RECORD OF JÖKULHLAUPS AT TULSEQUAH AND SALMON GLACIERS, NORTHWESTERN BRITISH COLUMBIA

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Abstract

Jökulhlaups (glacial outburst floods) from lakes dammed by Tulsequah and Salmon glaciers, northwestern British Columbia, have occurred periodically since the early and middle twentieth century, respectively. The floods commenced after decades of substantial downwasting and retreat of the glaciers from their Little Ice Age maximum positions. We use hydrometric data and other records to reconstruct the times and peak discharges of the floods. Tulsequah Lake, which is dammed by Tulsequah Glacier, and Summit Lake, dammed by Salmon Glacier, initially grew in surface area and volume, but, with continued glacier retreat, they have gradually decreased in size. The first jökulhlaups from these lakes were the largest, and discharges decreased as the lakes diminished in size. Tulsequah Glacier impounds two lakes that have developed at different times as the glacier retreated. Tulsequah Lake formed and began to produce outburst floods approximately a half century before Lake No Lake. Today, Tulsequah Lake is much smaller in size, and produces much smaller floods, than Lake No Lake. As glaciers in northwestern B.C. continue to shrink in response to climate warming, additional glacier-dammed lakes may form. Thus, the hazard of catastrophic outburst floods is expected to continue.

Résumé

Des jökulhlaups (inondations catastrophiques) résultant de l'effondrement de barrages glaciaires formés par les glaciers Tulsequah et Salmon, situés au nord-ouest de la Colombie-Britannique, se sont produits périodiquement au début et au milieu du vingtième siècle, respectivement. Les débâcles ont débuté après une période d'amaigrissement considérable et un retrait des glaciers depuis leur position maximale datant du Petit âge glaciaire. Or, nous nous sommes servis de données hydrométriques parmi d'autres relevés pour reconstituer les moments d'inondations et leurs débits de pointe. A priori, les lacs glaciaires Tulsequah et Salmon étaient très grands mais avec un retrait continu de ces glaciers, ils ont diminué de surface et de volume. Les premiers jökulhlaups étaient les plus importants mais au fur et à mesure que les lacs rapetissaient, leurs débits diminuaient. Le barrage du glacier Tulsequah a créé deux lacs à différents moments lors du retrait du glacier. L'effondrement du barrage glaciaire du lac Tulsequah a provoqué des jökulhlaups approximativement 50 ans avant ceux du lac No Lake. Présentement, le lac Tulsequah est considérablement plus petit et produit de plus petites inondations que le lac No Lake. Au nord-ouest de la Colombie-Britannique, les effets du changement climatique se font ressentir par une diminution des glaciers et une augmentation probale du nombre de lacs glaciaires. Par conséquent, les dangers reliés aux jökulhlaups se maintiendront.

1. INTRODUCTION

Catastrophic floods resulting from the breaching of glacier-dammed lakes are relatively common in the Canadian Cordillera, particularly in the Coast Mountains. Some lakes drain and fill frequently, whereas others remain empty for years after draining (Clague and Evans 1994). In this paper, we describe lakes dammed by Tulsequah and Salmon Glaciers (Figure 1). The lakes empty frequently through subglacial channels. The resulting floods are referred to as jökulhlaups, an Icelandic term meaning *glacier burst*.

Floods emanating from lakes dammed by Tulsequah Glacier (Kerr 1934, 1936, 1948; Marcus 1960; Souther 1971; Clague and Evans 1994; Septer and Schwab 1995; Geertsema 2000) and Salmon Glacier (Mathews 1965, 1973; Gilbert 1969, 1971, 1972; Fisher 1973; Mathews and Clague 1993) have been well documented. The purposes of this paper are to update the record of jökulhlaups from these lakes, to compare the floods, and to discuss the implications of climate warming on jökulhlaup activity in the Canadian Cordillera.

