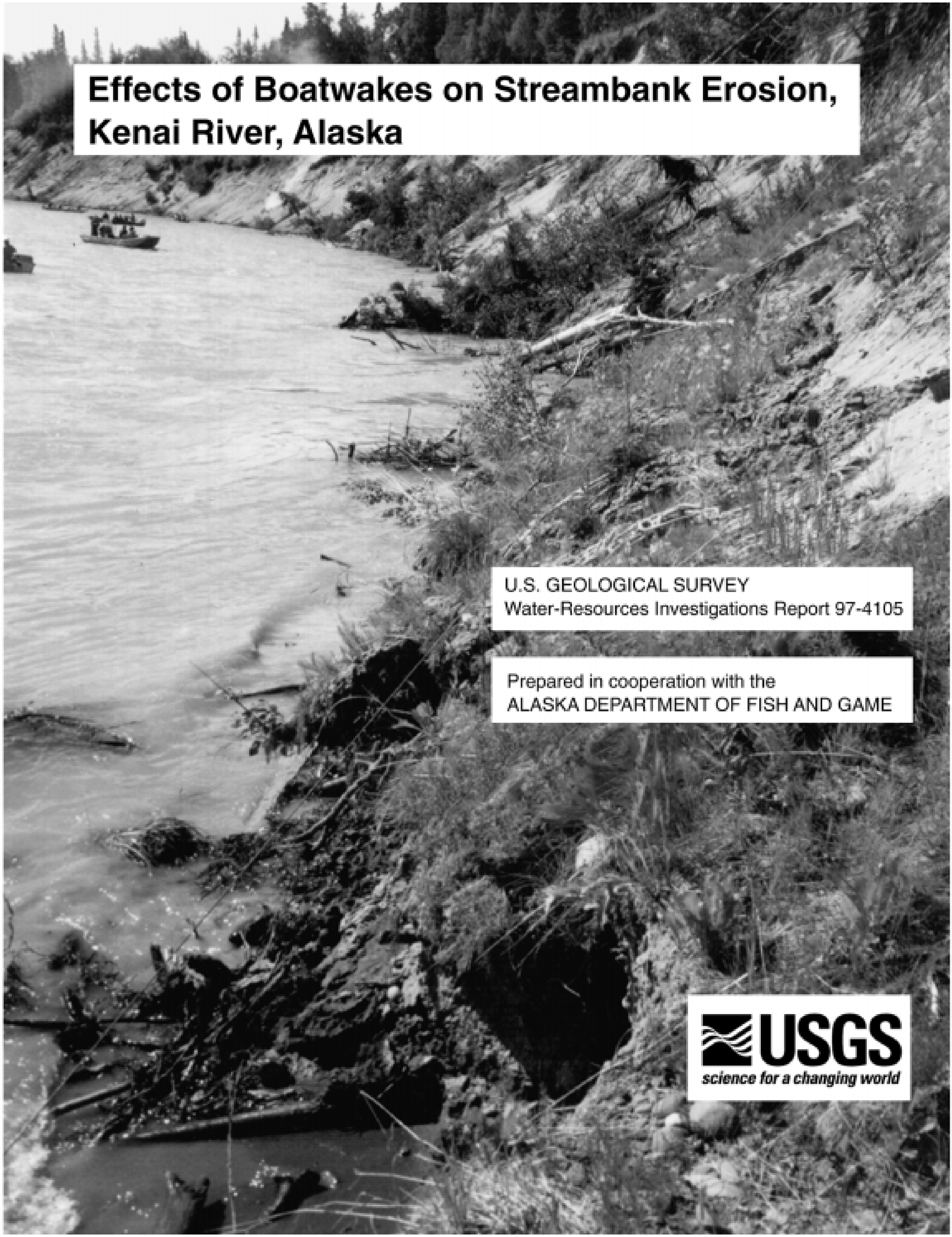
Effects of Boatwakes on Streambank Erosion, Kenai River, Alaska



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97-4105

Prepared in cooperation with the
ALASKA DEPARTMENT OF FISH AND GAME

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Cover: Boatwakes striking streambank along the outside of a meander bend across from RW's Campground, near river mile 16 of the Kenai River. Boats are upstream.
(Photograph courtesy of Aaron H. Morse, July 20, 1996.)

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By Joseph M. Dorava and Gayle W. Moore

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CONVERSION FACTORS

Multiply	by	To obtain
inch	25.4	millimeter
foot	0.3048	meter
yard	0.9144	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
foot per second	0.3048	meter per second
foot per second, squared	0.3048	meter per second, squared
foot per year	0.3048	meter per year
cubic foot per second	0.02832	cubic meter per second
foot pound per foot	4.448	Newton meter per meter
foot pound per square foot per day	14.593	Newton meter per meter squared per day
pound (avoirdupois)	0.4536	kilogram
pound per square foot	4.882	kilogram per square meter
pound per cubic foot	16.018	kilogram per cubic meter

Effects of Boatwakes on Streambank Erosion, Kenai River, Alaska

By Joseph M. Dorava and Gayle W. Moore[1]

ABSTRACT

The Kenai River in southcentral Alaska is an economically important salmon river generating as much as $78 million annually in direct benefits. Resource-management agencies are concerned that increased sedimentation and loss of streamside cover associated with accelerated erosion rates caused by boat activity may threaten salmon returns to the river. Bank loss and boat activity were characterized during 1996 along 67 miles of the Kenai River, including a segment of the river several miles long where boat activity is restricted to non-motorized uses. Bank loss in the non-motorized segment of the river was about 75 percent less than that observed in the highest boat-use area of the river and 33 percent less than that observed in the lowest boat-use area of the river.

Dates of peak boat activity coincided closely with chinook salmon returns to the Kenai River and with peaks in measured bank erosion. The boat activity period began in late May, peaked on weekend days in mid-July, and declined in early August. Observed boat traffic on the Kenai River included boats from 10 to 26 feet in length that transported 1 to 8 passengers. The most commonly observed boats were between 16 and 20 feet long and carried 4 or 5 passengers. The number of boats operated by commercial fishing guides represented 40 percent of the boats counted by the Alaska Department of Natural Resources, 55 percent of the boats counted by the Alaska Department of Fish and Game, and 57 percent of those recorded by observers during this study. The maximum boat activity and the maximum bank loss were measured at the RW's Campground study site about 16 river miles upstream from the mouth of the Kenai River. Between July 12 and September 10, 1996, more than 20,100 boats traveled by this site and the streambank along the inside of the meander bend was undercut to a depth of 45 inches at one measuring point. Boat activity and bank loss were greatest in areas of the river between about river miles 9 and 18 and river miles 39 and 46. These two segments of the river are popular residential and fishing areas and have banks composed of non-cohesive soils. In addition, a meandering, un-armored channel makes the banks along these two segments susceptible to erosion.

During 1996, bank loss on the Kenai River occurred primarily during about 60 days in mid-summer when both streamflow and boat activity were at their annual maximums. Streamflow in the Kenai River was generally about 25 to 35 percent below normal during the study period, except for a short period in early August when the rapid release of water stored by a glacier in the headwaters of Snow River increased streamflow above normal rates. Boatwakes contributed about 80 percent of the total energy dissipated against the banks of the study sites during the peak flow and peak boat activity period. At the RW's Campground and the Kenai Keys study sites, water was adjacent to the vegetated riverbanks only for about 60 days during 1996. During this 60-day period, boatwakes accounted for 97 and 94 percent of the energy dissipated against the streambanks at these two sites respectively. At the middle river study site in Soldotna, boatwakes accounted for about 20 percent of the energy dissipated against the banks between June 24 and September 24. Large semi-circular embayments cut into the

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bank along the inside of meander bends at the RW's Campground and Skilak Lake study sites indicate that the wake-induced erosion may have been prevalent for some time.

Several different types of bank-protection measures were evaluated along the Kenai River for their ability to reduce or eliminate bank erosion. These include complex engineered systems of coconut-fiber biodegradable logs attached to the bank with live willow sprouts and covered with elevated walkways, simple series of spruce trees cut down and cabled to the bank, rock riprap piled against the bank, and vertical wooden retaining walls. With the exception of one site where the cabled spruce trees were washed away during the study and the bank eroded considerably, no substantial erosion was visible near the protection systems investigated. These sites include additional ones where cabled spruce trees withstood substantial flooding while protecting the bank from erosion.

INTRODUCTION

The Kenai River (fig. 1) is Alaska's most popular salmon sport fishery and contributes as much as $78 million in direct economic benefit to the local economy annually (Liepitz, 1994). Elsewhere in the Pacific Northwest, the erosion and sedimentation process has been recognized as one of the leading causes of salmon population declines (Beschta, 1989; Bjorn, 1969; Meehan, 1974; Meehan and Swanston, 1977). In a stream the size and type of the Kenai River, increased suspended-sediment transport will be the first general human effect that has the potential to be deleterious to the physical stream system (Scott, 1982). Fish habitat provided by streamside vegetation, overhanging banks, and appropriately sized substrate can be altered or destroyed by accelerated rates of bank erosion. Recently, residents, visitors, and fishermen on the river have observed increases in the rate of streambank loss in areas of heavy boat activity, indicating to them that the two processes may be linked.

Purpose and Scope

Because of the economic importance of the Kenai River fishery, the Alaska Department of Fish and Game (ADF&G) and other resource management organizations are interested in quantifying the present rate of erosion along the river and estimating the amount of streambank erosion caused by boatwakes. In August 1995, the U.S. Geological Survey and the ADF&G began a cooperative water-resources project to study the effects of boatwakes on different types of streambanks. The study results described in this report will be used by the ADF&G to help in the assessment of design alternatives and permitting of streambank protection and restoration projects.

The specific objectives of the study were to: (1) estimate the amount of streambank erosion on the Kenai River during 1996 that was caused by boatwakes and (2) evaluate the ability of streambank protection measures to reduce erosion. These objectives were accomplished by (1) correlating boat activity and bank-loss measurements and (2) evaluating the results of an experiment in which boat-operating conditions were controlled.

Acknowledgments

Appreciation is expressed to Mr. William Wirins and Mr. Will Josey who greatly assisted this project by allowing repeated access to their Kenai River properties for instrument installation and data collection. The project was funded in part by a grant from the National Oceanic and Atmospheric Administration, Award NA56FZ0511, provided to the ADF&G through the National Marine Fisheries Service for the protection and restoration of salmon habitat on the Kenai River.

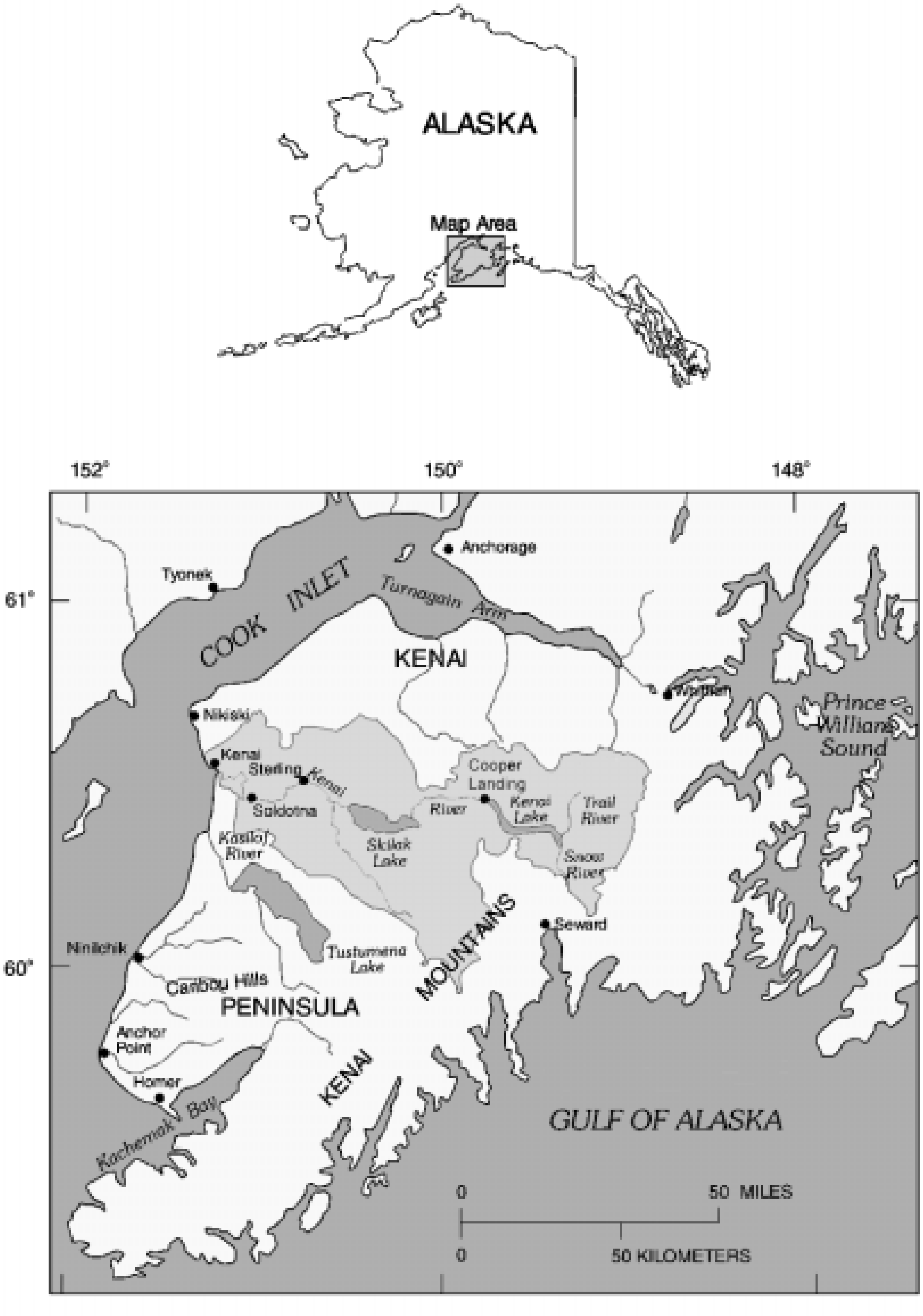


Figure 1. Kenai River watershed on the Kenai Peninsula, Alaska.

STREAMBANK EROSION

Excessive streambank erosion is a significant problem in many areas of the United States (Koisch, 1969). Many problems—such as increased turbidity, reductions in channel depth, and loss of streamside vegetation—arise as a result of excessive streambank erosion (Smith and Patrick, 1979; Stern and Stern, 1980; Yousef, 1974). Streambank erosion is, however, a natural process and necessary to the health of fish producing systems providing spawning gravels and stream morphology necessary to maintain all life stages. Many factors—such as climate, geology, and land use—control the rate at which a stream will erode its banks. When streambank erosion is accelerated above normal rates, controversy often develops about the cause of the increased erosion and how best to mitigate it.

Along the Kenai River in southcentral Alaska, bank erosion has been the primary topic of many investigations (Barrick, 1985; Inghram, 1985; Reckendorf, 1989; Reckendorf and Saele, 1991; and Scott, 1982). The first quantitative information about average erosion rates on the Kenai River, which ranged from less than 1 to as much as 5 feet per year during the period 1950-77, was provided by an investigation of changes in streambank position over time determined from aerial photography (Scott, 1982). This initial identification of the average erosion rates and the relative sensitivity of different segments of the river to streamside development provided the necessary background for many of the subsequent erosion studies, including this investigation of the effects of boatwakes on streambank erosion. When comparing this study with that of Scott (1982) and of other previous erosion investigators on the Kenai River, the results must be evaluated in terms of the methods used (Hooke, 1980). Results from large areal evaluations of erosion—such as those based on map or aerial photographs—may indicate greatly different rates of erosion (Hooke, 1980) and will be less detailed than site-specific investigations such as the erosion-pin study described in this report.

The rate of erosion at a specific streambank is controlled by numerous natural properties of the river environment, which can vary over time and along the river. These properties include the depth, velocity, approach angle, and sediment content of the river; the type and density of vegetation; the height and slope of the banks; the soil type; and the size of particles making up the potentially eroded material. The roles of some of these properties are described generally for the Kenai River in this report but are explained in greater detail for all rivers by Leopold and Maddock (1953) and Osterkamp and others (1983).

A history of extensive glaciation in the Kenai River watershed produced a river channel that is underfit in many places. This underfit condition means that the river is small relative to the size of the valley in which it flows. In addition, much of the present river channel is armored with large coarse-grained material that is more resistant to motion than materials in a river channel that would have formed without the history of extensive glaciation. Glaciers currently occupy about 10 percent of the Kenai River watershed and influence streambank erosion by producing large seasonal streamflow fluctuations. Breakouts of glacier-dammed lakes in the Kenai Mountains also periodically produce outburst floods from the release of water stored in them (Post and Mayo, 1971). These outburst floods greatly alter streamflow and can initiate or accelerate bank erosion.

Because much of the Kenai River meanders through a wooded or entrenched valley, wind-generated waves have limited opportunities to generate substantial erosion. Where the river valley is more open, such as near the outlet of Skilak Lake or near the mouth at Cook Inlet, wind waves must travel across a wide channel to affect the banks, and the meandering channel pattern reduces the amount of bank exposed to any specific wind direction. During this study, wind waves measured by boatwake gages were small and infrequent. Therefore, wind-generated waves were not considered a significant source of bank erosion along the Kenai River.

Natural erosion occurs as a result of many factors acting alone or in concert. One of the most significant factors is bank slumping. Slumping may occur above or below the water line as gravity pulls materials downward. This may occur gradually as creep or catastrophically as a sudden slump. The presence of ground water in the banks, particularly if the ground water is moving toward the face of the bank, decreases the stability of the bank and increases the rate of erosion. Freezing and thawing of the bank materials may also increase the rate of slumping and erosion. Below the water line, material may be eroded by the tractive force of the flowing water. This erosion may undercut the bank and lead to increases in slumping of the overlying materials as the bank becomes oversteepened. Because accounting for all the natural erosional forces is impractical and because river currents act continuously, the rate of all the natural erosion processes on the Kenai River is assumed to be proportional to the tractive force of the river currents. This assumption is supported by observational data collected at three primary study sites; these data indicated that no substantial natural erosion occurred from processes other than river currents.

In addition to watershed and river characteristics, human factors—such as bank alterations and river use—affect erosion rates. Although historically, human presence in the watershed has been sparse, during the past few decades, residential and commercial structures have proliferated adjacent to the river. This concentration of streamside development produces numerous human influences on streambank erosion, including clearance or destruction of streamside vegetation, construction of streamside and in-stream structures, and increased river use. River use and streamside development may continue to increase up to a level of crowding that significantly affects comfortable use of the river or up to its carrying capacity (Whittaker and Shelby, 1993). Likewise, streambank erosion can also increase until the river width and depth achieve some process equilibrium. During this study, sites for investigation were selected at places where the effects of humans on erosion were minimal. Three primary study sites were selected where the bank was protected from human access naturally or by some bank-protection measure, such as an elevated walkway. By selecting sites in this way, the primary human influence on bank erosion was from boatwakes.

Natural erosion caused by river currents and human-induced erosion caused by boatwakes are very different mechanisms. River currents flow generally parallel to the riverbank and move sediment towards and away from the bank as well as transport it downstream. Boatwakes travel essentially perpendicular to the bank and move sediment by dislodging it upon impact, by splashing up and down the bank, and by causing a rapid inflow and outflow of water from permeable banks (Simons and Li, 1982). The relative importance of these two erosion mechanisms—river currents and boatwakes—at the sites studied is described below.

River Current Erosion

River currents produce tractive erosional forces that are distributed along the river’s bed and banks. A greater force is exerted on the river bed than on the banks because the water depth is less against the banks (Chow, 1959, p. 169). The energy exerted by river current tractive forces is determined by the velocity and depth of the river and the amount of streambank exposed to the currents. This tractive erosion is commonly evident along the outside edge of meander bends where water depths and velocities are greater than along the inside of the bend where deposition of sediment is more prevalent.

Streambanks respond to river currents differently depending on their configuration, geometry, and orientation. Additionally, the type and size of material composing the bank will affect its resistance to erosion. For example, if the bank is vertical and oriented perpendicular to the river flow, and is composed of material that is loose, unconsolidated, fine-grained, and unvegetated, it would erode more readily than a gently sloping bank that is oriented parallel to the river flow, and composed of consolidated, coarse-grained materials that are covered with thick vegetation. Because study sites along the Kenai River depict a variety of these characteristics, natural erosion rates also varied among the sites.

Boatwake Erosion

Wakes generated by boats have been recognized as a contributing cause of streambank erosion by many investigators (Alaska Department of Natural Resources, 1986; Barrick, 1984; Bhowmik and Demissie, 1982, 1983; Bhowmik and others, 1982; Bradbury and others, 1995; Bush, 1988; Camfield and others, 1980; Garrad and Hey, 1987; Hagerty, 1989; Horton, 1995; Jaakson, 1988; Johnson, 1994; Klingeman and others, 1990; Lagler and others, 1950; Limerinos and Smith, 1975; Nanson and others, 1994; Scholer, 1974; Sutherland and Ogle, 1975; Von Krusenstierna, 1990; and Yousef, 1974). Boats moving through the water will generate a system of wakes at the bow, stern, and wherever an abrupt change in the boat hull geometry causes a pressure change in the flow field around the hull (Herbich and Schiller, 1984; Sorenson and Weggel, 1984; Walker, 1988). This system of wakes generally consists of two sets of diverging wakes traveling laterally away from the sides of the boat and one set of transverse wakes traveling in the same direction as the boat (fig. 2A). The transverse and diverging wakes meet on each side of the boat along two sets of lines called the cusp line (Walker, 1988). The generation of wakes by boats is a complex interference pattern, where the amplitude of wakes can increase when wakes are in phase (crests coincide with crests and troughs coincide with troughs), or the amplitude can decrease if the wakes are out of phase (Walker, 1988). Diverging wakes from passing boats are concentrated on the inside of the meander bend where a river tends to deposit material (fig. 2B).

Boatwakes reach the streambank as a series or train of wakes. This wake train is composed of varying sized wakes. The size, number, and erosive force of wakes in a wake train depend on the geometric form, size, draft, and speed of the boat as well as on the depth of water and distance the boat is from the bank (Sorenson, 1973; Bhowmik and Demissie, 1982). The maximum height of wakes in a wake train is an easy characteristic to measure and investigators have used it as a significant indicator of the erosive power in a wake train (Nanson and others, 1994; Von Krusenstierna, 1990). Other wake-train characteristics are more difficult to measure and were not used for this study because they are not significantly better indicators of boatwake erosive power (Nanson and others, 1994; Von Krusenstierna, 1990).

Wakes generated by a boat on the Kenai River deliver erosive energy to the riverbanks during a short time period, commonly 0.25 to 0.75 minute for a single wake train. An example of a wake train from a boat passing near the center of the channel at the Kenai Keys study site on August 27, 1996, is shown on figure 3. This wake train began with a small rapid 0.10-foot fluctuation in the water surface at 15:50:16, included 18 individual wakes, had a maximum height of about 0.56 foot at 15:50:32, and lasted about 27 seconds before ending at 15:50:43 when the water surface fluctuations decreased to the background level of about 0.05 foot. The maximum wake height for the wake train was 0.56 foot. This report typically documents the effects of a wake train as an individual boatwake. As described earlier, the energy dissipated on the streambank by this wake train is accurately represented by this assumption (Nanson and others, 1994; Von Krusenstierna, 1990).

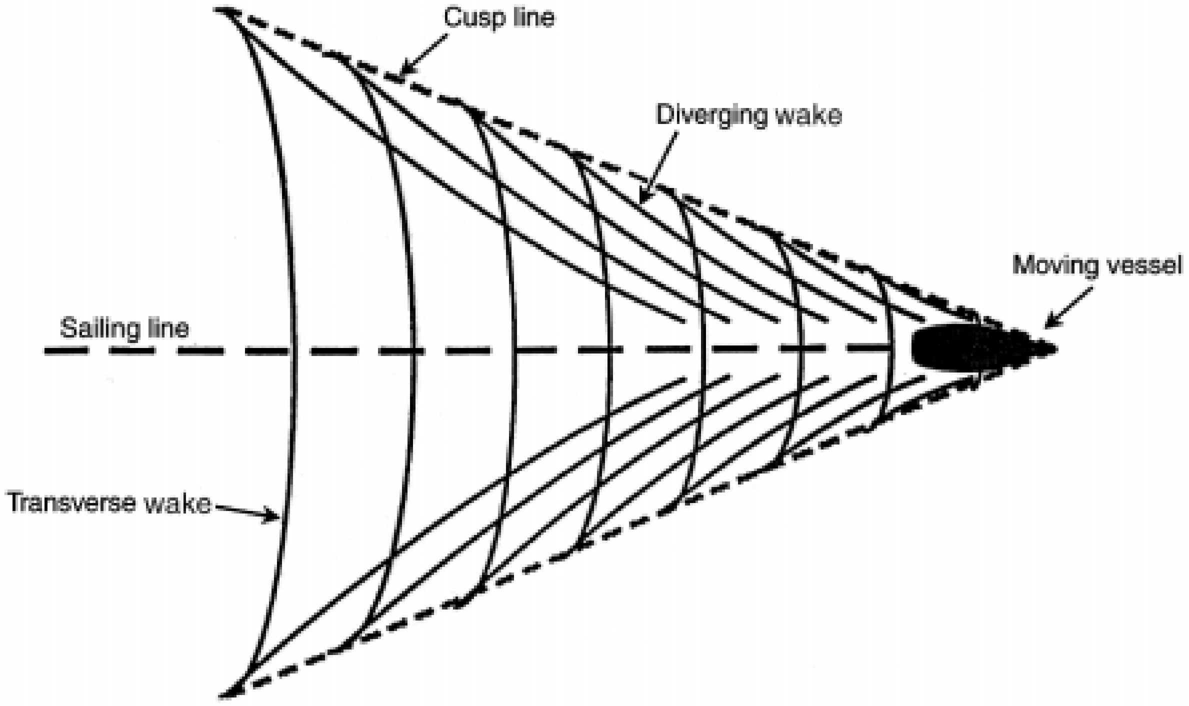


Figure 2A. Typical wake pattern produced by a moving vessel.

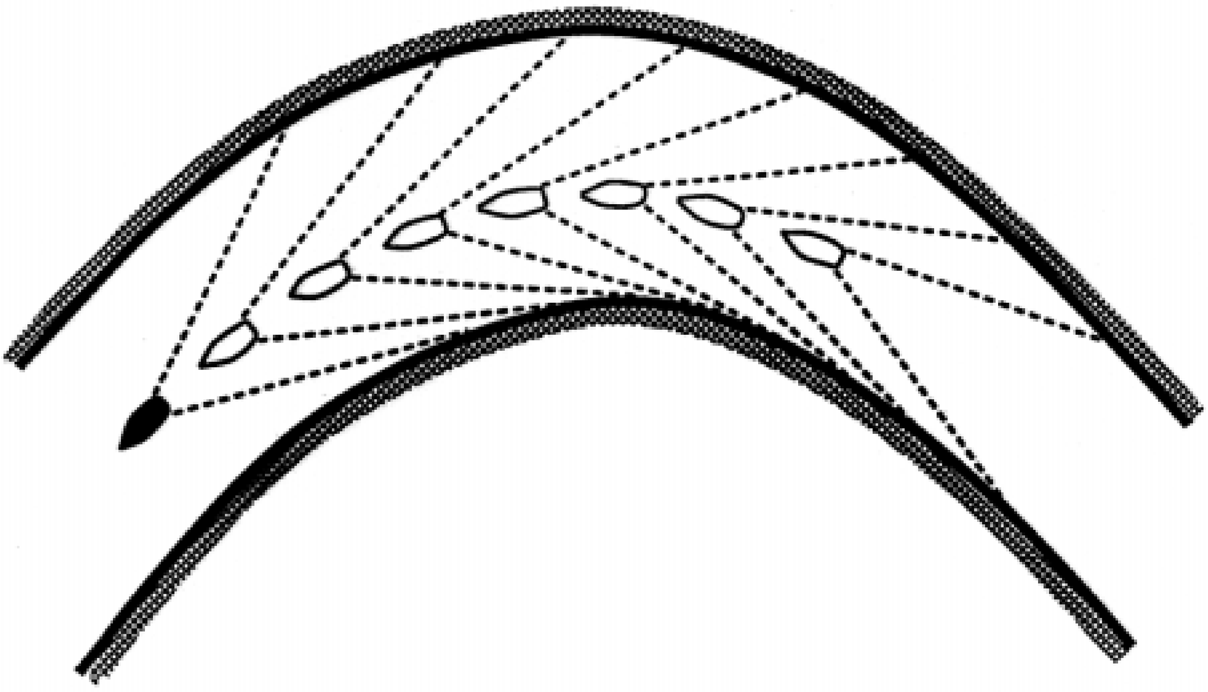


Figure 2B. Concentration of diverging wake energy on the inside bank at bends.

