PERIODIC DRAINAGE OF GLACIER-DAMMED TULSEQUAH LAKE, JUNEAU ICEFIELD, B.C.

by

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PERIODIC DRAINAGE OF GLACIER-DAMMED TULSEQUAH LAKE, BRITISH COLUMBIA*

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PERIODIC outbursts of water from glacier-dammed lakes are of economic as well as of scientific interest. This phenomenon, sometimes called *jökulhlaup* (a term used in Iceland for a glacial outburst, which may or may not be associated with volcanic activity), entails the *sudden* release of ice-impounded water. The subsequent flooding may have disastrous consequences, depending on reservoir capacity and the intensity of down-valley occupance. Fortunately, glacier-dammed lakes are usually isolated and not adjacent to valley settlements, but the exceptions are numerous enough to cause serious loss of life and property. The most disastrous outbursts have recently been summarized by Stone[1] and Morrison.[2] Equally important, glacial outbursts exert an influence on stream morphology, by periodically removing and redepositing vast quantities of sediments. In only a few days a large jökulhlaup may alter the form of a flood plain almost beyond recognition.

At least eight types of lakes on or in ice or ice-dammed drain periodically. Hutchinson[3] includes seven in his classification of lakes: lakes on the surface of glaciers; lakes within glaciers; lakes on ice sheets; lakes in lateral stream valleys dammed by ice in the main valley; lakes in main valleys dammed by ice from lateral valleys; lakes between glacier and valley walls; and lakes

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1 K. H. Stone: Alaskan Ice-Dammed Lakes: Final Report to the Arctic Institute of North America on Project ONR 67 (Madison, Wis., 1955; mimeographed).

2 C. C. Morrison: Glaciers and Human Activities, *in* Geographic Study of Mountain Glaciation in the Northern Hemisphere (9 parts, American Geographical Society, New York, 1958), Part 9, Chap. 1.

3 G. E. Hutchinson: A Treatise on Limnology, Vol. 1, Geography, Physics, and Chemistry (New York and London, 1957).

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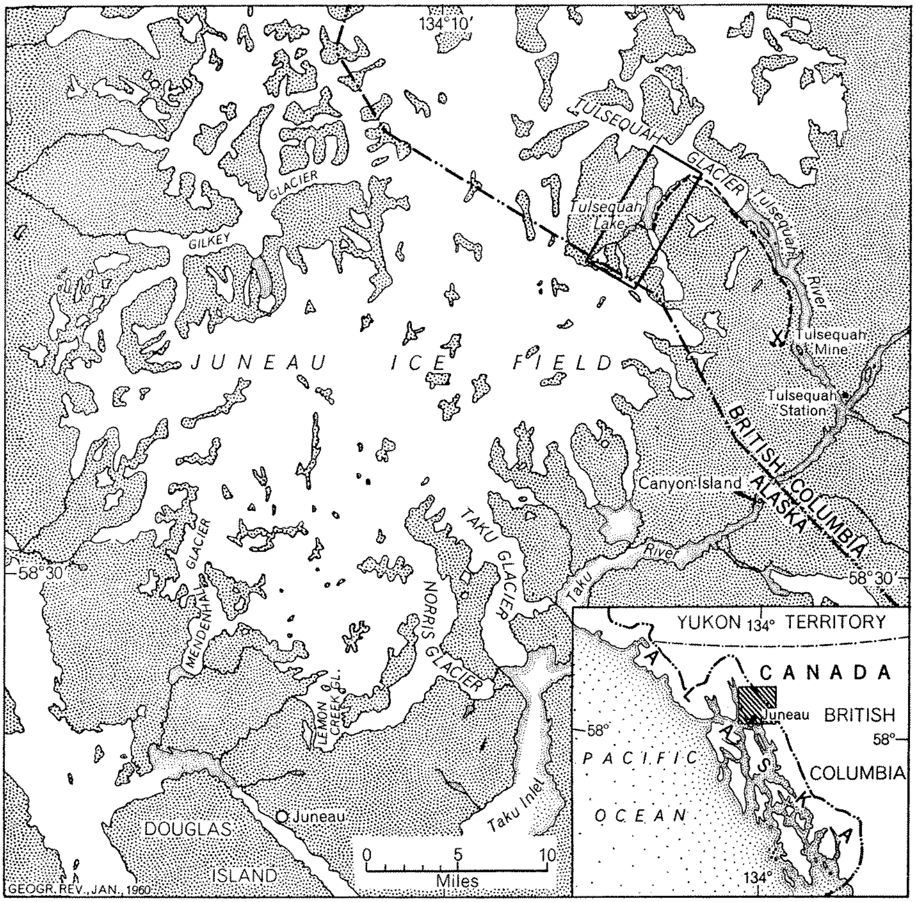


