Glacial History and Runoff Components of the Tlikakila River Basin, Lake Clark National Park and Preserve, Alaska

By Timothy P. Brabets, Rod S. March, and Dennis C. Trabant

Prepared in cooperation with the National Park Service

Scientific Investigations Report 2004-5057

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

U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2004

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Suggested citation:
Brabets, Timothy P., March, Rod P., and Trabant, Dennis C. 2004, Glacial history and runoff components of the Tlikakila River Basin, Lake Clark National Park and Preserve, Alaska: U.S. Geological Survey Scientific Investigation Report 2004-5057, 24 p.

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Conversion Factors, Water-Quality Information, and Vertical Datum

Multiply	by	to obtain
Millimeter (mm)	0.03937	inch
Meter (m)	3.281	foot
Kilometer (km)	0.6214	mile
Square kilometer (km^2)	0.3861	square mile
Cubic meter per second (m^3/s)	35.31	cubic foot per second
Degrees Celsius (°C)	1.8(°C) + 32 = °F	degrees Fahrenheit

Chemical concentration and water temperature are given only in metric 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 thousand micrograms per liter is equivalent to 1 milligram 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 (mS/cm) at 25°C.

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

Mapping Sources

Figures 1, 3, 5, 12

Base map modified from U.S. Geological Survey 1:63,360 State base maps.
U.S. Geological Survey Digital Line Graphs published at 1:250,000 and 1:63,360.
Publication projection is Albers Equal Area.
Standard parallels are 55°00′ and 65°00′, central meridian 154°00′, latitude of projection origin 50°00′.

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ABSTRACT

The Tlikakila River is located in Lake Clark National Park and Preserve and drains an area of 1,610 square kilometers (622 square miles). Runoff from the Tlikakila River Basin accounts for about one half of the total inflow to Lake Clark. Glaciers occupy about one third of the basin and affect the runoff characteristics of the Tlikakila River. As part of a cooperative study with the National Park Service, glacier changes and runoff characteristics in the Tlikakila River Basin were studied in water years 2001 and 2002.

Based on analyses of remote sensing data and on airborne laser profiling, most glaciers in the Tlikakila River Basin have retreated and thinned from 1957 to the present. Volume loss from 1957-2001 from the Tanaina Glacier, the largest glacier in the Tlikakila River Basin, was estimated to be 6.1 x 10^9 cubic meters or 1.4 x 10^8 cubic meters per year. For the 2001 water year, mass balance measurements made on the three largest glaciers in the Tlikakila River Basin—Tanaina, Glacier Fork, and North Fork—all indicate a negative mass balance.

Runoff measured near the mouth of the Tlikakila River for water year 2001 was 1.70 meters. Of this total, 0.18 meters (11 percent) was from glacier ice melt, 1.27 meters (75 percent) was from snowmelt, 0.24 meters (14 percent) was from rainfall runoff, and 0.01 meters (1 percent) was from ground water. Although ground water is a small component of runoff, it provides a critical source of warm water for fish survival in the lower reaches of the Tlikakila River.

INTRODUCTION

The Tlikakila River, a federally designated Wild River, is located entirely in Lake Clark National Park and Preserve, approximately 160 km (100 mi) southwest of Anchorage, Alaska (fig. 1). It is the second largest watershed of the Lake Clark Basin (fig. 2) and embodies all of the resource qualities (glaciers, rivers, waterfalls, mountain scenery, and salmon habitat) for which the park was established: "...to protect the watershed necessary for perpetuation of the red salmon fishery in Bristol Bay;...maintain unimpaired the scenic beauty and quality, including...glaciers, wild rivers, lakes, waterfalls...in their natural states." Lake Clark, the sixth largest lake in Alaska, provides critical spawning and rearing habitat for Bristol Bay salmon. Escapement data have shown that the number of salmon that enter the Kvichak River system (fig. 1) from 1956 to 2002 has ranged from 250,000 to over 24 million (Regnart, 1998).

The large number and size of Tlikakila River Basin glaciers (fig. 3) suggests that the annual runoff is probably dominated by seasonal snow and glacier ice melt. Glaciers store an enormous amount of water in the form of ice and this feature alone makes any drainage basin containing glaciers both unique and complex. Runoff from glacier-fed rivers is influenced by the glacier behavior and differs from non-glacier watersheds. For example, during a single year, the mass of a glacier may increase, decrease, or remain the same. When a glacier shrinks (negative mass balance), the basin will yield more water than a similar basin without glaciers. A growing glacier stores and

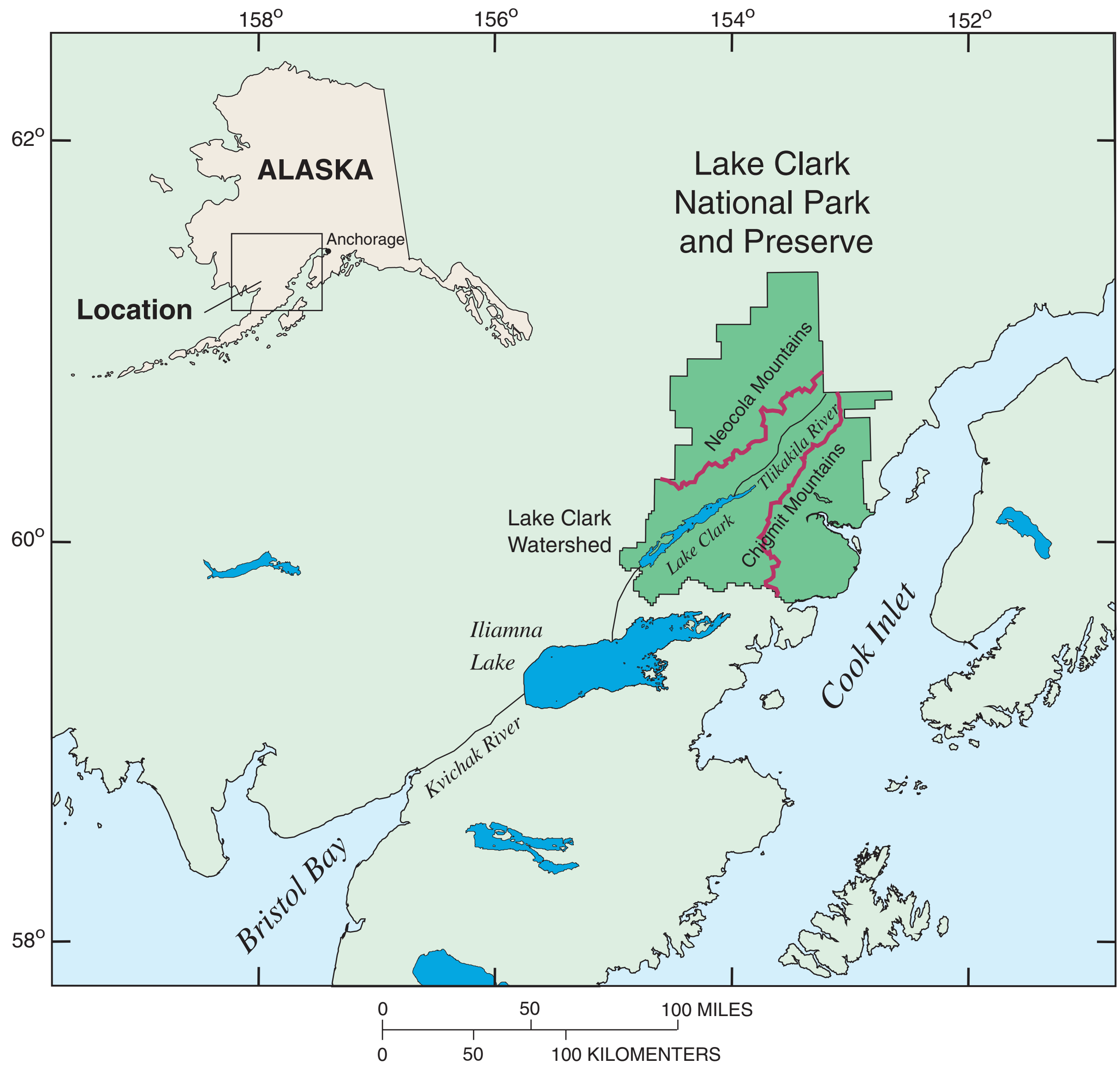
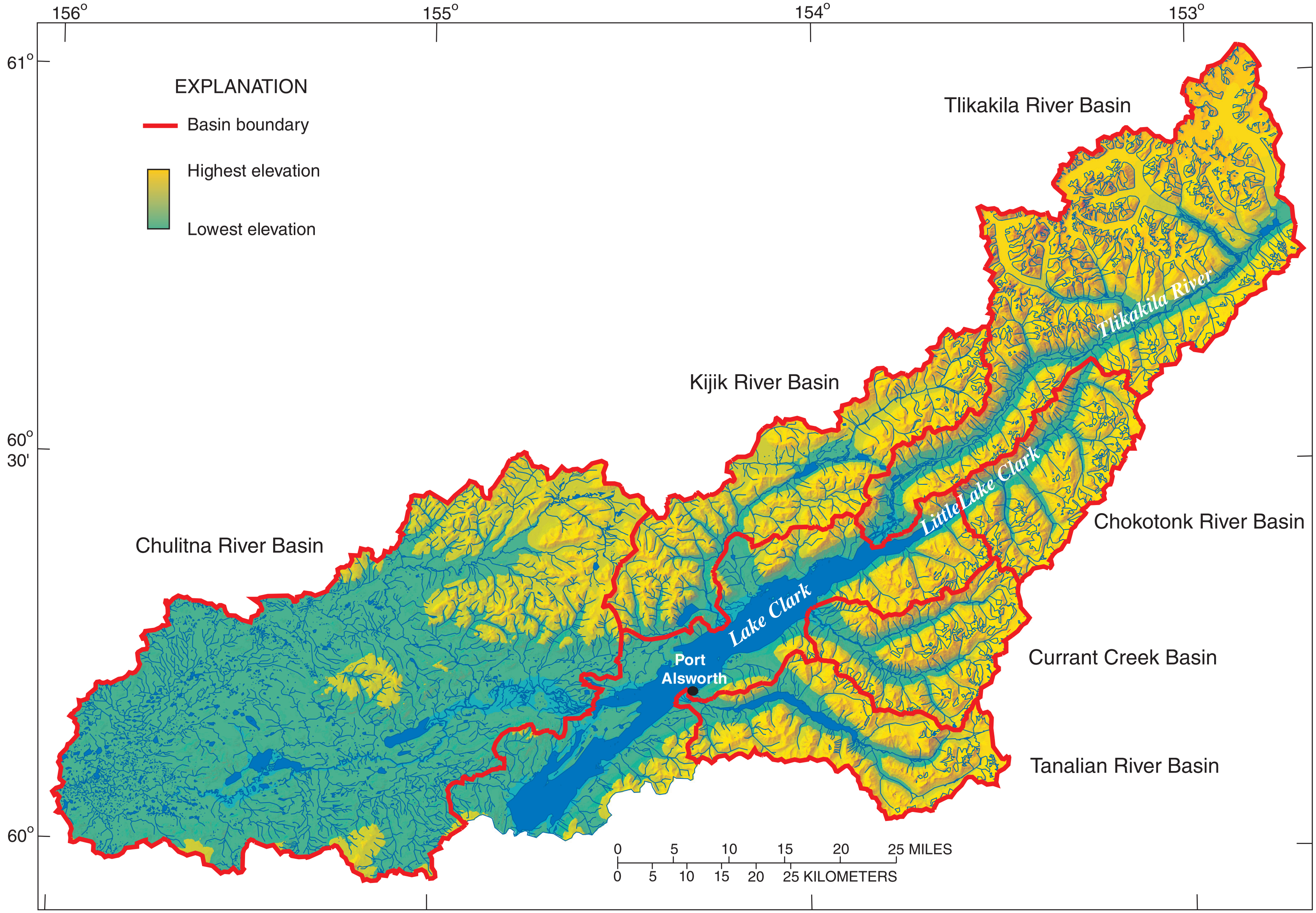


Figure 1. Location of the Tlikakila River and Lake Clark National Park and Preserve.

withholds water from the normal runoff in the stream. If a glacier is in equilibrium, most of the glacier meltwater will be released during the short summer season, adding an additional component and sustaining the flow of a river throughout the summer (Meier, 1969). The peak runoff from glaciers occurs later than from lower altitude, non-glacier areas (Meier and Tangborn, 1961). The extra water withheld by the glaciers may affect the amount of runoff from the basin. For example, Fountain and Tangborn (1985) found that in certain years the water yield from a glacierized basin was 20 to 30 percent higher than the water yield from a non-glacierized basin.

