An Investigation of Glacial Outburst Floods from Abyss Lake, Glacier Bay National Park, Alaska

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Technical Report NPS/NRWRD/NRTR-2003/312

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Introduction

Glacier Bay National Park (GLBA) is one of the nation's largest National Park units, comprising over 13,000 square kilometers (3.2 million acres). Located in southeast Alaska about 95 kilometers (60 miles) west of Juneau, the park has a climate dominated by its proximity to the ocean. Precipitation can exceed 450 cm (180 in) per year, sustaining dense rainforests at low elevations and ice fields and glaciers at higher elevations. West of Glacier Bay the Brady Glacier flows southward from the Fairweather Mountains. One arm of this glacier blocks an un-named tributary valley, creating a glacial lake (Map 1). Called Abyss Lake, it is prone to glacial outburst floods, which usually flow into the West Branch of the Oscar River (Map 2). This paper summarizes fieldwork by National Park Service (NPS) staff in 1997 and 2001; estimates the peak flow of the 1997 outburst flood using a slope-area computation; compares the result with other flow estimation methods; and examines the recurrence interval for such large outburst floods using aerial photographs and tree ring data.

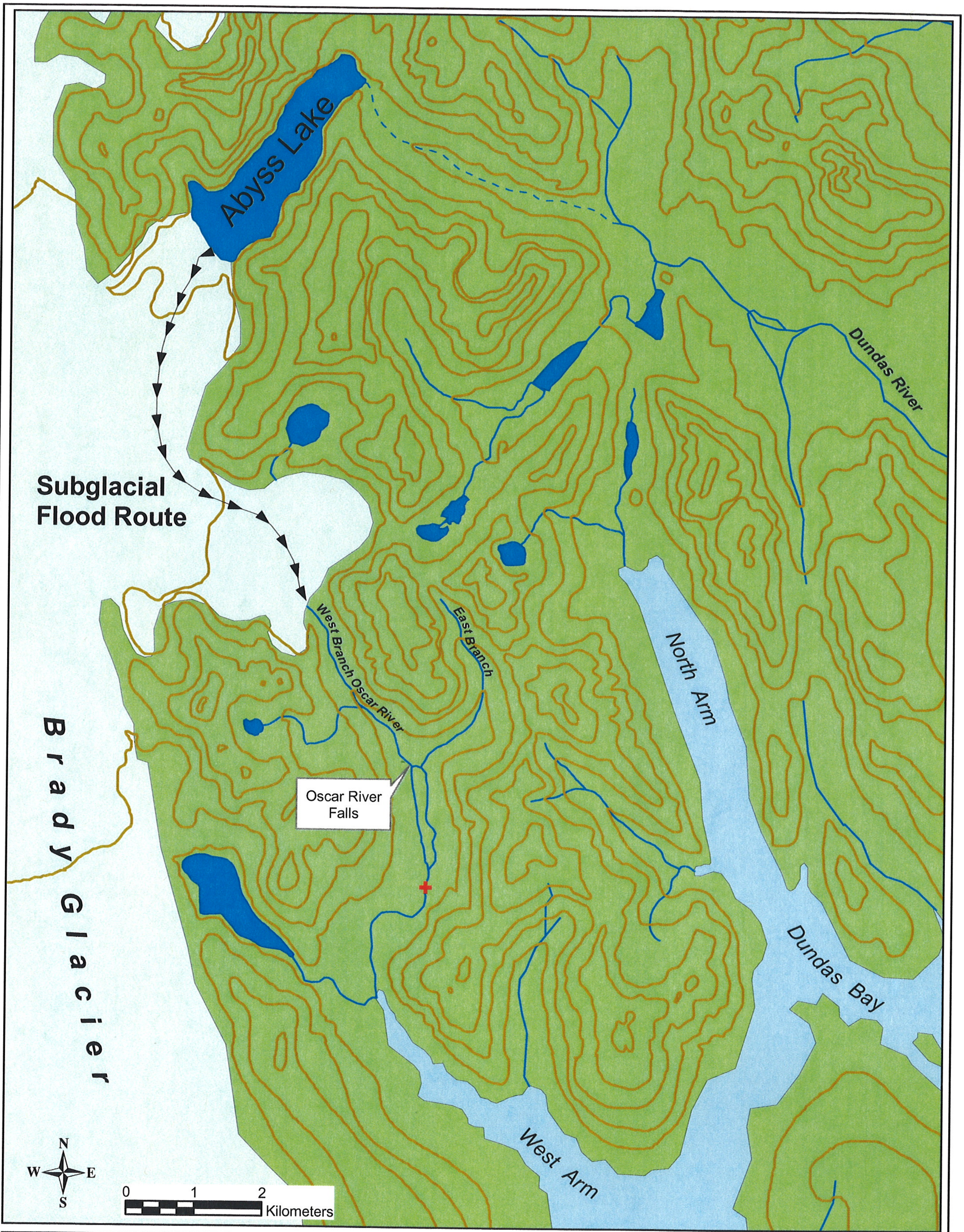
Background

Southeast Alaska has one of highest concentrations of glacial lakes in the world (Stone, 1963). A glacial lake is formed when an arm of a glacier extends from the main trunk into a tributary valley, creating a dam of ice. Water may flow into or under the ice to some extent, but it is very common for the blockage to be so complete that water accumulates behind the ice dam, creating a glacial lake.

Glacial ice dams which form glacial lakes can be breached in several ways and are subject to repeated failure (Post and Mayo, 1971). Often, these failures are catastrophic, releasing vast amounts of water in short spans of time. Such an event has several names: GLOFs (Glacial Outburst Flood), jökulhlaup (an Icelandic term), or simply "outburst flood." The actual processes which cause glacial outburst floods are still subject to controversy. Study of the processes and events is hampered by extreme climate, topography, relative event infrequency, danger and expense of safely exploring the ice, inability to see through the ice, and accessibility problems due to topography and dense vegetation.

