An Investigation of the 1997 Abyss Lake Jökulhlaup in Glacier Bay National Park

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November, 1997

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Introduction

Glacier Bay National Park is one of the nation's largest Park units, comprising over 3.2 million acres. This Park is located in Southeast Alaska, about 95 kilometers west of Juneau, the state's capitol. The Park is marine in nature, containing over 1200 miles of pristine shoreline. These shores are found within the bay proper, and also on the exposed 'outer coast' in the Gulf of Alaska (refer to Map 1).

The climate in Southeast Alaska is dominated by the proximity of the ocean. Dense rainforests are created by average annual precipitation amounts that exceed 450 cm. The Fairweather Mountain Range is located within the southwestern portion of the park, where much of this precipitation falls as snow. Over time, this snow has accumulated to become ice many hundreds of meters thick. With the assistance of gravity and the extreme relief of the mountain terrain, this ice begins to move downhill in the form of glaciers.

The glaciers can fill valleys and are, in essence, frozen rivers. The rate of movement for the glaciers varies, but rates can exceed 200 meters per year. A glacier in a 'trunk' or main valley may be composed of several smaller glaciers whose accumulation areas lie at very high elevations. Lower tributary valleys to the trunk valley may be free of snow and ice for much of the season due to slightly warmer temperatures, however these lower valleys can be blocked by glacial ice in the trunk valleys. An 'arm' of the glacier may extend into the tributary valley which creates a dam of ice. Liquid water may flow into, or under the ice, but it is common for the blockage of the ice to be so complete that water accumulates in the tributary valley behind the ice. Thus, this type of blockage creates a 'glacial lake.' Southeast Alaska has one of the largest concentrations of glacial lakes in the world (K.H. Stone, 1963).

Ice dams forming glacial lakes can be breached in several ways. Usually the failure of an ice dam is catastrophic: releasing vast amounts of liquid water in relatively short spans of time. The actual processes that control glacial outburst floods, or jökulhlaups, are still subject to controversy. Study of such events is hampered by extreme climates, topography, relative event infrequency, and of course, the ice itself. Some theories, however, have been put forth. S. Thorarinsson (1939) outlined a relationship between water depth in the glacial lake and height of the dam. He stated that due to density differences the ice would actually begin to float when the lake reached a certain 'critical' depth. This would allow for water to escape subglacially (under the ice). W. B. Whalley (1971) states that it is simply changes within the internal drainage system of the trunk glacier which allow for the initiation of flow. Whatever the mechanics of the initial flows, O. Liestol (1955) states that the escape route becomes exponentially larger with time. His calculations show that "water at 1 degree C and flowing at only 1m^3/sec can theoretically melt over 270 m^3 of ice in 24 hours." In essence, the flowing water melts the constricting ice, which allows more water to flow.

This increased flow, in turn, melts additional ice and flows increase accordingly. This process continues until the glacial lake is drained.

Background

Abyss Lake is a glacial lake formed by the Brady Glacier in Glacier Bay National Park (Map 2). The lake is known to occasionally ‘dump’ or release water during outburst floods. One event was noted by a boat captain (Jim de la Bruere) on June 17, 1994. He noted in his log: "lots of trees in bay from glacier run off river in the sw bay of Dundas Bay" and "I wonder what dammed the river." No documented local references to events prior to 1994 are known, and no studies or previous investigations of Abyss Lake jökulhlaups have been found for reference.

During a flight seeing tour over the Brady Glacier area on September 15, 1997, the pilot and passengers (Art Hayes and the Grover family) noted that Abyss Lake had lost a substantial amount of water. There appeared to be a “bathtub ring” left at the former water level. The lake was not dry, but the water level had obviously decreased significantly. A subsequent review of radio transmissions logged by Park staff revealed that on September 1, 1997, a local charter boat captain (Rusty Owen) reported “many trees” floating in Dundas Bay, and that it appeared that “a dam has broken.”

In each instance, massive volumes of water and flood debris entered Dundas Bay via the Oscar River. A subsequent helicopter flight through the area confirmed that the Oscar River stream channel had been impacted by extremely high flows. The Oscar River originates from beneath the Brady Glacier 6.5-km ‘downhill’ from the Abyss Lake ice dam. Thus, it appeared that a Jökulhlaup had impacted Abyss Lake.