Glacier-fed rivers such as the Tlikakila also transport much higher suspended sediment loads than non-glacier rivers. The effect of the Tlikakila River on Lake Clark is pronounced and readily visible. The river has deposited a large delta of glacially-derived sediments that frequently prevent boat passage from Lake Clark into Little Lake Clark (Brabets, 2002). As glacial runoff increases throughout the summer, a sediment plume moves down the lake, giving Lake Clark its characteristic turquoise color. The sediment plume affects light penetration 40 km (25 mi) or more from the Tlikakila River mouth (Chamberlain, 1989). The significance of this sediment plume is that it



Base from U.S. Geological Survey digital data, 1: 63,360, 1957
Albers Equal-Area Conic projection
Standard parallels 55°00' and 65°00', central meridian -154°00'

Figure 2. Major river basins of the Lake Clark Basin.

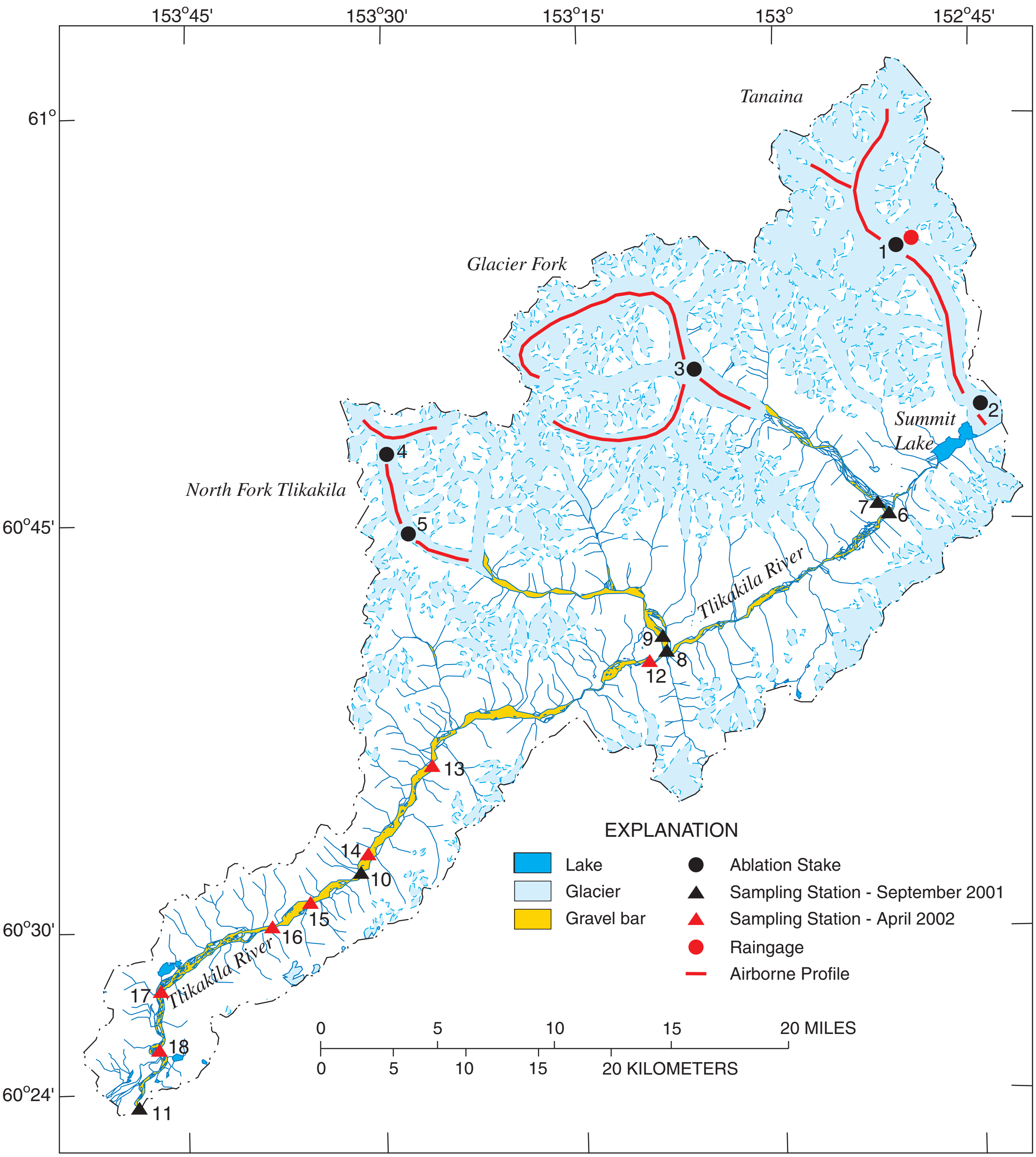


Figure 3. Location of ablation stakes, sampling stations, airborne profiles, and raingage in the Tlikakila River Basin.

reduces the light transmissivity of the water column. A reduction in light transmissivity combined with other limnology factors can affect the productivity of Lake Clark (Stottlemeyer, 1990).

One of the most noticeable results of climate change in Alaska is the melt and retreat of glaciers. For example, 40 years ago, glaciers dammed the Tlikakila River valley at Lake Clark Pass, the primary air route between Anchorage and the Iliamna region. As the glaciers have retreated, river habitat available for sockeye salmon, and for the predators and scavengers that rely on them, has increased. In 1999, a telemetry study of salmon returning to Lake Clark to spawn discovered salmon spawning in silt-laden water about 77 km (48 mi) upstream from the mouth. As glaciers continue to retreat, runoff characteristics from the basin will continue to change. Given that the Tlikakila River provides greater than one-half the inflow to Lake Clark (Brabets, 2002), changes in runoff patterns will alter the hydrology of the lake. This, in turn, will affect nutrient inputs, habitat availability and habitat quality for the sockeye salmon fishery. During the winter low flow season, numerous springs or open-water leads are present along the course of the river, providing over-wintering habitat to juvenile salmon. Thus, from both a 'high-flow' and 'low-flow' aspect, the Tlikakila River is important to the salmon habitat of Lake Clark.

Purpose and Scope

This report summarizes the results of a cooperative study by the National Park Service (NPS) and the U. S. Geological Survey (USGS) to study the glacier changes and runoff characteristics of the Tlikakila River. The objectives of the study were to (1) construct a history of glacier change in the Tlikakila River Basin, (2) determine the runoff components (rainfall, snowmelt, glacier melt, and ground water) and their respective contributions to the Tlikakila River, and (3) document springs or ground-water inflow along the Tlikakila River.

Field data collected during this study represent the hydrologic conditions in the 2001 water year. Hydrologic conditions in other water years are not the same as 2001. For example, in a previous study, Brabets (2002) documented the runoff from the Tlikakila River into Lake Clark for the 1999–2001 water years and noted considerable variations. Thus, relative contributions from icemelt, snowmelt, or rainfall may vary with each water year. However, the data collected in water year 2001 still provide insights into the mechanisms and processes of runoff in the Tlikakila River.

Acknowledgements

Keith Echelmeyer and By Valentine of the University of Alaska Fairbanks, Geophysical Institute, obtained and analyzed the airborne profiling data of the Tanaina, Glacier Fork, and North Fork glaciers. Dan Long of the U.S. Geological Survey digitized glacier terminus boundaries from 1978 color infrared photography and 1999 Landsat Imagery and created a Geographical Information System (GIS) showing glacier termini for 1957, 1978, and 1999. Dan Young of Lake Clark National Park and Preserve provided information on spawning locations for the Tlikakila River.

DESCRIPTION OF STUDY AREA

Flanked by the Neacola and Chigmit Mountain ranges, the Tlikakila River begins at Summit Lake and flows about 80 km (50 mi) through a deep, narrow valley before emptying into Lake Clark (fig. 1). About 150 glaciers, covering 588 km^2 (230 mi^2), exist in the Tlikakila River Basin (fig. 3). This represents about one-third of the entire basin area of 1,610 km^2 (622 mi^2). The three largest glaciers (Tanaina, Glacier Fork, and North Fork, fig. 3), total 56 percent of the glacier area in the basin. Precipitation in the basin varies between 1.5 and 3.0 m (70 and 118 inches). Water of the Tlikakila River is classified as calcium bicarbonate and the river transports an average of 907,000 metric tons (one million tons) of suspended sediment per year into Lake Clark (Brabets, 2002). Most of the Tlikakila River Basin consists of rough mountainous lands. Vegetation is sparse and is primarily alpine tundra and tall shrub. Many areas of metamorphosed igneous and sedimentary rocks of Cretaceous and Jurassic age are present (Nelson and others, 1983).

METHODS OF DATA COLLECTION AND ANALYSIS

To reconstruct the glacial history, determine the runoff components, and identify ground-water contributions from the Tlikakila River Basin, several types of information are needed. These include, but are not limited to, aerial photography, river flow, and ice melt. For this study, both established and relatively new techniques were used to accomplish the study objectives.

One technique used to obtain a historical perspective of glacier change was remote sensing. Color infrared photography from 1978 and Landsat 7 Imagery from 1999 of the Tlikakila River Basin was obtained. Glacier termini were digitized from each set of imagery, entered into a Geographical Information Systems (GIS), and then compared with the glacier termini from the 1957 USGS topographic maps (developed from black and white aerial photography). Advances or retreats of glaciers were then determined.

A technique to reconstruct trends in glacier mass was developed by Echelmeyer and others (1996) and uses a small, lightweight airborne system for surface elevation profiling of glaciers in narrow mountain valleys. The technique involves a small airplane flying low over the surface of the centerline of a glacier. The aircraft position is determined by kinematic global positioning systems (GPS) methods, and the distance to the glacier is determined with a laser ranger. As the plane flies over the glacier, the elevation of many points along the glacier surface centerline is obtained. From these profile points, the entire glacier surface is extrapolated to obtain a 'topographic' map of the glacier. This elevation map can then be compared to previous or future elevation maps of a glacier to determine if the volume of a glacier has increased or decreased. This technique was used to determine volume change of the Tanaina, Glacier Fork, and North Fork Tlikakila glaciers (fig. 3) from 1957 (when the topographic maps were created) to 2001.

Mass balances of the three largest glaciers, Tanaina, Glacier Fork, and North Fork Tlikakila (fig. 3), were measured using traditional methods of glacier surface mass balance (Mayo and others, 1972, Østrem and Brugman, 1991, and Østrem and Stanley, 1969). In general, it is best to begin mass balance measurements on a glacier near the end of the melt season in late summer or early fall. At this time, one can determine the equilibrium line altitude (ELA) of the glacier, which separates the ablation zone from the accumulation zone of the glacier. However, due to logistical problems, mass balance measurements did not begin until June 2001, after the melt season had begun, and no mass balance measurements were made in the accumulation zone. Thus, some additional error was introduced in calculations of snowmelt.

Ablation stakes were installed at five locations on Tlikakila River Basin glaciers on June 8, 2001 (fig. 3). The stakes consist of 1-inch metal tubing with wood plugs in the bottom and were drilled 11 to 14 m into the glacier with a portable steam drill (fig. 4). Stakes are made up of multiple 3 m lengths joined with custom couplings. Two stakes each were installed on the North Fork Tlikakila Glacier and the Tanaina Glacier. One stake was installed as near as possible to the terminus and one stake was installed slightly below the ELA. One stake was installed in the Glacier Fork glacier in the lower to mid ablation zone.