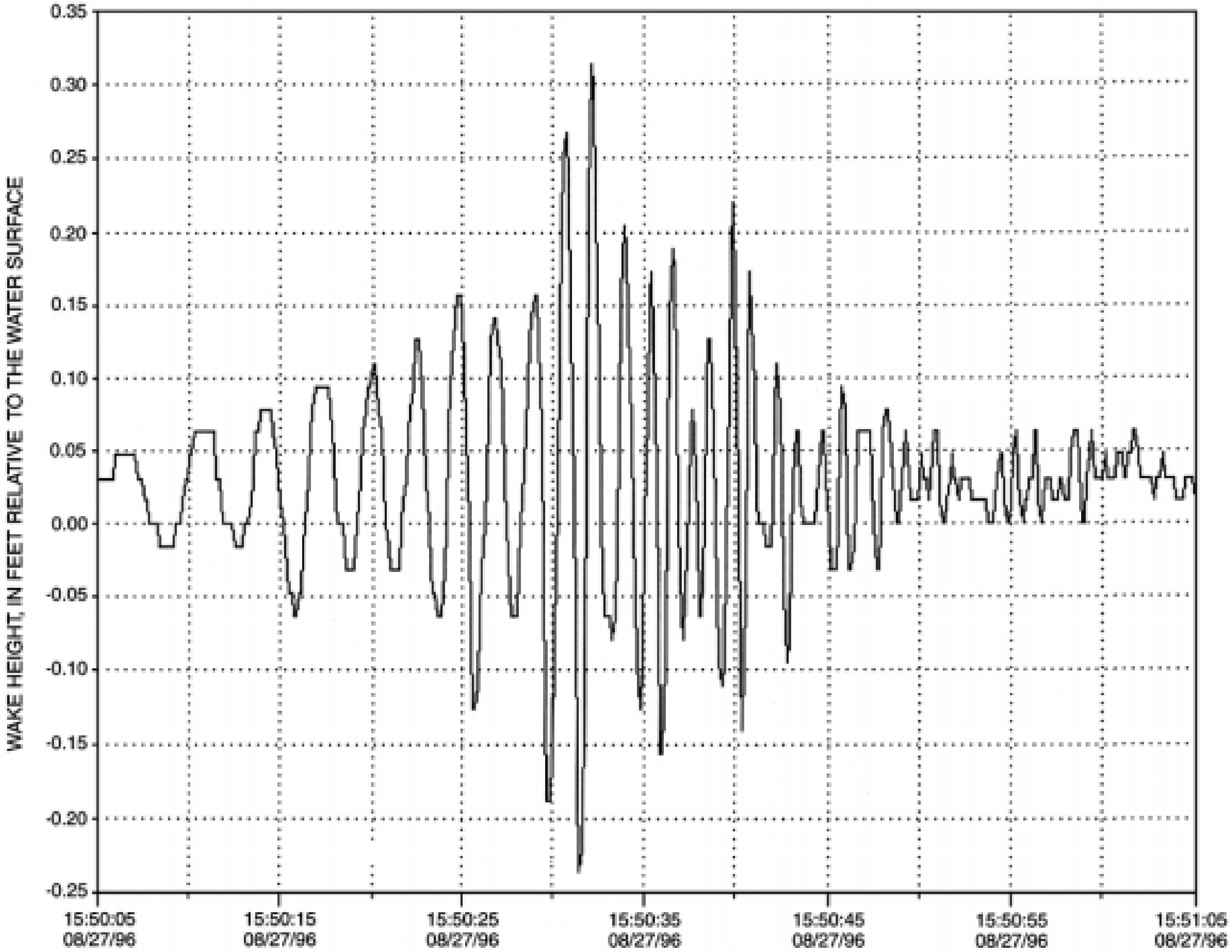


Figure 3. Example of a wake train generated at the Kenai Keys wake gage by a single boat pass.

KENAI RIVER STUDY AREA

Surface-Water Characteristics

The Kenai River watershed drains an area of about 2,200 square miles of the Kenai Peninsula in southcentral Alaska (fig. 1). The Kenai River begins at the outlet of Kenai Lake, a narrow, 22-mile long glacially sculpted, moraine-impounded lake, and flows for 17 miles before it passes through Skilak Lake, another large moraine-impounded lake approximately 12 miles long (fig. 4). These two lakes moderate river flow by attenuating high flows during floods and by sustaining river flow during periods of reduced runoff. The lakes also reduce the sediment movement into the lower river and provide overwintering habitat for fish. From Skilak Lake, the river flows another 50 miles before entering Cook Inlet near the city of Kenai (fig. 1). Motorized boats are prohibited on several miles of the 17-mile-long segment between the lakes; motorized boats are limited to a maximum motor size of 35 horsepower on the 50-mile-long segment downstream from Skilak Lake.

Streamflow data are collected from two stream-gaging stations on the Kenai River: at Cooper Landing (gaging-station No. 15258000) and at Soldotna (gaging-station No. 15266300) (fig. 4). These data indicate that maximum river flows commonly occur in July or August when snow and glacier melt are the greatest and that minimum flows occur in March when glacier melting and runoff are reduced (table 1). Fluctuations in daily streamflow during the 1996 water year (fig. 5) resulted in water depth variations of as much as 7 feet at the Soldotna stream-gaging station.

Table 1. Mean monthly discharges and stages at two stream-gaging stations on the Kenai River
[Discharge in cubic feet per second; stage in feet]

Station name and period of record	Oct.	Nov.	Dec.	Jan.	Feb.	Mar	Apr.	May	June	July	Aug.	Sept.
Cooper Landing (1947-95)	**Discharge**											
	3,321	1,853	1,158	806	652	511	538	1,906	5,352	6,958	6,425	5,298
	Stage											
	9.11	7.73	6.78	6.11	5.73	5.30	5.38	7.79	10.42	11.29	11.11	10.39
Soldotna (1965-95)	**Discharge**											
	7,158	3,480	2,283	1,889	1,669	1,367	1,557	3,171	8,428	13,310	14,660	12,010
	Stage											
	7.94	6.57	5.98	5.75	5.60	5.21	5.48	6.43	8.33	9.60	9.90	9.29

This water depth or stage variation exposes the streambanks to increasing tractive erosive forces as the water depth increases and to decreasing forces as water depths decline. Some streambanks along the Kenai River have water adjacent to them only during the highest streamflow months of the summer, whereas other banks have water flowing adjacent to them even during the lowest streamflow months. During 1996, discharge in the Kenai River generally was 25 to 30 percent below the long-term average discharge except for a short period in August. During this period,

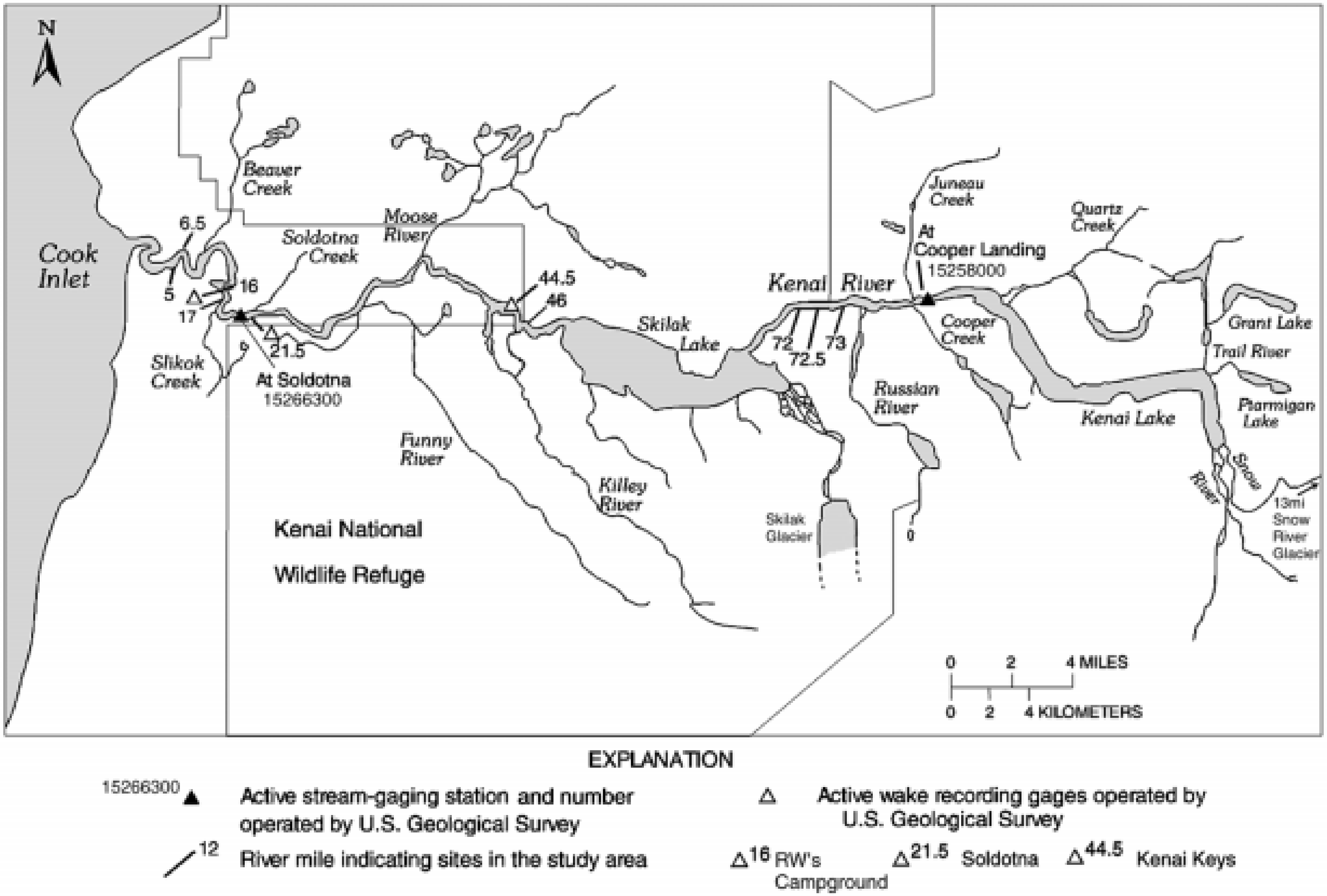
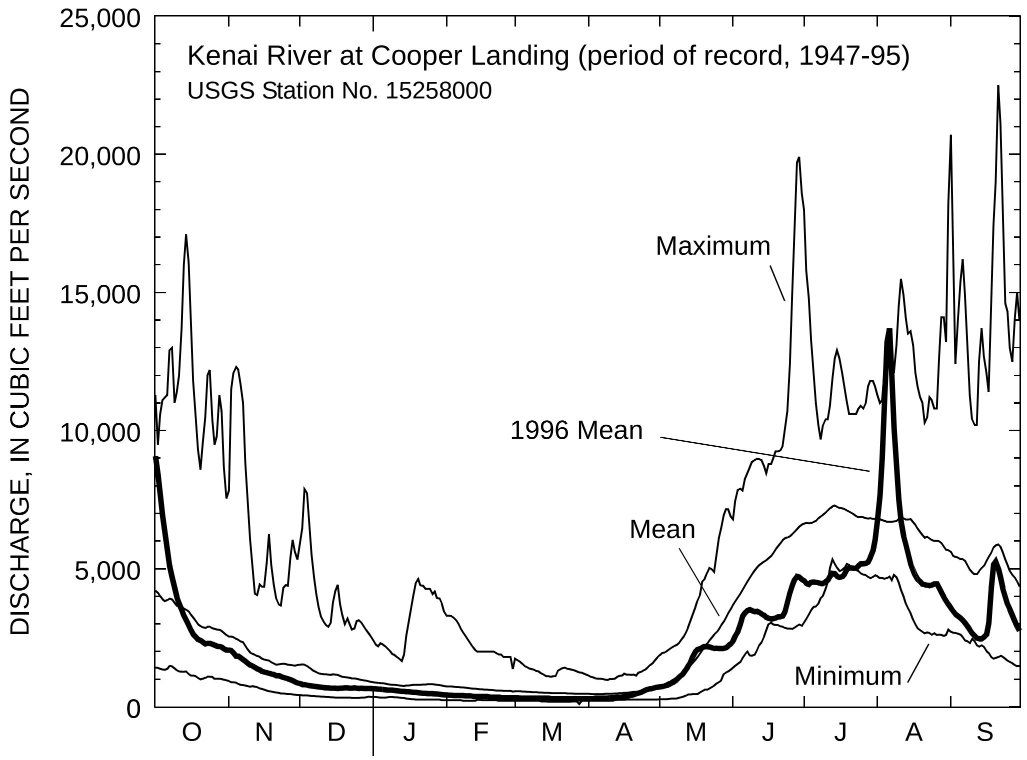


Figure 4. Kenai River, its major tributaries, and data-collection sites.



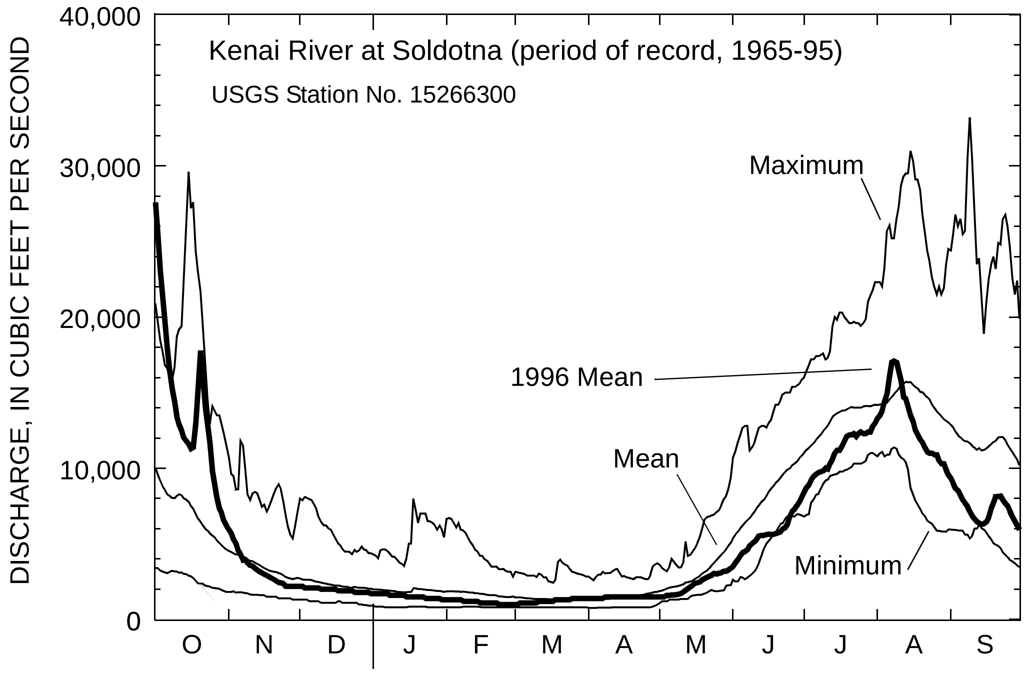


Figure 5. Maximum, mean, and minimum daily discharge for period of record, and preliminary mean daily discharge for 1996 of the Kenai River at Cooper Landing and at Soldotna.

an outburst flood from release of water stored by a glacier in the headwaters of Snow River increased flows above the mean at the Soldotna stream-gaging station and above the maximum values at the Cooper Landing stream-gaging station (fig. 5).

Site Selection and Characterization

Variations in the physical environment along a river may significantly influence streambank erosion. Scott (1982) described characteristics of distinct segments of the Kenai River downstream from Skilak Lake. These segments were distinguished by channel characteristics, the rate of bank erosion, and their relative sensitivity to streamside development (table 2). Using this information as a preliminary guide, study sites were selected for investigation from segments of the river having different characteristics.

Table 2. Channel characteristics pertinent to determining sensitivity of the Kenai River to development
[Table modified from Scott, 1982]

Segment of channel (river miles)	Pattern and degree of entrenchment	Underfit conditions	Degree of armoring	Average rate of bank erosion (1950-77) (feet per year)	Relative sensitivity to streamside 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	Mainly armored	<1.0	Low
21.8 to 17.6	Meandering; entrenched within Soldotna terrace	Underfit	Mainly armored	<1.0	Low
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	High
9.0 to mouth	Meandering in tidal regime; channel is free to migrate	Channel is mainly product of present flow regime	None	2.0	Moderate

For this study, the sites were distributed along approximately 67 miles of river including 50 miles of river downstream from Skilak Lake and 17 miles of river between Skilak and Kenai Lakes. Hydrologic and hydraulic properties along the river varied greatly among the study sites. The streamflow and water-stage data from the two stream-gaging stations were used to estimate discharge and related hydraulic characteristics at the study sites. Geomorphic characteristics of the study sites—such as their location in relation to the meander pattern of the river, inflowing tributaries, and major geologic features—were considered when selecting the sites and must be considered when comparing erosion rates among the study sites. For example, the upper river control sites are in a segment of the river that is narrower, meanders less, and carries less water than segments farther downstream.

Additional hydrologic and geomorphic characteristics of each study site were determined from field investigations and interpretation of aerial photographs to assess their potential influence on the erosion rates at the site. Pre-study erosion rates of as much as 5 feet per year were reported for study sites along the Kenai River by Inghram (1985), Reckendorf (1989), and Scott (1982). Soils along the Kenai River are generally of glacier origin including cohesive, clay-rich tills and non-cohesive, outwash alluvium. Vegetation varies from dense, mature hardwood and spruce forest in the upper river to lowland marsh wetlands in the lower river. Detailed information on soils and vegetation for the sites was obtained from field investigations and reports by Lehner (1994), Reckendorf (1989), and Reckendorf and Saele (1991). Particle-size differences in bank material among the sites were determined by a dry-sieve analysis of a sample collected at each site during the study.

Ten sites along the Kenai River were selected for investigation of the effects of boatwakes on streambank erosion. Fixed measuring points or erosion pins were utilized to quantify erosion, and three of the sites included wake gages for enumeration of boat activity (table 3). Seven of the ten study sites are downstream from Skilak Lake and three are upstream from the lake (fig. 4; table 3). Two of the sites downstream from Skilak Lake are in the lower river segment, where the river is generally wider and deeper than the rest of the river. This segment is influenced by ocean tides, and average erosion rates were reported to be about 2 feet per year (table 2). Three study sites are in the middle river segment, where the river channel is generally armored and underfit, and average erosion rates were reported to be less than 1 foot per year (table 2). Two other study sites are in the upper motorized segment of the river where the river is meandering and migrating, and average erosion rates are reported to be about 5 feet per year (table 2). The three study sites upstream from Skilak Lake are in the segment of the river where motorized boats are prohibited.

Table 3. Study sites and type of instrumentation installed on Kenai River

Site name	River mile (fig. 4)	Boatwakes recorded	Number of erosion measuring points
Lower river			
Warren Ames Bridge	5	No	4
Cunningham Park	6.5	No	2
Middle river			
RW's Campground	16	Yes	7
Big Eddy State Recreation Site	17	No	5
Soldotna	21.5	Yes	3
Upper river (motorized segment)			
Kenai Keys	44.5	Yes	6
Skilak Lake	46	No	6
Upper river (non-motorized segment)			
Control Site 1	72	No	5
Control Site 2	72.5	No	4
Control Site 3	73	No	3

METHODS OF MEASURING BOATWAKES, EROSION, AND THEIR EFFECTS

The effect of boatwakes on streambank erosion along the Kenai River was investigated using techniques described by Bhowmik and others (1990), Goudie (1981), and Thorne (1981). These methods require detailed measurements of bank loss and boat activity. The measured bank loss is then compared among sites where boat use is restricted to non-motorized uses and sites where boat use is unrestricted. For the Kenai River study, periodic erosion measurements that were made where boat use was unrestricted were correlated with continuous counts of the number of boat passes. The objective was to determine when the maximum amount of erosion and the maximum number of boat passes occurred. The depth of water adjacent to the banks was recorded continuously at the three sites with wake gages. Two stream-gaging stations at Cooper Landing and Soldotna (fig. 4) operated continuously during the study. Data from these gaging stations provided discharge, water depth, and velocity information that was used to compute the total tractive energy in the river currents. The depth of water adjacent to the bank was used to compute the portion of the total available tractive energy dissipated against the study-site banks by river currents. Energy dissipated by wakes was determined at the three sites where wake gages were installed. Erosive energy generated by boatwakes and that generated by the natural streamflow were compared in order to determine their relative contribution to measured erosion during the study.

Erosion Measurement

The primary method of quantifying bank loss during this study was repeated measurements of the exposure of erosion pins. The use of erosion pins as a measure of bank loss was pioneered by Wolman (1959). Details of their use, installation, and limitations are found in reports by Goudie (1981) and Thorne (1981). The erosion pins used in this study were smooth round metal rods that were driven horizontally into the streambank (fig. 6). The pins were most commonly 0.375 inch in diameter and 3 feet long. The erosion-pin measurements were supplemented by bank geometry measurements above and below the pins and by horizontal distance measurements from additional metal pins or wooden stakes driven vertically into the riverbank several feet inland. Where no erosion pins were installed, distance measurements were made from firm locations along the riverbank such as trees, house corners, signposts, walkway footings, and dock piers (fig. 6).

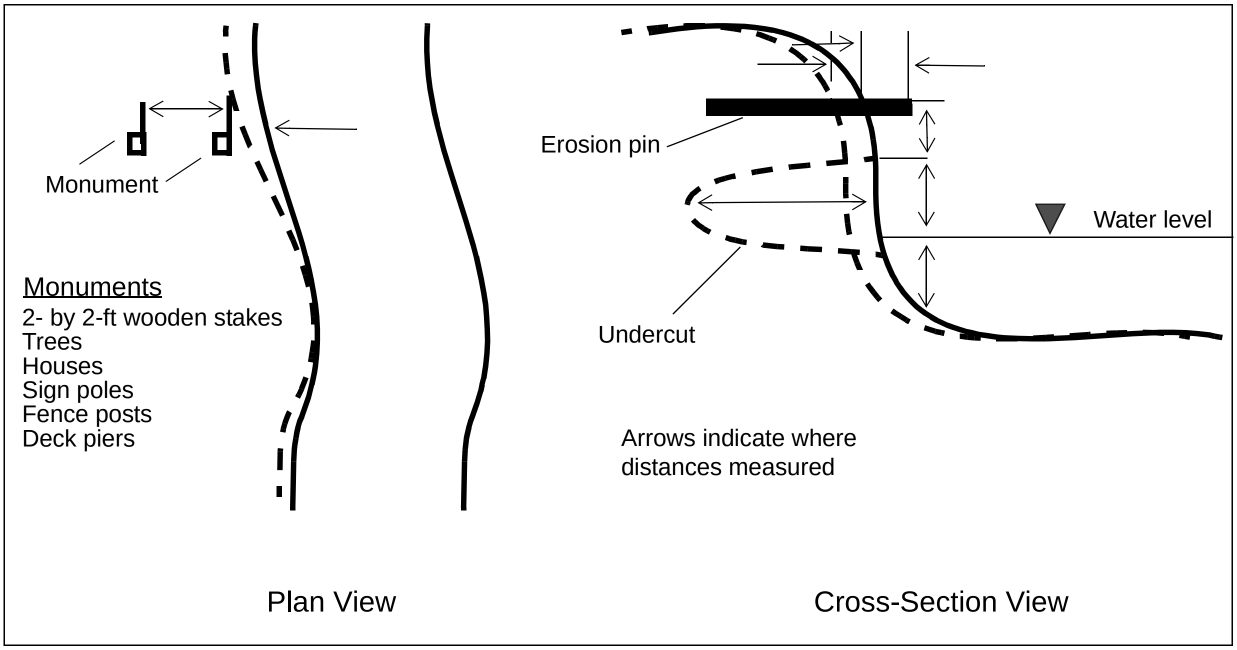


Figure 6. Schematic of typical erosion measurement techniques.

Measurements of erosion began in August 1995 and continued through September 1996. Measurements of the exposure of the pins relative to the streambank were made initially when the pins were installed, again the following spring to account for over-winter erosion, and then about once a month during the boating season (May to September 1996).

Wake Gages

Wake gages, which used a float suspended in a screen-mesh cylinder, recorded small fluctuations in the water surface as an ink drawing on a paper chart (fig. 7). The paper chart advanced at a rate of about 1.5 inches per hour and each time a boat passed by the wake gage, an abrupt rise and fall of the water surface was drawn on the chart by the ink pen recording the maximum amplitude of the boat-generated wake train that impacted the streambank (fig. 7). The amount of boat

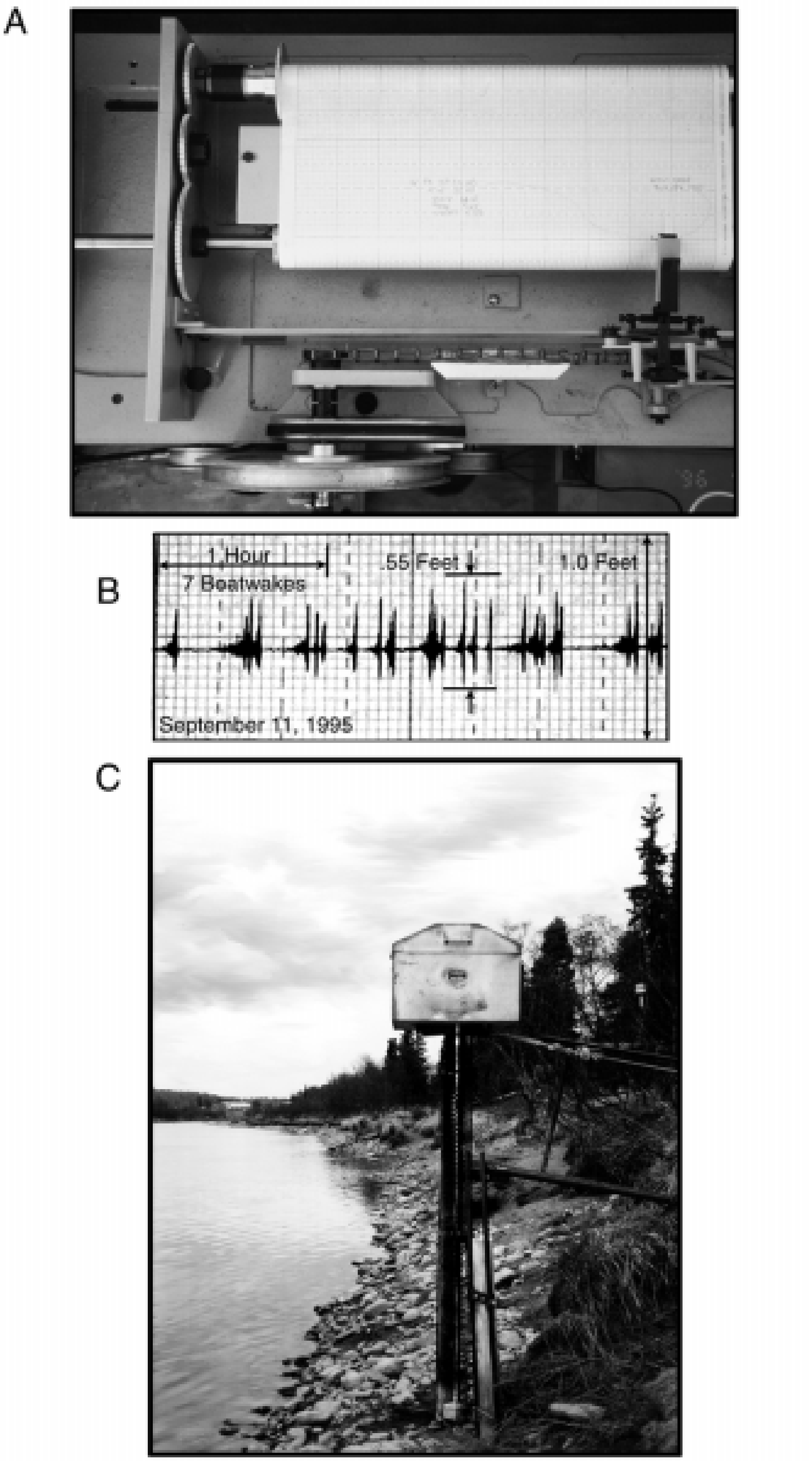


Figure 7. Wake gage instrumentation (A), example of wake record (B), and typical installation adjacent to streambank (C).

activity at each study site was determined from continuous chart records of these water-surface fluctuations. Three wake gages were installed along the river: one at RW's Campground near river mile 16, one in Soldotna at about river mile 21.5, and one at the Kenai Keys near river mile 44.5 (fig. 4; table 3). The wake gages also provided an accurate continuous record of the depth of water adjacent to the riverbank during the study period.

