Erosion and Sedimentation in the Kenai River, Alaska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1235

Prepared in cooperation with the U.S. Fish and Wildlife Service

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Scott, Kevin M., 1935-
Erosion and sedimentation in the Kenai River, Alaska.

(Geological Survey professional paper ; 1235)
Bibliography: p. 33-35
Supt. of Docs. no.: I 19.16:1235
1. Sediments (Geology)--Alaska--Kenai River watershed. 2. Erosion--Alaska--Kenai River watershed. I. U.S. Fish and Wildlife Service. II. Title. III. Series: United States. Geological Survey Professional Paper 1235.
QE571.S412 553.7'8'097983 81-6755
AACR2

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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Multiply inch-pound unit	*By*	*To obtain metric unit*
°F (degree Fahrenheit)	$5/9(F-32)$	°C (degree Celsius)
in. (inch)	2.540×10	mm (millimeter)
ft (foot)	3.048×10^{-1}	m (meter)
mi (mile)	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)
ft^3/s (cubic foot per second)	2.832×10^{-2}	m^3/s (cubic meter per second)

National Geodetic Vertical Datum of 1929 (NGVD of 1929), the reference surface to which relief features and altitude data are related, and formerly called "mean sea level," is herein called "sea level."

EROSION AND SEDIMENTATION IN THE KENAI RIVER, ALASKA

By KEVIN M. SCOTT

ABSTRACT

The Kenai River system is the most important freshwater fishery in Alaska. The flow regime is characterized by high summer flow of glacial melt water and periodic flooding caused by sudden releases of glacier-dammed lakes in the headwaters. Throughout most of its 50-mi course across the Kenai Peninsula Lowlands to Cook Inlet, the river meanders within coarse bed material with a median diameter typically in the range 40-60 mm. Every nontidal section of the stream is a known or potential salmon-spawning site.

The stream is underfit, a condition attributed to regional glacial recession and hypothesized drainage changes, and locally is entrenched in response to geologically recent changes in base level. The coarseness of the bed material is explained by these characteristics, combined with the reservoirlike effects of two large morainally impounded lakes, Kenai and Skilak Lakes, that formed as lowland glaciers receded. Throughout the central section of the river the channel is effectively armored, a condition that may have important long-term implications for the ability of this section of channel to support the spawning and rearing of salmon.

The 3.8-river-mile channel below Skilak Lake contains submersed, crescentic gravel dunes with lengths of more than 500 ft and heights of more than 15 ft. Such bed forms are highly unusual in streams with coarse bed material. The dunes were entirely stable from 1950 to at least 1977, so much so that small details of shape were unmodified by a major glacial-outburst flood in 1974. The features are the product of a flood greatly in excess of any recorded discharge.

The entrenched section of the channel has been stable since 1950-51 or earlier; only negligible amounts of bank erosion are indicated by sequential aerial photographs. Bank erosion is active both upstream and downstream from the entrenched channel, however, and erosion rates in those reaches are locally comparable to rates in other streams of similar size. Although erosion rates have been generally constant since 1950-51, evidence suggests a possible recent decrease in bank stability and an increase in erosion that could be related to changes in river use.

The high sustained flow of summer encourages a variety of recreation-related modification to the bank and flood plain—canals, groins, boat ramps, slips, embankments, as well as commercial developments. As population and recreational use increase, development can pose a hazard to the productivity of the stream through increased suspended-sediment concentration resulting directly from construction and, with greater potential for long-term impact, indirectly from bank erosion. A short-term hazard to both stream and developments is the cutoff of meander loops, the risk of which is increased by canals and boat slips cut in the surface layer of cohesive, erosion-resistant sediment on the flood plain within nonentrenched meander loops. A significant long-term hazard is an increase in bank erosion rates resulting from the loss of stabilizing vegetation on the high (as high as 70 ft) cutbanks of entrenched and partly entrenched sections of channel. Potential causes of erosion and consequent vegetation loss are river-use practices, meander cutoffs, and groin construction.

INTRODUCTION

The Kenai River is a large proglacial stream draining the inland side of the Kenai Mountains and crossing the lowlands of the Kenai Peninsula to Cook Inlet. The most obvious feature of the river in the lowlands is the presence of coarse bed material in association with a meandering pattern; in the spectrum of bed-material sizes of meandering streams, the Kenai River is near the coarse end. Both the bed material and the channel pattern reflect previous geologic intervals when discharge was greater and glaciers were more widespread. Glaciers continue to influence the hydrology of the river, extending today within the watershed to altitudes below 500 ft. The major flood discharges have originated historically from outbursts of a glacier-dammed lake every 2 to 4 years.

The Kenai River system is the most heavily used freshwater fishery in Alaska (U.S. Army Corps of Engineers, 1978, p. 126). Salmon fishing attracts increasing numbers of visitors from the Anchorage area during the summer, particularly for the runs of king salmon. The development associated with this recreational use, though small in scale, is expanding rapidly along the downstream 45.5 river miles that lies mainly in a corridor of State-owned and private lands outside the Kenai National Moose Range (fig. 1). The potential for further development, evidenced by the demand for recreational property and the population increases in communities within the corridor, is large. For details on the environment of the river and the associated 197-mi^2 corridor, readers can refer to the comprehensive survey by the U.S. Army Corps of Engineers (1978).

The section of the river described in this report is the 50.3 mi of channel below Skilak Lake, a large moraine-impounded lake with influence on the flow regime of the river (fig. 1). The purpose of the study is to describe the recent history, geomorphic characteristics, and sedimentation system of the stream downstream from Skilak Lake and to indicate the types, locations, and timing of development that could prove harmful to the fluvial habitat in its ability to support the spawning and rearing of salmon. This report is concerned mainly with developments in the

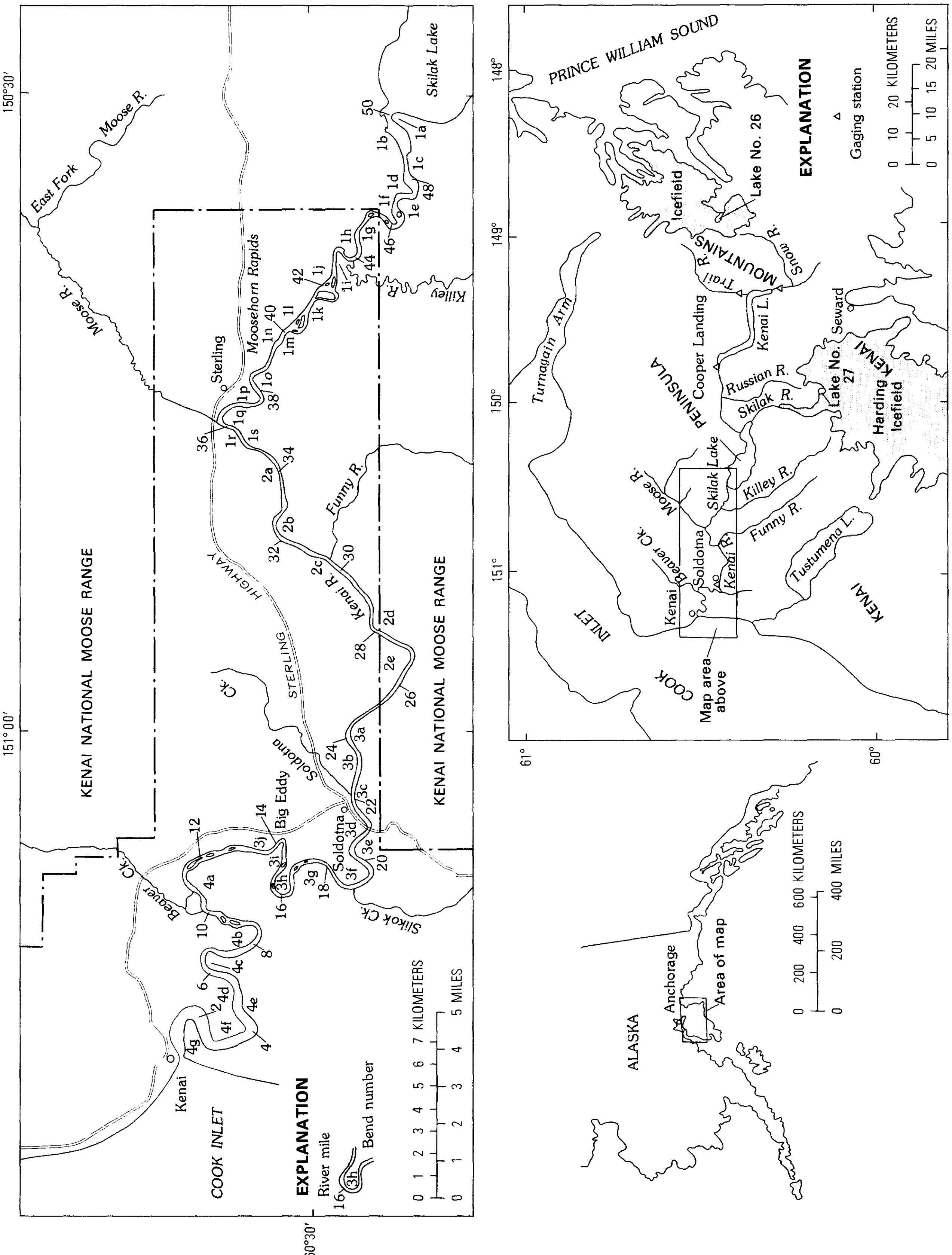

FIGURE 1.—Configuration of the Kenai River downstream from Skilak Lake. Glacial lakes capable of yielding potentially hazardous flood discharges are numbered in accordance with Post and Mayo (1971).

category of alterations to the navigable channel for which a permit from the Department of the Army is required. Upland development and land-use changes are not considered.

In a stream the size and type of the Kenai River, increased suspended-sediment transport will be the first general effect of development with the potential to be deleterious to the physical stream system, chiefly through deposition of fine sediment in the pores of the streambed gravel. Consequently, the present levels of suspended-sediment concentration and the possible causes of future increases are emphasized. Other changes in the sediment system are, of course, possible.

The most important feature of the environment to the economy of the area is the ability of the Kenai River to act as the freshwater habitat for salmon taken directly by sport fishing and indirectly by commercial fishing in Cook Inlet. Four species (king, sockeye, silver, and pink) use the river for spawning in runs from early spring to as late as December. The presence of chum salmon has also been reported. The young of three valuable species (king, sockeye, and silver) are found in the stream year round. Every nontidal part of the river is a known or potential spawning site for at least one species (U.S. Army Corps of Engineers, 1978, fig. 27).

Salmon-producing habitats are sensitive to many factors, but most importantly to sedimentation and water temperature (Meehan, 1974, p. 4). The deposition of fine sediment, with the consequent loss of permeability in streambed gravel during the time of egg and fry development, has been described by many studies as the most detrimental sedimentation effect (for example, Meehan and Swanston, 1977, p. 1). The deposited sediment reduces the flow of oxygen-bearing water within the gravel where eggs and alevins (preemergent fry) are incubating. It may also act as a physical barrier to the emergence of fry and may cause changes in the population of aquatic insects on which the young salmon depend for food.

Erosion and sedimentation have been described as the most insidious of civilization's effects on aquatic life, in that the processes may go unnoticed and the damage can be widespread, cumulative, and permanent (Cordone and Kelley, 1961, p. 189). Unlike most causes of degradation in water quality, erosion and the resulting increase in sediment transport may be triggered by a set of conditions and then may continue to increase or even accelerate after the triggering circumstances have ceased. The possible causes of such a response and why this form of response could occur along the sections of the Kenai River with high, presently stable cut banks are one focus of this report.

Acknowledgments.—This study was completed in cooperation with the U.S. Fish and Wildlife Service, to the personnel of which the writer is indebted for much helpful discussion and the supply of aerial photographs. Many local residents shared their knowledge of the past behavior of the Kenai River and helped form the writer's historical perspective on the stream.

THE KENAI RIVER WATERSHED

The Kenai River drains 2,200 mi^2 of the Kenai Peninsula, encompassing a watershed that extends from the icefields of the Kenai Mountains westward to Cook Inlet. Summer flow originating as melt water from ice- and snow-covered terrain dominates the hydrologic system of the river. Approximately 210 mi^2 of the drainage basin consists of glaciers or permanent snowfields, of which 130 mi^2 is part of the Harding Icefield and attached valley glaciers (fig. 1).

CLIMATE

The climate of the watershed is transitional between the wet and relatively mild marine climate of coastal areas and the colder and dryer continental environment of interior Alaska. The high sustained flow in the Kenai River in middle and late summer reflects the combination of melt water and superimposed storm runoff. More than half the annual precipitation falls in the 4-month period from July through October, with an average of almost 4 in. occurring in September, the wettest month.

Annual rainfall totals vary greatly within the drainage basin because of the orographic effect of the Kenai Mountains on storm systems moving northward from the Gulf of Alaska. In the lowlands downstream from Skilak Lake the annual precipitation is less than 20 in. Southeastward in the progressively higher parts of the basin, precipitation totals increase markedly and probably exceed 80 in. at the crest of the range. The regional distribution of precipitation is reflected in the altitudes to which glaciers descend—many outlet glaciers extend to the tidewater of the Gulf of Alaska; within the Kenai River drainage basin, however, valley glaciers reach no lower than 500 ft.

VEGETATION

The flood plain of the Kenai River and the surrounding terrain are covered by Alaskan taiga association of white spruce and hardwoods, locally with black spruce on north-facing slopes and poorly drained areas (Helmers and Cushwa, 1973, figs. 1, 2; U.S. Army Corps of Engineers, 1978, fig. 31). Evidence of stream behavior can be obtained from vegetation bordering streambanks and on flood plains. Areas of active bank erosion may be characterized by spruce trees leaning at angles into the river as their root support is progressively eroded. When nearly horizontal, the trees are known as "sweepers," named with good reason by early-day raftsmen and hazardous to modern river runners as well. Ice damage in spruce trees on flood plains is evidence of ice-jam flooding and, if datable by dendrochronology, can serve as evidence of flood frequency (Levashov, 1966). Several episodes of ice damage are detectable on trees of the flood plain within meander loop 3-H.

The interior meander loops of the Kenai River do not show the vegetational age succession that would be expected under conditions of rapid channel change. Some meanders do, however, show a variation in vegetation type within the point-bar deposits that corresponds to differences in sediment texture. As documented by Gill (1972) in the Mackenzie River delta, coarse-textured deposits with a lower water content and higher soil temperature encourage the growth of such hardwoods as balsam poplar. The finer textured deposits commonly support mature stands of spruce. The differences in texture mark the episodic accretion by which the meander loops develop—the coarser deposits correspond to the more rapid periods of accretion.

HYDROLOGY

The most obvious characteristic of flow in the Kenai River is the continuous rise in discharge that begins in May, followed by flow at sustained high levels throughout the summer and then by recession during the period from October to January (fig. 2). It is this unusual pattern of relatively uniform high flow during the summer months, reflecting the melting of glaciers and lake storage of melt water, that makes feasible the riverbank development in which bed and bank material is simply bulldozed to form canals, boat slips, and groins. The stage variation of a typical subarctic stream would make this kind of development nearly useless.

The mean annual flow of the Kenai River at Soldotna is 5,617 ft^3/s or 37.95 in.(1965-78). Annual peak flows generally occur in August or September at discharges in the range 20,000-30,000 ft^3/s. From freezeup in late November or December to breakup, occurring ordinarily in April but as early as February, flow levels base within the range 800-1,700 ft^3/s.

The Kenai River begins at the outlet of Kenai Lake, a glacially sculpted lake extending fiordlike for 22 mi inland from the front of the Kenai Mountains to within 15 mi of Seward on the Gulf of Alaska. Downstream from the outlet of Kenai Lake at Cooper Landing, the river flows for 17 mi before entering Skilak Lake. The 50-mi course of the stream between Skilak Lake and Cook Inlet is the subject of this report; the 17-mi segment between the major lakes is excluded.

Major headwater tributaries of the Kenai River are the Trail and Snow Rivers, which enter Kenai Lake from the north and south, respectively. The major tributary entering the Kenai River between the lakes is the Russian River, famous for a run of sockeye salmon during which they can be taken on artificial lures. Other large tributaries include the Skilak River, which drains the Harding Icefield and flows directly into Skilak Lake, and the Killey River, which joins the Kenai River 6 mi below the outlet of Skilak Lake. All these streams have significant areas of their headwaters covered by permanent ice and snow, and as a group they supply the high summer melt-water flow of the Kenai River.