The remaining winter snowpack water equivalent was measured at three of the five ablation stake sites on June 8, 2001 where snow was still present. Water equivalent was determined by using a McCall sampler that cores the entire snowpack down to the ice surface. By weighing the snow core and determining the density of the snow, the water equivalent can be calculated. The ablation stakes were revisited on September 9, 2001 to measure the amount of icemelt and/or snowmelt. Once the amount of ice melt or snowmelt was determined at each stake, the results were extrapolated to the entire glacier to determine the total amount of icemelt and snowmelt.

To obtain an estimate of the ground-water contribution and to identify sites along the Tlikakila River that might be ground-water fed, several techniques were used. Continuous discharge records were collected on the Tlikakila River near the mouth during the 1999-2001 water years. Analysis of the flow data at the beginning and at the end of the runoff season (mid-May and late September) is essentially the baseflow period and thus provided information on the ground-water contribution to the Tlikakila River. In September 2001 and April 2002, the usual time of baseflow conditions, sites along the Tlikakila River were visited. If possible, flow measurements were made at these sites to provide additional information on ground-water characteristics. In addition, the NPS provided data detailing tagged salmon locations along the Tlikakila River in September 2001. This type of information proved useful since recent studies (Maclean, 2003) have shown that salmon tend to overwinter near ground-water inflows.

A streamgage was operated near the mouth of the Tlikakila River (fig. 3, site 6) to obtain flow data. The gage was operated from May 1 to September 30, 2001, when most runoff occurs. A National Weather Service station is located at Port Alsworth (fig. 2) and thus precipitation (both as rainfall and snowfall) was available. To determine if there were differences in precipitation between Post Alsworth and the upper part of the Tlikakila River Basin, a tipping bucket raingage was installed on the Tanaina Glacier (fig. 3). Although this is a different type of raingage from that used at Port Alsworth, it was placed where it was not affected by wind and thus provided good data.

GLACIER CHANGES IN THE TLIKAKILA RIVER BASIN

Many factors affect the advance or retreat of a glacier and its volume change. These may include glacier size, aspect, elevation, and geographic location with respect to changing weather patterns. Glacier terminus positions were mapped for 85 different glaciers, representing about 57–85 percent of the total number of glaciers in the Tlikakila River Basin, to access the long-term trend in glacier behavior and any spatial variation in behavior around the basin (fig. 5, table 1). Glacier terminus positions were determined from two sources and compared with the 1957 USGS topographic map positions. One source was 1978 1:60,000-scale color infrared photography from the statewide Alaska High Altitude Aerial Photography collection. The other source was 1999, 25-m pixel color Landsat 7 imagery.

Errors in measuring terminus position result from errors in registering the imagery, visually deciding where the terminus is on the imagery, and deciding what point along the terminus to compare with positions from other years. Deciding where the terminus is on one image can be very difficult if the terminus is heavily covered with debris or the terminus is in a shadow. Choosing what part of a terminus to compare with other year terminus positions can be difficult

Figure 4. Propane-fired portable stream drill used to install ablation stake for measuring glacier melt on Tanaina Glacier (photograph by Rod March).

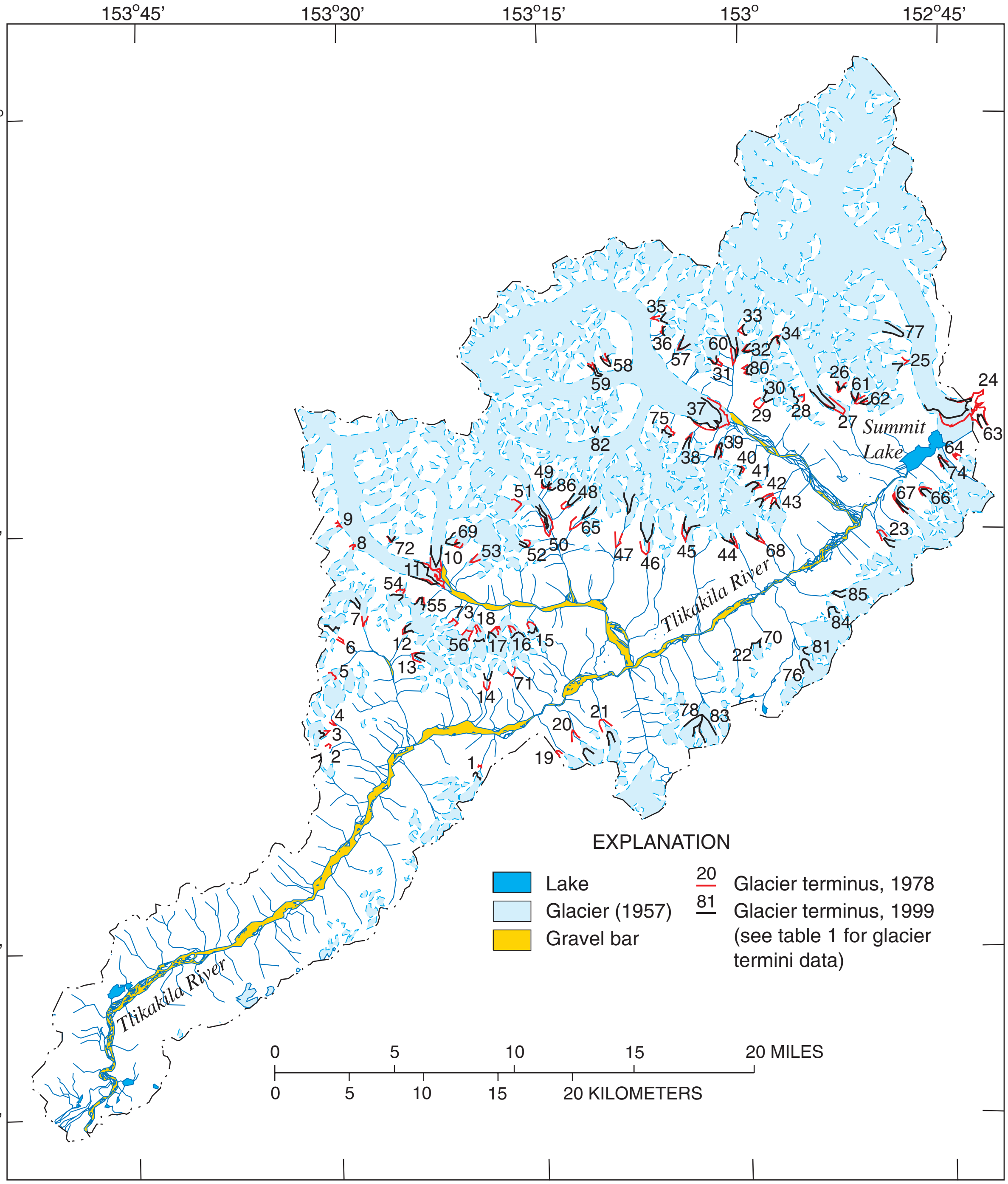


Figure 5. Terminus locations of glaciers in the Tlikakila River Basin based on 1957 black and white photography, 1978 color infrared photography, and 1999 Landsat 7 imagery.

because the glacier may advance or retreat unevenly across the width of its valley. For this study it was estimated that these combined errors vary from 150-500 m in terminus position, which translates into terminus advance/retreat rate errors of 7-34 m per year.

Results of the all the terminus measurements (fig. 5, table 1) indicated that about 48 percent of the glaciers were retreating during 1957–78. Retreat increased to about 83 percent during 1978–99. Because many glacier termini were only measured once, a better way to examine the data for differences

Table 1. Advance or retreat of glacier termini in the Tlikakila River Basin

[ID, site identification number; negative numbers indicate retreat; m, meters; m/yr, meters per year; -- not determined]

ID	1957-1978			1978-1999			1957-1999		
(figure 5)	Distance (m)	Rate (m/yr)	Error (m/yr)	Distance (m)	Rate (m/yr)	Error (m/yr)	Distance (m)	Rate (m/yr)	Error (m/yr)
1	400	19	24	-550	-26	34	- 150	- 7	24
2	950	45	24	-950	-45	34	0	0	24
3	200	10	24	-400	-19	34	- 200	-10	24
4	900	43	24	--	--	--	--	--	--
5	0	0	7	--	--	--	--	--	--
6	650	31	24	-1100	-52	34	- 450	-21	24
7	-500	-24	7	-1300	-62	12	-1,800	-86	10
8	0	0	7	--	--	--	--	--	--
9	0	0	24	--	--	--	--	--	--
10	-400	-19	7	-250	-12	12	- 650	-31	10
11	-500	-24	7	-400	-19	12	- 900	-43	10
12	-350	-17	7	-150	-7	12	- 500	-24	10
13	-250	-12	7	-200	-10	12	- 450	-21	10
14	950	45	24	-650	-31	34	300	14	24
15	-800	-38	24	600	29	34	- 200	-10	24
16	-950	-45	7	-650	-31	25	-1,600	-76	24
17	-1050	-50	7	-650	-31	25	-1,700	-81	24
18	-250	-12	7	-1050	-50	25	-1,300	-62	24
19	450	21	24	--	--	--	--	--	--
20	950	45	24	-1500	-71	34	- 550	-26	24
21	450	21	24	-950	-45	26	- 500	-24	10
22	--	--	--	--	--	--	0	0	24
23	-350	-17	7	-650	-31	12	-1,000	-48	10
24	-850	-40	7	-500	-24	12	-1,350	-64	10
25	0	0	7	-400	-19	12	- 400	-19	10
26	100	5	24	-150	-7	34	- 50	- 2	24
27	-600	-29	7	-700	-33	12	-1,300	-62	10
28	-300	-14	7	50	2	25	- 250	-12	24
29	500	24	24	-700	-33	34	- 200	-10	24
30	-50	-2	24	-150	-7	26	- 200	-10	10
31	150	7	7	-500	-24	12	- 350	-17	10
32	-200	-10	7	-50	-2	12	- 250	-12	10
33	200	10	7	-350	-17	25	- 150	- 7	24
34	-150	-7	7	-100	-5	25	- 250	-12	24
35	200	10	7	-650	-31	25	- 450	-21	24
36	0	0	7	-100	-5	25	- 100	- 5	24
37	-500	-24	7	-550	-26	12	-1,050	-50	10
38	-100	-5	24	-250	-12	26	- 350	-17	10
39	-600	-29	7	200	10	12	- 400	-19	10
40	-50	-2	24	-150	-7	34	- 200	-10	24
41	-350	-17	24	-50	-2	26	- 400	-19	10
42	450	21	24	-700	-33	26	- 250	-12	10
43	0	0	24	-300	-14	26	- 300	-14	10
44	0	0	24	-450	-21	26	- 450	-21	10
45	-650	-31	7	-450	-21	12	-1,100	-52	10
46	100	5	24	-850	-40	26	- 750	-36	10
47	1300	62	7	-2400	-114	25	-1,100	-52	24
48	0	0	24	-450	-21	26	- 450	-21	10
49	200	10	24	-150	-7	34	50	2	24
50	100	5	7	-500	-24	12	- 400	-19	10
51	-500	-24	7	--	--	--	--	--	--
52	-650	-31	7	-250	-12	25	- 900	-43	24
53	-750	-36	7	--	--	--	--	--	--
54	-450	-21	7	-400	-19	25	- 850	-40	24
55	50	2	24	0	0	34	50	2	24
56	-850	-40	7	--	--	--	--	--	--
57	-550	-26	7	-50	-2	12	- 600	-29	10
58	-250	-12	7	400	19	12	150	7	10
59	-250	-12	24	250	12	34	0	0	24
60	200	10	24	-400	-19	34	- 200	-10	24
61	0	0	24	0	0	26	0	0	10
62	-400	-19	24	-400	-19	34	- 800	-38	24
63	0	0	7	-500	-24	12	- 500	-24	10
64	-650	-31	7	200	10	12	- 450	-21	10
65	800	38	24	-1150	-55	26	- 350	-17	10
66	-300	-14	7	-150	-7	12	- 450	-21	10
67	-900	-43	7	-450	-21	12	-1,350	-64	10
68	200	10	24	-500	-24	34	- 300	-14	24
69	-800	-38	7	600	29	12	- 200	-10	10
70	--	--	--	--	--	--	350	17	24
71	500	24	24	--	--	--	--	--	--
72	-600	-29	24	-100	-5	34	- 700	-33	24
73	200	10	7	--	--	--	--	--	--
74	400	19	24	--	--	--	--	--	--
75	-150	-7	7	-350	-17	25	- 500	-24	24
76	--	--	--	--	--	--	- 850	-40	10
77	--	--	--	--	--	--	- 400	-19	24
78	--	--	--	--	--	--	- 800	-38	10
79	--	--	--	--	--	--	--	--	--
80	0	0	24	-350	-17	26	- 350	-17	10
81	--	--	--	--	--	--	- 400	-19	10
82	--	--	--	--	--	--	- 300	-14	10
83	--	--	--	--	--	--	- 800	-38	10
84	--	--	--	--	--	--	- 500	-24	10
85	--	--	--	--	--	--	- 700	-33	24
86	-250	-12	24	0	0	26	- 250	-12	10