This report is an attempt to qualify and (within certain limits) to quantify the outburst flood event which occurred on or about September 1, 1997.

Methods

The first of two excursions into the area was to make volumetric measurements of Abyss Lake and calculate, as much as possible, how much water was lost. This involved a boat ride to the head of East Dundas Bay from Bartlett Cove, and a hike over some small passes to the Dundas River valley. Upon reaching the confluence of the East and West Dundas Rivers (Map 2) the West Dundas stream channel was used as a conduit to the Lake. This stream channel was known to be relatively dry, as the channel terminates at the northern end of Abyss Lake (which was obviously quite low). Water exits via this channel only when the lake level is very high. In effect, West Dundas River is merely an ‘overflow’ channel from Abyss Lake. In the absence of the ice blockage, water would drain towards the south, into an entirely different watershed.

Several channel cross sections were performed and existing streamflow in the lower reaches of the West Dundas River was estimated. At the Lake, side slopes leading down to the waters’ edge were measured using hand held clinometers. Short distances were measured with standard tapes and longer distances were measured with a laser rangefinder (Leica Geovid).

The second excursion began with a boat journey to West Dundas Bay (the mouth of the Oscar River; Map 2). The channel of the Oscar River was hiked, up to a point approximately 1.6 km downstream from where the river originates from beneath the ice (progress was halted by an early snow squall). Two detailed channel cross sections were completed, in addition to measuring existing streamflow. High water marks were observed at the cross section locations and vertical distances measured.

The cross sections were used to compute a cross sectional area (A) of the channel, to calculate the wetted perimeter (W_p), and to thus find the hydraulic radius (r):

$$r = A/W_p$$

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

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

where Q is flow (in m^3/second), s is slope, and n is a roughness coefficient. The roughness coefficient is used to factor in the effects of friction between the flowing water and the channel bottom. ‘n’ can be computed using measurements of local variables (Jarrett, 1985), or estimated from existing tables which describe stream configurations (Chow, 1959). Both methods were used for the calculations in this paper.

Photographs and notes of observations were taken on each trip. Additionally, a GPS receiver was used to obtain control points for georeferencing high altitude aerial photographs. These photographs include color infrared, 1:63000 scale images flown in August, 1996 and August 1979. Black and white images from 1948 were also available for study from the Park’s archives. The referenced photographs were used in a GIS to confirm distances, areas, and elevations. The images were also invaluable for noting stream morphology changes.

Results

Lake Volume Estimation

As the hike proceeded up the almost dry West Dundas River channel, it was apparent that very high flows occasionally visited the channel, but were not perennial. Existing water flow was estimated to be 1 – 2 m^3/sec in the lower reaches and tapered to zero near the lake outfall. This conclusion (of intermittent high flows) was based on vegetation in the channel proper, and was confirmed by the observance of flotsam and vegetation within the rim of the Lake. Water intolerant mosses were found growing 3 vertical meters below the 'lip' of the outfall into the West Dundas channel. These mosses (and flotsam) were 5 meters below the 'bathtub ring' or extreme high water mark. This high water mark is created by the presence/absence of lichens and is unmistakable as is evident in Photo 1 (ground photograph locations are noted in Map 2). Thus it appears that water exiting from Abyss Lake and into the West Dundas channel is the exception rather than the rule, at least in the very recent past (2-10 years). The 1996 aerial photograph shows the lake level to be approximately 5-10 m below the lip of outfall. In the 1979 photograph, water was exiting the lake via the West Dundas route, but flows could not be estimated. 15.0 m^3/sec was estimated (using the Manning-Chezy formula) to be the maximum flow at the outfall into West Dundas. This is a relatively small value compared to the seasonal peak flows entering the Dundas drainage via the East Dundas River (which emanates from the Geikie glacier). Thus, the 'missing' contributions from Abyss Lake into the Dundas system should have negligible impacts.

Measurements made from the estimated mean high water line to the waters' edge indicated a drop in the lake level of 56.6 m. Lake width at the pre-existing water level was measured at 575 m, and was verified using the GIS. The GIS was used to calculate a lake surface area of 2,570,000 m^2. This value multiplied by 56.6 yields 145,462,000 m^3 of water if the lake were 'square.' Volume in the lake side slopes was calculated from a conservative estimate of 45 degree slopes and a perimeter of 9200 m (calculated by the GIS) to be 14,720,000 m^3. This value when subtracted from the initial water volume of the 'square' lake yields a loss of 130,742,000 m^3 of water.

