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

Channel Stability and Water Quality of the Alagnak River, Southwestern Alaska

Water-Resources Investigations Report 02-4184

Prepared in cooperation with the
NATIONAL PARK SERVICE

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Cover photograph:

Agnes Estrada's historic cabins at river kilometer 51 stand just downstream of the Alagnak River's most extensive actively eroding bank and the location of the most substantial channel changes in the past 50 years (oblique aerial photograph by Janet H. Curran, U.S. Geological Survey, June 4, 2001).

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By JANET H. CURRAN

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Anchorage, Alaska
2003

U. S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information:

Chief, Office of Water Resources
U.S. Geological Survey
Alaska Science Center
4230 University Drive, Suite 201
Anchorage, AK 99508-4664

Internet URL:
Alaska Science Center: http://alaska.usgs.gov

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CONVERSION FACTORS AND WATER-QUALITY INFORMATION

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter per second (m^3/s)	35.31	cubic foot per second ft^3/s
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass per unit volume (liter) of water. One milligram per liter is equivalent to 1,000 micrograms per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter (µS/cm) at 25°C.

MAPPING SOURCES:

FIGURE 1:

Base map from U.S. Geological Survey, 1994, 1:250,000
Shaded park boundaries modified from National Park Service, 1997 Katmai map.

OTHER MAPS:

Base map modified from U.S. Geological Survey, 1951 and 1952, 1:63,360 and
U.S. Geological Survey Digital Line Graphs, 1982-1997, 1:63,360

PROJECTION:

Publication projection is Albers Equal Area.
Standard parallels are 55°00′ and 65°00′, central meridian –154°00′, latitude of projection origin 50°00′.

Channel Stability and Water Quality of the Alagnak River, Southwestern Alaska

By Janet H. Curran

Abstract

The Alagnak River, a National Wild River located in southwestern Alaska, drains an area of 3,600 square kilometers and is used for recreational and subsistence activities—primarily angling, camping, rafting, and hunting—by visitors and seasonal residents, and for commercial guiding by several lodges. Increases in visitor use in the 1990s included an increase in the use of high-horsepower motorboats on the river, primarily for angling, and raised concerns regarding human impacts on water quality.

Downstream from its confluence with the Nonvianuk River at river kilometer (RK) 93, the Alagnak River is formed in glacial drift and outwash with a single, low bedrock outcrop. Analysis of aerial photography from 1951, 1982, and 2001 shows that the river's multiple channels from RK 57 to 93 have been relatively stable. In contrast, long reaches of multiple channels from RK 35 to 57 changed substantially between 1951 and 1982, creating a new complex of channels. Downstream from RK 35, channel changes in the past 50 years consist largely of minor meander migration.

Analysis of water samples collected during this study at RK 21, 46, and 93 and in the Alagnak and Nonvianuk Rivers at the outlets of the lakes that form their source shows that the Alagnak River is a nutrient-poor, calcium-bicarbonate water with low suspended-sediment concentrations. Water chemistry changes little over time or in a downstream direction. Weak patterns over time include high late May/early June concentrations of some nutrients, carbon, and iron. Weak patterns over distance include downstream increases in iron, manganese, and phosphorous. No pervasive human impacts on Alagnak River water chemistry were detected. Local effects that could be diluted within a kilometer downstream of the source were not detectable by this study.

Data collected at three continuously recording wake gaging stations at RK 21, 46, and 93 showed that 1999–2000 motorboat use was heaviest in the lower reaches of the river, moderate in the middle reaches, and very light in the upper reaches. Maximum boat use was 137, 40, and 4 wakes per day at RK 21, 46, and 93, respectively. The mean height of the maximum wave generated in each wake was about 0.15 m (meters) at all three gaging stations.

Bank erosion monitoring at 14 sites between RK 21 and 93 quantified erosion rates ranging from 0 to 1.1 m/yr (meters per year). Erodibility (based on grain-size analysis) increases in a downstream direction, as do measured erosion rates. Alagnak River banks are noncohesive and erode by grain-by-grain removal of sediment in an alternating pattern of water-driven erosion and gravity-driven erosion. Periodic surveys at bank erosion monitoring sites detected the development of a shallow underwater shelf formed by the action of wind waves and boat wakes at several sites. This shelf contains sediment eroded from the bank and redeposited adjacent to the bank; the shelf reformed as water levels changed but maintained the same wave-generated form throughout much of the season.

Measurements of bank erosion processes, particularly the development of a wave-generated shelf, and visual observations suggest that boat wakes increase bank erosion rates, especially at high, exposed banks. Analysis of aerial photography and other assessments of bank erosion processes indicate that this increase in erosion rates has not altered the mechanisms of channel change, which in the past 50 years have included complex, compound channel changes and meander migration.

INTRODUCTION

The Alagnak River, also known as the Branch River, drains a 3,600-km^2 (square kilometer) watershed in southwestern Alaska and empties into the Kvichak River near Bristol Bay (fig. 1). The river and its major tributary, the Nonvianuk River, flow westward from lakes in Katmai National Park and Preserve. National Wild River status was granted to the Nonvianuk River and all but the lower 29 km (kilometers) of the 127-km long Alagnak River by the 1980 Alaska National Interest Lands Conservation Act (ANILCA, Public Law 96-487) amendment to the Wild and Scenic Rivers Act (as amended, Public Law 90-542). This amendment added the Alagnak and Nonvianuk Rivers to the list of rivers "free of impoundments and generally inaccessible except by trail, with watersheds or shorelines essentially primitive and water unpolluted" and charged the National Park Service (NPS) with administering the Wild River areas. The State of Alaska comanages the Alagnak Wild River with the NPS (Weeks, 1999).

The Alagnak River supports recreational, commercial, and subsistence uses, including angling, camping, rafting, and hunting. Local lodges that operate during the summer provide accommodations, guides, and boats for guests. The use of motorboats is possible and permissible throughout the Alagnak and Nonvianuk Rivers but is most common in the lower half of the Alagnak River. The Alagnak River supports all five species of Pacific salmon, rainbow trout, grayling, arctic char, Dolly Varden, and pike, and is particularly popular for remote, fly-in sportfishing. The deeper meanders of the lower river are a documented

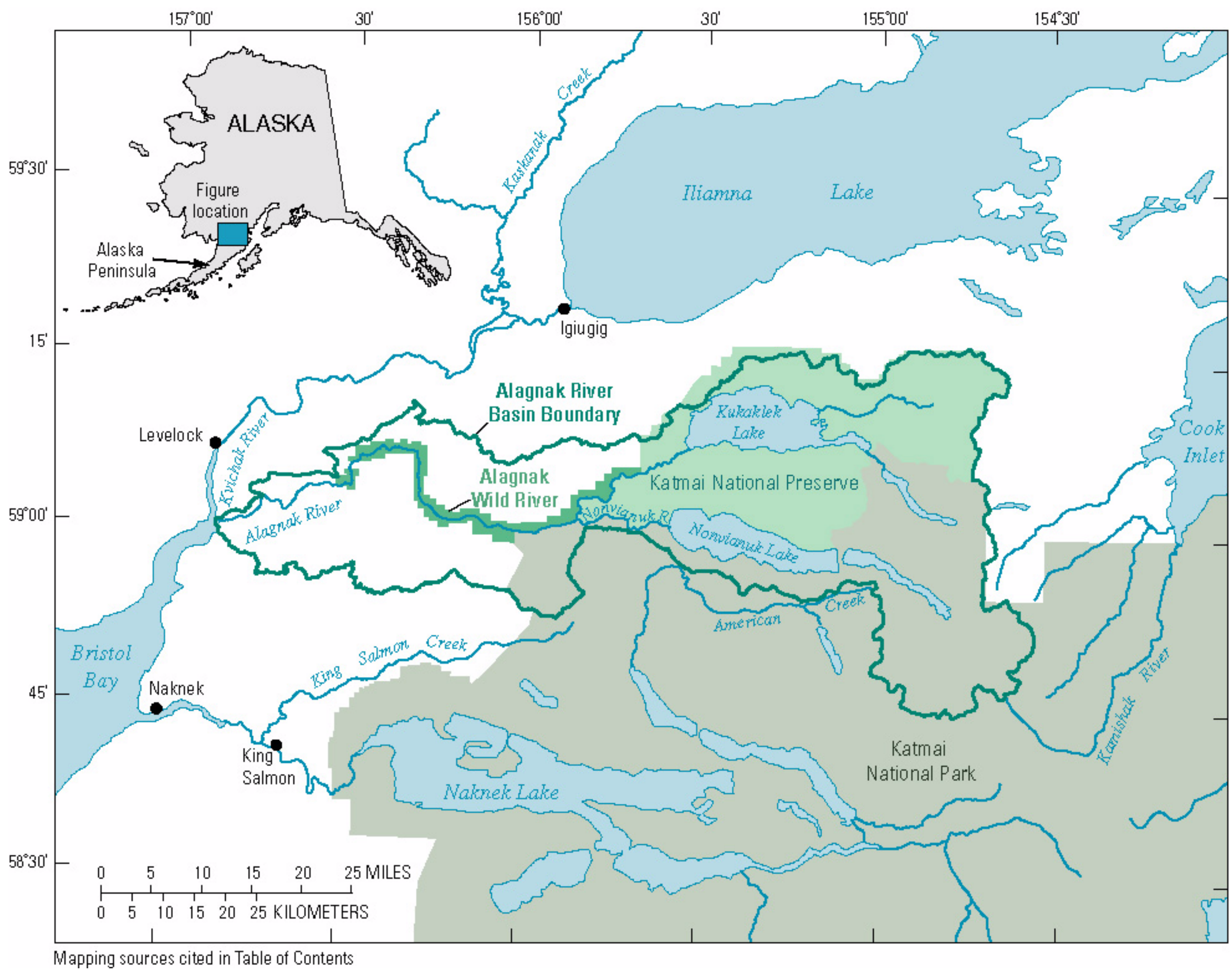


Figure 1. Location of the Alagnak River Basin and vicinity, Alaska.

Chinook salmon fishery (Naughton and Gryska, 2000) and the multiple-channeled reaches of the middle river are considered a trophy rainbow trout fishery.

Increasing visitor use in the 1990s (fig. 2) prompted the NPS and users of river resources to express concern about the influence of human activities in the basin on the water quality of this important fishery. No prior assessment of water quality had been documented along the Alagnak River. The impact of motorboat use on erosional processes along the Alagnak River and thereby on the quality of the salmonid habitat of this Bristol Bay area fishery was of particular concern to the NPS and river users. Although jetboat impacts on channel-bed fish habitat have been shown in other rivers (Sutherland and Ogle, 1975; Bush, 1988, Horton, 1994) and are possible on the shallower reaches of the Alagnak River, the present investigation of motorboat impacts was limited to bank erosion generated by boat wakes. This study provides a reconnaissance-level assessment of chemical constituents of water quality in the Alagnak River and a more detailed study of bank erosion processes, which may contribute sediment to aquatic habitats.

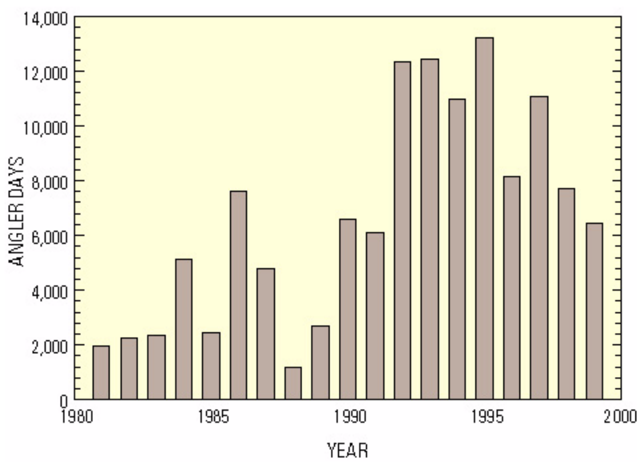


Figure 2. Visitor use of the Alagnak River (as measured in angler days). Angler days is the sum of the number of anglers on the river multiplied by the respective number of days they fished and is compiled annually by the Alaska Department of Fish and Game (Naughton and Gryska, 2000; Howe and others, 2001).

Purpose and Scope

This project is part of the NPS–U.S. Geological Survey (USGS) Water Quality Monitoring and Assessment Partnership program. This report summarizes environmental information about the Alagnak River Basin from other sources and presents the results of (1) a baseline measurement of water-quality constituents, (2) boat wake monitoring, and (3) bank erosion monitoring. The results of these measurements are discussed in a geomorphic, geologic, and geographic context. Measurements for this study were limited to the Alagnak River below the confluence with Nonvianuk River with the exception of water-quality sampling at the outlets of Kukaklek and Nonvianuk Lakes.

Description and History of Study Area

Physical Setting

The Alagnak River Basin occupies the western part of the base of the Alaska Peninsula (fig. 1), south of Iliamna Lake, and drains into the Kvichak River 11 km downstream of Levelock and 35 km north of King Salmon. Headwater elevations range from 300 to 1,570 m (meters) along the eastern part of the basin, where mountainous areas support snowfields and small glaciers that amount to less than 1 percent of the basin area (fig. 3). Headwater streams drain to long, narrow lakes that trap much of the upland-generated sediment load. Repeated Pleistocene glaciations formed a landscape dominated by lakes and a large plain of glacial deposits over the central and western parts of the basin. Eastward-retreating glaciers left moraine-impounded Kukaklek and Nonvianuk Lakes (Detterman and Reed, 1973), which occupy 174 and 132 km^2, respectively, and form the sources of the Alagnak and Nonvianuk Rivers (fig. 3). In addition, small kettle lakes and ponds dot much of the basin (fig. 3). Collectively, lakes and ponds of all sizes cover 12 percent of the basin's area. The Alagnak River is joined by the Nonvianuk River 34 km downstream of Kukaklek Lake and flows from the confluence 93 km downstream through a tundra lowland[1]. Drainage is poorly integrated over this part of the basin, such that no major tributaries enter the river in the lower 93 km. Instead, numerous small streams drain into the river from lakes and ponds and watershed subbasins, and many small ponds appear to be in closed drainage basins.

[1] Locations are reported in terms of river miles or river kilometers and latitude and longitude, defined as the distance along the main channel upstream from the river mouth. River miles and kilometers were calculated from geographic information system (GIS) hydrography coverage (Alaska Geospatial Data Clearinghouse, 2000) and may vary from values obtained from other sources. Because channel length varies as the river changes course, river miles or kilometers may not remain an accurate measure of the distance from the river mouth. Latitudes and longitudes for whole river miles (appendix 1) were obtained from the GIS coverage and record the river position at the time the aerial photographs were flown for the hydrography coverage.

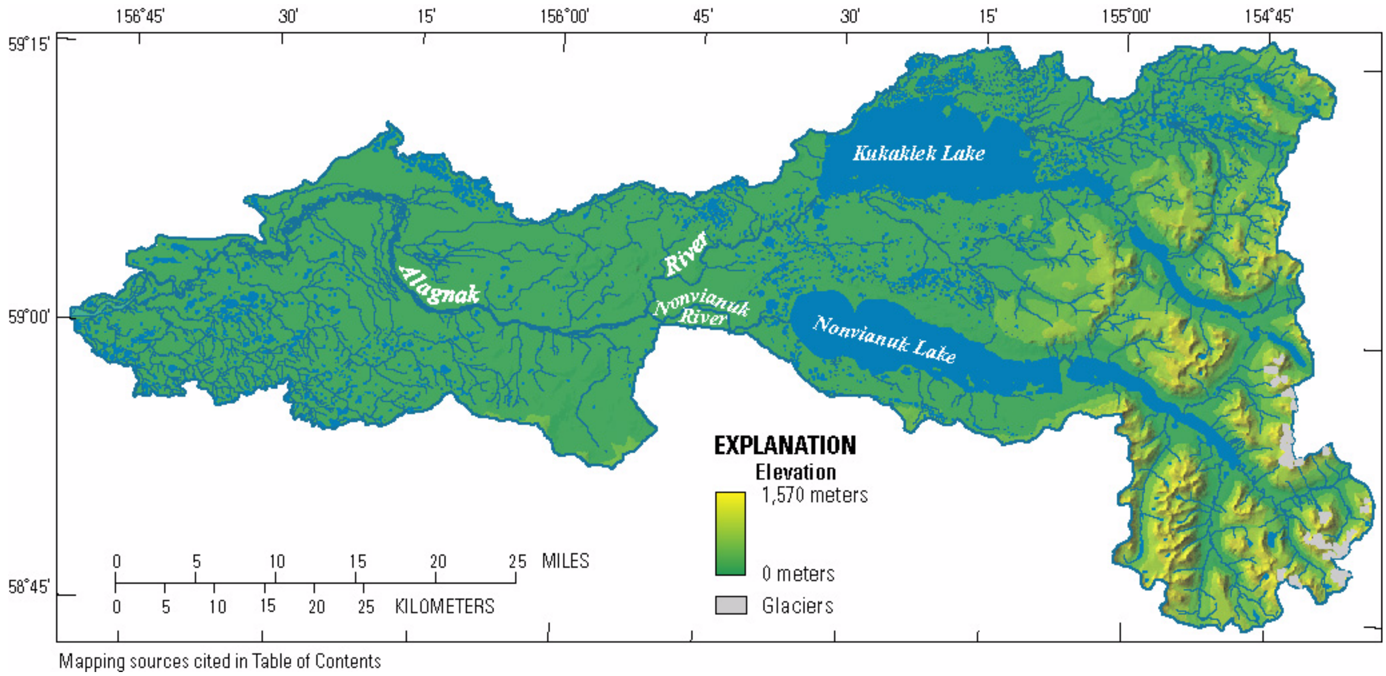


Figure 3. Topography of the Alagnak River Basin (from digital elevation model).

Historic and Prehistoric Use of the Alagnak River

Humans probably have occupied permanent, semi-permanent or temporary encampments near the banks of the Alagnak River for thousands of years (Mike Hilton, NPS, oral commun., 2001). Park archeologists have identified several dozen prehistoric sites near the banks of the Alagnak and Nonvianuk Rivers, including many along the upper and middle reaches of the study area. Although some sites are found on terraces 2 to 3 m high a few hundred meters from the river, most are within about 50 m of the present-day river. Sites are generally absent from the highest terraces (such as the 15–20 m high, right-bank terrace from RK 50 to 60). The condition of structures and physical artifacts at the sites suggests that they are less than 2,000 years old (Mike Hilton, NPS, oral commun., 2001), despite the discovery of sites as much as 8,000 years old within the surrounding region (Dumond, 1998).

Historical human use of the Alagnak River Basin includes trapping and subsistence uses of the river, its source lakes, and their margins. A cultural resources study of Katmai National Park and Preserve (Clemens and Norris, 1999) documented six remaining historic trapping cabins and subsistence sites along the Alagnak River. A seventh site, near the middle of the study area, contains the remains of a log Russian Orthodox chapel and Russian Orthodox grave markers.

Modern Use of the Alagnak River

The Alagnak River is accessible by floatplane, by wheelplane at a private airstrip, and by motorized or non-motorized boat. Noninflatable motorized boats enter the river from Bristol Bay via the Kvichak River and can travel the entire length of the Alagnak and Nonvianuk Rivers. Shallow river depths upstream from about RK 57 generally restrict motorized travel to jet boats, and reaches upstream of the Alagnak–Nonvianuk confluence are not readily passable to motorized boats at particularly high or low water levels. Inflatable boats, with or without motors, typically enter the Alagnak or Nonvianuk Rivers at Kukaklek or Nonvianuk Lake, respectively, and are usually flown out from middle or lower river reaches. There are no developed foot trails along the Alagnak Wild River corridor, although bears and anglers form informal paths along much of the river.

Angling is the primary recreational use of the Alagnak River. Because the river is remote, multiday trips with overnight stays at lodges or temporary camps dispersed along the river corridor are common. About 80 percent of anglers are guided, based on surveys conducted in the lower river (Naughton and Gryska, 2000). Concentrated use occurs at favorable campsites and at commercial lodges operated on a private inholding at RK 81, and RK 34, and RK 38 outside the Wild River corridor at RK 11 and RK 16. The largest commercial lodge has a stated capacity of 24 guests (Becky Brock, Chief Concessions, Katmai National Park and Preserve, written commun., 2001) as well as guides, housekeepers, and management staff, who remain all summer. Other cabins on private inholdings are used seasonally.

Subsistence uses of the Alagnak River are common, and seasonal camps with permanent structures are in use at several of the many Native allotments along the river corridor. Other Native allotments have permanent structures that are no longer in use, or are undeveloped.

Telemetry data from radio-tagged fish (Meka and others, 2000) indicate that the Alagnak River provides important spawning habitat for wide-ranging trout populations. Meka and others (2000) documented that rainbow trout populations that overwinter in Kukaklek and Nonvianuk Lakes migrate as far downstream as the middle reaches of the study area during open-water periods, particularly during the spawning period of May–June. The multiple-channeled, shallow, swift, and coarse-grained reaches in an area known informally as *The Braids* (RK 57–69) appear to provide spawning habitat preferred by trout.

Previous Studies

Previous studies of water quality in Katmai National Park and Preserve have reported high levels of sulfate (Gunther, 1992) and high proportions of chloride and sodium (LaPerriere, 1997) in lakes upstream of the Alagnak and Nonvianuk Rivers and suggested that these result from volcanic and coastal influences. LaPerriere and Edmundson (2000) classified Kukaklek and Nonvianuk Lakes, as well as two other lakes within the Alagnak River watershed, as oligotrophic based on Secchi-depth transparency and photosynthetically active radiation (PAR) penetration. An investigation of erosion adjacent to a lodge highlighted localized Alagnak River bank erosion issues (Ken Karle, NPS, written commun., 2000). An assessment of general conditions on the Alagnak River from Kukaklek Lake to the river mouth by the Alaska Department of Natural Resources (Clay and others, 1983) for the purposes of determining navigability of the river included discharge measurements and a travelog noting bank conditions at selected locations along the river. No documented water-quality measurements have been made within the Alagnak River corridor, and no systematic assessment of bank conditions and erosion processes has been made prior to this study.

Approach

Assessing the effects of human activities on the environment ideally includes two types of surveys of environmental conditions. The first, termed “background,” is the condition before human influence, and the second, termed “baseline,” is the current condition (Wanty and others, 1999). Background conditions are difficult to assess once humans are present, although some types of conditions can be inferred from evidence such as historical aerial photographs or long-lived vegetation. Past water-quality conditions are difficult or impossible to reconstruct, so a baseline is commonly the only information available. Repetition of a baseline monitors changes over time.

The historical presence of humans along the Alagnak River and significant increases in recent use of the river makes a background difficult to obtain but warrants a baseline survey of environmental conditions. Human impacts on water quality of the Alagnak River can be interpreted from an understanding of the present water quality, the present condition of the riverbanks, the amount and type of human use, and the type and rate of geomorphic processes that alter the river. To address these needs, this study included (1) a summary of topographic, historical, and environmental data for the Alagnak River Basin, (2) collection of continuously recorded boat wake data at three locations established for this study, (3) collection and analysis of discharge, sediment, and chemical water-quality data, (4) analysis and interpretation of aerial photography, (5) topographic surveys of bank conditions, and (6) bank erosion monitoring.

Acknowledgements

The assistance of Katmai National Park and Preserve staff, particularly Troy Hamon, Jane Bacchieri, Sue Bookless, Bill Hobbins, Thor Tingey, and Chris Wall, with logistical arrangements, transportation, and field tasks is gratefully acknowledged. Joe Dorava, former USGS hydrologist, helped establish the framework of this study and began the field program.

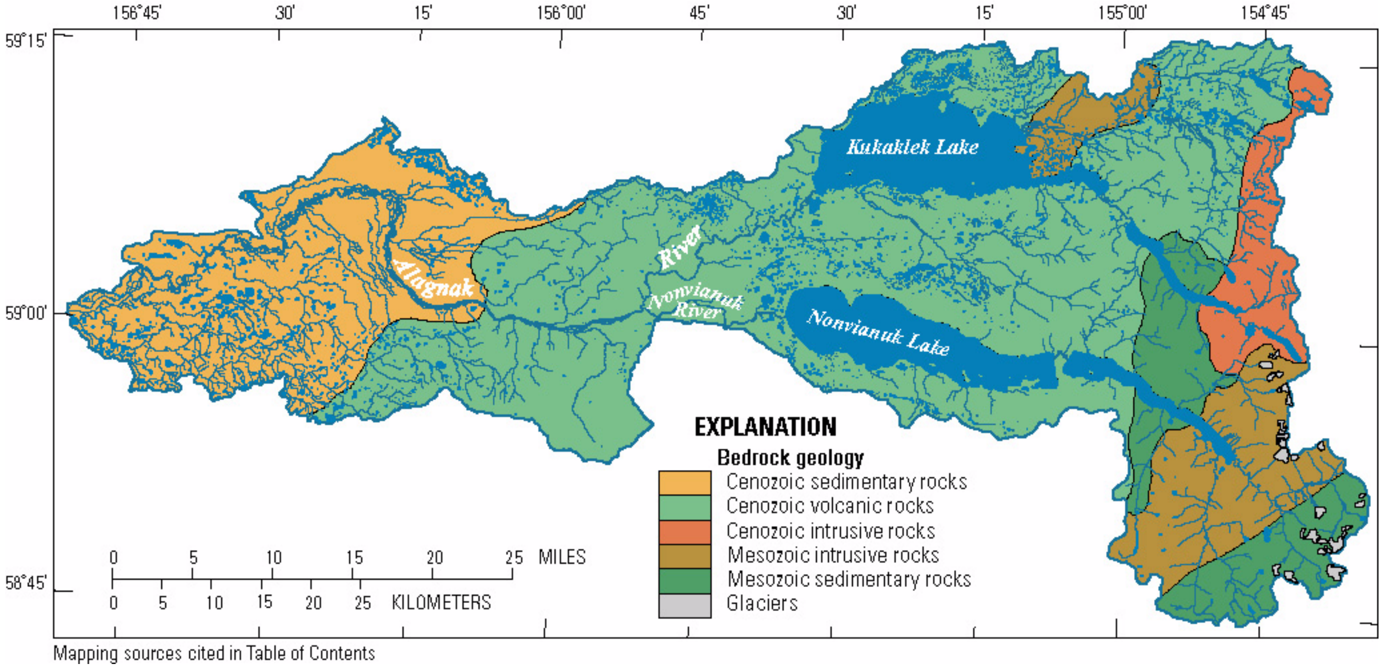


Figure 4. Generalized bedrock geology of the Alagnak River Basin (from Beikman, 1980; geographic information system coverage from Alaska Geospatial Data Clearinghouse, 2000).