Table 2. Summary of glacier termini that were mapped in 1978 and 1999.
[Negative advance/retreat rates indicate glacier terminus retreat]

Glaciers mapped in both periods	1957 - 78	1978 - 99
Number	64	64
Number advancing	21	7
Number stable	8	3
Number retreating	35	54
Average retreat rate in meters/year	-4	-14

between the two periods is to look only at the glaciers that were measured in both periods (table 2). Sixty-four glacier terminus positions were mapped in both 1957-78 and 1978-99. Between 1957 and 1978, 33 percent show advance, 12 percent were stable, and 55 percent showed retreat. Between 1978 and 1999, 11 percent show advance, 5 percent were stable, and 84 percent showed retreat. The average terminus advance/

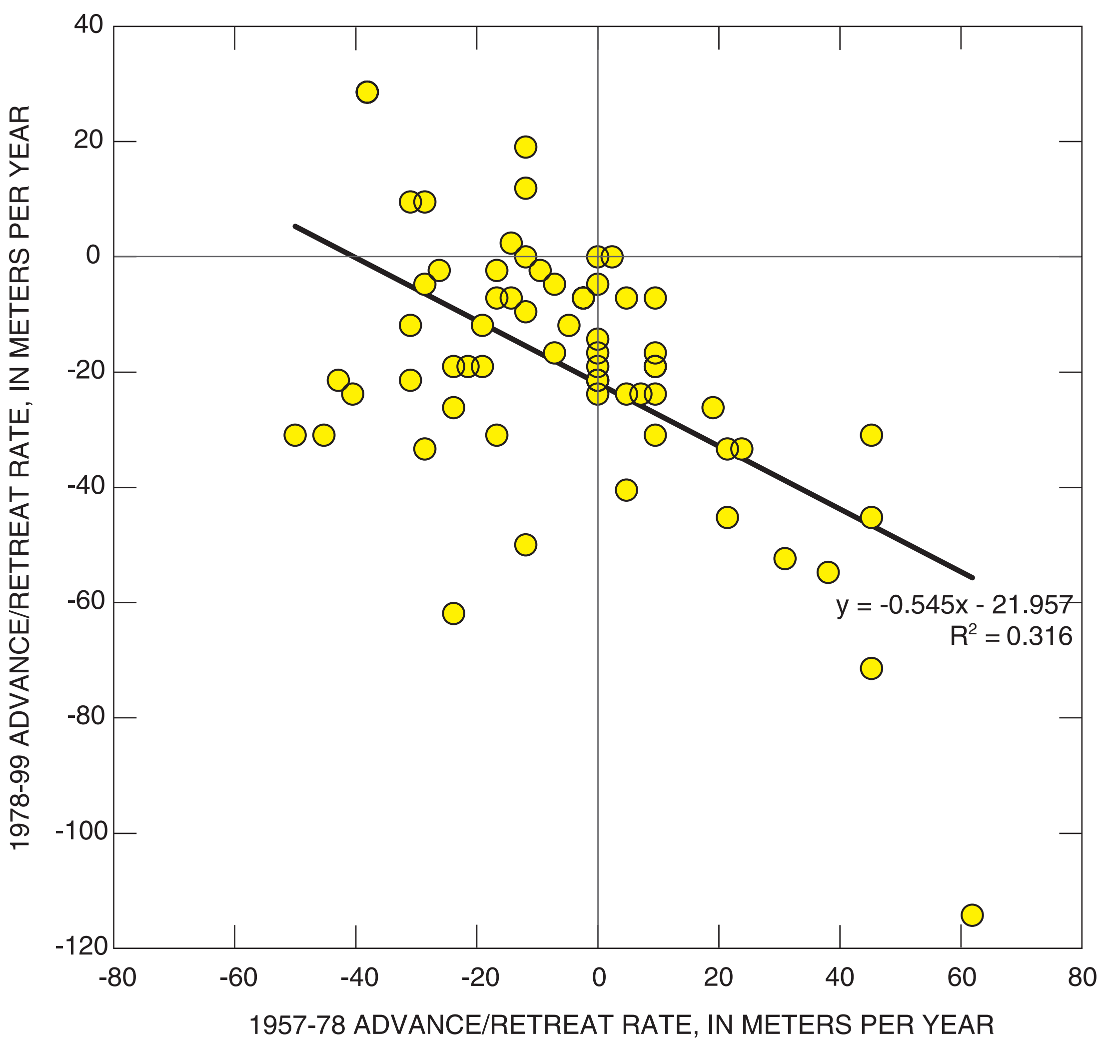


Figure 6. Advance and retreat rates for glaciers in the Tlikakila River Basin. Note the inverse correlation between the two periods. Glaciers that retreated fastest in the first period, retreated the slowest in the second period.

retreat rate increased from a retreat of 4 m per year in 1957-78 to a retreat of 14 m per year in 1978-99.

There is a slight tendency for the glaciers that retreated fastest in the first period to retreat the slowest in the later period (fig. 6). This could be due to a systematic error in the some of the measurements, or there could be a physical explanation for why the glaciers retreating fastest in the first period would tend to slow down. As previously noted, there are about 150 small glaciers in the Tlikakila River Basin. Some of the smaller glaciers may be near or have reached equilibrium during the first period and may not change, or change only slightly in future years. Another possibility is that the climate was warmer or significantly different in the first period compared to the second period.

The spatial distribution of advance/retreat of the glaciers was examined by plotting the advance/retreat rates as a function of their west to east location in the basin, which is effectively a line perpendicular to the crest of the Aleutian Range (fig. 7). No strong spatial patterns emerge from this analysis although there is some indication that the western most glaciers were advancing in the early period and then strongly retreating in the latter period.

Results from the airborne profiling also confirmed that the termini of the three major glaciers retreated from 1957 to 2001 (table 3). North Fork Glacier retreated the least amount, (454 m, 10.3 m/year), while Tanaina Glacier retreated the most, (1,210 m, 31 m/year). Errors in these calculations are estimated to be 0.2 m. Airborne profiling confirmed volume

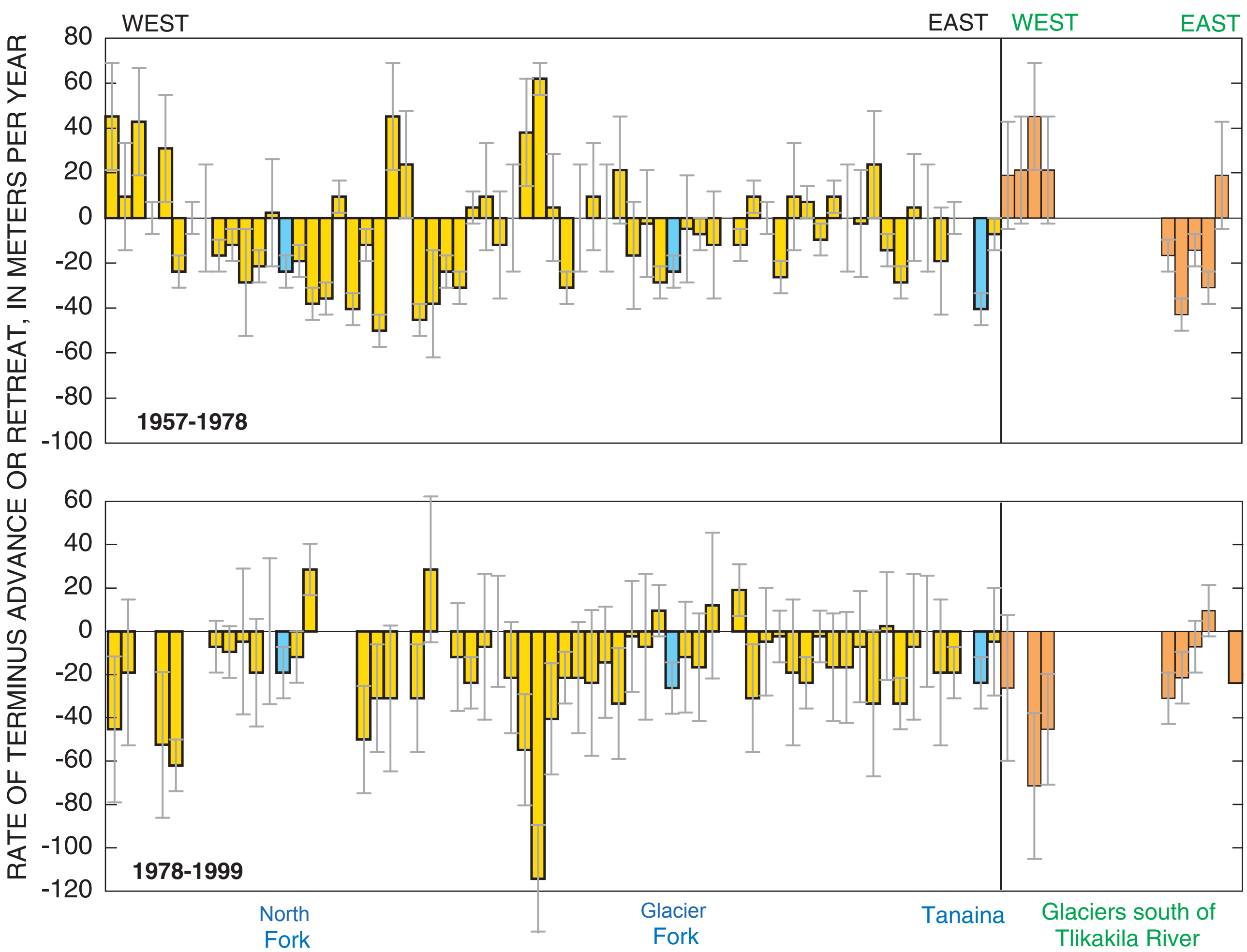


Figure 7.
from
retreating in the latter period

Table 3. Volume and terminus change of Tanaina, Glacier Fork, and North Fork Tlikakila glaciers, 1957-2001
[m^3, cubic meters; m/yr, meters per year; m^3/yr, cubic meters per year; m, meters]

Glacier	Volume Change			Terminus Change	
	Total (m^3)	Rate (m/yr)	Rate (m^3/yr)	Total (m)	Rate (m/yr)
Tanaina	- 6.1 x 10^9	- 0.8	- 1.4 x 10^8	-1,210[a]	-31[a]
Glacier Fork	- 2.5 x 10^9	- 0.5	- 5.7 x 10^7	-587	-13.3
North Fork	- 1.7 x 10^9	- 0.9	- 3.8 x 10^7	-454	-10.3
Total (3 glaciers, 44 years)	-1.03 x 10^{10}		-2.3 x 10^8		

[a] Terminus change for Tanaina Glacier is 1957-1996.

losses from the three major glaciers. The volume loss from Tanaina Glacier was 6.1 x 10^9 m^3, from North Fork Glacier 1.7 x 10^9 m^3 and from Glacier Fork 2.5 x 10^9 m^3 from the 1957 mapping to 2001 (table 3). In calculations of the glacier volume change, the primary error is considered to be the change in thickness of the glacier and is estimated to be 5 m. The total volume lost from these three glaciers, which represent 44 percent of the total glacier area, over 44 years is 1.03 x 10^{10} m^3 or an average of 2.3 x 10^8 m^3/yr. Assuming similar changes for the other glaciers in the Tlikakila River Basin, the average loss over the glacier area would be 0.7 m/yr and 0.3 m/yr over the entire basin. These values represent the volume loss due to glacier thinning, not that volume lost by melting of snow and ice from winter to fall.