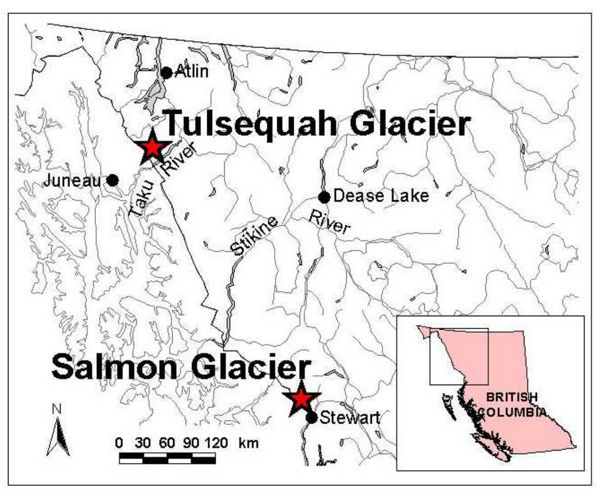

Figure 1. Map of the study area.

2. SETTING

Tulsequah and Salmon Glaciers are located in the Boundary Ranges of the Coast Mountains (Holland 1976), near the International Boundary in northwestern British Columbia (Figure 1). This part of BC is a rugged landscape, with extensive snow and ice cover.

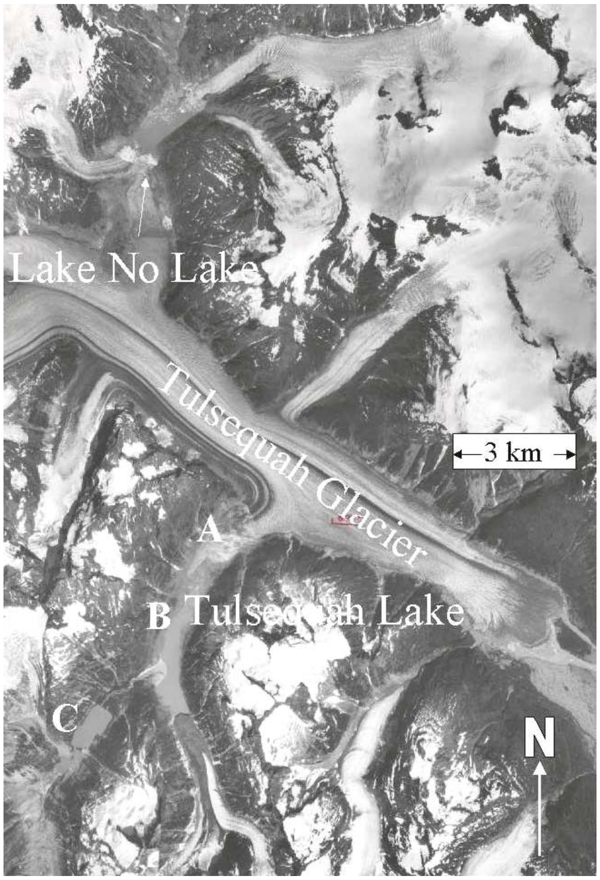

Figure 2. Composite aerial photograph of Tulsequah Glacier, Tulsequah Lake, and Lake No Lake, July 21, 1982. Photographs 15BC82009: 86, 87, 102, and 103 were stitched digitally to form the composite image. In 1920, Tulsequah Lake extended continuously from A to C; now three small lakes exist at different elevations at A, B, and C. Breaching of an early twentieth century moraine dam between B and C occurred before August 1974.

Tulsequah and Salmon Glaciers lie within the Alpine Tundra and Mountain Hemlock biogeoclimatic zones, and terminate in the Coastal Western Hemlock zone (Meidinger and Pojar 1991). These areas have a coastal climate with heavy snowfall and cool summers.

Tulsequah Glacier is 30 km long and terminates at 170 m asl at the eastern margin of the Juneau Icefield. Meltwater from Tulsequah Glacier flows 50 km via Tulsequah and Taku Rivers to tidewater at the head of Taku Inlet. The glacier dams two lakes, Tulsequah Lake and Lake No Lake (informal name), which are located, respectively, 8 and 15 km from the glacier terminus (Figure 2). The two lakes have a long history of catastrophic drainage.