ENVIRONMENTAL CHARACTERISTICS OF THE ALAGNAK RIVER BASIN

Geology

Volcanic and sedimentary rocks underlie the headwaters of the Alagnak River Basin (fig. 4). Exposed bedrock adjacent to the upper reaches of the study area and along the Alagnak River upstream of the Alagnak–Nonvianuk confluence consists of isolated outcrops of Tertiary volcanic rocks, which include andesite and basalt (Riehle and others, 1993; Detterman and Reed, 1980). Bedrock in a high bluff adjacent to the channel at RK 76 was classified as rhyodacite based on thin-section analysis (Frederic Wilson, USGS, oral commun., 2002). Throughout the rest of the study area, the river flows through sediments thought to be Pleistocene glacial deposits, based on preliminary geologic mapping (Frederic Wilson, USGS, oral commun., 2001). Maps of adjacent areas describe at least three distinct Pleistocene glacial advances: the pre-Wisconsin Johnston Hill; the early or pre-Wisconsin Mak Hill; and the late-Wisconsin Brooks Lake, which left morainal material near the present-day large lakes, Iliamna, Kukaklek, and Nonvianuk, and drift and outwash deposits over the large plain extending west from the lakes (Riehle and Detterman, 1993; Detterman and Reed, 1973). In general, surficial deposits are progressively older from east to west along the Alagnak River corridor. Deposits from all but the Brooks Lake glaciation have been moderately to highly modified by mass movements, stream dissection, thermokarst activity, and loess deposition.

Climate

Average annual precipitation in the Alagnak River Basin ranges from as much as 200 cm (centimeters) in the mountainous eastern basin to about 60 cm along the length of the Alagnak River and averages 99 cm over the entire basin (fig. 5). Moderate to high winds are common in the study area. Cooler winter temperatures typically result in persistent snow cover on upland surfaces and ice cover on the river for several months of the year.

Vegetation

Vegetation observed adjacent to the river within the study area includes taiga, spruce-birch woodland, and lowland tussock-tundra (Thor Tingey, NPS, oral commun., 2001). Dominant tree and shrub species includes black spruce, willow, paper birch, and dwarf birch. Ground cover species includes Labrador tea, low bush cranberry, crowberry, blueberry, tussock and other grasses, lichens, and mosses.

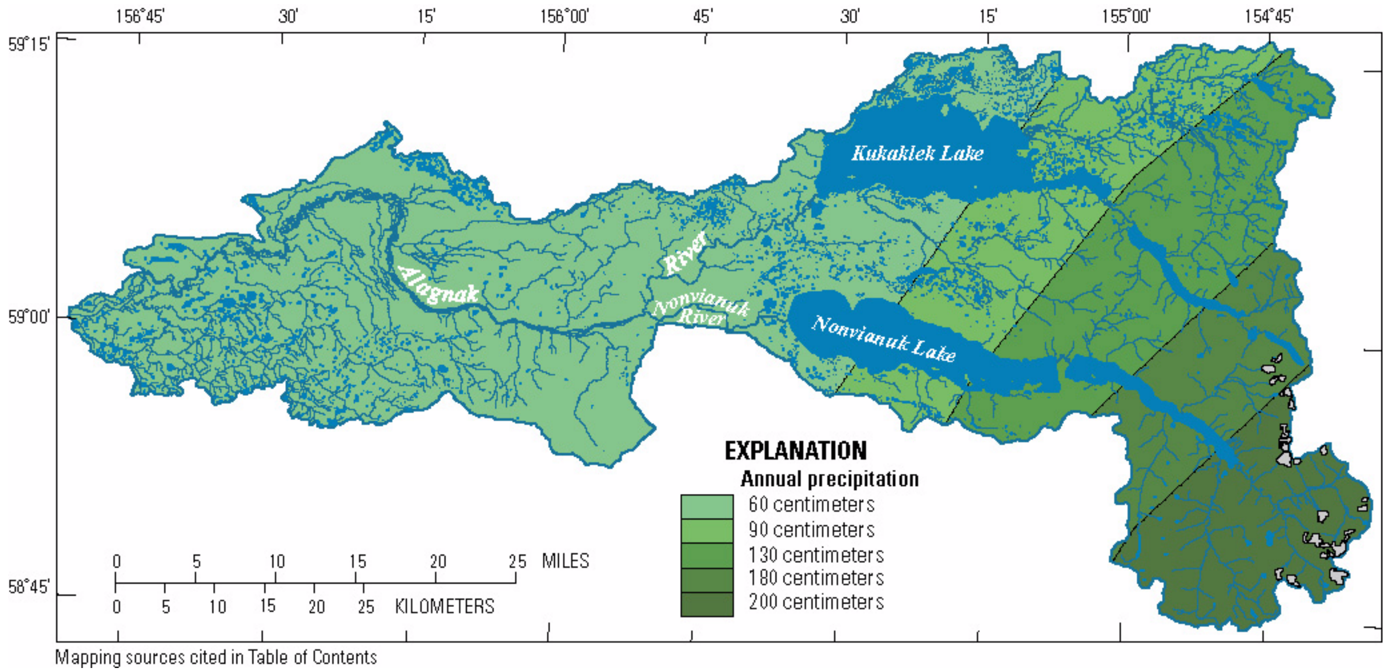


Figure 5. Precipitation regions of the Alagnak River Basin (from Jones and Fahl, 1994; geographic information system coverage from Alaska Geospatial Data Clearinghouse, 2000).

Vegetation on terraces and other higher flood plain surfaces along the Alagnak River forms an interwoven mat that retains its integrity for weeks to years as it drapes over eroding banks. The strength of this root mat is typically sufficient to support trees in a leaning position (fig. 6) for several years, even as erosion removes the underlying bank. The mat is not attached to the bank face, such that the bank face is unvegetated. Eroding banks where a draped mat is not present are also unvegetated. High eroded banks with exposed faces revegetate once the bank toe is no longer subjected to active erosion.

HYDROLOGY OF THE ALAGNAK RIVER

Hydrologic conditions pertinent to water quality and geomorphologic processes include streamflow and ground-water movement that interacts with streamflow. Seasonal rises in river stage can flush nutrients from bars, saturate riverbanks, deliver waves higher up on riverbanks, increase suspended-sediment concentrations, and dilute dissolved-chemical concentrations. Discrete discharge measurements made at five locations established for this study provided streamflow data that describe seasonal and annual streamflow variability and provided a means for analysis of suspended-sediment loads.

Ground-water interactions can dilute or strengthen chemical concentrations and decrease or increase streamflow. Although field observations of bankside springs from RK 51.6–53.1 and the inconsistent relation of streamflow with downstream increases in drainage area suggest that ground-water interactions with streamflow are potentially significant to Alagnak River hydrology, a systematic effort to identify the extent of these interactions was beyond the scope of this study.

Methods of Discharge Measurement

Discharge was measured at USGS partial-record stations at RK 21, RK 46, and RK 93 (fig. 7) on 13 occasions between June 1999 and February 2001 (table 1). Discharge was measured at USGS partial-record stations at RK 127, (Kukaklek Lake outlet) and at the Nonvianuk Lake outlet in August 2000 (table 1).

Discharge was measured using a standard Price AA current meter suspended from a boat-mounted boom or, in shallow water, mounted on a wading rod. Stage recorders were installed at the three stations on the Alagnak River main stem (fig. 7), primarily for recording boat wakes. Daily variations in stage were visually assessed from the stage records to qualitatively determine the extent of water level fluctuations between measurements.

Figure 6. Vegetation mat draped over bank at erosion monitoring site 7 on the Alagnak River.
(A) High stage. Person is standing in line with erosion pins. Photograph by author, June 12, 2000.
(B) Low stage. Leaning tree visible in (A) has fallen into river and is collecting debris. Photograph by author, August 8, 2000.

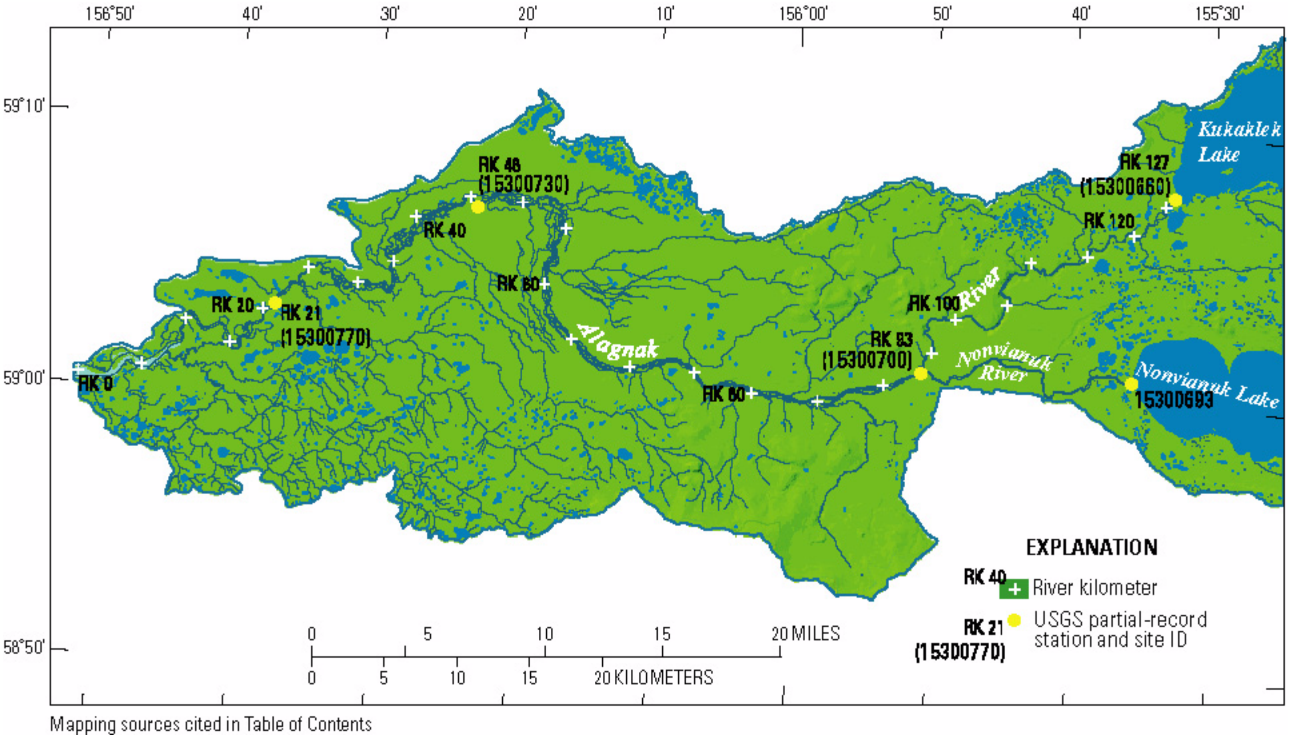


Figure 7. Locations of partial-record stations on the Alagnak and Nonvianuk Rivers.

Table 1. Measured discharge of the Alagnak and Nonvianuk Rivers, 1999–2001

[USGS, U.S. Geological Survey; RK, river kilometer; m^3/s, cubic meters per second; --, not measured; E, estimated]

USGS station 15300770, Alagnak River at RK 21		USGS station 15300730, Alagnak River at RK 46		USGS station 15300700, Alagnak River at RK 93		USGS station 15300660, Alagnak River at RK 127 (Kukaklek Lake outlet)		USGS station 15300693, Nonvianuk River at Nonvianuk Lake outlet	
Date	Discharge (m^3/s)	Date	Discharge (m^3/s)	Date	Discharge (m^3/s)	Date	Discharge (m^3/s)	Date	Discharge (m^3/s)
6/3/1999	121	6/3/1999	113	6/4/1999	99.7	--	--	--	--
6/24/1999	289	--	--	6/23/1999	295	--	--	--	--
7/15/1999	212	7/13/1999	E181	7/14/1999	189	--	--	--	--
8/25/1999	120	8/25/1999	108	8/26/1999	107	--	--	--	--
9/14/1999	98.8	9/15/1999	96.6	9/16/1999	96.9	--	--	--	--
6/1/2000	85.0	6/1/2000	83.3	6/2/2000	88.9	--	--	--	--
6/13/2000	137	6/12/2000	132	6/14/2000	152	--	--	--	--
6/27/2000	186	6/26/2000	172	--	--	--	--	--	--
7/19/2000	174	7/18/2000	169	7/20/2000	170	--	--	--	--
8/8/2000	142	8/8/2000	126	8/9/2000	113	8/11/00	54.1	8/10/00	51.8
8/29/2000	97.7	8/28/2000	89.8	8/30/2000	82.7	--	--	--	--
--	--	2/28/2001	40.2	2/27/2001	40.2	--	--	--	--
6/5/2001	113	6/4/2001	108	6/6/2001	125	--	--	--	--

Streamflow of the Alagnak River

Discharge measurements (fig. 8), field observations, and stage records show that the Alagnak River is snowmelt-dominated, rising in stage before late May or early June, and peaking in mid-June to early July. After the snowmelt peak, flows decrease during the summer and early fall, except for short, rainfall-induced peaks. According to the NPS and lodge personnel familiar with the river, ice begins to form on the river in late September to October and typically remains until about April or May.

Measured discharge (table 1) at sites in the main-stem Alagnak River ranged from a low of 40 m^3/s (cubic meters per second) at RK 46 and 93 in February 2001 to a high of 295 m^3/s at RK 93 in June 1999. From its over-bank nature and accounts from NPS and lodge personnel familiar with the river, the June 1999 streamflow appears to have been relatively large. The largest discharge measured in 2000 was 186 m^3/s, also in June.

Expected discharge can be obtained from regional flood-frequency regression equations (Jones and Fahl, 1994) and mean monthly discharge regression equations developed from streamflow and basin characteristics of local rivers (Clay and others, 1983). The 2-year peak discharge estimated from regional flood-frequency regression equations and Alagnak River Basin characteristics (table 2) is 289 m^3/s for the river mouth and the 100-yr peak discharge estimate is 666 m^3/s. The mean monthly value for June, the month with the highest observed discharges, was estimated to be 365 m^3/s by Clay and others (1983), using drainage area, precipitation, and their regression equations for local rivers. This locally based estimate is higher than the 2-year peak discharge regionally based estimate, suggesting that a longer-term streamflow measurement program would be required to overcome the errors inherent in the estimates and confirm Alagnak River streamflow statistics.

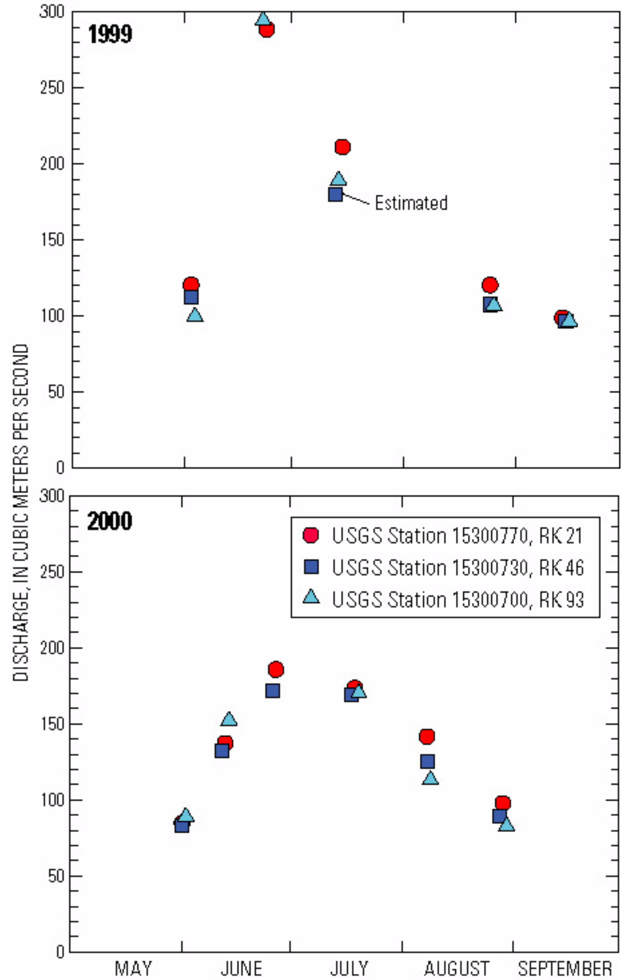


Figure 8. Measured discharge at Alagnak River river kilometer 21, 46, and 93 in 1999 and 2000.

Detailed comparisons of measured discharge between sites would require adjustment for river stage, which fluctuated by as much as 0.1 m over the 3-day periods of measurement. In addition, each discharge measurement is considered accurate to within 5 to 8 percent of actual discharge. In spite of these uncertainties, comparisons of the unadjusted measured discharge

Table 2. Selected basin characteristics of the Alagnak River Basin, Alaska (calculated according to procedures in Jones and Fahl, 1994)

Drainage area, in square kilometers (square miles)	Mean annual precipitation, in centimeters (inches)	Area of lakes and ponds, in percent of basin area	Mean basin elevation, in meters (feet)	Mean minimum January temperature, in degrees Celsius (degrees Fahrenheit)
3,595 (1,388)	99 (39)	12	341 (1,120)	-13 (8)

between stations show general trends. August 2000 measurements (table 1) show that, at their sources, the Nonvianuk and Alagnak Rivers have similar discharges. Observations at the rivers' confluence and comparison of drainage areas (table 3) confirm that these rivers are roughly equal tributaries to the Alagnak River main stem, although high flows may occur in one river without occurring in the other. Streamflow between RK 93 and RK 46 sometimes increased, sometimes remained relatively constant, and sometimes decreased, despite a 24 percent increase in drainage area. Streamflow between RK 46 and RK 21 always increased, reflecting a 12 percent increase in drainage area.

Table 3. Drainage areas above U.S. Geological Survey streamflow-gaging stations in the Alagnak River Basin on the Alagnak River

[RK, river kilometer]

Streamflow-gaging station	Location	Drainage area (square kilometers)
15300693	Nonvianuk Lake outlet	933
15300660	RK 127 (Kukalek Lake outlet)	1,190
15300690	RK 94	1,350
15300700	RK 93	2,390
15300730	RK 46	2,970
15300770	RK 21	3,320

GEOMORPHOLOGY OF THE ALAGNAK RIVER

Bed and Bank Material

Repeated Pleistocene glaciations generated a broad plain of glacial drift and outwash through which the Alagnak River flows. The banks at the outer edges of the river flood plain are almost entirely composed of these glacially derived materials, which are typically noncohesive, unconsolidated mixtures of sand and gravel, with occasional cobbles, that decrease in size in a downstream direction. Peat is exposed at RK 32 and may be present elsewhere. Bedrock is exposed near river level at only one location in the study area, RK 76, where it is present along the left bank for several hundred meters as low, isolated outcrops and as high bluffs adjacent to the river. Banks within the flood plain consist of low terraces and islands that are primarily Alagnak River alluvium but may locally contain glacial deposits. Bed material consists primarily of Alagnak River alluvium with occasional large boulder lag from glacial deposits.

Bank materials were described (based on visual assessment) and sampled at 14 erosion-monitoring sites (fig. 9). Particle-size distributions were prepared from the results of sieve analysis (appendix 2) and median

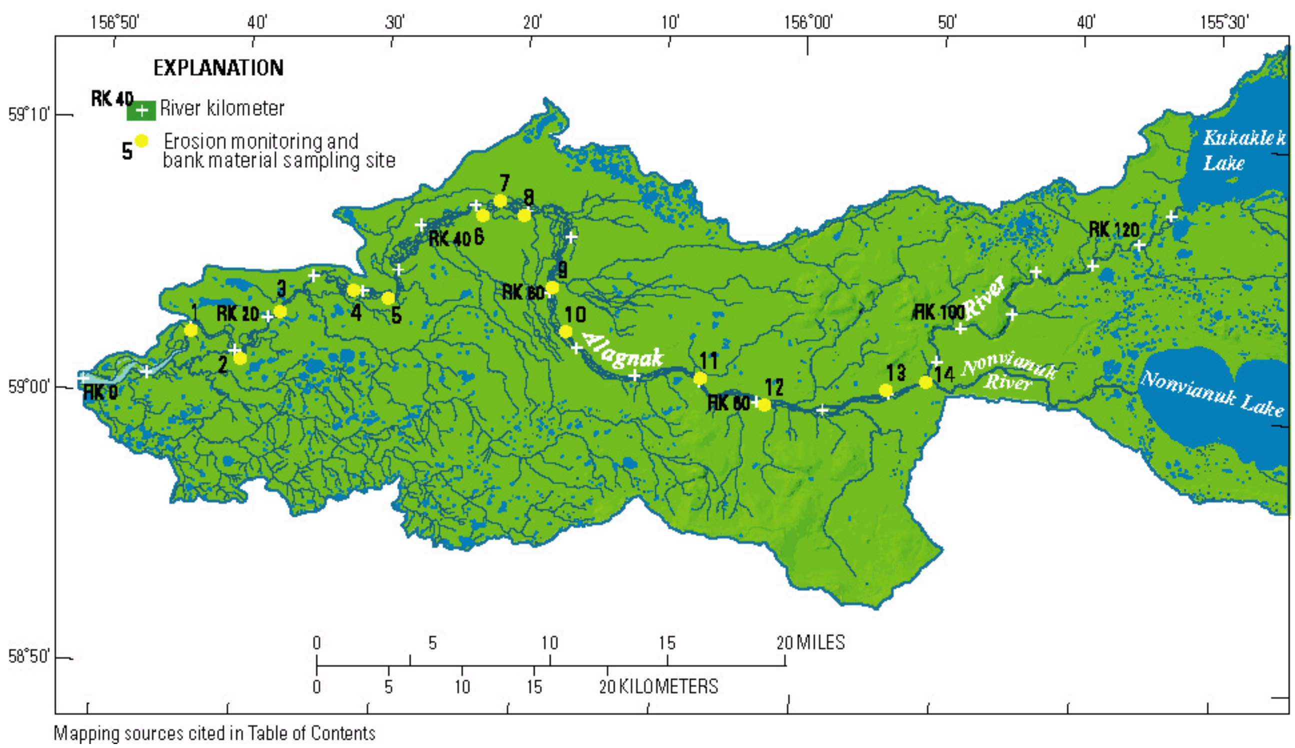


Figure 9. Locations of erosion monitoring and bank material sampling sites on the Alagnak River.

diameters determined from the distribution were analyzed to detect spatial trends in bank material.

Bed material characterization consisted of grid-type pebble counts. Intermediate diameters of surficial bed particles were measured at 11 sites from RK 15 to 89 in 2000 and 2001 (appendix 3). Measurement sites consisted of heads of unvegetated midchannel bars that appeared to have been deposited by the river in or near its present position. These sites were chosen because they are more likely to contain particles carried and deposited by the river, rather than lag deposits, and are hydraulically consistent. Measurements were made at the head of the bars near water level during low to moderate flow conditions. Bars within a single main channel were preferred, but between RK 64 and RK 88, where none could be found, bars were chosen within the largest channel. These bars appeared to be the result of a shift in channel direction rather than depositional processes within the existing channel. Measurements were made with a metal tape at 0.6-m intervals in a grid as wide as the head of the bar, typically about 6 m, and as long as needed to measure 100 particles.

Physical descriptions of bank materials indicate a downstream progression from gravel and cobbles in a sandy matrix to fine sand, silt, and clay in a downstream direction. This downstream trend is confirmed by the particle-size analysis (fig. 10). Bank material exposed in high eroding terraces ranges from sand and gravel near RK 50 to primarily sand near RK 10.

Physical descriptions also show downstream fining of bed material, from cobbles and boulders to sand. The downstream-fining trend is supported by particle-size analysis of bar heads (fig. 10). The slight decrease in median bed material particle diameter in 2001 at sites close to one another cannot necessarily be interpreted as the range of interannual variability because of the high levels of uncertainty in sampling coarse bed material.