The remote sensing and airborne profiling data indicated that most glaciers in the Tlikakila River Basin have retreated and thinned from 1957 to 2001. Airborne profiling data from four other nearby glaciers show the same trends. These glaciers (Turquoise, Shamrock, Double, and Tuxedni) also are located in Lake Clark National Park and Preserve. Volume changes from 1957–96 have ranged from 5.2 x 10^8 m^3 for Shamrock Glacier (1.3 x 10^7 m^3/yr) to 6.7 x 10^9 m^3 for Double Glacier (1.7 x 10^8 m^3/yr). Termini of three of the glaciers (Shamrock, Double, and Turquoise) have retreated, averaging from 10 m/yr for Turquoise Glacier to 36 m/yr for Double Glacier. Tuxedni Glacier, a tidewater glacier, has advanced slightly, averaging 7 m/yr.

The 1978–99 accelerated retreat and thinning of the glaciers in the Tlikakila River Basin may be related to one facet of climate change known as the Pacific Decadal Oscillation (PDO). The PDO is an El Nino-like (moderately warmer-than-normal sea-surface temperatures) or La Nina-like (moderately cooler-than-normal sea-surface temperatures) pattern of Pacific climatic variability that persists for 20–30 years (Mantua and others, 1997). The climatic fingerprints of the PDO are most visible in the North Pacific/North American sector. Several independent studies find evidence for just two full PDO cycles in the past century: 'cool' (negative) PDO regimes prevailed from 1890 to 1924 and again from 1947–76, while 'warm' (positive) PDO regimes dominated from 1925–46 and from 1977 through (at least) the mid - 1990's (fig. 8). PDO variability is strongly expressed in regional snow pack and stream flow anomalies, especially in western North America.

Bitz and Battisti (1999) determined that 68 percent of the variance in the mass balance of Wolverine Glacier, a long-term monitored glacier located in south-central Alaska, was explained by the PDO. However, it is not known if the glaciers in the Tlikakila River Basin behave similarly to Wolverine Glacier. In addition, Bond and others (2003), believe that the PDO stopped dominating the North Pacific about 1989, not 1998. Comparing the PDO index (fig. 8) with the imagery used in determining glacier termini locations indicates that 1957 was in the middle of a negative or cold phase of the PDO, 1978 was at the beginning of a positive or warm phase of the PDO, and 1999 was at the beginning of a negative or cold phase of the PDO. Thus, perhaps the accelerated retreat of most of the glaciers in the 1978–99 time period (fig. 8) might be attributed to the warm phase

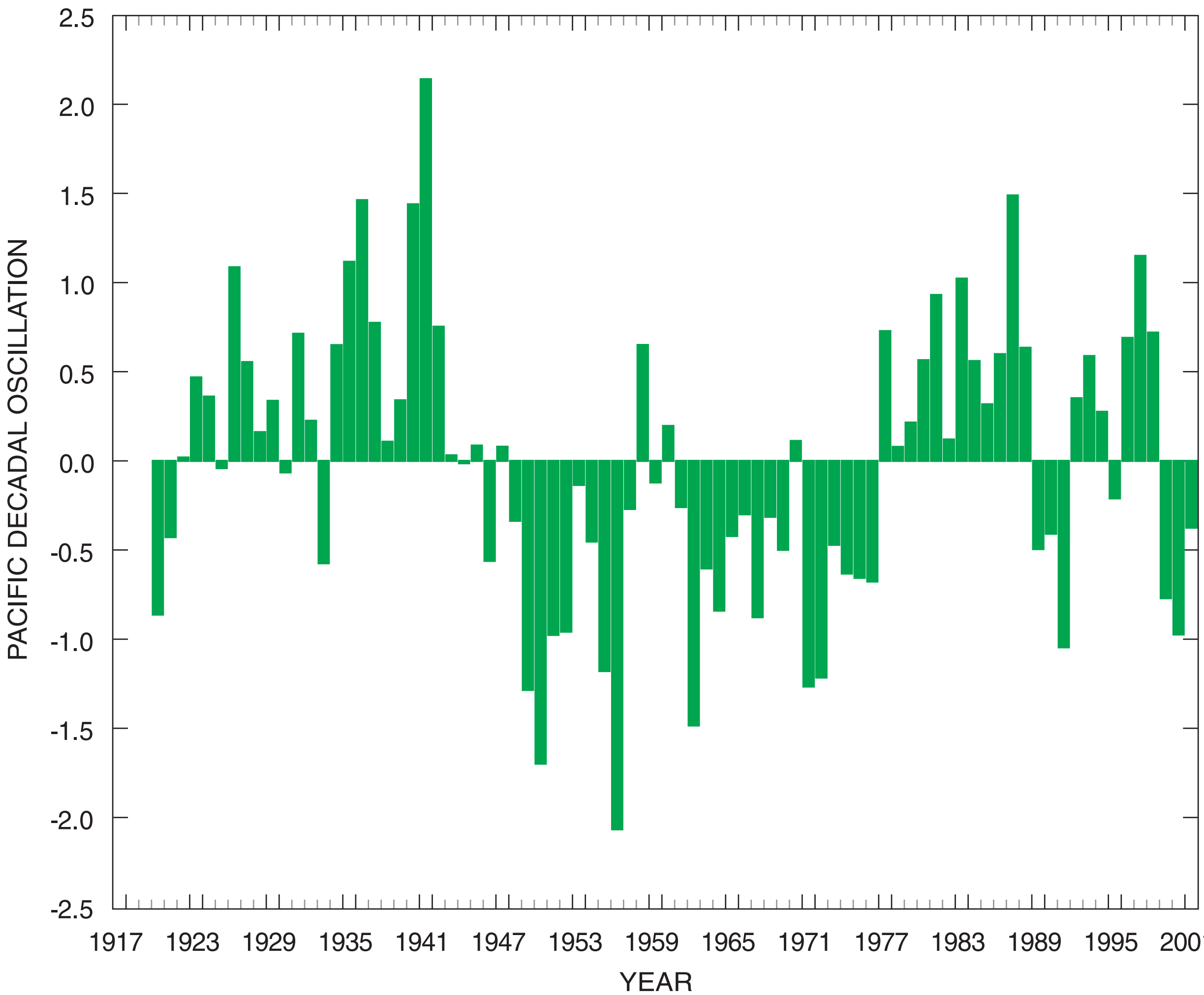


Figure 8. Pacific Decadal Oscillation Index from 1917 to 2001.

of the PDO during this period but most glaciers also retreated from 1957–78, which was a cold phase of the PDO.

RUNOFF COMPONENTS OF THE TLIKAKILA RIVER

Most of the annual runoff from the Tlikakila River occurs from about June 1 to the September 30. Whereas ground water is the only component during the winter, meltwater from ice and snow, and rainfall constitute most of the runoff during the summer season. Thus, most of the effort for this study was focused on determining the portion of runoff contributed by these components.

Glacier Mass Balance

The annual net balance for the Tanaina, Glacier Fork, and North Fork Tlikakila glaciers was determined from the change in the glacier ice surface height on the ablation stakes between June 8 and September 9, 2001. To supplement these measurements, additional locations were mapped on the North Fork Tlikakila and Tanaina glaciers to estimate the ELA. This was complicated by the presence of new fall snow at and slightly below the ELA. The ELA was estimated by landing and digging through the new fall snow to see if there was bare ice or firn under the snow and by looking in crevasses. Though less than ideal, the ELA was determined. Additionally, the new firn accumulation at one site above the ELA on the Tanaina Glacier was measured by digging a pit and coring the snow and new firn. However, this was complicated by the presence of superimposed ice and difficulty determining the summer surface.

The glacier area altitude distribution was taken from the 1957, 1:250,000 scale USGS digital elevation models. Area altitude distributions were measured separately for each of the three largest glaciers, and additionally for the entire glacier area of the basin (fig. 9). The large difference in areas makes it difficult to compare the distribution or area with altitude. However, expressed as percentages (fig. 10), the Tanaina Glacier has the greatest percentage of its area at the highest altitudes and the North Fork Tlikakila and Glacier Fork glaciers have relatively more area at lower altitudes.

Mass balance measurements were calculated at the five sites (fig. 11, table 4). The glacier wide average net balance was calculated (table 5) using the weighted index-site method (March and Trabant, 1996). To use this method it is necessary to have balance values from the accumulation zone. As noted previously, no measurements were made in the accumulation zone because measurements would be unreliable due to the late start. Because these values were not available, net balance estimates at 1,800 m altitude in the accumulation zone were made by extrapolation from lower sites by slightly flattening the gradient of balance with altitude to account for the higher albedo in the accumulation zone. Use of this procedure may result in large errors in the accumulation zone balances. For example, errors of ±0.5 m in the net balance at 1,800 m altitude generate errors of ±0.1, ±0.2, and ±0.2 m. in the glacier wide net balances for the North Fork, Glacier Fork, and Tanaina glaciers, respectively. Hence, this error alone is enough to change the sign of the net balance for all but the North Fork Glacier. The full error in the calculated glacier wide averaged balances is extremely difficult to assess, but was estimated to be ±0.4 m. The balances for the Tanaina Glacier were felt to most closely represent the entire basin because those values were intermediate between those from the North Fork Glacier and the Glacier Fork Glacier. The Tanaina Glacier balances also spanned the greatest range of altitudes. Hence, a net balance for all glaciers in the basin was calculated using the Tanaina Glacier bal-

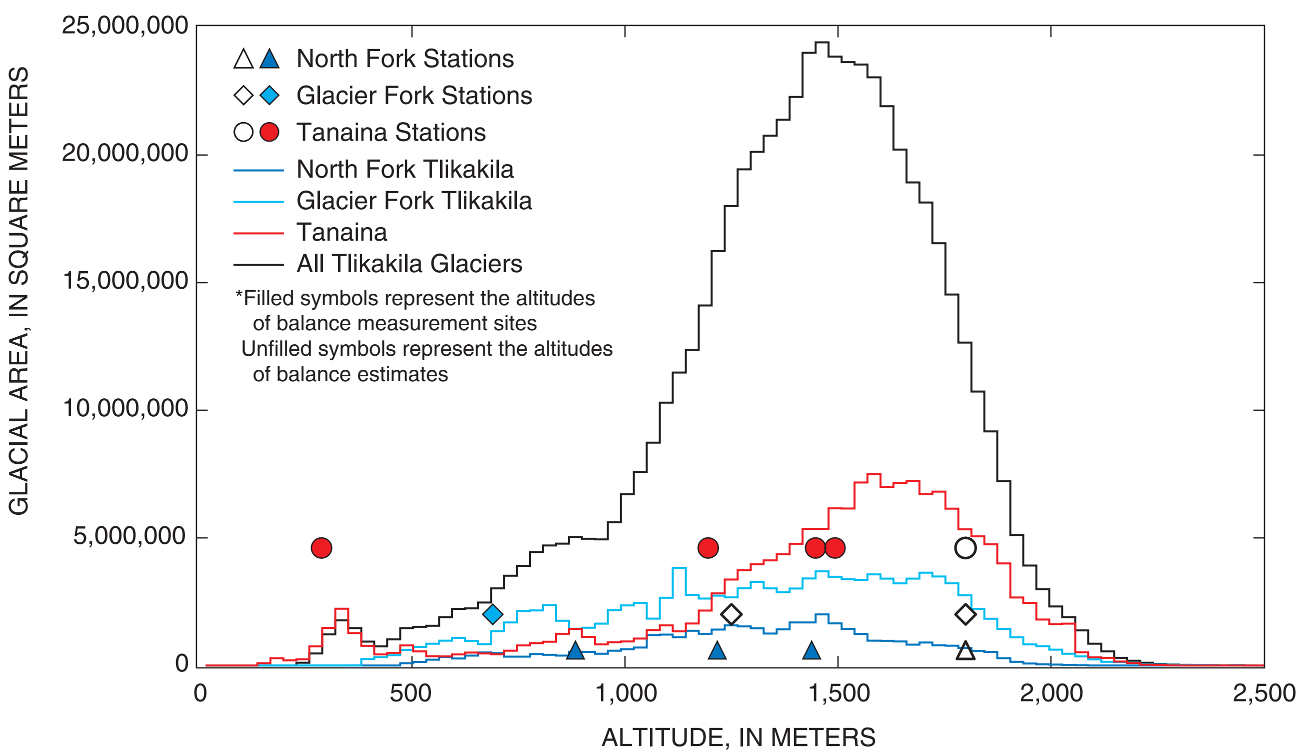


Figure 9. Glacier area-altitude distribution for glaciers in the Tlikakila River Basin.