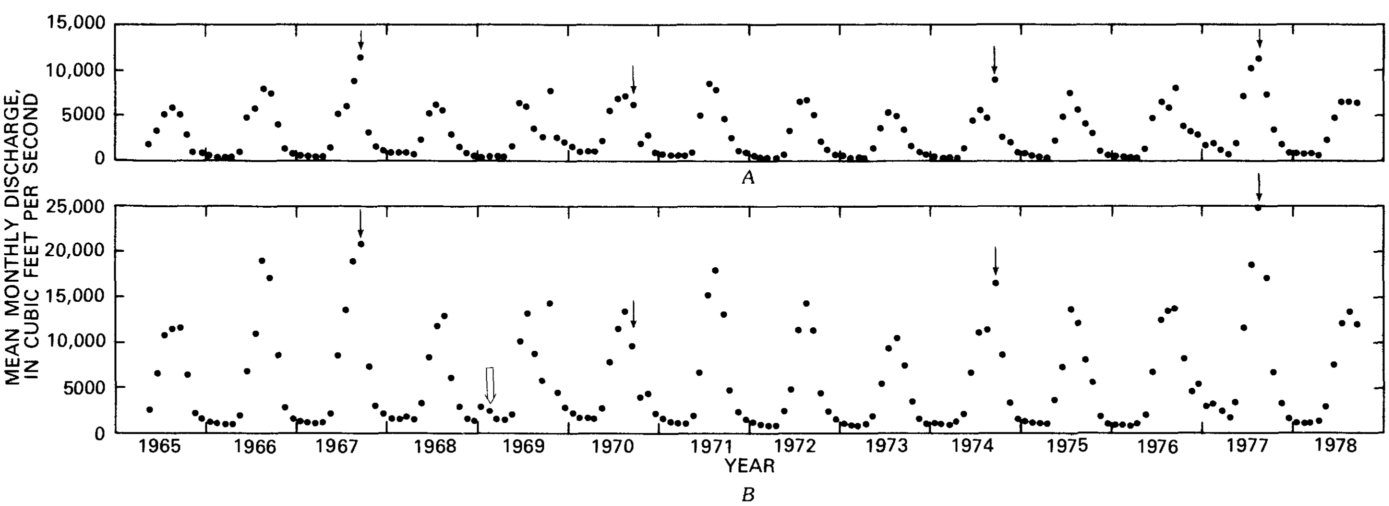

FIGURE 2. —Mean monthly discharges at gaging stations. *A*, Kenai River at Cooper Landing. *B*, Kenai River at Soldotna. Black arrows show times of release of glacial lakes in Snow River; white arrow shows times of release of glacial lakes in Skilak River.

Downstream from the Killey River, all tributaries to the Kenai River drain only the Kenai Lowlands. Runoff from these streams is dominated by snowmelt runoff, with annual peaks generally in April or May. Poorly integrated drainage and numerous lakes and marsh areas, as well as lower rates of precipitation, result in comparatively low annual runoff. The largest of these streams is the Moose River, which joins the Kenai River at river mile 36.2. The Funny River, and Beaver, Soldotna, and Slikok Creeks, are other lowland tributaries, of which Beaver Creek is the only stream with more than sporadic flow records (1967-78).

Anderson and Jones (1972, pl. 2) presented a summary of all discharge information for the Kenai River downstream from Skilak Lake as of 1972. These data and subsequent information can be obtained from the series of annual reports entitled "Water Resources Data for Alaska," published by the U.S. Geological Survey. Gaging-station records on the Kenai River have been obtained since 1947 at Cooper Landing, and since 1965 at the Soldotna bridge at river mile 21.1.

The Kenai River is noteworthy for a low variation in annual peak flows during the period of measurement. There are, however, three potential sources of major flooding on the stream in addition to the normal sources of flow—melt water and storm runoff: (1) sudden discharges from glacially dammed lakes, (2) outburst floods of water stored in or under glaciers, and (3) ice jams. Each is discussed in the following paragraphs.

The annual peak discharges from melt water and storm runoff have been generally less than the annual peaks that resulted from the sudden release of glacially dammed lakes. The historical peak discharge at Soldotna occurred September 9, 1977—instantaneous peak discharge was 33,700 ft^3/s—in response to the release of a glacially dammed lake in the Snow River drainage basin (fig. 1). The lake is one of two potentially hazardous such lakes in the watershed for which Post and Mayo (1971, sheet 1) recommended monitoring. The lake at the headwaters of the Snow River has caused outburst flooding periodically since 1911 or earlier. Typical of the floods is that occurring in 1974 (fig. 3) and yielding the peak discharge of record on the Kenai River at Cooper Landing. This lake has yielded floods at intervals, most commonly from 2 to 4 years in length and at levels apparently related to systematic changes in glacier size. Post and Mayo (1971, p. 4) cited reports that flooding historically has occurred most commonly in November, December, or January. In recent years (1964, 1967, 1970, 1974, 1977), however, flooding has occurred in August and September at times of high base flow derived from melt water. If this trend continues, the flood hazard from lake releases will increase.

The second potentially hazardous glacial lake occurs in the headwaters of the Skilak River (fig. 1) and discharges directly to Skilak Lake. This glacial lake yielded a comparatively small volume of flow in January 1969 (fig. 2), but the flood wave fractured large volumes of ice on the Kenai River, thereby causing locally serious flooding from the resulting ice jams (Post and Mayo, 1971, p. 4). Aerial observations by the U.S. Weather Service on October 18, 1979, revealed that the lake has refilled (S. H. Jones, oral commun., 1980), apparently setting the stage for another outburst flood.

A phenomenon similar to glacial lake discharges is the outburst of water impounded beneath glaciers. Though potentially originating from any glacier of at least moderate size, floods entirely from subglacial outbursts have not been specifically recorded on the Kenai River. They may not, however, have been observed if originating in uninhabited areas like the Skilak or Killey River drainage basins in the period before to flow measurement at Soldotna (before 1965). Part of the glacial lake in the Skilak River headwaters is formed beneath the Skilak Glacier, and that lake discharges subglacially into the Skilak River (S. H. Jones, written commun., 1980).

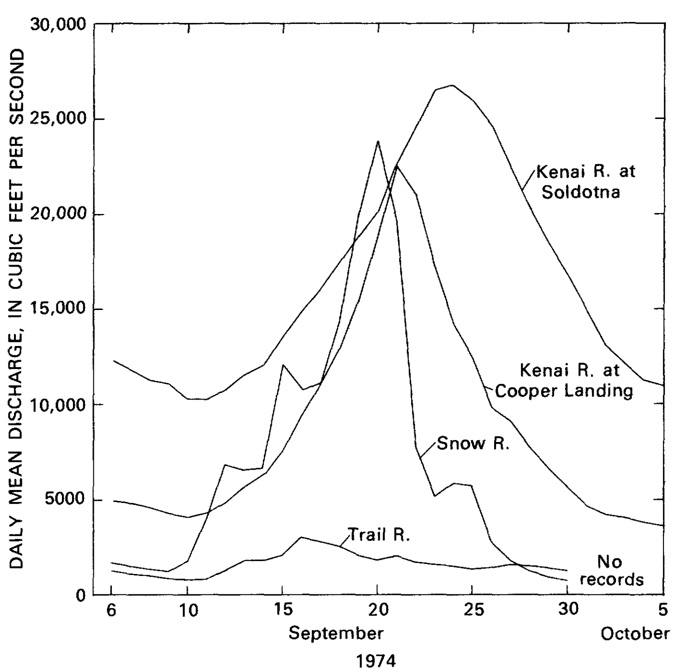

FIGURE 3.—Successive downstream hydrographs for flood of September 1974 originating from an unnamed glacially dammed lake (No. 26 of Post and Mayo, 1971) in headwaters of the Snow River. Concurrent discharge record of nearby Trail River is illustrated for comparison. Instantaneous peak discharges were 26,400 ft^3/s in the Snow River, 23,100 ft^3/s in the Kenai River at Cooper Landing, and 26,900 ft^3/s in the Kenai River at Soldotna.

The final cause of flooding is ice jams, from which an additional hazard is the channel-erosion effects with which they are associated on other northern rivers (MacKay and others, 1974). Jams on the Kenai River are most common near Big Eddy, a point of constriction in a tight meander at river mile 14.3 (fig. 1). The probability of ice jamming at Big Eddy led the U.S. Army Corps of Engineers (1967, exhibit 4) to calculate upstream flood-hazard levels that are as much as 10 ft above the stage of a flood, with a recurrence interval of 50 years. Potential levels of flooding from ice jams at Big Eddy exceed levels of the 50-year flood as far upstream as Soldotna.

QUATERNARY HISTORY OF THE KENAI RIVER VALLEY

The flood plain, terraces, and valley of the Kenai River reflect the influence of glacial events to a high degree. The modern landscape of the river, extending even to variations in channel pattern and size of channel-bed material, is partly a function of glacial action, including sculpture by glacial ice, deposition from receding ice sheets, and changing base levels related to the effects of glaciation or tectonics. The final major Quaternary glaciation of the Kenai Lowlands did not end until about 5,000 years ago, and today an outlet glacier from the Harding Icefield reaches to within 7 mi of the head of Skilak Lake.

An understanding of the recent glacial history of the Kenai Lowlands is prerequisite to interpreting the modern Kenai River. The sequence of events, their ages, and an interpretation of their effects on the river are presented in table 1. The glacial history of the Kenai River area and the surrounding region was studied in detail by Karlstrom (1964), and most of the general aspects and terminology in the following discussion are based on his work.

The Cook Inlet region has undergone five major Pleistocene glaciations and two major subsequent advances. In stratigraphic order (youngest to oldest), the major glaciations are:

Naptowne
Knik
Eklutna
Caribou Hills
Mount Susitna

Much of the Kenai Lowlands was covered by ice during the first three major glaciations. During Knik time, however, glaciers from the Kenai Mountains reached only as far as river mile 26.7. According to Karlstrom (1964), farther southwest in Cook Inlet, Knik glaciers from the Kenai Mountains coalesced with those from the Alaska Range and dammed the regional drainage into a proglacial lake that existed periodically and at successively lower levels until near the end of the Naptowne Glaciation. However, the periodic existence of this lake—a major premise of Karlstrom's interpretations—has not been verified by subsequent investigations in the Cook Inlet region.

Deposits of the three youngest major glaciations are present along the Kenai River in the study area, but it is the events of the youngest episode, the Naptowne Glaciation, that dominate the geomorphic history of the stream. The spatulate Naptowne end moraines are the most prominent topographic feature of the Kenai Lowlands, extending as far as river mile 38.9. The type localities of the Naptowne Glaciation and several of its subsidiary advances are located along the river within the study area (the town of Naptowne is now known as Sterling). The sequence of advances within the Naptowne Glaciation is, stratigraphically:

Tanya
Skilak
Killey
Moosehorn

The age of the Naptowne Glaciation has been revised downward to less than 14,000 B.P. (Péwé, 1975, p. 14), considerably later than reported by Karlstrom (1964). Dating by Karlstrom of the post-Moosehorn events appears reasonable in light of this revised age and is shown in table 1.

The initial phase of the Naptowne Glaciation, the Moosehorn advance, was named for the Moosehorn Rapids in the Kenai River at river mile 39.4 near the margin of the Naptowne end moraine. Moraines of the Killey advance, named for exposures along the Killey River, a major tributary to the Kenai River, extend to river mile 40.5; and those of the subsequent Skilak advance, named for exposures around the edge of Skilak Lake, occur as far downstream as river mile 48.4.

EVIDENCE OF PROGLACIAL LAKE IN COOK INLET

The existence of a proglacial lake in Cook Inlet, or at least its chronology as interpreted by Karlstrom, has been thrown open to question by a revised origin and radiometric age of a unit previously thought to represent a middle Wisconsinan interstadial event. In the Anchorage area a distinctive deposit of silty clay, the Bootlegger Cove Clay (Miller and Dobrovolny, 1959), occurs beneath and adjacent to the local equivalent of the Naptowne end moraine (Trainer and Waller, 1965, p. 170). The unit was believed to be mainly lacustrine in origin and middle Wisconsinan in age (Karlstrom, 1964, p. 37-38). Because failure of the Bootlegger Cove

TABLE 1.—*Late Quaternary (Wisconsinan to present) history of the Cook Inlet area and correlation with the geomorphology of the Kenai River*

[Glacial events and strandlines after Karlstrom (1964, table 3); correlation with classical sequence in part modified from Péwé (1975, table 2)]

Epoch	Glaciation		Thousands of years before present	Glacial event and associated radiocarbon dates			Strandlines of hypothesized proglacial lakes (feet above present sea level)	History of the Kenai River in study area: Depositional events	History of the Kenai River in study area: Erosional events
Holocene				Alaska Glaciation	Tunnel II advance	A.D. 1550±150 A.D. 1500±200			
			1		Tunnel I advance	A.D. 565±200			
			2		Tustumena III advance	300±300 B.C. 420±100 B.C.			
			3		Tustumena II advance	1250±150 B.C.			
			4		Tustumena I advance	2550±450 B.C.			
					Pro-Tustumena advance				
			5				5–10 (marine transgression)	Deposition of tidal sediment exposed below river mile 12.3	Erosion of tidal flats continuing to present
			6	Naptowne Glaciation	Tanya III advance	3850±500 B.C. 4850±550 B.C.			
			7		Tanya II advance		50 (Best developed levels)		Entrenchment of river into Soldotna terrace begins and continues to present
			8		Tanya I advance		100–125 (Best developed levels)	Fluctuating levels of hypothesized proglacial lake in inlet with one or more complete withdrawals	Soldotna terrace formed
			9		Skilak III advance	7050±750 B.C.		Possible lacustrine, glaciolacustrine, and deltaic deposition in river valleys below strandlines indicated	
Pleistocene	Wisconsin	Late	10 (Scale variable)		Skilak II advance	7920±250 B.C. 8420±350 B.C.	275		
					Skilak I advance			Glacial advance to river mile 48.4	
					Killey advances	10,950±300 B.C. 11,550±400 B.C.	500	Glacial advance to river mile 40.5	Fluctuating levels of hypothesized proglacial lake in Cook Inlet with one or more complete withdrawals. Lake terraces possibly cut at strandlines indicated
					Moosehorn advance		750	Glacial advance to river mile 38.9	
		?			Pro-Naptowne advance				
		Early						Glacial advance to river mile 26.7	
				Knik Glaciation			~1000		

Clay caused disastrous slides during the 1964 Alaska earthquake, it has been the subject of additional study that has established an entirely marine origin (Hansen, 1965, p. 20) and an age of about 14,000 B.P. (Schmoll and others, 1972, p. 1109). Péwé (1975, p. 74) concluded that the interpretation of a glacial lake occupying the upper part of Cook Inlet during Knik and Naptowne time is refuted by this later evidence.

At least some of the features attributed by Karlstrom to a freshwater lake have other explanations. The Soldotna terrace, a well-developed surface bordering the Kenai River over much of its lower course, was interpreted as a lake terrace in mapping by Karlstrom (1964, pl. 4) but is described here as a former floodplain surface, an origin in common with other alluvial terraces. The Soldotna terrace grades to one of two well-developed terrace levels bordering Cook Inlet. These levels occur 50 and between 100 and 125 ft above present sea level and were interpreted by Karlstrom as lake terraces (table 1). They are, however, more likely marine in origin, on the basis of the extent of their development. It is difficult to envision an ice-floored lake spillway being sufficiently stable for the interval necessary for cutting of the terraces. The changes in base level consequently are more likely due to isostatic rebound or tectonic uplift than to changes in level of the hypothesized lake. Favoring the lake hypothesis is Karlstrom's mapping of other higher strandlines indicating lake levels at altitudes too high (table 1) for reasonable explanation by sea-level change due to isostatic rebound or tectonics. The existence of these higher strandlines could not, however, be confirmed during field investigations in the Kenai River watershed.

FIGURE 4.—Kenai River at the Soldotna bridge. The river is entrenched 30 to 40 ft below the Soldotna terrace, upon which part of the town of Soldotna is visible here. Wakes in the river are caused by large boulders, the presence of which is characteristic of the entrenched section of the stream. Direction of flow is toward upper left. Reach visible in photograph extends from approximately river miles 21.5 to 20.7. Scale, 1:4,800, or 1 in.= 400 ft. Photograph credit: U.S. Army Corps of Engineers.

TERRACES AND RIVER ENTRENCHMENT

The Soldotna terrace, here named informally for the town constructed upon it (fig. 4), is the most prominent topographic feature in the Kenai River valley between river miles 13 and 31. The terrace averages about a mile in width, is covered with mature taiga vegetation, and occurs at altitudes generally from 25 to 50 ft above the present Kenai River flood plain. It dominates the valley upstream from river mile 17.6, above which point the river is entrenched in the terrace surface and little modern flood plain exists. The entrenchment, which extends beyond the upstream end of the terrace as far as river mile 39.4, is a result of a lowering in base level, from the level to which the terrace was graded, to present sea level.

Karlstrom (1964, pl. 4) interpreted the section of the Soldotna terrace between river miles 31 and 27 as a river terrace and the remaining part as a hanging deltaic complex associated with a proglacial lake of Naptowne age. The entire terrace upstream from Soldotna (river mile 22) is here interpreted as a former flood plain of the Kenai River. Profiles of the terrace and river channel measured along the valley axis (fig. 5) show that the terrace is graded to a height above present sea level.