Salmon Glacier is 20 km long and dams Summit Lake (Figure 3) 11 km from its terminus. Meltwater from Salmon Glacier flows 23 km south past the towns of Hyder, Alaska, and Stewart, British Columbia, to tidewater at the head of Portland Canal.

Figure 3. View south of Summit Lake and Salmon Glacier. Note icebergs in the lake.

3. JÖKULHLAUPS

3.1 Introduction

Most glacier-dammed lakes occur at the margins of glaciers, but some are located beneath, within, or on top of them (Figure 4; Hutchinson 1957, Marcus 1960, Costa and Schuster 1988, Clague and Evans 1994).

Glacier-dammed lakes generally drain through subglacial tunnels. The tunnels rapidly grow in size as the water flowing through them melts the surrounding ice. When the outflow ceases, the tunnels close by plastic flow of ice, allowing the lake to refill (Nye 1976).

Many lakes drain during or after the melt season in the summer or early fall, but drainage can occur at any time of the year. Hydrographs of jökulhlaups show an exponential increase in discharge followed by an abrupt decline (Figure 5). Water temperature decreases markedly during a jökulhlaup because the water discharging from the lake is colder than that of the background flow of the river.

3.2 Tulsequah Glacier

The earliest reports of jökulhlaups at Tulsequah Glacier are from the International Boundary Commission (1910) and Kerr (1934, 1936, 1948). Dates on jökulhlaups during the periods 1942-1948 and 1949-1957 are reported, respectively, by Stone (1955) and the Consolidated Mining and Smelting Company of Canada Ltd. Marcus (1960) reports these dates, as well as a jökulhlaup from Tulsequah Lake in 1958. We witnessed a jökulhlaup in September 1996 and the onset of one in October 2001. Additional data come from a hydrometric station operated by the Water Survey of Canada, just upstream of the confluence of Tulsequah and Taku Rivers from 1953 to 1987. In 1988, a hydrometric station was established on Taku River, 15 km downstream from the Tulsequah confluence, by the United States Geological Survey. It has operated to this day.

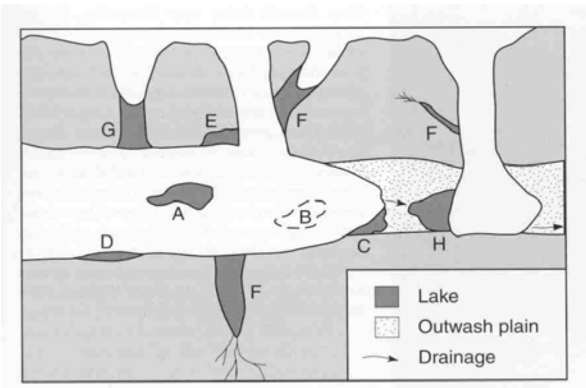

Figure 4. Schematic diagram showing locations of different types of glacier-dammed lakes. A, supraglacial; B subglacial; C, proglacial; D, embayment in slope at glacier margin; E, area of coalescence between two glaciers; F, tributary valley adjacent to a trunk or tributary glacier; G, same as F except glaciers dam both ends of lake; H, main valley adjacent to a tributary glacier. Light toned area is land, white area is ice (after Clague and Evans 1994).

Jökulhlaup data are summarized in Table 1. Tulsequah Glacier has been the source of up to three jökulhlaups each year (Table 1). There are some discrepancies between reported jökulhlaups and the hydrometric records. For example, there is no correlation between reported jökulhlaup dates and hydrographs for the period 1953-1957. Because the gauging station was just upstream of the Tulsequah–Taku confluence at that time, some floods may not have registered on the hydrographs. Recorded peak discharges increase after 1989. This is likely due to relocation of the hydrometric station in 1988.