A few theories concerning release initiation have been put forth. Thorarinsson (1939) outlined a relationship between water depth in a glacial lake and height of its ice dam. He stated that due to density differences the ice dam would begin to float when the lake reached a certain critical depth–about 90% of the dam height. This would allow for water to escape subglacially (under the ice) or laterally (through gaps between the ice dam and adjacent rock walls). Conversely, Whalley (1971) states that it is simply changes within the internal drainage system of the trunk glacier that allow for the initiation of flow. Liestol (1955) states that regardless of the mechanics of the initial flows the escape route becomes exponentially larger with time. His

Map 1: Southwestern Region of Glacier Bay National Park



Legend

Lakes	Streams & Rivers
Ice Field / Glacier	Lake Overflow - Intermittent
Cross Section Location	500 ft Elevation Contour

Map 2:
Outburst Flood Route via West Branch Oscar River

calculations show that "water at 1 degree C and flowing at only 1 m^3/sec can theoretically melt over 270 m^3 of ice in 24 hours." In essence, the flowing water melts the constricting ice, allowing more water to flow. The increased flow, in turn, melts additional ice, and flow increases accordingly. This melting process continues until the glacial lake is drained or a resistant base level is reached.

Abyss Lake is located in the southwest region of GLBA (Photographs 1 and 2). Actual lake depth is estimated at 200-300 m–based on the slope of adjacent valley walls and assuming the bottom of the valley has the typical u-shape of a glaciated valley.

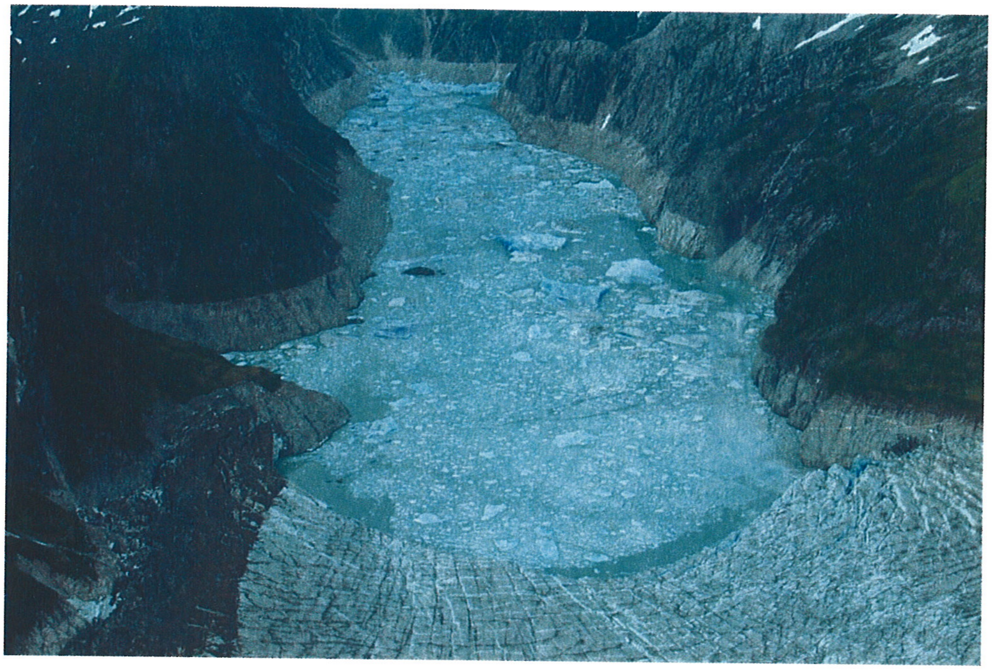
The only known records of outburst floods from Abyss Lake have been kept by GLBA staff. These records list floods of unknown magnitudes occurring in 1994, 1997, 1998, and 2000 (Soiseth, 1997-2002). During these floods, a large portion of Abyss Lake drained via the West Branch of the Oscar River (Map 2). Flood magnitudes probably varied, but the time of release was relatively consistent–late summer or early fall. The volumes drained and the peak discharges were probably functions of ice-margin fluctuations, rates of lake filling, water temperatures, and alterations of the subglacial and englacial passages (Russell, 1989).