The extension of the Soldotna terrace below the town probably correlates with the 100- to 125-ft-high marine terrace. A well-developed 50-ft marine terrace is also present, and figure 5 portrays possibility that the alluvial part of the Soldotna terrace grades to this lower level. The town of Kenai is mainly on this lower terrace, which is not represented by obviously correlative alluvial equivalents along the Kenai River.

TOPOGRAPHY OF THE KENAI LOWLANDS AND COURSE OF THE KENAI RIVER

The poorly drained, lake-dotted Kenai Lowlands contain many abandoned channels that are visible on aerial photographs yet do not form a drainage system which is obviously integrated with the present network. The channels, though well developed at some localities, are discontinuous and not easily traceable. Karlstrom (1964, p. 15) believed that the pattern locally suggests scabland topography formed under torrential-flood conditions.

Changes in the drainage of the Kenai River system have occurred within a geologic time span that is apparently too short for any but partial adjustment of the channel—in pattern and bed material size, for example. A change in pattern (an increase in wavelength downstream from river mile 36; fig. 6) below the point of inflow of the tributary Moose River suggests that discharges proportionally larger than those now supplied by the Moose River have occurred in the past. If true, the Kenai River downstream from the Moose River is underfit to a greater degree than is the river

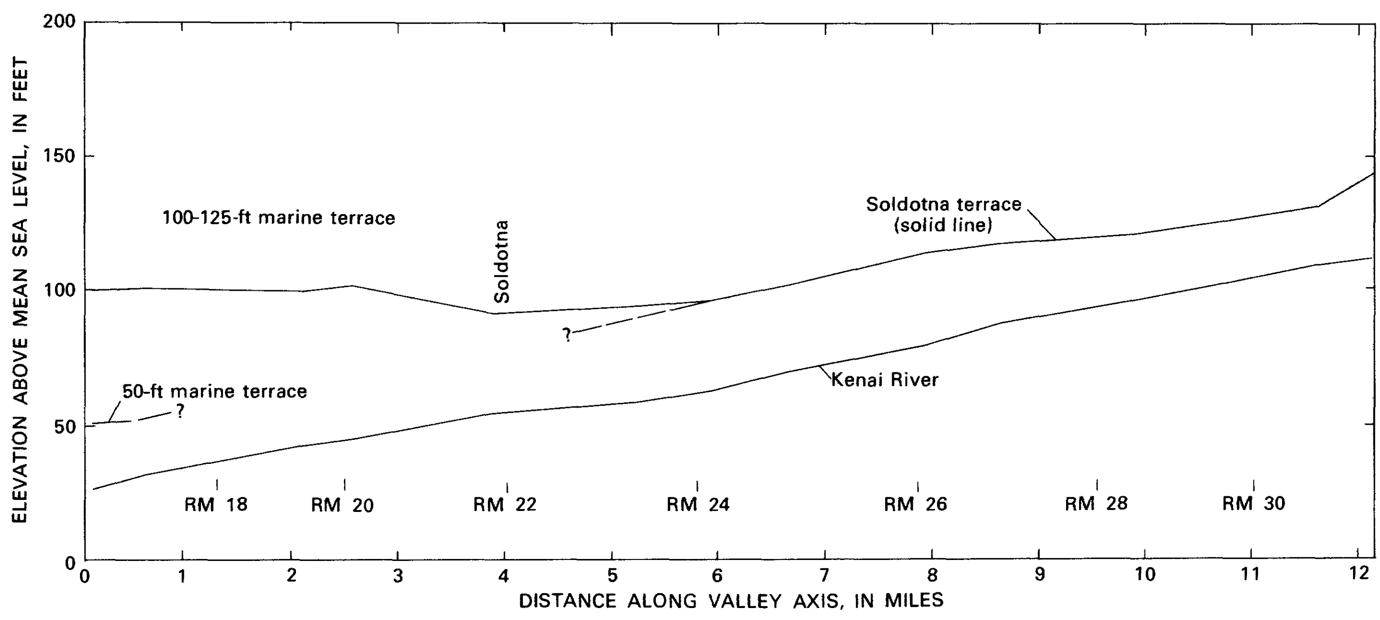

FIGURE 5.—Profiles of the Soldotna terrace and the Kenai River (water surface at intermediate flow level) measured along the valley axis. River miles are shown inset. Altitudes were derived photogrammetrically, and absolute values are only accurate within the approximate range of ±10 ft. Relative differences between altitudes of terrace and river at a point are believed accurate to within ±2 ft.

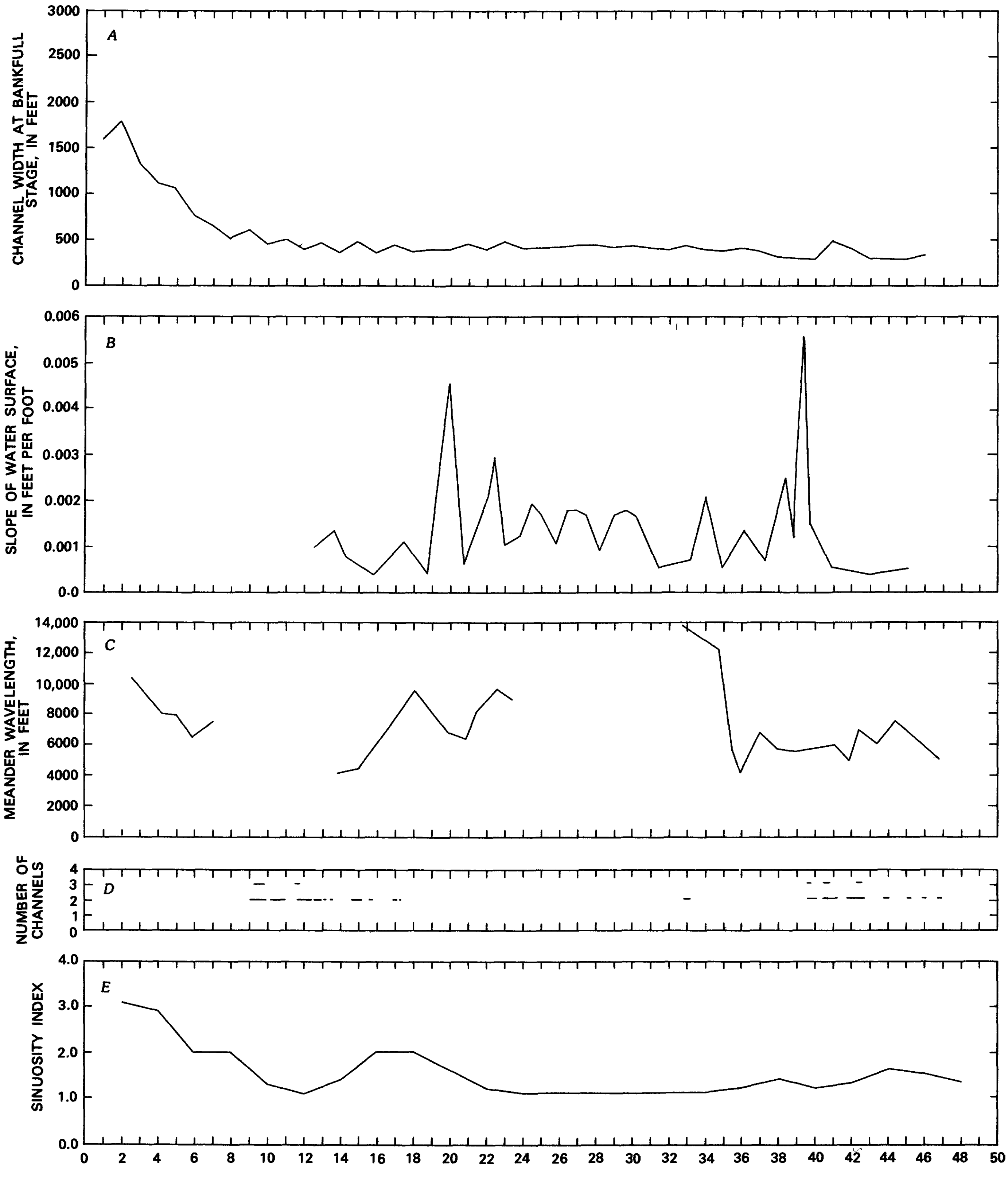

FIGURE 6.—Distance above channel mouth (in river miles) against: channel width at bankfull stage (*A*), slope of water surface (*B*), meander wavelength (*C*), number of channels (*D*), and sinuosity index (*E*).

upstream from the junction. This effect would be in addition to the probable basinwide underfit condition reflecting the general reduction in precipitation that has occurred with glacial recession.

Figure 7 illustrates the channel of the Moose River a short distance upstream from its junction with the Kenai River. The underfit condition is pronounced. The present channel is approximately 80 ft wide where it meanders within a paleochannel 600 to 700 ft wide. The Moose River paleochannel appears to be a natural upstream extension of the lower part of the Kenai River, from both the similarity in pattern and the trends of the two channels at their junction.

Topography at the front of the Kenai Mountains indicates several past variations in drainage in which the Moose River would have yielded much greater flow than at present. It is possible to project an extension of the Skilak Glacier to the head of Skilak Lake where it could divert the Kenai River into the headwaters of the East Fork of the Moose River (fig. 8). The course of probable diversion is today a chain of lakes, beginning with Hidden Lake in the gap between Hideout Hill and the hills north of Skilak Lake and continuing with the Seven Lakes, each connected by the drainage that becomes the East Fork of the Moose River. This hypothesized diversion probably occurred with the Skilak advance of the Naptowne Glaciation and could also have occured during the Tanya advance. Tanya end moraines have not been recognized in the Skilak Lake area, although they were mapped by Karlstrom (1964, pl. 4) at their type locality near Tustumena Lake. An advance of the Skilak Glacier similar in distance and gradient to the relation between the Tanya end moraines and the Tustumena Glacier, the extension of which was the type Tanya advance, could have diverted the Kenai River into the Moose River drainage.

The effects of earlier glaciations on the drainage pattern would have been greater. Drainage from the area of Kenai Lake, which was glacier filled during much of pre-Tanya Naptowne time, may also have entered the Moose River drainage north of Hideout Hill (fig. 8). During the maxima of Skilak and earlier Naptowne advances, glacial lobes from the Kenai Lake valley entered the Moose River basin and discharged large volumes of melt water.

No matter what scenario of melt-water drainage is hypothesized, during each of the Naptowne advances the tendency was for greater proportions of the total discharge of the Kenai River basin to have entered the Kenai Lowlands from the Moose River than from the present Kenai River channel above the confluence with the Moose River. The Kenai River channel downstream from the Moose River thus has had a constant drainage area, and the overall decrease in discharge in that channel has reflected the general climatic change. The channel upstream from the Moose River, however, re-

FIGURE 7.—Moose River channel between 1.3 and 2.6 mi upstream from its junction with the Kenai River—a striking example of confined meanders occurring within a large sinuous paleochannel. Flow is toward bottom of photograph. Downstream change in pattern of present channel from meandering to straight is in response to entrenchment of the Kenai River. Scale, 1:12,000, or 1 in. = 1,000 ft. Photograph credit: U.S. Army Corps of Engineers.

flects partially offsetting changes in climate and drainage area. The effects of change in drainage area have been to reduce the high discharges at times of glacial maxima. In consequence, the channel of the Kenai River below the Moose River reflects a history of adjustment to greater absolute change in discharge than does the channel upstream from the tributary, and this difference in adjustment is reflected in the channel and sediment characteristics described in the following sections.

CHANNEL OF THE KENAI RIVER

Study of the channel pattern, degree of entrenchment, position of riffle bars, symmetry of cross sections, and slope permits a description of the Kenai River that, in combination with the subsequent sections on bank erosion and development, can be used to assess the relative susceptibility of various sections of the stream to the actions of man. The information will be presented in the following section but will be applied in the final section on river development.

STREAM TYPE

The Kenai River can be fitted to an engineering classification of streams (Brice and Blodgett, 1978, p. 94; Brice, 1981, fig. 5) that emphasizes lateral stability—the potential for bank erosion. The classification is based on observable channel properties that show an association with varying degrees of lateral stability. The section of the Kenai River between river miles 39.4 and 17.6 has characteristics similar to the type described as equiwidth point bar. Such streams are relatively stable. Upstream and downstream from this section the Kenai River more closely fits the category described as wide-bend point bar. This type of stream is generally less stable than equiwidth point-bar streams.

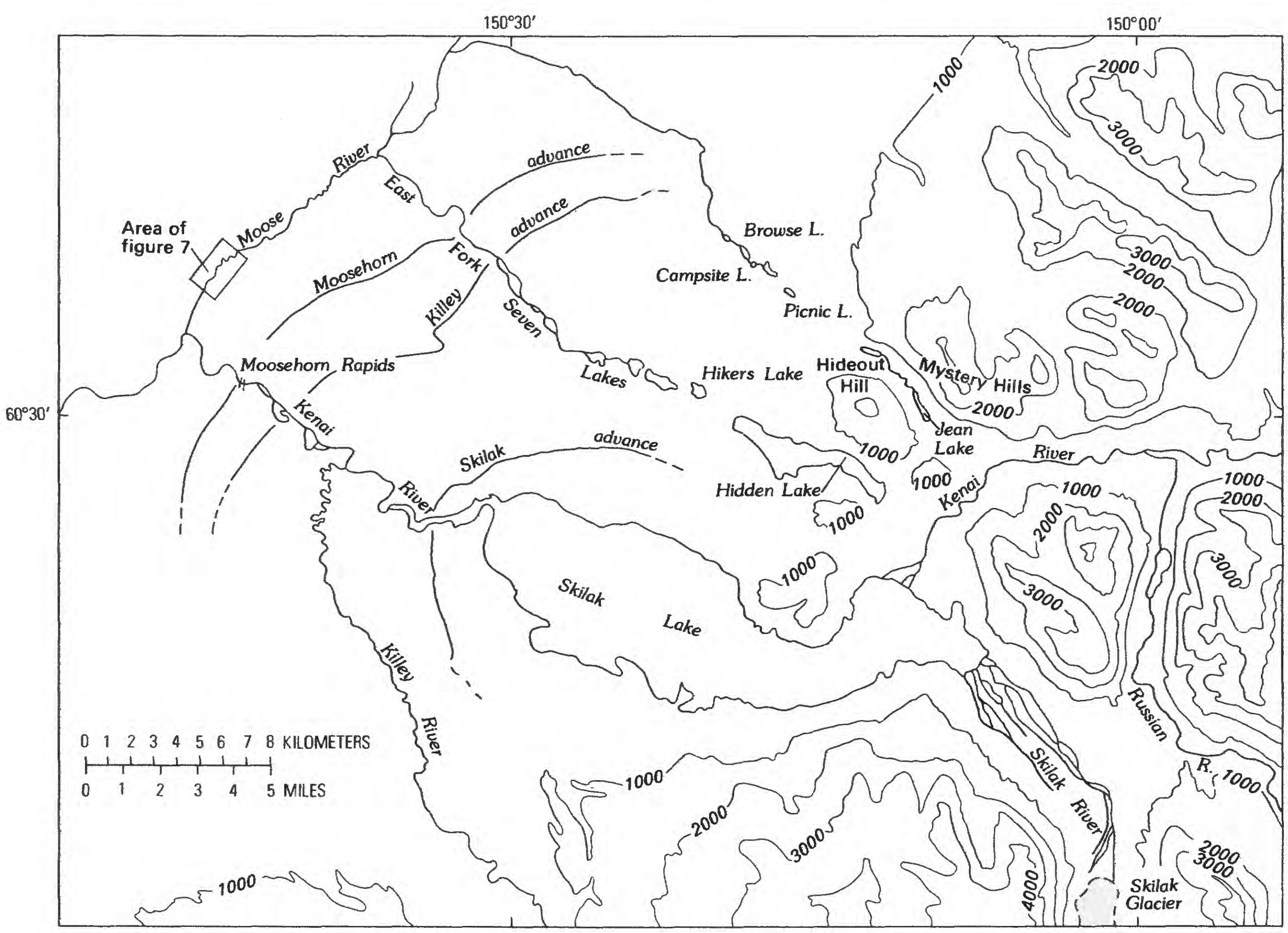

FIGURE 8.—Drainage network in the Kenai River watershed near the front of the Kenai Mountains. Limits of subsidiary advances within the Naptown Glaciation are shown (mainly from Karlstrom, 1964, pl. 4).