Without eyewitness accounts, it is difficult to know whether Tulsequah Lake or Lake No Lake was the source of a particular jökulhlaup. However, Lake No Lake did not begin to form until about 50 years ago, thus early jökulhlaups were probably entirely derived from Tulsequah Lake. By 2000, Lake No Lake had grown to ~ 5 km^2 in area and was larger than Tulsequah Lake.

3.2.1 Tulsequah Lake

Tulsequah Lake has a history of jökulhlaups dating back to the beginning of the 20th century (Kerr 1948; Marcus 1960; Souther 1971; Clague and Evans 1994). In the middle 19th century, the valley of Tulsequah Lake was occupied by glaciers flowing from the Juneau Icefield. These glaciers merged with Tulsequah Glacier. Sometime towards the end of the 19th century, the tributary glaciers began to downwaste and recede. In the late 1800s or early 1900s, the glacier occupying the tributary valley separated from Tulsequah Glacier, and a lake formed between the two. The snout of the tributary glacier must have then stabilized for some time because a large end moraine was constructed about 1.5 km into the valley (Figure 2).

By about 1920, glaciers had receded several kilometres back into their own valleys, greatly increasing the size of Tulsequah Lake. Lake levels at that time were higher, and outburst floods larger, than in later years.

The level of Tulsequah Lake began to drop after 1930. By 1936, an upper moraine-dammed lake, named Upper Tulsequah Lake (Kerr 1948), separated from the main lake (Figures 2 and 6). Falling lake levels (Table 1) coincided with downwasting of Tulsequah Glacier and the evolution of the subglacial drainage system.

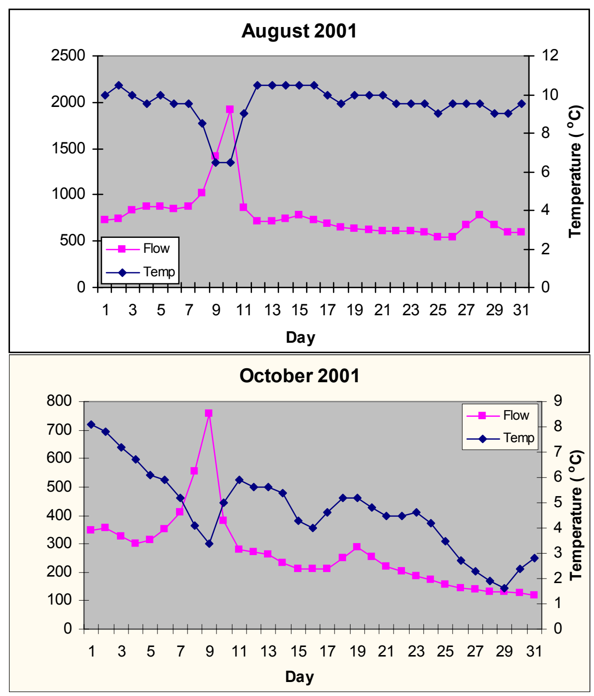

Figure 5. Graphs showing relationship between water temperature and discharge during jökulhlaups in August and October 2001. Note the difference in the peak discharges of the two floods.

Tulsequah Lake's floods diminished in magnitude from 0.91 km^3 in 1910 to 0.23 km^3 in 1958 (Marcus 1960;

Table 1). High water levels in the lake basin have continued to decline, and the lake now commonly drains two times per year (Table 1). A linear depression has developed on the west side of Tulsequah Glacier near the valley wall. This depression may mark the site of a developing tunnel collapse. Tulsequah Lake's days may be numbered.

Figure 6. Tulsequah Lake in July 1955 (left), and September 1996 (right). Left photo by Malcom Greary (from Marcus 1960).

