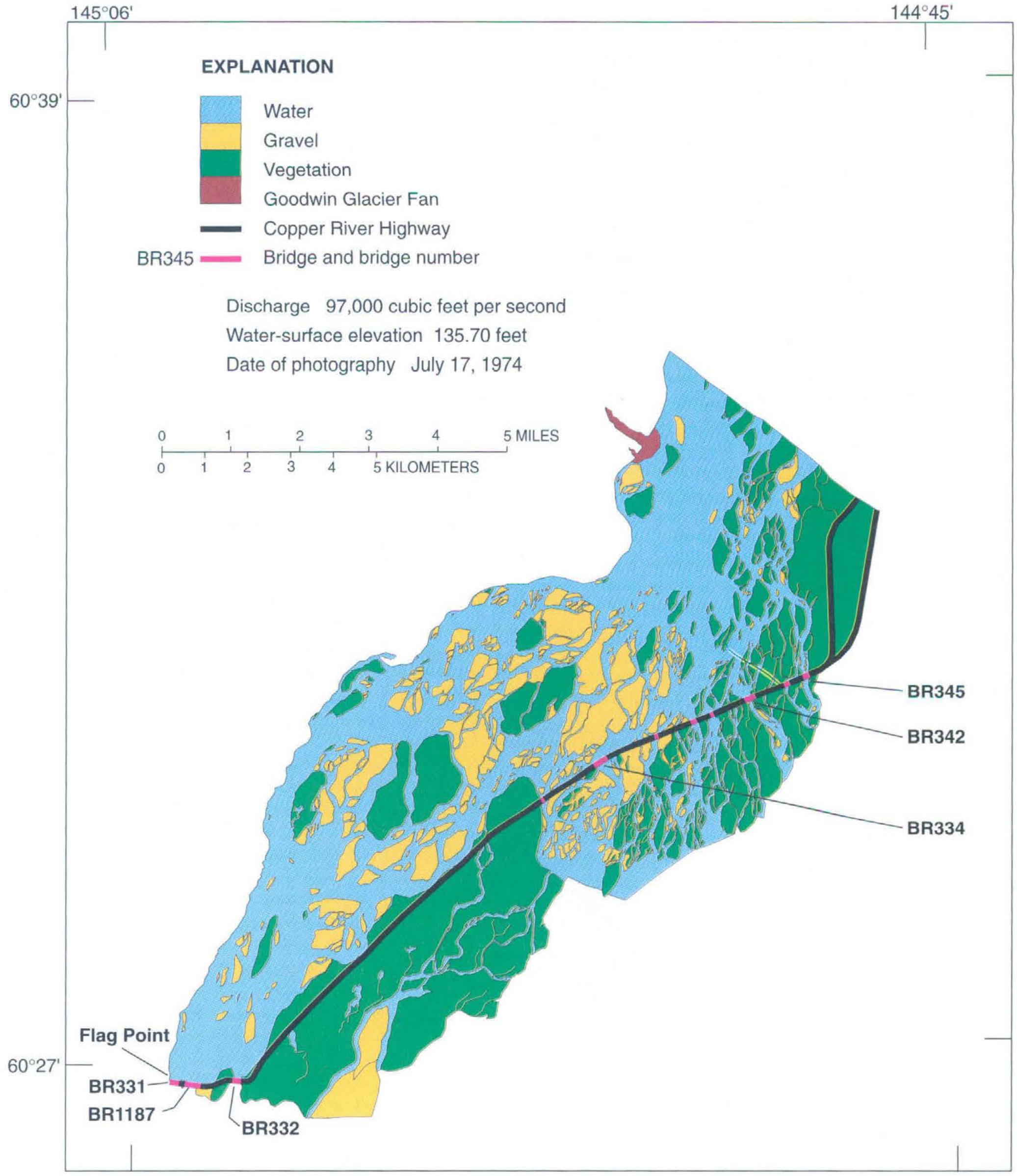

Figure 44. The lower Copper River based on aerial photographs taken in 1974.

Comparison of the 1971 and 1974 photography (fig. 45) indicates the change in the alluvial fan near Goodwin Glacier. One other significant feature is the change of vegetated areas near Bridge 342 and Bridge 334 to gravel or water. This may indicate the start of channel shifting. However, the immediate approach to Bridge 342 remains virtually the same. Reflecting the lower discharge and water surface in 1974 than in 1971, a number of areas changed from water to gravel.

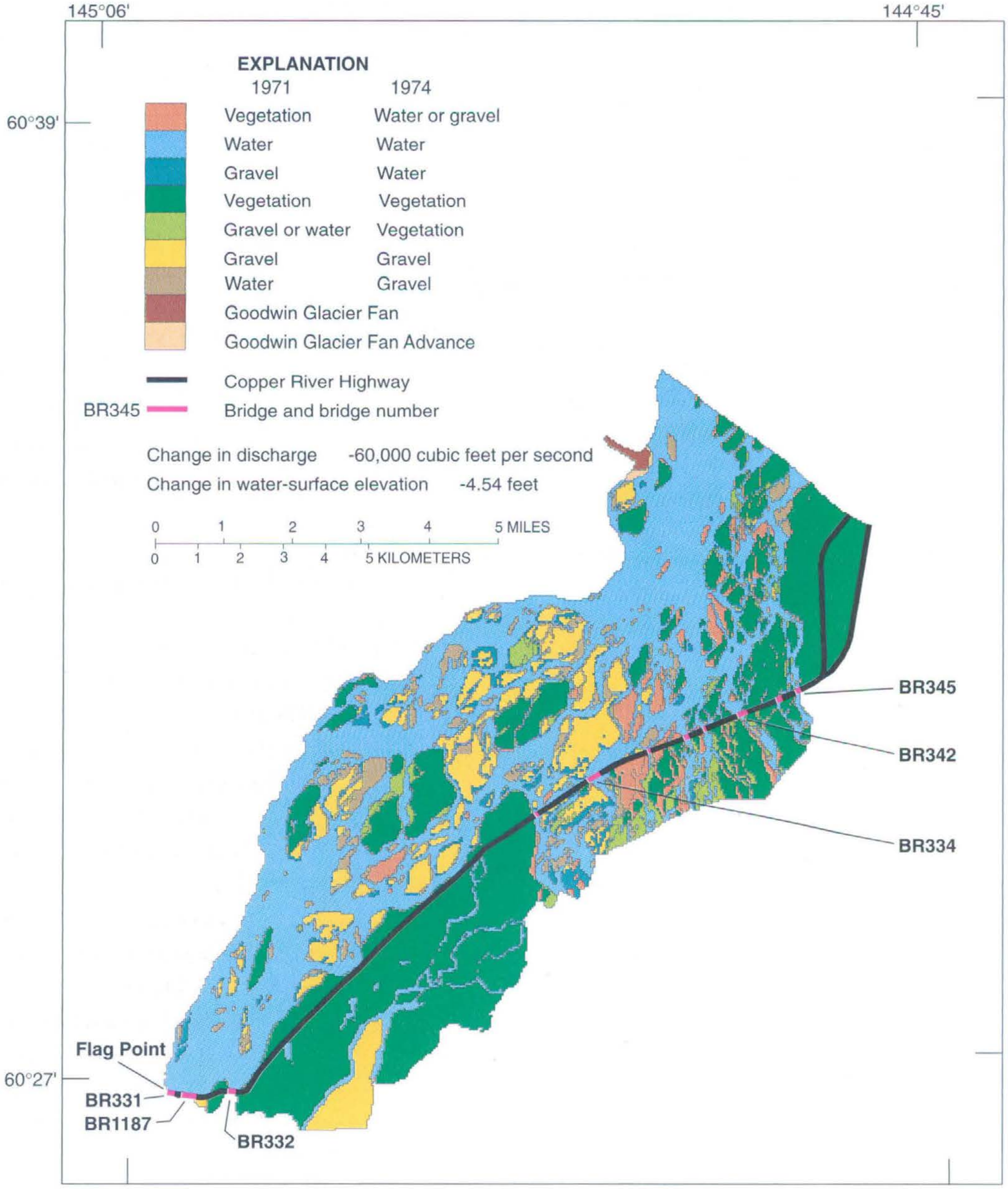

Figure 45. Comparison of the lower Copper River, 1971 to 1974.

1974 to 1978

Between 1974 and 1978, the most notable flows occurred in the 1975 and 1977 water years, when the flow of the Copper River exceeded 200,000 ft^3/s for 15 and 16 days respectively. During this period, annual peak discharges were relatively low, with the highest peak discharges equivalent to a 5-year recurrence interval. The average discharge was approximately equal to the long-term average.

The 1978 photography (fig. 46) indicated flow patterns similar to those in 1974. Because the water-surface elevation at the time of the 1978 photography was higher than the water-surface elevation at the time of the 1974 photography, some areas of gravel changed

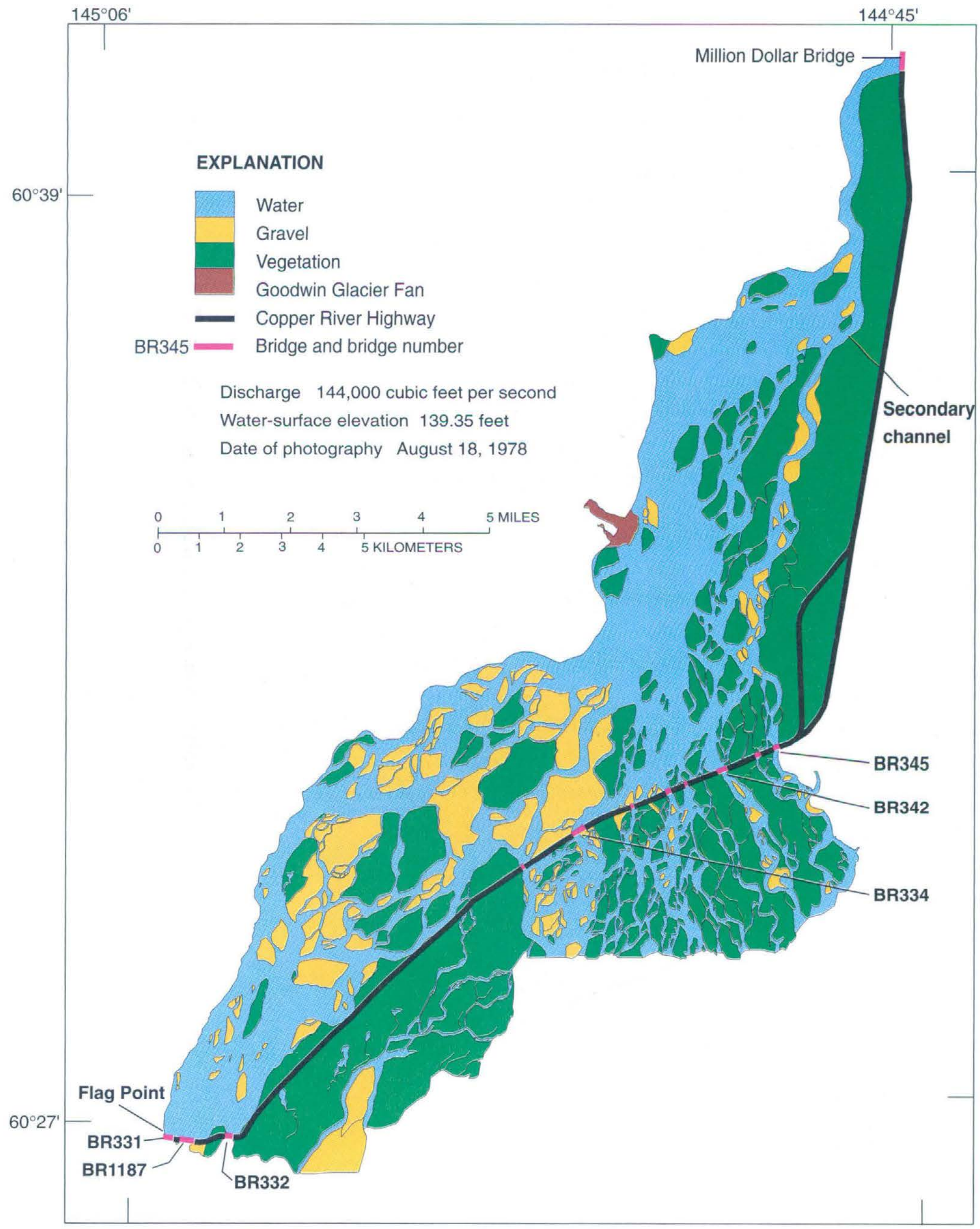

Figure 46. The lower Copper River based on aerial photographs taken in 1978.

to water. Downstream from the Copper River Highway, from Bridge 334 to Bridge 342, no major channel changes were noted. Comparison of the 1974 and 1978 photography (fig. 47) indicated a few vegetated areas that changed to gravel or water. Only a slight advance of the Goodwin Glacier fan was noted, but no major changes had occurred immediately upstream from Bridge 342.