Ordinarily, drainage from the Abyss Lake valley would flow southwest into Taylor Bay via the valley in which the Brady Glacier resides. However, the presence of the Brady Glacier, or a sub-glacial lateral moraine, appears to act as a diversion to water flowing from the lake, sending it instead southeast down the West Branch of the Oscar River into the West Arm of Dundas Bay. When lake levels are very high, indicating a very effective ice dam, water flows from the eastern end of Abyss Lake (opposite end from the ice dam) into the West Branch of the Dundas River and, eventually, into the eastern arm of Dundas Bay (photograph 3).

1997 Survey

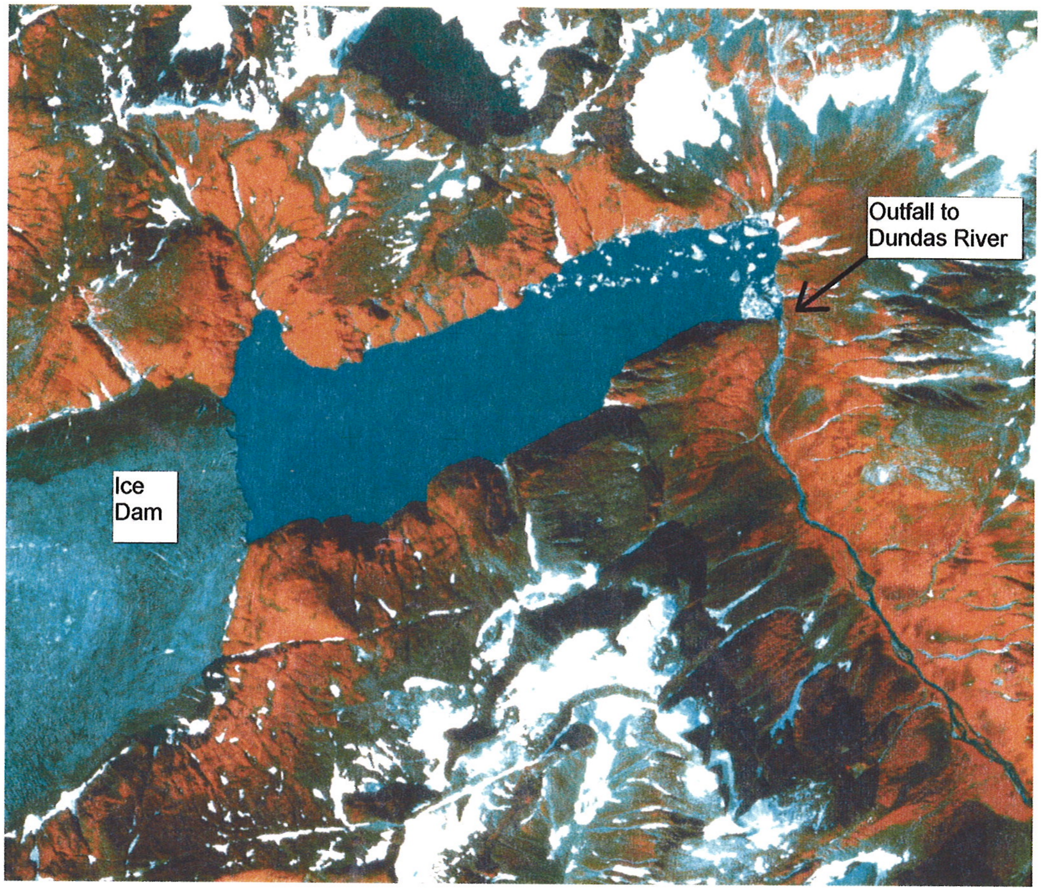
In September 1997, GLBA staff (Grover, Eichenlaub, Soiseth, Van Leeuwen, Yerxa, Borson) conducted a survey of the Abyss Lake area following an outburst flood from the lake (Grover, 1997). This investigation found that drainage from the east end of the lake down the West Branch of the Dundas River is the exception rather than the rule for Abyss Lake drainage. The West Branch of the Dundas River channel was well defined, but vegetation and debris within the channel indicated that flows have been relatively infrequent. Most aerial photographs (Photograph 4) show the lake level to be consistantly below the outfall lip of the West Branch of the Dundas River. Thus, contrary to the USGS and National Geographic maps published for the area, the West Branch of the Dundas River flows intermittently.