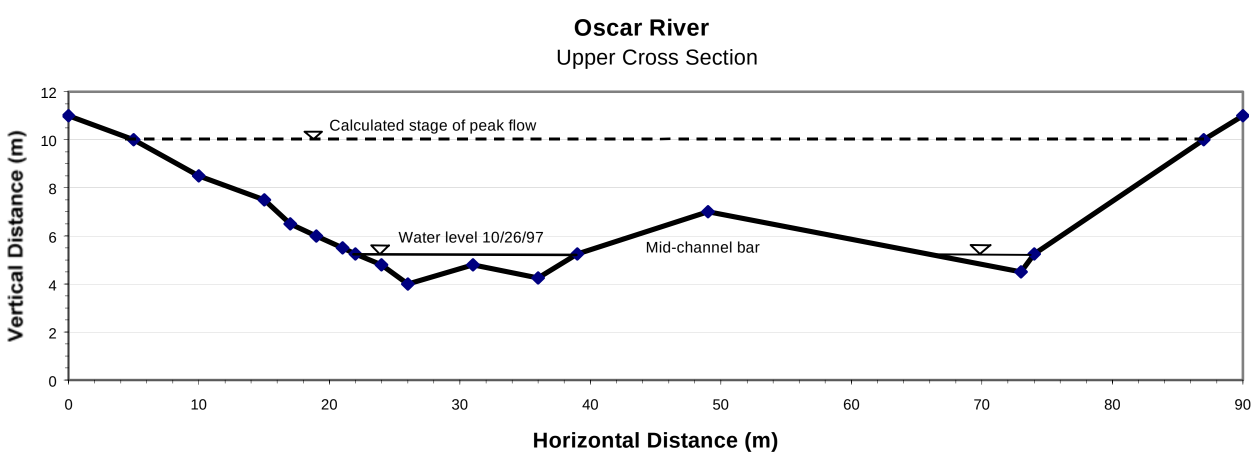
Peak Flow Estimation

The Manning-Chezy formula was used with measurements taken from each cross section to estimate peak flows. The upper cross section was located upstream of all significant tributaries, and appears as the northern most black line on Map 2.

High water stage was estimated by inspection of removed soils, scared trees, and exposed roots. The figures for the upper cross section were as follows:

Manning's 'n':	0.09
Cross sectional area:	300 m^2
Hydraulic radius:	3.57
Slope:	0.0175 (1.75%)