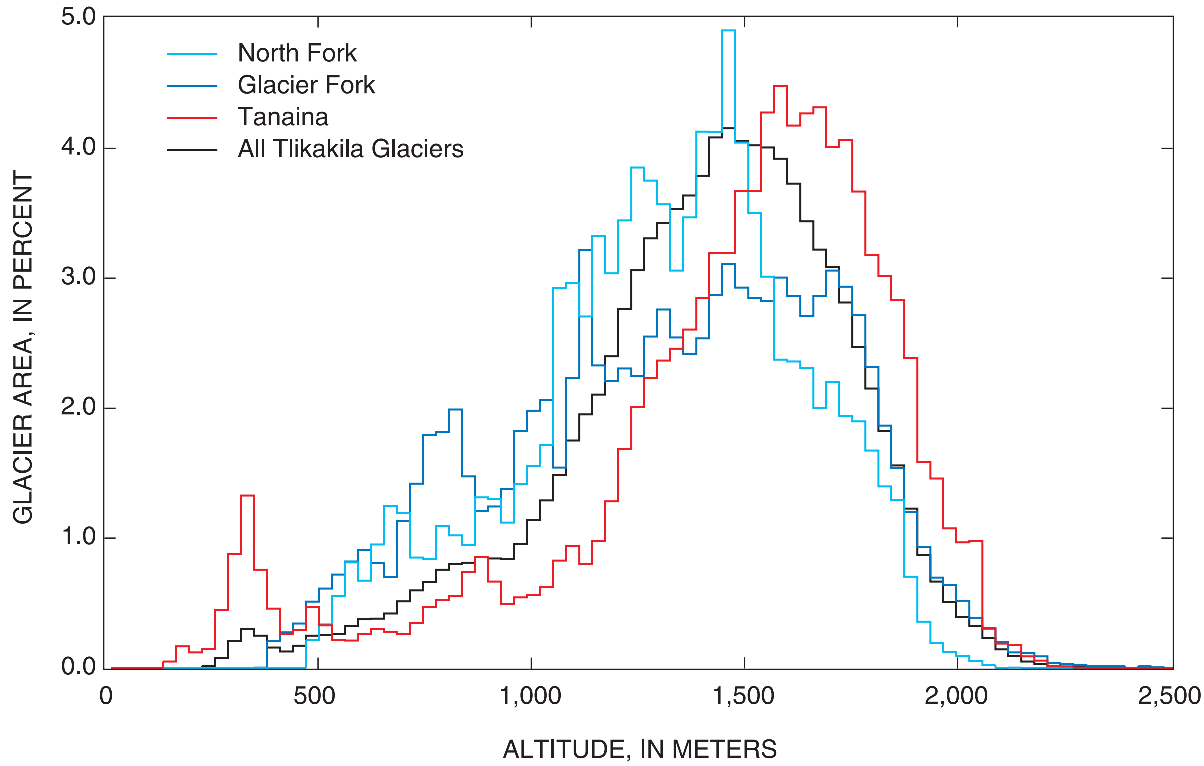


Figure 10. Glacier area-altitude distribution in percent of total area for glaciers in the Tlikakila River Basin

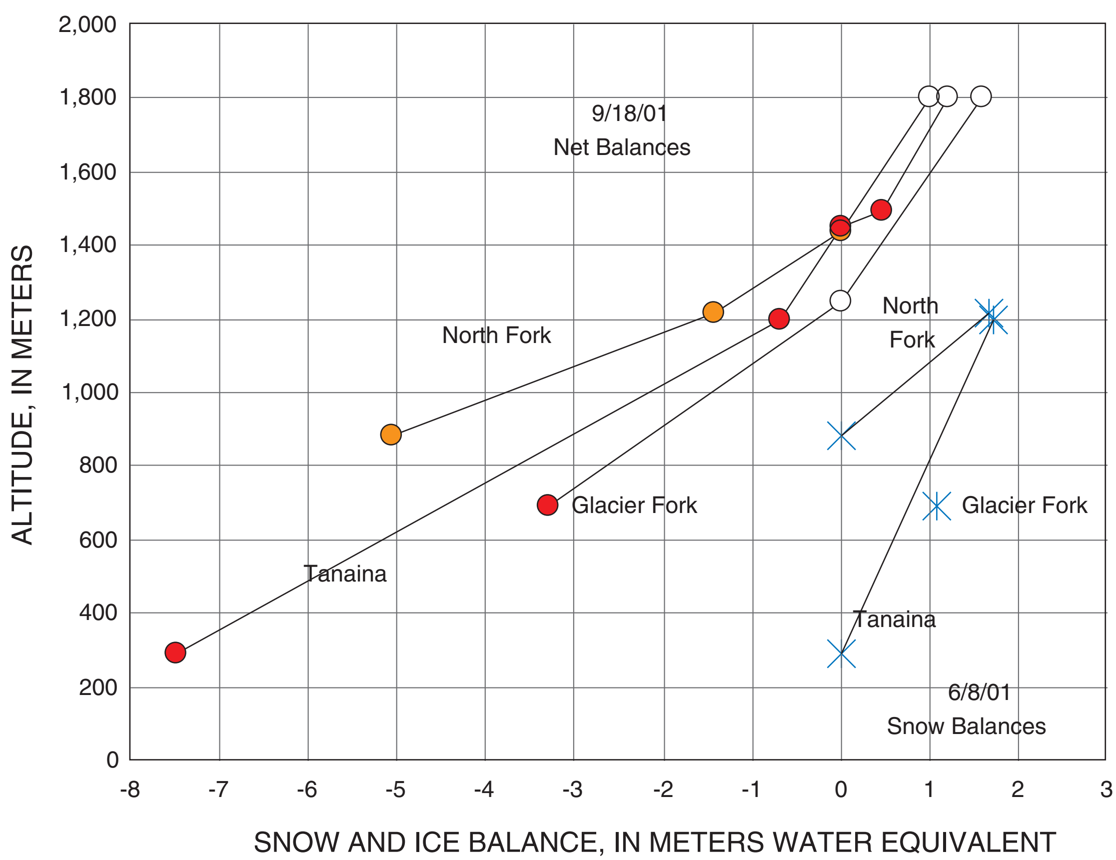


Figure 11. Snow and ice balance as a function of altitude for Tanaina, Glacier Fork, and North Fork glaciers.

Table 4. Glacier mass balance measurements for Tanaina, Glacier Fork, and North Fork Tlikakila glaciers.
[m, meters; kg/L, kilograms per liter; m_{we}, meters water equivalent; ELA, equilibrium line altitude]

Date	Location (fig. 4)	Elevation (m)	Surface strata	Snow depth (m)	Snow density (kg/L)	Snow b(s) (m_{we})	Firn b(f) (m_{we})	Ice b(I) (m_{we})	Net bn (m_{we})
				North Fork Tlikakila Glacier					
6-8-01	5	884	snow	0.00	--	0.00	0.00	--	--
9-18-01	5	884	ice	0.00	--	--	0.00	-5.06	-5.06
6-8-01	4	1,217	snow	2.66	0.63	1.66	0.00	--	--
9-18-01	4	1,217	ice	0.00	--	--	0.00	-1.43	-1.43
9-18-01	ELA	1,439	--	--	--	--	--	0.00	0.00
9-18-01	High Est	1,800	--	--	--	--	--	--	1.00
				Glacier Fork Glacier					
6-8-01	3	690	snow	1.73	0.62	1.07	0.00	--	--
9-18-01	3	690	ice	0.00	--	--	0.00	-3.29	-3.29
9-18-01	ELA	1,200	--	--	--	--	--	--	0.00
9-18-01	High Est	1,800	--	--	--	--	--	--	1.60
				Tanaina Glacier					
6-8-01	2	288	snow	0.00	--	0.00	0.00	--	--
9-18-01	2	288	ice	0.00	--	--	0.00	-7.49	-7.49
6-8-01	1	1,196	snow	3.02	0.57	1.72	0.00	--	--
9-18-01	1	1,196	ice	0.00	--	--	0.00	-0.68	-0.68
9-18-01	ELA	1,448	--	--	--	--	--	0.00	0.00
9-18-01	abv ELA	1,494	--	0.14	0.40	0.06	0.47	--	0.47
9-18-01	High est	1,800	--	--	--	--	--	--	1.20

ance values (table 5). Ablation area measurements are good on the three measured glaciers and fair over the basin. The estimated basin wide ablation was 2.9 x10^8 m^3 (table 5).

While the mass balance of each of the three glaciers was negative, there was considerable variation between the water equivalent mass balance of the North Fork Glacier (-1.15 m), and the water equivalent mass balance of Glacier Fork Glacier (-0.05 m) and Tanaina Glacier (-0.15 m). Whether or not a trend exists is difficult to assess based on one year of mass balance data. Although these mass balance calculations represent only one year, the results are consistent with the findings of the laser profiling that indicate a general loss of glacier volume.

Snowmelt and Rainfall

Snowpack measurements are made by the Natural Resource Conservation Service (NRCS) (U.S. Department of Agriculture, 2001) at a number of sites throughout Alaska. Data from these sites are then 'integrated' to develop a statewide map of snowpack (or water equivalent). For March, 2001, the time of maximum snowpack, the NRCS estimated the snowpack in the Tlikakila River Basin to be 110–130

Table 5. Glacier area, mean altitude, 2001 area altitude ratio (AAR), 2001 equilibrium line altitude (ELA), and summany of net balance calculations for the three glaciers measured in the Tlikakila River Basin and for all glaciers in the basin.
[E; estimated, --; not determined, all values in meters unless otherwise noted]

Characteristic	North Fork	Glacier Fork	Tanaina	All glaciers
Total area	4.1×10^7	1.2×10^8	1.7×10^8	5.9×10^8
Percent of all glaciers	7.0	20.2	28.5	--
Mean altitude	1,310	1,328	1,458	1,401
2001 ELA	1,439	1,250E	1,448	--
2001 AAR	0.36	0.61E	0.62	--
Measurement Elevations				
Low	884	690	288	288
Mid	1,217	--	1,196	1,196
ELA	1,439	1,250E	1,448	1,448
High Estimate	1,800E	1,800E	1,800E	1,800E
Weighting factor for each area				
Low	0.175	0.194	0.073	0.041
Mid	0.313	--	0.171	0.284
ELA	0.326	0.437	0.327	0.386
High	0.186	0.369	0.429	0.289
Measured winter balance on June 8, 2001				
Low	0.00	1.07	0.00	0.00
Mid	1.66	--	1.72	1.72
ELA estimate	1.66E	1.72E	1.72E	1.72E
High estimate	1.66E	1.72E	1.72E	1.72E
Whole glacier estimate	1.37E	1.59E	1.60E	1.65E
Snow melt (water equivalent)				
Low	0.00E	--	0.00E	0.00E
Mid	-1.66E	--	-1.72E	-1.72E
ELA estimate	-1.66E	--	-1.72E	-1.72E
High estimate	-0.66E	--	-0.52E	-0.52
Whole glacier estimate	-1.19E	--	-1.08E	-1.30E
Net Balance (meters water equivalent)				
Low	-5.06	-3.29	-7.49	-7.49
Mid	-1.43	--	-0.68	-0.68
ELA	0.00	0.00	0.00	0.00
High	1.00	1.60	1.20	1.20
Whole glacier	-1.15	-0.05	-0.15	-0.15
Net Balance, in cubic meters	-4.7×10^7	-5.6×10^6	-2.5×10^7	-8.9×10^7
Ablation, in cubic meters	-5.4×10^7	-7.6×10^7	-1.1×10^8	-2.9×10^8

percent of average. On June 8, 2001, snow depth measured on the three major glaciers was 1.7 m at 690 m altitude on the Glacier Fork Glacier, 2.7 m at 1,217 m altitude on the North Fork Glacier, and 3.0 m at 1,196 m altitude on the Tanaina Glacier (table 4). The higher snowpacks were found at the higher elevations. Snow density at the time of measurement in June was fairly uniform, ranging from 0.57 kg/L to 0.63 kg/L (table 4). Snowmelt was estimated to be 4.8 x 10^7 m^3 (water equivalent) for the North Fork Glacier and 1.8 x 10^8 m^3 (water equivalent) for the Tanaina Glacier. No estimate of snowmelt was made for the Glacier Fork Glacier because the June snow balance was only measured at one site at a relatively low altitude.