Data from the 1997 investigation shows that the outburst flood caused the lake level to drop 77 m (250 ft). Distances were measured from the debris/strand line to the existing water surface. This flood released approximately 130,000,000 m^3 of water

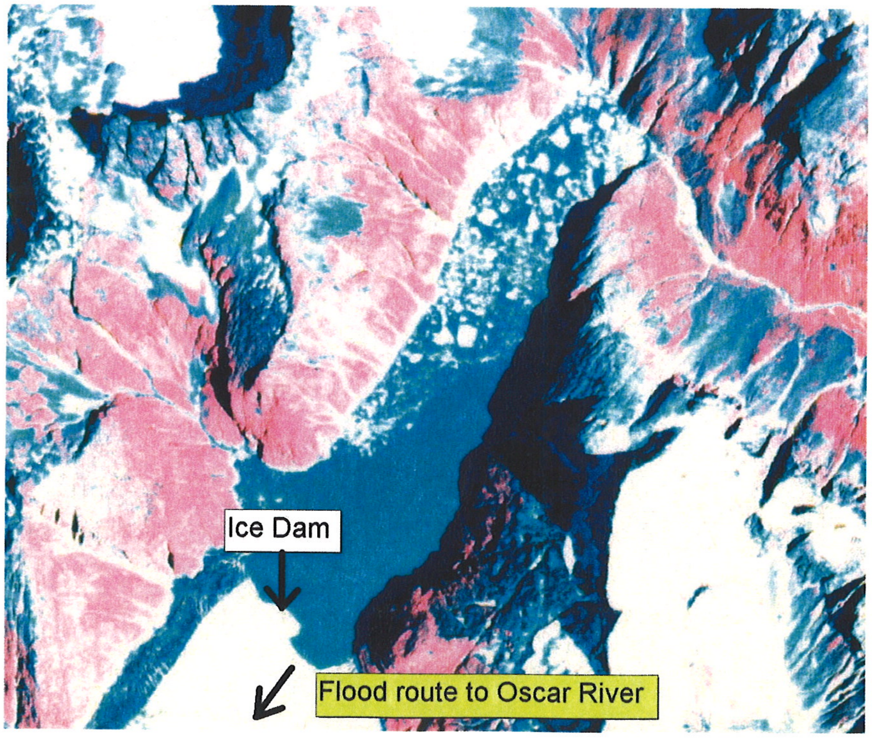


Photograph 1: Oblique low-altitude aerial view of Abyss Lake. Photo taken on August 23, 2001 following a flood event during the previous week. Ice dam with stress fractures is visible in foreground. Ice burgs are created when the ice dam collapses – presumably collapsing occurs when water supporting the ice drains away during flood event. Water surface is estimated to be 45 m (150 ft.) below the high water line. Photo by Rusty Yerxa.

Photograph 2: View of Abyss lake taken from Dundas River outfall, and looking towards Brady Glacier and ice dam. Photo taken in October 1997, about two months after the large outburst flood. Note the stranded ice burg at the right edge of the photo. Distance from the all-time high water line to water surface measured as 87 m (285 ft). Water level drop resulting from the 1997 outburst flood measured as 77m (250 ft). Distance to ice dam is about 3.25 km (2 mi). Photo by Scott Grover.



Photograph 3: High Altitude color infrared image of Abyss Lake taken in 1979. Vegetation appears as red, ice as white or grey, and water as blue. In this image the lake water level is very high, and water is draining via the Dundas River. Outburst floods occur when water drains under the ice dam and into the West Branch of the Oscar River (not shown). USFS / NPS photograph.



Photograph 4: High altitude color infrared image of Abyss Lake taken in 1996. Note that the lake level is moderately high, but insufficient for flow to enter the Dundas River. Subglacial flood route is marked. USFS / NPS photograph.