CHANNEL PATTERN

Variations in channel pattern can be empirically useful in assessing differences in susceptibility to bank erosion. For example, the straighter, less sinuous reaches of a stream tend to be significantly more stable than the more sinuous reaches, solely on the basis of the observation that bank erosion is most intense at channel bends. Channel pattern can be in part described by means of a sinuosity index (*S.I.*), defined as the ratio of the thalweg length to the length of the meander-belt axis (Brice, 1964, p. 25). Although the symmetry of channel bends is not considered in calculating the index, channels can be described by boundary values of the index. In the classification used here, reaches with a sinuosity index greater than 1.25 are described as meandering, those with an index between 1.05 and 1.25 are sinuous, and those with an index less than 1.05 are straight (Brice and Blodgett, 1978, p. 70).

The sinuosity indexes of overlapping reaches 4 mi in length are shown in figure 6, where values are plotted at midpoints 2 mi apart. That the Kenai River varies in sinuosity is readily seen. Three intervals of meandering channel are present: the first, between Skilak Lake and river mile 34.8; the second, between river miles 21.8 and 13.4; and that farthest downstream, between river mile 9.0 and the mouth. This last interval shows the downstream increase in channel width and meander amplitude associated with tidal augmentation of flow.

The river branches into multiple distinct channels (anabranches) in two reaches (fig. 6). The upstream anabranched reach, between river miles 42.7 and 39.6, is part of the first meandering section. The downstream anabranched reach, between river miles 15.8 and 11.4, includes part of the middle meandering section. The islands within the upstream anabranched section of channel are mainly covered with mature spruce. Vegetation on islands in the downstream anabranched section is less dense, but is generally mature and indicates that the islands are only rarely inundated.

INVESTIGATION OF UNDERFIT CONDITION

The possibility of an underfit condition can be investigated by comparison of the channel pattern with discharge and channel width. Paired observations have shown that meander wavelength is a function of bankfull discharge according to the relation (Inglis, 1949, p. 147; Leopold and Wolman, 1970, p. 216)

$$\lambda = 36Q^{0.5}.$$

Dury (1965, p. 5; 1970, p. 273; 1976, p. 223) analyzed several sets of paired observations of wavelength and discharge. His original set of 105 pairs of data gives the relation (Dury, 1970, p. 273)

$$\lambda = 30Q^{0.5}.$$

Also, meander wavelength is related to width of bankfull channel according to the relation (Leopold and Wolman, 1970, p. 216)

$$\lambda = 6.5w^{1.1}.$$

Dury (1976, fig. 2) summarized 173 pairs of values of wavelength and width and calculated the relation

$$\lambda = 9.76w^{1.019}.$$

Leopold and Wolman (1970, p. 216-217) showed that wavelength was more directly dependent on width than on discharge when data were compared for a large range of stream sizes. Bankfull discharge is considered here as equivalent to channel-forming discharge and is calculated as the discharge at a recurrence interval of 1.58 years in the annual series.

The plot of wavelength with bankfull discharge (fig. 9) indicates that the channel in each of the three meandering sections tends to be underfit; that is, the data points are in or above the upper ranges of the data of Inglis and Dury. In such cases of apparent underfit, a meander of a given size is associated with an uncommonly low channel-forming discharge, leading

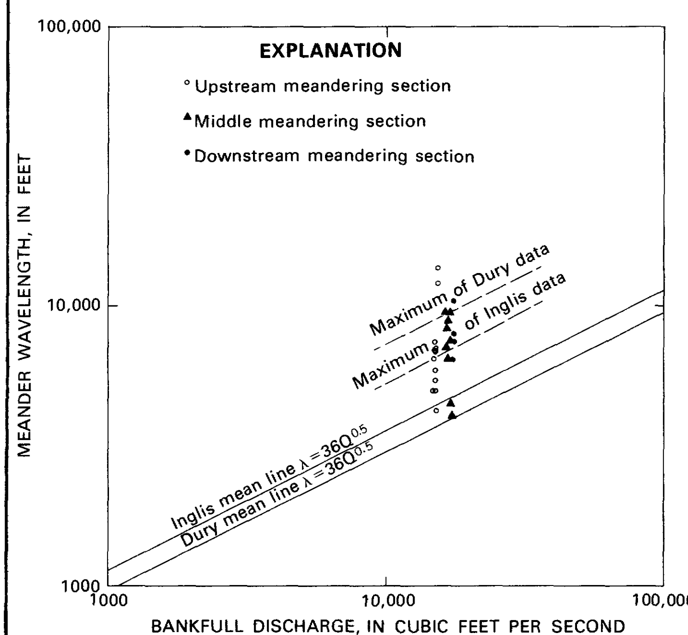

FIGURE 9.—Meander wavelength against bankfull discharge. Lines representing limits of Inglis (1949) and Dury (1965, 1970, 1976) data are approximate.

to the assumption that discharge has decreased since the meanders were formed.

The data points in the plot of wavelength against width at bankfull stage (fig. 10) tend to cluster in or above the upper ranges of the data plotted by Leopold and Wolman (1970, fig. 7.13) and Dury (1976, fig. 2). Thus the channel width is smaller for a given wavelength than would be expected by comparison with other streams, as the likely result of the meander pattern of the Kenai River having been formed during a previous period of higher discharge with, of course, the width of the channel reflecting the present, lower discharge.

Meanders from the tidal section of channel mainly plot below the mean lines of the data in the Leopold-Wolman and Dury studies (fig. 10), but the significance of this relation is not known because those authors included no data from tidal reaches. The downstream meandering channel reflects tidally augmented flow and shows the consequent characteristic increase in channel width, and so it should expectably indicate an underfit condition relative to the freshwater discharge of the stream, as it does in the plot of figure 9.

FLOW DEPTH VARIATION WITHIN MEANDERS AND WITH DIFFERING CHANNEL PATTERN

The measurement of a series of cross sections by the

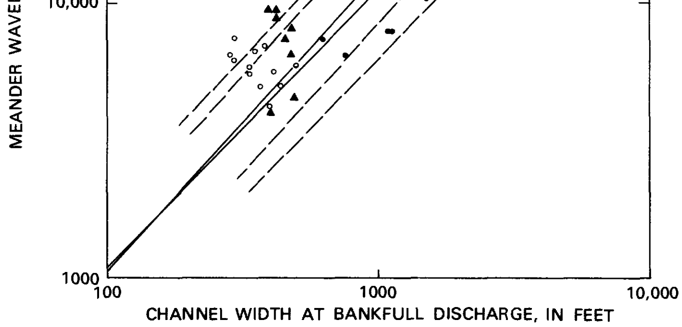

FIGURE 10.—Meander wavelength against channel width at bankfull stage. Lines representing ranges of previous data are approximate.

U.S. Army Corps of Engineers (1967, 1973, 1975, 1978) permits analysis of flow depths according to position in the meander course and the type of channel pattern. The discharge at Soldotna during the 2-day period of the survey was in the relatively narrow range of approximately 11,500 to 11,900 ft^3/s. The cross sections, therefore, represent the bed at a moderate flow level, approximately 70 percent of bankfull discharge, in the reaches between river miles 47 and 26.

In meandering streams the shallows analogous to riffles occur at the crossovers or points of inflection in the meander curve, and the pools are found at the bends, with the deepest point near the outside or concave bank. If this pattern of pools and riffles is not present or if it occurs with a different spacing relative to the meanders, some aspect of the fluvial environment is preventing the normal adjustment of the bed response to flow. For example, the meanders may be relict from a period of previous, generally higher discharge, or the mobility of the bed may have been reduced by the process of armoring, in which finer sediment is selectively removed and the bed is rendered progressively immobile. Dury (1970, p. 268) recognized an underfit condition in which the old meanders continue as the stream channel, but in which the pools and riffles assume an irregular distribution reflecting the new reduced discharge.

The following statistical analysis was made to investigate the spacing of bars. Maximum depths in selected sections were grouped in table 2 according to whether the channel was meandering or sinuous to straight. The data from meandering channels were subdivided by location—whether the section was at a bend or at or near a crossover—and were further grouped according to whether the meander was free to migrate laterally or was entrenched. Hypothesis testing of the differences between the means of the data subgroups for meandering channels yielded unexpected results. There was no significant difference between the maximum depths in bends and at crossovers, a result suggesting, when considered with other evidence, that the channel is underfit. The morphology is similar in some respects to that of the Illinois River (Rubey, 1952, p. 123-136), a stream with a stable and deep uniform channel that occupies a valley formed by large proglacial discharges.

There was also no significant difference between the maximum depths in the channels of meanders that are free to migrate and those that appear to be entrenched. The only significant difference was found between the depths in all meandering channels and the depths of sinuous or straight reaches. Maximum depths in the channel where it is sinuous or straight are less than those where the channel meanders, with a probability in excess of 0.99.

ASYMMETRY OF CROSS SECTIONS AT BENDS

Cross sections of the channel of a meandering stream are characteristically asymmetric at bends, with the point of maximum depth close to the outside of the bend. Of the nine sections located at meander bends, only four show the expected asymmetry, each in meanders free to migrate. Although none of the sections from entrenched meanders shows asymmetry, the sample size is too small for significance tests. Absence of or abnormal asymmetry can be regarded as evidence of underfitness, as exemplified by the Illinois River (Rubey, 1952, p. 129), where the normal asymmetry is reversed and the deepest part of the channel is close against the inside of meander bends.

SLOPE

The slope of the water surface of the Kenai River has a variation of at least an order of magnitude in the values determined from 5-ft contour increments and plotted at the midpoint of each increment (fig. 6). These data should be viewed as approximations to the actual slope because of their photogrammetric derivation. The accuracy of photogrammetric altitudes is such that, over short longitudinal increments of channel, expectable inaccuracies in altitude can yield significant differences in slope. Field observations likewise fail to confirm some of the slope data in figure 6 as more than approximations, useful for comparison only.

At the largest scale there is a difference in slope between the meandering reaches and the long middle section of the river with only a slightly sinuous configuration. The meandering reaches generally have the lesser slope, in accord with the general inverse correlation between sinuosity and slope.

At a smaller scale within the meandering reaches, the tendency toward anabranching, which is commonly associated with an increased gradient (see Mollard, 1973, fig. 1), does not fit this tendency, according to the data of figure 6. The anabranched and meandering sections of the river apparently have a lesser slope than some sections of single meandering channel. The reason for this anomaly is that parts of the upstream and middle meandering sections are entrenched. The entrenched meanders have the greatest slope, shown in figure 6 and verified by field observations, of any part of the river except the Moosehorn Rapids.

BED MATERIAL

The bed material of the Kenai River is among the coarsest recorded for a meandering channel of similar size (compare data in Kellerhals and others, 1972). The reasons are both geologic and hydrologic. The coarse material reflects initial transport by glaciers, which throughout the Pleistocene covered at first all, and then successively lesser, parts of the drainage basin. Coarse bed material was supplied directly from melting ice and outwash discharges and subsequently was derived throughout the length of the stream from erosion of previous glacial deposits. Numerous boulders too large for transport by even the highest discharges remain in the channel throughout the entrenched sections of the river (fig. 4).

TABLE 2.—*Statistical analysis of maximum flow depths at cross sections measured August 23-24, 1974*
[Location of sections, between river miles 26 and 47. Probable variation in discharge, less than 5 percent. Depths are in feet. *S.I.*, sinuosity index]

				Data grouped as indicated					
Channel pattern	Position in meander	Channel "free" or entrenched	n	$\bar{x}$ (range)	σ_x	$\bar{x}$ (range)	σ_x	$\bar{x}$ (range)	σ_x
meandering (S.I.>1.25)	Bend	Nonentrenched meanders	6	11.1 (8.7-13.5)	1.9	10.9 (7.7-13.7)	2.1	10.8 (7.7-15.1)	2.1
		Entrenched meanders	3	10.7 (7.7-13.7)	3.0				
	Crossover	Nonentrenched meanders	4	10.3 (8.3-12.0)	1.5	10.7 (8.3-15.1)	2.2		
		Entrenched meanders	3	11.4 (9.2-15.1)	3.3				
Sinuous or straight (S.I.<1.25)	Not determined	Entrenched to varying degrees	8	7.9 (5.8-10.2)	1.7				

As glaciers receded within the Kenai Mountains, transition from a braided to a meandering channel occurred as the flow regime changed to one of lesser discharge and greatly decreased sediment supply. Similar changes in pattern have been widely noted throughout areas peripheral to receding glaciers. In the Kenai River, formation of the large lakes left by the receding glaciers—first Skilak Lake and then Kenai Lake—acted much as the construction of reservoirs. Downstream degradation and partial armoring of the channel occurred in response to the sediment-entrapment effects of the lakes. The pronounced entrenchment of the channel below the Soldotna terrace, however, is attributed mainly to degradation consequent to change in base level rather than to the downstream effects of the lakes.

The size of bed material in the active channel is shown in figure 11 as the median diameter (D_{50}). These data were obtained from large emersed bars by pebble-counting techniques that are statistically valid for coarse sediment (Wolman, 1954). Several estimates of the median grain size were made during a boat traverse of the river, and these points are so designated. The estimates were made only for the submersed gravel dunes found in the reaches downstream from Skilak Lake (fig. 12).

The distribution of median sizes of bed material (fig. 11) reflects the entrenchment and partial armoring of parts of the river. The comparatively finer grained bed material upstream from river mile 39.4, site of the Naptowne end moraine and the Moosehorn Rapids, coincides with the reaches in which higher erosion rates were documented (see section on bank erosion). The extremely coarse bed material (D_{50} = 122 mm) in the channel at the end moraine functions as the base level for the river upstream to Skilak Lake and has prevented upstream extension of the entrenchment. The bed material below river mile 39.4 is coarser than that upstream, remaining in the range 40-60 mm throughout the entrenched part of the channel downstream from the Moose River. Below river mile 20, bed material becomes gradually finer, and, correspondingly, bank-erosion rates locally increase to rates comparable to those in the reaches upstream from river mile 39.4.

The roundness (Meehan and Swanston, 1977) and size (McNeil and Ahnell, 1964) of bed material have been related to success rates of salmon spawning in southeastern Alaska. Survival of salmon eggs was slightly higher in angular than in round gravel. The roundness of Kenai River bed material fell within categories defined as subrounded or rounded, and no significant longitudinal variation was detected. Little variation in productivity consequently can be ascribed to this factor. Gravel permeability, which correlated strongly with salmon survival rates, was found to be negatively related to the percentage by volume of sediment passing a 0.833-mm sieve. In measuring the size distribution of Kenai River bed material, the percentage of material in size fractions finer than sand was not determined because, for statistical validity of the results, large volumes of material would have to be excavated and separated before the fine components could be sieved. However, the percentage of sediment of sand size or finer (<2 mm) was determined during the pebble-counting process. Using those percentages for comparison—a conservative approach because only part of the sediment finer than 2 mm would pass the 0.833-mm sieve—the bed material of the Kenai River is highly permeable and contains a relatively small proportion of fine sediment. The streams studied by McNeil and Ahnell (1964, fig. 7) contained bed material of which 5 and 20 percent was finer than 0.833

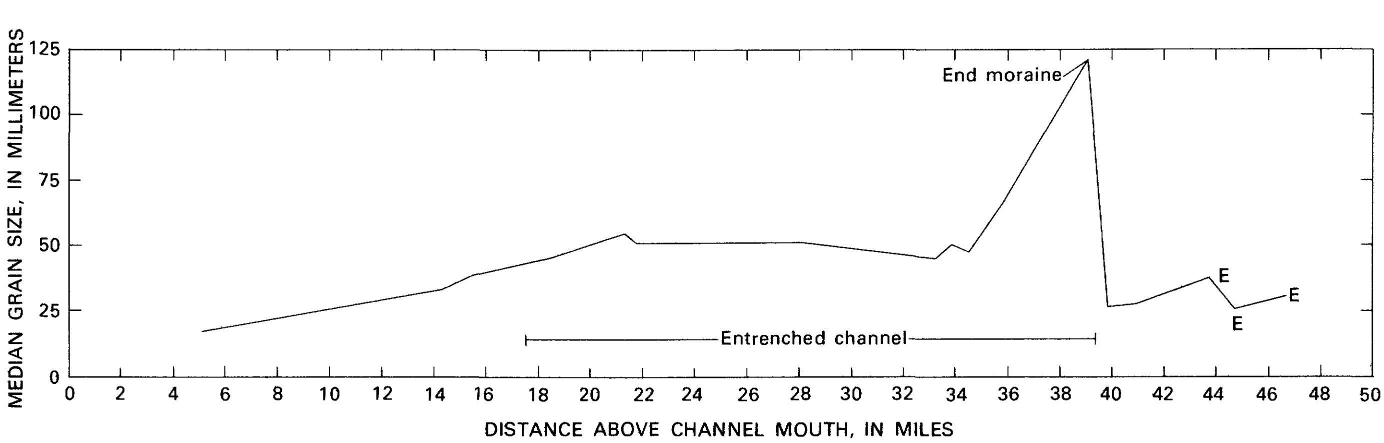

FIGURE 11.—Bed-material size against river miles. E, estimated.

mm. At all measurement sites the surficial bed material of the Kenai River contained less than 5 percent sediment finer than 2 mm. No great significance should be placed on this comparison because of the greater coarseness of the Kenai River bed material and the differences in sampling techniques. If it had been possible to measure samples of the Kenai River bed near the thalweg, the percentage of fine sediment would have been greater.