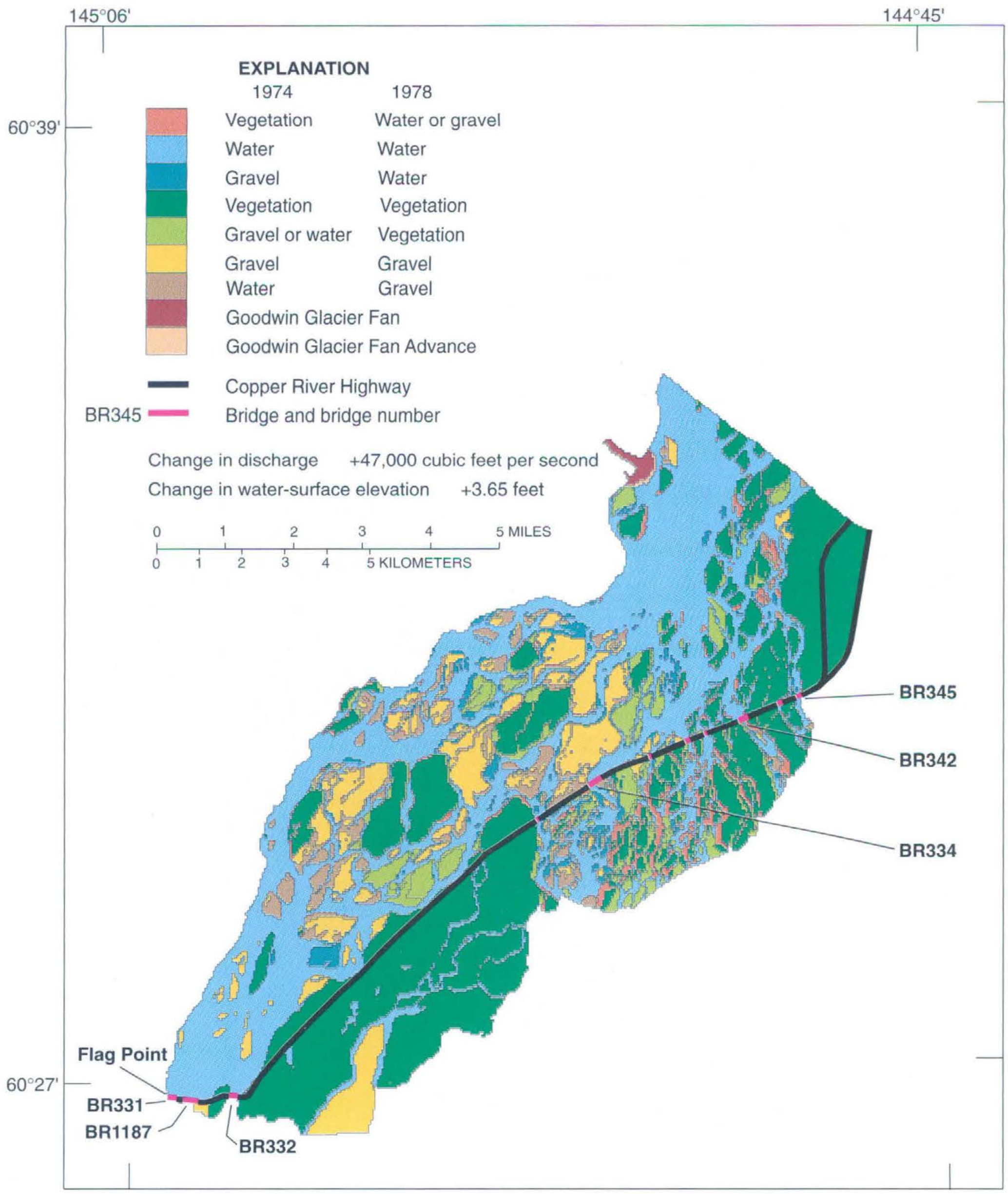

Figure 47. Comparison of the lower Copper River, 1974 to 1978.

1978 to 1982

The period from 1978 to 1982 was marked by several significant hydrologic events. A breakout of Van Cleve Lake occurred in 1979. The average flow of 1981 was approximately 70,000 ft^3/s, which is about 13,000 ft^3/s more than the long-term average of 57,400 ft^3/s (fig. 21A). The estimated peak discharge of 1981 was estimated to be approximately 470,000 ft^3/s, equivalent to a recurrence interval greater than 100 years. Finally, on 29 days during the 1981 water year, the discharge of the Copper River exceeded 200,000 ft^3/s. During the flood of 1981, the Copper River cut through the Copper River Highway at the approach to Bridge 342.

When the 1982 aerial photography was obtained, the discharge of the Copper River was estimated to be 200,000 ft^3/s, or 56,000 ft^3/s higher than the discharge that was occurring when the 1978 aerial photography was obtained. The water-surface elevation in 1982 at the time of the photography was 3.58 ft higher than it was at the time of the 1978 photography. Yet the 1982 photography clearly shows more gravel areas than does the 1978 photography (fig. 48). The area downstream from Bridge 334 also shows more gravel areas and sug-

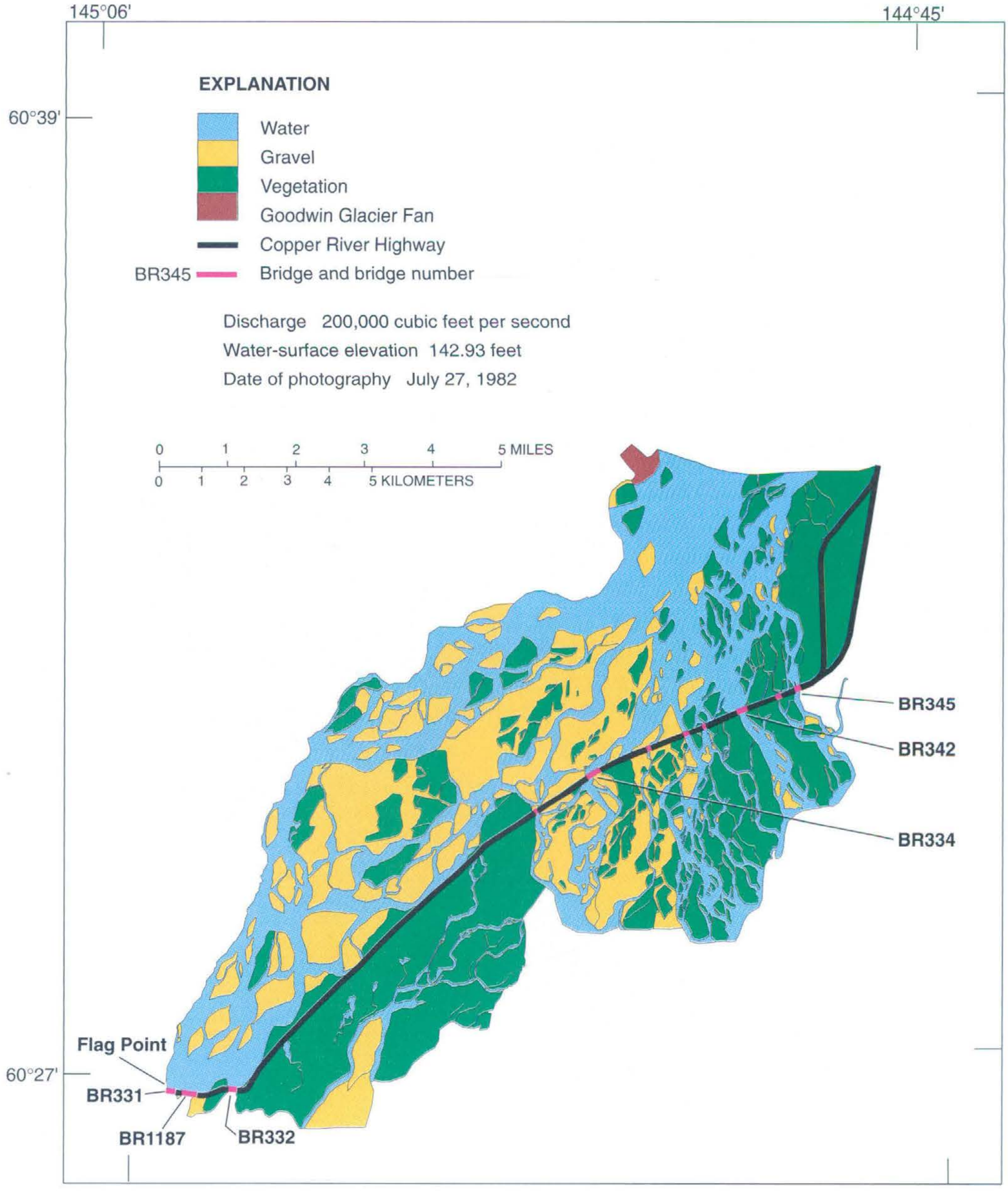

Figure 48. The lower Copper River based on aerial photographs taken in 1982.

gests that (1) the flood of 1981 deposited a large amount of sediment—possibly from the Goodwin Glacier fan or other sources—in the southwest part of the study area, and (2) the flood of 1981 caused a major channel shift away from this part of the lower Copper River towards Bridge 342. As a further indicator of channel change, it is evident that the channel was wider downstream from Bridge 342 in 1982 than it was in 1978.

Comparison of the 1978 and 1982 photography (fig. 49) shows some areas of gravel that have changed to water, which is to be expected because the discharge of the Copper River at the time of the 1982 photography was higher than it was during the 1978 photography. In the lower part of the study area, vegetated areas became gravel, most likely due to the high flood waters of 1981. Areas of vegetation north of Bridge 342 changed to water and gravel, possibly indicating the formation of a channel. The amount of area near Flag Point that changed from water to gravel at higher discharge may also be an indicator of channel change.

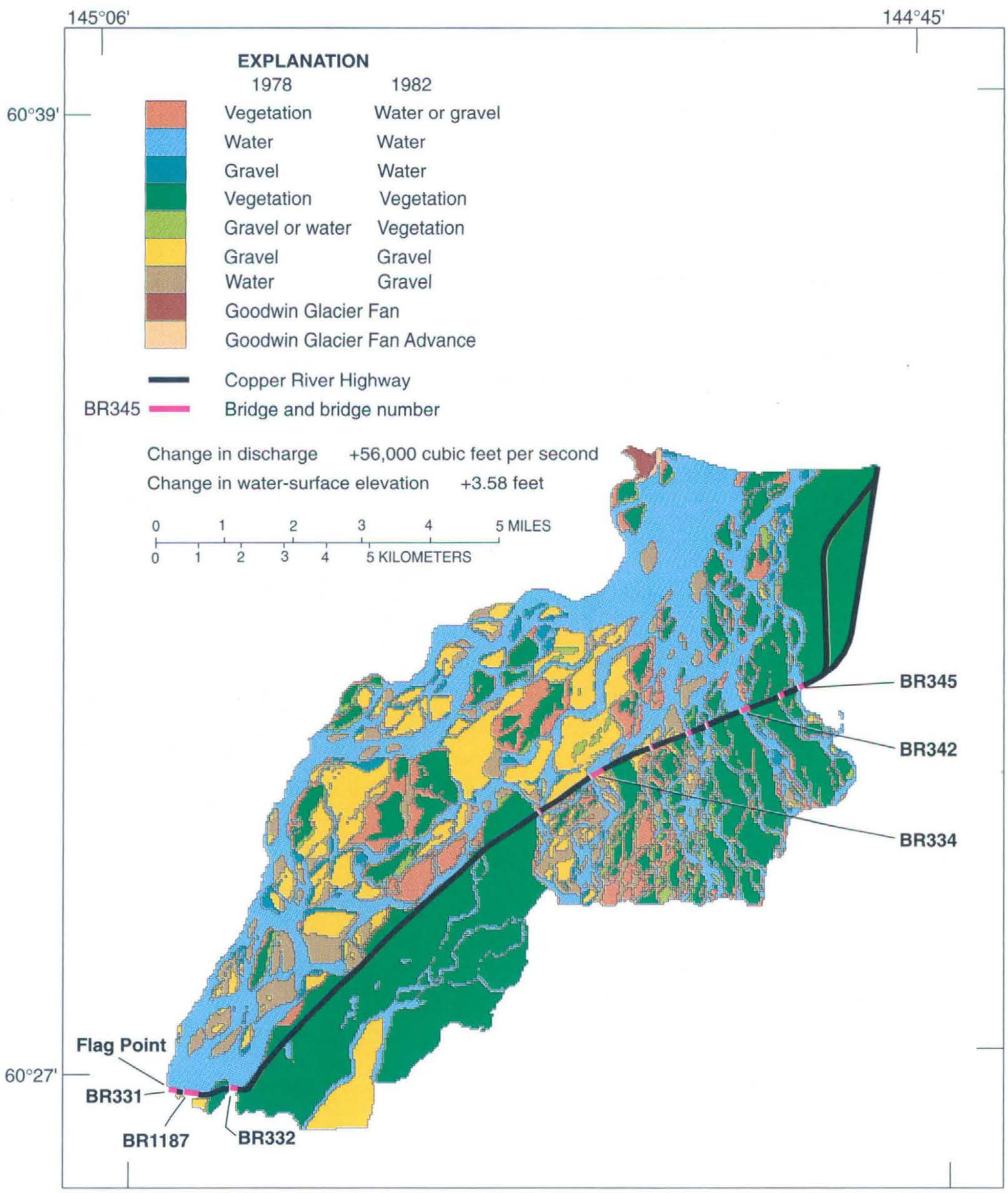

Figure 49. Comparison of the lower Copper River, 1978 to 1982.