Observations of Boat Activity

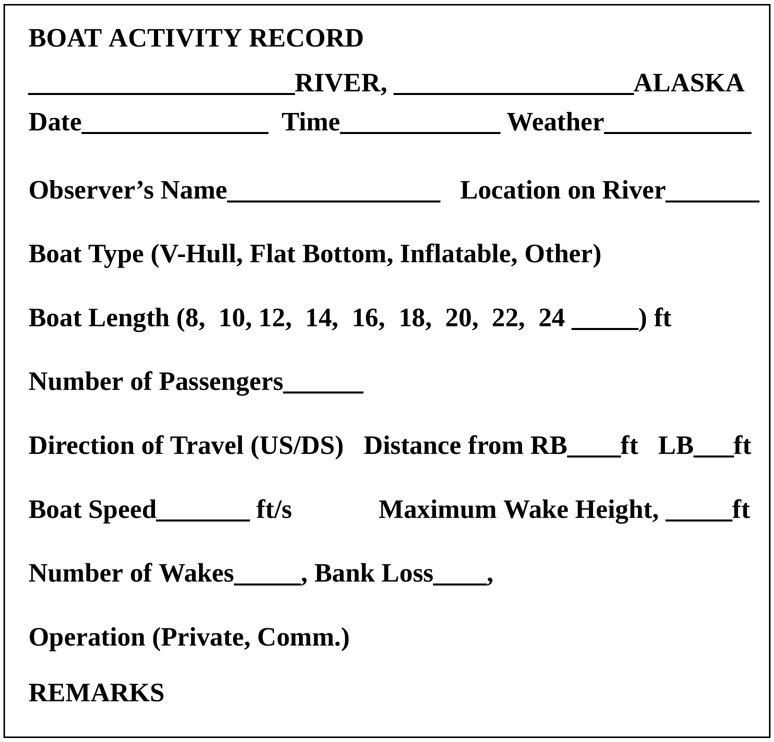
The wake gages operated during this study are designed to record the number of wake trains that impact the bank, which should be equal to the number of boats that pass by the gage. However, the gages do not record the operating characteristics of the boat that generated the wake. For example, factors such as the number of passengers the boat was carrying, how far away from the bank it may have been, or if it was traveling upstream or downstream, potentially affect wake generation, but are not recorded by the wake gages.

Many types of boats are used on the Kenai River, but generally they are wider and have a shallower draft than boats typically found on lakes or in saltwater. State of Alaska regulations limit the maximum motor size to 35 horsepower and maximum passenger load to six. Some information other than the direct observations made during this investigation is available to describe the type and quantity of boat traffic on the Kenai River. The Alaska Department of Natural Resources (ADNR), and the ADF&G counted the number of boats operating in certain segments of the river on specific days during 1996. These boat counts from State agencies are not made every day and do not indicate the number of boats passing any single point along the river. However, these counts do provide information about trends in boat traffic along the river and whether the boats are private (unguided) or commercially operated (guided).

In order to obtain more specific information about various boat-operating characteristics and their effects on generated wakes, a "boat activity observation form" was designed (fig. 8). The form was distributed to several riverside residents and the State agencies mentioned above for recording periodic direct observations. In addition, boat observations were used on a few occasions to compare with boatwake gage records or to supplement the wake-gage records when water levels were too low for the gage to record wakes. Information obtained from the observations of boat activity led to the design of an experiment during which boat-operating conditions were controlled and measurements of wake size and bank erosion were made.

Controlled Boat Experiment

An experiment was designed in which the effect of passenger load, distance from the bank, and boat hull design could be evaluated for their influence on the wake size and bank erosion generated by a boat (fig. 9). This Kenai River experiment was designed after a similar controlled experiment done on the Gordon River in Tasmania, which evaluated the effect of boat speed on wake height and bank erosion (Nanson and others, 1993; Von Krusenstierna, 1990). During the Gordon River experiment, a boat passed the study site with the same passenger load at a fixed distance from the bank, but varied its speed during subsequent passes. The effects of the changes in boat speed were evaluated by comparing measured variations in basal swash load—a measure of the weight of material removed from the banks of the river—which was collected in a pan, and variations in suspended-sediment load which was collected in a submerged bottle. The Gordon River data indicated that for wake heights greater than about 1 foot, basal swash load increased



BOAT ACTIVITY RECORD

____________________RIVER, __________________ALASKA

Date______________ Time____________ Weather___________

Observer's Name________________ Location on River_______

Boat Type (V-Hull, Flat Bottom, Inflatable, Other)

Boat Length (8, 10, 12, 14, 16, 18, 20, 22, 24 _____) ft

Number of Passengers______

Direction of Travel (US/DS) Distance from RB____ft LB___ft

Boat Speed_______ ft/s Maximum Wake Height, _____ft

Number of Wakes_____, Bank Loss____,

Operation (Private, Comm.)

REMARKS

Figure 8. Boat activity observation form.

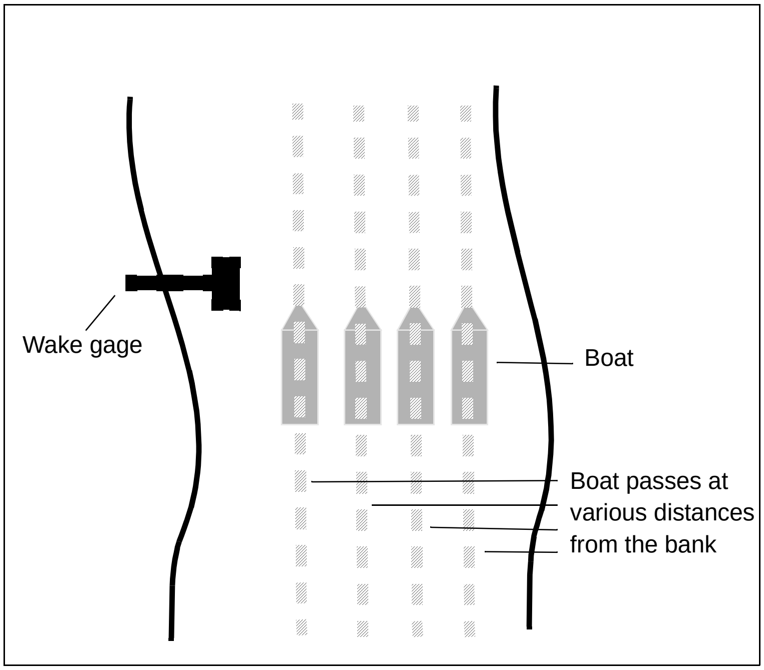


Figure 9. Schematic of boat design.

exponentially, while suspended-sediment load remained linearly proportional to wake height (fig. 10).

During the Kenai River experiment, sediment that was moved by each boat pass was collected in a 12-by 18- by 2-inch baking pan, which was pinned to the river bottom near the base of the streambank. The sediment collected by the pan was used as the primary assessment of boat-generated wake effects at the streambank during the experiment.

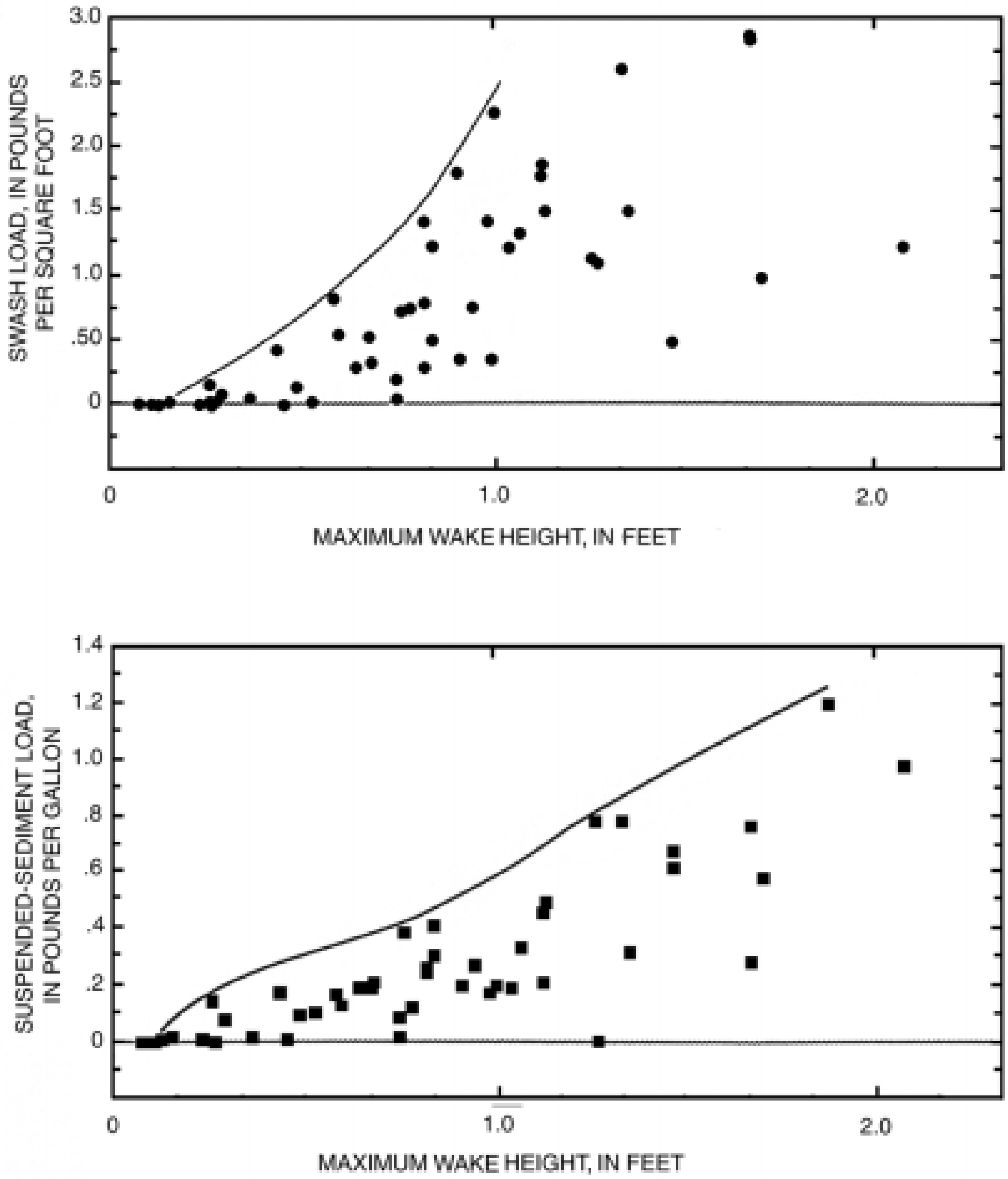


Figure 10. Data from Gordon River experiment (modified from Von Krusenstierna, 1990).

Energy Dissipation Calculations

During 1996, the maximum water flows and the maximum boat activity, both of which can cause streambank erosion, occurred closely together in time. To separate boatwake-induced streambank erosion from natural erosion is a difficult process. In addition, continuous observations of erosion were impractical. The technique used to separate these two primary sources of erosion was to compare the relative amount of energy delivered to the streambanks by flowing currents and that delivered by boatwakes during the period between erosion measurements. In a study of the causes of levee erosion in the Sacramento-San Joaquin Delta, Limerinos and Smith (1975) used a similar energy comparison process and found that the relative energy contribution from boat-generated wakes in channels not subjected to flood flows during their study, was as much as 80 percent of the annual total. However, for channels that carried significant flood flows, boatwakes contributed about 20 percent of the annual total energy (Limerinos and Smith, 1975).

Assuming that the erosion measured between site visits is due only to tractive forces of the natural streamflow and boatwakes and not to wind waves or other natural or human processes, an energy comparison will provide an indication of which is the more prevalent erosion mechanism on the Kenai River. Energy dissipated against the streambank by the tractive forces of the river currents is computed by determining the hydraulic characteristics of the channel near the streambank of interest. The hydraulic characteristics needed include channel hydraulic roughness, water depth both in the channel and next to the bank, and water velocity (Limerinos and Smith, 1975). Since only the depth of water next to the bank was collected at the study sites, hydraulic characteristics at the closest Kenai River stream-gaging station were used to estimate conditions near the study sites. This technique estimates velocity near the streambank at the study site as the mean velocity at the stream-gaging station. Generally, this results in an overestimate of tractive forces because velocity near the study site’s streambank is generally less than the mean velocity at the stream-gaging station. During a study of the hydraulic characteristics near streamside structures along the Kenai River, all the velocity measurements made within 6 feet of the riverbank were less than the mean velocity in the river channel during a wide range of seasonal discharges (Dorava, 1995). Energy dissipated against the streambanks by boatwakes was determined from wake characteristics recorded at the study sites and additional wake characteristics estimated from data collected during observations of boat activity and the controlled boat experiment. Generally, boatwake energy was underestimated because a slow mean velocity of the wakes was used to compute their energy. The wake velocity used to compute wake energy was determined for a wake generated by a boat passing near the center of the river channel. Whenever a boat passed by the bank closer than mid-channel, the wake velocity would most likely be greater than that used in the energy calculations. Additionally, when wake gages malfunctioned, instead of the energy of individual recorded wakes being totalled during a day, the number of wakes was estimated from the other wake gages and their total energy was calculated. This calculation was made by assuming that each wake had the same mean maximum height, which was determined from a subset of the wake records at each site. Additional details of the methods used to compute tractive and boatwake energy can be found in Limerinos and Smith (1975).

STUDY RESULTS

The first erosion pins installed along the Kenai River for this study were set in place on August 31, 1995. Before any post-installation erosion measurements were made, all the pins were washed away on September 24 by a flood that had an estimated recurrence interval of 100 years. Large rare floods are commonly responsible for major changes in channel shape and course. Visual observations after the flood showed that the riverbank eroded about 8 feet in vegetated areas having no residential development near river mile 44.5 upstream from the Kenai Keys. In a residential area of the lower river near river mile 10, the riverbank eroded as much as 25 feet. Erosion pins were re-installed after the flood and before winter at many sites, and boat activity data collection was started that fall at two sites. These data will be discussed for the study sites beginning at the downstream end of the Kenai River and proceeding upstream.

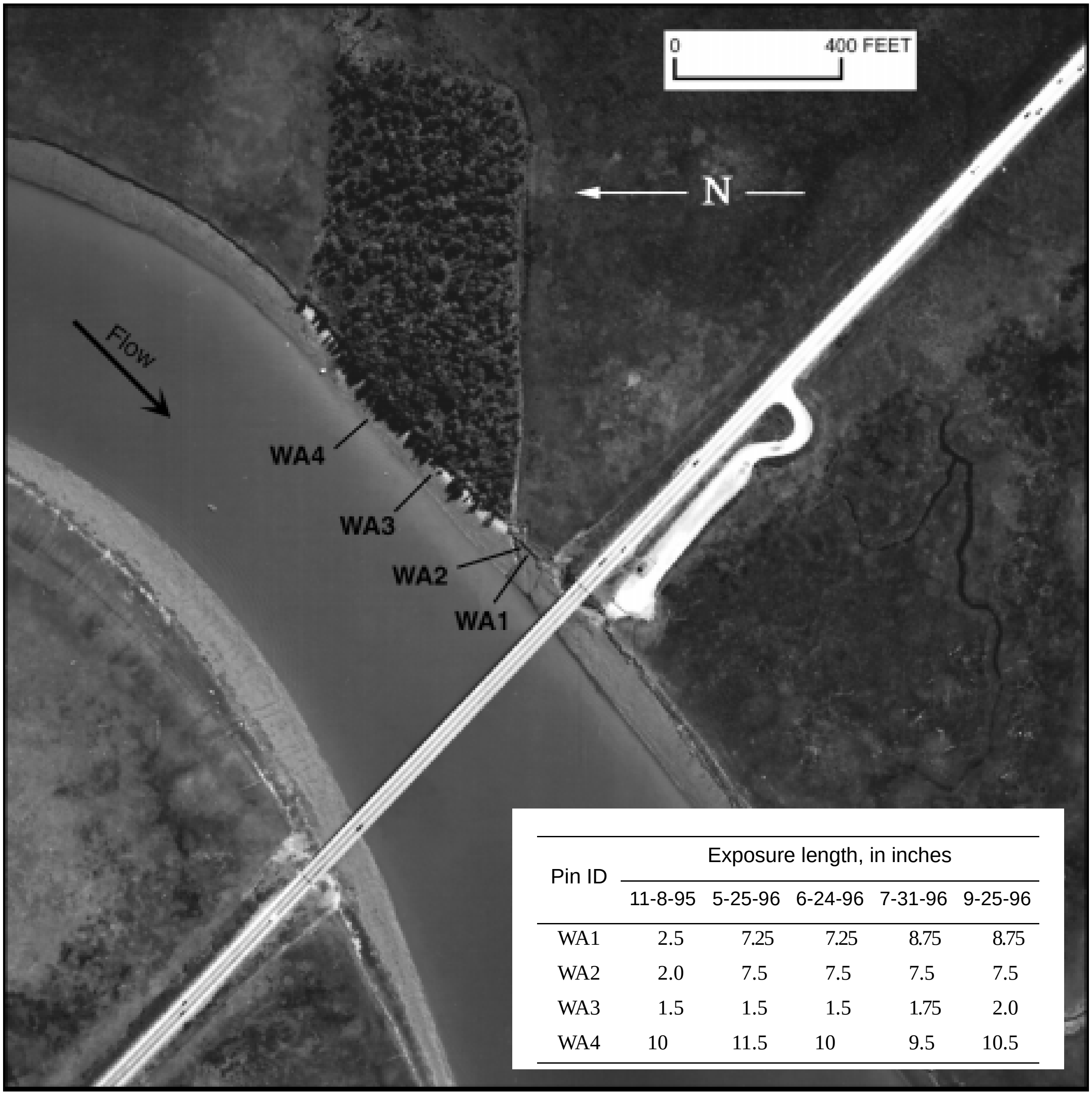
Lower River Segment

The mouth of the Kenai River is at the city of Kenai on Cook Inlet (fig. 1). The twice-daily tide fluctuation can be as high as 28 feet at the Kenai city pier (Elliot, 1995), and tidal influence on the water surface commonly extends upstream to about river mile 12. Streambed and bank materials are smaller in this tidally influenced segment of the river compared with streambed and bank material at upstream segments. Also, because the flood plain and channel are wider in this segment of the river than they are farther upstream, the influence of wakes on the riverbank is reduced.

Warren Ames Bridge Site

The most downstream study site is at river mile 5 (fig. 4), near the Warren Ames Bridge (fig. 11). This site was selected because it has no residential development and is influenced by the action of tides. Erosion pins were installed on November 8, 1995 and measured periodically through September 25, 1996 (fig. 11). Pins WA1 and WA2 were installed about 25 feet apart and both about 6 inches below the vegetation mat near the high tide elevation, in a near vertical bank of fine-grained, moist, cohesive soils (fig. 12A). Pins WA3 and WA4 were installed about 100 feet apart and about 6 inches below the vegetation mat, which was above the high tide elevation, in an approximately 10-foot-high sloping bank of coarser grained, non-cohesive soils (fig. 12A). About three-fourths of the post-installation exposure of pin WA1 and all the post-installation exposure of pin WA2 occurred during the period November 8, 1995 to May 25, 1996. During this period, the river is commonly frozen. This time of year is typically not a heavy boat-use period and the erosion measured at this site likely resulted from a combination of natural forces, including tides and ice. Additional increased exposure of pin WA1 of about 1.5 inches occurred during the time period of heaviest boat activity in the lower river.

Pins WA3 and WA4 indicated a total loss of 0.5 inch of bank during the study period. These pins were never directly exposed to the erosive actions of the river because they were installed above the high-tide line. Therefore, measurements of their exposure indicated that the bank material migrates downslope by gravity. At times, this movement of the bank material will increase the pin exposure and at other times, the bank movement will decrease it. Scott (1982) reported an average erosion rate of 2 feet per year for the segment of the river between river mile 9 and the mouth (table 2); the more detailed measurements at this specific study site indicated that a maximum of 6.25 inches of the bank eroded during almost all of 1996.



Pin ID	Exposure length, in inches				
	11-8-95	5-25-96	6-24-96	7-31-96	9-25-96
WA1	2.5	7.25	7.25	8.75	8.75
WA2	2.0	7.5	7.5	7.5	7.5
WA3	1.5	1.5	1.5	1.75	2.0
WA4	10	11.5	10	9.5	10.5

Figure 11. Location and exposure lengths of erosion pins at Warren Ames Bridge site, at river mile 5 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

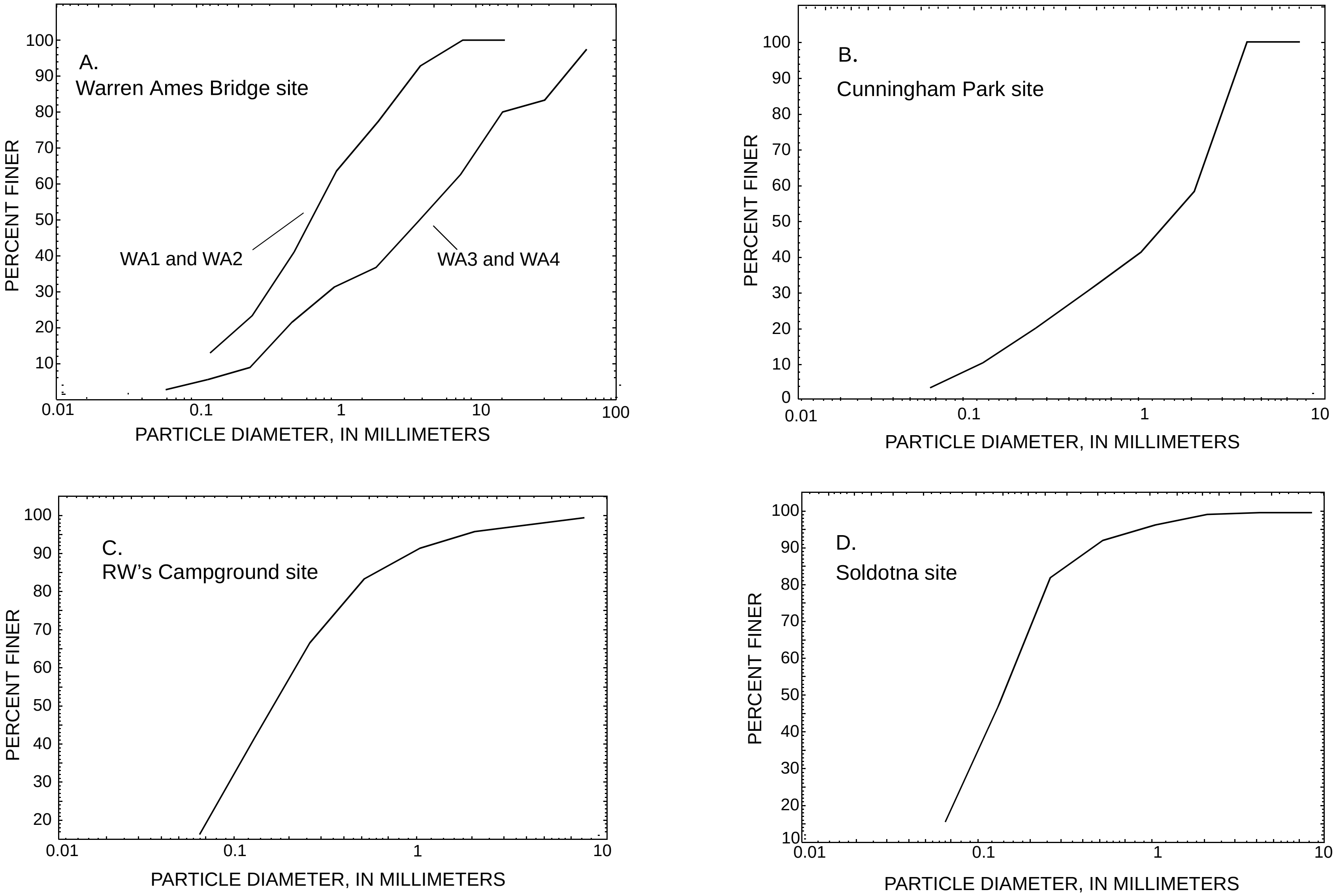


Figure 12. Particle-size distribution for bank material at selected Kenai River study sites.

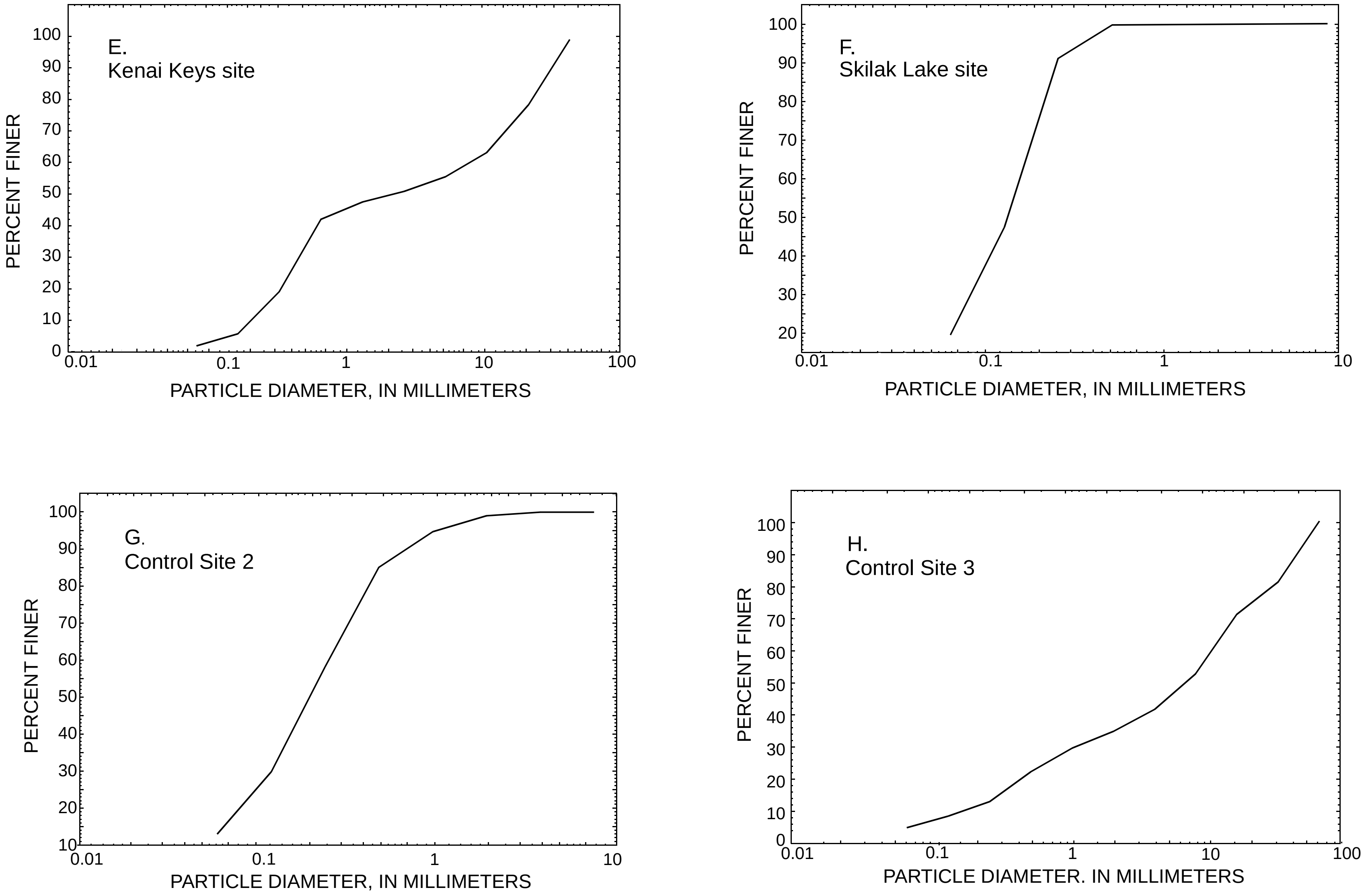


Figure 12. Continued.