GRAVEL DUNES IN CHANNEL BELOW SKILAK LAKE

The reach containing crescentic gravel dunes that are visible on aerial photographs between the outlet of Skilak Lake and river mile 46.5 is among the most productive on the river in its ability to support heavy spawning of several types of salmon (see data summarized by U.S. Army Corps of Engineers, 1978, fig. 27). Whether the productivity relates to the bedforms or to the effects of suspended-sediment retention in Skilak Lake, leading to minimal deposition of fine sediment in this reach, is not known. Crescentic dunes are a highly unusual mode of transport in gravel-bed streams. Both the coarseness of the bed material composing the dunes in the Kenai River and the scale of the dune forms (fig. 12) are exceptional.

Active dunes of comparable and larger sizes occur in much larger rivers, such as the Mississippi and Missouri Rivers, but are associated with finer, generally sand size bed material. The dunes in the Mississippi River are as much as 22 ft in height and range in length from 100 to 3,000 ft (Lane and Eden, 1940). The dunes of the Kenai River likewise vary in size, as indicated by their submersed images on aerial photography. The largest dunes are at least 500 to 600 ft in length, approximately equivalent to the mean channel width in this reach. Smaller dunes are developed on the larger forms and are common in lengths of more than 50 ft. The maximum height of the dunes, estimated from water depths in the intervals between the shallow riffles that mark the crests of the forms, is at least 15 ft. The ratio of height to length for the Kenai River gravel dunes appears to be greater than that for the sand dunes measured in larger rivers.

Features of comparable coarseness and scale have been reported to result from an exceptional flood discharge, such as a surge from a dam failure (Scott and Gravlee, 1968, fig. 18), but in these unusual instances the features are not subsequently active. The gravel dunes of the Kenai River were examined with aerial photography taken in 1950, 1972, and 1977 to determine the degree of their activity. Where best developed, between river miles 48.5 and 46.5, the dunes show a surprising and remarkable similarity in position. Resolution is relatively poor on the 1950 photographs, but the positions of the major forms are clearly the same as those in 1972 and 1977. Striking comparisons of the 1972 and 1977 photographs show that even the small irregularities of dune morphology did not change in that interval, one that included a major flood

FIGURE 12.—Kenai River between approximate river miles 47.5 and 46.9. Crests of large crescentic gravel dunes appear just below water surface as darker areas. Flow is from bottom of photograph toward top. Scale 1:4,800 or 1 in. = 400 ft. Date: July 11, 1977. Photograph credit: U.S. Army Corps of Engineers.

discharge in 1974 (fig. 3). The dune forms, like the traveling bars of an incipiently meandering channel and nearly all other types of submersed dune forms, are the type of bedform that migrates progressively and changes position at least seasonally. The rate of movement of the Mississippi River dunes described above ranged from a few ft per day to as much as 81 ft per day (Lane and Eden, 1940). The historical stability of the Kenai River dunes indicates that, like the forms described by Scott and Gravlee (1968), they are the product of an exceptional flood event, one probably greatly in excess of any flood during the period of flow records.

The question of why the dune forms are confined to the 3.8 river miles downstream from Skilak Lake is not so easily answered. The presence of the dunes coincides almost exactly with the reach that appears "drowned"; that is, the channel shows evidence of having been formed at lower water-surface elevations. This part of the river presently functions in part as an extension of the lake—channel width is large and irregular; banks show little evidence of erosion. The most likely reason for the "drowned" channel is the presence of gravel in the form of the dunes, which have effectively plugged the reach. The cause of the flood that introduced the gravel and molded it into dunes is unknown, but, as noted, the event was of exceptional recurrence interval. The effect of wave action in introducing suspended sediment into the river at the outlet of Skilak Lake is described in the discussion of suspended sediment. Similarly, it is possible that a flood surge traversing the lake mobilized sufficient coarse sediment at the lake outlet to form the dunes and aggrade the channel to its present configuration.

ARMORING OF THE CHANNEL

Armoring is the process whereby finer sediment is progessively removed, leaving the coarsest material to armor the bed surface. It occurs when the high flows that transport the coarse material no longer occur, as happens when a reservoir is built upstream. In places where the change in flow regime is engineered, the armoring commonly involves only the surface of the bed, is one particle diameter in thickness, and is easily observable (Vanoni, 1975, p. 181-182). As the term is applied here, to the sedimentologic response to a long-term natural reduction in flow, the results are less obvious and do not appear as a pronounced size difference immediately below the bed surface.

The bed material within the entrenched channel (between river miles 39.4 and 17.6) has a size distribution in which a significant proportion of the particles is not erodible under the present flow regime, and the evidence of this condition includes sediment size and channel stability. The causes are threefold: the long-term decline in flow accompanying glacial recession, the reservoirlike effects of Skilak Lake, and, to an unknown extent, the presence of coarser underlying gravel than is present outside the entrenched reaches.

The size data in figure 11 are mainly from emersed bar surfaces; the average bed material in a cross section is likely to be coarser. The most visible feature of the armored reaches is the presence of large boulders, which protrude above the water surface at normal levels of summer flow (see fig. 4) and may exceed 13 ft in intermediate diameter. In other streams the size of the Kenai River, the bed material normally will be moved by discharges not greatly in excess of bankfull discharge. Field calculations of tractive force compared with known critical values (for example, Baker and Ritter, 1975, fig. 1) indicate that only discharges greatly in excess of bankfull or channel-forming discharge will transport the coarse fractions of the size distributions in the entrenched reaches. These calculations are not presented here because of the confidence limits applicable to the slope data and therefore to the values of tractive force. The general conclusion is believed to be valid.

It should not be concluded that no movement of coarse bed material occurs in the entrenched channel. Competence is sufficient to transport coarse sediment supplied from reaches upstream and from tributaries to the entrenched reaches. Both sources have lower flow competence, in the case of the upstream river because of a lesser slope. The basic gravel framework of the entrenched channel is, however, stable at bankfull flow.

As will be documented in the discussion of bank erosion, the entrenched channel has been generally stable since 1950. Over much of the entrenched channel no detectable erosion has occurred, within the limits of accuracy of the measurement techniques. This situation contrasts with that both upstream and downstream, where extensive amounts of bank erosion have occurred.

Excavation of the submersed bed material to determine the size gradation within the bed was not practical because of flow levels during the fieldwork in summer and early fall. The size gradation is probably slight compared with the armoring resulting from such engineered changes in flow as that seen in the channel downstream from a dam. The size difference may exist chiefly with respect to comparison of the size of bed material with that of the underlying outwash gravel. The important observation, however, concerns the competency of flood flows of a frequency that in nonarmored channels would readily move most sizes of particles present in the bed. In the Kenai River, only the most extreme floods would mobilize the bed material in the entrenched section of channel.

POSSIBLE EFFECTS OF ARMORING ON SALMON HABITAT

From spawning to the time the young salmon leave the interstices of the gravel, the oxygen supply is critical (see Phillips, 1974, p. 65-68). The initial shaping and sorting of the redd by the adult fish serves the dual purpose of increasing the flow rate within the gravel, through the irregularity of bed surface thus produced, and removing deposits of fine sediment from within the pores of the gravel. For the several months during which the young remain in the gravel, they are vulnerable to any renewed deposition of fine sediment. Even where dissolved-oxygen concentration is high, newly deposited sediment can act as a physical barrier to fry emergence.

Einstein (1968) studied the progressive clogging of spawning gravel in flume experiments and observed that silt particles filter slowly down through the pores without any systematic horizontal motion, settling on top of individual clasts and filling the pores from the bottom up. These observations show that the armoring of the channel has important implications for the productivity of the Kenai River in terms of its ability to support the spawning and rearing of salmon. If bed material is too coarse to be moved by a normal range of flow, as is the gravel in the entrenched channel, fine sediment will gradually accumulate within the pores of the gravel and reduce the permeability. Because the infiltrating fine sediment was observed to move only in a general vertical direction, lateral redistribution in the bed apparently will not occur. Thus, in an armored bed the clogging of the gravel pores is an irreversible process. Only the movement of the gravel framework, by either the spawning fish or an exceptional flood, will flush out the accumulating fine material.

Observations by personnel of the U.S. Fish and Wildlife Service (Wayne Pichon, oral commun, 1979) show that salmon, particularly king salmon, can construct redds in bed material as coarse as that in the armored channel. Study of spawning locations verifies that the armored reaches are the sites of active spawning (U.S. Army Corps of Engineers, 1978, fig. 27). Although salmon are capable of building redds in the material and thus cleansing it at a point, it seems likely that the productivity of a progressively silting reach would decline.

The historical rate of fine-sediment deposition in the gravel of the armored reach has not detectably reduced the permeability of the bed at the depth necessary for spawning and rearing. Before concluding that this will continue to be true, two factors should be considered. First, the rate of interstitial deposition will increase with any increase in suspended-sediment transport that may result from development or other man-induced change. Second, an exceptional flood competent to mobilize and cleanse the armored bed will not necessarily occur. The flood that emplaced the gravel dunes in the reach below Skilak Lake may have been competent to mobilize the bed material in the armored reach, but its magnitude and cause, as well as its age (other than pre-1950), are unknown. Similar floods are likely to be the result of geologic events, such as the breaching of landslide and glacial dams, and thus their probabilities are not predictable from a short series of annual flows.

The stability of the reach containing the gravel dunes indicates that the above conclusions apply to it as well. This at first seems unlikely because of the relatively finer bed material of which the dunes are composed. The dunes themselves, however, have dammed the channel and reduced the slope and thus the competence of a given discharge.

SURFICIAL DEPOSITS OF THE MODERN FLOOD PLAIN

A flood plain exists lateral to the nonentrenched sections of the Kenai River, but only small segments are found along the entrenched channel. Like the flood plains of the group of streams described by Wolman and Leopold (1957), the underlying material consists mainly of channel deposits. Only at the surface is there a distinct segregation of cohesive material within the size range of silt (0.004-0.625 mm) and clay (<0.004 mm). This layer of sediment deposited during overbank flow is as thick as 6 ft and is laced with roots that act as a strong binding agent. It is well developed in the interior of nonentrenched meander loops.

A "mat" of root-bound fine-grained sediment is a characteristic of northern rivers and, because of either the absence of permafrost or the presence of a thick active layer (depth of summer thaw in permafrost), is particularly well developed in subarctic streams. This layer serves the important function of stabilizing riverbanks by retarding the slumping that occurs in response to erosion of the underlying noncohesive channel deposits (Scott, 1978, p. 11). As the channel deposits are eroded, the cohesive layer may fold down to protect the bank from further erosion for a period as long as years. In such cases it has been likened by Russian observers of northern streams to a cloth draped over the edge of a table. The layer also acts to protect meander loops from cutoffs. Observations of arctic and subarctic streams by the writer indicate that cutoff is preceded by stripping of the surface cohesive layer.

This process may extend over several successive high flows in smaller streams, or it may occur entirely at the time of the flow causing the cutoff in larger streams.

Any cutting or removal of the surface layer where it occurs along the banks on the active flood plain of the Kenai River will create an increased potential for bank erosion. A boat slip without riprap, for example, and cut transverse to the flow direction creates a point of attack from which the cohesive layer can be stripped. Once the cohesive layer is lost, the underlying channel deposits are subject to rapid erosion that could lead to a meander cutoff.

SUSPENDED SEDIMENT

Sediment sufficiently fine grained to be transported in suspension affects the salmon habitat in a variety of direct and indirect ways (see Meehan, 1974, p. 5-7). As described previously, the main detrimental effect of fine sediment occurs consequent to deposition, through the reduction of gravel permeability during egg and fry development. Suspended sediment can be directly harmful to fish if concentrations are both high and persistant, but the requisite levels are not well defined. After a literature survey, Gibbons and Salo (1973, p. 6) concluded that prolonged exposure to sediment concentrations of 200–300 mg/L is lethal to fish, although other studies report higher levels. High concentrations may also detract from the esthetic and recreational values of a fishery. Because salmon are sight feeders, angling success is reduced and competition with species more tolerant of turbidity is increased with a significant rise in suspended-sediment concentration (Phillips, 1971, p. 65).

Subarctic alpine streams are characterized by a limited and specialized macroinvertebrate fauna that is adapted to the glacial melt-water environment (Hynes, 1970). It is logical to assume that even minor changes in habitat could affect the macroinvertebrate population and thus the fish fauna dependent on it for food (U.S. Army Corps of Engineers, 1978, p. 102).

Unfortunately, the effects on the salmon habitat of specific values of suspended-sediment concentration have not been established. The preferred environments and times for salmon spawning are clearly those with the least suspended sediment. Concentrations were observed to be "minor" (less than about 30-50 mg/L) during the spawning and incubation periods in the most stable producing areas for sockeye and pink salmon (Cooper, 1965, p. 6). Also, experiments comparing deposition rates from flows with 20 and 200 mg/L of suspended sediment indicate the "necessity for maintaining very low suspended sediment concentration in waters flowing over salmon spawning grounds" (Cooper, 1965, p. 61).

Values of suspended-sediment concentration in the Kenai River at Soldotna ranged as high as 151 mg/L in 24 samples collected from 1967 to 1977. The typical concentration during summer flow fell within the range 10-100 mg/L. A sample taken on September 9, 1977—the date of the peak discharge of record, 33,700 ft^3/s—yielded a concentration of 104 mg/L. The only comparable nearby stream, the Kasilof River, has a similar melt-water flow regime and likewise drains a large moraine-impounded lake, Tustumena Lake. The stream is, like the Kenai River, the site of important salmon runs. Suspended-sediment concentration in that stream, from 19 samples collected between 1953 and 1968, fell within the uncommonly narrow range 15-45 mg/L. This lower, narrower range can be ascribed mainly to the greater sediment-retention effect of Tustumena Lake, but it could be due in some part to lesser river use and bank development relative to the Kenai River.

Limited sampling from the Kenai River at Cooper Landing, at the outlet of Kenai Lake, suggests the presence of generally low concentrations of suspended sediment at that point. The concentrations in 24 samples taken between 1956 and 1974 at discharges from 420 to 19,100 ft^3/s ranged from 2 to 26 mg/L, except for one measurement of 72 mg/L. Concentration at the discharge of 19,100 ft^3/s was only 2 mg/L, sampled September 20, 1974—the day before the peak discharge of record that resulted from release of the glacial lake in the Snow River drainage (hydrograph in fig. 3).

All pre-1979 measurements from the Kenai River at Soldotna are plotted in figure 13. A sharp distinction in the relation between water discharge and sediment concentration is evident in the data representing discharges of January through May and those for the period June-September. A similar difference is evident in the sediment-transport curve for the station (not shown), in which water discharge is compared with sediment discharge rather than concentration. The groupings of data seen in figure 13 represent the sustained low-flow period of winter and spring and the prolonged period of high melt-water flow throughout the summer. They illustrate the important conclusion that concentrations can vary widely within each range of flow. The biota of the Kenai River consequently will be at greatest risk to increases in concentration due to construction activity during the low-flow period. An influx of sediment that caused little change in concentration levels during the summer could result in significant adverse impact during winter and spring.

Neither the base concentration levels nor the short-term variations in concentration are evident from the scattered historical samples shown in figure 13. To illustrate these aspects of the sediment system of the river and to provide a basis for future comparison, daily sampling at Soldotna was begun on August 23, 1979, and continued until December 5, 1979 (fig. 14). During this period, suspended-sediment concentration ranged from 1 to 52 mg/L, at mean daily discharges of 5,260 to 21,600 ft^3/s. In comparison with previous flow records (fig. 2), the mean discharge of 11,800 ft^3/s in September 1979 was typical. Unfortunately for purposes of comparison, flow later in the fall of 1979 was abnormally high. The mean discharge for October of 14,000 ft^3/s was more than 50 percent above the previous high mean discharge for the month, and the mean flow in November of 7,330 ft^3/s exceeded the previous high by a similar proportion.

Throughout the period of daily sampling, concentration levels based near or below 10 mg/L and generally increased above that level in the early stages of a rise in flow (fig. 14). An unexpected pattern of variations in concentration with flow is the seeming gradual rise in base concentration as discharge underwent its seasonal decline in late October and November. From base values of approximately 5 mg/L in early September and mid-October, the typical base concentration increased to about 10 mg/L in the period from late October to the end of data collection on December 5. Although the reason for this anomalous increase as flow declined is not known, one possible cause is wind-generated wave action on Skilak Lake.