1982 to 1985

Between 1982 and 1985, average discharge for the period was below the long-term average (fig. 21A). The highest peak discharge was estimated to be 229,000 ft^3/s, equivalent to a 3-year recurrence interval. Also, the number of days when the discharge of the Copper River exceeded 200,000 ft^3/s were relatively few. A breakout of Van Cleve Lake occurred on August 2, 1985.

Several prominent features are noted in the 1985 photography (fig. 50). At Mile 44 of the Copper River Highway, a considerable quantity of bank material had eroded. This feature was not present in the 1978 photography and thus had formed between these two years of photography. However, this erosion is likely to have occurred in 1981 during the large flood.

The 1985 photography was obtained when the water-surface elevation was considerably less (-6.46 ft)

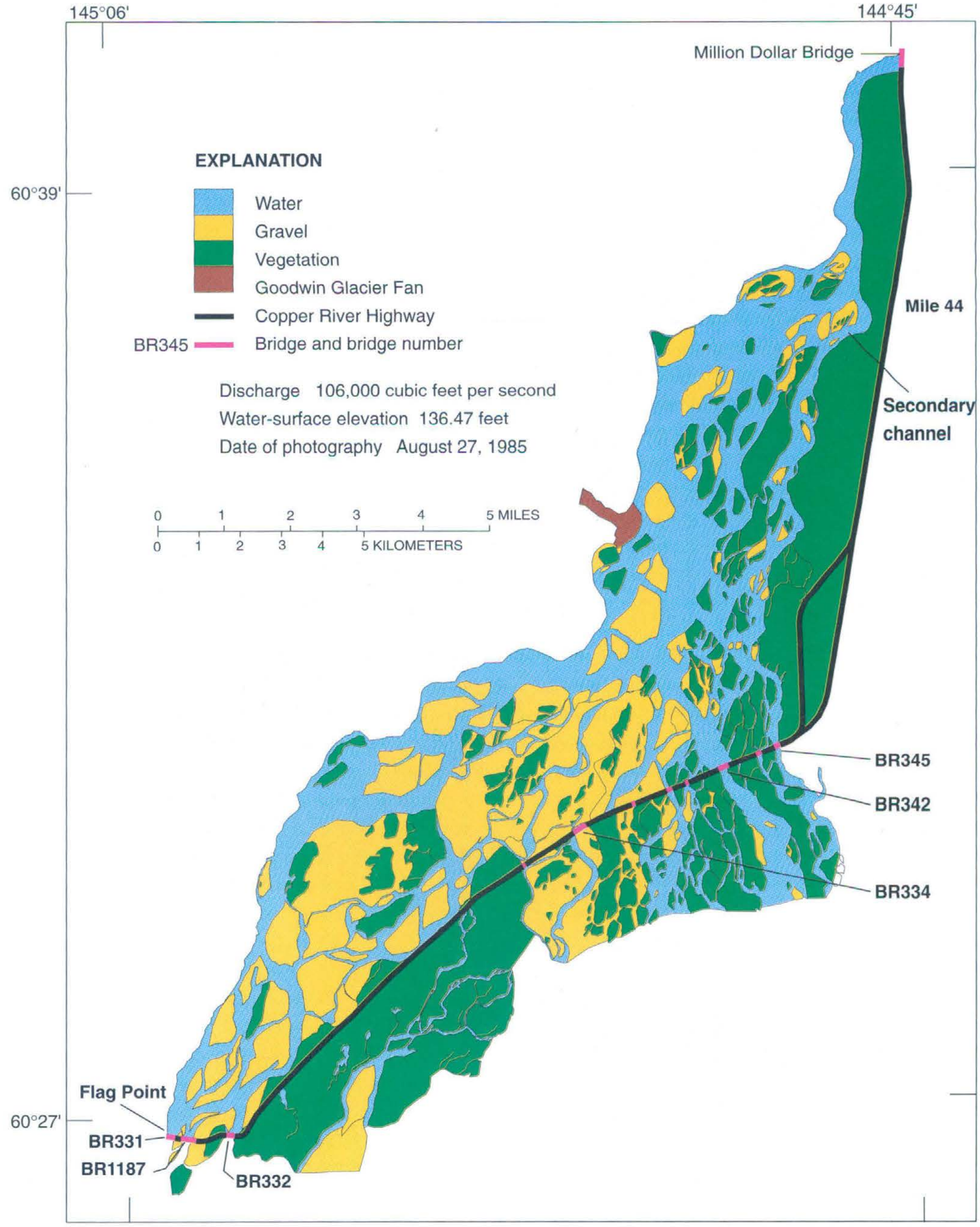

Figure 50. The lower Copper River based on aerial photographs taken in 1985.

than it was during the 1982 photography. Thus, more gravel areas are exposed and some channels appear to be smaller. Another feature of the photography is the presence of two distinct channels: one leading to Bridge 342 and the other leading to Flag Point. The channel downstream from Bridge 342 is wider, indicating that more flow was passing through Bridge 342. An overlay of the 1982 and 1985 photography (fig. 51) primarily shows the change in state from water to gravel, reflecting the lower discharge in 1985. It does not appear that the breakout of Van Cleve Lake caused any major channel movements.

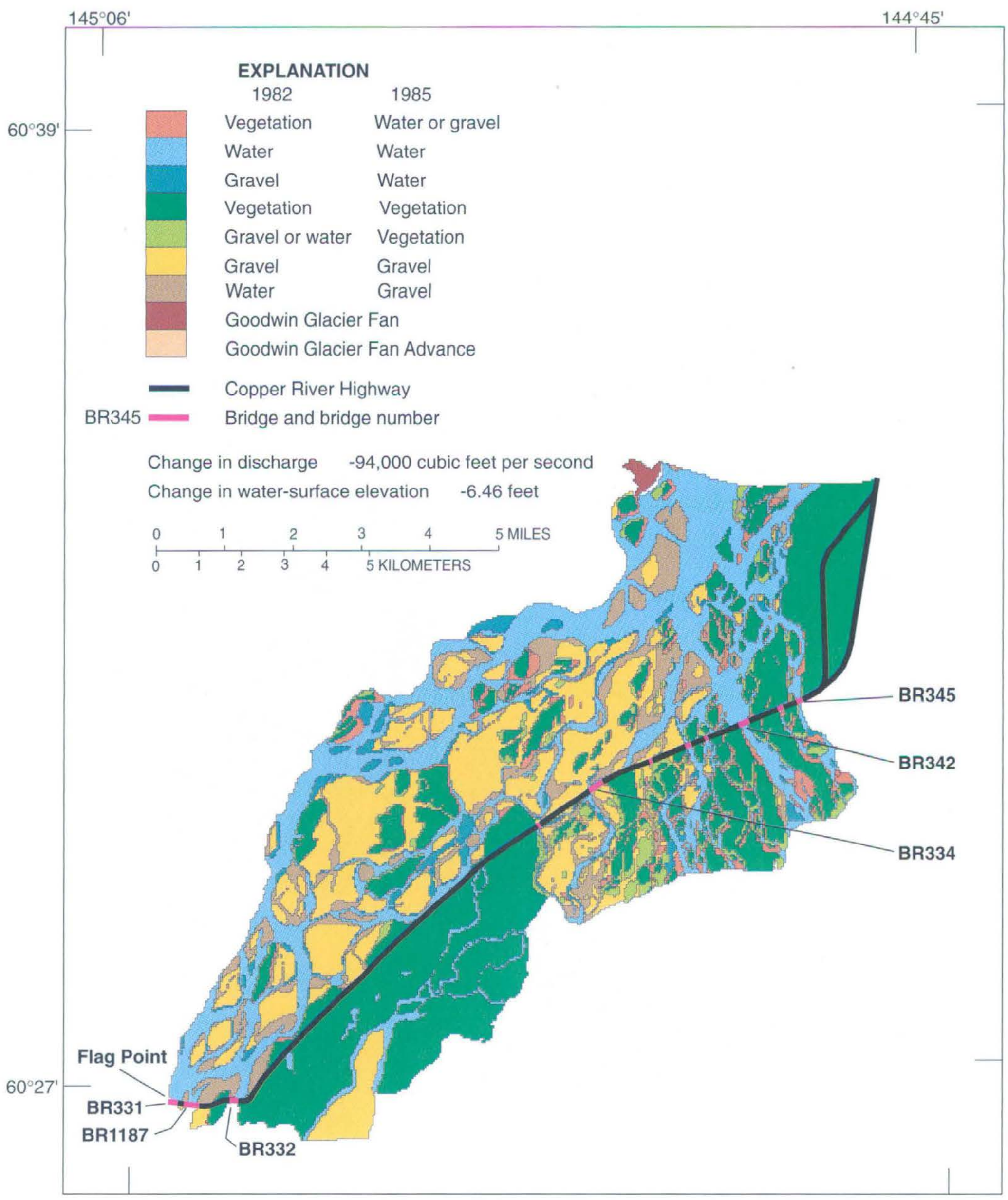

Figure 51. Comparison of the lower Copper River, 1982 to 1985.

1985 to 1991

Between 1985 and 1991, the average discharge of the Copper River for the 1989 and 1990 water years was higher than the long-term average discharge (fig. 21A). On 26 days in both of these water years, the flow of the Copper River exceeded 200,000 ft^3/s. In 1990, the fifth highest peak discharge on record occurred: 273,000 ft^3/s.

Several features are notable on the 1991 photography (fig. 52). A major channel change occurred about 1.5 mi west of mile 41.5 of the Copper River Highway. At this location, a new channel bisected a large vegetated island. This channel change decreased flow in the channels leading to Bridges 344 and 345. During 1991-95 these channels were dry except during high flows. Two distinct channels, one towards Bridge 342 and one towards Flag Point, are still evident.

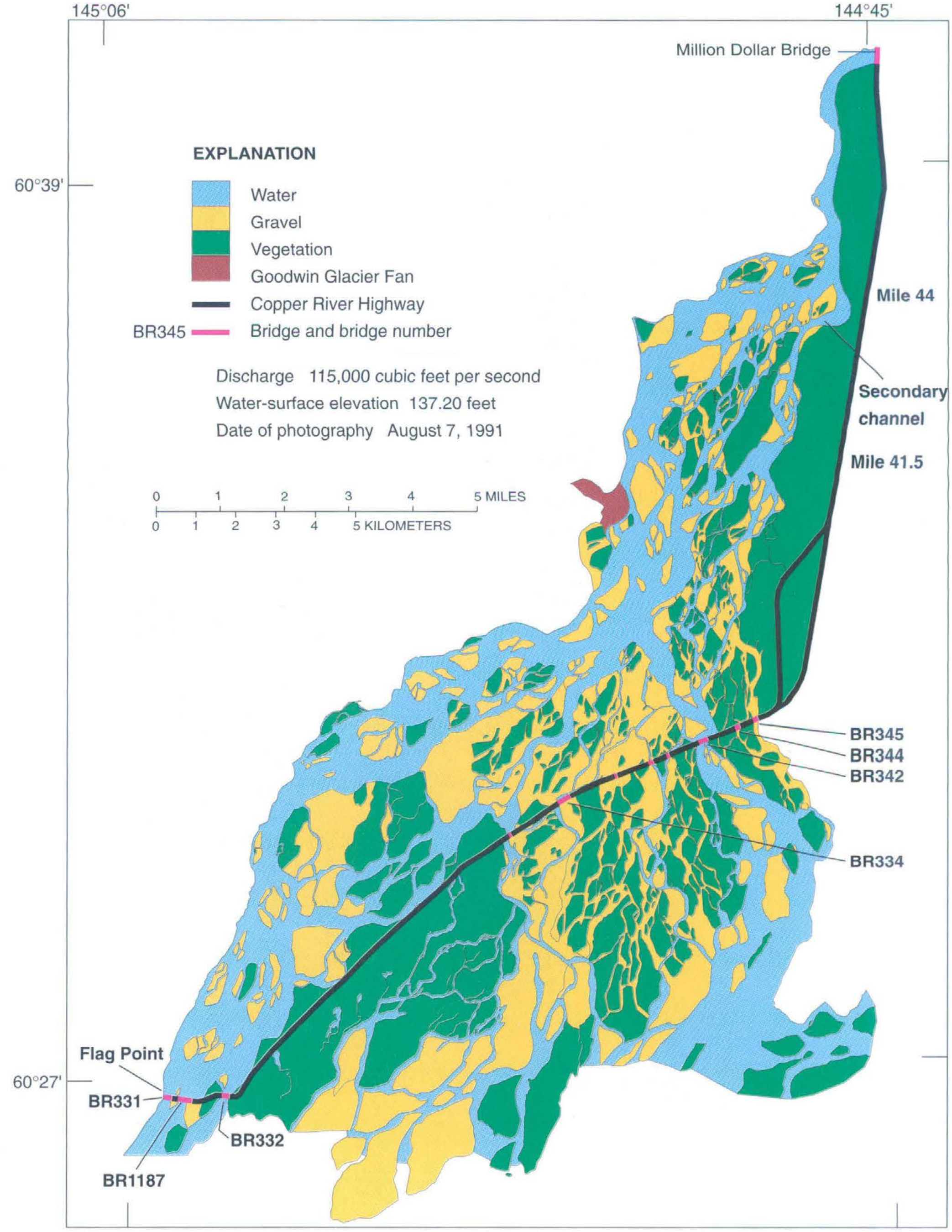

Figure 52. The lower Copper River based on aerial photographs taken in 1991.