Without a count of boat traffic at this specific site, it was difficult to accurately estimate the amount of erosion that was induced by boatwakes. The ADF&G counted boats present in the river from the Warren Ames Bridge to the Sterling Highway Bridge on most days from July 2 to August 4, 1996 (table 4) and the ADNR counted boats in this river segment sporadically from June 8 to August 29, 1996 (table 5). The ADF&G divided their boat counts into areas upstream and downstream from their sonar counter at river mile 8.5. For example, their boat counts showed that on July 20—the day with the highest boat count—1,071 boats were present between river miles 5 and 20 and 107 boats were present between river miles 5 and 8.5 (table 4). These numbers indicate that only about 10 percent of the boats on this counted segment of the river on July 20 were within 3.5 miles of the Warren Ames Bridge. During the entire period of boat counts, the number of boats downstream from river mile 8.5 averaged about 9 percent of the total number counted between river miles 5 and 20. These boat counts by State agencies indicate the number of boats on the river, but do not indicate the number of times boats pass a particular site. Many people fish the river by drifting down through a fishing hole and then powering back upstream to repeat the float. They may do this dozens of times per day. Thus, the number of boat passes by a point may be many times the number of boats on the river. However, these counts by State agencies do indicate a trend in boat distribution in which commonly less than 10 percent of the boats in this lower 20-mile-long segment of the river are downstream from river mile 8.5.

Cunningham Park Site

In August 1995, a study site was established at river mile 10 near the mouth of Beaver Creek. However, the Beaver Creek site was substantially altered during the September flood and an extensive bank restoration project began at the site. Therefore, erosion measurements were discontinued at the Beaver Creek site, and a new study site was established downstream near river mile 6.5 (fig. 4) at Cunningham Park on May 25, 1996 (fig. 13). This new site was selected because it was in the tidal segment of the river and it was being developed as a park. The park included public river access and parking as well as pathways along the riverbank.

Erosion pins were installed in fine-grained (fig. 12B) organic-rich soils near the high tide elevation. Measurements of the exposure of these pins indicated no large changes during the study (fig. 13). However, the loss of pin CP1 between June 24 and July 31 resulted from an extensive localized slump of bank material. About 4 feet of bank material along a 20-foot section of the park collapsed into the river (fig. 14). This bank failed along a walking path and included material into which pin CP1 was originally driven. The process of bank slumping is common in many streams, especially in the northern latitudes where permafrost is prevalent (Scott, 1978) and where the freeze/thaw cycle acts on banks that contain abundant moisture. Along the lower Kenai River, where cohesive bank soils are often very wet because they are affected by tides, this slumping process may be the dominant erosion mechanism. The loss of pin CP2 between July 31 and September 25 (fig. 13) was associated with vandals removing the pin. A round clean hole where the pin had been was clearly visible and provided measurable evidence that no additional erosion had taken place at the site.

The erosion resulting from tides, ice, and slumping along the lower segment of the river, especially from the mouth to river mile 12, prohibited separation of the measured erosion into different mechanisms that could be compared relative to one another.

Table 4. Number of boats on the Kenai River counted by the Alaska Department of Fish and Game, July and August 1996

[ND, no data; -- not applicable]

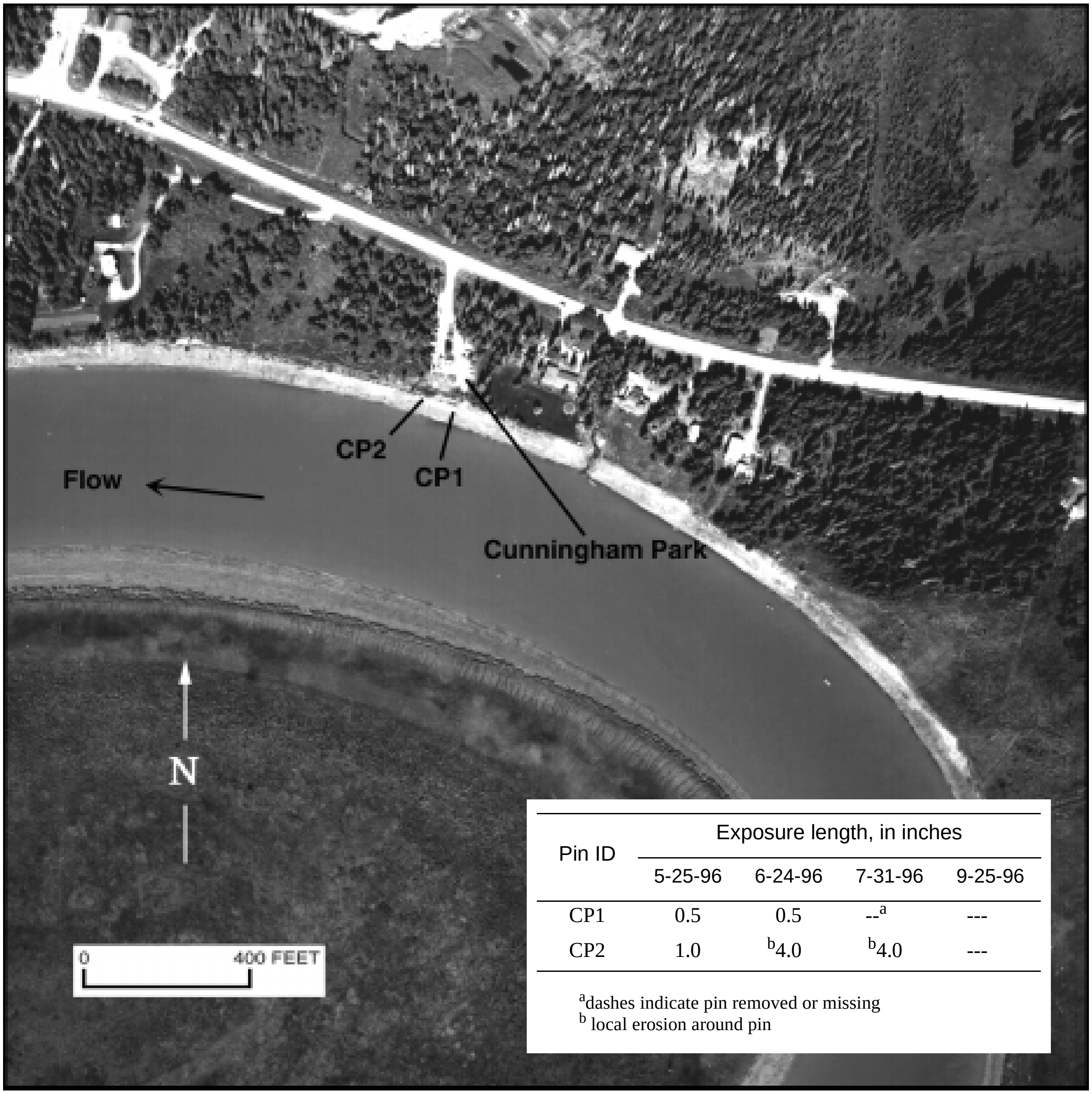
Date	Downstream (mile 5 to mile 8.5)		Upstream (mile 8.5 to mile 20)		Total number of boats
	Unguided	Guided	Unguided	Guided	
July 2	8	13	97	161	279
3	5	11	38	132	186
4	15	5	133	102	255
5	3	6	58	35	102
6	18	8	156	41	223
7	17	0	251	0	275
[a]8	ND	ND	ND	ND	--
9	10	25	108	231	374
10	8	16	115	223	362
11	7	17	261	196	481
12	15	4	210	255	484
13	18	12	368	207	605
14	17	0	459	0	476
[a]15	ND	ND	ND	ND	--
16	25	6	181	308	520
17	26	17	412	226	681
18	38	37	321	266	662
19	32	14	191	259	496
20	72	35	668	296	1,071
21	80	0	739	0	819
[a]22	ND	ND	ND	ND	--
23	22	11	244	236	513
24	41	15	335	251	642
25	27	13	249	205	494
26	18	18	329	264	629
27	62	31	545	236	874
28	51	0	685	0	736
[a]29	ND	ND	ND	ND	--
30	20	2	351	220	593
31	11	8	298	186	503
August 1	6	7	47	97	157
2	20	28	74	87	209
3	53	25	129	72	279
4	35	15	78	63	191

[a] No fishing allowed from boats on Mondays during July

Table 5. Number of boats on the Kenai River counted by the Alaska Department of Natural Resources, June to August 1996

[--, no data]

Date		Upper river (Skilak Lake to Naptowne)		Middle river (Naptowne to Soldotna)		Lower river (Soldotna to mouth)	
		Unguided	Guided	Unguided	Guided	Unguided	Guided
June	8	--	--	13	1	--	--
	9	--	--	--	--	54	112
	15	20	4	--	--	63	98
	21	--	--	--	--	22	54
	22	43	7	--	--	24	38
	29	--	--	--	--	27	42
	30	15	3	--	--	48	64
July	4	--	--	--	--	33	89
	5	6	5	22	3	33	114
	6	--	--	35	8	--	--
	7	6	4	--	--	93	--
	9	17	6	--	--	61	168
	10	--	--	--	--	37	78
	11	--	--	--	--	84	173
	13	6	9	18	33	--	--
	14	6	5	37	--	--	--
	15	9	11	--	--	--	--
	22	9	4	49	12	--	--
	29	11	14	--	--	--	--
	30	--	--	--	--	174	152
August	1	--	--	--	--	64	70
	2	47	--	--	--	47	74
	3	--	--	--	--	124	76
	6	--	--	7	2	58	63
	7	--	--	--	--	38	26
	8	--	--	--	--	13	22
	9	--	--	--	--	19	31
	14	--	--	--	--	45	36
	15	--	--	--	--	64	42
	17	--	--	--	--	29	33
	18	--	--	84	10	--	--
	20	--	--	--	--	64	49
	21	--	--	--	--	19	22
	24	--	--	42	24	--	--
	28	--	--	--	--	30	25
	29	--	--	7	2	43	29



Pin ID	Exposure length, in inches			
	5-25-96	6-24-96	7-31-96	9-25-96
CP1	0.5	0.5	--[a]	---
CP2	1.0	[b]4.0	[b]4.0	---

[a] dashes indicate pin removed or missing

[b] local erosion around pin

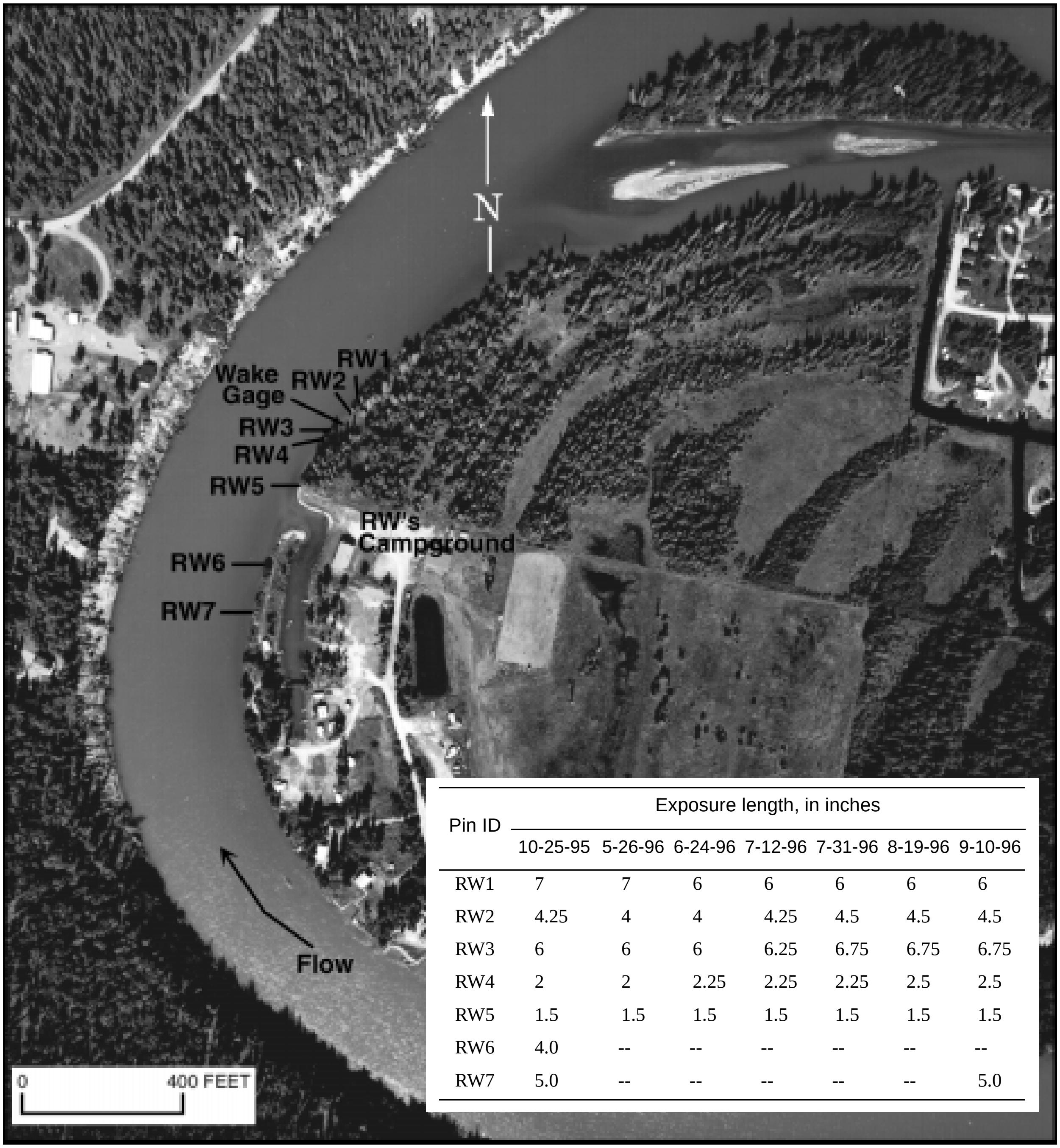
Figure 13. Location and exposure lengths of erosion pins at Cunningham Park site, at river mile 6.5 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

Figure 14. Slump of cohesive bank material at the Cunningham Park study site, July 31, 1996.

Middle River Segment

RW's Campground Site

The first study site in the middle river segment was at RW's Campground (fig. 15), near river mile 16 (fig. 4). This site was one of the primary data-collection sites for this study and included seven erosion pins and a wake gage. The site was selected because of its reported high sensitivity to streamside development and its erosion problems mentioned by two previous Kenai River erosion investigators (Scott, 1982; Inghram, 1985). Additionally, homeowners on top of the bluff along the outside of the meander bend at this site have been losing property to the erosive action of the river. These property owners have expressed concern that boats may be accelerating the rate of erosion. One resident claimed that more than 400 boats passed his property the previous 4th of July and that each boat generated a wake that struck the bank at least 20 times (Bill Gibbs, Kenai River waterfront property owner, oral commun., 1996). Scott (1982) described an increase in the number of slide scars on the outside of this meander and speculated that this phenomenon possibly reflects a recent adaptation of fishing, in which a boat drifts by the meander, then powers back up river to re-drift by the same area. This method of repetitive drifting in this potentially productive fishing area was witnessed during this study and is reflected in the large number of wakes recorded by the wake gage. Scott (1982) also presented data indicating an increase in chinook salmon har-



Pin ID	Exposure length, in inches						
	10-25-95	5-26-96	6-24-96	7-12-96	7-31-96	8-19-96	9-10-96
RW1	7	7	6	6	6	6	6
RW2	4.25	4	4	4.25	4.5	4.5	4.5
RW3	6	6	6	6.25	6.75	6.75	6.75
RW4	2	2	2.25	2.25	2.25	2.5	2.5
RW5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
RW6	4.0	--	--	--	--	--	--
RW7	5.0	--	--	--	--	--	5.0

Figure 15. Location and exposure lengths of erosion pins and location of wake gage at RW's Campground site, at river mile 16 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

vest between 1974 and 1979, possibly reflecting an increase in boat use responsible for the increase in slide scars at this study site. The continued increase in the number of chinook salmon taken by sport fishing since Scott's study ended (table 6), indicates possible subsequent increases in fishing activity and boat use.

Table 6. Number of chinook salmon taken by sport fishing in the Kenai River, 1974-95
[Data from Alaska Department of Fish and Game. Annual catch is limited by State regulation]

Year	No. salmon	Year	No. salmon	Year	No. salmon	Year	No. salmon
1974	4,910	1980	5,554	1986	16,565	1992	8,045
1975	2,970	1981	9,810	1987	25,608	1993	23,006
1976	7,018	1982	10,276	1988	30,259	1994	20,022
1977	7,321	1983	15,534	1989	16,383	1995	20,452
1978	7,120	1984	12,332	1990	7,982		
1979	8,295	1985	16,026	1991	7,740		

Erosion data collected at RW's Campground are complemented by a near-continuous record of boat wakes recorded by the wake gage (fig. 16). Although the wake gage was installed in May 1996, recording of wakes did not begin at this site until July 5, 1996 when water was first adjacent to the bank on the inside of the meander bend. The highest number of wakes recorded by the RW's Campground gage was on weekends, and the maximum number of about 1,100 was recorded on Sunday July 28, 1996. The lowest number of wakes typically occurred on Mondays (fig. 16). However, two gaps in the wake data represent periods when the wake gage malfunctioned: August 1 to 18 and August 23 to September 10. After September 4, the water was too low to be recorded by the gage or to affect the bank. Thus, the number of wakes striking the banks at this site may have been greater during the periods when records were not collected. However, the trend was towards decreasing boat activity after the recorded peak on July 28. Missing wake data were estimated from records at the other wake gages and from the State agency counts of boats on the river. Additionally, the wake-gage data indicated that water was adjacent to the inside bank only during the period July 5 to September 4. Erosion measured during this study can be attributed to the river currents or boatwakes only while water was adjacent to the bank.

Erosion pins were installed along the inside of this large meander bend in non-cohesive soils (fig. 12C) on October 25, 1995. The base of the high bank along the outside of the meander bend was undercut and material was actively migrating down its face. Erosion pin measurements along the base of this high outer bank would have been impractical because the material would have deformed and eroded as pins were driven into it. Additionally, the identification of the effects of boatwakes on streambank erosion is easier along the inside meander bend where natural erosion is a minimum (Daniel Hawkins, Professor Emeritus, University of Alaska, Fairbanks, oral commun, 1996) and the effects of boatwakes are concentrated (fig. 2). This sampling strategy is designed to quantify bank erosion in a location where the most likely cause is not natural river currents. Utilizing this strategy results in a comparison of boatwake-induced erosion at a location where erosion caused by other processes is at a minimum.

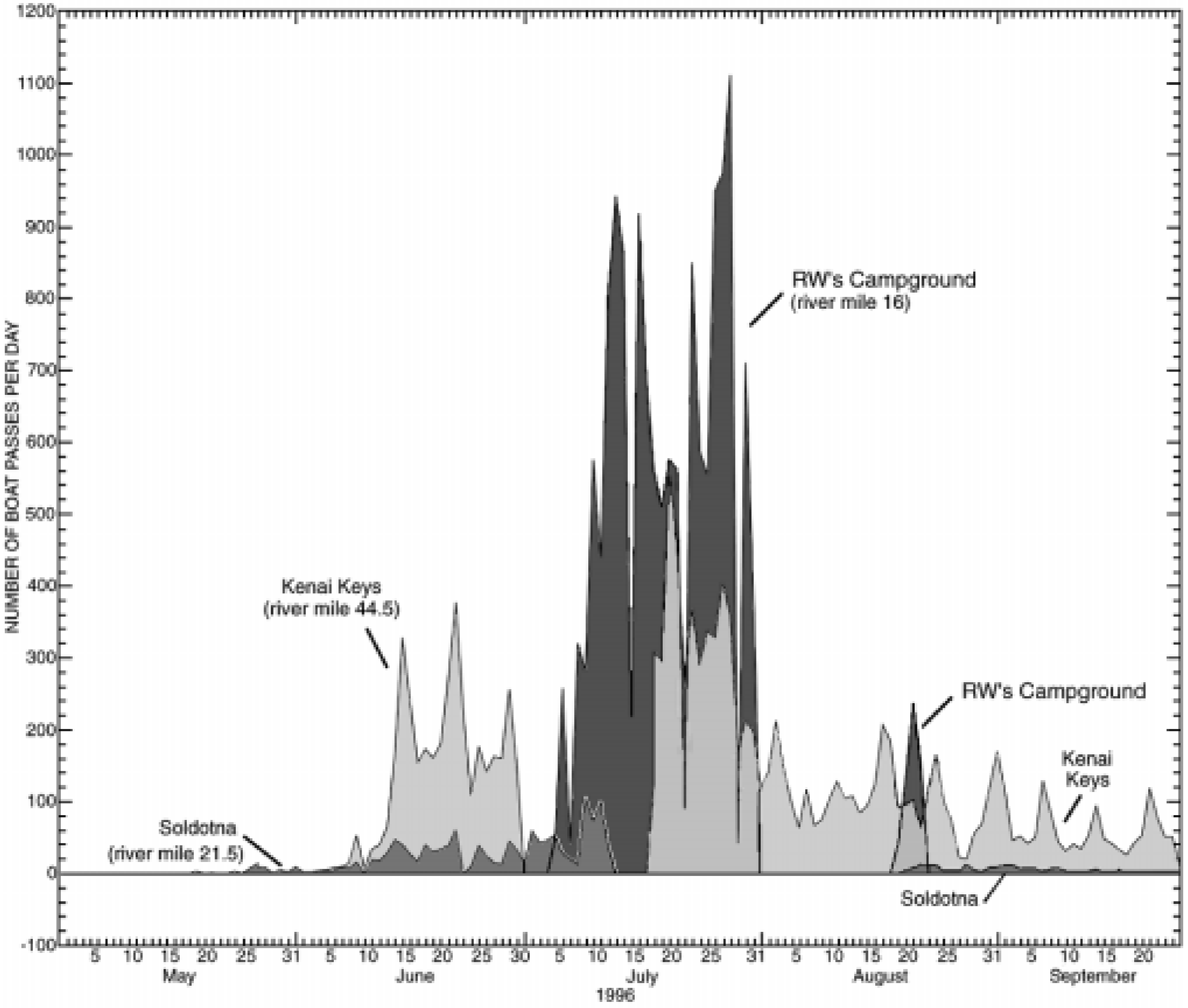


Figure 16. Boat passes by wake gages on the Kenai River.

Exposure-length measurements from the seven pins along the inside of meander bend at RW's Campground did not indicate any large rapid changes (fig. 15). Small increases in the exposure of pins RW2 and RW3 of about 0.25 to 0.5 inch occurred between July 12 and July 31. During this period, boat activity at this site and discharge in the river were near their maximums for the year. Between July 5 and September 4—while water was adjacent to the bank—more than 22,000 boats passed by this site (Appendix table A-1). Extensive bank undercutting was evident in supplementary bank geometry measurements made at pin RW4. Below this pin site, 5 inches of vertical scour extended horizontally inland to a depth of 45 inches (fig. 17). This undercutting of the

Figure 17. Undercut below erosion pin at RW's Campground study site, September 10, 1996.

bank was evident during the site visit on September 10, but had not been evident on July 12, 1996. In addition, increases of as much as 12 inches in the vertical distance between erosion pins and the streambed, indicated additional erosion of the streambed. This streambed erosion likely reflects the removal of new material that was deposited along the bank during the September 1995 flood.

Physical features of the inside bank along the meander bend at RW's Campground include several semi-circular indentations or embayments into the bank that are about 2.5 feet high and extend inland about 7 feet (fig. 18). One of these embayments was rapidly being modified by wake action on July 31. A boatwake would enter the embayment opening at the bank and refract toward the edges. As the wake broke against the embayment, bank and bed material was removed and washed into the river channel where it was subsequently transported downstream. This appeared to be a very efficient mechanism for rapidly increasing the size of the bank embayment. However, this action was effective only during times when the river was almost bankfull, which typically is only for a short period of time near annual peak flows.

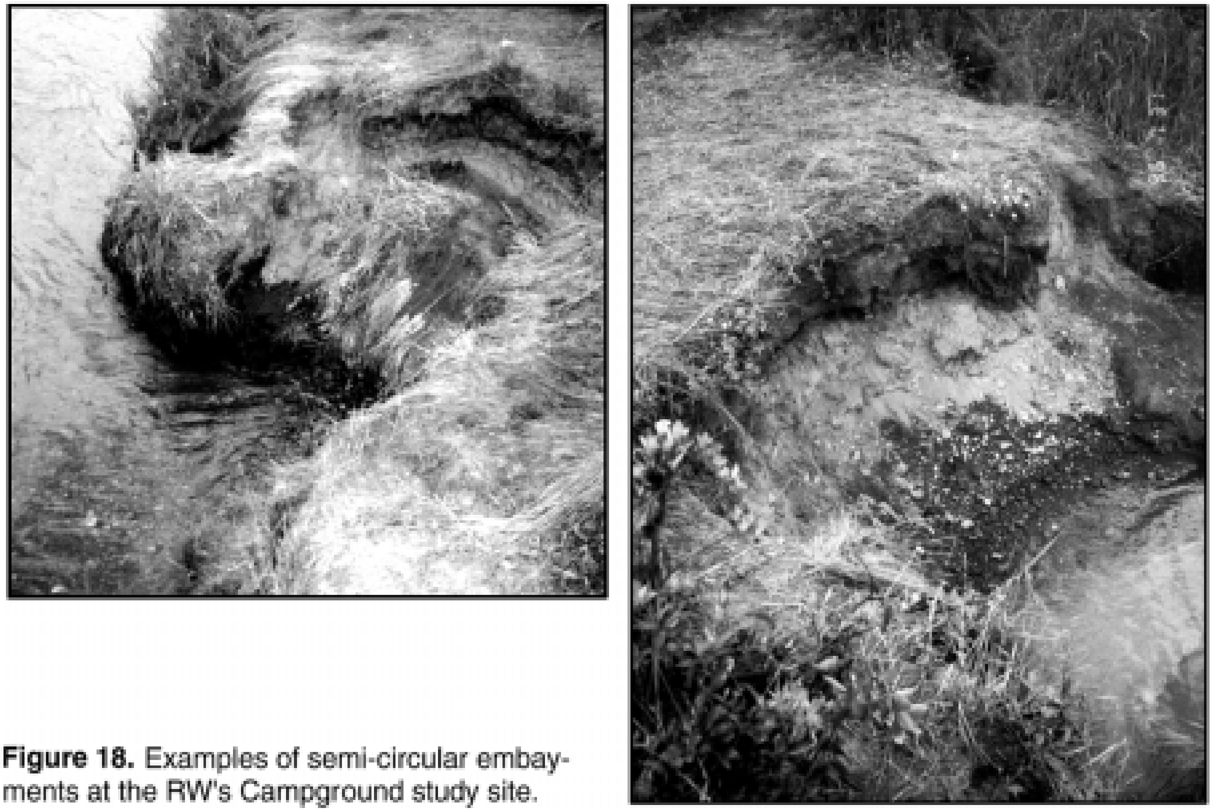
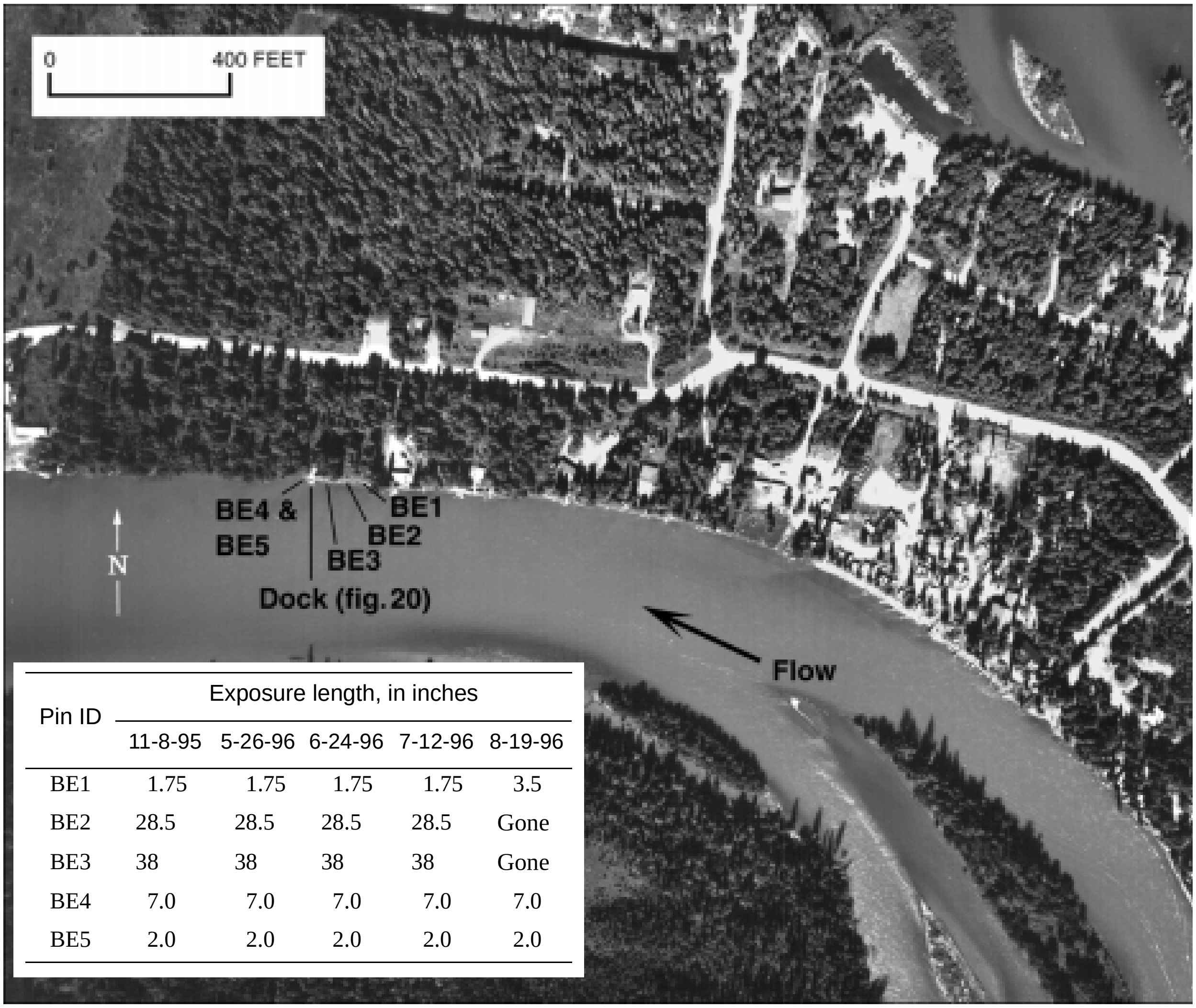


Figure 18. Examples of semi-circular embayments at the RW's Campground study site.