Each daily rise in concentration of more than 5 mg/L accompanied a significant increase in discharge in comparison with the preceding day (fig. 14). The sharpest daily changes in concentration and discharge occurred early in both major rises in discharge during the measurement period. On days following the peak in concentration, discharge continued to increase, most notably during the rise in discharge that began on September 13. Concentration peaked on September 15 and then generally declined for the five subsequent days as discharge continued to increase.

Speculations concerning the sources of this suspended sediment are possible. The relation of water discharge and sediment concentration described in the preceding paragraph is designated as advanced (or leading) sediment concentration (Guy, 1970, p. 22); that is, the peak concentration precedes the peak of the water-discharge hydrograph, in this case markedly so. This relation is the most common and is consistent with transport of loose sediment by the first direct runoff. However, in the Kenai River at Soldotna the concentration is so advanced that the bulk of the sediment is clearly of local derivation, originating in the section of watershed downstream from Skilak Lake. This conclusion is expected, given the sediment-entrapping function of the lake, and narrows the sources of much of

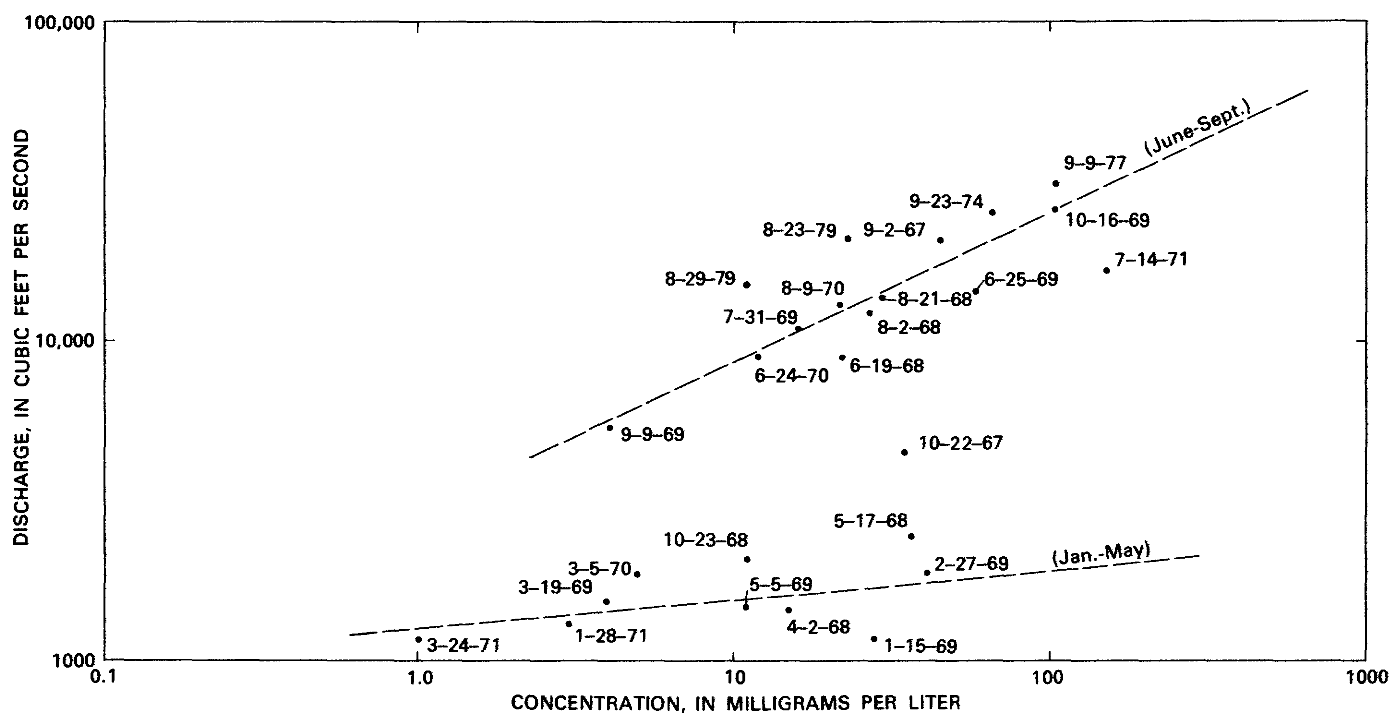

FIGURE 13.—Water discharge against suspended-sediment concentration, Kenai River at Soldotna. All pre-1979 data are shown.

the sediment to the Killey River basin and bank erosion along the Kenai River.

Scattered sampling of the tributaries entering the river downstream from Skilak Lake shows that suspended-sediment concentration is generally very low, especially in the subordinate storm-runoff peaks of middle and late summer. Snowmelt peaks are the dominant discharge events in the flow records of these lowland streams, and the runoff is greatly retarded—typical of marshy subarctic terrain. The Killey River is the exception: it drains a watershed that extends to nearly 6,000 ft in altitude (timberline is approximately 2,000 ft) and includes the Killey Glacier, an extension of the Harding Icefield. Runoff from the Killey River basin contributes to the early part of any rise in the Kenai River that occurs in response to a basinwide storm. Traveltime of flood waves from the headwaters is unknown, but it would be measured in hours as opposed to days for a flood wave from the Snow River drainage (fig. 3). Unfortunately, storm sediment concentrations of the Killey River are unknown. Observations indicate that they are relatively high. Two sets of aerial photographs (1950, 1977) of the Kenai-Killey confluence show a turbid plume, representing the unmixed contribution of the Killey River, extending several miles downstream in the Kenai River. Sequential aerial photography also indicates that the Killey River channel is actively eroding; a neck cutoff of a meander 1.5 mi upstream from the confluence occurred between 1950 and 1972.

The dispersion in concentration at a given discharge is mainly due to variations in natural sediment-producing processes. There is no increase in concentration over time evident in the limited data of figure 13 that can be ascribed to development or river use. This result may reflect the small number of samples taken at low flows. The effect of canal dredging and cleaning, which are probably accomplished mainly during low-flow periods, are limited in time and would have been sampled only by extreme change. Local residents report that episodes of abnormally high turbidity are caused by dredging of canals. This high turbidity prob-

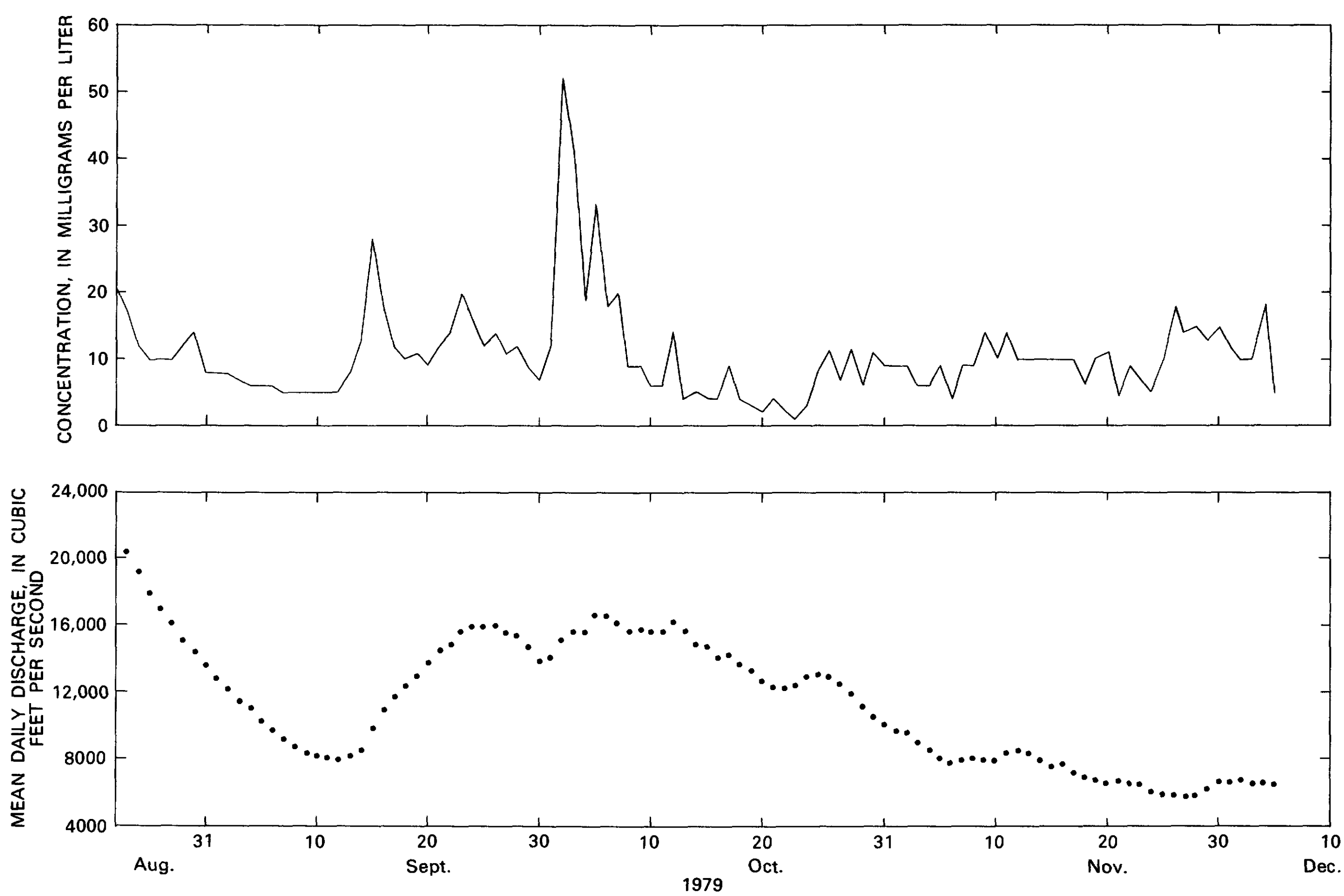

FIGURE 14.—Water discharge against suspended-sediment concentration, Kenai River at Soldotna, August 23 to December 5, 1979.

ably correlates with increased suspended-sediment concentration.

One cause of dispersion in concentration levels at a given discharge is wind action on Skilak Lake. The lake is at the foot of large icefields and is periodically swept by violent winds that have caused the deaths of more than 20 boaters. The association of wind action on the lake, high turbidity levels in the lake, and turbid flow in the downstream part of the Kenai River has been observed by S. H. Jones of the U.S. Geological Survey (written commun., 1979). These observations coincide with those of Smith (1978), who described sediment movement in a glacier-fed lake in Alberta in response to wind-generated currents. In addition to generating high turbidity throughout Skilak Lake, wind-induced waves may erode lake-bottom and shoreline sediment in the vicinity of the outlet. The entrained sediment may then be introduced into the river as part of the suspended-sediment load.

Size measurements of the suspended sediment from the Kenai River at Soldotna indicate that 38 to 71 percent falls within the size ranges of silt and clay. Comparison with data from other Alaskan streams, including those fed by glacial melt water and controlled by lakes, shows that size distribution to be typical. Turbidity measurements from the station are too few for comparison or generalization.

BANK EROSION

An unknown but probably significant amount of the suspended-sediment load in the Kenai River is presently derived from bank erosion. Future increases in suspended sediment thus will be caused by any type of development or river use that increases bank erosion. The historical rates at which banks have been eroded can indicate which sections of the river are likely to be the most vulnerable to future man-induced changes.

Bank-erosion rates were determined by comparing aerial photographs taken in 1950-51, 1972, and 1977 (table 3). Additionally, the 1977 photographs were compared with ground photographs of the present (1979) bank configuration in channel bends. These comparisons showed that since 1950 the entrenched section of the stream has been exceptionally stable. Elsewhere, erosion rates have been comparable with those to be expected in a river the size of the Kenai. There is an indication that a recent increase in bank erosion may be occurring in response to river-use practices.

METHODOLOGY

Amounts of erosion were measured by superimposing the projected image of one photograph on another of a differing date. If the projection is precise, the differences in bank position correspond to erosion and accretion of the channel in the interval between the sets of photography. For this study, projections were made with a Bausch & Lomb Zoom Transfer Scope. This technique permits immediate comparison of photographs of greatly differing scale—a distinct advantage over previous methods. Because the procedure is not described in the literature, it will be discussed here in detail.

TABLE 3.—*Aerial photography of the Kenai River downstream from Skilak Lake*

Date	Agency	Scale	Area covered
June, August 1950 June, August 1951	U.S. Geological Survey	1:36,000	Entire river
May 1965	U.S. Army Corps of Engineers	1:12,000	Downstream from Soldotna.
September 1972	U.S. Army Corps of Engineers	1:12,000	Upstream from Soldotna.
July 1977	U.S. Army Corps of Engineers	1:4,800	Entire river

Use of the Zoom Transfer Scope involves viewing one photograph directly through a binocular eyepiece. On that photograph is projected the image of a second photograph, with the scale of the projection continuously variable with a zoom control to as much as 14×. The image of the smaller scale photograph is projected on to the larger, and the illumination of either may be varied with a rheostat. In matching the images, it is useful to vary one of the illumination controls rapidly so that the two photographs are seen in alternating succession. Then, once the scale and position of the photographs have been correctly matched, channel changes will stand out with remarkable clarity.

The main obstacle to precise measurement of channel change is scale variation in the aerial photographs. On each photograph the scale changes with distance from the center, reflecting the vertical orientation of the camera. Consequently, on each pair of photographs it is necessary to match geographic features in the immediate vicinity of each bank segment as it is analyzed. Features useful in matching photographs of the Kenai River include individual trees, large boulders, roads, and houses. The need to match features on or near the bank segment being studied cannot be overemphasized. Generally, the scale variation was such that, if one bank was matched, the opposite bank of the stream would not be matched, even in reaches where no bank erosion had occurred.

MECHANICS OF BANK EROSION—LOW BANKS AND HIGH BANKS

Although permafrost is not present in significant amounts, the low banks bordering most of the nonentrenched parts of the Kenai River, and its flood plain where present, erode in a manner similar to the bank erosion of streams in permafrost areas (Scott, 1978, p. 10). Channel deposits erode, thereby undercutting the stabilizing surficial layer of cohesive sediment. All areas of relatively rapid bank erosion, with rates comparable to those of small and medium-sized rivers elsewhere (Wolman and Leopold, 1957, table 4), involve the low banks.

The low banks downstream from approximately river mile 14 are composed of cohesive, clay-rich sediment interbedded with less cohesive silt and sand, and locally with coarser sediment. Erosion progresses most rapidly in the sand and gravel layers and triggers bank failure by slumping. This bank material represents tidal and shallow marine deposition during the marine transgression near the close of the Naptowne Glaciation (table 1). Modern tidal deposition is occurring as far upstream as river mile 12, but the deposits now subject to erosion mainly represent the earlier interval of deposition.

The high banks are those extending well above the level of bankfull stage to heights as much as 70 ft. They occur along entrenched sections and locally along nonentrenched sections of the river. The banks are composed mainly of glacial-outwash gravel that is distinctly finer grained and more poorly sorted than the modern channel deposits. Most cut banks are covered with mature spruce and historically have been stable. Where the high banks are eroding, the slope is undercut at the base, and the vegetated surface is progressively unraveling. Trees and mats of vegetation slide into the river until the entire slope becomes composed of loose gravel at the angle of repose. The slope angle is nearly the same as that of the completely vegetated banks, showing that the history of the banks is one of erosion interrupted by a geologically recent interval of low erosion rates that has allowed the mantling and stabilizing of the slopes by vegetation. The period of high-bank stability may now be ending in response to increased river use, a possibility discussed below.

RATES OF BANK EROSION

The position of the high banks of the entrenched channel in 1977 was remarkably similar to their position in 1950-51. Rates of erosion less than 1 ft per year were the rule. At most sites there was no detectable change in bank position, within the limits of accuracy of photographic comparisons and with adjustments for differing flows levels shown on the photographs.

Unfortunately, this generalization does not apply to the entire river. Above river mile 39.4 and below river mile 17.6—the limits of the entrenched channel—are areas with low banks eroding at rates as high as 5 ft per year. Figures 15 and 16 illustrate the distribution of erosion within parts of these two sections of the river. Several observations on these figures are pertinent.

First, the eroding areas are local in distribution, and even in these less stable reaches, much of the bank has not been affected by measurable amounts of erosion. The positions of the rapidly eroding banks are not predictable from the configuration of the channel. This effect is not unusual and has been shown in some other rivers to be caused by a wandering thalweg. Composition of the banks is a chief control on erosion of the Kenai River banks, along with the correlative factor of bed-material size. For example, at river mile 40.4 (fig. 15) the flow impinges at a 90° angle on the right bank, yet only negligible erosion of that bank has occurred. This section of bank is part of a topographic lineament against which the north sides of meanders are deformed upstream from river mile 39.4 (fig. 1). Cut banks along the lineament reveal glacial till that is resistant to erosion because of its clay-rich matrix.