Comparison of the 1985 and 1991 photography (fig. 53) indicates two predominant features. First, areas of water changed to gravel in the upper eastern part of the study area and in the channel leading towards Bridge 334. This particular change reflected the recent channel formation at mile 41.5. A number of areas also changed from gravel to water, most likely reflecting the higher water surface in 1991 than in 1985. Some vegetated areas just upstream from Bridge 342 changed to water or gravel indicating a widening of the approach section to the bridge. At mile 44, vegetated areas continued to erode in a southerly direction. Finally, a slight advance of the Goodwin Glacier fan can be seen. Downstream from Bridge 342, an area of vegetation changed to gravel, reflecting the change in flow direction when the spur dike was overtopped in 1989.

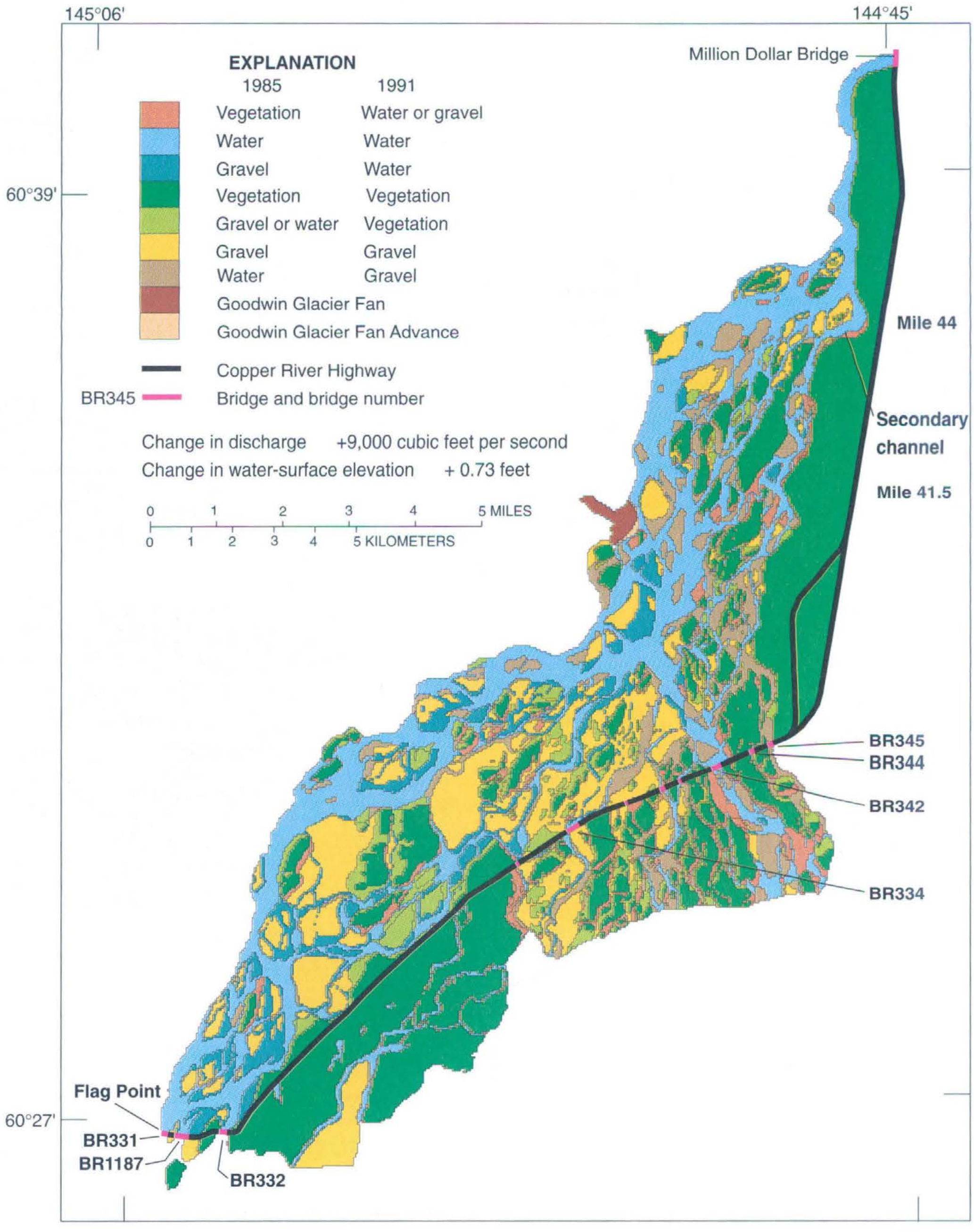

Figure 53. Comparison of the lower Copper River, 1985 to 1991.

Future Trends of the Copper River

One of the possible methods in analyzing changes in an alluvial system is to consider the system as indeterminate and to use statistical procedures as much as possible. Fluvial processes are so complex that it is unlikely that precise predictions are possible in any case, but alternative approaches utilizing a probabilistic geographic approach may provide enhanced predictive capabilities.

Graf (1981) developed a method of channel analysis which was used in this study. In this technique, maps of a river system from different years are transformed into grids with a selected cell size. A tabulation is made for each cell as to the number of times the cell is occupied by water. If a cell is always occupied by water for each map, Graf concluded that the channel was stable. If a cell is not always occupied by water in each map, the channel is considered to be unstable. The fewer times a cell is occupied by water, the more unstable the channel.

Another probabilistic technique utilized was a Markov analysis. A Markov analysis is a process, natural or artificial, that has an element of randomness or unpredictability, but in which a past event has an influence on a subsequent event. This aspect, in which a subsequent event remembers a past event, is termed the Markov property (Lin and Harbaugh, 1984). Many natural processes are strongly Markovian in that previous events influence subsequent events. The extent to which a previous event influences a subsequent event is a measure of the strength of the Markov property, which may range from weak to strong.

In this study, a Markov analysis was applied to the lower Copper River to determine if channel changes exhibit Markov properties. If channel changes in the lower Copper River did exhibit Markov properties, the channel changes that have occurred are not completely random. Markov techniques used for the analysis have been described by Lin and Harbaugh (1984), Davis (1986), and Kemeny and Snell (1976).

Probability Analysis

GIS techniques were used for Graf's analysis. The digitized photography of each year was converted to a grid with a cell size of 50 by 50 meters. Grid coverages were then overlaid or stacked on each other. A tabulation was then made for each cell as to how many times it is occupied by water. If a particular cell was occupied by water for all 8 years of photography, it was assigned a value of 8. Because the 1974 and 1982 photo coverages of the study area are not complete, approximately the northern third of the study area was analyzed with only six layers. In this area, if a cell was occupied by water for all 6 years of coverage, it would have a value of 6. After these computations were made, a tabulation grid was developed, each cell of which contained a numeric value equal to the number of times it was occupied by water.

Two primary features can be seen from the Graf analysis (fig. 54). First, the cells that were occupied by water seven or eight times (five or six for the northern third) indicate and define the most stable channels of the lower Copper River. Second, areas that never were occupied by water or remained vegetated areas indicate stable areas that have not become prone to erosion. The remaining cells indicate various percentages of time that they were occupied by water. These cells were further analyzed to determine their degree of channel stability.

The grids of each year's photography were analyzed a second time. However, in this analysis, the 1991 grid was considered a reference or base grid. If a cell of the 1991 grid was not occupied by water, comparisons were made to the other grids, starting with the 1985 grid, to determine if the cell was ever occupied by water. The resultant grid (fig. 55) contained cells which were assigned a value equal to the number of years before 1991 that a particular cell was occupied by water. For example, if a cell was not occupied by water in 1991 but was occupied by water in 1985, it was assigned a value of 6 (1991 minus 1985). If a cell was not occupied by water in 1991 but was occupied by water in 1950, it was assigned a value of 41 (1991 minus 1950).

Although somewhat subjective, the preceding analysis provides a better understanding as to whether or not a particular area is stable or unstable. For example, at mile 44, the values of the cells indicate that they have been occupied by water one or two times (fig. 54). However, in 1991, these cells were occupied by water (fig. 55), indicating that this particular area may be unstable and a new channel is forming. In other areas where the cell value indicates that the channel has been occupied by water one or two times (fig. 54), its corresponding cell has not been occupied by water since 1950 (fig. 55), which indicates that this area is relatively stable.

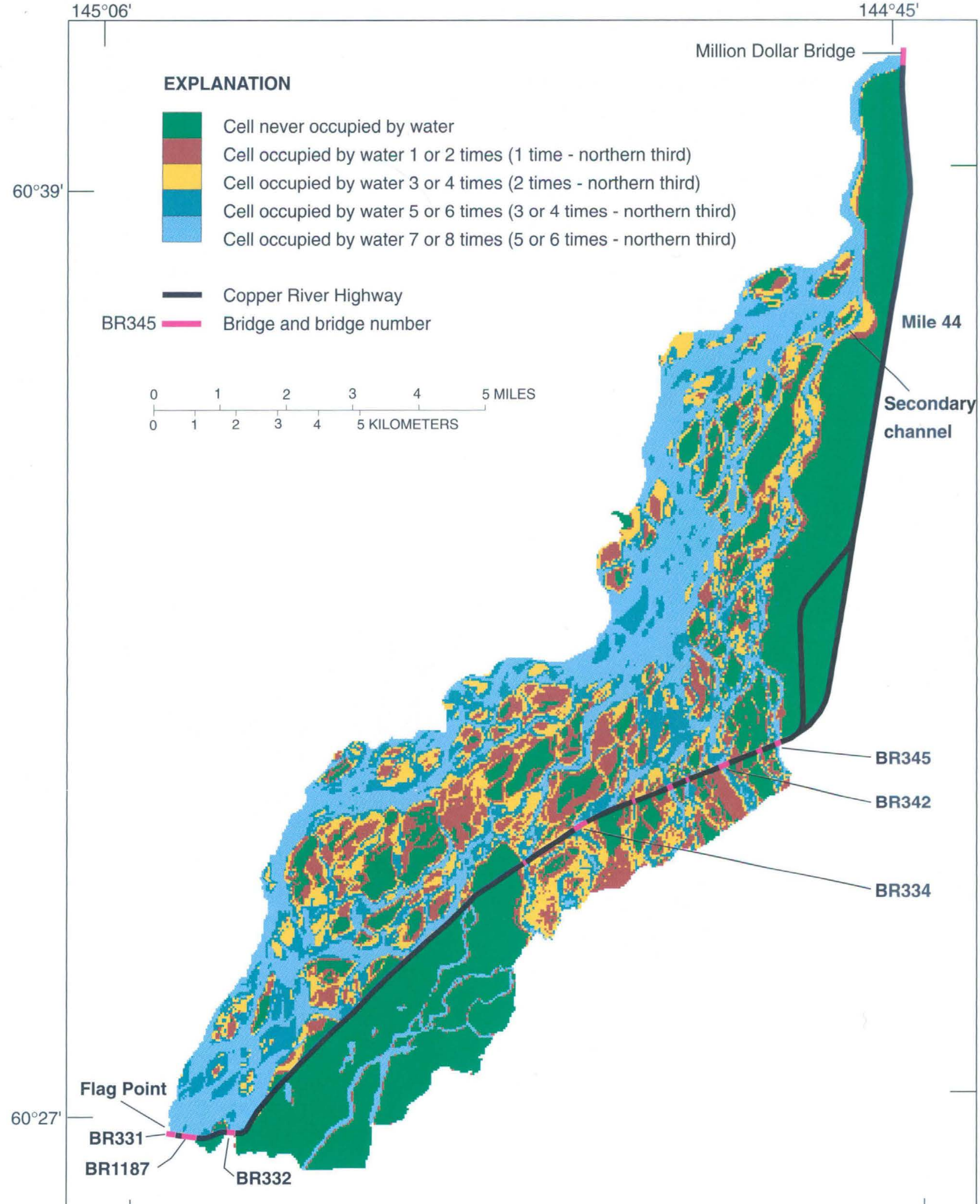

Figure 54. The lower Copper River showing the number of times a cell has been occupied by water.