Planform

The Alagnak River flood plain is defined almost everywhere by the maximum extent of lateral channel migration against terraces of Pleistocene glacial outwash. High terraces of glacial outwash can be traced along the right edge of the flood plain from at least RK 57 downstream to near the river mouth. Lower terraces flank the right bank farther upstream as well as selected portions of the left bank. Bedrock confines the channel at RK 76, and lower terraces of uncertain age constrain the channel elsewhere. The active channel belt, defined here as the distance between the left bank of the leftmost channel and the right bank of the rightmost channel (or the average meander amplitude of single-thread channels), is typically about one-third to one-half of the flood plain and averages about 400 to 500 m in width.

Although both the Alagnak and Nonvianuk Rivers form a single-thread channel upstream of their confluence, much of the main-stem Alagnak River maintains a multiple-channeled, or anabranching (Nanson and Knighton, 1996), course. About 1 km downstream from the Nonvianuk River confluence, the Alagnak River divides into multiple channels that intertwine over short distances, creating a web of channels separating low islands across the floodplain. This anabranching pattern, most pronounced in The Braids (fig. 11), persists down-

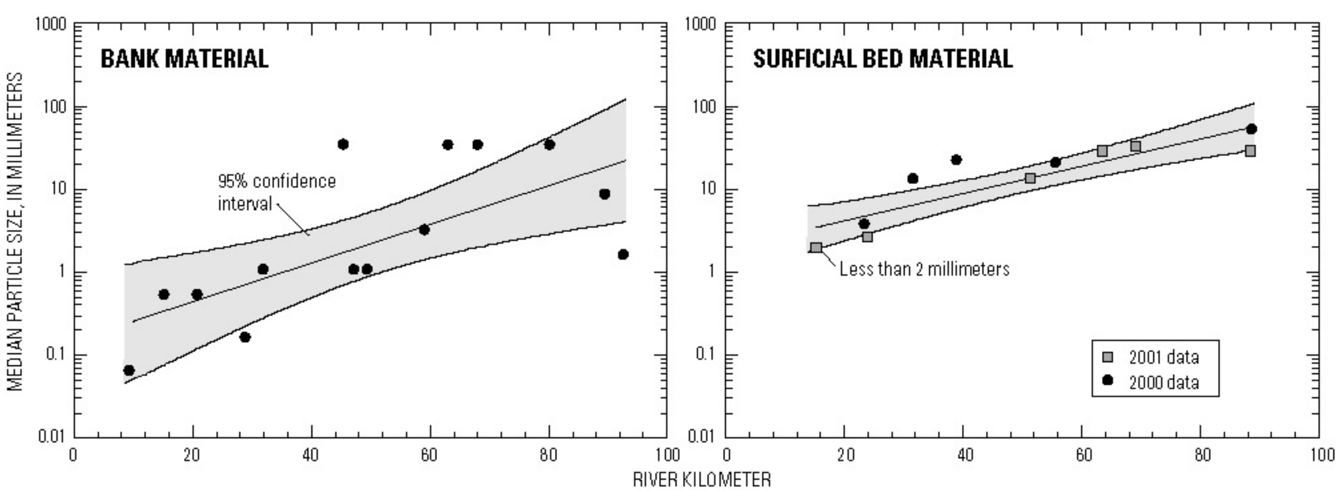


Figure 10. Downstream distribution of median particle size of bank material and surficial bed material in the Alagnak River. Regressions are significant at alpha = 0.05. R^2 is 0.49 for bank material and 0.68 for bed material.

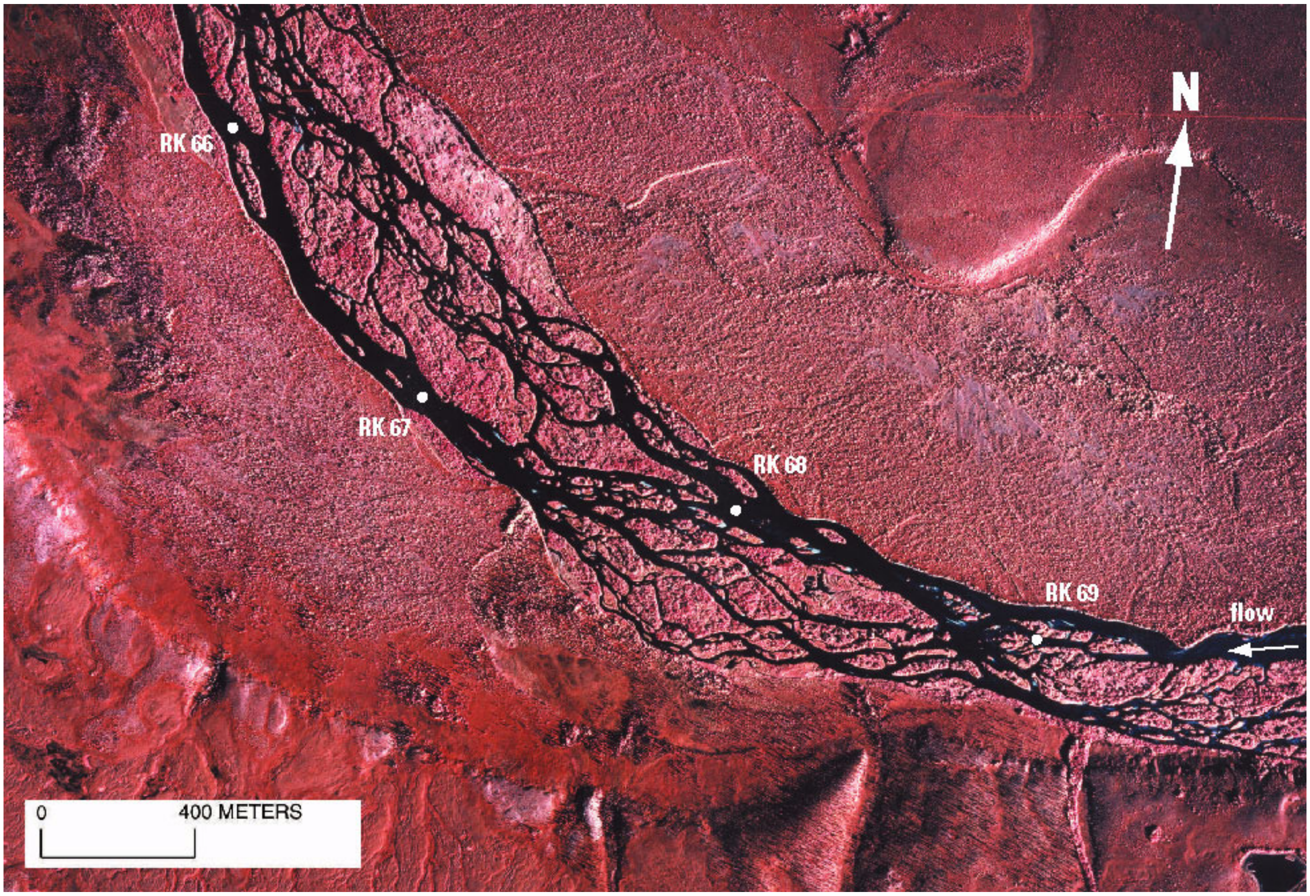


Figure 11. The Alagnak River from river kilometer 65.6 to 69.8. Aerial photography by Aeromap U.S. for the National Park Service, September 16, 2000.

stream to various degrees to about RK 35. Unlike the rapidly shifting channels of true braided rivers, however, the anabranching channels of the Alagnak River remain stable for tens of years and are separated by vegetated islands.

Meanders become more pronounced downstream from The Braids, corresponding roughly to a decrease in valley gradient (fig. 12). Downstream from RK 35, the Alagnak River is a single-thread meandering river having a few midchannel islands and the meander-cutoff scars, point bar-cutbank topography, and meander scrolls typical of a meandering river (fig. 13).

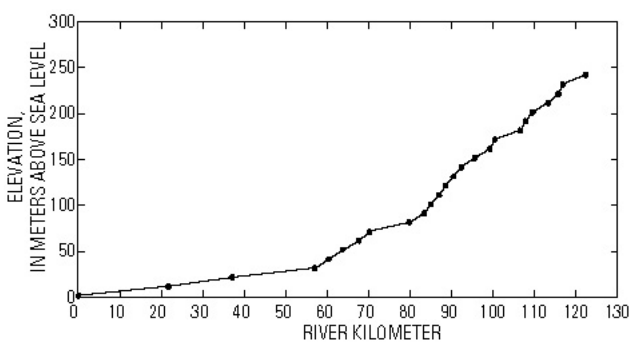


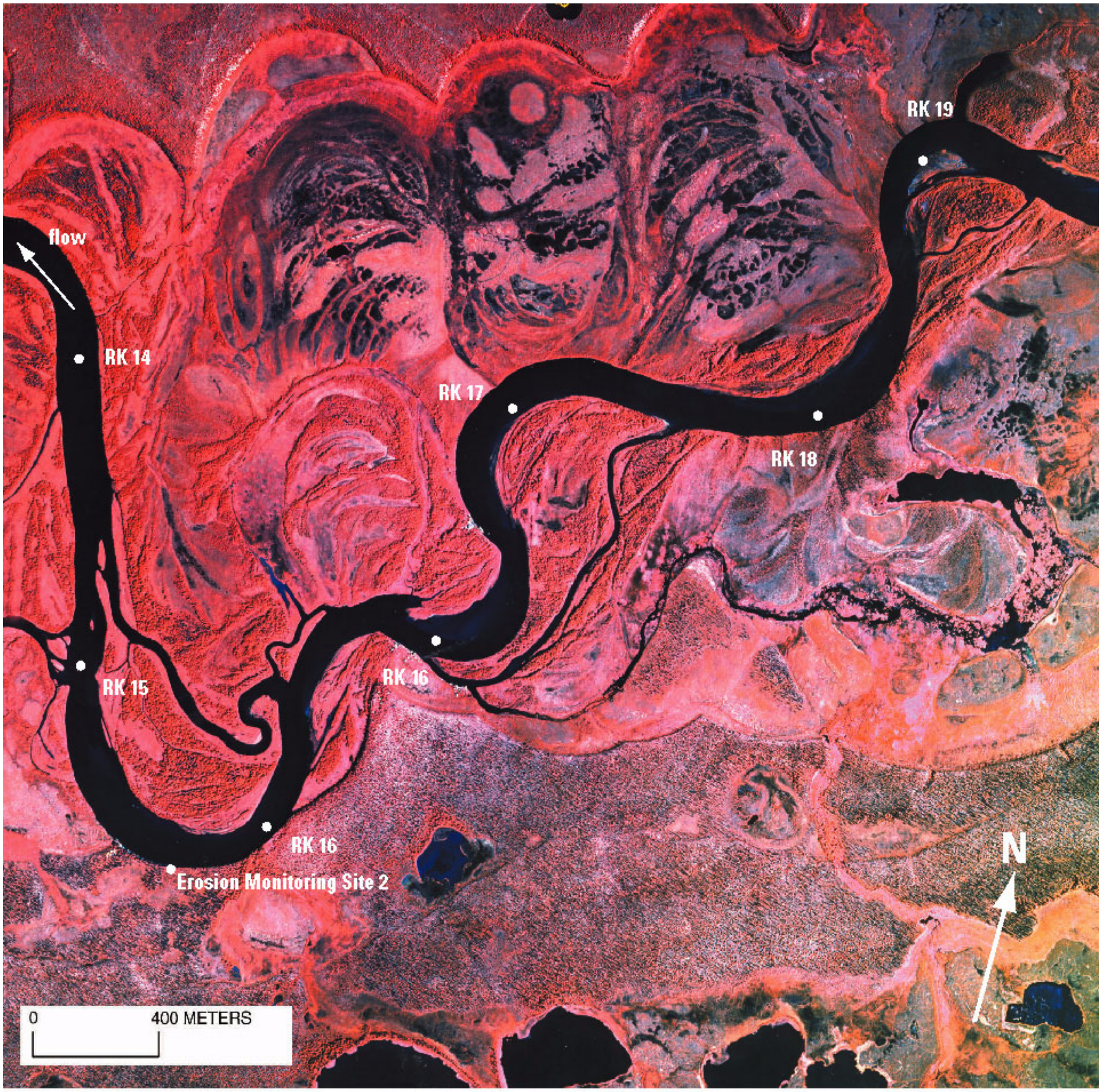
Figure 12. Longitudinal profile of the Alagnak River.

Channel Stability

Historical Channel Change

The type and distribution of changes to Alagnak River channels were summarized from analysis of aerial photographs taken in 1951, 1982, and 2000. Alagnak River channels have changed location but have retained the planforms described in a previous section. They have also maintained the same types of interactions with other channels. Nowhere did multiple-channeled reaches become single-thread reaches, for example, and nowhere did multiple-channeled reaches begin to actively braid.

In the past 50 years, most of the channels in the study area upstream of RK 65 have been stable, such that detectable change is minor and limited to one or two short reaches. The complicated network of channels



Mapping sources cited in Table of Contents

Figure 13. The Alagnak River from river kilometer 13.6 to 19.6. Aerial photography by Aeromap U.S. for the National Park Service, July 26, 2000.

present today at RK 67–68 (fig. 11), for example, is similar to the 1951 network—the widest channel still shifts from the right bank to the left bank in a downstream direction, and many of the individual small channels and islands are still identifiable.

Downstream from RK 65, however, channels have moved by complex, compound adjustments of the network where multiple channels are present (about RK 35–65) and by meander migration where a single channel is present (downstream from RK 35). Changes in multiple-channeled reaches consist of both channel avulsion and lateral channel migration over a given length of channel (complex changes); these changes have occurred to multiple channels across the flood plain at roughly the same time (compound changes). Particularly pervasive changes occurred to the reach from RK 50 to 65 between 1951 and 1982 (fig. 14). Complex channel changes that began upstream of the location of the photographs of the river shown in figure 14 created a new network of channels at location “A” and shifted a portion of the flow from a main southern channel at "B" to a northern channel between 1951 and 1982. A lodge owner familiar with the river recalled major changes to this reach that occurred in 1981 or 1982 (Tony Sarp, Katmai Lodge owner, oral commun., 2001), suggesting that the change occurred suddenly. This is consistent with avulsion as a mechanism of channel change. Between 1982 and 2000, the northern channel at "B" (fig. 14) became the main channel and meanders between "B" and "C" became more sinuous, causing as much as 45 m of bank retreat at "C."

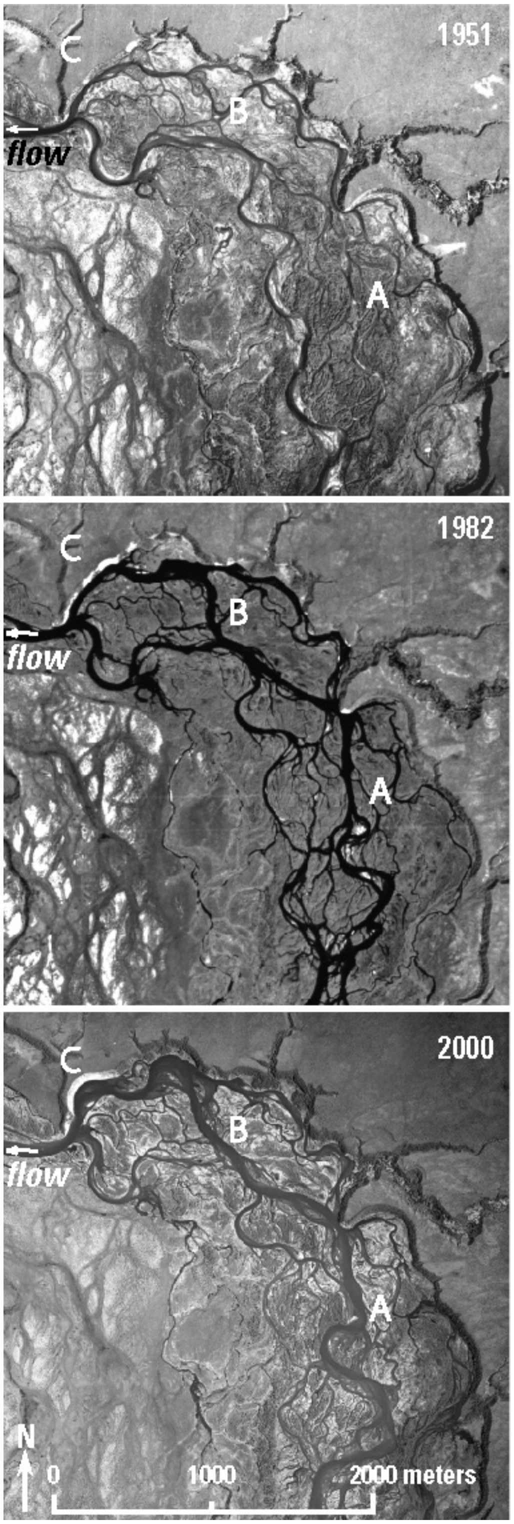


Figure 14. Channel conditions at Alagnak River river kilometer 51–56 in 1951, 1982, and 2000. Labels A, B, and C are in identical positions in each photograph. Aerial photography by U.S. Navy (1951), NASA Ames Research Center (1982) and Aeromap U.S. for the National Park Service (2000).

Inventory of Eroding Banks

As used in this report, the term "banks" refers to sloping surfaces that can be affected directly or indirectly by river currents or waves. This process-based definition encompasses low surfaces adjacent to flood plains as well as high surfaces formed by terrace risers. Most of the landforms along the Alagnak River where bank erosion is a concern are terrace risers. Visibly eroding banks along the Alagnak River range from 1 to 30 m in height above the water surface, and occur where the channel intersects Pleistocene terraces or lower, flood plain surfaces. Less obvious eroding banks are low, about 1 m high, and have bare faces obscured beneath a vegetation mat draped over the top of the bank.

An inventory of eroding banks more than about 1 m high, compiled from field reconnaissance and review of aerial photographs (table 4), documented 26 zones of eroding banks between RK 10.4 and 70.1, which collectively amount to 6 percent of banks in this area (counting each side of the river as a separate bank). Banks between RK 70.1 and the Nonvianuk River confluence were not systematically inventoried, but erosion in this reach appears to be limited to several short zones. Many of the presently eroding banks are visible as unvegetated scars in 1982 and 1951 aerial photographs, indicating that these are either sites of active erosion that have persisted for at least 50 years or that these banks are slow to revegetate once active erosion ceases. Of the eroding banks in table 4, only the high bluff that protrudes into the flood plain at Allotment 01-132 (location "C" in fig. 14) has been substantially modified since 1951. Here, a large concavity eroded into the formerly nearly straight, vegetated side of the bluff has created a neck in the once wedge-shaped terrace (location "C" in fig. 14). Continued erosion here will ultimately breach the neck of the terrace or substantially shorten its tip.

Table 4. Inventory of eroding banks taller than 1 meter between river kilometer 10.4 and 70.1

[RK, river kilometer; m, meter; R, right; L, left; BLM, Bureau of Land Management; NPS, National Park Service]

Informal name	RK	Bank height (m)	Length of exposed bank (m)	Side of river
Alagnak Lodge	10.6	9	700	R
Anglers Alibi	15.7	4	500	L
Crossbedded bank	25.9	17	450	R
Park boundary	29.3	16	120	R
Intermediate terrace I	29.3	6	60	R
Intermediate terrace II	31.3	6	90	R
Intermediate terrace III	31.8	11	90	R
Peat bank	32.4	3	450	L
Near Branch River Lodge	34.3	5	75	R
Katmai Lodge	37.8	8	200	L
Allotment 01-108	45.9	2	350	L
BLM Monument	47.6	2	100	R
NPS mid-river camp	49.7	2	100	L
Allotment 01-132	51.3	30	600	R
Radio Hill	52.1	25	50	R
Allotment 01-113	53.4	20	50	R
Tip of Allotment 01-113	53.5	20	50	R
Allotment 01-114	57.7	20	100	R
Upstream of Allotment 01-114I	57.8	20	30	R
Upstream of Allotment 01-114II	58.0	20	60	R
Allotment 01-116	59.6	2	300	R
Near erosion site 10 (discontinuous erosion)	63.6	2	500	R
Upstream of erosion site 10	64.2	2	350	R
Rock Garden	65.3	10	275	R
Between Rock Garden and Eye of the Needle	66.5	3	250	L
Upstream of Eye of the Needle	69.4	5	1,400	R

BOAT WAKES AND OTHER WATER SURFACE FLUCTUATIONS ON THE ALAGNAK RIVER

Hourly to seasonal fluctuations in water surface change erosional processes at Alagnak River banks and can either increase or decrease erosion rates, whereas the rapid fluctuations from waves generally only increase erosion rates. At very low stage, river energy at and below the water surface is lower than at high stage and is directed at bed material, which is typically coarser (fig. 10) and more difficult to entrain than bank material. An increase in erosion occurs naturally as stage rises, both because increases in near-bank velocity and depth lead to an increase in tractive energy and because river energy becomes directed at banks as well as the bed. Erosion at any water level is temporarily increased when waves strike the bank.

Long-term changes in Alagnak River stage include seasonal changes from spring snowmelt and fall freeze-up, fluctuations over hours to days that result from rainstorms, and, in at least the lowermost 21 km of the river, tidal fluctuations. Short-term changes in stage (waves) are caused by wind, hydraulic conditions, and the passage of motorboats and float-equipped aircraft. This study focused on changes in stage that are introduced by human use of the river and can be controlled. Although visual observations suggest that aircraft generate larger wakes than the boats used on the river, aircraft travel only short distances during landing and take-off and only operate in a few areas suitable for aircraft navigation. For these reasons, the measurements of this study focused on boat wake magnitude and frequency.

Measures of Boat Use

Data documenting specific uses of the Alagnak River are limited to scarce and incomplete summaries of angling. The Alaska Department of Fish and Game publishes annual counts of angler days for the Alagnak

River (fig. 2), but these data do not provide information about the number of motorboats operating on the river or about the spatial and temporal variability of boat use. The NPS began dated counts of the number of boats and their location in 2000, but this survey likewise does not provide data detailed enough to analyze effects on bank erosion.

For more complete motorboat use information, boat wake gaging stations were installed at RK 21, 46, and 93 (figs. 15, 16), where the river is contained within a single channel. At each wake gaging station, the movement of a float suspended in a screened, vertical cylinder in response to water level fluctuations was continuously recorded onto a paper chart. The passage of a motorboat appears on the chart as series of waves, or wake (fig. 17, page 19). Although it is difficult to discern each wave within the wake, the largest wave appears as a spike on the chart, which was used as an indicator of a single boat pass. Chart speed was set at 4 cm per hour so that boats passing in quick succession could be distinguished. The gaging stations were operated from June 2 to September 14, 1999, and from May 31 to August 16, 2000, and were removed each winter to protect from ice damage. Pen carriage assembly jams from large waves and other gage malfunctions limited all data from some periods (see days with no data, fig. 18, page 20), and limited time of occurrence data from other periods.

From each paper chart, we extracted counts of the number of boat passes, the date and time of passage, and the height of the largest wave generated in each wake. Boat wake counts at RK 21 are considered a minimum because of the frequent presence of wind waves. Boat wakes smaller than the maximum height of these natural waves cannot be detected (fig. 17). Similarly, boat wake counts recorded at RK 93 are a minimum because the site is in a riffle, where currents and hydraulically generated surface waves can attenuate and obscure boat wakes. In addition, although most of the channel is navigable at this site, if boat operators follow the deepest part of the channel, the point of wake generation is nearly 60 m from the gaging station. In tests of the ability of the gaging station at RK 93 to detect wakes, a boat was driven past at several different distances from the gaging station. Nearly one-half of the wakes were not detected in this test.