(105,000 acre-feet). Also, the 1997 data led to a calculation of the peak flood flow of the Oscar River of just over 2200 m^3/sec (77,700 ft^3/s). This estimate was made using channel cross-section survey data, an estimate of bed roughness, and Manning's equation for steady flow (a slope-area measurement).

2001 Return Visit

In August 2001, Abyss Lake again released an outburst flood. Coincidentally, a second visit to the area had already been planned for September 2001. During this visit, NPS staff had planned to conduct a more detailed survey of the 1997 peak flow using more precise survey equipment and better flow estimation methods. The team of Chad Soiseth and Dan VanLeeuwen, both of GLBA, and the author, now with the Water Resources Division of NPS, arrived at the West Arm of Dundas Bay on September 4, 2001, and began the hike up the Oscar River toward the Brady Glacier. Unfortunately, a low-pressure system also arrived in SE Alaska on this date, bringing heavy rains. In September 1997, the hike to the glacier had been simplified by using the dry overflow channels of the West Branch of the Oscar River. In September 2001, however, these channels were flowing full with swift, silty water (Photograph 6). Hiking was confined to the steep, western bank of the lower Oscar River, and progress was slow. Eventually, heavy rain made it unsafe to cross any stream, and all progress stopped.

The team retreated to lower, more moderate terrain and surveyed a river cross-section from the right bank (Map 2), using a Leica laser rangefinder. Unable to ford the river, the team estimated the main channel thalweg (deepest part) water depth based on adjacent bank slopes. Distance to the left bank high-water mark (HWM) was measured with the electronic rangefinder. (Note: While the 2001 survey was not as detailed as initially hoped, the team believes that the electronic data from this lower reach is a significant improvement over the data from the 1997 survey).

The surveyed cross-section was used to compute a cross sectional area (A) of the channel, to calculate the wetted perimeter (W_p), and thus to determine the hydraulic radius (r):

$$r = A/W_p$$

These values were used in the Manning-Chezy formula (Hewlett, 1982) to compute streamflow at peak flow:

$$Q = (1/n)(A)(r^{2/3})(s^{1/2})$$

where Q is flow (in m^3/second), s is slope, and n is a roughness coefficient. The roughness coefficient was used to factor in the effect of friction between the flowing water and the channel. The value of n was calculated using Arcement and Schneider (1989). Unlike the 1997 survey, which used a single cross-section, the

2001 survey was divided into four sub-sections (based on channel characteristics) to better estimate flow.

Results

The 2001 survey results for the 1997 outburst flood peak are displayed in Figure 1 as a cross-sectional profile of the Oscar River study reach. Figure 1 also delineates the four sub-sections. Table 1 shows how Manning's n value and other values used in Manning's equation were computed for each sub-section.

Based on analysis of the 2001 survey data, the 1997 flood peak flow was estimated at 2480 m^3/sec (87500 ft^3/sec). For comparison, the 1997 survey data lead to a calculated peak flow of 2200 m^3/sec (77700 ft^3/sec) for the same event. Due to improved survey methods, the higher figure of 2480 m^3/sec is considered more accurate.

The 2001 survey site was about 1.6 km (one mile) downstream of the 1997 survey site, which increases the drainage area by about 11.6 km^2 (4.5 mi^2). An increase in the drainage area typically increases the volume of streamflow. To quantitatively compare these two estimates, the expected increase in discharge due to the increase in drainage area was estimated as follows: the period of record average delivery ratio of two nearby streams[1] for August and September was about 11 ft^3/sec per $mi.^2$ Thus, it was expected that the increase in drainage area for the downstream cross-section would increase calculated discharge by about 50 ft^3/sec (1.4 m^3/sec) when compared to the upstream cross-section (50 = 4.5 x 11). This amount was considered insignificant when compared to the estimated flood volumes, and no adjustment for drainage area was made.

Discussion and Comparison

The actual hydrograph of an ungaged flood event can only be estimated. Estimating streamflow following a flow event is known as an "indirect measurement." According to the USGS (Arcement and Schneider, 1989), a "good" indirect measurement is one within 10% of the "true" value; a "fair" measurement is one within 15%; and a "poor" measurement is one within 25% or greater. Because this slope-area estimate used a single cross-section and some estimated depths, it is reasoned that the margin of error for this analysis was in the 25% (poor) range.