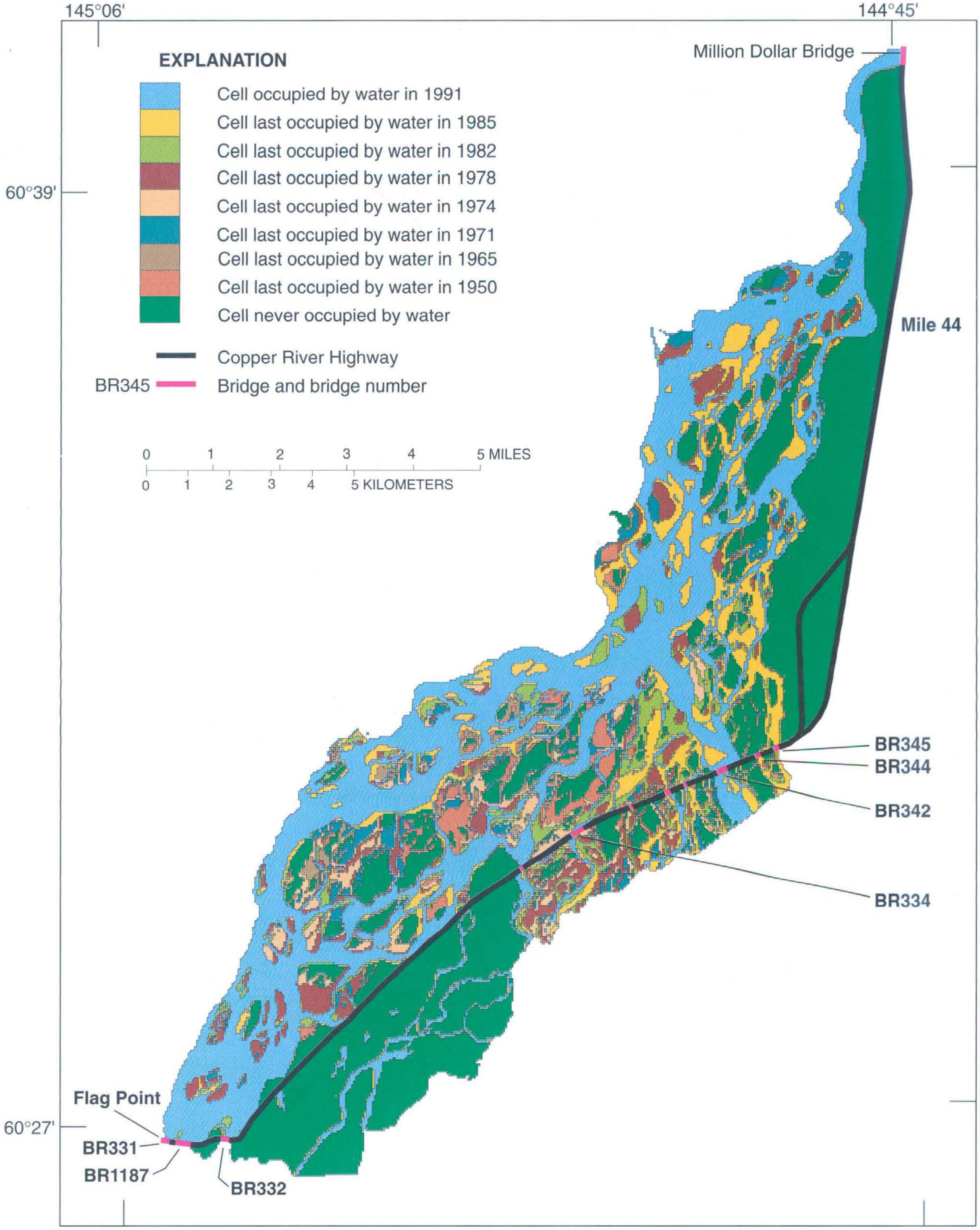

Figure 55. The lower Copper River showing the latest year a cell has been occupied by water.

Markov Analysis

A Markov analysis describes the frequency or probability attached to the transition from one state to the next, as for example, the transition from a gravel bar to water. The analysis is not concerned with the process, for instance, of how a gravel bar changed to water. Thus, a Markov analysis can occupy an intermediate position in the spectrum ranging from purely deterministic models to purely random models. In a purely deterministic model, the state of the system at any point in time or space can be predicted precisely by evaluating the model. In a purely random model, the state of the system at any point in time or space is completely independent of previous events. A Markov-chain model is intermediate in that a random component or components are present, but the state of the system at any point in time or space is not independent of the previous event or events.

One of the most important considerations before beginning the Markov analysis was to define the boundaries. For example, if the boundaries were chosen to include areas that may never change, the analysis would indicate Markov properties, but in a biased manner (Davis, 1986). In the lower Copper River, the primary concern is whether or not the Copper River will impact the Copper River Highway. Using this concept, the boundaries for the Markov analysis were defined as follows: the Copper River Highway from Flag Point to the Million Dollar Bridge represented the southern and eastern boundaries; the right bank of the Copper River from the Million Dollar Bridge to Flag Point represented the northern and western boundaries. The land cover within these boundaries is subject to change and, although the northern third of the area has remained essentially the same, much of this area was inundated by flood waters in September 1995 and is subject to erosion. The right bank of the Copper River has not changed appreciably because it is bounded by Childs and Goodwin Glaciers, and a mountain range near Flag Point. Only a section of the river near the middle of the area has changed slightly over the years and thus the right bank could be considered a stable boundary. Because the 1974 and 1982 aerial photography did not cover these boundaries, it was not used in the Markov analysis.

Although not required, most Markov analyses use a discrete time increment. Ideally, for the lower Copper River, annual aerial photography obtained at the end of the runoff season would provide the best information on changes in state of the land cover. Although yearly aerial photography was not available, an analysis of the available photography indicated that when the 1950 photography was excluded, the remaining sequence was as follows:

1965, 1971, 1978, 1985, 1991

The time, in years, between the photography was between 6 and 7 years or an average of about 6.5 years. Thus, the Markov analysis was done using only these 5 years of photography, which provided a 6.5 year time increment.

To begin the Markov analysis, each cell of each particular grid was assigned a number dependent on whether it represented a gravel area, vegetated area, or water. The grids were then compared on a paired basis, starting with the 1965 and 1971 grids and proceeding to the 1971 and 1978 grids, the 1978 and 1985 grids, and the 1985 and 1991 grids. For each comparison, a tally or transition count matrix was developed (table 15). These matrices are a tabulation of the frequencies of the transitions from one land cover to another. For example, in the comparison of the 1965 and 1971 grids (table 15), 17,856 cells were classified as vegetated in 1965. Between 1965 and 1971, 15,290 cells remained as vegetated, 276 cells changed from vegetated to gravel, and 2,290 cells changed from vegetated to water.

After the transition count matrices were computed, the transition probability matrices were computed (table 16). The transition probability matrix is computed by dividing each entry from the transition count matrix by the total for its row. For example, for the 1965–71 period (table 15), 15,290, 276, and 2,290 are each divided by the total, 17,856, to obtain 0.857, 0.015, and 0.128 (table 16). The resulting fractions express the relative number of times one land cover is succeeded by another land cover. In a probabilistic sense, these are estimates of the conditional probability, the probability that a particular land cover will be the next to occur, given the present land cover.

In examining the transition probability matrices as well as the change in water-surface elevation between the sets of aerial photography, the 1965–71 and the 1978–85 matrices were affected by relatively large changes in water-surface elevations. In the 1965–71 comparison, the change in water-surface elevation was +3.7 ft. The effect of this difference was to change more gravel land cover to water cover. Thus, one might conclude that there is no Markov tendency for the gravel land cover to remain the same. In a similar manner, the 1978–85 comparison was characterized by a

Table 15. Transition count matrices for the Copper River, 1965 to 1991

	Vege-tated	Gravel	Water	Total	Change in water-surface elevation (feet)
		1965 to 1971			
Vegetated	15,290	276	2,290	17,856	
Gravel	1,406	3,113	4,018	8,537	
Water	556	1,725	21,441	23,722	
				50,115	+3.7
		1971 to 1978			
Vegetated	16,017	167	1,215	17,399	
Gravel	873	2,872	1,339	5,084	
Water	1,559	4,048	21,925	27,532	
				50,015	-0.9
		1978 to 1985			
Vegetated	14,675	1,933	1,755	18,363	
Gravel	357	5,307	1,384	7,048	
Water	712	7,486	16,353	24,551	
				49,962	-2.9
		1985 to 1991			
Vegetated	13,999	727	853	15,579	
Gravel	2,074	8,173	4,468	14,715	
Water	1,155	4,652	13,911	19,718	
				50,012	+0.73
		Average: 1965 to 1991			
Vegetated	14,995	775	1,528	17,298	
Gravel	1,178	4,866	2,802	8,846	
Water	996	4,478	18,408	23,882	
				50,026	
		Average: 1971 to 1978 and 1985 to 1991			
Vegetated	15,008	447	1,034	16,489	
Gravel	1,474	5,522	2,904	9,900	
Water	1,357	4,350	17,918	23,625	
				50,014	

Table 16. Transition probability matrices for the Copper River, 1965 to 1991

	Vege-tated	Gravel	Water	Total	Change in water-surface elevation (feet)
		1965 to 1971			
Vegetated	0.857	0.015	0.128	1.00	
Gravel	0.165	0.365	0.470	1.00	
Water	0.023	0.073	0.904	1.00	
					+3.7
		1971 to 1978			
Vegetated	0.920	0.010	0.070	1.00	
Gravel	0.172	0.565	0.263	1.00	
Water	0.057	0.147	0.796	1.00	
					-0.9
		1978 to 1985			
Vegetated	0.799	0.105	0.096	1.00	
Gravel	0.051	0.753	0.196	1.00	
Water	0.029	0.305	0.666	1.00	
					-2.9
		1985 to 1991			
Vegetated	0.898	0.047	0.055	1.00	
Gravel	0.141	0.555	0.304	1.00	
Water	0.058	0.236	0.706	1.00	
					+0.73
		Average: 1965 to 1991			
Vegetated	0.867	0.045	0.088	1.00	
Gravel	0.133	0.550	0.317	1.00	
Water	0.042	0.188	0.770	1.00	
		Average: 1971 to 1978 and 1985 to 1991			
Vegetated	0.910	0.027	0.063	1.00	
Gravel	0.149	0.558	0.293	1.00	
Water	0.058	0.184	0.758	1.00	

water-surface elevation change of -2.9 ft. The effect of this difference was to change more water cover to gravel cover, although the Markov tendency is still evident for water states to remain water.

The 1971–78 and the 1985–91 comparisons are considered to represent a steady state of the lower Copper River since the changes in water-surface elevations between the sets of aerial photography was less than 1 ft. In these two comparisons, the transition probabilities were quite similar except for a slight difference in the water-to-gravel and the water-to-water states. This may be attributed to the fact that after the 1981 flood, there was considerably more gravel cover and less water cover, indicating that some channelization may have occurred. The 1985–91 comparison may be an indicator that some additional channelization is taking place.

The average transition probability matrices for the 1965–91 period and the 1971–78 and 1985–91 periods were computed (table 16). Slight differences can be seen, but both matrices indicate strong Markov properties showing that the tendency of a particular land cover is to remain the same. The analysis of the aerial photography in the previous section supports this conclusion. From 1950 to 1978, there were no major channel changes in the lower Copper River and it was not until the flood of 1981 that significant changes took place. Thus, infrequent, high magnitude floods appear to be the primary cause for changes in the lower Copper River.

Additional Markov techniques are not presented in this report. These techniques could be used to compute the transition probability matrix for the next time step (Lin and Harbaugh, 1984) or the mean passage time (Kemeny and Snell, 1976). They were tested but the results were inconclusive. The uncertainty of the results was possibly due to the following: (1) changes in the lower Copper River occur annually but only a 6.5-year time cycle was available for analysis, and (2) when the aerial photography was obtained, the water levels of the Copper River were not the same, and thus steady-state conditions were not present.