Spatial Distribution of Boat Wakes

Boat traffic as recorded by wake counts at gaging stations is minimal near the Alagnak–Nonvianuk confluence and increases downstream (fig. 18). Boat traffic at

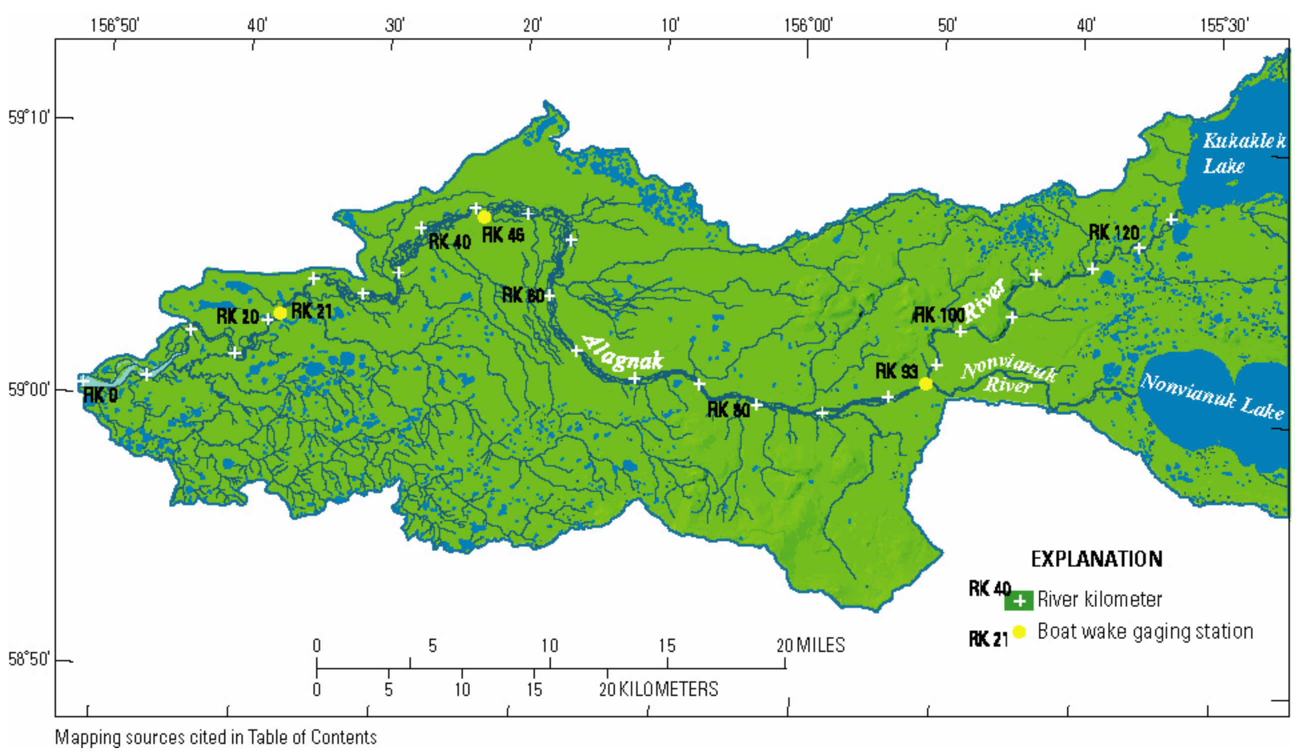


Figure 15. Locations of boat wake gaging stations on the Alagnak River.

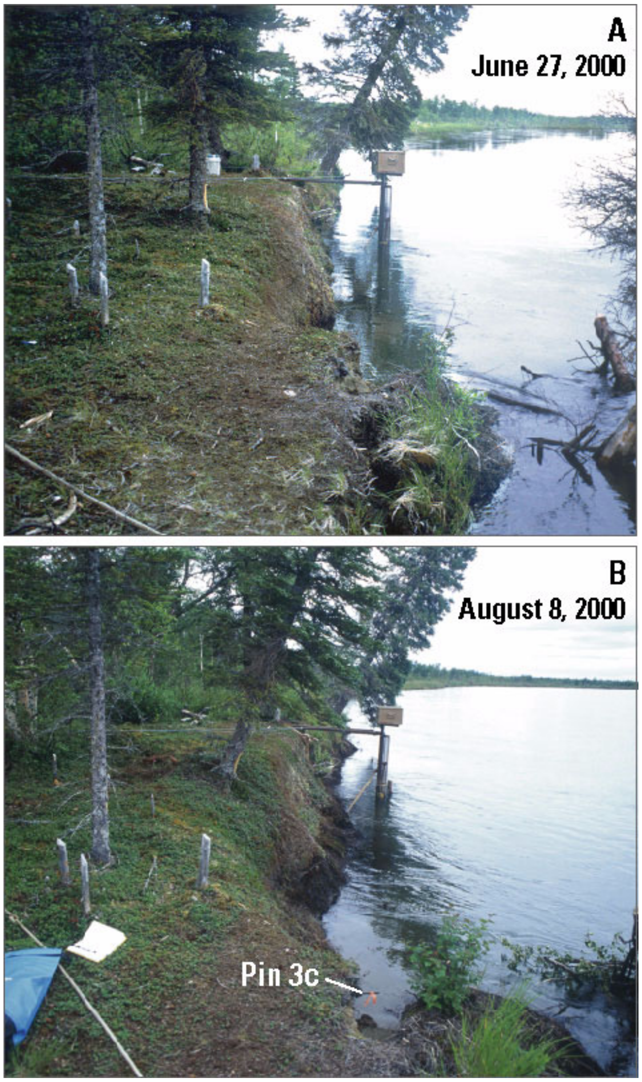


Figure 16. Study site at Alagnak River river kilometer 21. Note vegetation mat draped over bank in (A) and (B) and bank erosion marked by second leaning tree in (B). Wake gage has been moved back in (B) to accommodate bank erosion. Photographs by author.

RK 93 was only a few wakes per day during the periods recorded, whereas boat traffic peaked at 40 wakes per day at RK 46 and 137 wakes per day at RK 21. Continuous data are available for all three sites for at least one of the two study seasons from July 15 through July 23. Median values for this 9-day period near the peak of boat use are 62 and 72 wakes per day at RK 21 in 1999 and 2000, respectively, 7 wakes per day at RK 46, and 1 wake per day at RK 93. Although the river supports all five species of Pacific salmon as well as rainbow trout, grayling, and other fish, the popularity of the king salmon fishery and the technique of repeatedly trolling a favorable location may focus motorboat traffic on the lower portions of the river, where the channel is most suitable for this style of fishing. The density of lodges and other encampments is also higher in the lower river. In addition to fishing, lower river uses observed during field visits include shuttling fuel from barges to a lodge at RK 38.

Although boat wake counts at RK 93 are an underestimate, the total motorboat traffic load at this site is estimated from our observations and the comments of river guides to be an order of magnitude less than in the lower and middle portions of the river.

Frequency and Timing of Boat Wakes

Motorboat use on the lower and middle reaches of the Alagnak River follows a seasonal pattern that has a midsummer peak. Because fishing is the primary use of motorboats on the Alagnak River, the seasonal pattern is tied to the fishing season and probably will not vary substantially from year to year as long as anglers continue to pursue the same species. During this study, motorboat use at RK 21 began with fewer than about 10 wakes per day in early June, rose to a peak in about mid-July, then tapered slowly through August and early September (fig. 18). Wake counts at RK 46 show a similar pattern through July, but data are insufficient to characterize the remainder of the season. Boat wakes occurred every day that the gaging stations were operational except for 5 days at RK 21 and 2 days at RK 46.

Motorboat use on the upper river is considerably less than on the lower and middle river and appears to be more constant throughout the season. No seasonal pattern was evident from a summary of the daily number of wakes at RK 93 (fig. 18). Days with no wakes were common at this site, occurring on 49 of the 84 days that the gaging station was operational in 1999 and 12 of the 25 days that the gaging station was operational in 2000.

Time-of-day data were analyzed to determine hours of operation and the presence or lack of groups of boats. Boat use occurs throughout the day and into the evening (table 5) at all three wake gaging stations. Peak times vary and are likely a function of the distance to camp/lodge facilities. Observations of boat traffic suggest that boats occasionally travel in groups of two but more commonly travel alone. At RK 21, where the highest frequency of boat wakes was recorded, the median time between wakes was 12 minutes. Twenty-eight percent of the wakes were less than 5 minutes apart but only 6 percent were less than 1 minute apart. The time between the last wake of the day and the first wake of the next day was eliminated from this analysis.

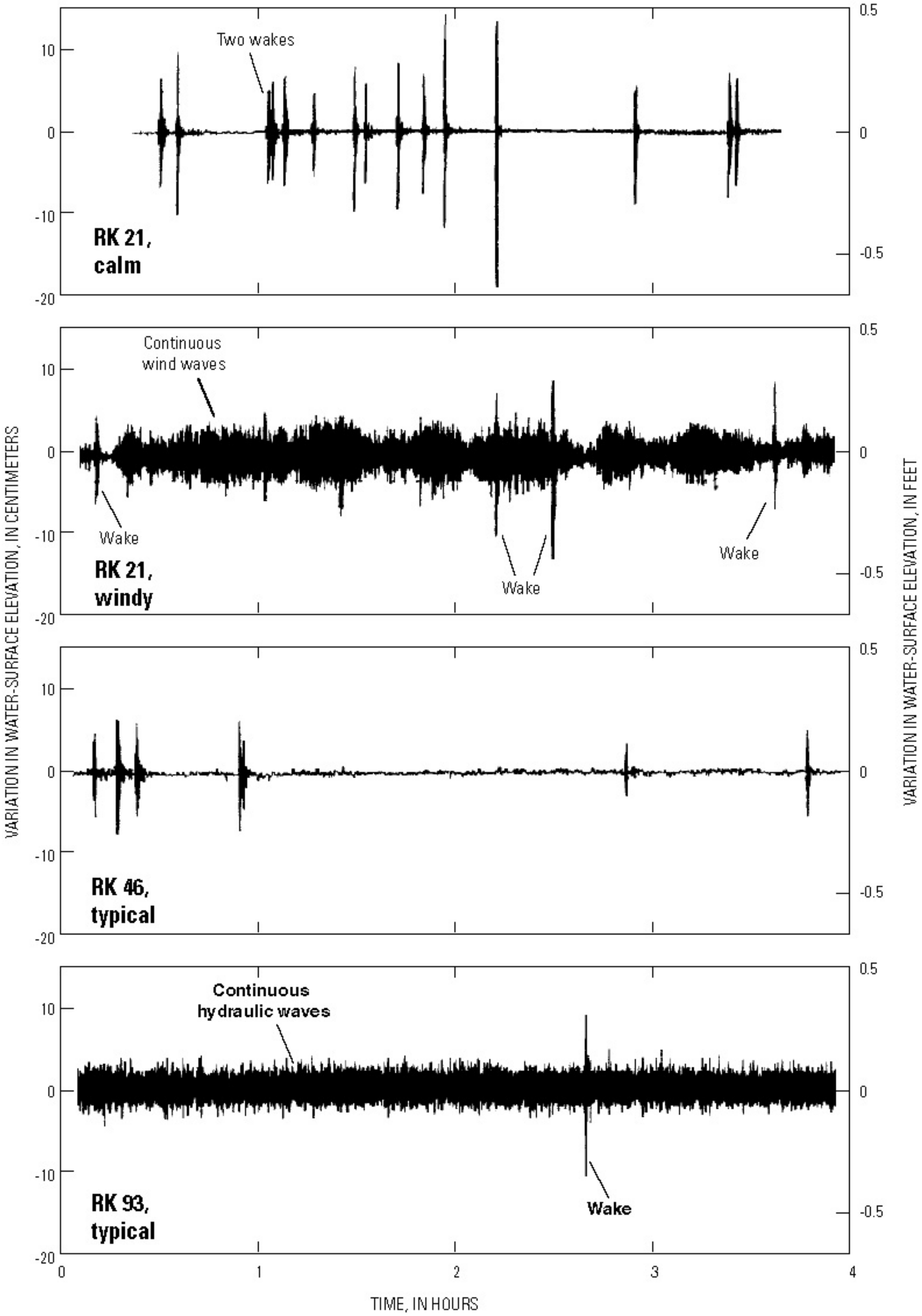


Figure 17. Wake charts showing typical conditions at Alagnak River river kilometer 21, 46, and 93.

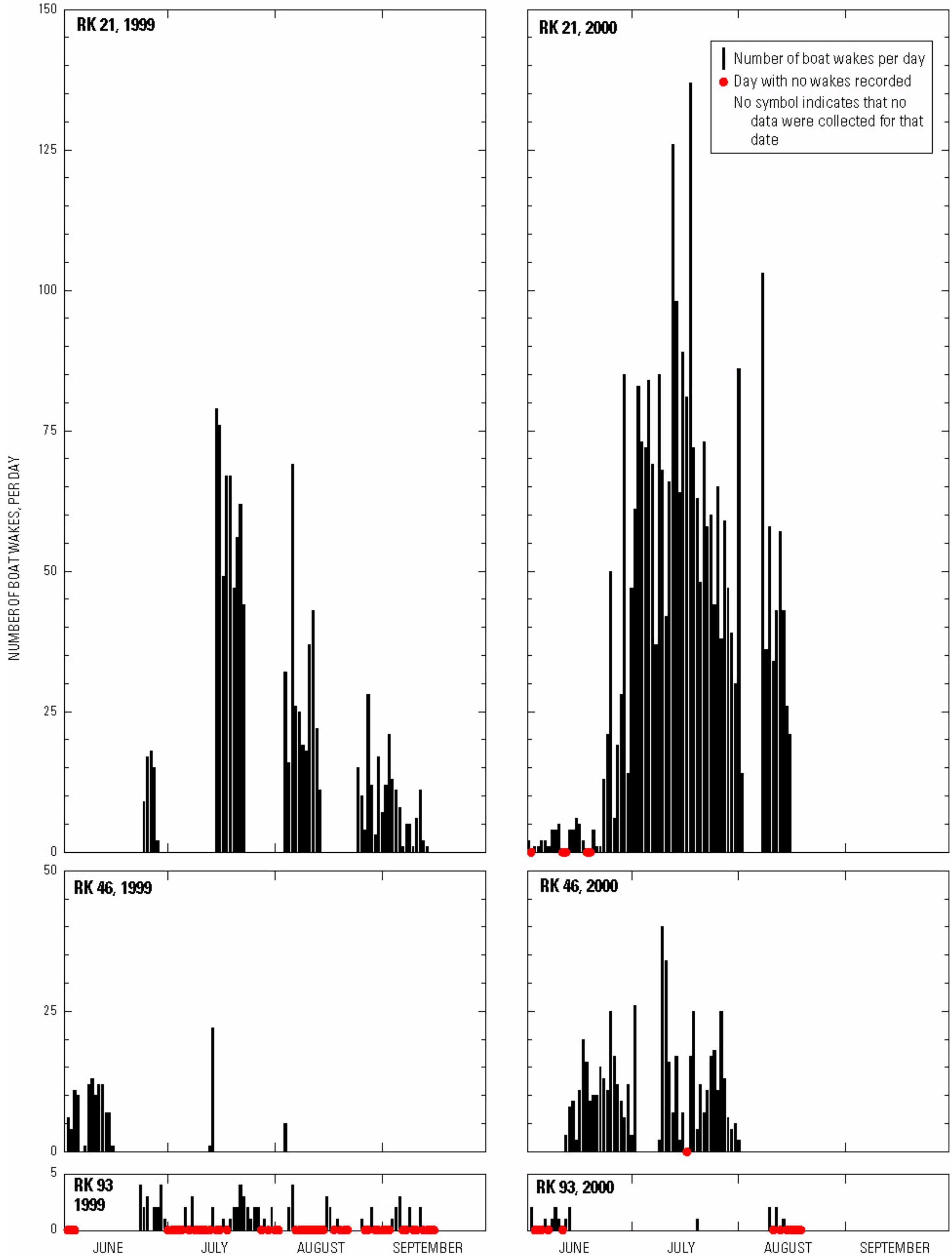


Figure 18. Daily boat wake counts from Alagnak River river kilometer 21, 46, and 93 in 1999 and 2000. Wake counts for RK 46 for the first and last few days of the season are minimums because the float was not yet freely floating.

Table 5. Typical periods of boat usage at wake gaging stations on the Alagnak River, 1999

[RK, river kilometer]

Location	Typical hours of use[a]	Peak hours
RK 21	8:00 a.m. – 9:30 p.m.	9:00 a.m. and 5:00 p.m.
RK 46	8:30 a.m. – 10:30 p.m.	None evident
RK 93	9:30 a.m. – 6:00 p.m.	2:00 p.m.

[a] 5th and 95th percentiles of wake times.

Boat use at RK 21 follows a weekly pattern as well, beginning with the lowest number of wakes on Mondays and rising to a peak late in the week. This cycle is weak but noticeable, with 50 percent more wakes occurring on Thursdays than on Mondays.

Height of Boat Wakes

The height, or distance from crest to trough, of a boat wake is dependent on motor power, hull design, boat weight, boat load, proximity to the bank, boat speed, direction of travel relative to current, and other factors that were not possible to detect with the wake gaging stations (Gadd, 1995; Dorava and Moore, 1997; Maynord, 2001). In addition, shore configuration and water depth at the site affect wake height. The same wake could have a different height if it were recorded a meter closer to shore. Because of the dependence of wake height on physical differences in site configuration, the height of the largest wave in each wake recorded from the wake charts (table 6) provides a sense of the magnitude of waves striking banks, but should not be used for detailed comparison between sites. The largest wave in each wake averaged 0.15 m or less in height, but waves larger than 0.3 m were recorded at each site.

Wind Waves, Hydraulic Waves, and Tidal Fluctuations

In addition to a continuous record of boat wakes, the wake gaging stations also captured water level fluctuations due to wind waves, hydraulic waves, and, occasionally at RK 21, high tides. Although study of these fluctuations was not originally in the study plan, the frequency of their occurrence on the wake charts is noteworthy.

Wind waves on the Alagnak River develop to heights sufficient for the investigation of bank erosion where straighter portions of the river provide adequate fetch, primarily in the lower reaches of the river. Although there are no meteorological stations on the river, our observations and comments from local pilots and river users indicate that strong winds can be frequent. During a period with a strong upriver wind, for example, we observed wind-generated waves estimated at more than 0.6 m in height between RK 16 and RK 21.

Wind waves have a recognizable signature on the boat wake charts because their period is much shorter than the waves in a boat wake and their maximum height is generally smaller (fig. 17). Frequent, large wind waves at RK 21 and minor wind waves at RK 46 and 93 were recorded on the wake charts. The effect of wind waves on bank erosion depends on the height of the waves and their frequency, which would be ideally obtained from the wake charts. Because the resolution of the inked line on the paper chart was insufficient to determine the height or number of individual wind waves, the waves were characterized by noting their presence or absence in half-hour periods and measuring the wind wave envelope, or the maximum height of all wind waves within that time period. An analysis of RK 21 for 1999, the period that better represents the entire open-water season, shows that wind waves occurred 36 percent of the time the gaging station was operational. The wind wave envelope was as large as 0.23 m and averaged 0.05 m, or about one-third the average height of boat wakes at this site.

Hydraulic waves are generated in reaches with steeper gradients, where the water surface fluctuates rapidly as a result of hydraulic conditions without the presence of wind or other wave-generating mechanisms. This was particularly evident at RK 93, located in a riffle where small hydraulic waves are continuous (fig. 17). The envelope of continuous waves recorded at this site ranged from 0.03 to 0.08 m in height. Hydraulic waves are common on the Alagnak River upstream of about RK 57.

Table 6. Summary statistics of wave height for wakes recorded on the Alagnak River in 1999 and 2000 at river kilometer 21, 46, and 93

[m, meter; RK, river kilometer; only the height of the maximum wave in each wake was recorded for analysis]

Location	Maximum wave height (m)	Mean wave height (m)	Standard deviation (m)	Number of wakes used in analysis
RK 21	0.38	0.14	0.06	4,003
RK 46	.37	.12	.04	683
RK 93	.32	.15	.05	95

Certain high tides generated an abrupt rise and slow decline in water surface that spanned several hours at RK 21. This effect was recorded only during periods of low streamflow, generally early June, August, and September. Tidal fluctuations during these periods at RK 21 ranged from less than 0.03 m to 0.3 m and occurred daily or twice daily, probably depending on the magnitude of the tidal range. No effect of low tides was recorded on the wake charts.

BANK EROSION PROCESSES AND RATES ALONG THE ALAGNAK RIVER

Bank erosion is a primary mechanism for sediment delivery to a laterally mobile channel such as the Alagnak River. Little sediment is transported from the headwaters of the Alagnak River Basin because of the trapping effect of the large lakes that form the source of the Alagnak and Nonvianuk Rivers. Sediment produced by bank erosion can have a local effect on suspended-sediment levels and can have a local, reach-level, or river-level geomorphic effect. Bank erosion monitoring quantifies the magnitude and spatial variation of bank erosion processes and rates.

Methods of Bank Erosion Monitoring

Erosion monitoring on the Alagnak River consisted of repeated measurements at 14 sites between RK 10 and 93 (fig. 9). Each site included one or more erosion pin and various markers to identify the site and the specific location of the pin (appendix 4). Erosion pins consisted of 76 or 91 cm long, 0.95 or 1.3 cm diameter, smooth, round metal rods driven horizontally into the bank face or near-vertically (perpendicular to the slope) into the bank base to provide a fixed reference point. Periodic measurements of the exposure of each pin provided a measure of bank retreat or colluvium accumulation. Pins were driven farther into the bank as erosion progressed; measurements of exposure before and after pin adjustment allowed correlation of final pin exposure to initial conditions. Cumulative erosion, or change in bank position relative to an arbitrary horizontal datum of 0 on the date of pin installation, was calculated as the total variation from the initial measurement and could be positive (bank retreat or removal of colluvium) or negative (accumulation of colluvium). Repeated surveys of the bank profile at the erosion pin sites documented bank changes in more detail (appendix 5), and photographs provided detail of the surrounding area. Most erosion pins were measured from July 1998 to June 2001, which included an open-water season with a large flood (1999) and a season with more typical streamflow (2000) (fig. 8). Bank profiles were surveyed in 2000 and 2001.

Bank Erosion Processes

Erosional processes in noncohesive banks generally are surficial. If banks are drained, failure occurs by dislodgement of individual grains or by shallow failures parallel to the slope (Thorne, 1982). If banks are undrained (such as when a previously underwater bank face is suddenly exposed to the air), failure can occur from increased pore water pressure (Thorne, 1982). Deep-seated or rotational failures do not generally occur in noncohesive banks because the shear strength increase with depth exceeds the shear stress increase (Selby, 1993).

Alagnak River banks consist almost entirely of unconsolidated, noncohesive sediments derived from glacial drift or river alluvium. From near erosion monitoring site 1 to the river mouth, banks include cohesive, estuarine deposits; this area is largely excluded from our analysis of erosion processes. On unvegetated slopes, our observations show that toe erosion oversteepens the overlying bank and promotes gravity-driven failure (ravel) of the unvegetated face of the bank. At several locations, erosion has undermined a terrace surface, leaving a mat of former terrace vegetation fully draped over the bank face (figs. 6 and 16). The bank face in this case is still unvegetated and fails by the same process of toe erosion/ravel. In contrast, where banks have restabilized, vegetation grows directly on the bank face. This vegetation may serve to further stabilize the banks and protect them from minor toe erosion.

A series of photographs from erosion monitoring site 2 (fig. 19) and surveys from site 6 (fig. 20) illustrate erosional processes at typical high eroding banks on the Alagnak River. Erosion progressed from water-driven erosion to gravity-driven erosion roughly in parallel with river stage during monitoring. This progression can be summarized by the following stages:

1. During winter and spring, river stage is low, a wedge of accumulated bank material (colluvium) covers the bank face in a near angle-of-repose slope, and the bank drops away steeply beneath the water (fig. 19B and 19E).

A
September 14, 1999

B
June 1, 2000

C
June 13, 2000

D
August 8, 2000

E
June 5, 2001

Figure 19. Changes to left bank at erosion monitoring site 2 on the Alagnak River. Arrows show location of erosion pins. Photographs by author.

2. As river stage rises, usually in early to mid-June, colluvium at the toe of the bank is fluvially entrained, creating a near-vertical scarp that progresses shoreward (fig. 19C). Boat traffic rises during this period as well (fig. 18), creating wakes that also remove colluvium from the base of the bank. The wave action of both boat wakes and large wind waves erodes the colluvium from the bank and deposits much of it in a shallow shelf just below the water surface (fig. 20A).

3. River and wave erosion continue to remove colluvium and, depending on the thickness of colluvium and the rate of erosion, expose the bank face (fig. 19D). Erosion of the exposed bank faces results in bank retreat and continues as long as river levels remain high. As long as waves are present, the shallow underwater shelf migrates with water level, reforming just under the water surface (fig. 20B).

4. As river stage drops, the active river and wave erosion ceases. The oversteepened bank returns to a near angle-of-repose slope over a period of many months by ravel of the loose, unconsolidated material overlying the eroded toe (process has begun in fig. 19A).

This seasonal progression results in slopes that have a similar form from year to year, when compared at the same time of year, but have retreated shoreward (fig. 20C).

Bank Erosion Rates

Upstream from RK 65, channel change appears to be infrequent and local. Downstream from RK 65, changes observed in aerial photographs, vegetation patterns, and the presence of abandoned channels indicate that the channel is laterally mobile and has changed course or noticeably eroded its banks over the past 50 years. Undermined streamside structures (fig. 21) provided additional evidence for local bank erosion. Historical channel change has varied from complex, compound channel changes between RK 50 and 65 to simple meander migration common in reaches downstream from RK 35.