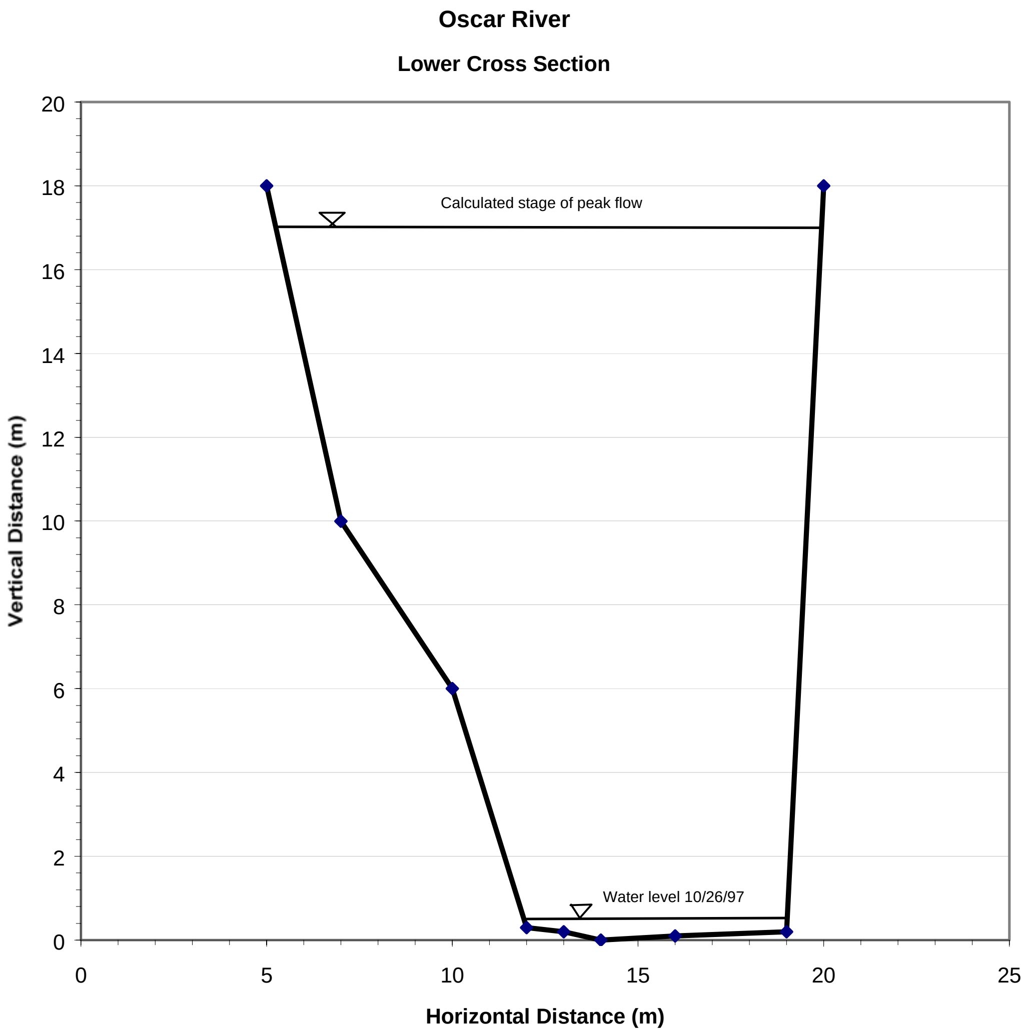
These values yield a Q (flow) of **1030 m^3/sec**. The Manning's 'n' value was intentionally computed conservatively to avoid over estimation of flow, as it is documented that the Manning-Chezy formula becomes less accurate when slopes over 1.5% are used. The upper cross section is reproduced below; note that vertical and horizontal scales are not proportional.