Second, erosion rates have been relatively constant during the period 1950-51 to 1977. This conclusion is based on the proportional amounts of erosion in subdivisions of this period. In the downstream area of high erosion rates (fig. 16), the amount of erosion between 1950 and 1965, a 15-year interval, is similar to or slightly greater than that between 1965 and 1977, a 12-year interval. Upstream (fig. 15), most of the erosion occurred between 1950 and 1972, with smaller amounts between 1972 and 1977. The intervals reflect the dates of the photographs.

Finally, the two sections of the river with the highest erosion rates coincide with those sections of the river having a tendency to anabranch. In each case the slope of the eroding reaches is controlled by a base level a short distance downstream. In the upstream reach the control is the Naptowne end moraine; in the downstream reach the control is sea level.

Tidal action extends upstream approximately as far as river mile 12 and affects the reach shown in figure 16. Jones (1969), in a study of the Kenai River estuary, measured tidal velocities at sections as far upstream as river mile 11.4, above the illustrated reach. The measurements revealed significant floodtide velocities at that point at a time of low streamflow and high tides (May, 1969). Bank erosion from upstream tidal flow is possible during such periods. The distribution of the re-

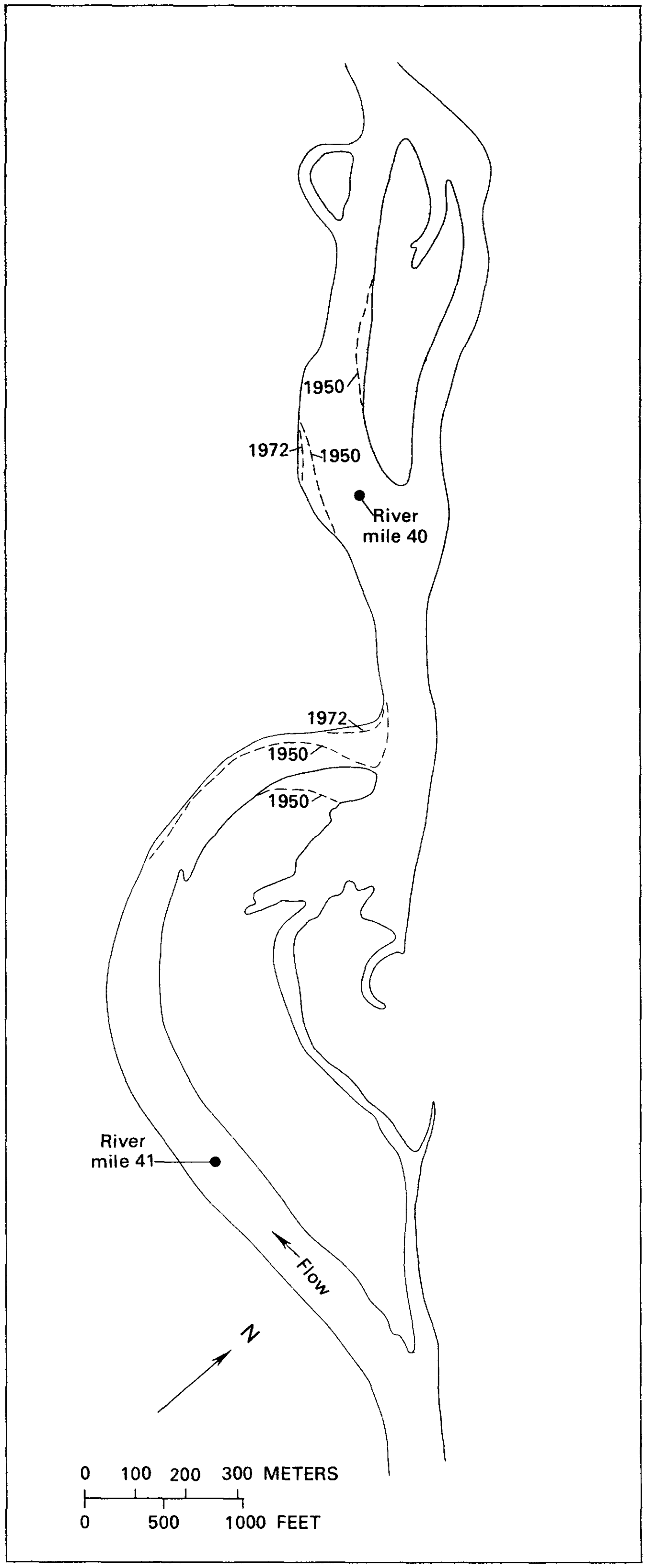

FIGURE 15.—Reach in upper section of the Kenai River, showing bank erosion rates. Solid line is bank position in 1977.

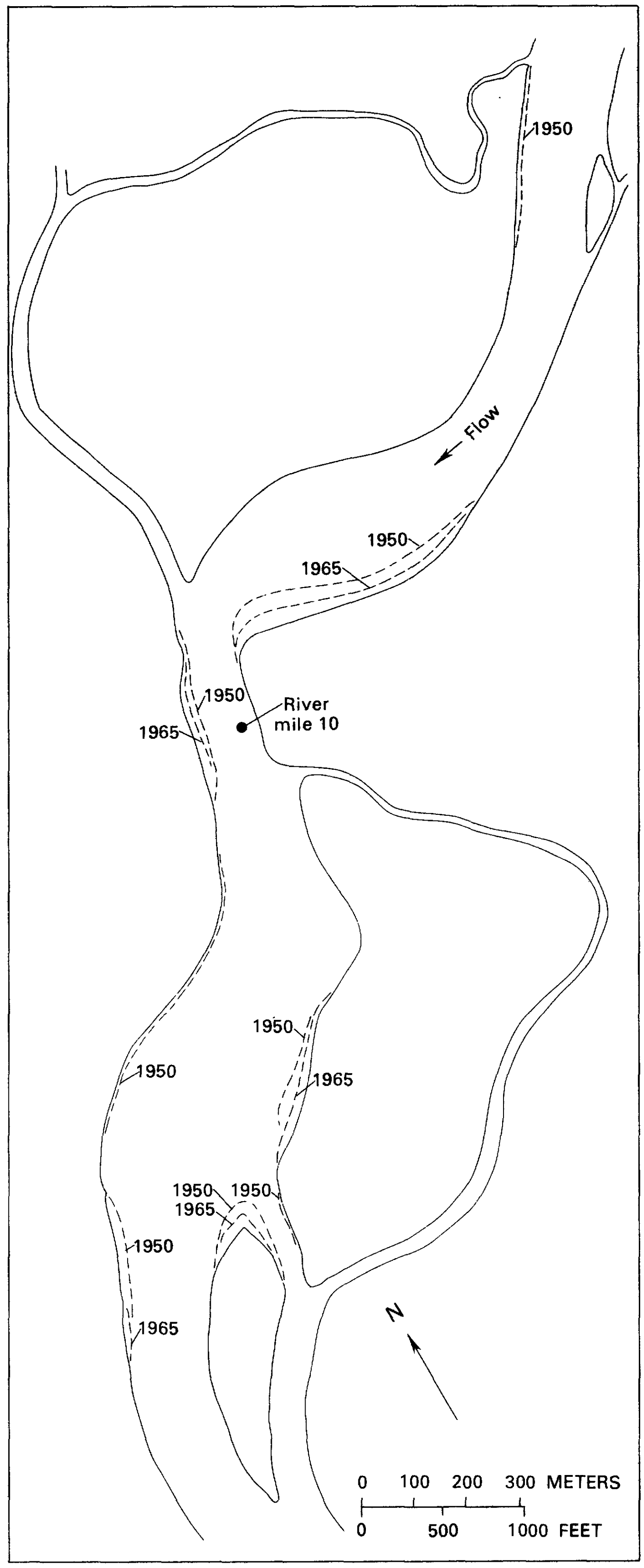

FIGURE 16.—Reach in lower section of the Kenai River, showing bank-erosion rates. Solid line is bank position in 1977.

corded erosion (fig. 16) indicates, however, that downstream flow is the main cause. The erosion of the head of the island at the bottom of figure 16 is an example, as is the erosion on the inner, upstream side of the bend immediately above river mile 10.

POSSIBLE RECENT INCREASE IN BANK EROSION

Although no obvious changes in bank-erosion rates could be determined in the period 1950-51 to 1977, there is evidence of recent change that possibly forecasts a period of more rapid erosion. The most noticeable change is the number of fresh slide scars on the high banks visible in the 1977 photographs. Figure 17 illustrates these scars on the high banks along the outside of meander 3-H. The features occur where a maturely vegetated bank is undercut and the bank surface slides off into the river. The amount of erosion in terms of distance of bank retreat has thus far been small. Nevertheless, if sliding continues and the entire lengths of meander cut banks become active, a serious erosion problem will result. Because of the heights of some banks (50-70 ft), small amounts of bank retreat will add large volumes of sediment to the stream.

To investigate this increase in erosion of the high banks, ground photographs were made of the inside of all meander bends and then compared with the 1977 aerial photography. The results suggest that the instability is of recent occurrence and is continuing and possibly increasing at the present time (1979). The evidence for this conclusion is based on the 1977 photographs, which are of larger scale (1:4,800) and consequently of greater resolution than any preceding photographs, as well as on a comparison of that photography with ground photographs. To establish the recent instability of the high banks without qualification, it may be necessary to compare the 1977 photography with a later set that is equivalent in scale and resolution.

There are several explanations for this apparent increase in slide scars on the high banks. The possibility that construction debris was dumped over the banks was excluded in most instances. Another possibility is that the increased deflection of flow into cut banks as a result of construction of groins, boat ramps, and bank-protection structures has thus far caused small amounts of erosion. The most obvious example is meander 1-P near Sterling, where the inside of the entrenched-meander bend is studded with 13 groins from 15 to 75 ft long (fig. 18). These groins create the potential for bank erosion of at least an equivalent distance on the opposite cut bank and the possibility of larger amounts once the stability of the bank is destroyed. The groins were constructed before 1972, and the opposite high bank is beginning to fail by slumping near the point opposite the largest groins.

Another explanation is a recent change in river use. Beginning approximately in 1974, it was discovered that the most efficient sport-fishing technique for king salmon consisted of "drifting"—the practice of trolling from a boat while floating downstream without power through a promising reach, and than using power to return to the head of the reach and repeat the maneuver. Fishing for most other species, such as silver salmon, has continued in large part from anchored boats. The practice of "drifting" for king salmon has resulted in a substantial increase in the use of high-horsepower sport boats and more intensive usage of the boats per man-day on the river. These effects are additive to the general increase in sport-fishing popularity (table 4). An assessment of this problem is beyond the scope of this report and should await conclusive study of the possible recent increase in erosion rates mentioned above. The potential for river-use practices as contributors to increased bank erosion is a significant one, however, and should be considered by planners whether an increase in erosion can be documented or not. Once the stabilizing vegetation on the high banks is lost, erosion can potentially accelerate, even if river use is subsequently controlled.

The effect of boat wakes on the banks is sufficient to initiate and cause continued erosion of the high banks without other significant changes. Observations along the cut bank of meander 3-H reveal that each wake runs up the loose gravel bank as much as 3 or 4 ft, eroding and entraining sediment and creating a zone of visibly turbid water at the edge of the stream. The bank is progressively undercut, and the slope profile is maintained by sediment from the upper sections of the bank. Where the bank is vegetated or formed of cohesive sediment, the resistance to boat-wake erosion is greater.

TABLE 4.—*King salmon taken by sport fishing in the Kenai River, 1974-79*

[Data from Alaska Department of Fish and Game. Annual catch is limited by State regulations]

Year	Early run (June)	Late run (July)	Total
1974	1,685	3,225	4,910
1975	615	2,355	2,970
1976	1,555	4,477	6,032
1977	2,173	5,148	7,321
1978	1,542	5,578	7,120
1979	3,661	4,634	8,295

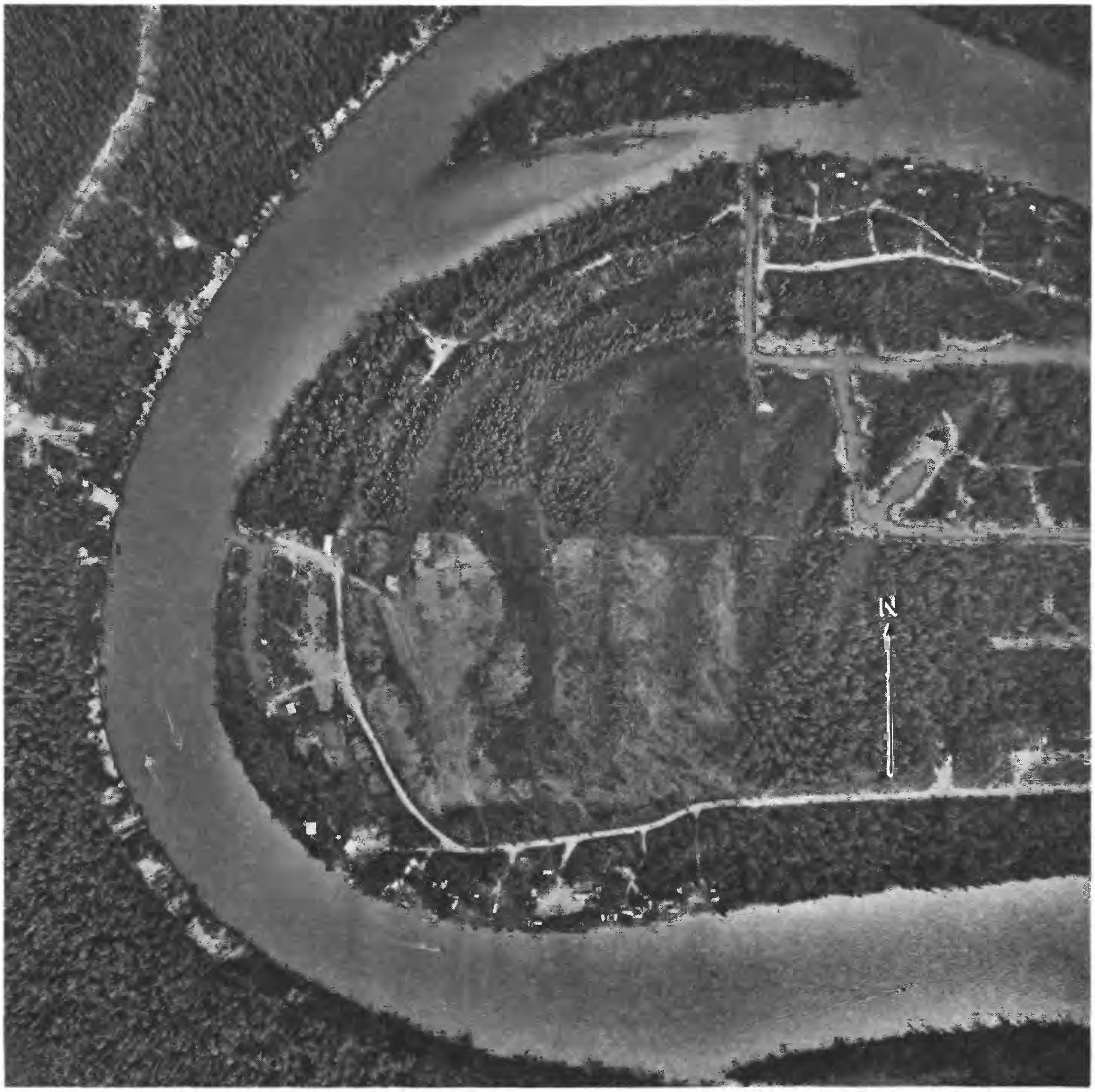

FIGURE 17.—Kenai River between approximate river miles 16.7 and 15.3. Note concave high bank with slide scars, and canal development and forest clearing on flood plain within meander loop. Wakes are caused by boats. Flow is from bottom of photograph to top. Scale, 1:4,800, or 1 in.= 400 ft. Date: July 9, 1977. Photograph credit: U.S. Army Corps of Engineers.

DEVELOPMENT AND THE KENAI RIVER CHANNEL

This part of the report discusses which sections of the river are most vulnerable to development and the types of development and impacts associated with each. Table 5 summarizes the channel characteristics and the sensitivity of each section of the stream to development. It will serve as background information on the channel for the discussion of development types that follows. For use by planners, this section is intended to be used in conjunction with the flood-hazard maps prepared by the U.S. Army Corps of Engineers (1967, 1973, 1975). The existing criteria for development permits are presented in the comprehensive report by the U.S. Army Corps of Engineers (1978, p. 16-52).

CONSEQUENCES OF DEVELOPMENT

Because the risks of development cannot be quantified, the definition of the hazards to the Kenai River salmon fishery must be subjective. The exact erosional response of the river's banks to certain types of development is unknown, although a significant response can be expected on the basis of our knowledge of river behavior. Nor can the increase in suspended-sediment transport that will result from increased bank erosion be stated with any degree of certainty. We know that suspended sediment will increase as bank erosion increases, and the studies cited in the section on suspended sediment indicate the potential for decline in the salmon fishery with increases in concentration only moderately above present levels. Conclusions regarding the range of concentration levels that may prove harmful will not, however, meet with agreement among those studying salmon habitats.