Monitoring at erosion pins throughout the study area quantified short-term erosion rates. Although channel changes involving sudden, major channel redirections (avulsions) cannot be adequately described by bank

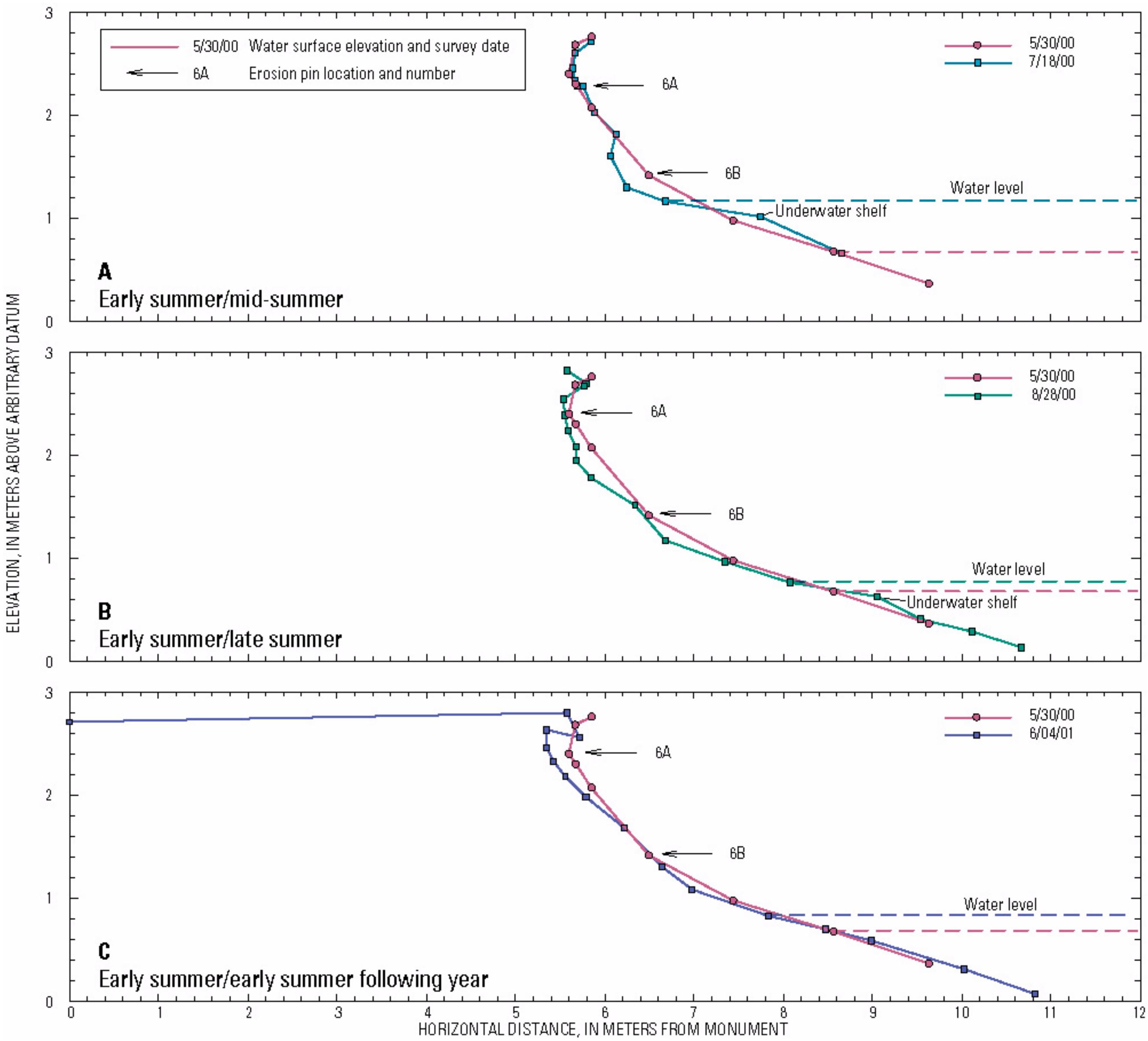


Figure 20. Bank profiles at erosion monitoring site 6 at river kilometer 45.9 on the Alagnak River, 2000–2001. Initial early summer conditions are plotted together with subsequent conditions in (A) mid-summer, (B) late summer, and (C) early summer the following year.

erosion rates, changes involving progressive bank retreat can. Erosion rates calculated from repeated erosion pin measurements at sites 1–14 (appendix 6) provide a measure of horizontal bank retreat at a single location along the bank profile. Erosion rates at representative pins at each site are averaged to provide a single erosion rate for each site (table 7).

Average annual erosion rates, based on erosion pin measurements, varied over the length of the study area from almost no erosion near the confluence of the Alagnak and Nonvianuk Rivers (RK 93) to as much as 115 cm/yr (centimeters per year) near the end of the Alagnak Wild River boundary (RK 30) (table 7). Erosion generally increases in a downstream direction but is highly variable (fig. 22). Erosion rates, processes, and driving forces vary from reach to reach, so erosion rates are discussed here in the context of their location.

The small or even negative erosion rates recorded in the upper part of the river (RK 65–93), coupled with visual observations, suggest that erosion is minimal in these reaches. Unvegetated banks are not common, even at high banks adjacent to the river and at banks on the outside of meander bends. The negative rates recorded at

Figure 21. Bank erosion beneath bankside structure, Alagnak River river kilometer 17. Photograph by author, June 5, 2001.

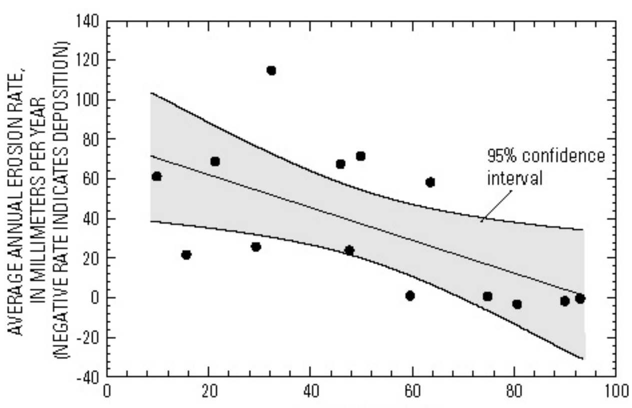


Figure 22. Downstream distribution of measured erosion rates along the Alagnak River. Regression is significant at $p = 0.02$ with $r^2 = 0.37$.

the erosion monitoring sites may reflect growth of moss and other vegetation over the pin, or soil creep.

Average annual erosion rates downstream of RK 65 are consistently greater than in the upper river. Strong variability in the measured rates between sites is consistent with visual observations of varying amounts of erosion along the channel and with measurements of varying rates between multiple erosion pins at a single site. Noticeable bank erosion is generally limited to one side of the channel and extends 30 to 1,400 m along a bank of similar composition and height; adjacent areas may have no measurable erosion. Within a bank erosion-monitoring site, factors such as treefall create temporally variable conditions. For example, at site 8 the top of the bank retreated suddenly when a stump collapsed into the channel on May 31, 2000, but then held position for an extended period while the root ball protected the bank (see pin 8B, appendix 7). No measurements linking the old and new pins (pins 8A and 8B) could be made after the event, but even if measurements had been possible, they would only have been representative of this short segment of bank.

Measurements at erosion pins not subjected to extenuating conditions such as treefall revealed seasonal patterns of erosion similar to those observed in the bank profile surveys (appendix 7). Bank erosion rates at a site vary both spatially and temporally. At pins near the middle and lower portions of high, unvegetated banks (such as pins 2B [also see fig. 19], 7B, 9A), strong increases in erosion during the open-water season are typically

Table 7. Summary of erosion rates at Alagnak River erosion monitoring sites

[Where more than one pin was present at a site, rates for the most representative pins were based on averaged visual observations of erosion at other locations along the bank. Periods for calculation of rates were chosen to begin and end as close as possible to the same time of year to avoid differences between seasons. Refer to appendix 6 for individual erosion pin measurements. cm/yr, centimeter per year]

Erosion monitoring site number	River kilometer	Average erosion rate at site (cm/yr)	Pins used for calculation	Beginning date for calculation	Ending date for calculation	Erosion rate for specified period (cm/yr)
1	9.8	61	1A	7/13/98	7/19/00	48
			1B	6/3/99	6/5/01	74
2	15.7	22	2A	9/16/98	8/29/00	15
			2B	7/13/98	7/19/00	29
3	21.2	69	3A	7/13/98	7/15/99	69
4	29.3	26	4A	9/16/98	8/31/00	33
			4B	7/13/98	7/15/99	19
5	32.3	115	5A	7/13/98	7/19/00	122
			5B	7/13/98	7/19/00	108
6	45.9	67	6A	7/15/98	7/18/00	88
			6B	9/16/98	8/28/00	47
7	47.6	24	7A	6/12/00	6/7/01	9
			7B	6/12/00	6/7/01	29
			7C	6/12/00	6/7/01	34
8	49.8	72	8A	7/12/98	5/31/00	76
			8C	7/15/98	6/28/00	67
9	59.5	1	9A	7/12/98	7/20/00	1
10	63.6	58	10A	9/17/98	8/31/00	58
11	74.8	1	11A	6/4/99	6/6/01	1
12	80.6	-3	12A	7/12/98	7/20/00	-3
13	89.9	-2	13A	7/12/98	7/20/00	-2
14	92.9	0	14A	7/12/98	7/20/00	0
			14B	7/12/98	7/20/00	-1

followed by minor or negative erosion rates between the last measurement of one season and the first of the next season. Negative erosion rates (deposition) occur as colluvial material buries the pin. At the top of the bank, erosion can be pulsed, with periods of little erosion followed by sudden rapid change (such as at pin 7A), or may occur later in the season than at the lower parts of the bank (such as at pin 2A).

Some sites, such as sites 5 and 6, were affected more strongly by the flooding in June 1999 than at any other time during the monitoring period, experiencing a sharp increase in erosion. Some high, unvegetated, noncohesive banks (for example, site 8) eroded back substantially in the flood and nonflood years. Conversely, some high, vegetated banks (such as site 14) remained stable throughout the study, except for minor aggradation attributable to soil creep. Fortuitous placement of erosion pins at site 4 resulted in apparent stability not echoed across the more exposed portions of the bank, followed by sudden erosion at the vicinity of the pin that also was not representative of the adjacent, more obviously exposed and eroding bank.

The thick vegetation mat draped over many Alagnak River banks often prevents direct observation of erosion and complicates measurements of erosion pins. Banks at site 3, for example, clearly show erosion in sequential photographs (fig. 16), a result not captured by the erosion pins. The pin, visible in the bottom center of fig. 16B, is partly behind the rootball of a tree that barely clung to the bank throughout much of the monitoring period. Erosion adjacent to the pin that is documented by the photographs demonstrates that erosion occurs beneath the vegetation mat.

Sites 2, 5, and 6 are along the outside bank of well-developed, short-radius meanders, a geomorphic feature where erosion rates are expected to be high. Sites 3, 7, and 8 are along the outside bank of poorly developed or long-radius meanders. Collectively, these sites include both high and moderate rates of erosion and, conversely, other sites have comparable rates of erosion. Although it is clear that locally, meander curvature is a factor that affects erosion rates, the longitudinal distribution of erosion rates cannot be attributed to meander curvature alone.

WATER QUALITY OF THE ALAGNAK RIVER

Water-quality sampling of the Alagnak River provided both a baseline for future comparisons and a basis for interpretation of the relative impact of seasonal, geologic, geographic, or human-related influences. Water samples were collected at three primary main-stem Alagnak River sites (fig. 23) on five to seven

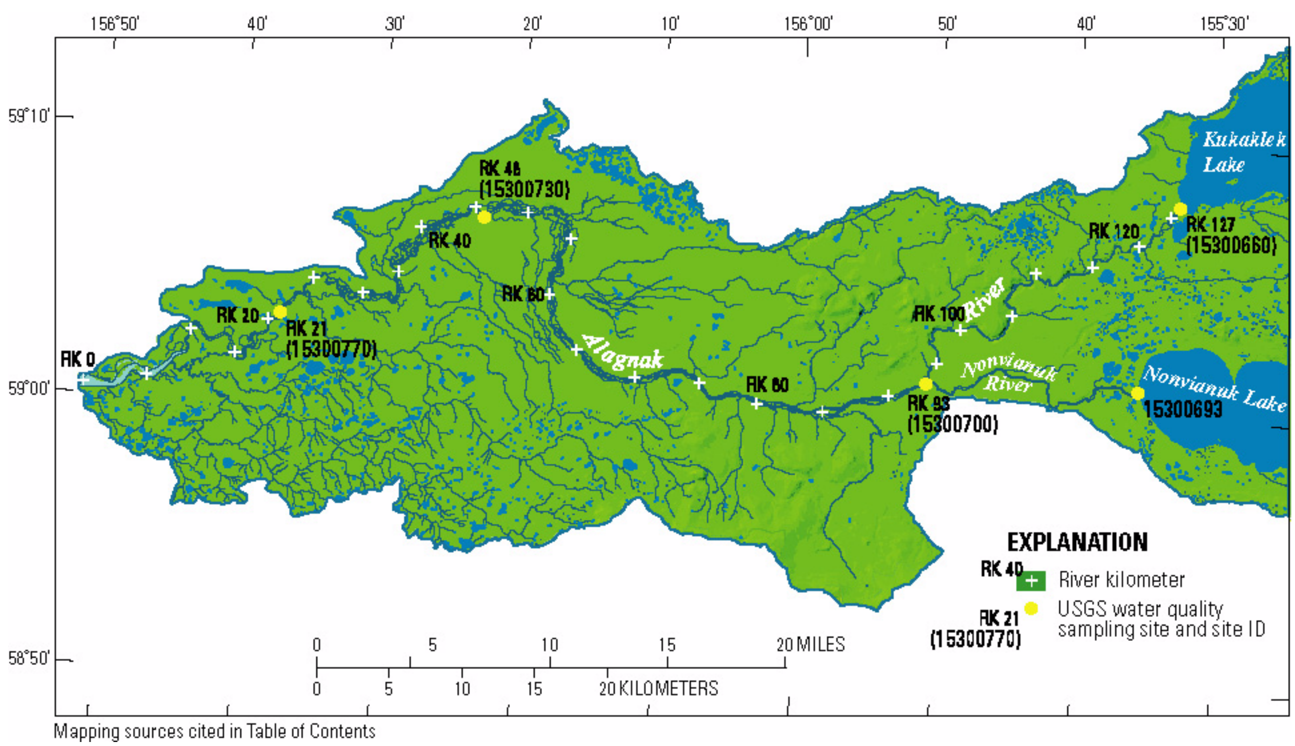


Figure 23. Locations of water-quality sampling sites on the Alagnak and Nonvianuk Rivers.

occasions between June 1999 and February 2001 and at two supplemental sites at the outlets of Nonvianuk and Kukaklek Lakes (fig. 23) on one occasion in August 2000. Water samples were submitted for laboratory analysis of nutrients, major ions, organic carbon, and suspended sediment. A bed sediment sample collected at RK 21 in September 1999 was submitted for laboratory analysis of trace-element chemistry. Physical parameters were measured at each water-sampling site, at an additional site in each of the Alagnak and Nonvianuk Rivers immediately upstream of their confluence, and at a creek at RK 86.

Results for selected analyses at the sites shown in fig. 23 are summarized here; results of additional analyses, results for additional sites, and additional details of sampling procedures are presented in Bertrand and others (2000) and Meyer and others (2001).

Water-quality data were analyzed to (1) detect spatial and temporal trends, (2) determine whether high concentrations of any constituents are present, and (3) determine whether human activities are likely to have influenced concentrations of constituents present in high concentrations.

Methods of Sampling and Analysis

Discharge

Discharge (table 1, fig. 8) was measured at each site just before sampling, except at RK 21 in late June 2000 and early August 2000, when discharge was measured one day before sampling. No adjustments were made for stage changes between the time of discharge measurement and the time of sampling. Discharge measurement techniques are described in the "Hydrology of the Alagnak River" section of this report.

Sample Collection and Processing

Water samples were collected using a US D-95 sampler suspended from a boat-mounted boom and reel. Water-chemistry and suspended-sediment samples were depth- and width-integrated (Edwards and Glysson, 1999; Wilde and others, 1999a) and processed according to methods described by Wilde and others (1999b). Water-chemistry samples were field composited, whereas suspended-sediment samples, with the exception of those from RK 93, were composited in the lab. The physical parameters of specific conductance, dissolved oxygen, pH, and temperature were measured in the river at the sampling points using a calibrated Hydrolab multiparameter field meter.

Major ion, trace-element, and nutrient samples were filtered through a 0.45-μm (micrometer) capsule filter. Dissolved organic carbon samples were filtered through a 0.45-μm silver filter, which was retained for suspended organic carbon analysis. Trace-element samples were preserved with nitric acid. Nutrient samples for analysis of dissolved concentrations were filtered. Whole nutrient samples were preserved with sulfuric acid and chilled.

Fine-grained bed sediment for bed-sediment trace-element analysis was collected from multiple points in depositional zones near the riverbank and composited in a glass bowl. The composited sample was wet-sieved in the field through a 63-μm sieve as described by Shelton and Capel (1994).

Quality Control

Duplicate water samples were collected at Kukaklek Lake outlet on August 11, 2000, and aqueous field blanks were collected at RK 93 on September 15, 1999, and RK 46 on June 28, 2000. Results of analyses of duplicate water samples agreed well, as would be expected in the absence of contamination during sampling or analysis. Analyses of field blanks indicated that procedures followed generally were capable of providing data in the ranges expected from the minimum reporting levels, which are given in table 8. However, measured values in the June 28, 2000, field blank for ammonia and orthophosphate were 0.033 mg/L (milligrams per liter) and 0.009 mg/L, respectively, which are close to the highest values measured in river water samples. Field cleaning of sampling equipment may have contributed to the high values. Minor variations in these constituents, which were detected in low concentrations in Alagnak River water, should be interpreted with caution.

Results reported for samples collected from RK 46 on July 13, 1999, for analysis of calcium, magnesium, potassium, sodium, silica, iron, and manganese had an anomalous cation/anion balance and were discarded. Other results from this sampling location and date were unaffected.

Table 8. Water-quality constituents analyzed for in water from the Alagnak River, 1999–2001

[USGS, U.S. Geological Survey; USEPA, U.S. Environmental Protection Agency; n/a, not applicable; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter]

Constituent	USGS parameter code	Minimum reporting level or method detection limit	USEPA [a] maximum contaminant levels	Unit
		Field determinations		
Water temperature	00010	0.1	n/a	Degree Celsius
pH	00400	0.1	n/a	Standard units
Dissolved oxygen	00300	0.1	n/a	mg/L
Specific conductance	00095	3	n/a	µS/cm
Alkalinity	39086	1	n/a	mg/L as $CaCO_3$
		Laboratory analyses—Inorganic constituents		
Hardness	00900	computed	n/a	mg/L as $CaCO_3$
Dissolved solids, residue at 180 degrees Celsius	70300	10	n/a	mg/L
Dissolved solids, sum of constituents	70301	computed	n/a	mg/L
Major ions				
Calcium	00915	0.011	n/a	mg/L
Magnesium	00925	0.008	n/a	mg/L
Sodium	00930	0.06	n/a	mg/L
Potassium	00935	0.09	n/a	mg/L
Bicarbonate	00453	1	n/a	mg/L as HCO_3
Sulfate	00945	0.11	n/a	mg/L
Chloride	00940	0.08	n/a	mg/L
Fluoride	00950	0.1	4	mg/L
Silica	00955	0.13	n/a	mg/L as SiO_2
		Nutrients		
Ammonia	00608	0.002	n/a	mg/L as N
Ammonia plus organic nitrogen	00623	0.1	n/a	mg/L as N
Nitrite plus nitrate	00631	0.005	10	mg/L as N
Nitrite	00613	0.001	1	mg/L as N
Phosphorus, dissolved	00666	0.004	n/a	mg/L as P
Orthophosphate	00671	0.001, 0.007	n/a	mg/L as P
Phosphorus, total	00665	0.0037	n/a	mg/L as P
		Organic carbon		
Dissolved organic carbon	00681	0.33	n/a	mg/L
Suspended organic carbon	00689	0.2	n/a	mg/L
		Trace elements		
Iron	01046	10	n/a	µg/L
Manganese	01056	2.2	n/a	µg/L

[a] U.S. Environmental Protection Agency (2000).

Standards and Guidelines

The U.S. Environmental Protection Agency (USEPA) (2000) has established standards for certain constituents in drinking water that are based on adverse effects to human health (table 8). USEPA standards exist for a range of inorganic chemicals not analyzed for inthis study, such that the analysis for this study does not constitute a complete test of Alagnak River water for drinking water suitability.

Bed sediment concentrations can be placed in context by comparing to known concentrations in other areas or to established guidelines for the health of aquatic organisms. Gough and others (1988) summarized the means and ranges of element concentrations from more than 15,000 unsieved samples of Alaskan stream and lake sediments (table 9). The Canadian Council of Ministers of the Environment (2001) has established guidelines for some trace elements in unsieved streambed sediments (table 9). These guidelines use two assessment values: a lower value called the interim freshwater sediment quality guideline (ISQG) and an upper value called the probable effect level (PEL). The ISQG is the concentration below which adverse biological effects are not expected to occur. The PEL is the concentration above which adverse biological effects are expected to occur frequently. The range between the ISQG and the PEL are concentrations at which adverse biological effects are occasionally observed.

Constituent concentrations in sieved sediment are generally higher than concentrations in unsieved sediment, so comparisons to the Alaska data or the Canadian guidelines can be considered conservative. For example, the Canadian guidelines may be overly stringent for sieved sediment.

Chemical Constituents of the Alagnak River

Water

The Alagnak River is a calcium-bicarbonate water (fig. 24) that has low concentrations of major ions and organic carbon and contains low concentrations of the trace elements which samples were analyzed for (appendix 8). Alagnak River water meets or exceeds drinking water standards for nutrients published by the USEPA (2000). Water-quality results varied little between sites, despite considerable distances between them.

Table 9. Results of analyses of sieved (<0.063 millimeter) Alagnak River bed sediment collected in 1999 at river kilometer 21 (U.S. Geological Survey site 15300770)

[USGS, U.S. Geological Survey; ISQG, interim freshwater sediment quality guideline; CCME, Canadian Council of Ministers of the Environment; PEL, probable effect level; LRL, laboratory reporting level; n/a, not applicable; MRL, minimum reporting level; ND, not detected; <, actual value is known to be less than value shown; µg/g, microgram per gram]

Constituent	USGS parameter code	Reporting level	Reporting level type	Mean Alaskan concentration in unsieved sediment (Gough & others, 1988)	ISQG (CCME, 2001)	PEL (CCME, 2001)	Concentration in sample	Unit
				Major Ions				
Calcium	34830	0.005	LRL	2.6	n/a	n/a	2.6	percent
Magnesium	34900	0.005	LRL	1.3	n/a	n/a	0.92	percent
Potassium	34940	0.005	LRL	5.1	n/a	n/a	0.94	percent
Sodium	34960	0.005	LRL	1.2	n/a	n/a	2.0	percent
Sulfur	34970	0.05	MRL	n/a	n/a	n/a	0.13	percent
				Nutrients				
Phosphorous	34935	0.005	LRL	n/a	n/a	n/a	0.17	percent
				Carbon				
Inorganic carbon	49269	0.01	MRL	n/a	n/a	n/a	0.03	percent
Total carbon	49267	0.01	MRL	n/a	n/a	n/a	6.37	percent
Organic carbon	49266	0.01	MRL	n/a	n/a	n/a	6.34	percent

Table 9. Results of analyses of sieved (<0.063 millimeter) Alagnak River bed sediment collected in 1999 at river kilometer 21 (U.S. Geological Survey site 15300770)—Continued

[USGS, U.S. Geological Survey; ISQG, interim freshwater sediment quality guideline; CCME, Canadian Council of Ministers of the Environment; PEL, probable effect level; LRL, laboratory reporting level; n/a, not applicable; MRL, minimum reporting level; ND, not detected; <, actual value is known to be less than value shown; µg/g, microgram per gram]

Constituent	USGS parameter code	Reporting level	Reporting level type	Mean Alaskan concentration in unsieved sediment (Gough & others, 1988)	ISQG (CCME, 2001)	PEL (CCME, 2001)	Concentration in sample	Unit
				Trace Elements				
Aluminum	34790	0.005	LRL	5.8	n/a	n/a	7.1	percent
Antimony	34795	0.1	LRL	n/a	n/a	n/a	0.76	µg/g
Arsenic	34800	0.1	LRL	17	5.9	17	14	µg/g
Barium	34805	1	LRL	810	n/a	n/a	550	µg/g
Beryllium	34810	0.1	LRL	2	n/a	n/a	0.79	µg/g
Bismuth	34816	1	LRL	n/a	n/a	n/a	<1.0	µg/g
Cadmium	34825	0.1	LRL	n/a	0.6	3.5	<0.1	µg/g
Cerium	34835	1	LRL	68	n/a	n/a	30	µg/g
Chromium	34840	1	LRL	120	37	90	52	µg/g
Cobalt	34845	1	LRL	18	n/a	n/a	11	µg/g
Copper	34850	1	LRL	37	36	200	34	µg/g
Europium	34855	1	LRL	n/a	n/a	n/a	1.2	µg/g
Gallium	34860	1	LRL	n/a	n/a	n/a	13	µg/g
Gold	34870	1	LRL	ND	n/a	n/a	<1.0	µg/g
Holmium	34875	1	LRL	ND	n/a	n/a	<1.0	µg/g
Iron	34880	0.005	LRL	3.7	n/a	n/a	4.1	percent
Lanthanum	34885	1	LRL	36	n/a	n/a	15	µg/g
Lead	34890	1	LRL	12	35	91	4.6	µg/g
Lithium	34895	1	LRL	29	n/a	n/a	13	µg/g
Manganese	34905	4	LRL	0.08	n/a	n/a	1,300	µg/g
Mercury	34910	0.02	MRL	n/a	0.17	0.49	0.04	µg/g
Molybdenum	34915	0.5	LRL	n/a	n/a	n/a	1.3	µg/g
Neodymium	34920	1	LRL	n/a	n/a	n/a	16	µg/g
Nickel	34925	2	LRL	37	n/a	n/a	14	µg/g
Niobium	34930	4	LRL	n/a	n/a	n/a	8.7	µg/g
Scandium	34945	2	LRL	14	n/a	n/a	15	µg/g
Selenium	34950	0.1	MRL	n/a	n/a	n/a	0.6	µg/g
Silver	34955	0.1	LRL	n/a	n/a	n/a	0.24	µg/g
Strontium	34965	2	LRL	490	n/a	n/a	280	µg/g
Tantalum	34975	1	LRL	ND	n/a	n/a	<1.0	µg/g
Thallium	4064	1	LRL	n/a	n/a	n/a	<1.0	µg/g
Thorium	34980	1	LRL	9.1	n/a	n/a	3	µg/g
Tin	34985	1	LRL	57	n/a	n/a	1.4	µg/g
Titanium	49274	0.005	LRL	0.45	n/a	n/a	0.46	percent
Uranium	35000	0.1	LRL	3.5	n/a	n/a	1.6	µg/g
Vanadium	35005	2	LRL	120	n/a	n/a	130	µg/g
Ytterbium	35015	1	LRL	4.3	n/a	n/a	2.2	µg/g
Yttrium	35010	1	LRL	n/a	n/a	n/a	22	µg/g
Zinc	35020	2	LRL	160	120	320	76	µg/g