Big Eddy State Recreation Site

About 1 mile upstream from the RW’s Campground study site is the Big Eddy State Recreation Site (fig. 19) near river mile 17 (fig. 4). The site was selected to evaluate the performance of the following bank-protection techniques (fig. 20): (1) a floating dock that extends into the river to discourage bank fishing; (2) an elevated metal walkway along the river to provide bank protection and river access; (3) spruce trees that were cut down, placed into the river parallel with the flow, and cabled to the bank to protect the bank from erosion; and (4) rock riprap placed against the bank near the floating dock for additional protection. Although site-specific wake records are not available, this site likely was exposed to a level of boat activity and river flow similar to those recorded at the nearby RW’s Campground wake gage (fig. 16).



Pin ID	Exposure length, in inches				
	11-8-95	5-26-96	6-24-96	7-12-96	8-19-96
BE1	1.75	1.75	1.75	1.75	3.5
BE2	28.5	28.5	28.5	28.5	Gone
BE3	38	38	38	38	Gone
BE4	7.0	7.0	7.0	7.0	7.0
BE5	2.0	2.0	2.0	2.0	2.0

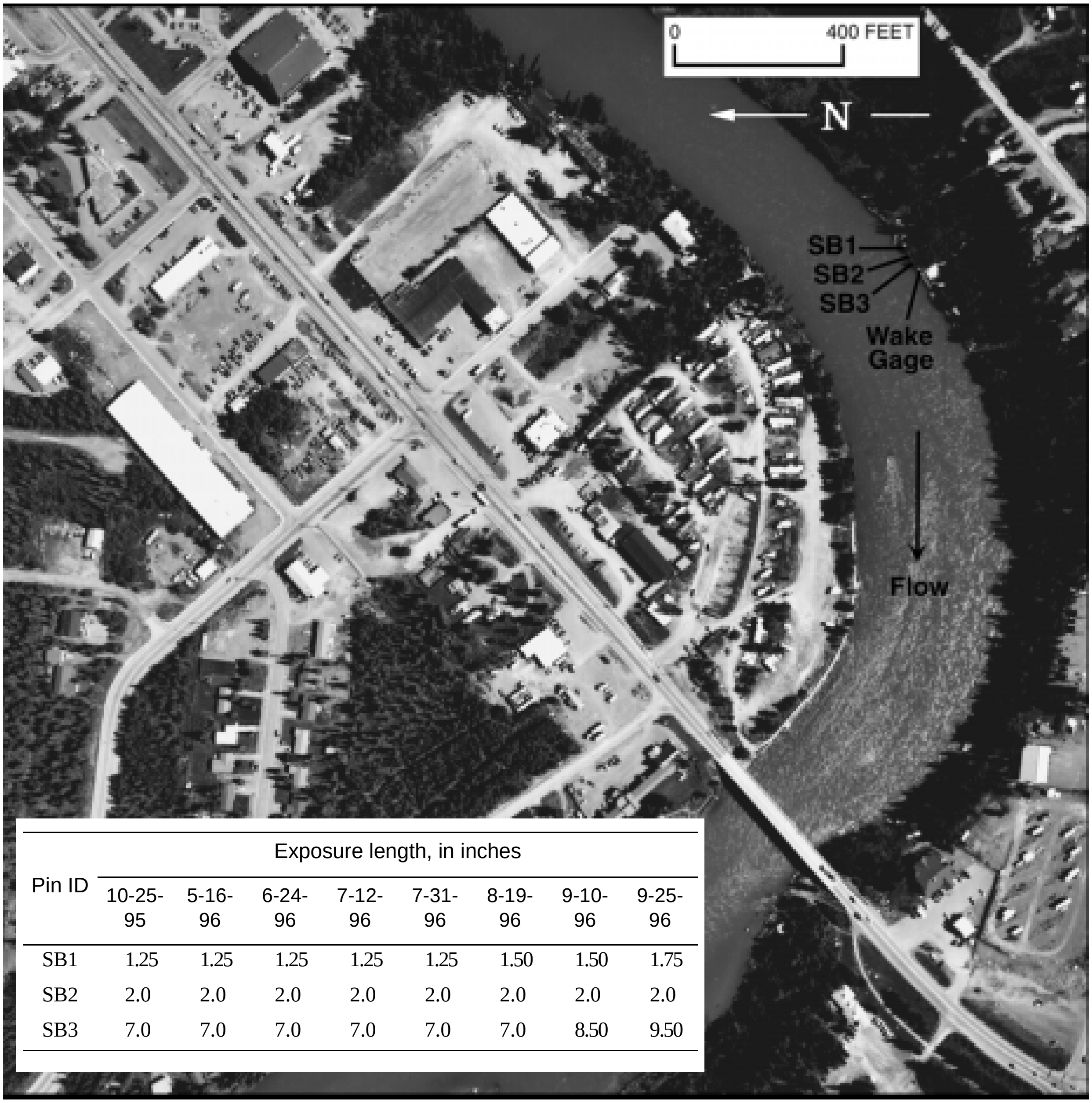
Figure 19. Location and exposure lengths of erosion pins at Big Eddy State Recreation Site at river mile 17 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

Figure 20. Bank protection techniques at Big Eddy State Recreation Site.

Erosion measurements at this site indicated that negligible erosion occurred between November 8, 1995 and July 12, 1996, but a large amount of erosion occurred between July 12 and August 19, 1996. Following this later period, the riverbank beyond the extreme upstream and downstream ends of the elevated walkway did not erode substantially. However, along the middle-to-upstream end of the walkway, the erosion measuring points that had been used were gone (pins BE2 and BE3, fig. 19) because of landward bank erosion. Along this approximately 30-foot-long section of the walkway, the bank was undercut about 32 inches and the walkway posts used to measure bank loss had disappeared. Spruce trees cabled to the bank at the upstream end of the site were gone on August 19. Their absence likely permitted an initiation of erosion at the site. The erosion extended inland to the edge of a path that was used prior to the installation of the elevated metal walkway. The rock riprap near the floating dock protected the remaining bank from the middle-to-downstream end of the walkway from erosion. Peak river flow for the year (fig. 5) and peak boat activity at the RW's Campground site just downstream occurred during the period when the erosion took place at this site. The peak flow included the addition of water released by the glacier in the headwaters of the Snow River (fig. 4).

Soldotna Site

The next upstream study site is along the southern streambank near river mile 21.5 (fig. 4) about 0.5 mile upstream from the Sterling Highway Bridge in Soldotna (fig. 21). This site was another primary data-collection point for this study and included three erosion pins and a wake gage. The site was selected for study because it represents the middle segment of the river where average erosion rates are less than 1 foot per year, the channel is underfit, and the relative sensitivity to streamside development is low (table 2). The site included a naturally vegetated bank approximately 30 feet long and a protected bank about 100 feet long. The bank protection included an elevated walkway, cabled spruce trees, planted live willows, and a series of biodegradable coconut-husk-weave logs anchored to the bank.



Pin ID	Exposure length, in inches							
	10-25-95	5-16-96	6-24-96	7-12-96	7-31-96	8-19-96	9-10-96	9-25-96
SB1	1.25	1.25	1.25	1.25	1.25	1.50	1.50	1.75
SB2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
SB3	7.0	7.0	7.0	7.0	7.0	7.0	8.50	9.50

Figure 21. Location and exposure lengths of erosion pins and location of wake gage at Soldotna site, at river mile 21.5 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

The wake gage at the Soldotna study site was in operation from October 25, 1995 to September 25, 1996. Fishing from boats near the Sterling Highway Bridge is restricted, so the Soldotna wake-gage records likely reflect only boat movement passing by the site and not the heavy fishing or drifting traffic that was recorded at the RW's Campground wake gage. Concurrent records indicated that the number of wakes at the RW's Campground site was much higher than that at the Soldotna study site. For example, during the second week in July, the number of wakes at the RW's Campground wake gage was as much as 20 times higher than, and averaged about 10 times higher than, the number of wakes at the Soldotna wake gage (fig. 16). Although the number of wakes is different, a similar temporal pattern in the wake records was evident. The number of wakes at the Soldotna gage was highest on weekends and lowest on Mondays (fig. 16). The relative numbers of wakes and their pattern of occurrence at the other wake gages were used to estimate days of missing wake data at the Soldotna wake gage, which included the period July 15 to August 19.

Records from the gage indicated that water was adjacent to the bank and was unfrozen from initial start-up on October 25 until November 5, 1995. Then the river was frozen or was not high enough to be adjacent to the bank again until June 4, 1996. Erosion measurements made at the site only reflect the effects of the river currents or boatwakes during the period when water was adjacent to the bank and unfrozen.

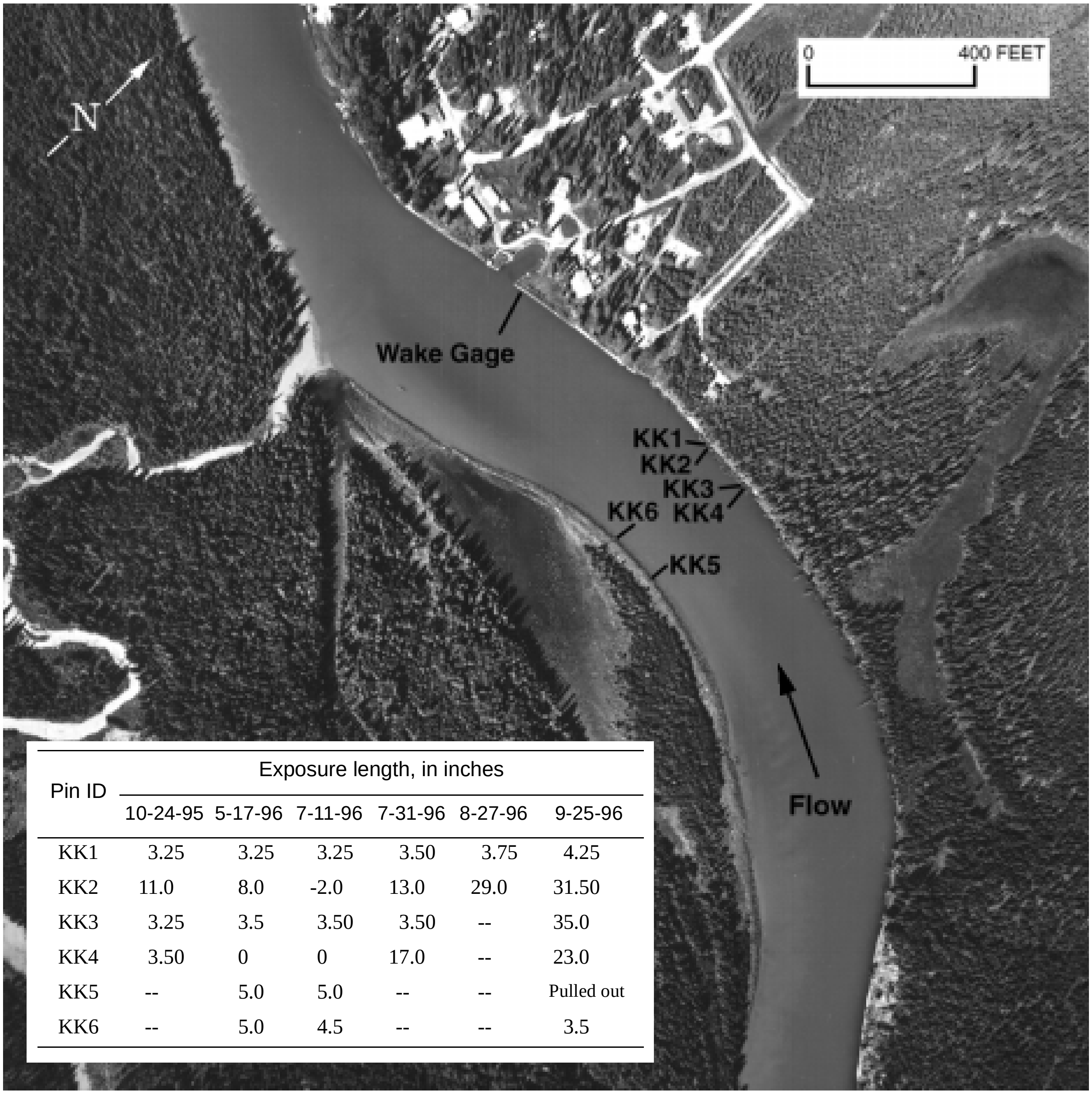
Erosion pins were installed at this site in the streambank and streambed at the same time as the wake gage was put into operation. The bank was fine-grained non-cohesive material (fig. 12D) and was covered with grasses and low willow and alder. Pins were installed along the unprotected segment of the bank upstream from the bank protection and walkway. Pin SB1 was installed high in the approximately 3-foot-vertical bank in the vegetation mat, and pin SB2 was installed in the lower bank in unconsolidated material. Pin SB3 was installed in the streambed, and the horizontal distance between this pin and the streambank was monitored. Exposure of these pins was measured periodically from installation through September 25, 1996 (fig. 21). In addition to the erosion indicated by the pin exposure measurements, the base of the streambank was undercut between 9 and 17 inches between June 24 and September 25. This segment of the river was predicted to erode less than 1 foot per year (table 2). No erosion was evident along the protected bank. In fact, this area appeared to accumulate fine-grained sediment in the spruce trees and logs. Although erosion measurements had not begun at this site prior to the September 1995 flood, this site was generally undamaged by the flood. The walkway and attached deck floated but were not moved downstream and the bank protection, including the cabled spruce trees, remained intact (Bill Wirins, Kenai River waterfront property owner, oral commun., 1996).

Upper River Segment

Kenai Keys Site

A site upstream from the Kenai Keys near river mile 44.5 (fig. 4) was selected as another primary data-collection point (fig. 22) to represent erosion and wake activity conditions in the upper motorized segment of the river. This segment was characterized by Scott (1982) as meandering and free to migrate in a channel that is generally the product of the present flow regime. This segment is rated high in relative sensitivity to streamside development and had an average erosion rate of 5 feet per year between 1950 and 1977 (table 2).

The wake gage was placed along a section of the bank protected from erosion by a vertical wooden retaining wall. Collection of wake-gage records began on October 24, 1995 and continued through September 25, 1996. These data indicated that the lowest number of wakes was recorded on Mondays and the highest number of wakes was recorded on weekends: the recorded peak in wake activity was on Saturday July 20, when 555 wakes were recorded. This peak is about half the maximum number of wakes recorded at the RW’s Campground site, and about five times the maximum recorded at the Soldotna gage. Wake-gage records for the period July 3 to September 1 are given in table A-1 of the Appendix for comparison among the three wake-gage sites. Wake data were estimated during the period July 1-17 because of an instrument malfunction. The peak in wake activity could have occurred during this time.



Pin ID	Exposure length, in inches					
	10-24-95	5-17-96	7-11-96	7-31-96	8-27-96	9-25-96
KK1	3.25	3.25	3.25	3.50	3.75	4.25
KK2	11.0	8.0	-2.0	13.0	29.0	31.50
KK3	3.25	3.5	3.50	3.50	--	35.0
KK4	3.50	0	0	17.0	--	23.0
KK5	--	5.0	5.0	--	--	Pulled out
KK6	--	5.0	4.5	--	--	3.5

Figure 22. Location and exposure lengths of erosion pins and location of wake gage at Kenai Keys site, at river mile 44.5 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

The wake-gage records and supplementary boat-activity observations indicate that the gage site is a popular fishing hole. Numerous passes of the same boats are evident in the observations (Will Josey, property owner, written commun., 1996) and wake records indicated times when more than one wake per minute are being recorded. The wake-gage records also indicated that the banks where erosion was measured were directly exposed to water and to wakes only during the period July 3 to September 1. These dates of bank exposure to water are similar to those identified for the RW’s Campground wake gage in the lower river.

Erosion pins were installed about 200 yards upstream from the wake gage (fig. 22), in an undeveloped, heavily vegetated bank of non-cohesive, coarse-grained material (fig. 12E). Erosion investigations at this site began prior to the September 1995 flood, but the pins were removed by the flood. Approximately 8 feet of the bank was removed at this site during that flood.

New erosion pins installed at this site on October 24, after the flood, indicated rapid and large bank erosion (fig. 22). These erosion pins were installed as two pairs: one pair, KK1 and KK2, was about 100 yards downstream from the second pair, KK3 and KK4 (fig. 22). Pins KK2 and KK4 were installed near the base of a nearly vertical, approximately 5-foot-high bank (fig. 23). Initially, decreases in the exposure of pins KK2 and KK4 indicated the downslope movement of upper bank material and the burial of these lower pins. Subsequently, removal of the bank material resulted in a total increased exposure of between 20 and 20.5 inches for these two pins. Pins KK1 and KK3 were installed near the top of the bank. Pin KK3 had a large increase of 31.75 inches in its exposure, whereas pin KK1 was exposed only an additional inch during the study period. Pin KK1 was installed in the vegetation mat of the upper soil, whereas the other three pins were installed in unconsolidated bank material. The average increase in exposure of the three pins in the unconsolidated bank material was about 24 inches. This erosion occurred during a short period of approximately 60 days when these banks were exposed to the heaviest boat activity and continuous currents. Pins KK5 and KK6 were installed on the opposite side of the channel (fig. 22), where the banks slope gently toward the water and are covered with thick grass. Sediment was deposited on this bank. Pin KK6 decreased in exposure 1.5 inches during the entire study period. Pin KK5 was found lying on the riverbed in freshly deposited material, providing additional evidence that this bank was a depositional area during the study period.

Skilak Lake Site

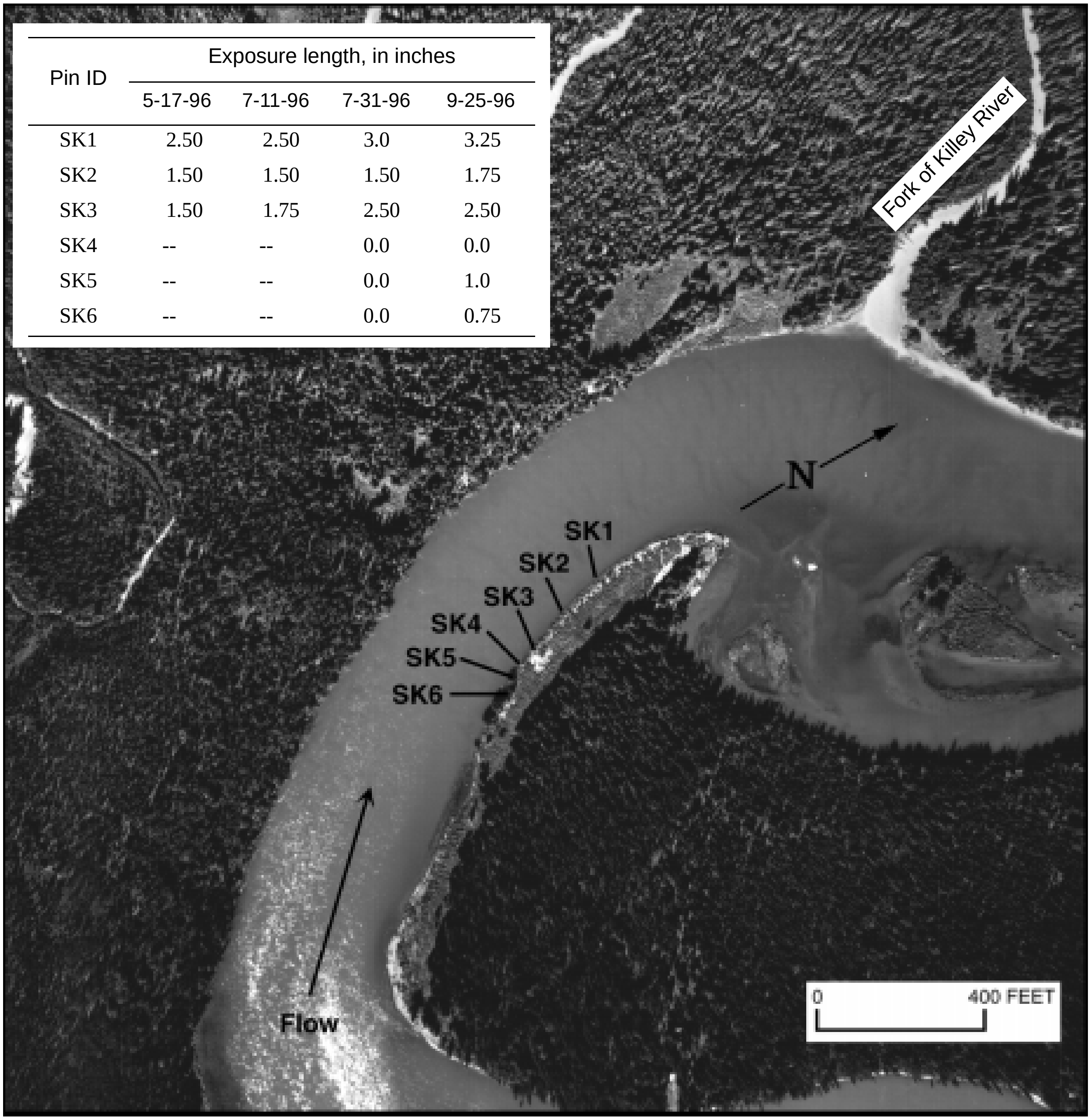
Additional erosion measurements were made in the upper river near river mile 46, about 4 miles downstream from Skilak Lake (fig. 4). This site was selected because it is a popular fishing area and had some fine-grained, cohesive bank material (fig. 12F). The site also had a wide channel where the effects of boats may be reduced. The study site is along an inside meander bend upstream from a fork of the Killey River (fig. 24). Boat activity was not recorded at this site, but the site is less than 2 miles upstream from the Kenai Keys wake gage, so wake activity at these two sites is assumed to be similar in quantity and timing.

Three erosion pins (SK1-3; fig. 24) were installed here on May 17, 1996 near the top of the vertical bank in the vegetation mat of the soil. On a subsequent visit on July 31, these pins were supplemented with three additional pins (SK4-6; fig. 24), which were installed at the water line. This area of the river is near a transition zone that begins at river mile 45.7, where average erosion rates change from about 5 feet per year to about 1 foot per year (table 2). Supplementary measurements of bank geometry below pins SK1-3 indicated downslope movement of bank material. The pins at the water line (SK4-6) provided direct measurement of erosion. Small increased exposures of 0.25 to 0.75 inch at pins SK1-3 in the upper bank occurred between measurements on July 11 and September 25 (fig. 24). Additional measurements of bank geometry near pins at this site indicated that the base of the bank had eroded between 6 and 8 inches. In addition, the bank was undercut 16 and 28 inches near pins SK2 and SK3, respectively, during the study period. Several large semi-circular embayments near the erosion pins extended about 7 feet into the bank indicating that the undercutting process may be effective at this site (fig. 25). The embayments were similar in shape and size to those noted at the RW’s Campground site in the lower river, which indicated a possible connection to wakes as witnessed at the RW’s Campground site.

A

B

Figure 23. River bank at the Kenai Keys study site, July 31, 1996. Total undercut in photo (A) is about 5 feet and pin exposure in photo (B) is about 30 inches.



Pin ID	Exposure length, in inches			
	5-17-96	7-11-96	7-31-96	9-25-96
SK1	2.50	2.50	3.0	3.25
SK2	1.50	1.50	1.50	1.75
SK3	1.50	1.75	2.50	2.50
SK4	--	--	0.0	0.0
SK5	--	--	0.0	1.0
SK6	--	--	0.0	0.75

Figure 24. Location and exposure lengths of erosion pins at Skilak Lake site, at river mile 46 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

Figure 25. Bank erosion at Skilak Lake study site. Note large pieces of cohesive material that have fallen from the bank.

Non-Motorized Segment

Three control sites were selected in the non-motorized segment of the Kenai River between Skilak and Kenai Lakes to assess the rate of bank loss for comparison with that measured in the motorized segments of the river. These control sites did not have any boatwakes affecting the banks and they included varying types and amounts of vegetation, as well as both cohesive and non-cohesive soils. Erosion measurements began at these three control sites on May 30, 1996 and therefore do not include the potential effects of ice, winter flows, or the freeze/thaw cycle. However, the measured open-water erosion can be compared with erosion that occurred during the same period at sites farther downstream in the motorized segment of the river. Discharge records from the Cooper Landing stream-gaging station and measurements of bank geometry at control sites 2 and 3 indicated that water was likely adjacent to the river banks of these two upper control sites only during the periods of June 24 to September 1 and September 18-25. If these dates are correct, the erosion that was measured at these sites most likely occurred during this 76-day period when water currents were adjacent to the banks.

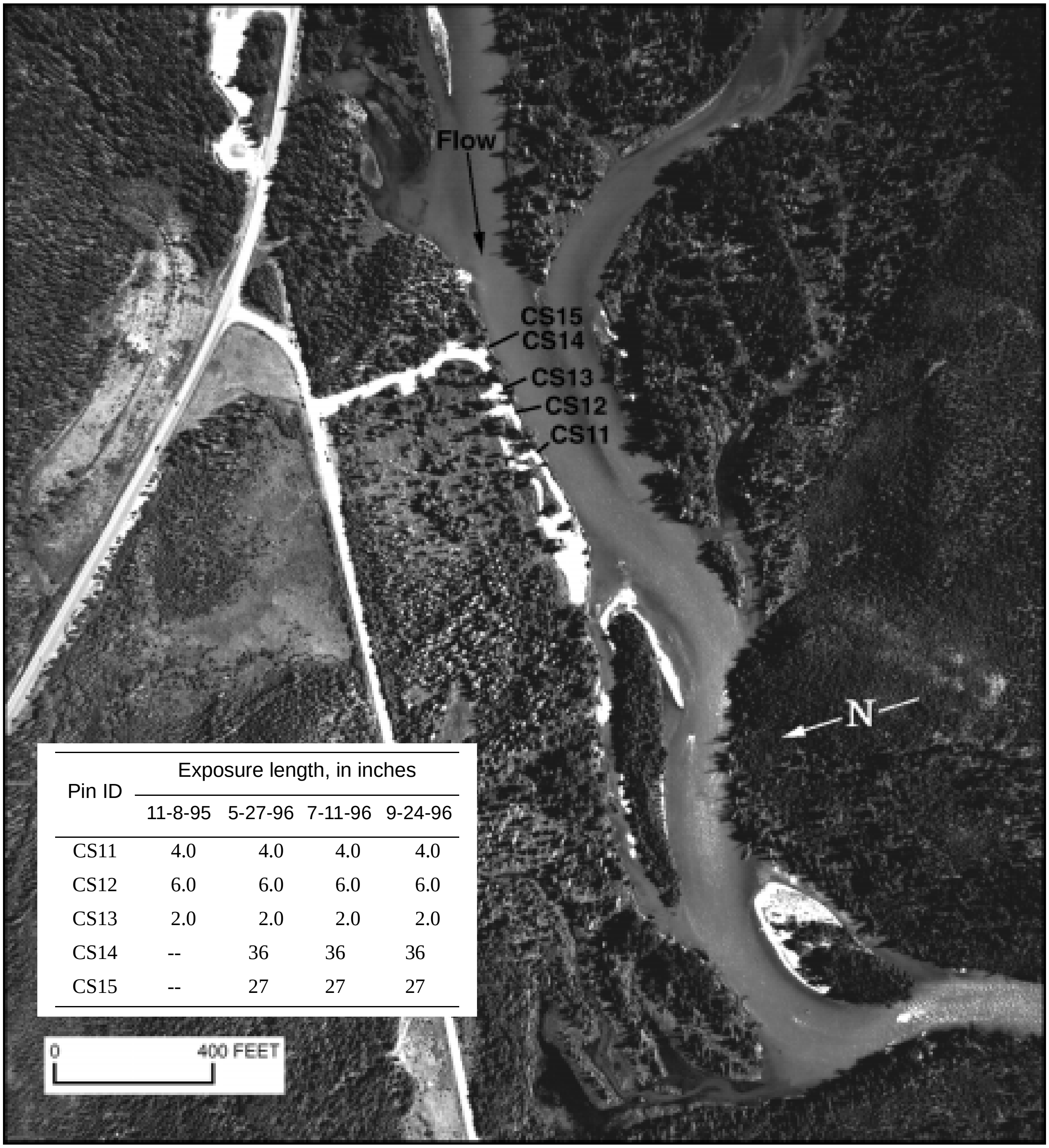
Control Site 1

Control site 1 is at Jim's Landing near river mile 72 (fig. 4; fig. 26). This site had some coarse non-cohesive bank material overlain by a thin soil and mature spruce and hardwood vegetation. Bank heights were about 4 to 6 feet above the river bottom and water flowed adjacent to the measured bank at some depth during the entire study period. Bank-protection measures installed at the site following the September 1995 flood included biodegradable logs, root wads, and willow cuttings. Erosion measured at this site was used to evaluate the performance of these bank-protection measures. Although the bank protection at this site included extensive fencing to restrict foot traffic access to the banks, many well-developed pathways are found at the site and some of the streamside vegetation had been previously damaged by these pathways.