SUMMARY AND CONCLUSIONS

The geomorphology of the lower Copper River has been studied using various techniques. Principal findings are:

- Van Cleve Lake is a glacier-dammed lake formed by Miles Glacier. The lake empties approximately every 6 years and releases more than 1 million acre-ft of water. At the peak outflow rate from the lake, flow in the Copper River will increase between 150,000 to 190,000 ft^3/s.
- A geophysical technique—continuous seismic reflection—was effective in detecting ice marginal fans near the terminus of Miles Glacier and a fine-grained sediment layer in the lake. These data, in conjunction with bedload data collected at the Million Dollar Bridge, indicate that Miles Lake traps virtually all the bedload that enters the lake from the Copper River.
- Most of the flow of the Copper River occurs from June to September. By correlating concurrent flows from two streamflow-gaging stations located on the Copper River, long-term flow characteristics of the lower Copper River were synthesized. Historical discharge data indicate that as late as 1970 most of the flow of the Copper River was through Bridges 331, 1187, and 332, located at Flag Point. Discharge measurements made during this study at bridges along the Copper River Highway indicate that currently 51 percent of the flow of the Copper River passes through these bridges and 40 percent of the flow of the Copper River passes through Bridge 342.
- At the Million Dollar Bridge, the Copper River transports more than 69 million tons of suspended sediment per year. No bedload transport occurs at the Million Dollar Bridge. The composition of bedload at the Flag Point bridges ranges from coarse sand to fine gravel and the composition of bedload at Bridge 342 ranges from coarse sand to medium gravel. Correlations between bedload and discharge were uncertain, due to the dynamic nature of the lower Copper River alluvial plain. Analysis of bed-material samples indicates that the size of bed material deceases in a downstream direction, due to the reservoir-like effect of Miles Lake.
- Comparisons of cross sections at bridge sites of the lower Copper River made in 1908 with cross sections made in 1993 at the same bridge sites indicated a significant difference in cross-sectional area at Bridge 342. Cross sections of the Copper River from the Million Dollar Bridge to the Copper River Highway that were surveyed in 1993 indicate two main channels of the Copper River. Water-surface elevations taken from the cross-section data indicate a slope of 0.0013 from the Million Dollar Bridge to Bridge 342 and a slope of 0.0010 from the Million Dollar Bridge to Flag Point.
- Utilizing the bed material and cross-section data, entrainment discharges for various sizes of bed material were computed at various locations of the lower Copper River. Compared with the actual discharges of the lower Copper River, sufficient stream energy exists to move bed material.
- No major channel changes were caused by uplift from the 1964 earthquake. A flood in 1981, with a recurrence interval more than 100 years, is believed to have caused a significant channel change in the lower Copper River, resulting in a significant quantity of additional flow passing through Bridge 342. The 1981 flood was more effective in causing channel changes than were discharges associated with the breakout of Van Cleve Lake.
- A probability analysis of the lower Copper River indicated stable areas and the long-term locations of channels. Using a somewhat subjective technique, potential areas of instability can be located. A Markov analysis of the digitized photography indicated that the tendency of the lower Copper River is to remain in its current state.

REFERENCES CITED

Abercrombie, W.R., 1900, Supplementary expedition into the Copper River valley, Alaska, 1884—Narratives of explorations in Alaska: Washington D.C., 56th Congress, 1st session, Senate Report 1023, p. 383–410.

Alaska Department of Highways, 1970, Copper River hydraulics study: Alaska Department of Highways report, 7 p.

Alaska Department of Transportation and Public Facilities, 1981, Foundation report, Copper River Bridge at Childs Glacier: Project No. E-R-040 (01), 22 p.

Allen, H.T., 1985, An expedition to the Copper, Tanana, and Koyukuk Rivers in 1885: Anchorage, Alaska Northwest Publishing Company, 96 p. [reprinting of narrative portion of the official report published in 1887 by the U.S. Government].

Andrews, E.D., and Smith, J.D., 1992, A theoretical model for calculating marginal bedload transport rates of gravel, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, John Wiley, p. 41–52.

Bathurst, J.C., Graf, W.H., and Cao, H.H., 1987, Bed load discharge equations for steep mountain rivers, *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment transport in gravel-bed rivers: New York, John Wiley, p. 453–491.

Brabets, T.P., 1992, Hydrologic data for the lower Copper River, Alaska, May to September 1991: U.S. Geological Survey Open-File Report 92-89, 15 p.

———1993, Hydrologic data for the lower Copper River, Alaska, May to September 1992: U.S. Geological Survey Open-File Report 93-162, 26 p.

———1994, Scour assessment at bridges from Flag Point to Million Dollar Bridge, Copper River Highway, Alaska: U.S. Geological Survey Water-Resources Investigations Report 94-4073, 57 p.

———1995, Application of surface geophysical techniques in a study of the geomorphology of the lower Copper River Alaska: U.S. Geological Survey Water-Resources Investigations Report 94-4165, 47 p.

Cohn, T.A., DeLong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937–942.

Cordova Times, 1983, Bridge problems may close highway: Cordova, Alaska, The Cordova Times, March 17, 1983.

Davis, J.C., 1986, Statistics and data analysis in geology: New York, John Wiley, 646 p.

Davis, J.L., and Annan, A.P., 1989, Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy: Geophysical Prospecting, v. 37, p. 531–551.

Desloges, J.R., and Church, M., 1992, Geomorphic implications of glacier outburst flooding—Noeick River valley, British Columbia: Canadian Journal of Earth Science, v. 29, p. 551–564.

Edwards, T.K., and Glysson, G.D., 1988, Field methods for measurements of fluvial sediment: U.S. Geological Survey Open-File Report 86-531, 118 p.

Ellsworth, C.E., and Davenport, R.W., 1915, A water-power reconnaissance in south-central Alaska: U.S. Geological Survey Water-Supply Paper 372, 167 p.

Emmett, W.W., 1980, A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler: U.S. Geological Survey Professional Paper 1139, 44 p.

Fahnestock, R.K., 1963, Morphology and hydrology of a glacial stream—White River, Mt. Rainier Washington: U.S. Geological Survey Professional Paper 422–A, 70 p.

Ferguson, R.I., 1994, Critical discharge for entrainment of poorly sorted gravel: Earth Surface Processes and Landforms, v. 19, p. 179–186.

Graf, W.L., 1981, Channel instability in a braided, sand bed river: Water Resources Research, v. 17, no. 4, p 1087–1094.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.

Haeni, F.P., 1986, Application of continuous seismic reflection methods to hydrologic studies: Ground Water, v. 24, no. 1, p. 23–31.

Helley, E.J., and Smith, W., 1971, Development and calibration of a pressure-difference bedload sampler: U.S. Geological Survey Open-File Report, 18 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier Science Publishing Company Inc., 522 p.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood-flow frequency: Hydrology Subcommittee Bulletin 17B, 28 p. [available from the National Technical Information Service as report PB-86-157278/AS].

Janson, L., 1975, The copper spike: Anchorage, Alaska, Northwest Publishing Company, 175 p.

Kachadoorian, R., 1968, Effects of the earthquake of March 27, 1964, on the Alaska highway system: U.S. Geological Survey Professional Paper 545–C, 66 p.

Kemeny, J.G., and Snell, J.L., 1976, Finite Markov chains: New York, Springer-Verlag, 224 p.

Klingeman, P.C., and Emmett, W.W., 1982, Gravel bedload transport processes, *in* Gravel-bed rivers: New York, John Wiley, p. 141–169.

Komar, P.D., 1989, Flow-competence evaluations of the hydraulic parameters of floods—An assessment of the technique, *in* Beven, K., and Carling, P., eds., Floods—Hydrological, sedimentological and geomorphological implications: New York, John Wiley, p. 107–134.

Lane, E.W., 1957, A study of the shape of channels formed by natural streams flowing in erodible material: Omaha, Neb., U.S. Army Engineers Division, Missouri River Corps of Engineers, M.R.D. Sediment Series, v. 9.

Leopold, L.B., and Maddock, T., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 56 p.

Lin, C., and Harbaugh, J.W., 1984, Graphic display of 2- and 3-dimensional Markov computer models in geology: Van Nostrand Reinhold, 179 p.

Maddock, T., 1969, The behavior of straight open channels with movable beds: U.S. Geological Survey Professional Paper 622–A, 70 p.

Neill, C.R., 1968, A re-examination of the beginning of movement for coarse granular bed materials: Wallingford, United Kingdom, Hydraulics Research Station, Report No. INT 68, 37 p.

Plafker, G., 1969, Tectonics of the March 27, 1964 Alaska earthquake: U.S. Geological Survey Professional Paper 543-I, 74 p.

Post, Austin, 1967, Effects of the March 1964 Alaska earthquake on glaciers: U.S. Geological Survey Professional Paper 544–D, 42 p.

Post, Austin, and Mayo, L.R., 1971, Glacier-dammed lakes and outburst floods in Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA-455, 3 sheets.

Quinn, A.O., 1995, Iron rails to Alaskan copper—The epic triumph of Erastus Corning Hawkins: Bend, Oregon, Maverick Publications Inc., 195 p.

Schumm, S.A., and Winkley, B.R., 1994, The character of large alluvial rivers, *in* Schumm, S.A., and Winkley, B.R., eds., The variability of large alluvial rivers: New York, American Society of Civil Engineers, p. 1–9.

Scott, K.M., and Gravlee, G.C., 1968, Flood surge on the Rubicon River, California—Hydrology, hydraulics and boulder transport: U.S. Geological Survey Professional Paper 422–M, 40 p.

Tarr, R.S., and Martin, L., 1914, Alaskan glacier studies of the National Geographic Society in the Yakutat Bay, Prince William Sound, and Lower Copper River regions: Washington, D.C., National Geographic Society, 485 p.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 51 p., 6 plates.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, no. 1, p. 54–74.

GLOSSARY

Aggradation and degradation. The bed cutting and sedimentation of a channel over a relatively long period of time, usually measured in years.

Alluvial channel. A channel whose bed is composed of non-cohesive sediment that has been or can be transported by the flow.

Bed material. The material of which a streambed is composed.

Channel. The part of the river that carries flow.

Channel change. Change in channel geometry or bed elevation; change in its position, course, or pattern; and change in bed material, bank material, or vegetation density.

Flood plain. A relatively flat surface adjacent to the river, constructed by the river and being reconstructed by the river in the present climatic and hydrologic regime, and overtopped on average about 2 of every 3 years.

Median diameter. The midpoint in the size distribution of sediment such that half the weight of the material is composed of particles larger than the median diameter and half is composed of particles smaller than the median diameter.

Scour and fill. The bed cutting and sedimentation of a channel during relatively short periods of time. Channel scour and fill involves time measured in minutes, hours, days, or perhaps even seasons.

APPENDIX 1

Suspended-sediment data for the Copper River at bridges along the Copper River Highway

Appendix 1. Suspended-sediment data for the Copper River at bridges along the Copper River Highway

[ft^3/s, cubic foot per second; mg/L, milligram per liter; ton/d, ton per day; mm, millimeter]

Bridge name	Date	Time	Water discharge (ft^3/s)	Concen-tration (mg/L)	Discharge (ton/d)	Percent finer than 0.062 mm
331	6-20-91	0920	36,100	805	78,500	84
	7-02-91	1500	52,800	1,690	240,900	90
	7-24-91	1600	44,600	1,290	155,300	88
	8-14-91	1530	48,800	2,000	263,500	83
	8-29-91	1540	35,800	503	48,600	99
	9-12-91	1845	38,300	963	99,600	78
	9-23-91	1200	31,700	664	56,800	98
	6-11-92	1630	37,900	783	81,100	80
	6-23-92	1730	49,300	891	118,600	77
	8-12-92	1510	51,300	2,300	318,600	91
	9-09-92	1415	29,400	748	59,400	82
	9-22-92	1300	21,600	1,220	71,200	90
	6-08-93	1715	44,400	944	113,200	81
	6-22-93	1440	46,800	846	106,900	86
	7-20-93	1640	64,600	1696	295,800	91
	8-19-93	1050	73,600	1854	368,400	75
	9-01-93	1345	44,200	2236	266,800	78
	9-15-93	1400	41,200	660	73,400	--
1187	6-20-91	0830	16,700	840	37,900	81
	7-02-91	1400	35,000	1,780	168,200	86
	7-24-91	1445	26,100	1,240	87,400	88
	8-14-91	1500	29,500	2,020	160,900	84
	8-29-91	1445	14,400	772	30,000	93
	9-12-91	1830	19,000	913	46,800	82
	9-23-91	1215	11,500	564	17,500	98
	6-11-92	1600	18,400	843	41,900	78
	6-23-92	1700	30,300	788	64,500	82
	8-12-92	1430	30,300	2,160	176,700	94
	9-09-92	1345	11,500	592	18,400	90
	9-22-92	1310	6,950	309	5,800	94
	6-08-93	1700	23,900	876	56,500	87
	6-22-93	1515	24,300	738	48,400	88
	7-20-93	1615	35,300	1744	166,200	87
	8-19-93	1025	33,400	1770	159,600	74
	9-01-93	1325	15,800	2382	101,600	75
	9-15-93	1350	14,600	808	31,900	--