3.2.2 Lake No Lake

Marcus (1960) was unaware of Lake No Lake when he studied Tulsequah Lake. Lake No Lake only appeared on topographic maps as a small glacial lake at that time. Figure 7 illustrates the dramatic growth of the lake since 1948. By 1999, the lake was 150 m deep at the ice dam and had a volume of about 720 million m^3, approaching the early 20th century volume of Tulsequah Lake (Table 1).

The largest known increase in the area of Lake No Lake occurred in the summer of 1993, when a slab of Tulsequah Glacier about 500 m wide, 700 m long, and 170 m thick calved into the lake (Mitch Mihalynuk, personal communication, 1999). The slab broke off along a broad depression that extended across the glacier, perhaps separating grounded from floating ice.

As in the case of Tulsequah Lake, high water levels are declining in Lake No Lake. However, because its area has greatly increased, the lake is taking longer to fill (Norm Graham, personal communication, 1999). Graham (personal communication, 1999) has also observed up to two drainings of Lake No Lake in some years. One year, he found that the lake was half empty, and then, one month later, it was completely empty.

3.2.3 Future self-dumping lakes

Tulsequah Glacier lakes are at different stages in their development. Tulsequah Lake went through a period of areal expansion early in the 20th century, and is now near the end of its life. In contrast, Lake No Lake is still expanding, although its peak levels are also declining. Lake No Lake may thus be about 50 years behind Tulsequah Lake in its evolution. A new, smaller lake is developing along the western margin of Tulsequah Glacier above Lake No Lake. This lake too could experience a cycle of filling and catastrophic emptying.

If, however, Tulsequah Glacier continues to recede, all lakes will vanish, and the flow regime of Tulsequah River will return to that of a typical Holocene gravel-bed river.

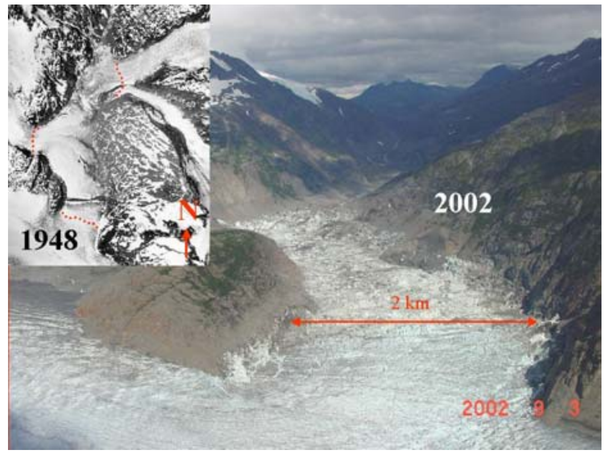

Figure 7. Lake No Lake in 1948 and 2002. The lake was subglacial in 1948. Note 2002 glacier positions (stippled) on the 1948 aerial photograph A11449: 292.

3.3 Salmon Glacier

Unlike Tulsequah Glacier, Salmon Glacier only impounds one lake -- Summit Lake. Salmon Glacier is fed by a large unnamed icefield, located between 1400 and 1700 m asl to its west. Salmon Glacier terminates at about 600 m asl. Water from Salmon Glacier flows 23 km via Salmon River to tidewater at the head of Portland Canal. A hydrometric station on Salmon River at Ninemile, 9 km downstream of the terminus of Salmon Glacier, was operated by the United States Geological Survey from August 1, 1963 to September 30, 1973. Hydrometric data are summarized in Table 2.

3.3.1 Summit Lake

Summit Lake has probably existed for most of the Little Ice Age (Mathews and Clague 1993; Clague and Mathewes 1996). The lake, more than 5 km long with a volume of 0.25 km^3 when full to overflowing, began its cycle of catastrophic drainage in 1961 (Mathews and Clague 1993). Southward drainage occurs via a 9-km-long network of subglacial tunnels. The earliest report of jökulhlaups from Salmon Glacier (Figures 1 and 3) comes from Mathews (1965). Details of flood records from 1961 to 1992 are provided by Mathews and Clague (1993). Their data and more recent records are summarized in Table 2. There are discrepancies in reported dates for 1994, 1995, and 1999.