Repeated measurements made from erosion pins and fixed points along the bank indicated that the bank did not erode substantially, but the bank was undercut during the study period. This undercutting was evident along the bank by an increase in the slope of the bank towards the river during the study period. No detailed measurements of the extent of undercutting were possible along part of the bank because the water was too deep. However, near the upstream end of the study site near pins CS14 and CS15 (fig. 26), the bank was undercut about 1 foot during the study period. This undercutting may lead to bank failure because some of the trees along the riverbank are beginning to lean towards the river. Additionally, some trees have been cut down along the bank and their leaning stumps remain adjacent to the bank.

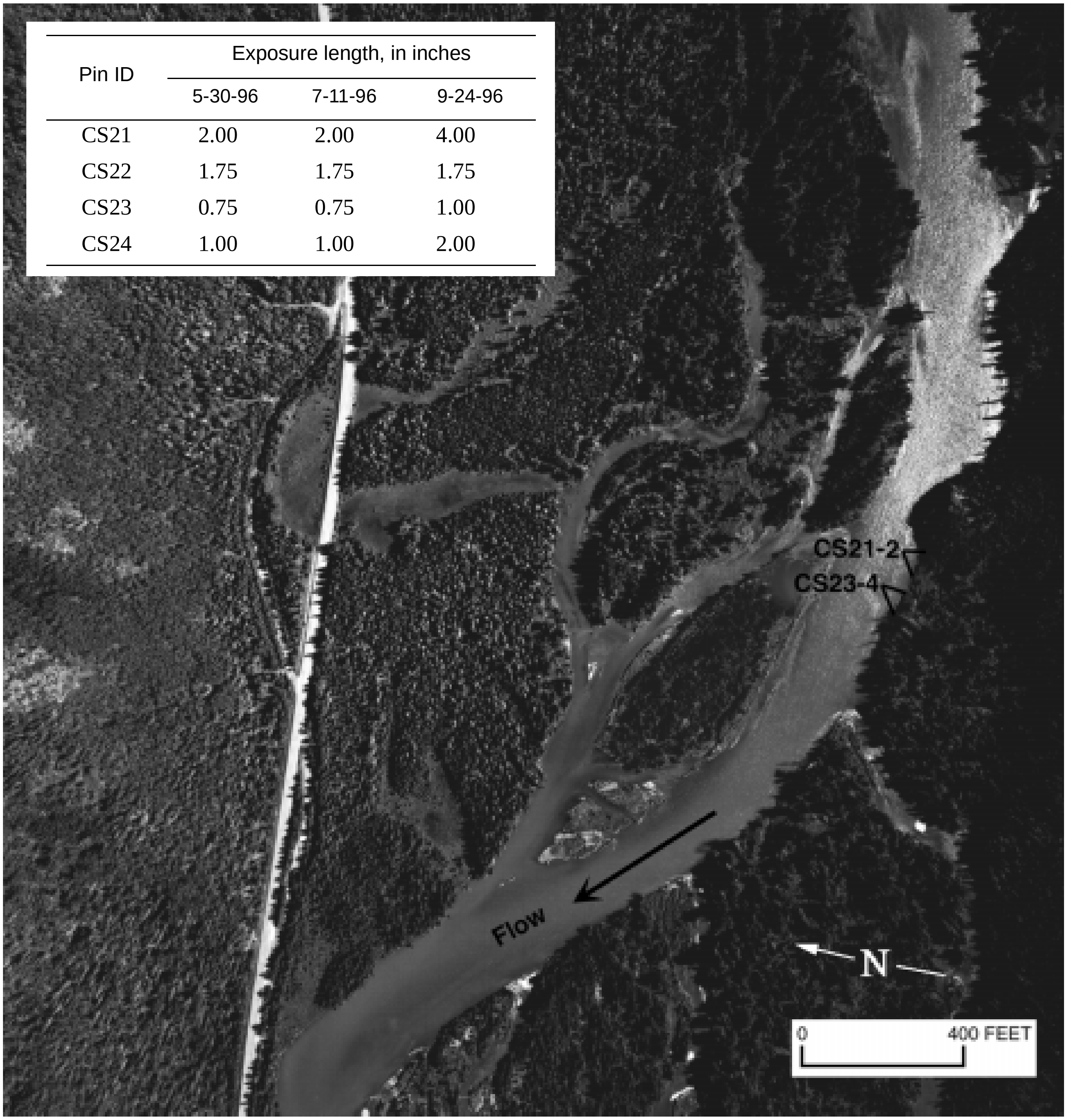
Control Site 2

Control site 2 was near river mile 72.5 (fig. 4; fig. 27). This site had fine grained, cohesive bank materials (fig. 12G) covered by a thick grass mat. Four erosion pins (CS21-4) were installed at this site as two vertical pairs separated by about 100 yards of riverbank (fig. 27). At each vertical pair, one pin was installed in the upper bank near the vegetation mat, and the second pin was installed lower in the bank, near the low-water line. Below pin CS24, the bank was undercut 8 inches when the pin was installed on May 30; this undercut had increased to 18 inches by the end of the study on September 24. Ten inches of bank undercutting at this site is about 77 percent less than the maximum of 45 inches measured at RW's Campground site farther downstream in the motorized segment. The average increase in exposure was about 0.8 inch for the four pins installed at this site (fig. 27).



Pin ID	Exposure length, in inches			
	11-8-95	5-27-96	7-11-96	9-24-96
CS11	4.0	4.0	4.0	4.0
CS12	6.0	6.0	6.0	6.0
CS13	2.0	2.0	2.0	2.0
CS14	--	36	36	36
CS15	--	27	27	27

Figure 26. Location and exposure lengths of erosion pins at Control Site 1, at river mile 72 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

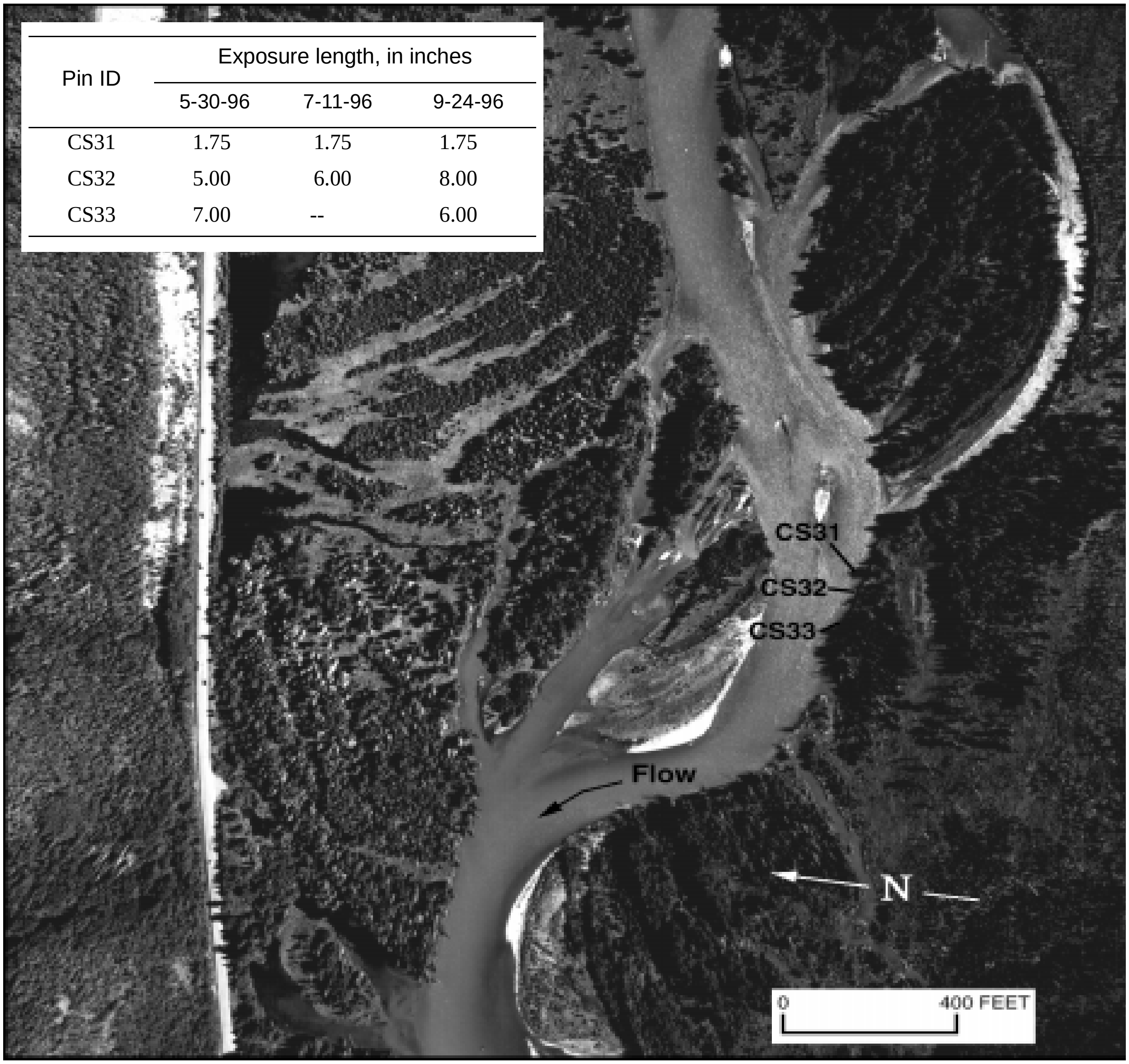


Pin ID	Exposure length, in inches		
	5-30-96	7-11-96	9-24-96
CS21	2.00	2.00	4.00
CS22	1.75	1.75	1.75
CS23	0.75	0.75	1.00
CS24	1.00	1.00	2.00

Figure 27. Location and exposure lengths of erosion pins at Control Site 2, at river mile 72.5 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

Control Site 3

Control site 3, the most upstream study site, was at about river mile 73 (fig. 4; fig. 28). This site had coarse-grained, non-cohesive bank materials (fig. 12H) that were overlain by a 20-inch soil layer and mature hardwood vegetation. Erosion at this site was characterized by exposure measurements at pins CS31 installed in the upper soil, CS32 installed below the soil in the unconsolidated bank, and pin CS33 placed in the streambed (fig. 28). Measurements at pin CS32 indicated 3.00 inches of bank erosion. Sediment deposits 1 inch thick on the streambed were indicated by height measurement data from pin CS33. Additional geometry measurements made near the erosion pins indicated that a maximum undercutting of the streambank of about 12 inches occurred during the study period. This undercutting was the largest measured in the non-motorized segment of the river and was about 73 percent less than the maximum of 45 inches measured at RW's Campground where boat activity had been the greatest.



Pin ID	Exposure length, in inches		
	5-30-96	7-11-96	9-24-96
CS31	1.75	1.75	1.75
CS32	5.00	6.00	8.00
CS33	7.00	--	6.00

Figure 28. Location and exposure lengths of erosion pins at Control Site 3, at river mile 73 along the Kenai River. [Date of aerial photograph is August 16, 1995.]

DISCUSSION OF STUDY RESULTS

Boat Activity

Although some boatwake data were lost due to instrument malfunctions, a comparison of the recorded wake-gage data indicated that more wake activity occurred in the RW’s Campground area than in either the Kenai Keys or Soldotna areas. Recorded peaks in the wake data indicated that during peaks in activity, about 10 times as many wakes were recorded at RW’s Campground (river mile 16) than at Soldotna (river mile 21.5), and about twice as many wakes were recorded at RW’s Campground than at the Kenai Keys (river mile 44.5). From the boat counts, it is evident that more boats use the Kenai River between river mile 8.5 and 20 than use the segments farther upstream or downstream. Guided boats represent 40 percent of the boats counted by the ADNR, 55 percent of the boats counted by the ADF&G, and 57 percent of those recorded by direct observation during this study.

Boatwake Activity and Boat Operation

The timing of boatwake activity on the Kenai River closely follows the pattern of chinook salmon fishing. For example, Mondays are closed to fishing from boats during July (Hammerstrom, 1996a) and Monday is commonly the day with the lowest recorded wake activity. Additionally, the middle of July is typically the peak in late-run salmon returns to the Kenai River (Hammerstrom, 1996b) and also the period of peak recorded wake activity.

Boat traffic was correlated to recorded wakes by direct observation of boat passes at the wake gages and by comparisons with boat counts made in specific river segments by the ADNR and ADF&G. Direct observations of boat activity indicated that boats operating on the Kenai River varied in length from 10 to 26 feet, carried from 1 to 8 passengers, and generally had either a flat-bottom, semi-V, or inflatable hull design. The most commonly observed boats on the river were commercially guided flat bottom fishing boats that were between 16 and 20 feet long and carried 4 or 5 passengers. Observations made at the wake gages also indicated that a wide variety of wake sizes were generated by boats of similar size and carrying similar numbers of passengers, depending on how the boat was operated on the river. For example, the wake was smaller when a boat was farther across the channel from the gage then when it was closer to the gage.

Boat Experiment

To better understand the effects of unrecorded boat-operating conditions on wake generation, an experiment was undertaken near the Kenai Keys wake gage. During the experiment, three boats with different hull designs passed by the wake gage and an erosion measurement site at the Kenai Keys study site. Each type of boat passed by the study site at its maximum speed but carried various passenger loads and passed at different distances away from the streambank (fig. 9). The average maximum wake height recorded for each boat (table 7) was calculated from two measured wake heights generated as the boat passed by the wake gage traveling upstream and then traveling downstream. This procedure was done for three different boat hull designs, four different passenger loads, and five different distances across the channel. A logical pattern of increasing wake height with increasing passenger loads resulted (table 7). In addition, a pattern of decreasing wake heights resulted from increasing the distance between the gage and the boat being operated. For most tests,

Table 7. Boat-wake heights recorded on the Kenai River, August 27-28, 1996
[--, no data]

Type of boat and motor	Distance		Average of two maximum wake heights measured while boat passed upstream and downstream (Data in feet)				
	Percent of channel width	From riverbank (feet)	1 passenger (150 pounds)	2 passengers (300-400 pounds)	4 passengers (550-750 pounds)	6 passengers (1000-1100 pounds)	
Flat-bottomed 20 feet long 35/40 horsepower 2-cycle outboard	Next to bank	5-10	0.49	0.56	0.66	0.91	0.77[a]
	10	20-40	0.30	0.42	0.61	0.72	--
	25	60-80	0.26	0.39	0.38	0.49	0.48[a]
	50	140-160	0.28	0.26	0.25	0.38	0.52[a]
	75	180-200	0.18	0.27	0.26	0.29	--
Semi-V 20 feet long 35/50 horsepower 4-cycle outboard	Next to bank	5-10	0.54	0.57	0.78	0.93	--
	10	20-40	0.52	0.45	0.60	0.79	--
	25	60-80	0.47	0.42	0.52	0.63	--
	50	140-160	0.41	0.37	0.44	0.56	--
	75	180-200	0.22	0.30	0.36	0.48	--
Inflatable 16 feet long 30 horsepower 2-cycle outboard	Next to bank	5-10	--	0.47[b]	0.44	--	--
	25	60-80	--	0.31[b]	0.35	--	--
	50	140-160	--	0.23[b]	0.21	--	--

[a] Data for 40-horsepower motor
[b] Data for 3-passenger load

the semi-V-hull boat generated larger wakes than did flat-bottom or inflatable boats. During the experiment, the wake height generated by the flat-bottom boat was reduced by an average of 60 percent as the boat moved from the closest pass by the gage to the farthest away. The other two hull designs (semi-V and inflatable) had an average wake-height reduction of 52 percent when the boat's position in the channel changed from nearest to the gage to farthest away.

To assess the effect of the experimentally generated wakes on the streambanks, the swash load (weight of sediment transported at the base of the streambank) was measured after each round trip (upstream and downstream) boat pass (table 8). There was no movement of sediment into the swash load collection pan between boat passes when boats wakes were not striking the bank. The wake heights (table 7) that were used for comparison with the weights of sediment collected were the average of two maximum wake heights. One maximum wake height was recorded while the boat passed the wake gage traveling upstream and the other while the boat passed downstream. The greatest difference between 43 recorded upstream and downstream wakes was 45 percent, the minimum difference was less than 2 percent, and the difference averaged 18 percent of the measured wake heights.

Table 8. Swash load samples collected during boat-wake experiment on the Kenai River, August 27-28, 1996
[--, no data]

Type of boat and motor	Distance		Sediment weight collected while boat passed upstream and downstream (Data in pounds)				
	Percent of channel width	From riverbank (feet)	1 passenger (150 pounds)	2 passengers (300-400 pounds)	4 passengers (550-750 pounds)	6 passengers (1000-1100 pounds)	
Flat-bottomed 20 feet long 35/40 horse-power 2-cycle outboard	Next to bank	5-10	0.19	0.49	1.55	1.35	1.5[a]
	10	20-40	.07	.21	.28	.39	--
	25	60-80	.13	.12	.21	.56	.25[a]
	50	140-160	.03	.23	.16	.07	.19[a]
	75	180-200	.03	.02	.02	.04	--
Semi-V 20 feet long 35/50 horse-power 4-cycle outboard	Next to bank	5-10	.69	.86	.92	.58	--
	10	20-40	.37	.18	.17[b]	--	--
	25	60-80	.30	.08	--	--	--
	50	140-160	.17	--	.13	--	--
	75	180-200	.18[c]	.07	.14	--	--
Inflatable 16 feet long 30 horsepower 2-cycle outboard	Next to bank	5-10	--	.09[d]	.09	--	--
	25	60-80	--	.03[d]	.02	--	--
	50	140-160	--	.02[d]	.05	--	--

[a] Data for 40-horsepower motor
[b] Collection pan came loose
[c] Non-test boat passed by
[d] Data for 3-passenger load

A graphical display of all the swash-load data indicates that some quantity of sediment was transported by even the smallest wakes and that the quantity increased exponentially when the maximum wake heights were greater than a value of about 0.45 foot (fig. 29A). By converting the wake heights and swash load values to their corresponding logarithmic values, a more linear relation is evident [log swash load = 0.118 + 2.33 (log wake height)] (fig. 29B). This linear relation can be used for predicting swash load values at the Kenai Keys study site resulting from wake heights that were not directly measured but were within the range of the data measured and environmental conditions present during the experiment. However, because the environmental factors controlling erosion at this site, such as water depth and bank soil moisture content, will change over time, this predictive relation must be used with great caution. First, it is difficult to predict the effects of numerous future wakes accurately on the basis of the measured effects of a single wake. For example, if a 0.50-foot-high wake transported 0.20 pound of bank material per square foot of bank, will 100 similar future wakes transport 20 pounds? Secondly, the effect of wakes on the bank also likely changes over time as new material in the bank with different properties is exposed and

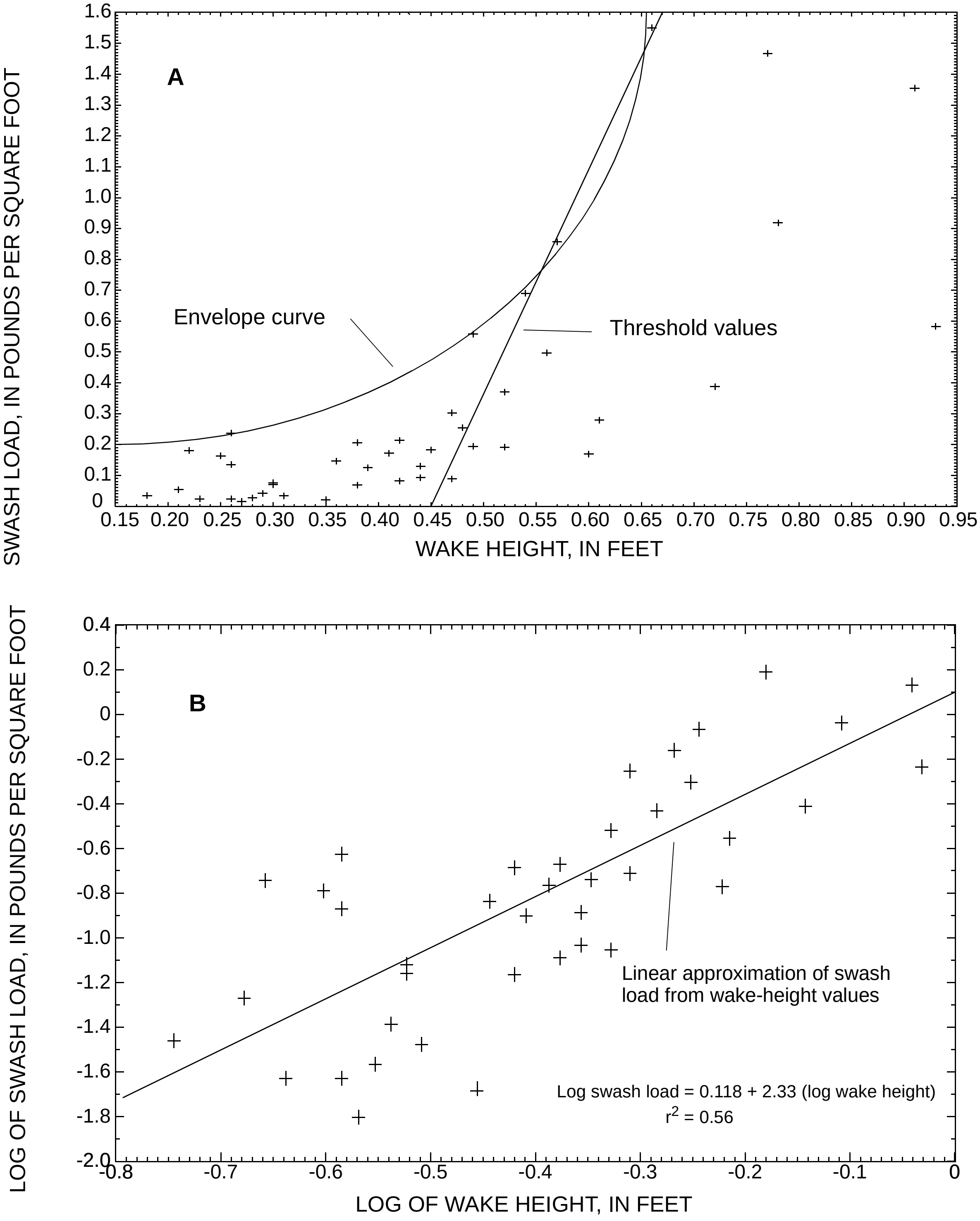


Figure 29. Swash load and maximum wake height for Kenai River boat experiment.

ambient conditions change. For example, the moisture content of the streambanks and the subsequent resistance of the banks to erosion change as water depth adjacent to the banks changes. Additionally, this linear relation between maximum wake height and swash load was established only for this one specific site and thus it should not be applied at other sites on the river. For example, in areas of the river where soil and vegetation characteristics are different, the relation between maximum wake height and swash load will likely be substantially different. Similar experiments at additional sites would be required to determine a broadly applicable relation between wake height and swash load and these additional experiments would have to be done under varying environmental conditions to characterize a reliable predictive relation.

The repetitive impact of numerous boatwakes on the streambank at the Kenai Keys study site was also evident in a flat shelf about 6 inches high and 12 inches deep that was eroded into the base of the bank near the sediment data-collection site during the experiment. This shelf was very similar to the one documented by a downstream property owner whose waterfront gravel bank had a similar-sized flat shelf cut into it after each boating season during the last 5 years (fig. 30) (David Morris, Kenai River waterfront property owner, written commun., 1996).

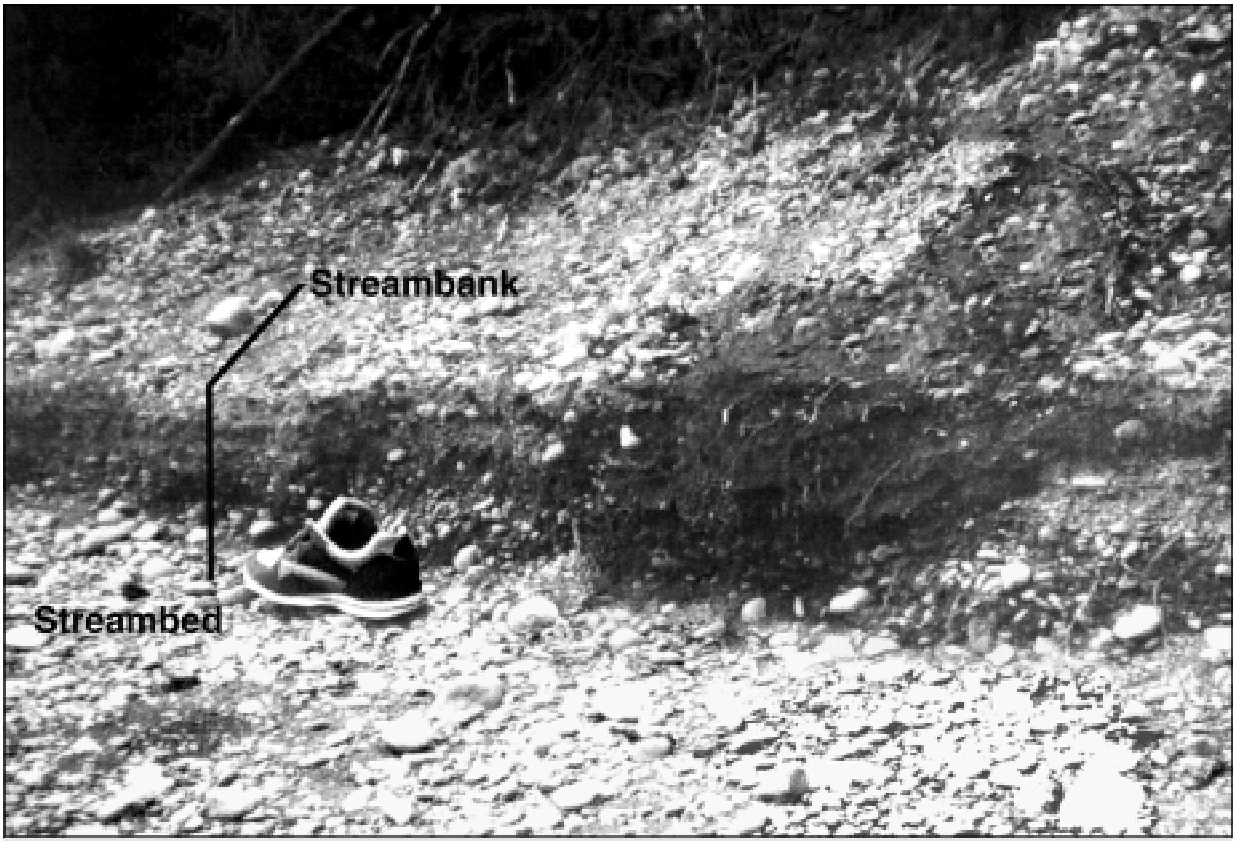


Figure 30. Shelf cut into streambank by boatwakes along the Kenai River. (Photo by David Morris.)