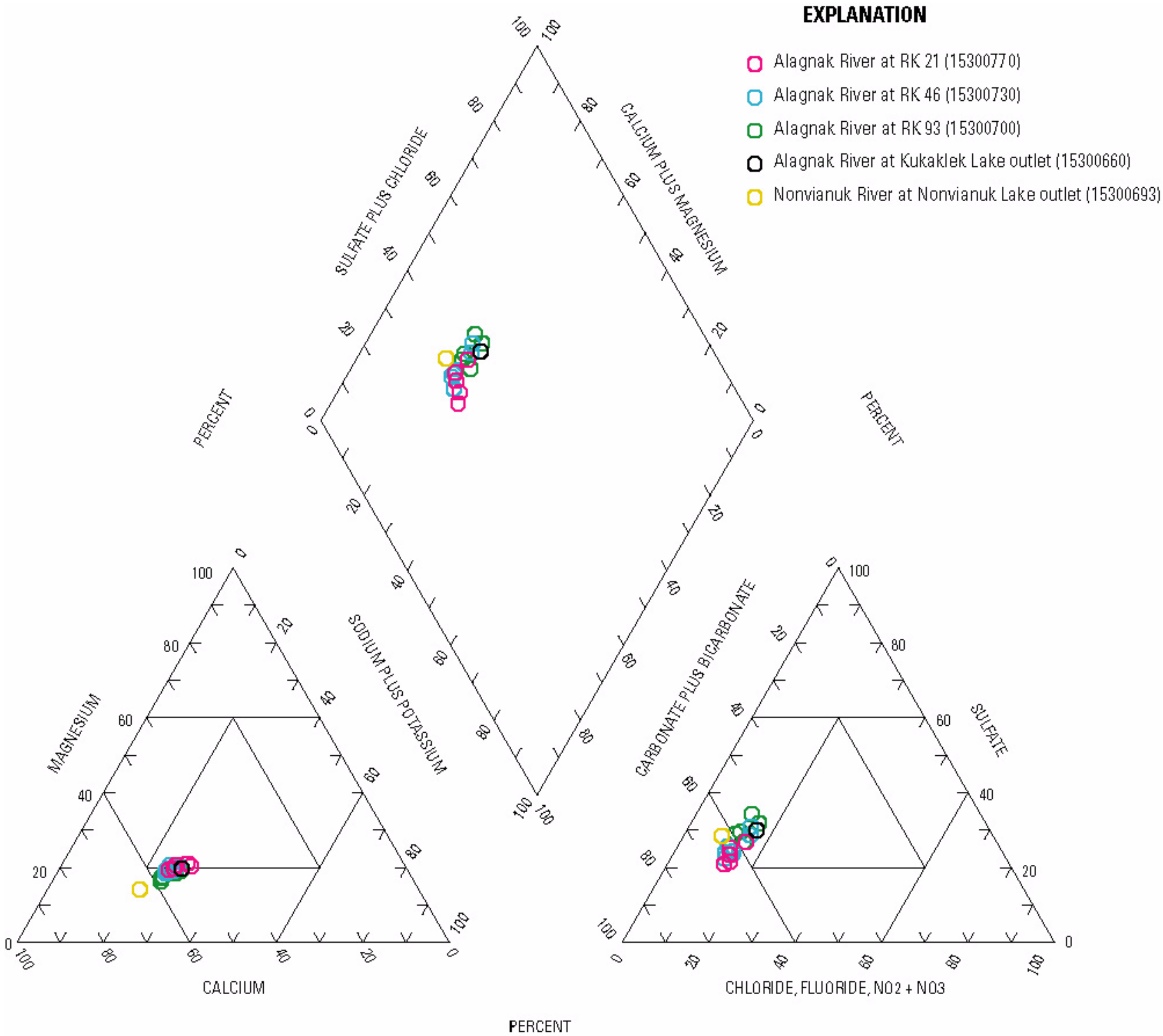


Figure 24. Trilinear diagram showing water chemistry of the Alagnak and Nonvianuk Rivers, 1999–2001.

A similarity in streamflow at the three sampling sites (fig. 8, table 1) allows general comparisons between sites without the computation of constituent loads (the product of concentration and discharge). Likewise, water-quality results varied little between seasons and between years. Weak but detectable patterns in constituent concentrations over time at a single site include consistently high nutrients and carbon in late May/early June (such as phosphorous, fig. 25) and a general decrease for the rest of the open-water season. Iron concentrations (fig. 26) similarly were high in late May/early June and fell in late June/early July, but increased again at some sites later in the open-water season, suggesting a correlation to streamflow. Slight but detectable differences in constituent concentrations over distance include downstream increases in phosphorous (fig. 25) and iron (fig. 26).

Field parameters consistently varied with distance across the channel at RK 93, where the waters of the Alagnak and Nonvianuk Rivers are not completely mixed (Bertrand and others, 2000; Meyer and others, 2001). Temperature and specific conductance were higher on the left side of the river (the Nonvianuk River side) on all sampling dates except February 2001, when ice present on both banks altered near-bank values. Dissolved oxygen was lower on the left side, probably as a result of warmer temperatures, in all samples except

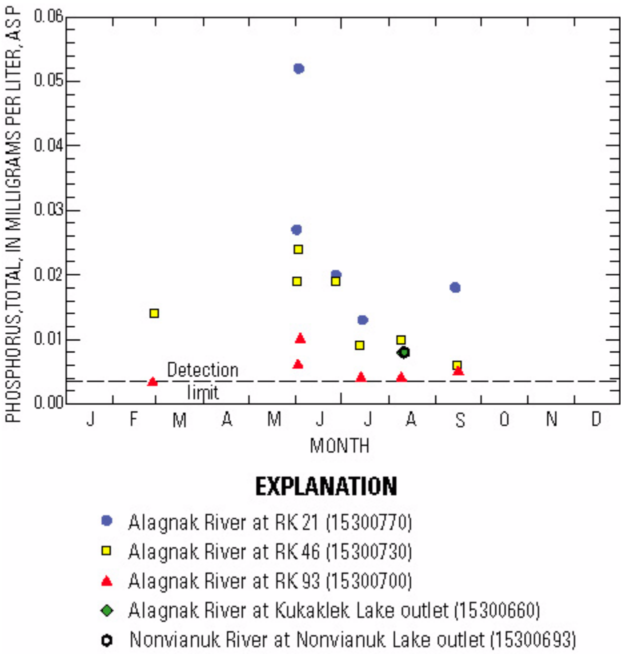


Figure 25. Total phosphorous concentrations in the Alagnak and Nonvianuk Rivers, 1999–2001

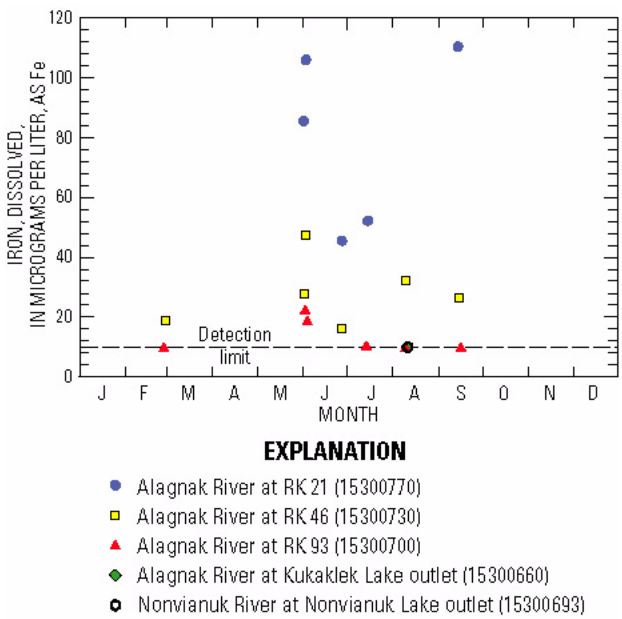


Figure 26. Dissolved iron concentrations in the Alagnak and Nonvianuk Rivers, 1999–2001

winter, but the water was fully saturated with oxygen in all cases. Water pH was slightly higher on the left side of the river in June and August 2000. Results from samples collected at the outlets of Kukaklek and Nonvianuk Lakes (the origins of the Alagnak and Nonvianuk Rivers, respectively) within 1 to 2 days of samples collected at Alagnak River RK 93 in August 2000 are consistent with most of the samples at the confluence. Temperature, specific conductance, and pH are all noticeably higher and dissolved oxygen lower in Nonvianuk Lake outlet samples than Kukaklek Lake outlet samples.

Bed Sediment

Bed sediments contain minerals from source rocks within the basin as well as chemical constituents sorbed onto clays, oxides, and organic layers. This increases trace-element concentrations relative to river water, providing a more thorough assessment of the elements present in the basin.

Concentrations reported for most Alagnak River bed sediment are low (table 9). However, concentrations of calcium, sodium, aluminum, iron, manganese, scandium, titanium, and vanadium in sieved Alagnak River bed sediment equaled or slightly exceeded mean concentrations in unsieved Alaskan stream and lake sediment reported by Gough and other (1988). Arsenic and chromium concentrations in the sieved sediment sample were above the ISQG but below the PEL for unsieved bed sediment. Arsenic commonly is elevated in Alaskan stream and lake sediments: the mean Alaskan concentration is higher than the PEL.

Suspended Sediment

The highest suspended-sediment concentration recorded in the Alagnak River (41 mg/L at RK 21 in early June 1999) is relatively low, even for a clearwater (nonglacial) river. Much of the suspended sediment carried by the Alagnak River consists of sand-sized particles. Thirteen to 31 percent of suspended sediment in samples was silt and clay (0.062 mm [millimeters] or finer). Suspended-sediment concentrations remained consistently low at RK 93, but varied seasonally at RK 21 and RK 46 (fig. 27, appendix 8). The highest suspended-sediment concentrations were recorded early in the open-water season, in late May and early June. The highest suspended-sediment discharge, calculated as the suspended-sediment concentration multiplied by water discharge, was 472 tons per day at RK 21 in early June 1999. No measurements were made during the late June 1999 flooding.

Occasional, brief periods of high suspended-sediment concentration were observed at RK 51, where a sediment plume originating at actively eroding bluffs was visible from the air and at river level. A large section of bank had failed shortly before the time this sediment plume was visible. Periodic pulses of high suspended-sediment concentrations that persist several hours also have been noted by Katmai Lodge staff (Tony Sarp, Katmai Lodge owner, oral commun., 2001).

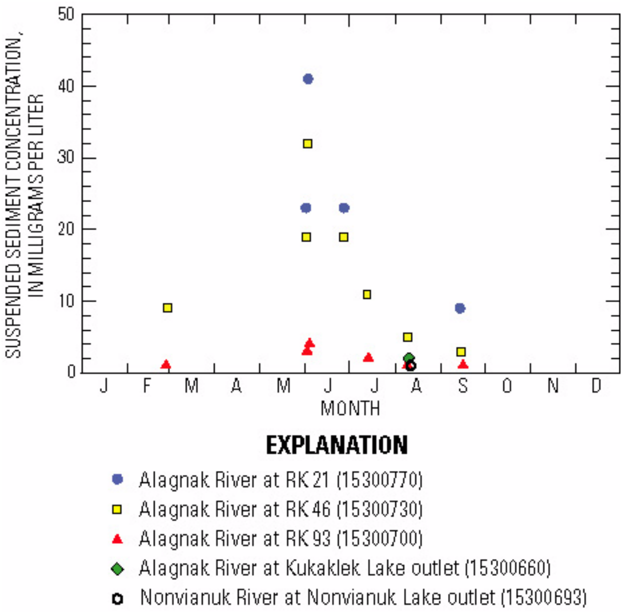


Figure 27. Suspended-sediment concentrations in the Alagnak and Nonvianuk Rivers, 1999–2001

DISCUSSION OF HUMAN IMPACTS ON WATER QUALITY OF THE ALAGNAK RIVER

Chemical Constituents

Consistency of major ion concentrations and proportions over more than 100 km of river suggests that the Alagnak River is strongly influenced by lake chemistry. Proportions of major ions in Kukaklek and Nonvianuk Lakes are similar to proportions in the Alagnak River main stem (fig. 24). The lack of major tributaries and the consistency of geologic materials (almost entirely glacial sediments) in the river's banks leave the Alagnak River's source—lake water—as the primary influence on its chemistry. Although analysis of large lakes in the upper basin suggests that volcanic source material influences sulfate concentrations (Gunther, 1992) and coastal proximity influences the proportions of chloride and sodium (LaPerriere, 1997), analysis of Alagnak River water suggests that these influences, if they exist, are not strong.

Downstream increases in iron and manganese concentrations (fig. 26, appendix 8) might be a result of ground-water discharge to the stream or the cumulative downstream increase in streamflow from poorly drained tundra and ponds. Poorly drained areas typically are reducing environments high in iron and manganese. At individual sites, weak inverse correlations exist between discharge and concentrations of both iron and manganese. Dilution of base flow and local flow by basinwide snowmelt and rainfall is a probable cause of this inverse relation.

Of the chemical constituents for which samples were analyzed in this study, nutrients are most likely to reflect changes brought about by human activity in the watershed, especially disposal of human and food waste. None of the results of this study suggest that human activities have generated a systematic increase in nutrients that can be detected at a river-long scale. Nutrient levels in the Alagnak River were low at all locations sampled. Observed patterns of nutrient concentrations are limited to a spring rise interpreted as the result of natural flushing of organic material. This does not imply, however, that humans have not affected water quality, only that if impacts are present, they are not detectable except at a local scale. Local impacts not detectable by this study could include concentrated waste streams (such as food, chemical, or human waste) discharged into small channels.

Sediment

Alagnak River Sediment Supply

Although the few small glaciers present in the upper Alagnak River Basin produce locally high sediment discharge in meltwater streams, sediment trapping within the large lakes of the basin virtually stops bed-load transport and minimizes suspended-sediment discharge into the Alagnak and Nonvianuk Rivers. Low relief, moderately erodible materials, and extensive vegetation cover limit the contribution of sediment from potential sources downstream of the lakes. Because sediment contribution from sources outside the channel is low, the contribution from channel banks and bed has more significance in this river system than in a system with steep, erodible uplands.

The overall low sediment load of the Alagnak River suggests that it could be easily influenced by human alterations to sediment inputs. The primary mechanism for human influence on sediment supply in the Alagnak River is bank erosion, which supplies sediment in both suspended-load and bed-load size ranges.

Relative Influence of Human Activities

Within the study area, human contributions or impediments to bank erosion are generated by foot traffic on banks, by bank protection and riverine structures at developed sites, and by motorboat traffic. Travel by foot was, at the time of this study, relatively minor, such that the contribution of human foot traffic is difficult to separate from the considerable bear traffic along the banks of the Alagnak River. Although foot traffic is responsible for the development of informal trails along the top edge of the riverbanks, which can contribute to bank failure by adding weight to unstable banks (Selby, 1993), mass failure is a minor issue for the noncohesive banks of the Alagnak. Foot traffic has not resulted in the devegetation of bank faces except locally where campsites have been heavily used.

The Alagnak River is largely undeveloped, with no major diversions, a cumulative total of several hundred meters of semihardened (fig. 28) or otherwise protected banks at lodges and other semipermanently occupied sites, and no riverine structures with the exception of docks at these same locations. River bank response to natural and anthropogenic processes such as tractive stress and boat wakes, respectively, is thus modified only locally by engineered alterations.

Motorboat traffic is the most widespread and potentially effective human impact on Alagnak River banks. Motorboats travel the entire length of the river, although their use is concentrated in lower reaches, and generate waves about 0.15 m high. Research regarding the effects of boat wakes on banks has concluded that regardless of the relative total energy of boat wakes compared to natural forces, boat wakes can have a substantial impact on bank erosion. In an Australian river, total energy from wind waves was similar to energy from boat wakes but boat wakes produced larger waves (Scholer, 1974). From boat wake experiments in rivers, Nanson and others (1994) found correlations between maximum wave height in a wake and bank erosion in a noncohesive sandy bank and Dorava (2001) found correlations between maximum wave

Figure 28. Trees and a revetment as erosion control, Alagnak River river kilometer 38. Photograph by author, June 7, 2001.

height in a wake and swash load. Based on the results of these studies, the physics of boat wakes, and the characteristics of Alagnak River banks, there is no question that boat wakes increase erosion. Although we cannot directly measure the increase in bank erosion rates because no measurements were made before the introduction of motorboats, we can use interpretations of changes to bank profile or channel planform to assess the significance of the increased erosion.

Effects of Boat Wakes on Bank Erosion and Channel Geomorphology

At least 40 wakes per day are generated at RK 21 for periods of several weeks each summer (fig. 18); at least 8 wakes per day are generated at RK 46 for continuous periods of more than a week. Boat traffic never exceeds a few wakes per day at RK 93. Analysis of the time of occurrence of wakes indicates boats are spaced far enough apart to generally limit constructive interference of waves, which increases wave height. Wakes generally occur in isolation and attenuate completely before another wake strikes. By comparison to the most heavily used sections of the Kenai River in Alaska, where wake counts in excess of 500 wakes per day occurred almost daily for several weeks in mid-July (Dorava and Moore, 1997), the boat traffic on the Alagnak River is moderate.

Wave energy differs from tractive energy generated by river currents in several respects. Boat wakes direct energy at angles nearly perpendicular to the bank, as opposed to river currents, which act parallel to the bank. The energy of a wave is dissipated at the interface between the water surface and the bank, whereas tractive stress is maximized at about two-thirds of the depth below the water surface (Simons and Li, 1982). The strength of waves relative to currents in a river can result in variations in bank profile. Waves in a river with a stable water surface can create a “beach” profile, with a shallow shelf, or swash zone, adjacent to the steeper, current-shaped channel. The water surface of the Alagnak River varies substantially over the open-water season, such that only a small, temporary, wave-generated shelf is constructed. Visual observations of wake action along Alagnak River banks indicate that erosion from wakes occurs both as breaking waves on shallower bank angles and as nonbreaking waves that impact steeper banks. With either type of wave, sand and gravel-sized particles were visibly dislodged from the bank above the non-wake-affected water level as the boat passed.

Wind and hydraulic waves occur on the Alagnak River but have smaller wave heights at the bank than boat wakes. They are probably less erosive than boat wakes except at times in the lower river, where fetch is longer and wind waves were observed to superimpose a second, small wind-wave-generated shelf on the wider wake-generated shelf.

Although published bank erosion rates for world rivers vary from near 0 to over 50 m/yr (meters per year) (Lawler, 1993), the bank erosion rates measured along the Alagnak River are not unusual for a laterally mobile river of this size. Erosion pin monitoring showed a maximum erosion rate during the study period of 1.1 m/yr (table 7). Analysis of aerial photographs showed a maximum erosion rate of, on average, 2.5 m/yr between 1982 and 2000 at RK 51, where rapid erosion occurred in conjunction with major changes in channel pattern (fig. 14). These values represent annual rates of lateral channel migration rather than rates of change by avulsion, such as the major channel shifts between 1951 and 1982 at RK 50–65.

Several factors combine to create higher bank erosion rates in the lower river. Bank particle size generally decreases in a downstream direction in the Alagnak River (fig. 10). Hydraulic effects of river currents are strong enough to help attenuate wind and boat-generated waves in reaches upstream of about RK 57, such that boat wakes generated in the upper river do not always reach the bank. These downstream increases in natural susceptibility to erosion are compounded by the downstream increase in boat traffic (fig. 18).

Drawing together the boat traffic, bank material, historical channel change, and hydrologic data suggests that boat wakes have increased lateral erosion rates in the reaches downstream of RK 65. Here, unvegetated, noncohesive banks are present and contain particle sizes in the sand and gravel range, hydraulic waves that attenuate boat wakes are small, and boat traffic is common. Upstream of RK 65, hydraulic waves are more common, boat traffic is less common, and particle sizes are larger, such that boat wakes probably do not have a substantial impact on most banks.

Evidence that boat wakes have affected bank erosion processes is limited to the presence of a wave-generated shelf just under the present water surface at high, unvegetated banks downstream of RK 65. This beach-like form is easily re-formed by the river and migrates up and down with water level, as shown in fig. 20. No permanent changes to the bank profile could be measured that indicated that this “beach” effect extended back a substantial distance from the channel. Banks within a few feet of the water line were typically near-vertical or at the angle of repose, depending on the time of year. Larger diameter material eroded from banks appears to be transported immediately or over the course of a single season from the point of erosion as bedload, based on the growth and removal of the "shallow shelf" of eroded sediment in the bank profiles and the lack of gravel bars adjacent to eroded areas. The lack of a gravel bar immediately downstream of actively eroding bluffs at RK 51, for example, suggests that most of the sediment is transported more than one channel width downstream. Growth on gravel bars 1,100 m downstream may be related to the erosion at RK 51, but also may reflect ongoing channel migration.

More critically, no changes in the process of channel planform change in the Alagnak River could be attributed to the effect of boat wakes. Lateral channel migration has been and continues to be the primary mode of channel change in the reaches downstream of RK 35. Although lateral channel migration has also been the most common mode of channel change between RK 35 and RK 57, avulsions have created the most significant channel changes in this reach. Avulsions are usually abrupt, occurring in a single flood or, in the case of ice-affected rivers, a single break-up period, and can cause the channel to create an entirely new channel or reoccupy old channels. In the case of the Alagnak River, some new channels were created and some old channels received additional flow at some time between 1951 and 1982, with the most obvious effect of markedly increasing bank erosion at RK 51 (fig. 14). The lack of additional major channel changes between 1982 and 2000 lends support to the concept that the effect of boat wakes is primarily an increase in erosion rates, not a shift in the major processes of channel change.

Effects of Bank Erosion on Water Quality

Although bank erosion on the Alagnak River has not affected the geomorphic processes that generate channel change, increases in the rates of bank erosion can affect water quality directly as additional sediment is introduced to the channel. Changes to the bank profile (such as undercut banks, loss of vegetation) are other possible effects of bank erosion but were not a primary focus of this study.

Suspended-sediment pulses persisting several hours to several days are possible where major bank failures deliver large volumes of easily erodible material directly into the channel. This is presently occurring at RK 51 and could occur at any of the high banks when the channel is aggressively eroding the banks. This type of failure would occur with or without boat wakes, but because boat wakes increase the rate of erosion, they may also increase the rate of large failures.

Of greater concern for aquatic habitat is the potential for a long-term, more persistent increase in suspended sediment that could be associated with boat wakes. The timing of the highest suspended-sediment concentrations (and highest suspended-sediment discharges) at the early part of the summer suggests that the erosional effects of boat wakes, which are most frequent at midsummer, may not have a direct effect on suspended-sediment concentrations that is measurable in a sample integrated across the river. That is, the most intensive periods of boat use do not appear to have a clear and immediate impact on the entire suspended load of the river. There are two caveats to this statement, the first that boat wakes most certainly have a direct impact on the overall rate of erosion, such that eventually more sediment is delivered to the channel. Thus, boat wakes may have an indirect effect on suspended-sediment concentrations. The second is that it is possible that effects of changes in suspended-sediment concentrations are not uniformly distributed across the river, such as would be most readily detected with an integrated sample. Near-bank habitats might be more affected than the center of the channel but were not specifically sampled for this study.

An estimate of the suspended-sediment concentrations generated by bank erosion on the Alagnak River was prepared from measured bank erosion rates, the measured size and extent of visibly eroding banks, measured discharge, and the assumption that all suspended sediment entering the river remains suspended (scenario 1, table 10). The concentration is calculated as the suspended-sediment load divided by the discharge. The resulting estimated concentration, 29 mg/L, is within the range of measured values (fig. 27, appendix 8). For the purposes of illustration, additional scenarios assume that the same banks erode at the maximum rate measured for this study (scenario 2) and that the erosion rate remains unchanged but the area of eroding banks doubles (scenario 3). The suspended-sediment concentration would increase to 62 and 57 mg/L, respectively, under these two scenarios. Even though these are overestimates, these concentrations are still low and demonstrate that a large increase in width-and-time-averaged suspended-sediment concentrations from bank erosion is not likely. Short-term, near-bank increases during periods of rapid erosion are more likely to be of concern but were not monitored for this study.