Due to inclement weather and rugged terrain, the lower cross section was required to be situated within a narrow canyon just above the Oscar River falls (Map 2). Values for the lower cross section were:

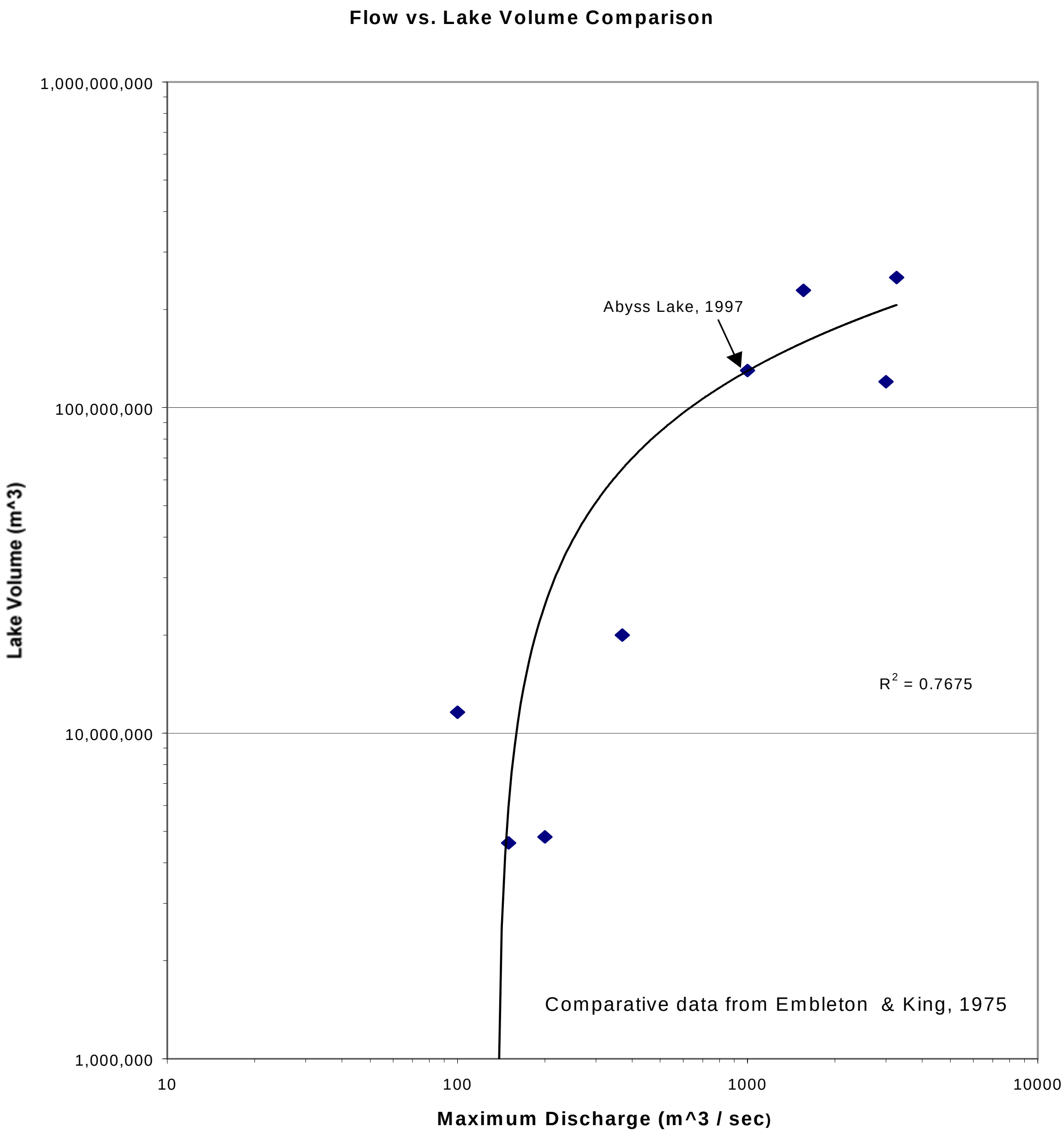
Manning's 'n':	0.09
Cross sectional area:	192 m^2
Hydraulic radius:	4.52
Slope:	0.035