To determine the accuracy of this analysis, the results were compared with the results of other outburst flood studies. Walder and Costa (1995) compiled a list of 115 outburst flood events, which had known or estimated peak discharges and lake volumes. The Walder and Costa data were plotted with the calculated Abyss Lake/Oscar River datum (Figure 2). The graph shows that the calculated magnitude

[1] USGS gages: 1) Kahtaheena River above Upper Falls, near Gustavus, AK, and 2) Situk River near Yakutat, AK

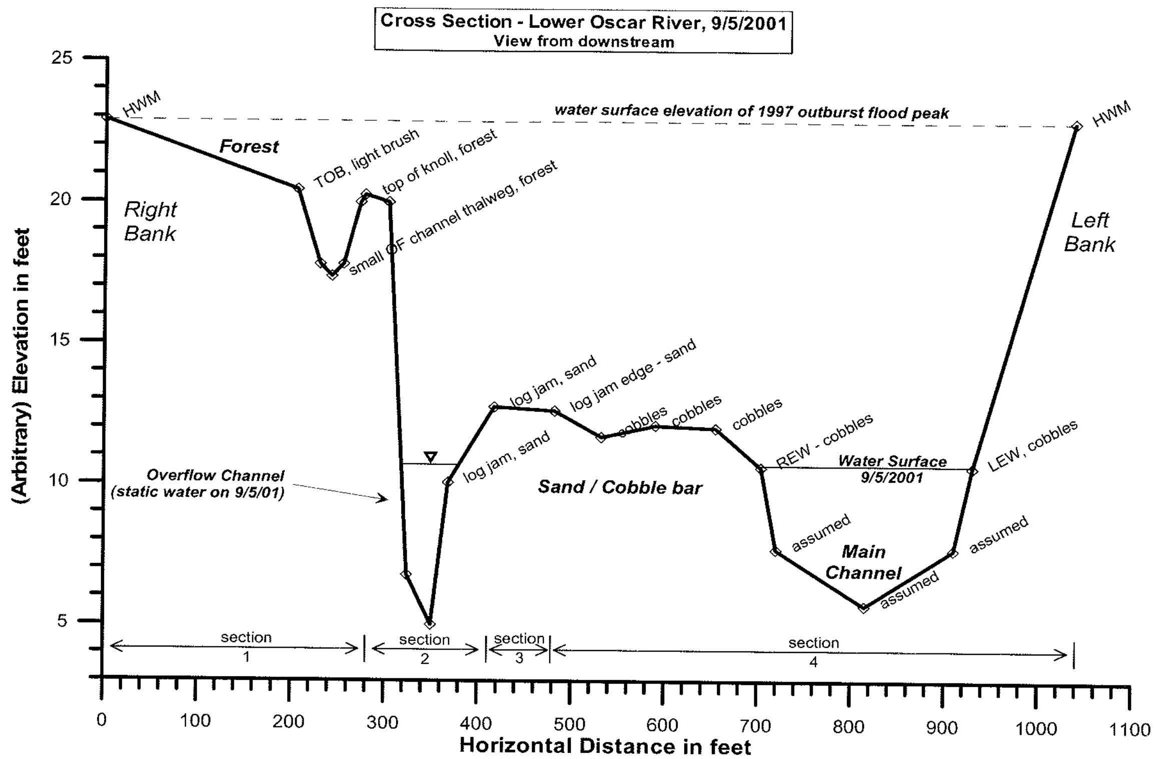


Figure 1. Cross-section profile of the Lower Oscar River as surveyed on September 5, 2001. Four sub-sections were identified based on channel characteristics for the slope-area (NPS, 2001).

		Forest **section 1**	***Sand/some logs*** **section 2**	***Sand/many logs*** **Section 3**	***Cobbles*** **section 4**
Area (sq. ft.)		480	1420	700	6730
WP (ft)		285	155	70	565
R (ft)		1.68	9.16	10.00	11.91
Base n		0.040	0.030	0.030	0.036
n1	**(irregularity)**	0.000	0.020	0.010	0.005
n2	**(variation)**	0.001	0.001	0.001	0.001
n3	**(obstructions)**	0.000	0.030	0.050	0.000
n4	**(vegetation)**	0.200	0.000	0.000	0.001
M	**(meander)**	1	1	1	1
N	**(FINAL n)**	0.241	0.081	0.091	0.043
Slope		0.004	0.004	0.004	0.004
mean velocity (ft/sec)		0.55	5.08	4.79	11.40
Sub Q (cu. ft./ sec)		265	7214	3356	76720
				(87554	ft^3/sec)
			Total streamflow =	***2480***	***m3/sec***

Table 1. Geometry, 'n' values, and calculated sub-section discharges for the outburst flood event. Total streamflow is estimated to be 2480 m^3/s (87500 ft^3/s) at the flood peak (NPS, 2001).

of the 1997 Abyss Lake outburst flood compares favorably with other flood magnitudes originating from lakes of similar size.