Mathews and Clague (1993) found that Summit Lake jökulhlaups have become smaller over time (from 0.28 km^3 in 1965 to 0.22 km^3 in 1972), as maximum lake levels dropped (Table 2). They also noted that the floods have occurred earlier in the year over time. Although flood discharge is no longer being measured, new dates of jökulhlaups (Table 2; Figure 8) seem to indicate a tighter clustering in the mid-July to mid-August period.

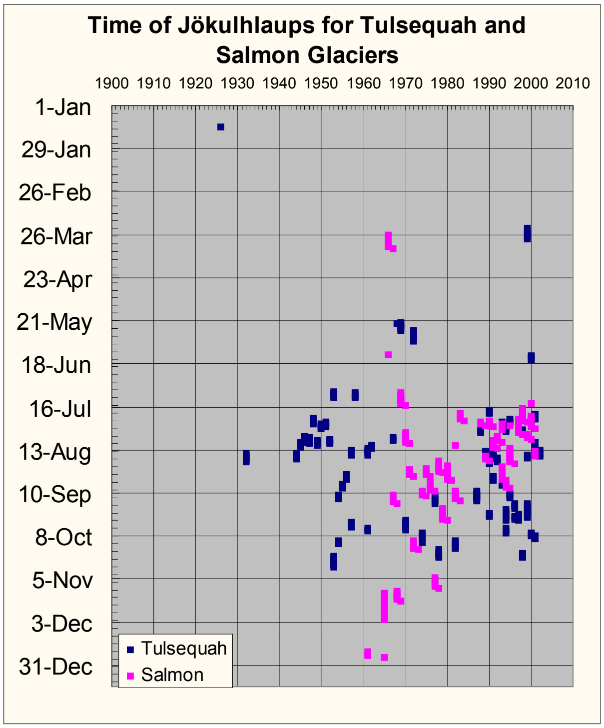

Figure 8. Times of jökulhlaups from Tulsequah and Salmon Glaciers.

4. DOWNSTREAM IMPACTS

River valleys that are impacted by frequent jökulhlaups tend to be aggraded, with little vegetation on the flood plains. During periods of normal discharge, the rivers are small and confined to channels. In contrast, at peak flow, a jökulhlaup may fill its valley from wall to wall (Figure 9). Rapid aggradation along the flood path can alter tributary streams. Jökulhlaups from Tulsequah Glacier, for example, have decreased the gradient of Shaza Creek, one of its tributaries.

In western Canada, most jökulhlaups occur in remote areas and cause little damage. However, a jökulhlaup from Summit Lake similar to that shown in Figure 9, washed out a bridge at Ninemile, Alaska. Likewise, a road and a bridge over Tulsequah River had to be rebuilt numerous times to provide access to a mine. Jökulhlaups typically transport and deposit coarse bouldery gravel along their paths. Expansion bars develop downstream of channel constrictions. Fines may accumulate in slackwater areas and as overbank deposits. Layers of mineral sediment within peat in wetlands may record jökulhlaups.

Figure 9. Jökulhlaup from Summit Lake. Note antidunes (standing waves), indicative of extreme discharge.

5. ROLE OF CLIMATE CHANGE

Mountain glaciers around the world expanded dramatically during the Little Ice Age, which began in the 13th century. Most glaciers in the Canadian Cordillera began to recede from their maximum Little Ice Age positions at various times during the 18th, 19th, and early 20th centuries (Ryder 1989). Trees on the higher of two lateral moraines between Tulsequah Glacier and Nakonake River are as much as 150 years old, thus Tulsequah Glacier achieved its Little Ice Age maximum extent before about 1850.