Table 10. Estimated concentrations of suspended sediment generated by bank erosion on the Alagnak River

[m^2, square meter; RK, river kilometer; m, meter; mm, millimeter; kg/m^3, kilogram per cubic meter; mg/s, milligram per second; m^3/s, cubic meter per second; mg/L, milligram per liter]

	Present condition	Banks erode at maximum erosion rate measured for this study	Twice as much bank area erodes
Area of bank face (uncorrected for slope angle) (table 4)	62,000 m^2 (Presently eroding tall banks between RK 10.4 and 70.1)	62,000 m^2 (Presently eroding tall banks between RK 10.4 and 70.1)	124,000 m^2 (Two times the area of presently eroding banks between RK 10.4 and 70.1)
Annual magnitude of erosion (table 7)	0.51 m (average of annual erosion at erosion pins 1–10)	1.1 m (maximum rate measured at any erosion pin)	0.51 m (average of annual erosion at erosion pins 1–10)
Time over which erosion occurs	92 days (June, July, August)	92 days (June, July, August)	92 days (June, July, August)
Maximum size of suspendable sediment (although most Alagnak River suspended sediment is sand-sized, this is an overestimate)	2 mm	2 mm	2 mm
Percent of bank material finer than maximum size of suspended sediment (appendix 2)	50 percent	50 percent	50 percent
Dry density of silty sand and gravel (Selby, 1993)	1,400 kg/m^3	1,400 kg/m^3	1,400 kg/m^3
Calculated sediment load (Volume of suspendable sediment eroded, divided by time to erode [92 days, in seconds], multiplied by dry density)	2,790,000 mg/s	6,010,000 mg/s	5,570,000 mg/s
Discharge at RK 21 (for worst case, use August discharge; assume that discharge at RK 10 is equal to the discharge at RK 21)	97.7 m^3/s	97.7 m^3/s	97.7 m^3/s
Calculated suspended sediment concentration (sediment load divided by discharge)	29 mg/L	62 mg/L	57 mg/L

CONCLUSIONS

Human use of the Alagnak River has evolved from historical uses for subsistence fishing and hunting to modern recreational and subsistence fishing and hunting. The introduction of motorboats to the river and the growing numbers of users since the early 1980s has increased the potential for human impacts caused by increases in concentrations of chemical constituents and suspended sediment in the river's water.

Human impacts were not yet apparent in the chemical constituents of the river's water at the five sites sampled. Lodges with food and human waste disposal systems may have affected local water quality but analysis for local impacts were not a part of this study. Lack of high levels of constituents that might indicate human impact at sampling sites suggests that the river's discharge may be sufficient to dilute any presently existing local impacts.

Human impacts on sediment supply to the Alagnak River consist primarily of an increase in bank erosion caused by boat wakes. Visual observations, physical properties of boat wakes, physical properties of Alagnak River banks, and the development of a wave-generated shallow underwater shelf at eroding banks indicate that boat wakes cause more erosion than would occur naturally. However, it was not possible to quantify the relative amounts of boat-related and natural erosion. The maximum erosion rate measured at erosion pins from 1998 to 2000 was 1.1 m/yr, and the maximum rate measured from historical aerial photographs was 45 m in 18 years, or 2.5 m/yr. Both rates are reasonable for the Alagnak River, so it is not possible from these rates alone to detect boat-related influences. However, inferences made from measurements of changes in bank profiles, historical channel changes, and observations of modern channel geomorphology suggest that the effect of boat wakes is an increase in the rate of erosion, not a change in bank erosion processes or the process of channel planform change. For example, the seasonal progression from fluvial-driven erosion of the bank toe to gravity-driven ravel of the overlying bank has been modified by the addition of wake-driven erosion of the bank toe. This process increases the rate of erosion and generates a shallow wave-generated shelf, but leaves the overall bank profile largely unchanged. Coarse-grained sediment eroded from the banks does not appear to have increased the formation of bars. Historical evidence indicates that few changes have occurred to channel planform upstream of RK 57, that avulsion has been the leading influence on channel planform between RK 35 and 57, and that lateral channel migration has been the primary mode of channel change downstream of RK 35, as well as an ongoing process accompanying avulsion between RK 35 and 57. Boat wakes are unlikely to change these processes, although boat wakes increase the rate of lateral channel migration.

Increased erosion rates from boat wakes may increase riverwide or near-bank suspended-sediment concentrations. Suspended-sediment concentrations in discharge-integrated samples do not suggest that bank erosion elevates the suspended-sediment levels in the river for prolonged periods. Suspended-sediment levels may be increased by bank erosion at near-bank areas, but this was not directly measured by this study. However, visual observations of a large sediment plume from the bank at RK 51 during a period of rapid erosion suggest that suspended-sediment levels can be temporarily increased; this observation was echoed by a lodge operator who has to periodically shut down water intakes for a few hours to allow the sediment pulse to pass.

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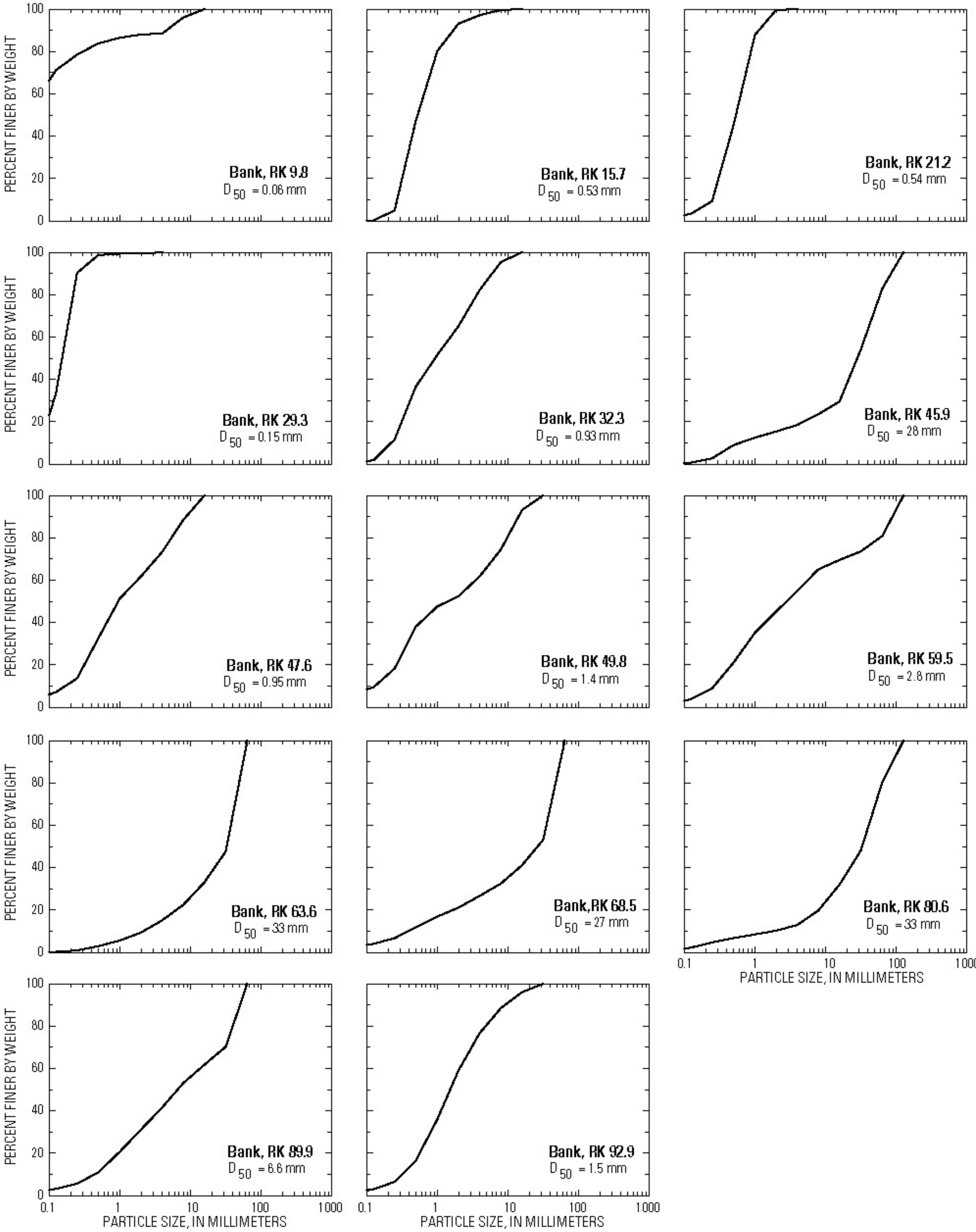
APPENDIXES

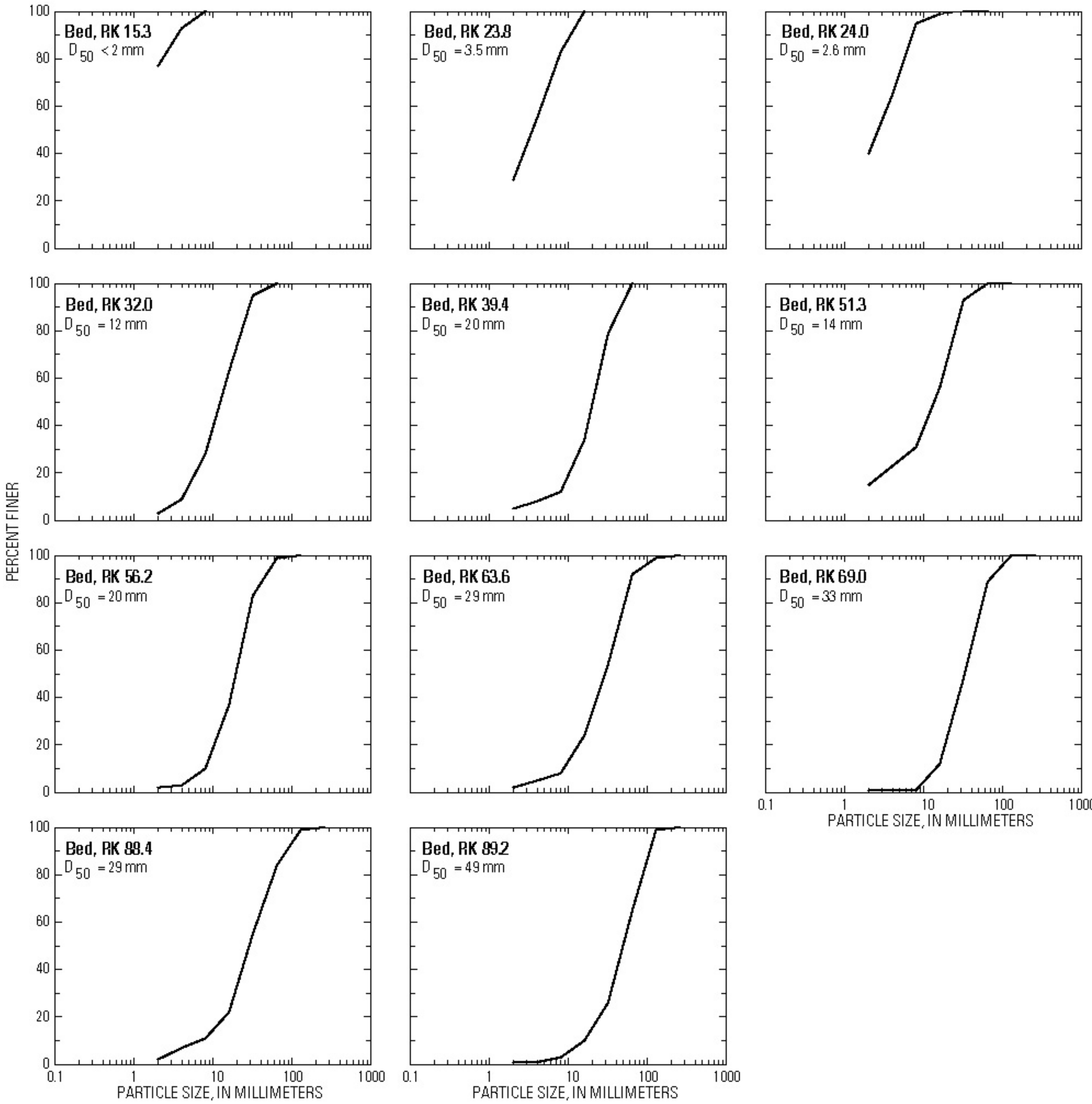
Appendix 1. Latitude and longitude calculated for river miles along the Alagnak River

[River miles and their latitudes and longitudes were calculated from digital hydrography (Alaska Geospatial Data Clearinghouse, 2000) using geographic information system (GIS) techniques to record the position of the river at the time of the aerial photography used to develop the digital coverage. Because channel length varies as the river changes course, river miles may not remain an accurate measure of the distance from the river mouth.]

River mile	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	River mile	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
0	59 00 19	156 51 20	40	59 02 24	156 16 20
1	59 00 13	156 49 40	41	59 01 45	156 15 25
2	59 00 39	156 48 23	42	59 01 16	156 14 11
3	59 00 41	156 46 59	43	59 01 09	156 12 37
4	59 00 59	156 45 34	44	59 01 10	156 11 02
5	59 01 30	156 44 18	45	59 01 29	156 09 29
6	59 02 11	156 43 49	46	59 01 22	156 07 53
7	59 02 26	156 43 02	47	59 00 45	156 06 48
8	59 02 07	156 41 51	48	59 00 35	156 05 27
9	59 01 50	156 40 42	49	59 00 37	156 03 53
10	59 01 28	156 39 47	50	59 00 21	156 02 30
11	59 02 06	156 39 25	51	59 00 19	156 00 57
12	59 02 30	156 38 12	52	59 00 07	155 59 32
13	59 02 56	156 37 22	53	59 00 05	155 57 57
14	59 03 34	156 36 33	54	59 00 24	155 56 34
15	59 04 07	156 35 41	55	59 00 41	155 55 03
16	59 04 33	156 34 27	56	59 00 47	155 53 26
17	59 04 18	156 33 29	57	59 01 03	155 51 58
18	59 03 57	156 32 33	58	59 01 27	155 50 59
19	59 04 02	156 30 60	59	59 02 01	155 50 12
20	59 03 46	156 29 38	60	59 02 42	155 50 29
21	59 04 12	156 28 52	61	59 03 17	155 50 03
22	59 04 52	156 29 19	62	59 03 13	155 48 43
23	59 05 15	156 28 22	63	59 03 20	155 47 13
24	59 05 47	156 27 36	64	59 02 58	155 45 53
25	59 06 33	156 27 32	65	59 03 38	155 44 60
26	59 06 36	156 25 59	66	59 04 13	155 45 06
27	59 06 53	156 24 37	67	59 04 58	155 44 38
28	59 07 13	156 23 34	68	59 05 16	155 43 30
29	59 07 06	156 22 29	69	59 05 09	155 42 22
30	59 07 20	156 21 06	70	59 05 16	155 41 11
31	59 07 06	156 19 59	71	59 05 26	155 39 39
32	59 07 17	156 18 35	72	59 06 01	155 38 37
33	59 06 56	156 17 26	73	59 06 24	155 37 33
34	59 06 18	156 16 51	74	59 06 25	155 36 24
35	59 05 42	156 17 29	75	59 06 30	155 35 13
36	59 04 60	156 17 24	76	59 07 01	155 34 13
37	59 04 19	156 18 04	77	59 07 34	155 33 36
38	59 03 35	156 17 39	78	59 07 53	155 32 35
39	59 02 55	156 17 33			



Appendix 2. Particle-size distribution, median diameter, and location of bank-material samples of the Alagnak River. (RK, river kilometer).



Appendix 3. Particle-size distribution, median diameter, and location of bed-material samples of the Alagnak River.

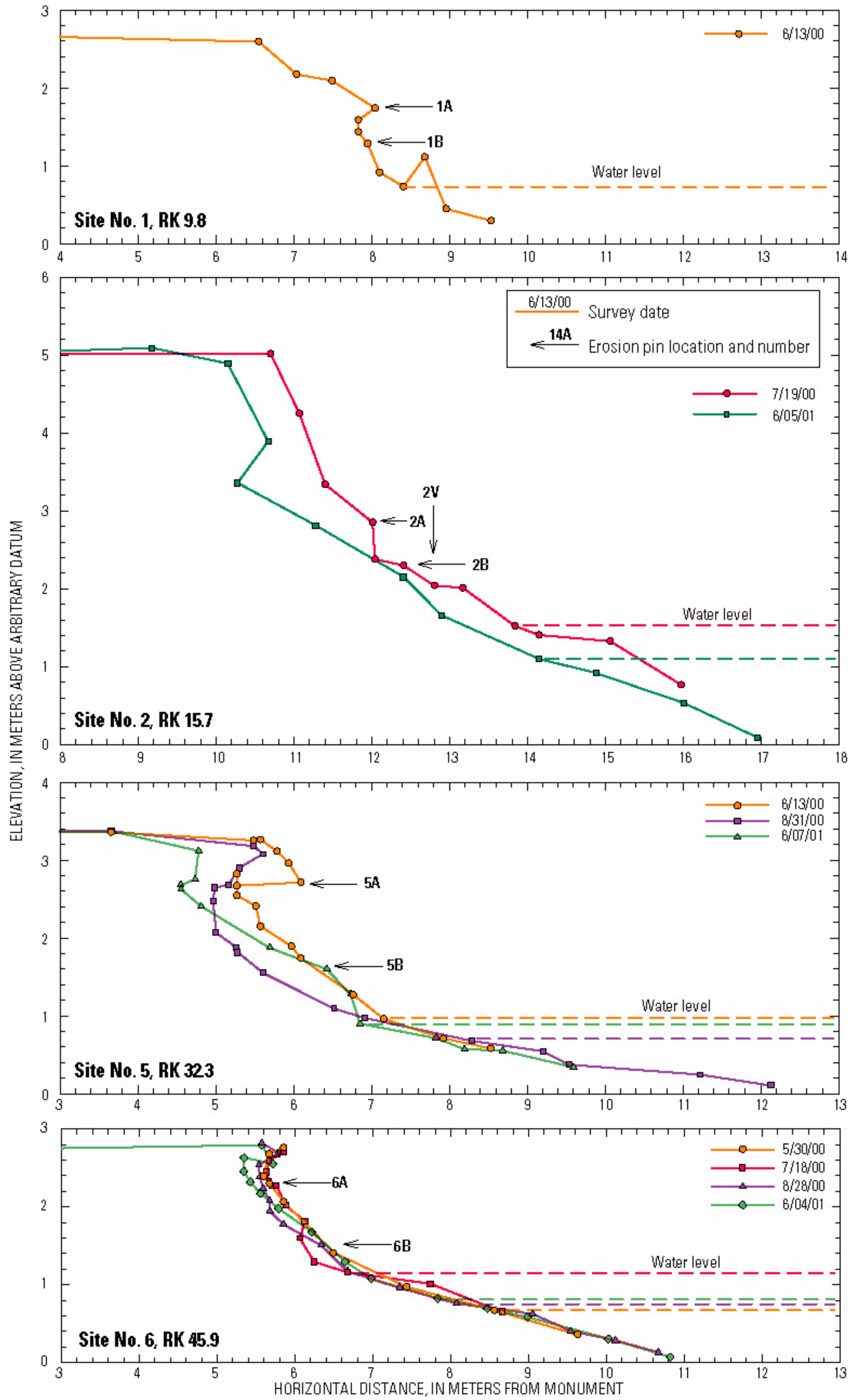
Appendix 4. Locations and descriptions of Alagnak River erosion monitoring sites, markers, and pins

[Site numbers correspond to site numbers on figure 9; m, meter; cm, centimeter. At each site, pin A is uppermost or upstream-most, pin B is below or downstream of pin A, pin C is below pin B, and pin V is a vertical pin]

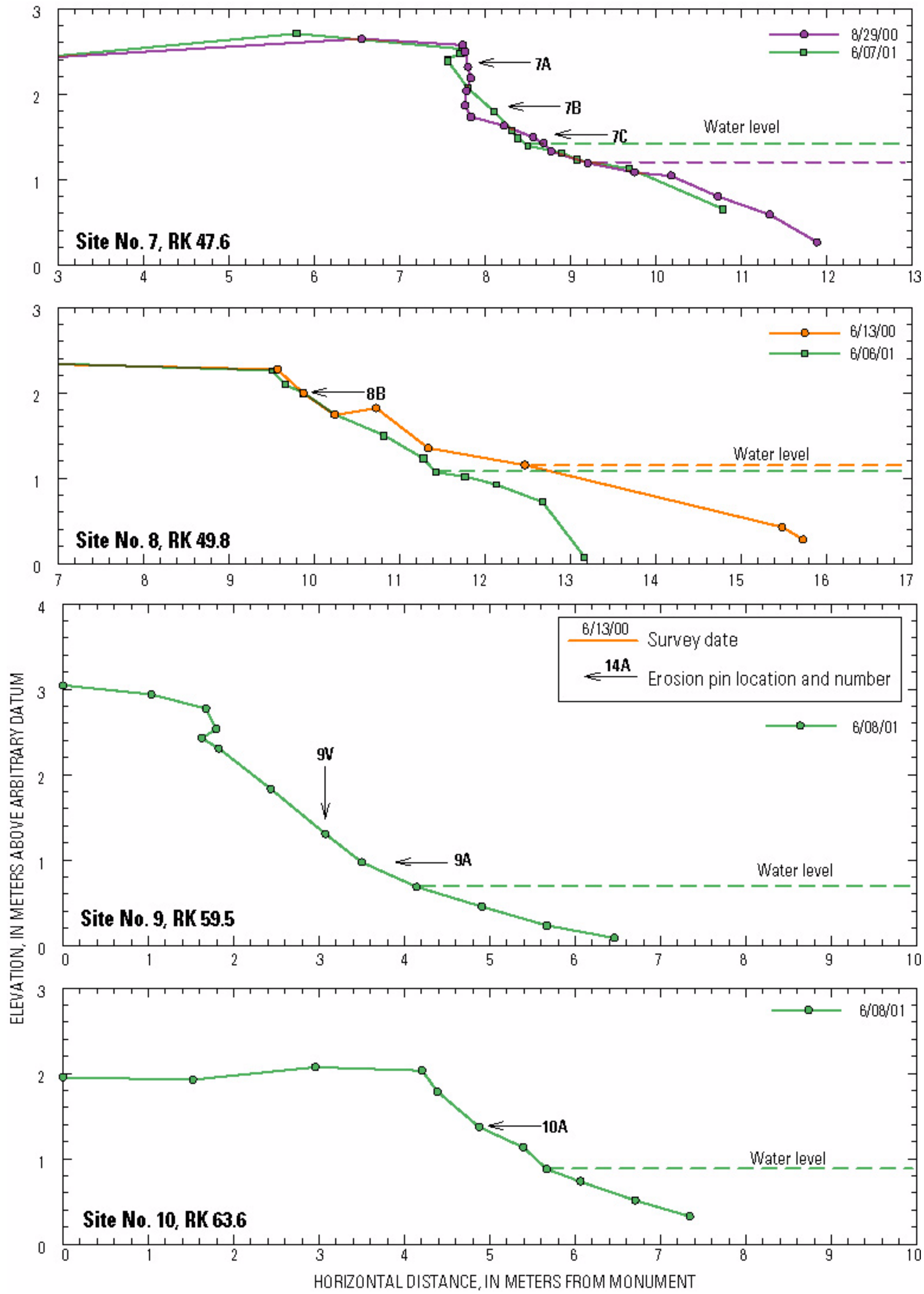
Site number	River kilometer	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Description of site markers	Description of erosion pins [a] (V in pin name denotes vertical pin)
1	9.8	59 02 15	156 43 44	Surveyors tape on bush.	Two horizontal pins at single location on left bank (1A above 1B).
2	15.7	59 01 17	156 40 05	White plastic disk nailed to base of spruce tree on bank.	Two horizontal pins and one vertical pin at single location on left bank (2A above 2B, both above 2V).
3	21.2	59 03 05	156 37 25	Red plastic disk, eyebolts for gage support cables.	One horizontal pin (3A) upstream of second horizontal pin (3B), replaced [b] by horizontal pin at similar location (3C) on right bank. 3B and 3C are in exposed bank shoreward of root ball of tipping tree.
4	29.3	59 03 58	156 32 10	No markers, site is tall exposed sandy bluff.	One horizontal pin (4A) upstream of second horizontal pin (4B) on right bank.
5	32.3	59 03 42	156 29 37	Two vertical pins about 1and 5 m from top of bank, in line with erosion pins.	Two horizontal pins at single location on left bank (5A above 5B). 5C is measured from a vertical pin to the top of the bank.
6	45.9	59 06 52	156 23 01	Red and white plastic disks nailed to tree bases. One vertical pin about 5.5 m shoreward of top of bank, in line with erosion pins.	Two horizontal pins at single location on left bank, replaced by two horizontal pins at close to same single location (6A above 6B).
7	47.6	59 07 26	156 21 50	White plastic disk nailed to base of spruce tree 6 m upstream of erosion pins. Two vertical pins 5 and 7.5 m shoreward of top of bank, in line with erosion pins.	Three horizontal pins at single location on right bank (7A above 7B, both above 7C).
8	49.8	59 06 57	156 20 07	Green plastic disk nailed to base of spruce tree about 9.5 m from top of bank, in line with upstream erosion pins.	One upstream horizontal pin (8A) replaced by one horizontal pin (8B). One downstream horizontal pin (8C). All on left bank.
9	59.5	59 04 19	156 17 52	One vertical pin about 1.5 m from top of bank, in line with erosion pins.	One horizontal erosion pin (9A) above one vertical erosion pin (9V) on right bank.
10	63.6	59 02 42	156 16 50	One vertical pin about 4.5 m from top of bank, in line with erosion pins.	One horizontal pin replaced [b] by one horizontal pin (10A) on right bank.
11	74.8	59 01 11	156 07 04	Wooden stake about 1.5 m from top of bank, in line with erosion pin.	One horizontal pin (11A) on right bank.
12	80.6	59 00 17	156 02 22	No markers.	One horizontal pin (12A) on left bank.
13	89.9	59 00 56	155 53 41	Red plastic disk nailed to base of spruce tree	One horizontal pin (13A) on right bank.
14	92.9	59 01 16	155 50 51	Red plastic disk nailed to base of spruce tree.	One horizontal pin on left bank (14A) opposite from one horizontal pin on right bank (14B).