Additions to suspended sediment that will occur directly from construction activities should be distinguished from the more significant increases in concentration that can occur with the increased bank ero-

FIGURE 18.—Kenai River between approximate river miles 38.2 and 37.0. Flow is from right to left. Scale, 1:4,800, or 1 in.= 400 ft. Date: July 11, 1977. Photograph credit: U.S. Army Corps of Engineers.

sion triggered by some types of development. (This section deals with the latter type of hazard unless stated otherwise.) An additional potential cause of increased suspended-sediment transport is such upland land-use changes as logging, but these effects are excluded from the analysis. And possibly more significant than any effect of development is the potential adverse impact from river-use practices described in the previous section.

In determining what types of development to allow, planners are faced with two problems. The first problem involves the fact that, although a type of development may now be insignificant in its effects on the river, the cumulative effect of many such developments, combined with other actions in the future, may have an important negative effect. An example of such a situation, discussed below, is the excavation of boat slips in the entrenched section of the river. An approach to this general problem is to continue to monitor the productivity and sediment content of the stream as development progresses.

The second problem involves the fact that, because none of the risks associated with any of the development types can be quantified, cost-benefit analysis cannot be used directly. This, however, should not serve as a rationale for lack of decisions concerning development. This report defines the impacts of each common type of development, ranks them in order of risk, and indicates (table 5) how the impact will vary along the river.

Each development type can be assessed for its potential to cause channel change. The most dramatic change, and one that poses a short-term hazard to the stream by increasing erosion and suspended sediment, is the cutoff of a meander loop. A cutoff is a sudden diversion of the main channel that may set up a disequilibrium which causes substantial channel change extending beyond the vicinity of the diversion. Cutoffs consist of two types: loop or neck cutoffs, in which a meander loop tightens until flow cuts across the narrow neck; and chute cutoffs, in which flow cuts across a meander loop, generally one less tightly developed and one which may have incipient channels between ridges of point-bar deposits.

The first effect of a loop cutoff will be seen in the change of shape of adjacent meanders in response to the local change in slope. The extent of this change has been variously reported to be slight or to consist of

TABLE 5.—*Summary of channel characteristics pertinent to determining sensitivity of the Kenai River to development*

Segment of channel (river miles)	Pattern and degree of entrenchment	Underfit conditions	Degree of armoring	Rate of bank erosion under present regime (ft/yr)	Relative sensitivity to development
50.3 to 45.7	Meandering; slightly entrenched.	Channel appears "drowned"—formed at lower streambed elevations.	Partly armored (stable crescentric dunes).	1.0	Low
45.7 to 39.4	Meandering; free to migrate.	Channel is product of present flow regime.	None	5.0	High
39.4 to 34.8	Meandering; entrenched.	Underfit, especially below junction with Moose River.	Mainly armored	<1.0	Low
34.8 to 21.8	Sinuous to straight; entrenched within Soldotna terrace.	Most underfit section of entire river.	do	<1.0	Do.
21.8 to 17.6	Meandering; entrenched within Soldotna terrace.	Underfit	do	<1.0	Do.
17.6 to 13.4	Meandering; Partially entrenched, but meanders are migrating.	Slightly underfit	Parts may be slightly armored.	2.0	High
13.4 to 9.0	Sinuous and anabranching.	Channel is product of present flow regime.	None	5.0	Do.
9.0 to mouth	Meandering in tidal regime; channel is free to migrate.	Channel is mainly product of present flow regime.	do	2.0	Moderate

channel realinement extending for miles beyond the site of the cutoff. Case histories of cutoffs in streams similar to the Kenai River are not useful in forecasting the likely effects. A loop cutoff of an entrenched subarctic stream—the Pembina River in Alberta—was described by Crickmay (1960), but little bank erosion outside the point of cutoff apparently occurred because the stream, unlike the Kenai River, was entrenched in resistant bedrock. Loop cutoffs on the White River in Indiana resulted in rapid growth of adjoining meanders, but the effect did not extend very far upstream or downstream (Brice, 1973, p. 191). In a new meander formed after a chute cutoff on the Des Moines River, erosion rates were initially high and then decreased as the equilibrium position approximated by the meander belt was approached (Handy, 1972). A contrasting result was described by Konditerova and Ivanov (1969), who documented a pattern of change in the Irtysh River, a tributary of the Ob River in Siberia, in which changes in a single "key" meander controlled the deformation of a long sequence of meanders. Perhaps the most comprehensive study of the effects of cutoffs is that by Brice (1980), who has compiled case histories on approximately 60 sites where artificial cutoffs have been made. In most places the results were slight, but in a few there were drastic effects. The reasons for this differential response are not yet known.

Probably the greatest long-term hazard to the stream is the loss of stability of the high banks. Once the vegetative cover of the banks is lost, erosion rates and sediment loads could increase rapidly to levels endangering the productivity of the river. After the process begins, the only means of restoring the stability of these banks could be a costly engineering solution. The possible effects of river use on the high banks were discussed in the section on bank erosion. A type of development that could have a similar effect is the building of groins and boat ramps on the convex banks of meanders. Some loss of high-bank stability could also result from a meander cutoff on a nonentrenched part of the stream.

CANALS

Where the channel is not entrenched, the interior of several meander loops has been developed by means of canals bulldozed within the active flood plain for the purpose of providing waterfront access to trailer sites and homesites. This unusual form of development is possible only because of the sustained high flow that keeps the water level in the canals within a restricted range throughout most of middle and late summer. The most extensive canal developments occur within meanders 3-H and 1-H (figs. 17 and 19, respectively).

The unriprapped canals in the interior of meander loops are of concern to the stability of the river. The canals create a point of attack for flood flows to cut through and peel away the surficial layer and erode the underlying channel deposits. Once a channel is formed in the underlying gravel, the potential is for a cutoff and a diversion of the entire channel through that point in the neck of the meander.

Meander cutoffs have occurred on the Kenai River, probably within historical time, although none has occurred within the post-1950 period documented by aerial photography. The bend labeled meander "1-J" may have been a fully developed meander, now cut off, the previous course of which is in part marked by a small residual channel. Meander loop 1-L (fig. 15) is a meander probably in the process of a gradual chute cutoff.

The areas at risk from a meander cutoff are those where the river channel is not entrenched and the level of the interior surface of the meander loop is below the level of the Intermediate Regional Flood—that which will recur once in 100 years on the average but which could occur in any given year. The risk of a cutoff is associated with lesser floods, but the frequency of flows or the depth of flow on the flood plain with which the risk is associated cannot be accurately stated.

In the upstream part of the river the areas at greatest risk of cutoff potentially triggered by unriprapped canal development include the meander loops in the reach that extends from river mile 45.7 to river mile 39.4. Below this section of channel the river is fully entrenched, and upstream to the mouth of Skilak Lake the meanders are stable, and the normal pattern of pools and riffles are replaced by gravel dunes.

In the downstream part of the river the area at risk from channel changes initiated by canals extends from river mile 17.6 to river mile 9.0. The channel upstream from river mile 17.6 is entrenched, and that downstream from approximately river mile 9 is relatively stable within the tidal regime. This section of the river includes the area of single greatest risk, meander 3-H. Here the stream is partly entrenched—the interior of the meander loop is active flood plain; the outside high bank is 40 to 45 ft in height. This bend is the tightest of any meander on the river, and the interior of the loop has been subject to canal development and forest clearing (fig. 17). The consequences of a loop cutoff of meander 3-H could be significant. Much of the area within downstream loop 3-I would potentially be subject to erosion as the channel adjusted to the postcutoff configuration. There is little impediment to a major realinement of the stream at this point. The high bank on the downstream side of meander 3-H is actively eroding; vegetative cover has been lost, and the bank is composed of relatively fine grained glaciofluvial sediment.

The area upstream from meander 3-I, the apex of which is the tight bend known as Big Eddy, is subject to periodic ice-jam flooding. The potential for channel cutting through the neck of meander 3-H is consequently increased. Ice scars in spruce trees growing on the interior-meander flood plain extend to heights of approximately 20 ft. Flooding and erosion risks associated with ice jams are present on the entire river, of course, but they are pronounced in this place.

GROINS AND BOAT RAMPS

Groins are structures placed at approximately a right angle to the bank, commonly for the purpose of preventing bank erosion. Along the Kenai River the structures are emplaced most commonly to provide docking facilities and a protected area for boat mooring. The coarseness of the bed material allows it to be formed into groins that are sufficiently stable to remain for years with the addition of riprap on the point and upstream side. The riprap may consist of rock- or concrete-filled drums, iron bars and cable, tires linked with chain, or dumped scrap metal. Without minimally maintained riprap, the groins and boat ramps are observed on the sequential aerial photographs to become blunted over a period of years as the material is slowly eroded.

The greatest development of groins is found on meander 1-P (fig. 13), as described in the section on bank erosion. They are mainly confined to the entrenched section of the channel, where they are the alternative to canals and boat slips because of the impracticality of excavation in the high banks.

Characteristic of a groin is the formation of an eddy downstream from its tip and a resulting deflection of flow that can erode the bank. The problem can be

FIGURE 19.—Kenai River between approximate river miles 44.8 and 42.9. Interior of meander loop has been developed with canals. Note natural channels across neck of meander; one channel has been partly excavated to form a canal. The Killey River enters from bottom of photograph. Flow direction is from right to left. Scale, 1:12,000, or 1 in.= 1,000 ft. Date: September 24, 1972. Photograph credit: U.S. Army Corps of Engineers.

minimized by emplacing the groin at a slight upstream angle. This type of bank scour associated with groins and boat ramps on the Kenai River is not normally a problem because of the coarse bed material.

The most obvious deleterious result of groin and ramp construction is the potential for displacement of the channel toward the opposite bank a distance equivalent to the length of the structure. This result has yet to occur at meander 1-P because the bank on the outside of the meander bend was stabilized by vegetation at the time of construction. At present (1979) the bank is beginning to fail by undercutting and slumping, a process that can be expected to increase in future years if the groins are maintained with the addition of riprap.

If the distance of channel displacement was confined to the length of the structures, a cost-benefit analysis of their construction would be possible. Unfortunately, once the stabilizing vegetation on the bank is lost, the erosion potential is much greater, and it is possible for a cycle of increased erosion over a period of years to begin.

EXCAVATED BOAT SLIPS

Boat slips excavated in the channel bank are probably the most common type of development along the Kenai River. In the past the excavated material has been dumped to form a small protective groin on the upstream side of the slip or just pushed into the channel. Both methods of disposal, however, are presently contrary to the conditions attached to a construction permit (U.S. Army Corps of Engineers, 1978, p. 43). The slips and the canal systems are excavated and cleaned, most commonly during the low-flow period.

The potential for harmful effects of unriprapped boat slips varies with location. Where excavated on the upstream side of a meander loop in the nonentrenched part of the stream, a single boat slip can pose a hazard by creating a point of attack for flood flows. Meander 1-H is a bend that would become more vulnerable to cutoff through the construction of slips on the upstream side, especially at the locations of natural channels visible in figure 19. Where slips are excavated at most locations on the entrenched part of the stream (table 5), the individual hazard will be slight, but each may form part of a cumulative effect. The need for riprap will also vary greatly with location. Where excavation is in the coarse channel deposits characteristic of the entrenched and partly armored sections of the river, the need for lining by even coarser material will be slight at most locations. Riprap will be advisable at most sites outside the entrenched channel.

There are other considerations illustrating the complexity of the impact of boat slips. Excavated boat slips are a type of development that is not necessary for recreational use of the river. For most owners of riverfront property, a slip can be viewed as a matter of convenience; small boats can be drawn up on the bank at any place where the bank height is low enough to make a slip feasible. Excavated slips, however, may encourage the use of large, high-horsepower boats of the sizes that may be contributing, disproportionate to their numbers, to the possible increase in bank erosion discussed previously. With unlimited river use, the granting of permits for boat slips could logically, therefore, be assessed for the potential additional effect of encouraging larger boats.

BANK-PROTECTION STRUCTURES

A variety of measures have been employed to support and protect homes constructed on the banks of the Kenai River. They include concrete walls, gravel berms, earthen embankments, piles driven into the bank, and chained tires. The purpose is commonly multifold: to provide docks, to provide foundations for structures, porch and patio areas, or to expand usable lot size, as well as acting as revetments to provide protection from bank erosion.

The effects on the stream channel of most such bank modifications will be slight as long as the original bank profile is not greatly changed. Loss of channel capacity and concentration of flow toward the opposite bank, leading to erosion of that bank, are possible if the structures are sufficiently extensive and of sufficient height to function locally as flood levees. Indirect effects, related to excavation of gravel and removal of the cohesive surface to supply fill for berms and levees, are also possible.

GRAVEL MINING AND COMMERCIAL DEVELOPMENTS

At several locations visible on the 1977 aerial photographs it appears that the banks have been mined for aggregate. The largest of these sites is on the north bank of the Kenai River, approximately 0.2 miles upstream from the junction of the Moose River. The impacts of gravel mining on stream channels have been described previously (for example, Scott, 1973; Bull and Scott, 1974) and need not be elaborated here. The hazards are clear, and, because of abundant sand and gravel deposits throughout the area, little rationale presently exists for permitting mining of the Kenai River banks. In addition to channel diversion and bank erosion, there is risk of dumping of the unmarketable fine-grained sediment fractions into the river.

Operators of many small fishing resorts have modified the banks to provide ramp access to the stream as well as convenient parking. At a few sites large volumes of gravel have been displaced, most of which has been used for fill. At a few resorts developed on higher banks, large volumes of gravel apparently have been pushed into the channel and subsequently transported by the stream. In some cases the gravel ramps extending into the stream are periodically maintained with newly excavated gravel. The impacts of these commercial developments, whether they involve extending or cutting the natural bank, will correspond to those previously discussed for groins, boat ramps, and slips.

CONCLUSIONS

Suspended-sediment concentrations in the Kenai River are naturally low because of sediment retention in upstream lakes; levels known from other streams to be harmful to salmon habitat are reached only rarely. More frequent elevated concentrations may result from increase in development of the types now present along the navigable channel of the river. These types of development are listed in the preceding section in the order of their magnitude of impact on the sediment system of the stream.

Rates of bank erosion since 1950-51 show that sections of the river differ greatly in their sensitivity to development, as indicated in table 5. Throughout the central section of the river (between river miles 39.4 and 17.6) the channel is entrenched, partly armored, and has undergone rates of bank erosion that are very low to undetectable. Upstream and downstream from this section the bank erosion rates are more typical of proglacial streams—as high as 5 ft per year. Two additional sections of channel are exceptions to this pattern: the initial 3.8 river miles of channel below Skilak Lake are highly stable because of the presence of large gravel dunes emplaced by a pre-1950 flood surge; also, the downstream 9.0 river miles of channel are moderately stable because of the dominance of the tidal regime.

Development along the navigable channel will affect the sediment system of the stream in several ways. Construction may increase suspended-sediment concentration temporarily, with the greatest potential for harmful impact between January and May, as indicated by the relation between discharge and concentration for that period. Development can increase bank erosion, and thus the suspended-sediment concentration, over the longer term by causing cutoff of meander loops, loss of stabilizing vegetation on banks, and loss of the cohesive surface layer of flood-plain sediment.

Throughout this report, emphasis has been placed on the potential for increased suspended-sediment transport because that is the first general effect of development which is likely to be harmful to the physical stream system. The effect on salmon habitat occurs mainly through deposition of fine sediment in the pores of the streambed gravel in reaches used for spawning and rearing. There is additional concern for habitat conditions throughout the entrenched and partly armored section of channel. Without the cleansing action of flood flows competent to mobilize the coarser bed material of those reaches, increased transport of fine sediment will result in deleterious rates of deposition within the bed. In contrast with normal reaches, flow magnitudes competent to move the bed material of the armored reaches are greatly in excess of bankfull discharge and may not recur at the frequencies necessary to maintain a viable fishery if suspended-sediment transport increases.

Bank-erosion rates have been generally constant since 1950-51. The high cut banks present in entrenched and partially entrenched sections of channel have been mainly vegetated and stable through the same period. Loss of stability of the high banks is of special concern because of the potential for large, long-term contributions to the sediment load of the river. Ground photography in 1979 suggests that the high banks have locally begun to erode more rapidly, although verification of this possibility must await future study. A likely contributing cause of such erosion is increased intensity of river use and a recent change in sport-fishing technique.

The Kenai River salmon fishery is a major component of the economic base of the Kenai Peninsula. It justifies continued concern for changes in the sediment system of the stream, in response to channel and flood-plain development as well as trends in land use and other changes within the watershed. This can be best accomplished by monitoring the suspended-sediment concentration and the stability of the high banks.

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