Since then, Tulsequah and Salmon Glaciers have dramatically thinned and retreated. Thinning and retreat have played a major role in the formation and evolution of the lakes dammed by these glaciers. Initially, glacier shrinkage led to the onset of a jökulhlaup cycle. The early floods were largest, but as the glaciers continued to thin, maximum lake levels and volumes decreased. Because Tulsequah Glacier has two lakes separated by 7 km, the lakes show cyclical, but out-of-phase behaviour. Lake No Lake may lag 50 years behind Tulsequah Lake in its cycle of formation and decline.

Most global circulation models predict increases in summer temperatures for British Columbia and continued glacier ice loss. Evans and Clague (1997) point out that the initiation of a jökulhlaup cycle occurs when a threshold of glacier retreat and thinning is reached. The floods then occur with decreasing magnitude and frequency until the dam ceases to exist. Thus with climate warming we expect certain glaciers to begin jökulhlaup cycles, and other glaciers to end their cycles of flooding.

Table 1. Depth, volume, and dates of drainage of Tulsequah Lake (TL) and Lake No Lake (LNL).

Year	Lake	Maximum lake depth (m)	Volume (km^3)	Reported date of drainage	Hydrometric station record	Peak discharge (m^3/s)
1910-1920	TL	195	0.91	summer 1910		
1926	TL	151	0.61	January		
1929 [a]	TL					
1930	TL	145	0.58			
1932	TL			Aug 15-20;18-21		
1939	TL	116	0.43			
1942	TL	106	0.38	July		
1943	TL			July		
1944	TL			Aug 15-19		
1945	TL			Aug 8-11		
1946	TL			Aug 4-8		
1947	TL	97	0.34	Aug 5-9		
1948	TL			July 23-27		
1949	TL			Aug 7-10		
1950	TL	88	0.29	July 27-30		
1951	TL			July 26-29		
1952	TL			Aug 6-9		
1953 [c]	TL			July 6-10	no spike; Oct 21-28	~ 530
1954 [c]	TL			Sept 11-14	no spike; Oct 11-13	~ 210
1955	TL			Sept 4-7	no spike	
1956	TL	78	0.25	Aug. 29 - Sept. 1	no spike	
1957 [c]	TL			Aug. 13-16	no spike; Sept 29–Oct 2	1440
1958 [c]	TL	73	0.23	July 7-10	July 7-10	1460
1959-1971 [b]	TL			Annually		
1960 [c]					Sept 7-16 ?	909
1961 [c]					Aug 12-16, Oct 3-5	1700, 917
1962 [c]					Aug 10-12	1300
1967 [c]					Aug 5-7	1230
1968					May 17-27 ?	1270
1969					May 21-28 ?	1520
1970					Sept 29-Oct 1 ?	1160
1972 [c]					May 26-Jun 4	1880
1974 [c]					Oct 6-9	926
1977 [c]					Sept 11-15	549
1978 [c]					Oct 18-20	1220
1979 [c]					Sept 12-20	800
1982 [c]					Oct 12-16	680
1983 [c]					Missing data	
1987 [c]					Sept 11-13	995
1988 [a c]	TL			Jul 31-Aug 2	Jul 31-Aug 2	1750
1988 [a]	TL			?-16-? Sept		
1989 [a c]	TL			14-18 August	Aug 14-18	2180
1990 [a c]	TL			July 18-20	July 18-20	1830
1990 [c]					Aug 19-22	1970
1990 [c]					Sept 23-25	1830
1991 [d c]	LNL			31 Aug. - 2 Sept.	31 August - 2 Sept.	1530
1991 [c]					Aug 13-15	1440
1992 [d]	LNL				Aug 18-21	2130
1993 [c]					July 26-29; Aug 30 – Sept 5	1990; 1180
1994 [c]	LNL				July 28 - Aug 1; Sept 21-28; Oct 3-6	2420; 1859; 1356
1995 [c]					Jul 24-27; Sept 10-13	2315; 1836
1996 [c]	LNL			Tuls Lake empty	Sept 17-20; Sept 25-27	1472; 1203
1997 [c]					July 25-28; Sept 24-28	1840; 1831
1998 [c]					July 31 – Aug 1; Oct 19-22	1760; 1132
1999 [c]					March 23-29; Aug 16-20; Sept 17 -26	376; 1596; 982
2000 [c]					July 24-26; Oct 6-8	2635; 1206
2001 [c]					Aug 8-10; Oct 8-10	1913; 756
2002 [c]					Aug 13-17	2009

a, Septer and Schwab (1995); b, Souther (1971); c, this paper; d, Mitch Mihalynuk (personal communication, May 1999); other data from Marcus (1960).