Precipitation as rainfall during the summer runoff season of 2001 (June through September) measured at two locations—Port Alsworth at 82 m altitude (fig. 2) and a site at 1,265 m altitude adjacent to the Tanaina Glacier (fig. 4)—varied considerably (table 6). Rainfall measured at Port Alsworth totaled 174 mm (6.84 in.), whereas rainfall measured on the Tanaina Glacier totaled 304 mm (11.98 in.), about 75 percent greater than Port Alsworth. The largest differences in rainfall between these two sites occurred in August, when 64 mm (2.51 in.) was measured at Port Alsworth and 203 mm (8.0 in.) was measured on the Tanaina Glacier. Averaging the rainfall amounts at these two sites we estimated 239 mm (9.41 in) for the Tlikakila River Basin in 2001.

Table 6. Precipitation as rainfall measured in 2001 at Port Alsworth, Alaska and at a location on the Tanaina Glacier.
[m, meter; mm, millimeter; in., inch]

Month	Port Alsworth (82 m altitude)		Tanaina Glacier (1,265 m altitude)		Average	
	mm	in.	mm	in.	mm	in.
June	5	0.20	5	0.20	5	0.20
July	79	3.12	53	2.10	66	2.61
August	64	2.51	203	8.00	134	5.26
September	26	1.01	43	1.68	34	1.34
Total	174	6.84	304	11.98	239	9.41

Ground Water

Typical of a glacier-fed river, flow in the Tlikakila River is low or near zero during the winter months. During that period, surface runoff does not occur and flow in the Tlikakila River is derived from ground water. However, studies in other rivers in Alaska (Finn and others, 1998, written communication; Maclean, 2003) have shown the importance of ground water during the winter period in providing suitable habitat for juvenile salmon survival. Thus, discharge measurements and basic water-quality information were collected at six sites September 17, 2001 (fig. 3, table 7) and at seven sites April 3, 2002 (fig. 3, table 8) in the Tlikakila River Basin in order to better understand the ground-water characteristics of the Tlikakila River Basin.

Due to late-fall precipitation, flow conditions for September 17, 2001 were not representative of low flow, but still provide information regarding the water quality of the major tributaries and along the Tlikakila River from the headwaters to the mouth. Water quality remained unchanged throughout the length of the Tlikakila River. Slight differences were noted in water temperature from the headwaters to the mouth, reflecting the input of colder water from the glacier fed Glacier Fork and North Fork Rivers. The water type was calcium bicarbonate, both along the mainstem of the river, and from the two major tributaries. Only field parameters and two discharge measurements were measured April 3, 2002 (table 8). These sites were located downstream of the North Fork Tlikakila River and were at open leads (ice-free sections of the river) (fig. 3). No open leads were seen above the North Fork. Based on the two measurements made at Sites 1 and 7, flow gradually increased in the lower section of the Tlikakila River and probably reflected ground-water inflow between these two sites. The most notable feature of this section of the river was the presence of numerous open leads with water temperatures above 0.0°C that indicated favorable conditions for juvenile salmon. Further evidence of ground-water conditions conducive to juvenile salmon is a fish tracking study conducted by Lake Clark National Park and Preserve in September 2001 that found 51 tagged fish (21 percent of all fish tracked to spawning areas in Lake Clark) returned to the Tlikakila River. Most of

Table 7. Physical properties and water-quality constituents of streamflow samples collected from six sites in the Tlikakila River Basin, September 17, 2001

[water-quality constituents in mg/L; mS/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius]

Site number (figure 3)	Station Name	Dissolved Oxygen	pH (units)	Specific Conductance (mS/cm)	Water Temperature (°C)	Calcium
6	Tlikakila River near Summit Lake	12.1	7.2	58	6.0	8.2
7	Glacier Fork near Summit Lake	12.2	7.4	59	5.3	8.4
8	Tlikakila River above North Fork Tlikakila	12.7	7.0	47	4.7	7.3
9	North Fork Tlikakila River	12.6	6.8	46	4.8	6.5
10	Tlikakila River 12 miles above mouth	12.3	7.1	54	5.8	7.8
11	Tlikakila River at mouth	12.1	7.1	60	7.1	--

Site number (figure 3)	Station Name	Magnesium	Potassium	Sodium	Alkalinity	Bicarbonate
6	Tlikakila River near Summit Lake	0.4	1.4	0.8	19	25
7	Glacier Fork near Summit Lake	0.5	1.3	0.7	20	22
8	Tlikakila River above North Fork Tlikakila	0.5	1.2	0.8	19	22
9	North Fork Tlikakila River	0.6	1.0	0.7	17	21
10	Tlikakila River 12 miles above mouth	0.6	1.2	0.9	21	23
11	Tlikakila River at mouth	--	--	--	--	--

Site number (figure 3)	Station Name	Chloride	Fluoride	Silica	Sulfate	Dissolved Solids
6	Tlikakila River near Summit Lake	0.32	<0.2	3.2	5.1	29
7	Glacier Fork near Summit Lake	0.23	<0.2	6.9	6.9	56
8	Tlikakila River above North Fork Tlikakila	0.36	<0.2	3.7	4.9	30
9	North Fork Tlikakila River	0.33	<0.2	3.6	4.7	29
10	Tlikakila River 12 miles above mouth	0.49	<0.2	4.3	5.1--	35
11	Tlikakila River at mouth	--	--	--		--

Site number (figure 3)	Station Name	Iron	Manganese	$^{2}H/^{1}H$ stable isotope ratio	$^{18}O/^{16}O$ stable isotope ratio
6	Tlikakila River near Summit Lake	42	12.0	-146	-19.2
7	Glacier Fork near Summit Lake	32	3.3	-147	-19.6
8	Tlikakila River above North Fork Tlikakila	33	5.8	-146	-19.4
9	North Fork Tlikakila River	33	3.2	-147	-19.4
10	Tlikakila River 12 miles above mouth	27	4.9	-144	-19.2
11	Tlikakila River at mouth	--	--	-142	-19.0

these fished spawned in the stretch from Otter Lake to Moose Pasture Pass (fig. 12). Based on the locations of the tagged fish and the field measurements made April 3, 2002, the lower stretch of the of the Tlikakila River from Moose Pasture Pass to Otter Lake is probably ground-water fed and is conducive to juvenile salmon survival.

Continuous flow record was collected on the Tlikakila River (USGS station ID 15297970) from

Table 8. Physical properties of streamflow samples collected from seven sites in the Tlikakila River Basin, April 3, 2002
[m^3/s, cubic meters per second; mg/L, milligrams per liter; ms/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius; --, not measured]

Site	Map number (figure 3)	Discharge (m^3/s)	Dissolved oxygen (mg/L)	pH (units)	Specific conductance (ms/cm)	Water temperature (°C)
604009153085800	12	1.5	15.0	7.2	90	1.1
603614153262000	13	--	15.0	7.1	100	0.5
603237153311400	14	--	15.0	7.0	98	0.6
603053153362000	15	--	15.0	6.9	87	1.7
603013153383700	16	--	14.9	6.9	96	0.2
602801153471400	17	--	15.0	6.9	99	0.2
602536153465400	18	2.2	14.9	6.8	109	0.3

1999-2001 only during the open water period (mid May through September). During this period, flow was dominated by surface runoff and it was difficult to separate the ground-water component. However, some winter and spring discharge measurements were made that provided some range in ground-water flow. Measured discharges near the gaging station ranged from 0.7 m^3/s (25 ft^3/s) in March 1999, to 2.2 m^3/s (79 ft^3/s) in April 2002. Based on these flow measurements, the ground-water component of the Tlikakila River was estimated to be 2.8 m^3/s (100 ft^3/s).

Streamflow

Hydrographs of the Tlikakila River (USGS station number 15297970) (July 15-31, 2001) illustrate the flow characteristics (fig. 13). Distinct diurnal fluctuations can be seen. The low flow of the day usually occurs in the early morning, and the flows peak at about midday. This reflects a time lag between melting of snow and ice and the arrival of the resulting meltwater at the streamflow gaging site. Most of the annual flow of the Tlikakila River is during June to September (fig. 14). Rising temperatures in May initiate snowmelt and consequent runoff throughout the basin, and near the end of June the melt increases to a maximum. Annual peaks in streamflow are in July and August due to glacial melt or storm runoff. Streamflow declines during September as air temperatures cool, and snowmelt and icemelt decrease. Occasional peaks are due to storms in late fall. Flow in June is dominated by snowmelt, and in July through August, by glacier ice melt and rainfall. Runoff from June 1 to September 30 during 2001 totaled 1.70 m (65.4 in.). Average discharge for this period was 244 m^3/s (8,600 ft^3/s).

The hydrologic balance, which is the difference between inflow (glacier ice melt, snowmelt, rainfall, and ground water) and outflow (runoff measured at the gaging station) was determined for the Tlikakila River Basin for the 2001 water year (table 9). This balance was based on the following assumptions:

1) The discharge measured at the gaging station was considered to be the most accurately measured of the variables.

2) A ground-water component of 0.01 m was used in the balance calculations.

3) All icemelt from the glaciers became runoff that was measured as discharge at the gaging station.

4) All precipitation as rainfall became runoff at the gaging station. Average rainfall across the basin is average of that at Port Alsworth and Tanaina Glacier site.

5) The amount of snowmelt that becomes runoff at the gaging station is the least accurate variable. This component was computed by subtracting the amount of ice melt, rainfall, and ground water from the total runoff measured at the gaging station.