Appendix 1. Suspended-sediment data for the Copper River at bridges along the Copper River Highway (Continued)

Bridge name	Date	Time	Water discharge (ft^3/s)	Concen-tration (mg/L)	Discharge (ton/d)	Percent finer than 0.062 mm
332	6-19-91	1700	15,000	750	30,400	85
	7-02-91	1300	29,400	1,530	121,500	92
	7-24-91	1300	19,700	1,170	62,200	90
	8-14-91	1410	21,600	1,860	108,500	85
	8-29-91	1345	9,000	875	21,300	94
	9-12-91	1800	13,000	861	30,200	85
	9-23-91	1240	7,200	664	12,900	98
	6-11-92	1530	12,200	852	28,100	74
	6-23-92	1515	21,800	798	47,000	83
	8-12-92	1330	15,000	2,100	85,100	96
	9-09-92	1245	2,280	560	3,450	89
	6-08-93	1530	13,900	922	34,600	83
	6-22-93	1550	12,600	799	27,200	84
	7-20-93	1555	23,200	1717	107,600	88
	8-19-93	0950	24,300	1587	104,100	79
	9-01-93	1305	9,480	2112	54,100	78
	9-15-93	1340	8,750	640	15,100	
333	7-02-91	1725	5,800	1,310	20,500	99
	7-25-91	1220	4,700	1,060	13,500	97
	8-15-91	1350	5,000	1,410	19,000	--
	8-28-91	1310	2,200	781	4,640	96
	9-25-91	1145	800	546	1,180	93
	6-10-92	1445	2,160	532	3,100	90
	6-23-92	1515	5,070	583	8,020	98
	7-13-92	1730	8,710	1,220	28,700	96
	7-31-92	1430	4,860	781	10,200	95
	8-13-92	1325	5,240	1,780	25,200	97
	8-27-92	1530	2,510	1,080	7,320	95
	9-09-92	1505	710	485	930	99
	6-08-93	1515	2,770	768	5,740	94
	6-22-93	1405	2,800	665	5,030	96
	7-20-93	1530	4,940	1560	20,800	96
	8-19-93	0930	7,120	1310	25,200	91
	9-01-93	1245	3,280	1960	17,400	85

Appendix 1. Suspended-sediment data for the Copper River at bridges along the Copper River Highway (Continued)

Bridge name	Date	Time	Water discharge (ft^3/s)	Concentration (mg/L)	Discharge (ton/d)	Percent finer than 0.062 mm
334	7-02-91	1720	12,000	1,320	42,800	96
	7-25-91	1215	5,000	1,050	14,200	97
	8-15-91	1345	6,000	1,560	25,300	93
	8-28-91	1225	600	624	1,010	98
	9-25-91	1130	400	304	328	99
	6-10-92	1430	620	299	500	100
	6-23-92	1500	5,560	640	9,610	95
	7-13-92	1550	13,100	1,180	41,700	97
	7-31-92	1330	5,540	706	10,600	98
	8-13-92	1315	8,470	1,990	45,500	97
	8-27-92	1500	3,860	1,120	11,700	96
	9-09-92	1515	246	252	167	100
	6-08-93	1500	4,820	746	9,710	96
	6-22-93	1350	5,200	577	8,100	99
	7-20-93	1435	12,700	1440	49,400	98
	8-19-93	0925	17,600	1210	57,500	95
	9-01-93	1230	6,120	2010	33,200	84
339	7-02-91	1710	5,400	1,140	16,600	98
	7-25-91	1155	2,300	1,060	6,580	97
	8-15-91	1330	1,900	2,230	11,400	--
	8-28-91	1130	600	634	1,030	100
	9-23-91	1115	40	212	23	98
	6-10-92	1415	368	439	436	98
	6-23-92	1430	2,240	654	3,960	94
	7-13-92	1510	3,700	1,150	11,500	98
	7-28-92	1200	3,200	878	7,590	90
	8-13-92	1300	3,800	2,170	22,300	96
	8-27-92	1430	2,160	1,260	7,350	89
	9-09-92	1525	425	412	473	100
	6-08-93	1445	2,590	755	5,280	96
	6-22-93	1345	2,600	595	4,180	99
	7-20-93	1305	9,210	1400	34,800	99
	8-19-93	0915	14,600	1240	48,900	97
	9-01-93	1210	4,530	1880	23,000	82

Appendix 1. Suspended-sediment data for the Copper River at bridges along the Copper River Highway (Continued)

Bridge name	Date	Time	Water discharge (ft^3/s)	Concen-tration (mg/L)	Discharge (ton/d)	Percent finer than 0.062 mm
340	6-20-91	1600	4,100	786	8,700	91
	7-02-91	1705	11,800	1,320	42,100	96
	7-25-91	1150	6,800	1,040	19,100	98
	8-15-91	1310	7,700	1,370	28,500	95
	8-28-91	1100	1,100	707	2,100	99
	9-25-91	1100	200	372	201	100
	6-10-92	1400	1,140	425	1,310	96
	6-23-92	1400	6,270	676	11,400	91
	7-13-92	1430	7,150	1,160	22,400	97
	7-28-92	1130	5,770	1,030	16,000	93
	8-13-92	1240	5,860	2,170	34,300	96
	8-27-92	1415	3,470	1,220	11,400	93
	9-09-92	1530	235	351	222	100
	6-08-93	1410	4,150	767	8,590	94
	6-22-93	1330	4,200	632	7,170	98
	7-20-93	1215	9,040	1440	35,100	98
	8-19-93	0910	10,600	1270	36,300	97
	9-01-93	1200	5,470	1680	24,800	88
342	6-18-91	1500	64,300	790	137,200	84
	7-02-91	1630	91,400	1,340	330,700	91
	7-24-91	1100	73,900	1,210	241,400	90
	8-14-91	1100	78,600	1,375	291,800	89
	8-29-91	0900	45,500	882	108,400	93
	9-12-91	1320	54,400	791	116,200	92
	9-23-91	1030	40,000	530	57,200	96
	6-10-92	1200	47,400	513	65,700	88
	6-23-92	1100	69,400	739	138,500	87
	8-13-92	1100	64,900	2,320	406,500	95
	9-09-92	1545	30,200	651	53,100	90
	9-22-92	1010	13,400	262	9,480	99
	6-08-93	1350	60,700	800	131,100	90
	6-22-93	1130	65,800	670	119,000	91
	7-20-93	0935	85,800	1474	341,500	94
	8-19-93	0845	92,100	1460	363,100	89
	9-01-93	1110	66,500	1758	315,600	85
	9-15-93	1300	66,100	734	131,000	--

Appendix 1. Suspended-sediment data for the Copper River at bridges along the Copper River Highway (Continued)

Bridge name	Date	Time	Water discharge (ft^3/s)	Concen-tration (mg/L)	Discharge (ton/d)	Percent finer than 0.062 mm
Million Dollar	6-28-91	1150	202,000	1,200	654,000	94
	8-07-91	1520	115,000	1,010	314,000	95
	8-29-91	1020	92,300	1,400	349,000	98
	9-11-91	1500	120,000	829	269,000	94
	9-24-91	1531	78,100	528	111,000	94
	6-19-92	1231	149,000	688	277,000	92
	7-10-92	1821	188,000	1,180	599,000	97
	8-13-92	0930	157,000	2,230	945,000	97
	9-04-92	1200	109,000	1,520	447,000	98
	9-22-92	0930	39,900	1,620	174,500	92
	6-08-93	1000	154,000	819	341,000	92
	6-18-93	1411	156,000	839	353,000	94
	7-21-93	1155	232,000	1,480	927,000	96
	7-30-93	1925	211,000	1,330	758,000	95
	8-17-93	0900	240,000	1,015	658,000	98
	8-24-93	1230	132,000	1,070	381,000	86
	9-16-93	1200	98,800	722	193,000	--
	10-07-93	1550	88,100	2,120	504,000	99
	6-03-94	1520	60,000	242	39,200	88
	9-07-94	1500	86,800	427	100,000	96
	10-13-94	1250	28,400	560	42,900	98

APPENDIX 2

Suspended-sediment and particle-size analyses for the Copper River at bridges along the Copper River Highway

Appendix 2. Suspended-sediment and particle-size analyses for the Copper River at bridges along the Copper River Highway

[ft^3/s, cubic feet per second; mg/L, milligram per liter; ton/d, ton per day]

Bridge	Date	Time	Water discharge (ft^3/s)	Suspended sediment: Concen-tration (mg/L)	Suspended sediment: Dis-charge (ton/d)	Suspended sediment, percent finer than size indicated, in millimeters: 0.002	0.004	0.008	0.016	0.031	0.062	0.125	0.250	0.500
331	7-14-92	1720	56,600	1,130	172,700	36.2	44.1	52.5	66.9	82.4	91	96	99	100
	7-30-92	1556	49,100	951	126,100	30.0	35.7	41.8	58.9	72.3	84	91	97	99
	8-26-92	1445	50,900	2,050	281,700	20.3	22.6	29.1	41.6	57.9	74	90	96	99
1187	7-14-92	1645	38,600	1,170	121,900	28.3	42.0	58.0	71.4	83.8	90	95	98	99
	7-30-92	1520	31,400	884	74,900	30.3	37.6	45.6	60.1	74.5	88	93	96	99
	8-26-92	1400	30,300	2,000	163,600	19.5	22.4	29.4	42.3	63.1	78	90	97	99
332	7-14-92	1610	26,900	1,110	80,600	33.8	45.8	55.7	71.3	83.3	91	95	98	100
	7-30-92	1455	18,000	871	42,300	31.2	43.0	50.7	64.6	81.3	88	93	97	99
	8-26-92	1315	14,700	1,810	71,800	19.5	20.8	28.7	43.7	64.7	81	91	98	100
342	7-13-92	1315	78,500	1,160	245,900	40.7	49.8	57.5	72.4	85.7	94	97	99	100
	7-28-92	1003	69,300	984	184,100	33.4	45.7	62.2	75.9	86.9	94	97	98	100
	8-27-92	1345	64,200	1,200	208,000	23.3	38.0	54.1	67.1	80.9	93	97	98	100
Million Dollar	7-29-92	1350	169,000	947	432,100	33.1	38.0	48.9	65.0	79.0	93	99	100	
	8-27-92	1030	160,000	1,020	440,600	20.0	20.7	27.3	39.7	58.4	93	98	99	100

APPENDIX 3

Bedload analyses for the Copper River at bridges along the Copper River Highway

Appendix 3. Bedload analyses for the Copper River at bridges along the Copper River Highway

[ft^3/s, cubic feet per second; ton/d, ton per day; mm, millimeter]