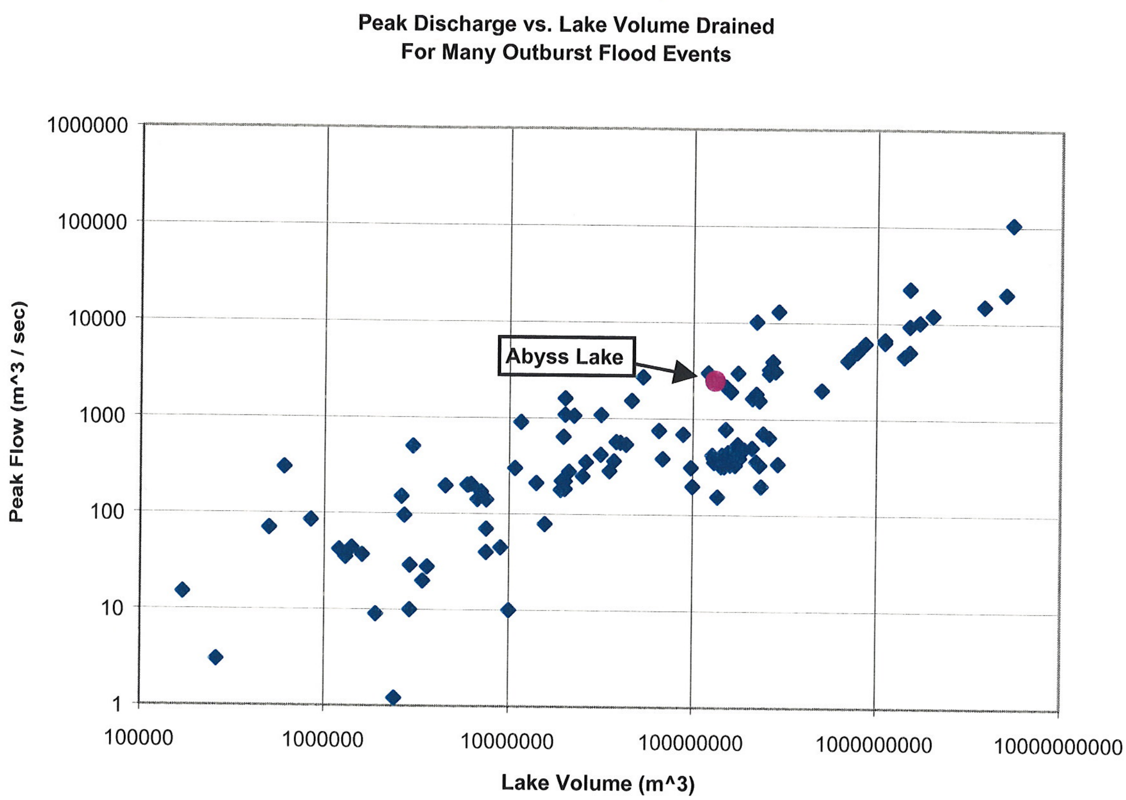


Figure 2. 1997 Abyss Lake outburst flood discharge compared to other outburst flood events. Data from Walder and Costa (1995).

Additionally, several investigators have developed formulas designed to predict peak flood flows based on associated lake volumes drained. Clague and Mathews (1973) are generally credited with developing this methodology. Their formula takes the form:

$$Q_{max} = 75Vmax^{0.67} \quad (r^2 = 0.96, \text{Vmax in } m^3 \times 10^6)$$

Costa (1988) used a larger data set to derive his formula to predict peak flood flows:

$$Q_{max} = 113V^{0.64} \qquad (r^2 = 80\%, \text{V in } m^3 \times 10^6)$$

Desloges and Jones (1989) developed a “correction factor” for the bias stated in the Costa model. This bias results from a linear regression being performed on logarithms and then back-transforming to arithmetic units. The Desloges and Jones form is:

$$Q_{max} = 179V^{0.64} \qquad (\text{V in } m^3 \times 10^6)$$

A comparison of the above formulas with the slope-area estimate of this report is listed in the table below. Lake volume used in the formulas for Abyss Lake is from the 1997 survey (130×10^6 m^3).

Formula	Estimated Oscar River peak flow
Clague & Mathews	1960 m^3/sec
J. E. Costa	2550 m^3/sec
Desloges & Jones	4050 m^3/sec
slope-area method (this report)	2480 m^3/sec

Based on the above comparisons, it appears that the slope-area estimated peak flow for the 1997 Abyss Lake outburst flood, although rated "poor," is reasonable and falls near the middle of the range.