The following boatwake erosion processes were observed during the experiment: (1) lifting of the streambed sediment into the water column as the wake began to break or curl over as it entered the shallow water near the shore, (2) dislodging of bank material by the impact of the wake against the bank and suspension of this material into the water, (3) washing of the bank and streambed as the wake returned to the river, and (4) transporting of the sediment downstream by the river. The swash load collection scheme employed during the experiment was designed to trap or collect the bank and streambed material as it was being washed into the river following the first three processes described above. The largest of the wakes observed during the experiment appeared to transport the most sediment by impact upon the bank, whereas the smallest wakes appeared to incorporate sediment most effectively by suspending previously dislodged material into the water when the wakes are breaking in the shallow water near the shore.

Boatwake Heights

The maximum height of wakes in a wake train is a significant factor influencing its ability to erode material from a river bank (Nanson and others, 1994; Von Krusenstierna, 1990). The maximum wake heights of thousands of wake trains were recorded at the three gages on the Kenai River. The maximum wake heights of all the measured wakes ranged from 0.10 to 1.50 feet. A subset of the wake data, collected during a period of high boat activity, was used to compute an average maximum wake height for each study site (table 9).

Table 9. Maximum wake heights recorded at wake gages on the Kenai River, July 1996

Site	Date	No. wake trains	Maximum wake height, in feet	
			Range	Average
RW’s Campground	July 12-16	3,550	0.10-0.65	0.35
Soldotna	July 5-9	224	0.15-0.70	0.30
Kenai Keys	July 19-23	2,200	0.15-1.20	0.46

If it is assumed that the most common boat types are similar at all three sites (as indicated by the observations), then the boat-operating conditions control wake heights at each site. Of the three wake-gage sites, the average maximum wake height was highest at the Kenai Keys site and lowest at the Soldotna site. This difference results primarily because many boats pass close by the Kenai Keys wake gage where the channel is deeper than it is along the opposite bank. In contrast, observed boat traffic near the Soldotna gage was often noted as going slowly and staying near the center of the channel because the channel is rocky and very difficult to navigate. The average maximum wake height at RW’s Campground wake gage was lower than that at Kenai Keys, because boat traffic near RW’s Campground was typically observed either drifting downstream next to the far bank or passing upstream more than halfway across the channel from the gage.

Evaluating Effects of Boatwakes

During this study, both the maximum height of boatwakes and detailed measurements of bank loss were recorded at only three specific sites along the Kenai River. As a result, there may be limited applicability of the wake-height and bank-loss information to other locations along the river. At each site where boatwakes and bank loss were measured, the maximum bank loss measured and the number of boats passing the site during the approximate period when the bank loss occurred are summarized on table 10.

Table 10. Comparison of maximum bank-loss and boat-activity data at selected sites on the Kenai River

Site	Bank loss (inches)	No. days during which bank loss occurred	No. boats passing each site during periods of bank loss
Motorized segment			
RW’s Campground	45	60	22,008
Soldotna	17	90	2,770
Kenai Keys	31.75	60	12,123
Non-motorized segment			
Control site 3	12	76	Not applicable

To evaluate the direct effects of boatwakes at these sites, it is also important to consider additional contributions to bank loss. The measured bank loss occurred at these sites without evidence of substantial erosion from foot traffic, from ground-water inflow, or from gravity-driven slumps. Additionally, with the exception of 0.25 inch of increased exposure at pin KK3 at the Kenai Keys site (fig. 22), no erosion occurred during the period October to May at the three sites in the motorized segment of the river (figs. 15, 21, and 22) indicating that ice or the freeze/thaw cycle were not significant erosion factors at these three sites. Therefore, by calculating and comparing the energy dissipated against these study site banks by the river currents to the energy dissipated against the banks by boatwakes, the two primary erosion-generating forces can be evaluated.

During the study period, unusual flow conditions occurred on the Kenai River: (1) a 100-year flood interrupted the early data collection, (2) streamflow was well below normal during the following spring and summer, and (3) an outburst flood occurred late in the study. These flood and low-flow conditions largely affected the energy contributions from the river’s current. Without additional data about past and future boatwake activity and bank erosion on the Kenai River, it will be difficult to evaluate data collected during this study in terms of what effects may occur in the future or may have occurred in the recent past. Additionally, because the study sites could not cover the entire river, the results of the energy comparisons cannot depict the relative importance of tractive forces and boatwakes universally along the river.

Tractive Energy

Tractive energy for the Soldotna and RW's Campground sites was calculated using hydraulic information derived from the on-site wake gages and discharge records from the Soldotna stream-gaging station (Appendix, tables A-2 and A-3). Tractive energy for the Kenai Keys site was calculated using hydraulic information from the on-site wake gage and discharge records from the Cooper Landing stream-gaging station (Appendix, table A-4). A relation between discharge and mean velocity, and discharge and mean depth was determined from numerous measurements of discharge at the two gaging stations using relations explained by Leopold and Maddock (1953) and by Rantz and others (1982). Using the 1996 discharge records from the stream-gaging stations, which were preliminary values at the time of these calculations, the applicable hydraulic characteristics of each study site were estimated. These hydraulic characteristics were then used to calculate the total available tractive erosion energy in the river channel at each study site using the equation of Limerinos and Smith (1975):

$$E_t = \frac{2.44 \times 10^6 V^3 n^2}{R^{1/3}} \tag{1}$$

where E_t is tractive energy, in foot pounds per square foot per day;

V is water velocity, in feet per second, determined as mean velocity in the channel from discharge measurements at the Cooper Landing or Soldotna stream-gaging station;

n is Mannings n or relative roughness of channel, assumed to be 0.035 for the natural undeveloped study sites along the Kenai River; and

R is hydraulic radius or mean depth of water in the channel, in feet, determined from discharge records at the stream-gaging stations.

The equation reduces to $\frac{2989\ V^3}{R^{1/3}}$ for a Mannings n of 0.035.

Once the total available tractive energy is determined for the river channel at a study site, the portion dissipated against the study site banks must be determined. Only a fraction of the total available tractive energy—between 0 and 0.76— is dissipated on the streambanks (Chow, 1959). The fraction of energy dissipated on the banks can be estimated from the theoretical distribution of tractive shear stress on the side boundary of a trapezoidal channel (Limerinos and Smith, 1975, p. 18). The calculation of the fraction of the total available tractive energy dissipated on the streambanks at a study site involves the following steps:

(1) Determine the depth (*D*) of water adjacent to the study site bank. This value is available from wake-gage recordings.

(2) Calculate the percentage of the mean depth of water in the channel represented by the depth of water adjacent to the bank. This simple calculation involves the ratio of *R* (mean depth) to *D* (depth of water) and multiplying by 100. *R* is determined from the stream-gaging measurement in equation 1 and *D* is determined in step 1. A generic example of this calculation is (D/R) x 100.

(3) Determine the energy distribution factor (E_{df}), which represents the fraction of the available tractive energy dissipated on the banks of the study site. This factor is derived from a theoretical distribution of shear stress with depth. It can be determined by using the percentage rela-

tion between depth of water adjacent to the bank and mean depth of water in the channel of the river determined in step 2 as input into a function described by Limerinos and Smith (1975, fig. 7, p. 18).

(4) Determine a value for tractive energy per square foot of study site bank (E_{ts}). Using the energy distribution factor (E_{df}) from step 3 multiplied by the total available tractive energy (E_t) from equation 1, an estimate of the tractive energy dissipated per square foot of the study site bank (E_{ts}) can be calculated. A generic example of this calculation is (E_t x E_{df}) = E_{ts}.

(5) Determine a value for tractive energy dissipated against each foot of the study site banks (E_{tb}) This value is calculated by multiplying the tractive energy per square foot (E_{ts}), determined in step 4 by the depth of water adjacent to the bank, D, determined in step 1. A generic example of this calculation is (E_{ts} x D) = E_{tb}.

An example of the calculations required for determining the tractive energy dissipated against each foot of bank at the Soldotna study site for a single day (July 10 in this example) involves the following steps. These steps are duplicated in daily tractive energy calculations summarized in tables A-2, A-3 and A-4 of the Appendix:

(1) Determine discharge for that day at the Soldotna study site, which was about 10,000 cubic feet per second at the nearby Soldotna stream-gaging station.

(2) Estimate V as mean velocity in the channel, from the records of 284 discharge measurements at the Soldotna stream-gaging station. V can be approximated by the relation:

$$[0.0184 \text{ x } (\textit{discharge})^{0.5911}] \ (r^2 = 0.90).$$

This relation results in an estimate of V of 4.23 feet per second.

(3) Estimate R as mean depth in the channel, from the records of 284 discharge measurements at the Soldotna stream-gaging station. R can be approximated by the relation:

$$[0.310 \text{ x } (\textit{discharge})^{0.374}] \ (r^2 = 0.61).$$

This relation results in an estimate of R of 9.70 feet.

(4) Determine tractive energy in the river from the equation $\frac{2989\ V^3}{R^{1/3}}$.

For July 10, 1996, about 106,000 foot pounds per square foot of channel is available in the river as tractive energy. Following calculation of this value, the portion of this available energy that is dissipated against the study site banks must be determined. This involves the following steps:

(5) Determine the depth of water adjacent to the bank at the Soldotna study site on July 10 from water-surface recordings at the wake gage. This value was 2.35 feet.

(6) Determine the percentage of mean depth of water in the channel that the depth in step 5 represents. The value of the depth of the water adjacent to the bank at Soldotna is about 24.8 percent of the mean depth of water. This percentage was calculated as 2.35/9.70 x 100.

(7) Calculate an energy distribution factor from the function described by Limerinos and Smith (1975, p.18). This factor was 0.145.

(8) Calculate the tractive energy dissipated along the study site per square foot of bank. This value was 15,500, which was calculated by multiplying the energy distribution factor from step 7 by the total available tractive energy from step 4.

(9) Determine the tractive energy dissipated per foot of bank by multiplying the value in step 8 by the depth of water adjacent to the bank (D) from step 5. This value was about 36,300.

Similar calculations were done for each day when water was adjacent to the streambank at each of the three study sites (Appendix tables A-2, A-3, and A-4). The computed tractive energy values follow a pattern crudely similar to that shown on figure 5, rising and falling with streamflow. After each daily value of tractive energy was calculated for each site, it can be compared with the value for wake energy dissipated against the bank, during the same day.

Boatwake Energy

Wake energy for the three sites having wake gages was calculated from the recorded wake heights and numbers. For days with missing wake data, the number of wakes was estimated from the records of the other wake gages. This estimation technique required assuming that the ratio of the number of wakes at one site to the number of wakes at the other sites remained constant, as described earlier. When the number of wakes was estimated, the wake energy was calculated by assuming that the maximum height of the wake was the average maximum height that was determined for each site from a subset of the available wake-height records (table 9).

The computations of boatwake-generated energy use equations and analyses similar to those used by Limerinos and Smith (1975), Nanson and others (1993), and Von Krusenstierna (1990). The equation used to define wake energy for this study is:

$$E_b = \frac{\rho g H^2 C n}{8}$$

where E_b is boatwake energy, in foot pounds per foot of wake crest;

ρ is density of water (1.94 slug per cubic foot, which is equal to 62.4 pounds per cubic foot);

g is gravitational constant (32.2 feet per second squared);

H is the maximum wake height, in feet;

C is wake speed towards the bank (This speed is estimated at about 15 feet per second for Kenai River boat traffic, which represents a wake traveling 10 miles per hour towards the bank. This value was determined during the wake-generation experiment from data collected while boats passed by the wake gage near the center of the river channel.); and

n is proportion of wake energy traveling with the wake train; it varies with the ratio of water depth to wake wavelength. For the wakes generated by typical boat traffic on the Kenai River, the ratio of water depth to wavelength has the characteristics for shallow water conditions where the value of n is 1.0 (U.S. Army Corps of Engineers, 1984; Komar, 1976).

Given these assumed conditions, the energy from individual wakes from typical boat traffic on the Kenai River reduces to

$$E = 3767.4H^2 .$$

A sample calculation of wake energy dissipated against the Soldotna study site during July 10, 1996 provides an example of this process. On July 10, 74 wakes with maximum heights between 0.2 and 0.5 foot struck the bank at the Soldotna study site. The energy from these wakes was individually calculated and totaled. For example, one 0.5-foot-high wake contributes about 940 foot pounds per foot of wake crest. The total energy for the 74 wakes on July 10 is about 18,400 foot pounds per foot of wake crest. This is about half of the energy dissipated by the natural streamflow during this day.

For days when individual wake heights were not available for energy calculations, the number of wakes at the site was estimated from other wake-gage records. Then the estimated wakes are each assumed to occur with a maximum height equal to the mean maximum wake height for the site. For example, on July 15 no wake records are available for the Soldotna site, so the number of wakes was estimated from the other wake gages to be 22 (Appendix table A-1). Assuming that these 22 wakes all had a maximum height of 0.30 foot (the average for the site) results in an estimate of 7,550 foot pounds per foot of wake crest representing the wake energy dissipated at this site for July 15 (Appendix table A-1).

When wake data were missing at the Kenai Keys site, an average value of 0.46 foot was used to represent the maximum height of the wakes. The number of wakes that occurred at the Kenai Keys was estimated as the average of 5 times the number of wakes at the Soldotna site and 0.5 times the number of wakes at RW's Campground site. Similar wake height and number estimation techniques using the average of measured wakes and the ratio of wake numbers between gaged sites were used when wake data were missing at the other gaged sites.

Erosive Energy Comparisons

For this study, energy dissipated on the banks of the study sites by tractive forces from natural streamflow currents and energy dissipated on the banks by boatwakes were calculated and compared at the three sites where boatwake gages were in operation. Although this energy comparison does not account for contributions to bank erosion from all possible mechanisms, it provides a sense of the relative magnitude for the two primary sources of erosion at the three data-collection sites considered during the period studied. These sites were selected because they had been altered very little by humans or they had been protected from human-induced erosion. The conclusions drawn from the energy comparison at these sites must be applied with care to other sites along the river. Additionally, as explained previously, the unusual flow conditions present on the river during 1996 (described in the section "Evaluating Effects of Boatwakes") substantially affected the energy calculations. Thus, any application of this energy comparison forward or backward in time must be done with these factors in mind.

The energy calculations and comparisons done at the three study sites indicated that boatwakes contributed 80 percent of the total erosive energy dissipated at the sites during the period of comparison in 1996 (table 11). As a percentage, this value is impressive and appears even more significant as a numeric comparison, where boatwakes total about 21,700,000 foot pounds per foot of wake crest. This value is more than four times the total tractive energy for the sites, which is about 5,200,000 foot pounds per foot of bank. Boatwakes contributed 97 percent of the total energy dissipated against the banks at the RW's Campground study site, 18 percent of the total energy at the Soldotna study site, and 94 percent of the total energy at the Kenai Keys study site. The smaller percentage at the Soldotna site results because the number of wakes was lower at this site, which decreased the total energy expended by the wakes. Furthermore, the water adjacent to the bank was deeper at this site compared with that at the other two sites, increasing the tractive energy component. Considering that during 1996, streamflow was generally below normal, tractive energy was likely also below normal. Without knowing more about historical boat traffic, it is difficult to say what level the boat traffic measured during the study represents.

Table 11. Comparison of erosive energy data on the Kenai River, 1996

Cause of erosion	Total energy (foot-pound per foot)	Percentage of total energy
Boatwakes	21,697,590	80.6
River currents	5,238,458	19.4
Total	26,936,048	100

During this study, the effects of the outburst flood were included in the tractive energy calculations. Outburst floods occur in the Kenai River every 2 to 3 years (Post and Mayo, 1971). Therefore, the prevalence of wake energy appears significant, because in non-outburst flood years, tractive energy will be less. When tractive energy is less, the wakes—if they occur in the same number and size as in 1996—will represent a greater proportion of the total erosive energy. In 1996, wakes represented nearly all the energy against the banks at the Kenai Keys and RW’s Campground.

For comparison, the tractive energy at the RW’s Campground wake-gage study site resulting from the 100-year flood during 1995 (September 21 to October 5), was more than three times the energy dissipated by the peak wake activity between July 16-31, 1996. Thus, for years with extreme flooding, the relation of tractive energy to wake energy may be significantly different from that for the low-flow year of 1996. Additionally, bank erosion measured as a result of the 1995 flood was more than 20 feet in a streamside subdivision near Beaver Creek and more than 8 feet in an undeveloped segment of the river upstream from Kenai Keys (Dorava, 1996).

Bank Protection

Numerous methods of bank stabilization and protection are employed along the Kenai River (Liepitz, 1994). During this study, several sites utilizing some of these methods were examined for their ability to prevent erosion. The methods of bank protection that were examined include an expensive and innovative bio-engineered system at the study site in Soldotna, a simple and inexpensive method of attaching spruce trees to the bank or piling rock against the bank at the Big Eddy Recreation Site, and a vertical wooden retaining wall at the Kenai Keys study site.

With the exception of the cabled spruce trees at the upstream end of the Big Eddy Recreation Site—which were washed away during the period July 11 to August 19—the bank-protection methods examined prevented erosion exceptionally well. The vertical wooden retaining wall at the Kenai Keys (fig. 31) protected the bank by stopping all erosion near it. Extending upstream from this wall was a wide flat board attached to a log and placed near the annual high-water line. This board/log wall extension (fig. 31) was specifically designed by the property owner to attenuate

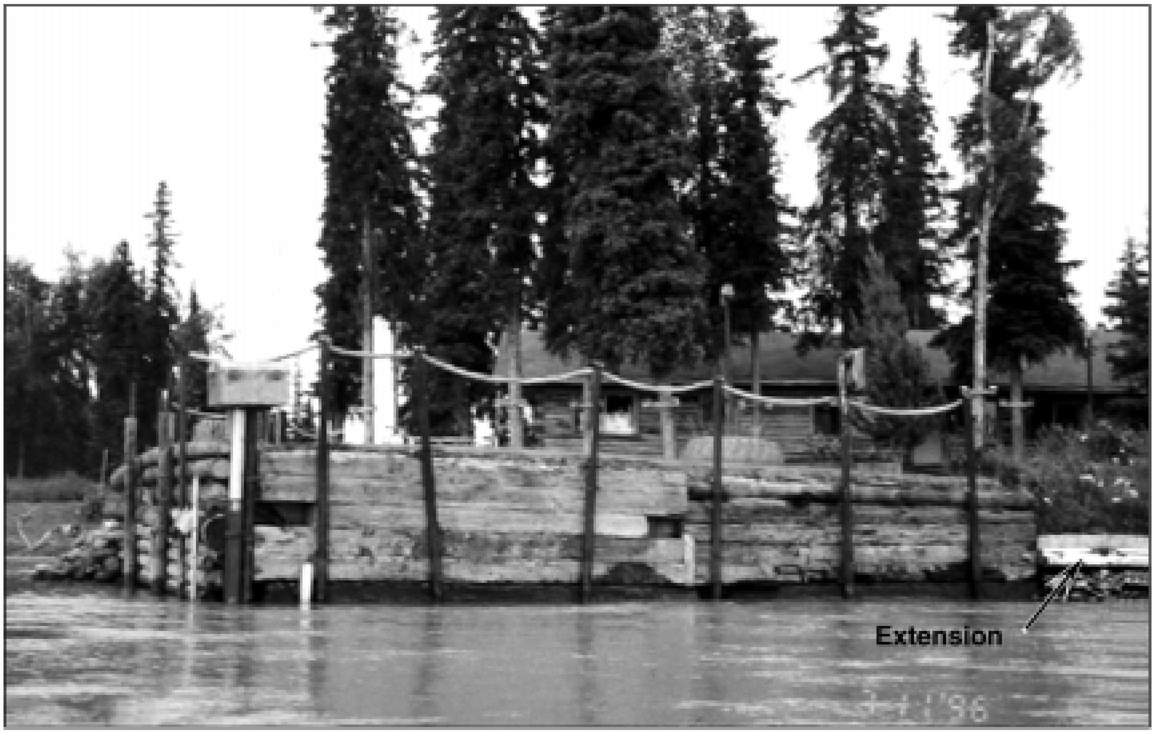


Figure 31. Vertical wooden retaining wall at the Kenai Keys study site. Extension of retaining wall includes a log and board assembly installed near the high-water line to protect bank from boatwakes. Note wake gage on left side of wall.

boatwakes, and it performed well. Except for a small area of erosion near the upstream end of the board/log wall extension where a neighbor's unprotected shoreline began, no erosion was visible along the entire wall. At the bio-engineered site near Soldotna, the system performed without visible erosion during the entire study period. The willows that were planted at this site were well rooted prior to the study and thus were less vulnerable to erosion than when they were initially set into fresh topsoil. Additionally, the spruce trees cabled to the bank at this site withstood the 100-year flood of September 1995 without being washed away and continued to trap fine sediment and provide fish with protective cover throughout the study period. The rock riprap at the Big Eddy Recreation Site protected the bank from erosion and although spruce trees cabled to the bank at this site washed away during the later part of the study, they withstood the extreme flooding of September 1995.

This limited examination of bank-protection methods indicated that both simple and more complex methods can protect a bank from erosion. However, many site-specific factors affect the rate of erosion at a particular location along the river. Additionally, protection methods deployed at a streamside site may affect fish habitat (Dorava, 1995). For example, rock riprap may provide adequate erosion protection, but it does not provide valuable protective cover created by live vegetation.

Significance of Results

Approximately 14 percent of the soils in a half-mile-wide corridor along the Kenai River between Cook Inlet and the Kenai National Wildlife Refuge (fig. 4) have been characterized by the Natural Resources Conservation Service as being easily eroded (Lehner, 1994). Additionally, about 48 percent of the banks of the Kenai River downstream from Skilak Lake have been characterized as being relatively sensitive to streamside development (table 2; Scott, 1982). By identifying the effects of boatwakes on streambank erosion along the Kenai River during this study, a better understanding of the vulnerability of these segments of the river already characterized as having potential erosion problems is possible. For example, bank undercutting and boat activity were greatest at the RW's Campground study site near river mile 16, where previous investigators had identified erosion problems (Scott, 1982; Inghram, 1985).

Downstream from RW's Campground, boat activity recorded at the ADF&G sonar counter near river mile 8.5 substantially decreased (table 4). Measured erosion at study sites near river mile 5 and 6.5 was also low during the boating season. In addition, the Soldotna study site near river mile 21.5 had the lowest boat activity of the three wake-gage sites and a low erosion rate. These data seem to justify a division of the river somewhere upstream from river mile 8.5 and downstream from river mile 21.5. The tidally influenced most downstream segment of the river will respond differently to erosion forces than non-tidal segments upstream from it, because the downstream channel is wider, the bank material more cohesive and consolidated, and the currents slower than those in the upstream channel. Therefore, the first 21.5 miles of the river can be separated into at least two segments: (1) between river mile 0 and 9 where boat activity is low and tides are likely the primary causes of erosion, and (2) between river mile 9 and about 18 where boat activity is high and channel geometry, soil type, and streamside development are contributing to greater erosion.

Upstream from river mile 18, boat activity and erosion were low during 1996. The streambank and bed material in this segment are generally non-cohesive and coarse, and the streambed is armored (Scott, 1982). The source of this coarse-grained material is glacier outwash from the most recent advance of the Kenai Mountain glaciers. Naptowne Rapids, near river mile 39, is the terminal moraine of this advance. These rapids represent the end of this river segment and a point where the rate of erosion changes along the river.

Upstream from Naptowne Rapids, the river morphology changes, and the rates of erosion and boat activity were high during 1996. The segment of the river that extends upstream from Naptowne Rapids to about river mile 46 is a popular boating area, has much streamside development, and historically has high average rates of erosion. The streambanks in this segment are generally loose alluvium which is eroded easily.

Upstream from river mile 46, the channel width begins to increase dramatically expanding to the outlet of Skilak Lake at about river mile 50. This segment of the river has no residential development because it is in the Kenai National Wildlife Refuge. It is also heavily vegetated with mature forest adjacent to the river and historically has a low average erosion rate.

The relative amount of boat activity and streambank erosion determined in this study for specific river segments is shown on table 12; maximum streambank erosion data are shown on table 13.

Table 12. Relative amount of boat activity and streambank erosion on the Kenai River

River mile	Boat activity	Streambank erosion
0-9	Low	Low
9-18	High	High
18-39	Low	Low
39-46	High	High
46 on	Low	Low

Table 13. Maximum bank erosion measured during the study period at sites along the Kenai River

Site name	River mile (fig. 4)	Maximum bank erosion (inches)	Type of erosion measurement	Average annual erosion for river segment from Scott (1982) (inches)
Lower river				
Warren Ames Bridge	5	6.25	Erosion pin	24
Cunningham Park	6.5	~48	Slump	24
Middle river				
RW’s Campground	16	45	Undercut	24
Big Eddy State Recreation Site	17	32	Undercut	24
Soldotna	21.5	17	Undercut	<12
Upper river (motorized segment)				
Kenai Keys	44.5	31.75	Erosion pin	60
Skilak Lake	46	28	Undercut	60/12[a]
Upper river (non-motorized segment)				
Control Site 1	72	12	Undercut	Not applicable
Control Site 2	72.5	10	Undercut	
Control Site 3	73	12	Undercut	

[a] Transition zone where erosion rates change

Specific features identified along the river, such as the square shelves cut into the bank, the semi-circular embayments extending inland, and the undercutting of the inside of meander bends, appear to be related to boatwake activity. These features were found along the river in 1996 and have been documented along the river in previous years. Because some of the features are large (embayments extend inland as much as 7 feet), they may be identifiable on aerial photographs taken before this study began. Examination of these photographs may help determine the approximate rate of formation of these erosion features. This examination might enhance conclusions from this study, which determined the magnitude of erosion and the relative significance of two primary causes of erosion at three sites along the Kenai River during 1996. There is little potential for extrapolating the information collected during this short study forward or backward in time without additional data collection and interpretation concerning historical and future rates of boat activity and streambank erosion. Additionally, erosion caused by foot traffic and slumping at some sites has been identified but not quantified along the remainder of the river. Information about the effects of other erosional processes, and the historical and future rates of boat use and streambank erosion would help to place the results of this boatwake investigation into context with other erosive forces and the expected future conditions along the Kenai River.

SUMMARY

The Kenai River is an economically important salmon stream in southcentral Alaska. The river is fed by glaciers in the Kenai Mountains and has a substantial fluctuation in seasonal flow. The fluctuations in Kenai River streamflow expose much of the riverbank to water only during peak summer flows. During this short period —approximately July 1 to September 1—both boat activity and erosion are typically at their maximum for the year.

Several miles of the upper Kenai River between Skilak Lake and Kenai Lake are restricted to non-motorized boat uses, whereas the remainder of the river is open to boats with six or fewer passengers and no more than a 35-horsepower motor. A popular chinook salmon sport fishery attracts fishermen to the Kenai River during June and July. The return of chinook salmon commonly peaks in mid-July resulting in a concurrent peak in boat activity. Typically, chinook salmon fishing is done from a boat that repetitively drifts through a potentially productive pool. Along the Kenai River, boat activity and bank erosion are greatest in the lower river between river mile 9 and 18, and in the upper river between river mile 39 and 46.

Observations of boat-operating characteristics on the Kenai River indicate that boats used on the river are generally greater than 10 and less than 26 feet in length. Many types of boats are used on the river, but generally they are wider and have a shallower draft than boats typically found on lakes or in saltwater. The most common boats on the Kenai River have a flat-bottom hull design, are 16 to 20 feet in length, and carry four or five passengers. Hull design, passenger load, and distance from the bank play a role in the size of wakes generated by these boats. Evaluation of bank loss associated with various-sized wakes indicates that for the non-cohesive sediments in the Kenai Keys area, wakes greater than about 0.45 foot in maximum height remove exponentially more material from the riverbanks than wakes less than 0.45 foot in height.

Erosion measured during the study at sites in the segment of the upper river that has restricted boat use is about 75 percent less than that measured in the most popular boating areas of the lower river and about 33 percent less than that in the least popular boating areas of the middle river. Sites along the river that should be depositional, such as the inside of the meander bend at RW's Campground, were undercut as much as 45 inches during this study. These areas also have bank embayment features indicating that this wake-generated undercutting may have been prevalent for some time. An example of this is the approximately 7-foot-diameter semi-circular embayments scoured into the streambank along the inside of meander bends at RW's Campground and at the Skilak Lake study sites.