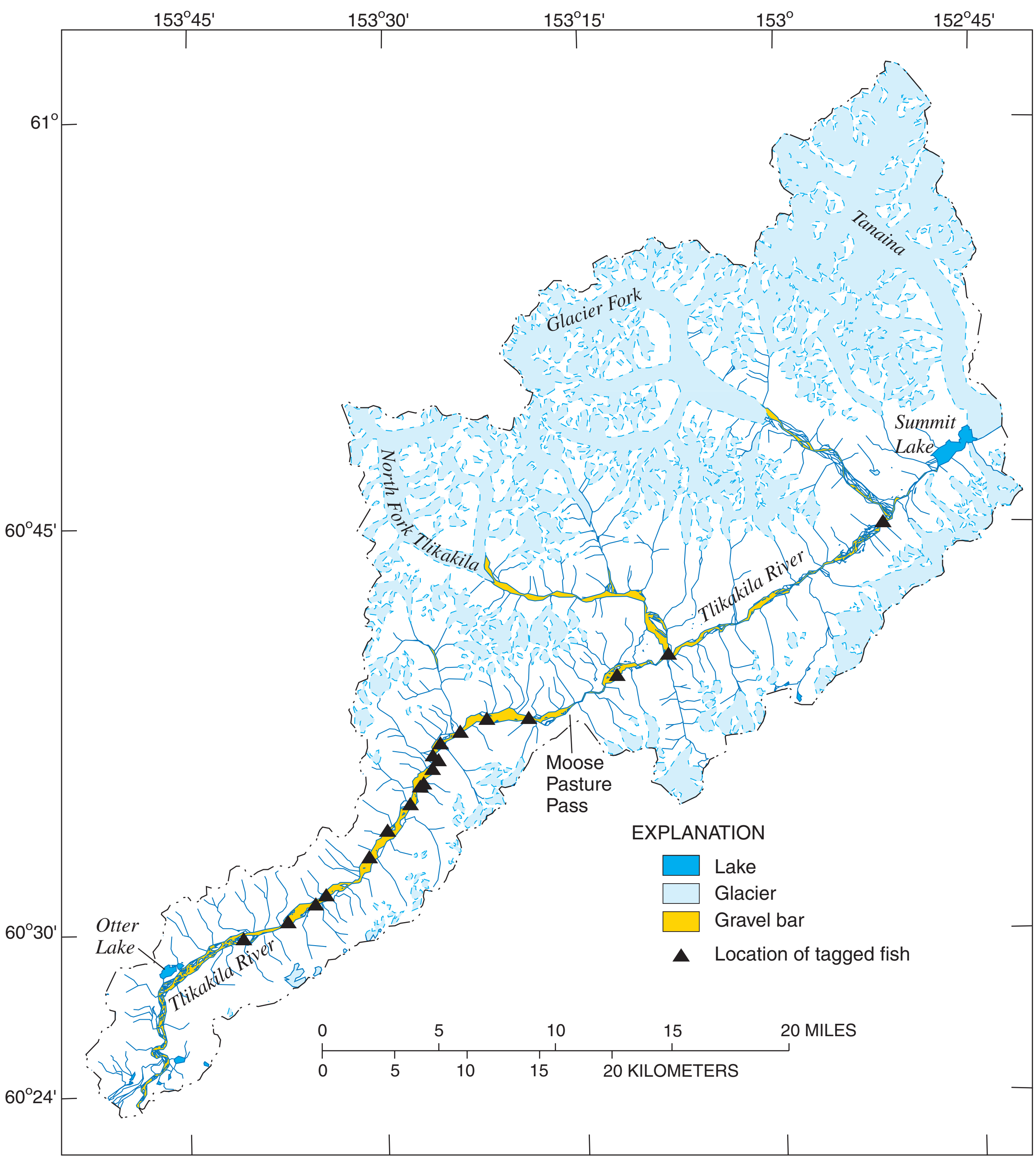


Figure 12. Location of tagged fish in the Tlikakila River Basin, September 2001

The hydrologic balance of the Tlikakila River Basin indicated that glacier icemelt contributes 11 percent of the flow in Tlikakila River. Snowmelt and rainfall account for 89 percent of the runoff. Although the estimate for icemelt runoff is considered to be fairly accurate, the estimates for snowmelt and rainfall runoff are considered to be quite variable. The reasons for this variability are: (1) the lack of detailed snowmelt and rainfall data for both basins and (2) the difficulty in determining the quantity of snowmelt and rainfall that actually becomes runoff.

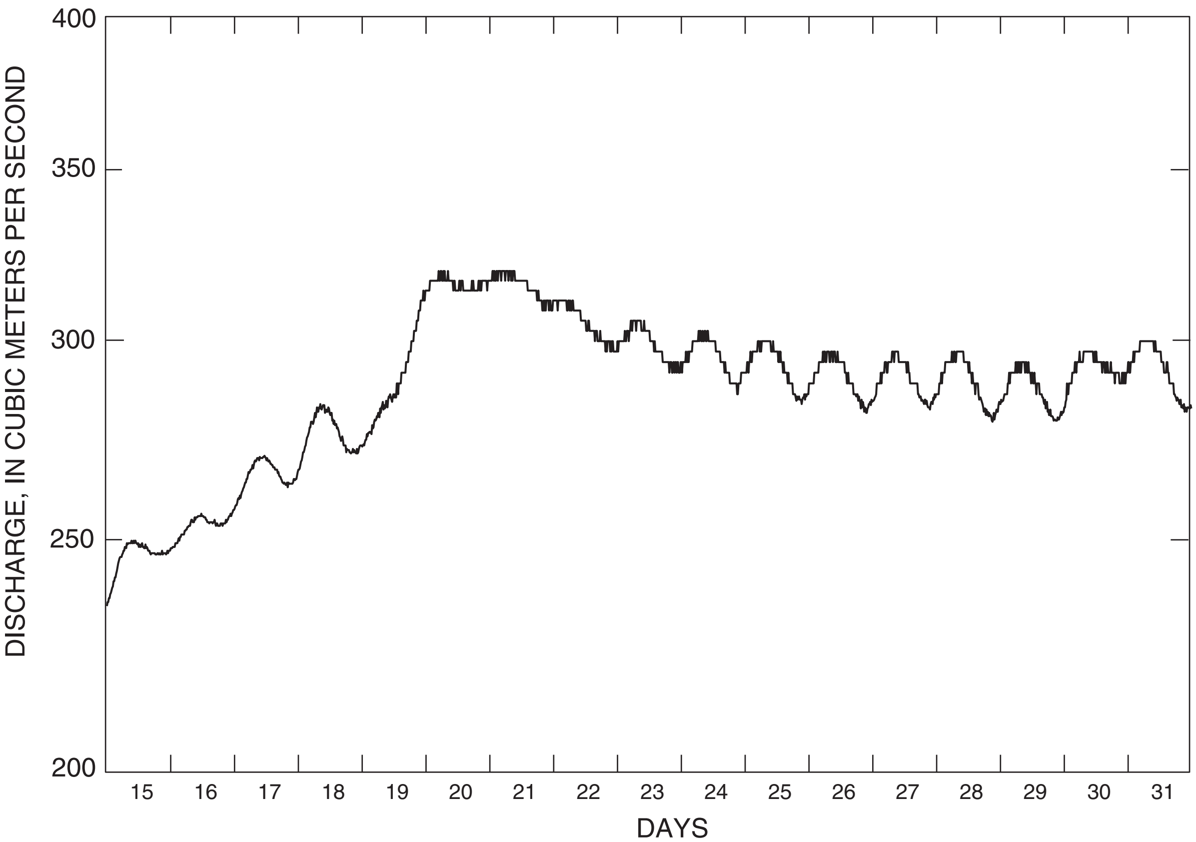


Figure 13. Discharge for the Tlikakila River, July 15-31, 2001

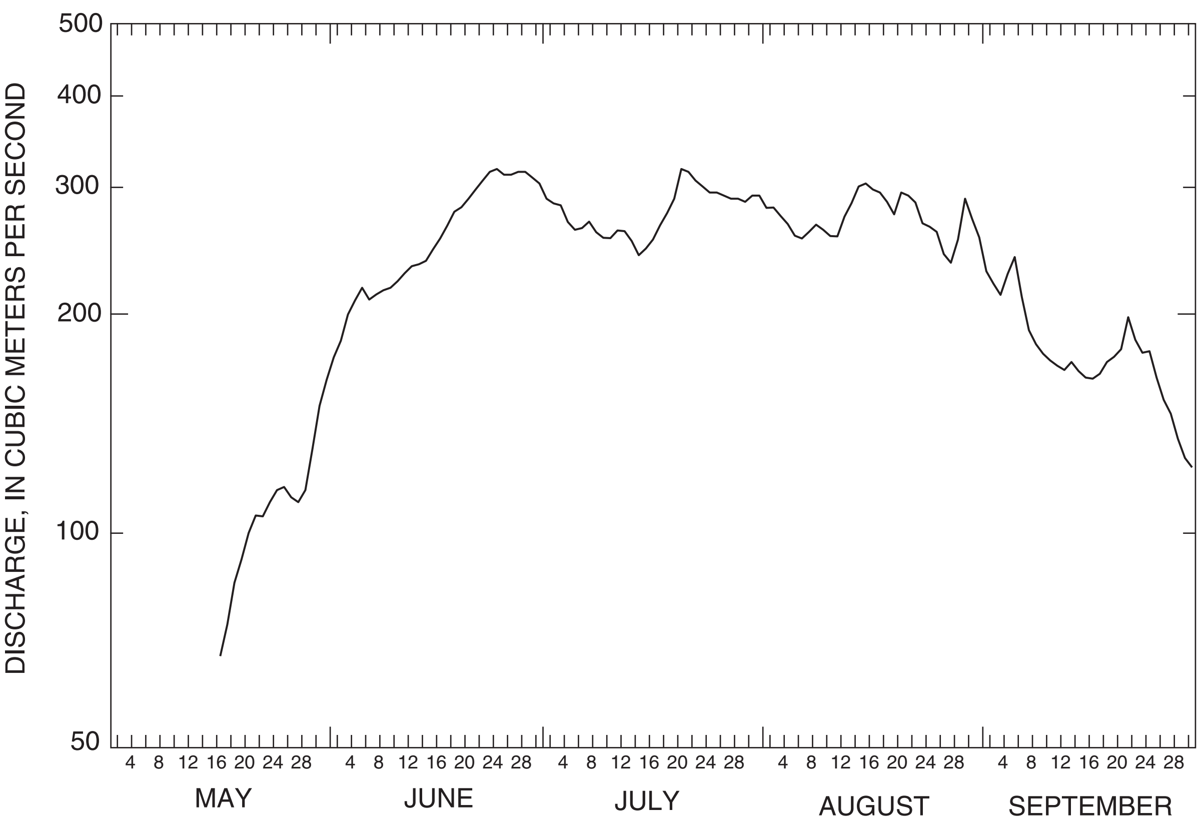


Figure 14. Discharge for the Tlikakila River, May through September 2001.

Table 9. Runoff components of the Tlikakila River, 2001.
[m, meters; m^3/s, cubic meters per second]

Runoff Component	Amount (m)	Percent of runoff	Remarks
Icemelt	0.18	10	Assumed all icemelt becomes runoff, estimated error - 0.5 m
Snowmelt	1.27	75	Least accurate variable, calculated, estimated error - 0.7 m
Rainfall	0.24	14	Assumed all rainfall becomes runoff, estimated error - 0.5 m
Groundwater	0.01	1	Assumes a baseflow component of 2.8 m^3/s (100 ft^3/s)
Total	1.70	100	Measured at gaging station, estimated error - 0.2 m

SUMMARY AND CONCLUSIONS

The Tlikakila River is located in Lake Clark National Park and Preserve approximately 160 km (100 mi) southwest of Anchorage, Alaska. Approximately one-third of the basin consists of glaciers and the runoff from this river accounts for approximately one-half the inflow into Lake Clark. As part of a cooperative study with the National Park Service, this basin was studied during the 2001 and 2002 water years to determine glacier changes, to determine its runoff components, and document springs or ground-water inflow along the Tlikakila River.

1) The termini of most glaciers in the Tlikakila River Basin have retreated from 1957 to the present. Airborne laser profiling indicates a loss in volume of the three main glaciers in the basin (Tanaina, Glacier Fork, and North Fork) ranging from 1.7 x 10^9 to 6.1 x 10^9 cubic meters from 1957–2001. The retreat and thinning of the glaciers may be partially attributed to the positive shift in the Pacific Decadal Oscillation (PDO) index from 1977 to 1998.

2) Mass balance measurements on the three main glaciers in the Tlikakila River Basin were made in the 2001 water year. The Tanaina, Glacier Fork, and North Fork glaciers all had negative mass balances ranging from 5.6 x 10^6 to 4.7 x 10^7 cubic meters and the mass balance for all glaciers was computed to be 8.9 x 10^7 cubic meters. Ablation ranged from 5.4 x 10^7 to 1.11 x 10^8 cubic meters for the three main glaciers and 2.9 x 10^8 cubic meters for all glaciers in the Tlikakila River Basin. Negative mass balance in 2001 augmented streamflow by 4 percent compared to what it would have been if the glacier had been in balance in 2001. This is slightly less than the long-term contribution.

3) For the 2001 water year, runoff measured at a streamgage near the mouth of the Tlikakila River was 1.70 meters. Of this total 0.18 meters (11 percent) was from glacier ice melt, 1.27 meters (75 percent) was from snowmelt, 0.24 meters (14 percent) from rainfall, and 0.01 meters (1 percent) from ground water. Snowmelt is the most difficult component to measure and has an estimated error of 0.7 meters.

4) Although ground water is only a small component of runoff to the Tlikakila River, it provides a critical source of relatively warm water for fish survival. Based on flow, water quality, and tagged fish data, the lower stretch of the Tlikakila River is a gaining reach of warm water of good quality that enhances fish survival.

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Brabets and others—**Glacial history and runoff components of the Tlikakila River Basin, Lake Clark National Park and Preserve, Alaska**—Scientific Investigation Report 2004-5057

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