Table 2. Historic record of jökulhlaups from Summit Lake.

Year	Reported date of drainage	Overflow to north	Flood volume (km^2)	Peak discharge (m^3/s)	High water elevation (m)
1961	Dec 22-29	? – Dec 1961			826
1962	none				
1963	none	Aug 20, 1963-			
1964	none	To			
1965	Nov 14 – Dec 1	Nov 15, 1965	0.28	3110	826
1966	Mar 26 – Apr 4				
1967	Sept 11-17	Aug 19 – Sept 11	0.26	2950	826
1968	Nov 13-19		0.21	1640	808
1969	Jul 7-15				
1970	Aug 2-9		0.26	3260	822
1971	Aug 26-30		0.27	3960	
1972	Oct 11-17		0.22	1830	
1973	Sept				
1974	Sept 9-12				
1975	Aug 25-30				
1976	Sept 3-9				
1977	Nov 4-11				
1978	Aug 20-28				
1979	Sept 20-28				
1980	Aug 23 – Sept 2				
1981	Aug ?-10				
1982	Sept 9-15				
1983	July 20-25				
1984-1987	No record				
1988	July 26-28				
1989	Aug 17-20				
1990	July 25-29				
1991	Aug 7-12				
1992	Aug 4-8				
1993[a]	July 27-31				
1994[a b]	Sept 3-7; Aug 24-Sept 5				
1995[a b]	July 28-?; Aug 12-22				
1996	No record				
1997[b]	Jul 24 – Aug 3				
1998[b]	July 17 – July 26				
1999[a b]	Aug 3-6; July 26-Aug 5				
2000[b]	July 22-30				
2001[a]	Aug 14-18				
2002	No record				

a, Rex Johnston, Premier Gold; b, Nate Lambert; other data from Mathewes and Clague (1993).

6. CONCLUSIONS

Lakes dammed by Tulsequah and Salmon Glaciers show cyclical behaviour with progressively diminishing floods in response to glacier thinning. The lakes and outburst floods, however, are different in a number of ways. 1. Tulsequah jökulhlaups were 3 to 4 times larger than those at Salmon Glacier, but, over time, they have decreased in magnitude to a much greater degree. 2. Tulsequah Lake and Lake No Lake formed after glaciers retreated from their Little Ice Age maximum positions, whereas Summit Lake was dammed by Salmon Glacier through most of the Little Ice Age. 3. Tulsequah Lake began its jökuhlaup cycle with a single flood per year. Now, Tulsequah Lake and Lake No Lake, collectively, flood up to three times per year. Summit Lake has produced only one jökulhlaup per year. 4. Tulsequah Glacier has impounded two lakes, and a third lake is now beginning to form. Salmon Glacier has only impounded a single lake. 5. The dates of floods from Tulsequah Glacier have greater scatter than those from Salmon Glacier.

Jökulhlaups may increase in frequency initially with global warming, as new lakes form. Eventually, however, they will taper off as glaciers continue to thin and retreat. Because glacier-dammed lakes can be in various stages of development at the same time, we can expect more jökulhlaups from different locations as glaciers continue to retreat.

ACKNOWLEDGEMENTS

We are grateful to Vanessa Egginton for preparing Figures 1 and 5. We thank Norm Graham, Caroline

Gutierrey, Rex Johnston, Nate Lambert, and Mitch Mihalynuk for providing information on jökulhlaups, and Andrée Blais-Stevens for translating the abstract.

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