During this study, the greatest amounts of bank loss measured occurred along the river during an approximately 60-day period when streamflow and boat activity on the river were near their annual maximums. Erosion measurements made at the study sites were less than the average annual erosion rates reported by Scott (1982) in the lower and upper river, and more than the average annual rates in the middle river (table 13). Comparisons of the amount of energy dissipated against the streambanks by river currents and boatwakes during this peak flow and peak boating period indicate that about 80 percent of the total energy came from boatwakes. This energy comparison does not account for all sources of erosion. The prevalence of boatwake energy relative to the energy from river currents indicated that boatwakes produced a substantial contribution to bank erosion at the sites investigated. However, this conclusion can not be applied throughout the river, where other erosion mechanisms, such as tides, human foot traffic, or slumping may dominate. This study compares energy dissipated against streambanks of the study sites during a short (60-day) period in 1996 when streamflow and boat activity were at specific levels. Therefore, the conclusions may not apply when conditions change. Streamflow during the 1996 study period was generally about 25 to 35 percent below normal, except for a short period in early August when an outburst flood from a glacier in the headwaters of Snow River increased streamflow above normal. During the 100-year flood in September 1995, more than 20 feet of streambank eroded along a residential subdivision near Beaver Creek (Dorava, 1996).

Methods to protect areas of high erosion from boatwakes may be available. However, the use of some bank-protection methods that produce smooth hard vertical surfaces adversely affect fish habitat, because they accelerate water velocities, and do not provide essential cover and substrate necessary for rearing juvenile fish. Bank stabilization techniques investigated during this study that reduced streambank erosion and provided valuable fish habitat included spruce trees cabled to the bank, coconut-fiber logs, and live willows. Bank protection was provided by rock riprap at the Big Eddy Recreation Site and a vertical wooden retaining wall at the Kenai Keys study site, but these bank-protection techniques did not provide valuable fish habitat. Cabled spruce trees at the Big Eddy State Recreation Site and at the Soldotna study site withstood the 100-year flood in September 1995 and provided some valuable fish habitat, but the trees at the Big Eddy State Recreation Site were washed away during the later part of this study.

Additional information quantifying the effects of other erosion processes such as bank slumping, tides, ice, and foot traffic, and quantifying the historical and future rates of boat use and streambank erosion would be required to evaluate the results of this boatwake investigation in relation to other erosive forces and the expected future conditions along the Kenai River.

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APPENDIX

Wake-energy data and tractive-energy calculations at selected sites along the Kenai River

Table A-1. Number of boatwakes and wake-energy data for selected sites on the Kenai River, Alaska, 1996
[ft-lb/ft, foot-pound per foot; --, no data]

Date	Soldotna		Kenai Keys		RW's Campground	
	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)
6-24	10	7,676	--	--	--	--
6-25	39	35,253	--	--	--	--
6-26	25	27,641	--	--	--	--
6-27	15	13,026	--	--	--	--
6-28	13	5,783	--	--	--	--
6-29	45	24,639	--	--	--	--
6-30	34	22,388	--	--	--	--
7-01	14	11,538	--	--	--	--
7-02	59	46,396	--	--	--	--
7-03	43	43,108	215	176,300	--	--
7-04	46	34,010	230	188,600	--	--
7-05	54	25,147	270	221,400	540	256,500
7-06	28	18,470	135	110,290	258	122,550
7-07	21	7,045	63	51,455	41	19,475
7-08	13	5,764	113	92,250	320	152,000
7-09	106	32,258	336	275,110	282	133,950
7-10	74	18,404	329	269,780	576	273,600
7-11	100	27,285	360	294,995	439	208,525
7-12	39	13,035	300	246,000	810	384,750
7-13	94	32,816	472	386,630	943	447,925
7-14	86	29,963	431	353,010	861	408,975
7-15	22	7,552	109	88,970	217	103,075
7-16	92	31,946	459	376,380	918	436,050
7-17	69	23,977	345	108,294	689	327,275
7-18	56	19,488	280	282,086	560	266,000

Table A-1. Number of boatwakes and wake-energy data for selected sites on the Kenai River, Alaska, 1996--Continued

[ft-lb/ft, foot-pound per foot; --, no data]

Date	Soldotna		Kenai Keys		RW's Campground	
	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)
7-19	55	19,192	297	375,572	509	241,775
7-20	84	29,319	555	604,197	575	273,125
7-21	73	25,561	453	445,335	563	267,425
7-22	32	10,997	271	234,973	90	42,750
7-23	79	27,596	368	378,708	850	403,750
7-24	59	20,358	291	247,735	588	279,300
7-25	62	21,419	338	125,728	555	263,625
7-26	80	27,944	328	268,960	950	451,250
7-27	89	31,059	405	332,100	975	463,125
7-28	91	31,755	357	292,740	1,111	527,725
7-29	19	6,612	170	139,400	40	19,000
7-30	57	19,749	212	193,475	711	337,725
7-31	40	13,850	198	134,892	400	190,000
8-01	24	8,352	120	98,400	240	114,000
8-02	28	9,814	141	115,620	282	133,950
8-03	42	14,755	212	173,840	424	201,400
8-04	29	10,092	145	118,900	290	137,750
8-05	20	6,890	99	86,782	198	94,050
8-06	13	4,385	63	64,149	126	59,850
8-07	23	8,143	117	95,940	234	111,150
8-08	13	4,663	67	54,940	134	63,650
8-09	15	5,220	75	61,500	150	71,250
8-10	21	7,169	103	84,460	206	97,850
8-11	26	8,909	128	104,960	256	121,600
8-12	21	7,238	104	85,280	208	98,800
8-13	22	7,517	108	88,560	216	102,600
8-14	17	5,846	84	68,880	168	79,800

Table A-1. Number of boatwakes and wake-energy data for selected sites on the Kenai River, Alaska, 1996--Continued

[ft-lb/ft, foot-pound per foot; --, no data]

Date	Soldotna		Kenai Keys		RW's Campground	
	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)
8-15	19	6,612	95	77,900	190	90,250
8-16	25	8,700	125	102,500	250	118,750
8-17	41	14,407	207	169,740	414	196,650
8-18	37	12,806	184	150,880	368	174,800
8-19	5	1,740	91	74,620	182	86,450
8-20	8	2,784	96	78,720	135	64,125
8-21	13	4,524	101	82,820	237	112,575
8-22	11	3,828	63	51,660	156	74,100
8-23	11	3,828	116	95,120	171	81,225
8-24	3	1,044	164	134,480	179	85,025
8-25	4	1,392	100	82,000	120	57,000
8-26	2	696	73	59,860	83	39,425
8-27	12	4,176	22	18,040	82	38,950
8-28	4	1,392	20	16,400	40	19,000
8-29	2	696	56	45,920	66	31,350
8-30	8	2,784	69	56,580	109	51,775
8-31	9	3,132	119	97,580	164	77,900
9-01	11	3,828	170	139,400	225	106,875
9-02	11	3,828	--	--	171	81,225
9-03	6	2,088	--	--	76	36,100
9-04	7	2,436	--	--	87	41,325
9-05	7	2,436	--	--	--	--
9-06	1	348	--	--	--	--
9-07	6	2,088	--	--	--	--
9-08	8	2,784	--	--	--	--
9-09	9	3,062	--	--	--	--
9-10	6	2,158	--	--	--	--

Table A-1. Number of boatwakes and wake-energy data for selected sites on the Kenai River, Alaska, 1996--Continued

[ft-lb/ft, foot-pound per foot; --, no data]

Date	Soldotna		Kenai Keys		RW's Campground	
	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)	No. wakes	Energy (ft-lb/ft)
9-11	8	2,854	--	--	--	--
9-12	7	2,366	--	--	--	--
9-13	11	3,689	--	--	--	--
9-14	19	6,612	--	--	--	--
9-15	10	3,341	--	--	--	--
9-16	8	2,923	--	--	--	--
9-17	7	2,297	--	--	--	--
9-18	5	1,810	--	--	--	--
9-19	9	2,993	--	--	--	--
9-20	11	3,689	--	--	--	--
9-21	24	8,282	--	--	--	--
9-22	16	5,429	--	--	--	--
9-23	10	3,550	--	--	--	--
9-24	10	3,550	--	--	--	--
Total	**2,770**	**1,111,995**	**12,123**	**10,131,796**	**22,008**	**10,453,800**

Table A-2. Tractive energy calculations for Soldotna study site, Kenai River, Alaska, June to September 1996

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge[1] (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[2]	Tractive energy at bank (ft-lb/ft)
6-24	6280	8.15	3.22	49,428	0.9	11.0	0.066	2,948
6-25	6840	8.41	3.38	56,896	1	11.9	0.071	4,058
6-26	7160	8.56	3.47	61,347	1.1	12.9	0.077	5,204
6-27	7330	8.63	3.52	63,764	1.2	13.9	0.083	6,381
6-28	7540	8.72	3.58	66,801	1.3	14.9	0.089	7,764
6-29	7760	8.82	3.64	70,042	1.4	15.9	0.095	9,340
6-30	8130	8.97	3.75	75,628	1.5	16.7	0.100	11,377
7-1	8420	9.09	3.82	80,123	1.6	17.6	0.106	13,535
7-2	8720	9.21	3.90	84,879	1.7	18.5	0.111	15,976
7-3	8900	9.28	3.95	87,785	1.8	19.4	0.116	18,383
7-4	9220	9.41	4.03	93,044	1.9	20.2	0.121	21,425
7-5	9480	9.50	4.10	97,406	2	21.0	0.126	24,595
7-6	9600	9.55	4.13	99,445	2.1	22.0	0.132	27,554
7-7	9700	9.59	4.16	101,157	2.2	22.9	0.138	30,643
7-8	9780	9.62	4.18	102,535	2.25	23.4	0.140	32,388
7-9	9830	9.63	4.19	103,400	2.3	23.9	0.143	34,064
7-10	10000	9.70	4.23	106,362	2.35	24.2	0.145	36,346
7-11	9940	9.67	4.22	105,313	2.4	24.8	0.149	37,620
7-12	10300	9.80	4.31	111,669	2.5	25.5	0.153	42,712
7-13	10600	9.91	4.38	117,077	2.54	25.6	0.154	45,732
7-14	11000	10.05	4.48	124,443	2.57	25.6	0.153	49,079
7-15	11200	10.12	4.53	128,192	2.6	25.7	0.154	51,398
7-16	11200	10.12	4.53	128,192	2.63	26.0	0.156	52,591
7-17	11500	10.22	4.60	133,897	2.66	26.0	0.156	55,639
7-18	11800	10.32	4.67	139,700	2.69	26.1	0.156	58,798

Table A-2. Tractive energy calculations for Soldotna study site, Kenai River, Alaska, June to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; $ft\text{-}lb/ft^2$, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge[1] (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy ($ft\text{-}lb/ft^2$)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[2]	Tractive energy at bank (ft-lb/ft)
7-19	12100	10.41	4.74	145,598	2.71	26.0	0.156	61,614
7-20	12200	10.44	4.76	147,586	2.74	26.2	0.157	63,649
7-21	12200	10.44	4.76	147,586	2.77	26.5	0.159	65,051
7-22	12300	10.48	4.78	149,584	2.8	26.7	0.160	67,162
7-23	12100	10.41	4.74	145,598	2.83	27.2	0.163	67,191
7-24	12300	10.48	4.78	149,584	2.86	27.3	0.164	70,071
7-25	12400	10.51	4.81	151,592	2.89	27.5	0.165	72,290
7-26	12300	10.48	4.78	149,584	2.92	27.9	0.167	73,042
7-27	12300	10.48	4.78	149,584	2.95	28.2	0.169	74,550
7-28	12400	10.51	4.81	151,592	2.95	28.1	0.168	75,323
7-29	12400	10.51	4.81	151,592	3	28.5	0.171	77,898
7-30	12800	10.63	4.90	159,731	3	28.2	0.169	81,112
7-31	13000	10.70	4.94	163,863	3	28.0	0.168	82,729
8-1	13300	10.79	5.01	170,139	3	27.8	0.167	85,167
8-2	13500	10.85	5.05	174,373	3	27.7	0.166	86,802
8-3	13800	10.94	5.12	180,802	3.07	28.1	0.168	93,480
8-4	14400	11.11	5.25	193,933	3.18	28.6	0.172	105,884
8-5	14900	11.26	5.36	205,149	3.24	28.8	0.173	114,800
8-6	16100	11.59	5.61	233,068	3.5	30.2	0.181	147,850
8-7	17000	11.82	5.79	254,915	3.69	31.2	0.187	176,124
8-8	17100	11.85	5.81	257,390	3.71	31.3	0.188	179,373
8-9	17000	11.82	5.79	254,915	3.69	31.2	0.187	176,124
8-10	16400	11.67	5.67	240,265	3.56	30.5	0.183	156,601
8-11	15800	11.51	5.55	225,957	3.43	29.8	0.179	138,635
8-12	14700	11.20	5.31	200,633	3.29	29.4	0.176	116,351
8-13	14600	11.17	5.29	198,389	3.26	29.2	0.175	113,250

Table A-2. Tractive energy calculations for Soldotna study site, Kenai River, Alaska, June to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge[1] (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[2]	Tractive energy at bank (ft-lb/ft)
8-14	14100	11.03	5.18	187,322	3.15	28.6	0.171	101,147
8-15	13500	10.85	5.05	174,373	3.01	27.7	0.166	87,381
8-16	13100	10.73	4.96	165,945	2.92	27.2	0.163	79,144
8-17	12500	10.54	4.83	153,611	2.8	26.6	0.159	68,555
8-18	12200	10.44	4.76	147,586	2.72	26.0	0.156	62,723
8-19	11900	10.35	4.69	141,655	2.65	25.6	0.154	57,679
8-20	11700	10.28	4.64	137,755	2.57	25.0	0.150	53,090
8-21	11400	10.18	4.57	131,985	2.5	24.5	0.147	48,603
8-22	11100	10.08	4.50	126,312	2.43	24.1	0.145	44,386
8-23	11000	10.05	4.48	124,443	2.36	23.5	0.141	41,386
8-24	11000	10.05	4.48	124,443	2.29	22.8	0.137	38,968
8-25	10900	10.01	4.45	122,585	2.22	22.2	0.133	36,198
8-26	10900	10.01	4.45	122,585	2.15	21.5	0.129	33,952
8-27	10500	9.87	4.36	115,263	2.08	21.1	0.126	30,299
8-28	10300	9.80	4.31	111,669	2.01	20.5	0.123	27,610
8-29	10300	9.80	4.31	111,669	1.94	19.8	0.119	25,720
8-30	9900	9.66	4.21	104,616	1.87	19.4	0.116	22,722
8-31	9560	9.53	4.12	98,763	1.8	18.9	0.113	20,137
9-1	9330	9.45	4.06	94,880	1.73	18.3	0.110	18,033
9-2	9020	9.33	3.98	89,743	1.66	17.8	0.107	15,904
9-3	8680	9.20	3.89	84,239	1.59	17.3	0.104	13,894
9-4	8520	9.13	3.85	81,696	1.52	16.6	0.100	12,401
9-5	8200	9.00	3.76	76,704	1.45	16.1	0.097	10,748
9-6	7900	8.88	3.68	72,136	1.38	15.5	0.093	9,284
9-7	7700	8.79	3.63	69,153	1.31	14.9	0.089	8,097
9-8	7460	8.69	3.56	65,638	1.24	14.3	0.086	6,968

Table A-2. Tractive energy calculations for Soldotna study site, Kenai River, Alaska, June to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge[1] (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribu-tion factor[2]	Tractive energy at bank (ft-lb/ft)
9-9	7130	8.54	3.47	60,924	1.17	13.7	0.082	5,856
9-10	6840	8.41	3.38	56,896	1.1	13.1	0.078	4,910
9-11	6640	8.32	3.32	54,182	1.075	12.9	0.078	4,515
9-12	6470	8.24	3.27	51,916	1.05	12.7	0.076	4,168
9-13	6390	8.20	3.25	50,862	1.9	23.2	0.139	13,433
9-14	6290	8.15	3.22	49,558	0.95	11.7	0.070	3,291
9-15	6330	8.17	3.23	50,078	0.9	11.0	0.066	2,978
9-16	6450	8.23	3.27	51,651	0.94	11.4	0.069	3,327
9-17	6750	8.37	3.36	55,668	1.03	12.3	0.074	4,233
9-18	7340	8.64	3.53	63,908	1.22	14.1	0.085	6,607
9-19	7700	8.79	3.63	69,153	1.32	15.0	0.090	8,221
9-20	8130	8.97	3.75	75,628	1.43	15.9	0.096	10,340
9-21	8150	8.98	3.75	75,935	1.43	15.9	0.096	10,372
9-22	8170	8.99	3.76	76,242	1.44	16.0	0.096	10,551
9-23	7920	8.89	3.69	72,437	1.38	15.5	0.093	9,314
9-24	7690	8.79	3.62	69,005	1.31	14.9	0.089	8,084
TOTAL								**4,402907**

[1] Discharge measured at Soldotna stream-gaging station

[2] Energy distribution factor from Limerinos and Smith (1975, p. 18)

Table A-3. Tractive energy calculations for RW's Campground study site, Kenai River, July to September 1996

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
7-6	9600	9.55	4.13	99,445	0.01	0.10	0.001	1
7-7	9700	9.59	4.16	101,157	0.02	0.21	0.001	3
7-8	9780	9.62	4.18	102,535	0.03	0.31	0.002	6
7-9	9830	9.63	4.19	103,400	0.04	0.42	0.002	10
7-10	10000	9.70	4.23	106,362	0.05	0.52	0.003	16
7-11	9940	9.67	4.22	105,313	0.06	0.62	0.004	24
7-12	10300	9.80	4.31	111,669	0.07	0.71	0.004	33
7-13	10600	9.91	4.38	117,077	0.11	1.11	0.007	86
7-14	11000	10.05	4.48	124,443	0.15	1.49	0.009	167
7-15	11200	10.12	4.53	128,192	0.19	1.88	0.011	274
7-16	11200	10.12	4.53	128,192	0.23	2.27	0.014	402
7-17	11500	10.22	4.60	133,897	0.27	2.64	0.016	573
7-18	11800	10.32	4.67	139,700	0.31	3.01	0.018	781
7-19	12100	10.41	4.74	145,598	0.35	3.36	0.020	1,028
7-20	12200	10.44	4.76	147,586	0.39	3.73	0.022	1,289
7-21	12200	10.44	4.76	147,586	0.43	4.12	0.025	1,568
7-22	12300	10.48	4.78	149,584	0.47	4.49	0.027	1,892
7-23	12100	10.41	4.74	145,598	0.51	4.90	0.029	2,182
7-24	12300	10.48	4.78	149,584	0.57	5.44	0.033	2,783
7-25	12400	10.51	4.81	151,592	0.59	5.61	0.034	3,013
7-26	12300	10.48	4.78	149,584	0.63	6.01	0.036	3,400
7-27	12300	10.48	4.78	149,584	0.67	6.40	0.038	3,846
7-28	12400	10.51	4.81	151,592	0.71	6.76	0.041	4,363
7-29	12400	10.51	4.81	151,592	0.75	7.14	0.043	4,869
7-30	12800	10.63	4.90	159,731	0.77	7.24	0.043	5,343
7-31	13000	10.70	4.94	163,863	0.8	7.48	0.045	5,883

Table A-3. Tractive energy calculations for RW's Campground study site, Kenai River, July to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
8-1	13300	10.79	5.01	170,139	0.85	7.88	0.047	6,837
8-2	13500	10.85	5.05	174,373	0.9	8.30	0.050	7,812
8-3	13800	10.94	5.12	180,802	1	9.14	0.055	9,918
8-4	14400	11.11	5.25	193,933	1.1	9.90	0.059	12,670
8-5	14900	11.26	5.36	205,149	1.25	11.11	0.067	17,087
8-6	16100	11.59	5.61	233,068	1.4	12.08	0.072	23,656
8-7	17000	11.82	5.79	254,915	1.55	13.11	0.079	31,076
8-8	17100	11.85	5.81	257,390	1.3	10.97	0.066	22,024
8-9	17000	11.82	5.79	254,915	1.2	10.15	0.061	18,626
8-10	16400	11.67	5.67	240,265	1.1	9.43	0.057	14,951
8-11	15800	11.51	5.55	225,957	1	8.69	0.052	11,784
8-12	14700	11.20	5.31	200,633	0.9	8.04	0.048	8,707
8-13	14600	11.17	5.29	198,389	0.85	7.61	0.046	7,699
8-14	14100	11.03	5.18	187,322	0.8	7.26	0.044	6,524
8-15	13500	10.85	5.05	174,373	0.75	6.91	0.041	5,425
8-16	13100	10.73	4.96	165,945	0.7	6.53	0.039	4,548
8-17	12500	10.54	4.83	153,611	0.65	6.17	0.037	3,694
8-18	12200	10.44	4.76	147,586	0.6	5.74	0.034	3,052
8-19	11900	10.35	4.69	141,655	0.5	4.83	0.029	2,053
8-20	11700	10.28	4.64	137,755	0.47	4.57	0.027	1,776
8-21	11400	10.18	4.57	131,985	0.43	4.22	0.025	1,438
8-22	11100	10.08	4.50	126,312	0.4	3.97	0.024	1,203
8-23	11000	10.05	4.48	124,443	0.37	3.68	0.022	1,017
8-24	11000	10.05	4.48	124,443	0.34	3.38	0.020	859
8-25	10900	10.01	4.45	122,585	0.3	3.00	0.018	661
8-26	10900	10.01	4.45	122,585	0.27	2.70	0.016	535

Table A-3. Tractive energy calculations for RW's Campground study site, Kenai River, July to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot; ft-lb/ft, foot-pound per foot]

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
8-27	10500	9.87	4.36	115,263	0.24	2.43	0.015	403
8-28	10300	9.80	4.31	111,669	0.21	2.14	0.013	301
8-29	10300	9.80	4.31	111,669	0.18	1.84	0.011	221
8-30	9900	9.66	4.21	104,616	0.16	1.66	0.010	166
8-31	9560	9.53	4.12	98,763	0.14	1.47	0.009	122
9-1	9330	9.45	4.06	94,880	0.12	1.27	0.008	87
9-2	9020	9.33	3.98	89,743	0.09	0.96	0.006	47
9-3	8680	9.20	3.89	84,239	0.06	0.65	0.004	20
9-4	8520	9.13	3.85	81,696	0.03	0.33	0.002	5
TOTAL								**270,842**

[1] Energy distribution factor from Limerinos and Smith (1975, p. 18)

Table A-4. Tractive energy calculations for Kenai Keys study site, Kenai River, July to September 1996

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot]; ft-lb/ft, foot-pound per foot

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
7-3	4430	5.22	2.85	40,089	0.10	1.9	0.0	46
7-4	4510	5.26	2.87	40,619	0.15	2.9	0.0	104
7-5	4520	5.26	2.87	40,685	0.20	3.8	0.0	186
7-6	4510	5.26	2.87	40,619	0.25	4.8	0.0	290
7-7	4490	5.25	2.87	40,486	0.30	5.7	0.0	417
7-8	4470	5.24	2.86	40,354	0.40	7.6	0.0	739
7-9	4470	5.24	2.86	40,354	0.47	9.0	0.1	1,021
7-10	4520	5.26	2.87	40,685	0.50	9.5	0.1	1,160
7-11	4580	5.29	2.88	41,080	0.53	10.0	0.1	1,310
7-12	4730	5.35	2.91	42,064	0.56	10.5	0.1	1,480
7-13	4830	5.39	2.93	42,714	0.60	11.1	0.1	1,712
7-14	4820	5.38	2.92	42,650	0.64	11.9	0.1	1,947
7-15	4720	5.34	2.91	41,998	0.68	12.7	0.1	2,181
7-16	4680	5.33	2.90	41,737	0.72	13.5	0.1	2,437
7-17	4710	5.34	2.90	41,933	0.76	14.2	0.1	2,722
7-18	4800	5.38	2.92	42,520	0.80	14.9	0.1	3,037
7-19	4960	5.44	2.95	43,555	0.84	15.4	0.1	3,390
7-20	5040	5.47	2.96	44,070	0.88	16.1	0.1	3,743
7-21	5040	5.47	2.96	44,070	0.92	16.8	0.1	4,091
7-22	5020	5.46	2.96	43,941	0.96	17.6	0.1	4,447
7-23	5020	5.46	2.96	43,941	1.05	19.2	0.1	5,320
7-24	5110	5.50	2.97	44,518	1.09	19.8	0.1	5,772
7-25	5180	5.53	2.98	44,965	1.13	20.5	0.1	6,235
7-26	5180	5.53	2.98	44,965	1.17	21.2	0.1	6,684
7-27	5200	5.53	2.99	45,092	1.21	21.9	0.1	7,159

Table A-4. Tractive energy calculations for Kenai Keys study site, Kenai River, July to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; $ft-lb/ft^2$, foot-pound per square foot]; ft-lb/ft, foot-pound per foot

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy ($ft-lb/ft^2$)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
7-28	5240	5.55	2.99	45,347	1.25	22.5	0.1	7,662
7-29	5400	5.61	3.02	46,359	1.29	23.0	0.1	8,253
7-30	5640	5.70	3.06	47,862	1.35	23.7	0.1	9,186
7-31	6070	5.85	3.12	50,514	1.40	23.9	0.1	10,154
8-1	6730	6.07	3.22	54,489	1.50	24.7	0.1	12,116
8-2	7640	6.36	3.33	59,804	1.65	26.0	0.2	15,372
8-3	9020	6.75	3.49	67,555	1.80	26.7	0.2	19,465
8-4	11000	7.25	3.70	78,147	1.95	26.9	0.2	24,604
8-5	13200	7.74	3.89	89,335	2.20	28.4	0.2	33,526
8-6	13700	7.84	3.94	91,806	2.55	32.5	0.2	45,673
8-7	12000	7.48	3.79	83,300	2.70	36.1	0.2	48,729
8-8	10100	7.03	3.61	73,401	2.65	37.7	0.2	44,012
8-9	8620	6.64	3.45	65,343	2.55	38.4	0.2	38,409
8-10	7480	6.31	3.31	58,882	2.45	38.8	0.2	33,624
8-11	6710	6.07	3.21	54,370	2.20	36.3	0.2	26,033
8-12	6190	5.89	3.14	51,245	2.00	33.9	0.2	20,876
8-13	5890	5.79	3.10	49,410	1.90	32.8	0.2	18,494
8-14	5560	5.67	3.05	47,363	1.80	31.8	0.2	16,244
8-15	5180	5.53	2.98	44,965	1.70	30.8	0.2	14,111
8-16	4940	5.43	2.94	43,426	1.50	27.6	0.2	10,793
8-17	4750	5.36	2.91	42,194	1.30	24.3	0.1	7,989
8-18	4610	5.30	2.89	41,278	1.10	20.8	0.1	5,656
8-19	4530	5.27	2.87	40,751	0.91	17.3	0.1	3,846
8-20	4440	5.23	2.86	40,155	0.90	17.2	0.1	3,733
8-21	4420	5.22	2.85	40,022	0.85	16.3	0.1	3,325
8-22	4410	5.21	2.85	39,956	0.80	15.3	0.1	2,942

Table A-4. Tractive energy calculations for Kenai Keys study site, Kenai River, July to September 1996--Continued

[ft^3/s, cubic feet per second; ft/s, feet per second; ft-lb/ft^2, foot-pound per square foot]; ft-lb/ft, foot-pound per foot

Date	Discharge (ft^3/s)	Mean depth (feet)	Mean velocity (ft/s)	Total tractive energy (ft-lb/ft^2)	Depth at bank (feet)	Percent of mean depth	Energy distribution factor[1]	Tractive energy at bank (ft-lb/ft)
8-23	4380	5.20	2.85	39,756	0.75	14.4	0.1	2,580
8-24	4410	5.21	2.85	39,956	0.70	13.4	0.1	2,253
8-25	4450	5.23	2.86	40,221	0.65	12.4	0.1	1,949
8-26	4450	5.23	2.86	40,221	0.60	11.5	0.1	1,661
8-27	4300	5.17	2.83	39,222	0.55	10.6	0.1	1,378
8-28	4140	5.10	2.80	38,145	0.50	9.8	0.1	1,123
8-29	3970	5.02	2.77	36,989	0.40	8.0	0.0	707
8-30	3840	4.96	2.74	36,097	0.30	6.0	0.0	393
8-31	3710	4.90	2.71	35,196	0.20	4.1	0.0	172
9-1	3590	4.84	2.69	34,356	0.10	2.1	0.0	43
TOTAL								**564,709**

[1] Energy distribution factor from Limerinos and Smith (1975, p. 18)