These values yield an estimate of Q to be **1090 m^3/sec**, which compares favorably with the value from the upper cross section. The lower cross section appears below.



Existing water levels appear in each plot for comparative purposes. Flow on November 26, 1997 was considered to be 'normal' and was measured to be 8.0 m^3/sec. Thus, peak flows were roughly 125 times 'base' flow.

The change in lake volume and estimated peak flow was plotted with similar values recorded for other jökulhlaups, and a regression line calculated. The following graph shows that the estimated values for the Abyss Lake jokulhlaup is of similar scale to these other events.



Flood Hydrograph Synthesis

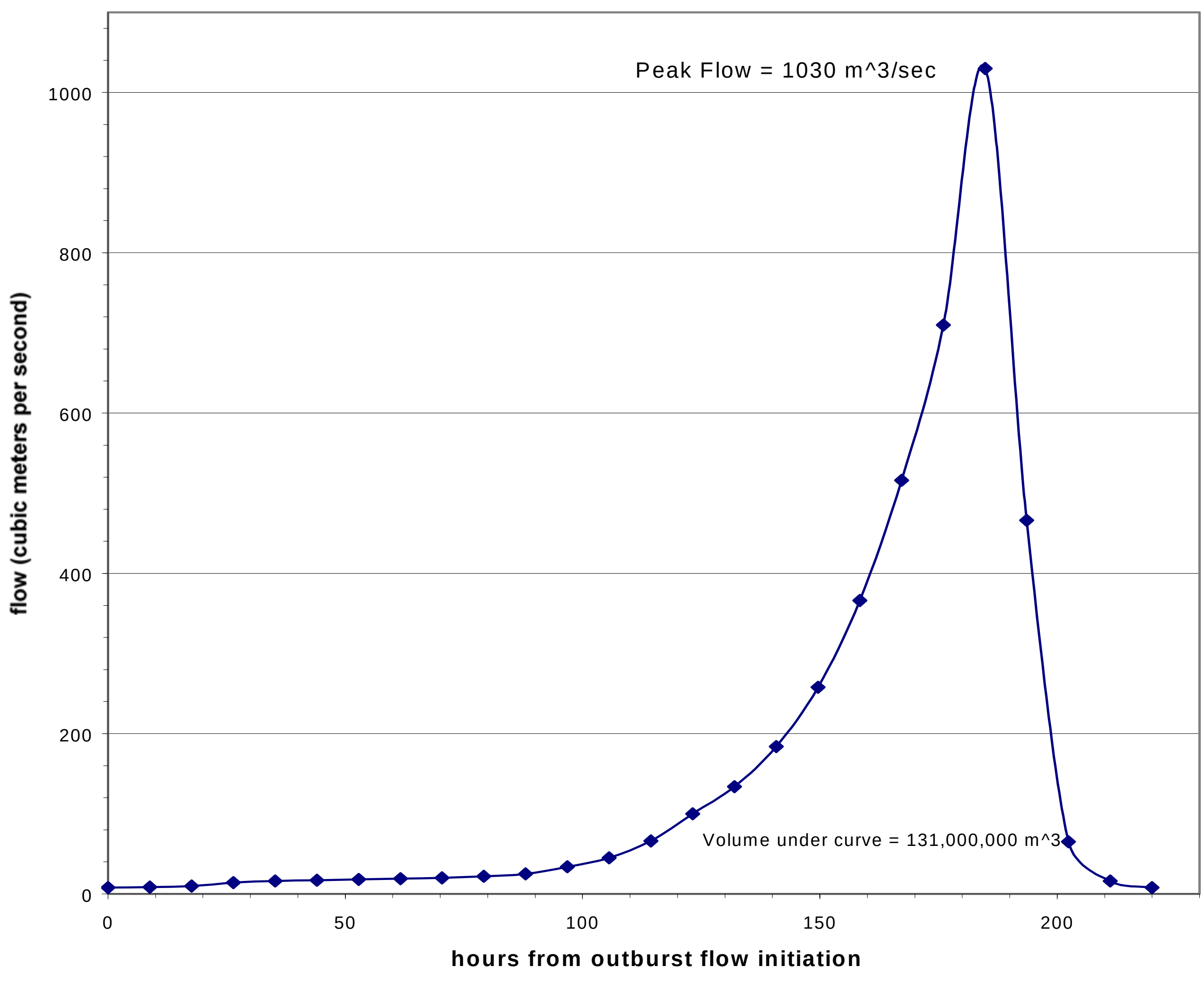
Samples of other jokulhlaup hydrographs were used to prepare a 'representative' hydrograph shape. The rising limbs of the hydrographs are known to be exponential curves, and follow similar patterns. The overall hydrograph shapes are quite similar between events, even though the scales can be very different. These hydrographs are characterized by rising limbs which are exponential; rising slowly initially, increasing at a rapid rate near the peak, and having a short, steep falling limb. The hydrograph rising limb is a result from the previously noted melting process of the water's escape path. The sudden drop occurs when the lake is emptied, or a base level is reached (a layer through which water can not further erode).

Base flow level is known from direct measurements (8.0 m^3/sec), and the hydrograph peak has been estimated from post-flood observations (~1000 m^3/sec). Also 'known' is the general hydrograph shape, as described above, and the lake volume (131,000,000 m^3). By integration of these known values, an estimate of the flood duration can be computed. The hydrograph x-axis (which represents time) was divided into 25 equal segments (units are seconds), and thus the area under the curve is the cumulative sum of the 'height' which is 4145 (units are m^3/sec) multiplied by x (the length of the unknown time unit).

$$131,000,000 = 4145x$$

Thus, x = 31600 seconds per unit, or about 8.8 hours per unit. Multiplying by 25 yields a duration of the event at 220 hours. Applying this to the graph (as shown below) yields a flood peak occurring about the 185th hour. As the graph shows, the flood event is estimated to have spanned 9 days, with the largest portion of the flood being concentrated in a 2.5-day period.

Synthesized Hydrograph for Abyss Lake Jokulhlaup



Potential sources of error in the previous calculations could arise in the following estimates:

- Lake Depth (+/- 5 m)
- Stream slope (+/- .0025)
- Manning's 'n' (+/- .03)
- Shape of hydrograph (effects duration of flood: +/- 50 hrs.)

Additional Observations

Abyss Lake did not drain completely, losing only 56.6 vertical meters of water. Analyses of the existing aerial photography and USGS topographic maps show that the elevation difference between the former lake surface and the flows' exit point into the Oscar River is approximately 55 meters. Thus it would appear that the erosive flowing water reached a base level underneath the glacier beyond which it could no longer down-cut. This base level elevation became the lake elevation (and the elevation at the exit point from the ice) and flow exiting the lake ceased. It appears that the flood flows were diverted into the Oscar River system by the Brady Glacier lateral moraine; otherwise the 'natural' path of the water would be the trunk valley which terminates in Taylor Bay (Map 1).