Bridge	Date	Water discharge (ft^3/s)	Bedload discharge (ton/d)	Particle-size distribution of bedload — Percentage, by weight, finer than size (mm) indicated										
				Pan	0.25	0.50	1.0	2.0	4.0	8.0	16.0	32.0	64.0	128
331	6-20-91	36,100[i]	4,300	0.0	0.4	5.6	27.7	51.3	69.3	86.7	98.3	100	100	100
	7-02-91	52,800[d]	1,300	0.1	1.3	11.3	37.3	61.2	73.9	86.3	96.9	100	100	100
	7-24-91	44,600[i]	750	0.4	5.4	64.7	92.7	97.0	98.3	99.6	100	100	100	100
	8-14-91	48,800[i]	1,850	0.0	0.2	9.7	32.7	47.6	60.3	77.7	94.7	100	100	100
	8-29-91	35,800[d]	550	0.1	0.3	22.6	49.4	61.1	68.0	79.1	96.0	100	100	100
	6-11-92	37,900[i]	2,600	0.1	0.9	11.2	30.6	47.8	62.9	79.8	94.1	99.2	100	100
	6-24-92	49,300[d]	3,450	0.1	0.5	7.4	23.3	42.2	55.6	73.0	93.9	100	100	100
	7-14-92	56,600[d]	3,300	0.0	0.4	11.1	41.9	60.2	71.8	87.1	97.9	100	100	100
	7-30-92	49,100[d]	1,750	0.2	1.3	21.0	42.6	54.5	64.6	77.3	93.0	100	100	100
	8-13-92	51,300[d]	730	0.4	3.1	28.7	68.7	81.5	85.6	90.6	98.3	100	100	100
	8-26-92	50,900[i]	2,170	0.3	1.8	33.0	49.9	58.2	67.7	79.4	94.3	100	100	100
	6-09-93	44,400[d]	3,640	0.1	0.2	5.7	24.1	52.9	76.1	91.3	99.1	100	100	100
	6-23-93	46,800[i]	2,960	0.1	0.4	17.0	52.9	78.1	88.3	94.7	99.5	100	100	100
	7-21-93	64,600[d]	310	0.1	0.2	9.8	36.4	59.6	70.2	83.2	98	100	100	100
	8-17-93	73,600[d]	1,920	0.0	0.1	2.0	5.8	15.9	32.1	56.9	86.9	100	100	100
	8-31-93	44,200[i]	1,900	0.7	2.7	49.5	77.4	85.5	90.4	95.2	98.5	100	100	100
1187	6-20-91	16,700[i]	1,700	0.3	9.2	40.4	70.1	88.4	94.7	98.4	100	100	100	100
	7-02-91	35,000[d]	2,200	1.0	7.4	40.7	75.2	89.0	94.9	98.6	100	100	100	100
	7-24-91	26,100[i]	3,500	0.0	0.8	10.0	32.7	53.5	66.8	83.3	97.6	100	100	100
	8-14-91	29,500[i]	3,600	0.0	0.8	31.2	53.2	65.2	79.2	91.1	99.6	100	100	100
	8-29-91	14,400[d]	1,300	2.8	17.0	58.0	76.9	82.7	89.1	95.5	100	100	100	100
	6-11-92	18,400[i]	1,540	0.4	6.5	50.8	82.6	95.0	97.8	99.5	100	100	100	100
	6-24-92	30,300[d]	1,450	0.0	1.0	19.8	52.8	74.5	84.6	96.0	100	100	100	100
	7-14-92	38,600[d]	4,010	0.0	1.8	37.6	72.7	85.6	90.7	97.0	100	100	100	100
	7-30-92	31,400[d]	3,880	0.2	1.2	22.6	58.1	75.9	85.2	94.1	100	100	100	100
	8-26-92	30,300[i]	4,690	0.1	0.7	16.6	41.7	59.1	72.6	85.5	97.9	100	100	100
	6-09-93	23,900[d]	1,080	0.1	1.6	52.8	72.2	83.5	90.5	96.9	100	100	100	100
	6-23-93	24,300[i]	2,610	0.1	1.0	34.4	71.8	87.2	95.0	98.7	100	100	100	100
	7-21-93	35,300[d]	4,240	0.2	1.7	30.9	69.2	84.5	91.7	96.9	99.5	100	100	100
	8-17-93	33,400[d]	6,840	0.3	0.8	16.7	44.2	60.9	67.8	83.2	97.7	100	100	100
	8-31-93	15,800[i]	3,980	0.2	1.8	23.0	53.2	69.5	80.2	90.5	99.3	100	100	100
332	6-19-91	15,000[i]	2,000	0.1	3.0	38.8	80.1	92.3	96.9	99.1	99.9	100	100	100
	7-02-91	29,400[d]	2,000	0.0	1.5	17.8	52.6	81.4	91.4	97.2	99.8	100	100	100

Appendix 3. Bedload analyses for the Copper River at bridges along the Copper River Highway (Continued)

Bridge	Date	Water discharge (ft^3/s)	Bedload discharge (ton/d)	Particle-size distribution of bedload — Percentage, by weight, finer than size (mm) indicated										
				Pan	0.25	0.50	1.0	2.0	4.0	8.0	16.0	32.0	64.0	128
332	7-24-91	19,700[i]	2,500	0.1	4.2	42.2	74.6	88.5	94.3	98.3	99.9	100	100	100
	8-14-91	21,600[i]	4,100	0.4	1.8	40.3	73.4	86.5	92.9	97.6	99.9	100	100	100
	8-29-91	9,000[d]	400	0.4	8.6	31.5	63.7	76.6	88.2	97.5	100	100	100	100
	6-11-92	12,200[i]	3,800	0.0	1.0	37.0	80.0	92.0	95.0	97.0	100	100	100	100
	6-23-92	21,800[d]	2,350	0.0	1.3	28.0	68.4	86.1	91.7	97.8	100	100	100	100
	7-14-92	26,900[d]	3,340	0.0	2.6	32.6	68.9	86.4	91.7	97.1	99.9	100	100	100
	7-30-92	18,000[d]	1,380	0.3	2.0	42.6	76.2	83.6	88.7	95.5	100	100	100	100
	8-26-92	14,700[i]	1,280	1.0	11.4	56.0	87.0	94.9	97.9	99.5	100	100	100	100
	6-09-93	13,900[d]	3,760	0.1	2.7	33.7	68.5	84.3	91.8	97.7	100	100	100	100
	6-21-93	12,600[i]	2,820	0.1	1.7	36.0	72.9	88.2	93.8	98.5	100	100	100	100
	7-21-93	23,200[d]	2,540	0.3	5.4	45.7	77.8	91.8	96.2	99.1	100	100	100	100
	8-17-93	24,300[d]	5,400	0.3	2.2	29.2	62.3	82.7	91.1	97.1	99.7	100	100	100
	8-31-93	9,480[i]	1,510	0.3	3.1	45.1	79.8	88.4	93.5	97.8	100	100	100	100
342	6-18-91	64,300[i]	14,700	0.0	0.2	1.5	5.2	11.1	18.9	34.9	57.8	83.7	100	100
	8-29-91	45,500[d]	1,700	0.0	0.2	0.8	1.7	4.0	15.6	41.8	72.5	92.8	100	100
	6-10-92	47,400[i]	1,000	0.0	0.2	11.1	43.2	61.3	69.2	74.5	82.4	98.0	100	100
	6-23-92	69,400[d]	8,540	0.0	0.0	0.6	1.5	3.9	10.0	20.8	39.6	70.4	100	100
	7-13-92	78,500[d]	12,800	0.0	0.1	8.6	29.9	40.5	45.3	55.4	68.1	85.1	94.9	100
	7-28-92	69,300[d]	7,140	0.1	0.2	10.6	52.9	74.5	84.5	92.3	98.2	100	100	100
	8-13-92	64,900[d]	3,510	0.1	0.6	13.4	28.3	36.9	43.9	53.1	70.0	88.9	100	100
	8-26-92	64,200[i]	2,770	0.1	0.4	10.3	16.0	19.8	24.8	33.7	55.7	85.5	100	100
	6-08-93	60,700[d]	6,500	0.0	0.2	10.5	15.6	22.5	30.5	44.5	63.3	83.8	100	100
	6-22-93	65,800[i]	4,340	0.0	0.1	4.9	14.9	27.3	39.3	56.2	74.4	93.2	100	100
	7-20-93	85,800[d]	6,580	0.1	0.4	6.4	15.8	25.0	33.3	42.0	57.5	74.1	95.6	100
	8-03-93	85,200[d]	6,910	0.0	0.1	2.4	9.9	15.9	20.3	31.3	50.4	75.2	100	100
	8-17-93	92,100[d]	10,700	0.1	0.2	2.1	4.0	5.7	7.1	10.3	15.8	49.5	100	100
	8-31-93	66,500[i]	2,950	0.0	0.2	4.2	13.1	28.0	38.5	52.7	71.9	95.2	100	100
Million Dollar	6-28-91	202,000	0											
	8-07-91	115,000	0											
	8-29-91	92,300	0											
	9-11-91	120,000	0											
	9-24-91	78,100	0											

[i]Increasing stage
[d]Decreasing stage

APPENDIX 4

Bedload and suspended-sediment data for the Copper River at bridges along the Copper River Highway

Appendix 4. Bedload and suspended sediment data for the Copper River at bridges along the Copper River Highway
[ft^3/s, cubic feet per second; mm, millimeter; ton/d, ton per day]

Bridge	Date	Water discharge (ft^3/s)	Bedload median diameter (d_{50})(mm)	Discharge (ton/d)		
				Bedload	Suspended sediment	Total sediment
331	6-20-91	36,100[i]	1.9	4,300	78,500	82,800
	7-02-91	52,800[d]	1.5	1,300	240,900	242,200
	7-24-91	44,600[i]	0.4	750	155,300	156,000
	8-14-91	48,800[i]	2.3	1,850	263,500	265,400
	8-29-91	35,800[d]	1.0	550	48,600	49,200
	6-11-92	37,900[i]	1.4	2,600	81,100	83,700
	6-24-92	49,300[d]	3.0	3,450	118,600	122,000
	7-14-92	56,600[d]	1.3	3,300	172,700	176,000
	7-30-92	49,100[d]	1.2	1,750	126,100	127,800
	8-13-92	51,300[d]	0.7	730	318,600	319,300
	8-26-92	50,900[i]	1.0	2,170	281,700	283,900
	6-09-93	44,400[d]	1.8	3,640	113,200	116,800
	6-23-93	46,800[i]	1.0	2,960	106,900	109,900
	7-21-93	64,600[d]	1.8	310	295,800	296,100
	8-17-93	73,600[d]	6.0	1,920	368,400	370,300
	8-31-93	44,200[i]	0.5	1,900	266,800	283,700
1187	6-20-91	16,700[i]	0.6	1,700	37,900	39,600
	7-02-91	35,000[d]	0.6	2,200	168,200	170,400
	7-24-91	26,100[i]	1.8	3,500	87,400	90,900
	8-14-91	29,500[i]	0.9	3,600	160,900	164,500
	8-29-91	14,400[d]	0.4	1,300	30,000	31,300
	6-11-92	18,400[i]	0.5	1,540	41,900	43,400
	6-24-92	30,300[d]	1.0	1,450	64,500	66,000
	7-14-92	38,600[d]	0.6	4,010	121,900	125,900
	7-30-92	31,400[d]	0.8	3,880	74,900	78,800
	8-26-92	30,300[i]	1.4	4,690	163,600	168,300
	6-09-93	23,900[d]	0.4	1,080	56,500	57,600
	6-23-93	24,300[i]	0.7	2,610	48,400	51,000
	7-21-93	35,300[d]	0.8	4,240	166,200	170,400
	8-17-93	33,400[d]	1.0	6,840	159,600	166,400
	8-31-93	15,800[i]	1.0	3,980	101,600	105,600
332	6-19-91	15,000[i]	0.6	2,000	30,400	32,400
	7-02-91	29,400[d]	0.9	2,000	121,500	123,500

Appendix 4. Bedload and suspended sediment data for the Copper River at bridges along the Copper River Highway (Continued)

Bridge	Date	Water discharge (ft^3/s)	Bedload median diameter (d_{50})(mm)	Discharge (ton/d)		
				Bedload	Suspended sediment	Total sediment
332	7-24-91	19,700[i]	0.6	2,500	62,200	64,700
	8-14-91	21,600[i]	0.6	4,100	108,500	112,600
	8-29-91	9,000[d]	0.7	400	21,300	21,700
	6-11-92	12,200[i]	0.9	3,800	28,100	31,900
	6-23-92	21,800[d]	0.8	2,350	47,000	49,400
	7-14-92	26,900[d]	0.7	3,340	80,600	83,900
	7-30-92	18,000[d]	0.5	1,380	42,300	43,700
	8-26-92	14,700[i]	0.5	1,280	71,800	73,100
	6-09-93	13,900[d]	0.8	3,760	34,600	38,400
	6-21-93	12,600[i]	0.8	2,820	27,200	30,000
	7-21-93	23,200[d]	0.5	2,540	107,600	110,100
	8-17-93	24,300[d]	0.8	5,400	104,100	109,500
	8-31-93	9,480[i]	0.5	1,510	54,100	55,600
342	6-18-91	64,300[i]	12.5	14,700	137,200	151,900
	8-29-91	45,500[d]	9.6	1,700	108,400	110,100
	6-10-92	47,400[i]	0.8	1,000	65,700	66,700
	6-23-92	69,400[d]	16.0	8,540	138,500	147,000
	7-13-92	78,500[d]	6.0	12,800	245,900	258,700
	7-28-92	69,300[d]	14.0	7,140	184,100	191,200
	8-13-92	64,900[d]	6.0	3,510	406,500	410,000
	8-26-92	64,200[i]	14.0	2,770	208,000	210,800
	6-08-93	60,700[d]	9.0	6,500	131,100	137,600
	6-22-93	65,800[i]	5.0	4,340	119,000	123,300
	7-20-93	85,800[d]	10.0	6,580	341,500	348,100
	8-03-93	85,200[d]	10.0	6,910	--	
	8-17-93	92,100[d]	12.0	10,700	363,100	373,800
	8-31-93	66,500[i]	5.0	2,950	315,600	318,600
Million Dollar	6-28-91	202,000	--	0	654,000	654,000
	8-07-91	115,000	--	0	314,000	314,000
	8-29-91	92,300	--	0	349,000	349,000
	9-11-91	120,000	--	0	269,000	269,000
	9-24-91	78,100	--	0	111,000	111,000

[i]Increasing stage
[d]Decreasing stage

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodical

Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879–1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962–1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" are available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 20192.

Note—Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

ISBN 0-607-87206-3
9 780607 872064