Flood Frequency

As the team walked up the Oscar River Valley on September 4, 2001, it was evident that the 1997 flow event was much larger than any event since that time (including the August 2001 event). Hundreds of debris piles and sand bars deposited in the forest by 1997 floodwaters were still in place. These traces of the flood were somewhat weatherworn after four years, but they still told a clear story concerning the high magnitude of the 1997 event. Similarly, many large logjams created by the huge flows of the 1997 event remained in place (Photograph 5). These jams had formed as acres of mature trees were undercut and swept downstream by the force of the river at flood stage. Four years later they appeared untouched by subsequent floods. Since 1997 a few "new" trees have been added to the logjams in the river and the mouth of the bay as the river continues to meander and undercut its banks. Undoubtedly, recent high flows, although of a smaller scale than those in 1997, have enhanced this lateral movement.

Most of the trees displaced during the 1997 event were washed out of a thick forest which covered a large, mid-channel bar or island located just below the falls (Map 2, Photograph 6). Cores of the trunks of these trees were collected during the 1997 survey. Their analysis indicates that the trees were of a consistent age–about 80 years. Thus, this stand of trees was established around 1918. A true "return interval" for a flood events cannot be calculated without many years of peak flow data, but it can be concluded from the tree ring data that the 1997 event was probably the largest flow event since 1918.

Additionally, Derksen (assisted by Greg Streveler, GLBA research scientist) used tree ring data collected in nearby Palma Valley to calculate a date of "about 1918" for a catastrophic flood in that valley (Derksen, 1976). Derksen speculated that the event in the Palma Valley was an outburst flood, which emanated from Bearhole

Photograph 5: GLBA biologist Chad Soiseth walks on newly formed point bar on right bank of the West Branch Oscar River. Bar is comprised of sand and cobbles. Large log jam of mature trees visible on left side of photo. Photo taken several weeks after the 1997 outburst flood. River visible in background. Photo by Scott Grover.

Photograph 6: Oblique aerial view of West Branch Dundas River. View is upstream. Brady ice field visible at top of photo. Dundas Falls visible just above point of river split. Photo taken August 23, 2001, during period of relatively high flow. Channel on left of photo was reclaimed by the 1997 outburst flood. Both channels are flowing bankfull in this photo. Aircraft wing strut visible in upper right. Photo by Rusty Yerxa.

Lake and drained under the Palma Glacier (Map 1). That two major flood events occurred independently in the same year in valleys only 20 km miles apart seems highly unlikely and points to a common cause. The USGS National Earthquake Information Center lists an earthquake of unknown magnitude occurring in December 1919 - very close to the estimated 1918 date. Historical records for this region are poor, but may also indicate a common climatic or seismic trigger for these events.

Aerial photography of the region has been flown by the NPS or USFS about every 20 years, starting in1936. These photographs show that the Oscar River Valley was heavily vegetated and geomorphicly largely stable through 1979. Between 1979 and 1996, the valley was subjected to a large flow event, which created large sandbars, reclaimed old overflow channels, and removed many acres of mature forest near the channel. This flood probably occurred in the summer of 1994 because fishing boat captain Jim de la Bruere reported he observed a large number of floating trees and a vast amount of muddy water in Dundas Bay at the mouth of the Oscar River (GLBA radio transcripts).

The 1997 outburst flood continued this reworking of the valley floor. A GIS analysis conducted by Grover for the 1997 flood survey concluded that an additional 11.3 hectares (28 acres) of mature forest were removed by the 1997 outburst flood waters along the 4.6 km (2.8 mi) reach between the falls and Dundas Bay (Map 2).

Summary and Conclusions

Glacier outburst floods occur when water dammed by glacial ice releases suddenly by tunneling around, under or flowing over the ice dam. The flowing water can cause rapid melting of the restricting ice, creating floods characterized by a relatively rapid flow increase, a very high peak, and a relatively sharp recession.

In recent years the outburst floods from Abyss Lake in Glacier Bay National Park, Alaska, have occurred almost annually in late summer or fall. Investigations outlined in this report show that the outburst flood from Abyss Lake in September 1997 was the largest in recent history, reaching a peak flow of 2480 m^3/second. A review of aerial photographs and seismic records indicated that the 1997 flood was probably the largest since 1918 or 1919.

The conditions of glacial ice, water, temperature and topography which created the Abyss Lake / Oscar River outburst flood cycle continue to exist, and there will be outburst floods in this and similar valleys until the conditions change. The glacial drainages of GLBA are a showcase of the massive, erosive forces for which the area was set aside as a National Park.

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Thank you.

As the nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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