Analyses of the aerial photographs show no significant stream changes between the 1948 and 1979. The 1996 aerial photograph reveals significant lateral movement of the channel at all 'outside' bends in the stream. Of special interest is the reclamation of an overflow channel which begins just below the falls and rejoins the main channel 1.5 km downstream. This channel is heavily vegetated in the earlier photos, but appears as a boulder/cobble scar in the 1996 photo (see Map 3). The removal of vegetation in this overflow channel is undoubtedly a result of the 1994 flood. Ragged tree stumps were seen in the overflow channel proper on the November 26 trip; the trees broken away. This overflow channel currently conducts about one half the total streamflow. Significant down cutting of the channel was observed below the base of the falls at the entrance of the overflow channel (see Photo 5).

The overflow channel and main channel surround what appears to be an ancient mid-channel bar composed of boulders and cobbles. This bar is old enough to have developed a soil layer dense enough for the establishment of a secondary Sitka spruce forest. It is probable that a jokulhlaup 100 + years ago created this bar, as tree core analyses indicate the trees are consistently aged at 80 years. Trees from various logjams created during the 1997 event also are 80 odd years old. Trees were completely removed from an area of approximately 1.6 hectares at the top of the mid-channel bar (Map 3). Most of these trees were undoubtedly carried downstream by the high flows, but about 150 trees were left in a logjam at the upstream side of the remaining forest.

Photographs 2, 3, and 4 show the extent of the logjams deposited along the stream, usually on massive sand and gravel bars on the inside bends of the channel. New sand and gravel deposits were numerous along the channel banks and often exceeded 2 m in height. Sand deposits were noted in the forest 200-m from the main channel.

Areas of significant vegetation removal (often accompanied by sever lateral movement of the stream channel) are noted in Map 3. Map 3 is based on the 1996 color infrared aerial photograph; vegetation appears as red, bare rock appears as white, and water is blue.

Conclusions

The 1996 outburst flood event was not unique to the Oscar River system. An event of similar scale was noted in 1994. However prior to the 1994 event, no records are known to indicate jökulhlaups in the Oscar drainage. Aerial photographs dating to 1948, and collected tree core data, show that the system was relatively stable for a significant length of time. The 1996 event originated when water from Abyss Lake found an exit path, probably along the Brady Glacier lateral moraine. Flow initiation may have resulted by a ‘floating’ of the ice dam, or by movement within the glacier which opened a conduit. The flowing water subsequently melted ice within this englacial path and allowed further water flow to increase exponentially. This process continued until the flowing water reached a resistant base level, probably the Brady Glacier lateral moraine. Peak flow was estimated to be over 1000 m^3/sec and lasted about 9 days. The highest flood stages were concentrated in a 2.5-day period towards the end of the flood. Thousands of trees were swept away in the ensuing flood either being deposited on bars in the stream channel or carried to Dundas Bay were tidal currents carried them to distant reaches. Many thousands of tons of sediment were deposited with the forests, in ancient overflow channels, on new channel bars, and in the mouth of the Oscar River. It is expected that Abyss Lake will eventually refill to its former level, setting the stage for future jokulhlaup events.

Photographs

Refer to Map 2 for photograph locations. All photographs by the author.

1. Oscar River mouth. Chad in foreground. Photo shows lateral erosion of stream channel and new deposits on mid channel bar.
2. New sand bar, logjam.
3. New sand bar, logjam.
4. View from forest of logjam on inside bend of stream. Photo from about 8 meters above existing water level.
5. View from falls, looking downstream at overflow channel. Forest was removed from barren area in foreground. Note logjam in front of remaining trees.
6. Oscar River Falls. Rusty in foreground. Photo taken from area of tree removal.
7. View of Abyss Lake from outfall. Brady Glacier in distance. Vertical distance from high water mark to water is 56.6 meters (about 200 feet).
8. Exit point of flow from Brady Glacier into Oscar River drainage (aerial view). Width of stream channel estimated to be 20 meters. Note large crevasses terminating at exit point. Water flow exiting ice at time of photograph estimated to be 5 – 10 m^3/sec.

References: PENDING

Acknowledgements

MANY thanks to the dedicated GLBA employees who assisted in the investigation: Chad Soiseth, Rusty Yerxa, Nathan Borson, and Bill Eichenlaub.