[a] Erosion pins consist of smooth, round, 0.953-cm or 1.27-cm diameter, 76.2 or 91.4-cm long metal rods.

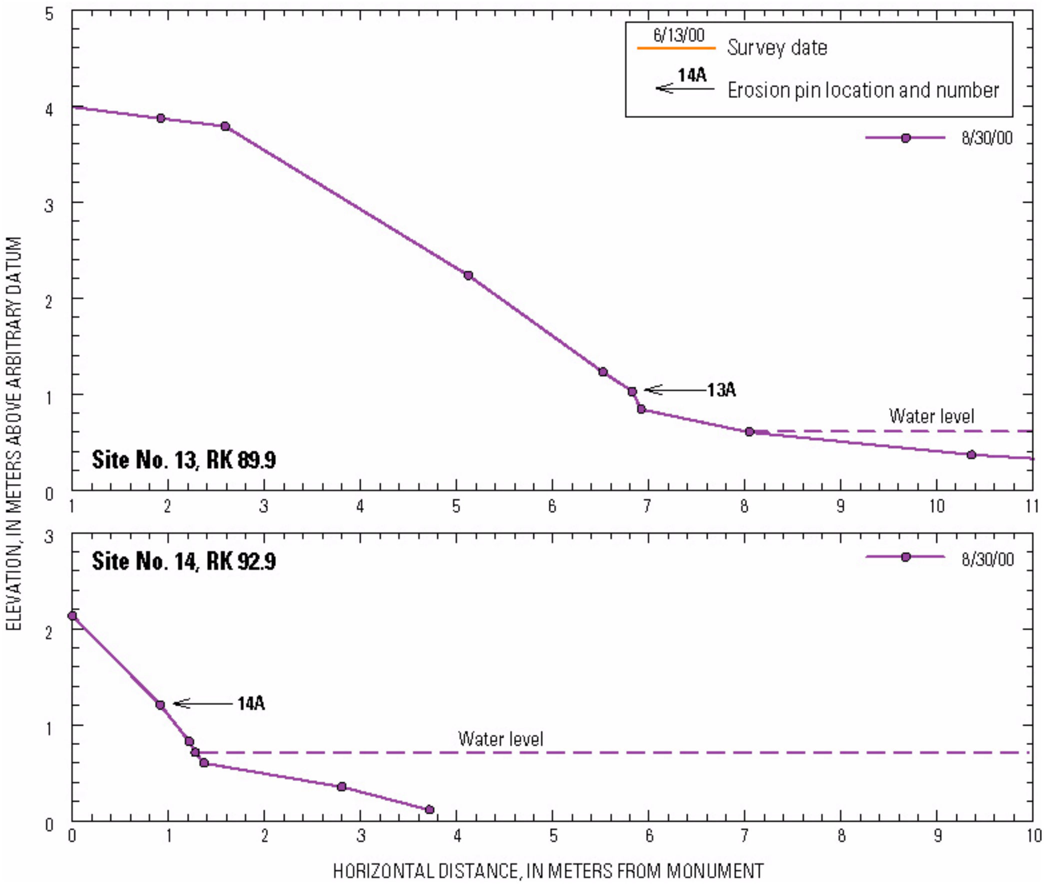
[b] Pins were replaced when washed out or buried beneath a vegetation mat. Pin name retained when replacement pin could be placed in same location with reasonable certainty. Pin measurement assumed to be entire length of pin (a minimum) when washed out.



Appendix 5. Bank profile surveys at erosion monitoring sites, 2000 and 2001. Erosion monitoring locations shown in figure 9.



Appendix 5. Bank profile surveys at erosion monitoring sites, 2000 and 2001. Erosion monitoring locations shown in figure 9.—Continued.



Appendix 5. Bank profile surveys at erosion monitoring sites, 2000 and 2001. Erosion monitoring locations shown in figure 9.—Continued.

Appendix 6. Cumulative erosion at Alagnak River erosion pins, 1998–2001

[All measurements are in centimeters. Cumulative erosion is the position of the bank relative to the initial position, an arbitrary horizontal datum of 0 cm. Positive values indicate bank retreat and negative values indicate bank growth toward the stream. At each site, pin A is uppermost or upstream-most, pin B is below or downstream of pin A, pin C is below pin B, and pin V is a vertical pin. ND, no data (pin not yet installed)]

Date	1A	1B	Date	2A	2B	2V	Date	3A	3B	3C	Date	4A	4B
7/13/98	0	ND	7/13/98	ND	0	ND	7/13/98	0	0	0	7/13/98	0	0
9/16/98	1	ND	9/16/98	0	36	ND	9/16/98	1	1	0	9/16/98	0	[a]
6/3/99	45	0	6/3/99	-8	[a]	ND	6/3/99	3	1	0	6/4/99	0	[a]
6/24/99	44	3	6/24/99	[a]	[a]	0	6/24/99	49	1	0	6/24/99	1	29
7/15/99	64	0	7/15/99	0	[a]	13	7/15/99	69	1	0	7/15/99	-1	19
8/4/99	72	10	8/4/99	0	[a]	19	8/4/99	[b]	1	0	8/4/99	-1	16
8/25/99	[c]	[c]	8/25/99	[c]	[c]	[c]	8/25/99	[b]	1	0	8/25/99	-1	4
9/14/99	75	5	9/14/99	8	[a]	18	9/14/99	[b]	1	0	9/14/99	-1	[b]
6/1/00	81	68	6/1/00	-9	[a]	-8	5/31/00	[b]	1	0	6/1/00	-1	[b]
6/13/00	[a]	84	6/13/00	-9	[a]	4	6/13/00	[b]	2	0	6/13/00	-1	[b]
6/27/00	[a]	84	6/27/00	-9	[a]	18	6/27/00	[b]	[a]	0	6/27/00	-1	[b]
7/19/00	97	85	7/19/00	11	58	19	7/19/00	[b]	[a]	-7	7/19/00	3	[b]
8/8/00	143	113	8/8/00	13	101	27	8/8/00	[b]	[a]	1	8/8/00	65	[b]
8/29/00	[c]	[c]	8/29/00	28	103	15	8/29/00	[b]	[a]	-17	8/31/00	64	[b]
6/5/01	149	148	6/5/01	[a]	57	[d]	6/5/01	[b]	[a]	10	6/7/01	62	[b]

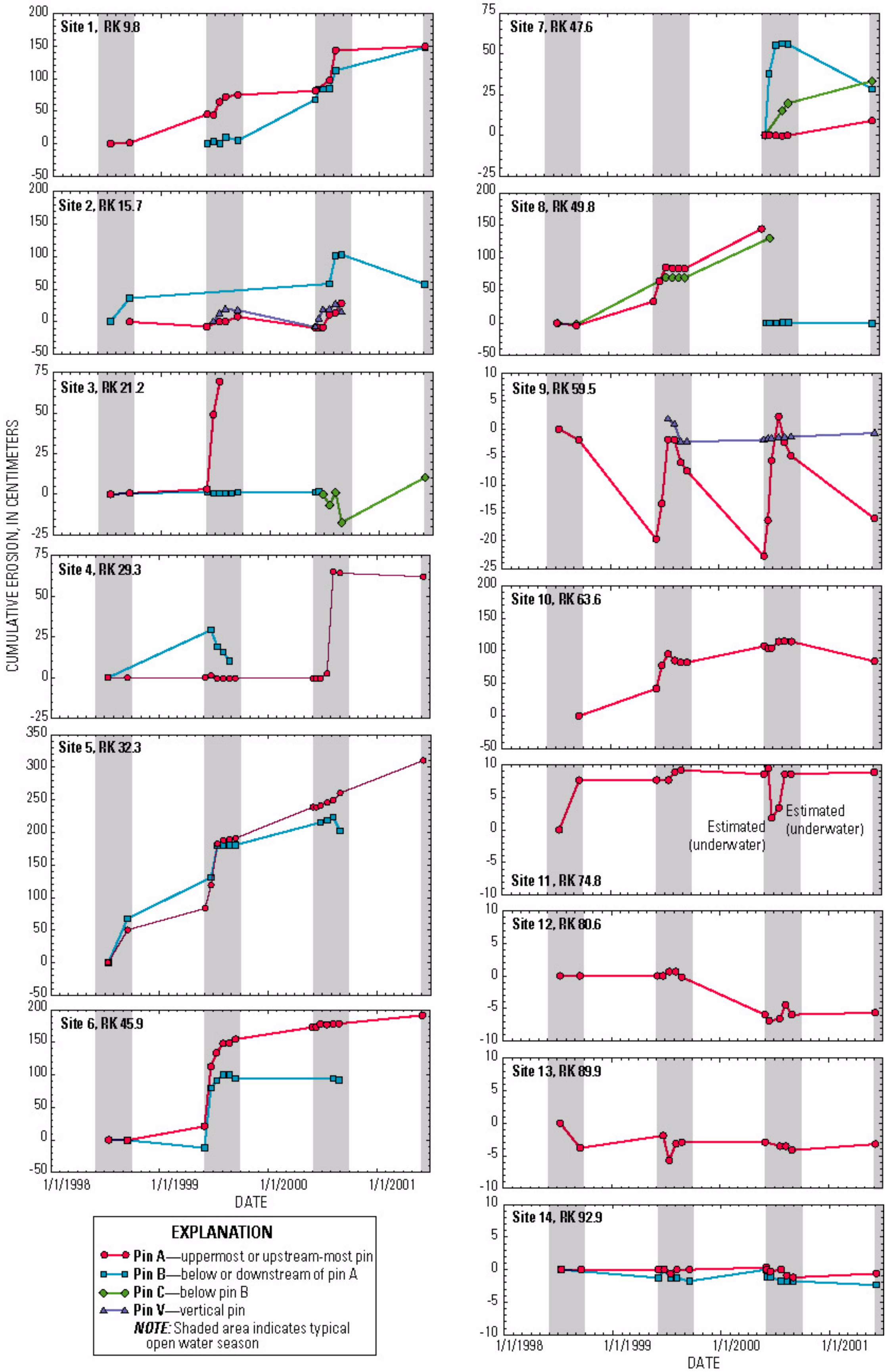
Date	5A	5B	Date	6A	6B	Date	7A	7B	7C	Date	8A	8B	8C
7/13/98	0	0	7/15/98	0	0	7/15/98	ND	ND	ND	7/12/98	0	ND	ND
9/16/98	50	67	9/16/98	-1	-1	9/16/98	ND	ND	ND	7/15/98	[d]	ND	0
6/4/99	83	[a]	6/2/99	21	-12	6/2/99	ND	ND	ND	9/16/98	-4	ND	-3
6/24/99	119	131	6/24/99	112	79	6/24/99	ND	ND	ND	6/2/99	33	ND	[c]
7/15/99	182	179	7/13/99	133	91	7/13/99	ND	ND	ND	6/22/99	64	ND	[d]
8/4/99	188	180	8/4/99	148	100	8/4/99	ND	ND	ND	7/14/99	85	ND	70
8/25/99	189	180	8/25/99	149	100	8/25/99	ND	ND	ND	8/5/99	84	ND	70
9/14/99	191	180	9/15/99	155	94	9/15/99	ND	ND	ND	8/26/99	84	ND	70
6/1/00	239	[a]	5/30/00	173	[a]	5/30/00	ND	ND	ND	9/15/99	84	ND	69
6/13/00	238	[a]	6/12/00	173	[a]	6/12/00	0	0	0	5/31/00	144	ND	[a]
6/27/00	241	215	6/26/00	177	[a]	6/26/00	0	38	[d]	6/13/00	[a,e]	0	[a]
7/19/00	246	218	7/18/00	177	[a]	7/18/00	0	55	[d]	6/26/00	[a,e]	0	[a]
8/8/00	249	223	8/9/00	178	94	8/9/00	-1	56	15	6/28/00	[a,e]	[d]	130
8/31/00	260	202	8/28/00	178	92	8/28/00	0	56	20	7/20/00	[a,e]	0	[a]
6/7/01	310	[a]	6/4/01	191	[a]	6/7/01	9	28	33	8/9/00	[a,e]	1	[a]
										8/30/00	[a,e]	1	[a]
										6/7/01	[a,e]	0	[a]

Appendix 6. Cumulative erosion at Alagnak River erosion pins, 1998–2001—Continued

[All measurements are in centimeters. Cumulative erosion is the position of the bank relative to the initial position, an arbitrary horizontal datum of 0 cm. Positive values indicate bank retreat and negative values indicate bank growth toward the stream. At each site, pin A is uppermost or upstream-most, pin B is below or downstream of pin A, pin C is below pin B, and pin V is a vertical pin. ND, no data (pin not yet installed)]

Date	9A	9V	Date	10A	Date	11A	Date	12A	Date	13A	Date	14A	14B
7/12/98	0	ND	7/12/98	ND	7/12/98	0	7/12/98	0	7/12/98	0	7/12/98	0	0
9/17/98	-2	ND	9/17/98	0	9/17/98	8	9/17/98	0	9/17/98	-4	9/17/98	0	[d]
6/4/99	-20	ND	6/4/99	42	6/4/99	8	6/4/99	0	6/4/99	[c]	6/4/99	0	-1
6/23/99	-13	0	6/23/99	77	6/23/99	[d]	6/23/99	0	6/23/99	-2	6/23/99	0	0
7/14/99	-2	2	7/14/99	95	7/14/99	8	7/14/99	1	7/14/99	-6	7/14/99	-1	-1
8/5/99	-2	1	8/5/99	85	8/5/99	9	8/5/99	1	8/5/99	-3	8/5/99	0	-1
8/26/99	-6	-2	8/26/99	82	8/26/99	9	8/26/99	0	8/26/99	-3	8/26/99	[d]	[d]
9/16/99	-7	-2	9/16/99	82	9/16/99	[c]	9/16/99	[c]	9/16/99	[c]	9/16/99	0	-2
5/31/00	-23	-2	6/2/00	107	5/31/00	9	5/31/00	-6	5/31/00	-3	5/31/00	0	[d]
6/14/00	-16	-2	6/14/00	104	6/14/00	9	6/14/00	-7	6/14/00	[c]	6/2/00	[d]	-1
6/26/00	-6	-2	6/26/00	104	6/26/00	2	6/28/00	[c]	6/28/00	[c]	6/28/00	[c]	[c]
7/20/00	2	-2	7/20/00	114	7/20/00	3	7/20/00	-7	7/20/00	-4	6/14/00	0	-1
8/9/00	-2	-1	8/9/00	114	8/9/00	9	8/9/00	-4	8/9/00	-4	7/20/00	0	-2
8/31/00	-5	-1	8/31/00	114	8/30/00	9	8/30/00	-6	8/30/00	-4	8/9/00	-1	-2
6/8/01	-16	-1	6/8/01	84	6/6/01	9	6/6/01	-6	6/6/01	-3	8/30/00	-1	-2
											6/6/01	-1	-2

[a] Site visited, pin presumed buried under colluvium or vegetation mat.
[b] Site visited, pin presumed missing.
[c] Site not visited.
[d] Site visited, pin not measured.
[e] Pin discontinued after burial by bank failure.



Appendix 7. Cumulative erosion recorded at erosion pins at 14 erosion monitoring sites on the Alagnak River.

Appendix 8. Results of water-quality analyses of Alagnak and Nonvianuk River water, 1999–2001

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm microsiemens per centimeter at 25°C; µg/L, micrograms per liter; mm, millimeter; alphanumeric entry following constituent name and preceded by "P" (e.g. P0010) is laboratory analysis code; number in parentheses after river kilometer is the U.S. Geological Survey site identification number; *, measured in laboratory; --, not available; <, actual value is known to be less than the value shown; E, estimated value]

	Field Determinations						Inorganic constituents	Major Ions							
Date	Water temperature (°C) P00010	pH, field (standard units) P00400	Dissolved oxygen (mg/L) P00300	Specific conductance (µS/cm at 25°C) P00095	Alkalinity, total dissolved, field (mg/L as $CaCO_3$) P39086	Bicarbonate, dissolved, field (mg/L as HCO_3) P00453	Solids, residue on evaporation at 180°C in mg/L P70300	Calcium, dissolved (mg/L as Ca) P00915	Magnesium, dissolved (mg/L as Mg) P00925	Potassium, dissolved (mg/L as K) P00935	Sodium, dissolved (mg/L as Na) P00930	Chloride, dissolved (mg/L as Cl) P00940	Fluoride, dissolved (mg/L as F) P00950	Silica, dissolved (mg/L as SiO_2) P00955	Sulfate, dissolved (mg/L as SO_4) P00945
Alagnak River at river kilometer 127 (Kukaklek Lake outlet) (15300660)															
8/11/00	11.5	7.1	10.4	38	9.6*	--	23	3.32	0.766	E.21	1.93	1.8	<0.1	2.9	5.2
Nonvianuk River at Nonvianuk Lake outlet (15300693)															
8/10/00	13	7.7	10	41	12.6*	--	24	4.72	.630	.4	1.52	1.0	<.1	3.3	5.5
Alagnak River at river kilometer 93 (15300700)															
6/4/99	various[a]	various[a]	various[a]	various[a]	9	11	36	3.79	.793	.27	2.04	1.7	<.1	3.4	5.3
7/14/99	various[a]	various[a]	various[a]	various[a]	12	14	24	4.27	.728	.51	1.78	1.4	<.1	3.5	5.4
9/16/99	various[a]	various[a]	various[a]	various[a]	9	11	28	4.31	.778	.33	1.89	1.4	<.1	3.4	5.6
6/2/00	various[a]	various[a]	various[a]	various[a]	11.2*	--	23	3.33	.741	E.21	1.91	1.8	<.1	3.3	5.0
8/9/00	various[a]	various[a]	various[a]	various[a]	11.2*	--	24	3.95	.734	.29	1.77	1.5	<.1	3.2	5.5
2/27/01	various[a]	various[a]	various[a]	various[a]	11	14	22	4.78	.829	.30	1.98	1.5	<.16	4.3	5.7
Alagnak River at river kilometer 46 (15300730)															
6/3/99	7	6.9	12.9	36	12	15	40	4.99	.997	.35	2.29	1.7	<.1	5.0	4.7
7/13/99	13.3	6.8	9.95	43	E10.	E12	31	--	--	--	--	1.6	<.1	--	5.4
9/15/99	10.5	7.3	11.4	43	13	16	29	4.68	1.03	.40	2.20	1.5	<.1	4.9	5.2
6/1/00	10	7	11.7	40	14.5*	--	26	4.37	1.04	.32	2.37	1.8	<.1	4.8	4.8
6/27/00	12.5	7.1	11.8	42	10	12	29	4.16	.891	.41	2.06	1.7	.1	3.9	4.8
8/9/00	14	7.3	--	41	13.8*	--	27	4.44	.925	.42	2.00	1.6	<.1	4.2	5.0
2/28/01	0	--	12.5	--	15	18	31	4.54	1.05	.34	2.17	1.9	<.16	6.0	5.3
Alagnak River at river kilometer 21 (15300770)															
6/3/99	5	7.3	11.7	38	13	16	45	4.05	1.04	.37	2.43	1.8	<.1	5.5	4.3
7/15/99	13	6.9	9.6	45	13	16	31	4.56	.979	.36	2.17	1.6	<.1	4.5	5.1
9/14/99	10.5	7.2	11.5	52	14	17	34	5.02	1.19	.45	2.59	1.8	<.1	5.8	5.0
6/1/00	9	7	10.7	43	15.6*	--	31	4.54	1.13	.60	2.76	2.0	<.1	5.1	4.8
6/27/00	13	7.1	11.3	45	11	13	26	4.38	.978	.33	2.24	1.8	<.1	4.3	4.8

Appendix 8. Results of water-quality analyses of Alagnak and Nonvianuk River water, 1999–2001—Continued

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm microsiemens per centimeter at 25°C; µg/L, micrograms per liter; mm, millimeter; alphanumeric entry following constituent name and preceeded by "P" (e.g. P0010) is laboratory analysis code; number in parentheses after river kilometer is the U.S. Geological Survey site identification number; *, measured in laboratory; --, not available; <, actual value is known to be less than the value shown; E, estimated value]

Date	Nutrients								Organic carbon		Trace elements		Suspended sediment		
	Ammonia, dissolved (mg/L as N) P00608	Ammonia+ organic nitrogen, dissolved (mg/L as N) P00623	Ammonia+ organic nitrogen, total (mg/L as N) P00625	Nitrite+ nitrate, dissolved (mg/L as N) P00631	Nitrite, dissolved mg/L as N P00613	Phosphorus, dissolved (mg/L as P) P00666	Phosphorus, ortho (mg/L as P) P00671	Phosphorus, total (mg/L as P) P00665	Organic carbon, dissolved (mg/L as C) P00681	Organic carbon, suspended (mg/L as C) P00689	Iron, dissolved (µg/L as Fe) P01046	Manganese, dissolved (µg/L as Mn) P01056	Suspended-sediment concentration mg/L P80154	Suspended-sediment load tons/day P80155	Suspended sediment, percent <.062 mm P70331
Alagnak River at river kilometer 127 (Kukaklek Lake outlet) (15300660)															
8/11/00	<0.002	E0.06	E0.10	<0.005	<0.001	<0.006	0.003	0.008	0.83	<0.20	<10	<2.2	1	5.2	--
Nonvianuk River at Nonvianuk Lake outlet (15300693)															
8/10/00	<.002	E.08	E.08	.015	<.001	<.006	.002	<.008	.98	<.20	<10	<2.2	2	9.9	--
Alagnak River at river kilometer 93 (15300700)															
6/4/99	.066	.18	.14	.012	<.001	.006	.001	.010	1.4	.20	20	E2.0	4	38	31
7/14/99	<.002	E.09	.16	.008	<.001	<.004	<.001	.004	.90	.20	<10	<3.0	2	36	19
9/16/99	.009	E.07	E.09	<.005	.001	<.004	.001	.005	.90	.30	E5.0	<2.2	1	9.2	--
6/2/00	.005	<.10	E.08	<.005	<.001	E.003	<.001	E.006	1.05	.24	20	E1.5	3	25	--
8/9/00	<.002	E.08	E.09	.007	<.001	<.006	.002	E.004	1.05	<.20	E5.8	<2.2	1	11	--
2/27/01	.003	.11	.08	.028	.001	<.006	<.007	E.003	.84	<.20	E6.8	<3.2	1	3.8	--
Alagnak River at river kilometer 46 (15300730)															
6/3/99	<.002	.11	.23	<.005	<.001	<.004	.002	.024	1.8	.30	50	4.7	32	344	18
7/13/99	.002	E.08	.19	.006	<.001	<.004	<.001	.009	1.0	.20	--	--	11	--	13
9/15/99	.034	E.06	<.10	.005	<.001	<.004	.009	.006	1.0	.30	30	4.4	3	28	--
6/1/00	<.002	<.10	.11	<.005	<.001	E.004	<.001	.019	1.0	.26	30	4.6	19	151	25
6/27/00	<.002	.11	.10	<.005	.001	.008	.004	.019	.94	<.20	20	4.5	19	313	27
8/9/00	<.002	E.06	E.10	.008	<.001	E.003	.003	.010	1.1	<.20	30	4.7	5	60	--
2/28/01	<.002	<.10	.10	.011	<.001	E.004	<.007	.014	.91	.27	20	8.4	9	35	--
Alagnak River at river kilometer 21 (15300770)															
6/3/99	<.002	.15	.28	.007	<.001	.008	.003	.052	2.5	1.2	110	8.8	41	472	22
7/15/99	<.002	.12	.12	.006	<.001	<.004	.002	.013	1.2	.20	50	8.4	--	--	--
9/14/99	.004	E.06	E.09	<.005	<.001	.006	.003	.018	1.6	.30	110	11.6	9	85	--
6/1/00	.003	<.10	.12	<.005	<.001	E.005	.001	.027	1.2	.30	90	9.6	23	186	--
6/27/00	.003	<.10	.11	<.005	.001	E.004	.004	.020	1.0	<.20	50	7.3	23	407	--

[a] Parameter varied across the channel near the confluence of the Alagnak and Nonvianuk Rivers. Cross-sectional measurements are presented in Bertrand and others (2000) and Meyer and others (2001).

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