Fig. 1—Location map of part of the Juneau Ice Field region, showing position of Tulsequah Glacier and Lake.

held by avalanches. An eighth type is formed by the retreat of a tributary arm from the trunk glacier. In this case the impounding ice wall is usually the snout of a distributary glacier that has intruded from the main stream into the tributary basin. Apparently this type of lake is infrequent in Europe and Iceland, where most self-dumping lakes have been observed. Hutchinson calls it "a rather special type of ice-dammed lake,"[4] and, except by Collet[5] and Rabot,[6] it has received no other discussion. Stone[7] noted this fact in his survey of glacier-dammed lakes in Alaska and British Columbia.

[4] *Op. cit.*, p. 53.

[5] L. W. Collet: Les lacs: Leur mode de formation—leurs eaux—leur destin (Paris, 1925).

[6] Charles Rabot: Glacial Reservoirs and Their Outbursts, *Geogr. Journ.*, Vol. 25, 1905, pp. 534–547.

[7] *Op. cit.* [see footnote 1 above].

He found that 51 of the 52 ice-dammed lakes in this region are impounded by main-stream ice after tributary retreat. It appears, therefore, that such lakes are the rule rather than the exception in western North America.

Tulsequah Lake,[8] on the eastern margin of the Juneau Ice Field in British Columbia (Fig. 1), is such a lake. This lake, impounded by a distributary arm of Tulsequah Glacier, has been draining annually for at least 17 years and is known to have drained periodically for at least 50 years. During the dumping period icy waters escape beneath the surface of Tulsequah Glacier for about four and a half miles and finally burst forth from cavernous outlets in the ice tongue. In four or five days some 60 billion gallons of water is discharged on the Tulsequah River flood plain, most of it during a 48-hour period. Rushing waters inundate the valley, diminishing in force as they near Taku Inlet, 25 miles downstream. The destructive force of the annual outburst has become a matter of grave concern to local residents and regional planners. Disruption of activities, property loss or damage, and the ever-present threat to life and limb have all influenced the pattern of valley occupance and projected watershed development. Thus an understanding of drainage mechanics and lake development satisfies practical needs as well as academic curiosity.

Lake Site and Historical Development

Tulsequah Lake occupies a steep-walled, glaciated basin between Tulsequah Glacier and an unnamed glacier originating on the upper slopes of the Devils Paw peak. The lake is about three miles long and averages about half a mile in width, narrowing to one-third of a mile at its upper, or southern, end. In 1958 the high-water mark stood 1200 feet above sea level, and the maximum depth of the lake was about 240 feet. A moraine-dammed lake 235 feet above the 1958 water line fills most of another tributary valley (Fig. 2d). This second lake, called "Upper Tulsequah Lake," has been almost bisected by cross-valley alluvial fans. Upstream the tributary valley divides, and two small glaciers flow down from the Juneau Ice Field plateau. Surrounding this valley complex, mountains rise abruptly to elevations of 6000 to 8000 feet. Smooth exfoliated walls characterize the lower slopes, and hanging glaciers have carved sharp arêtes and horns along the summits.

This, however, is a most impermanent portrait. Ice-dammed reservoirs are continually changing in form and dimensions. Slight climatic fluctuations influence the net accumulation or ablation of glacier ice, and this effect

[8] The lake, river, and glacier named "Tulsequah" have also been known by the name "Talsekwe," but this form is no longer used in official Canadian publications.

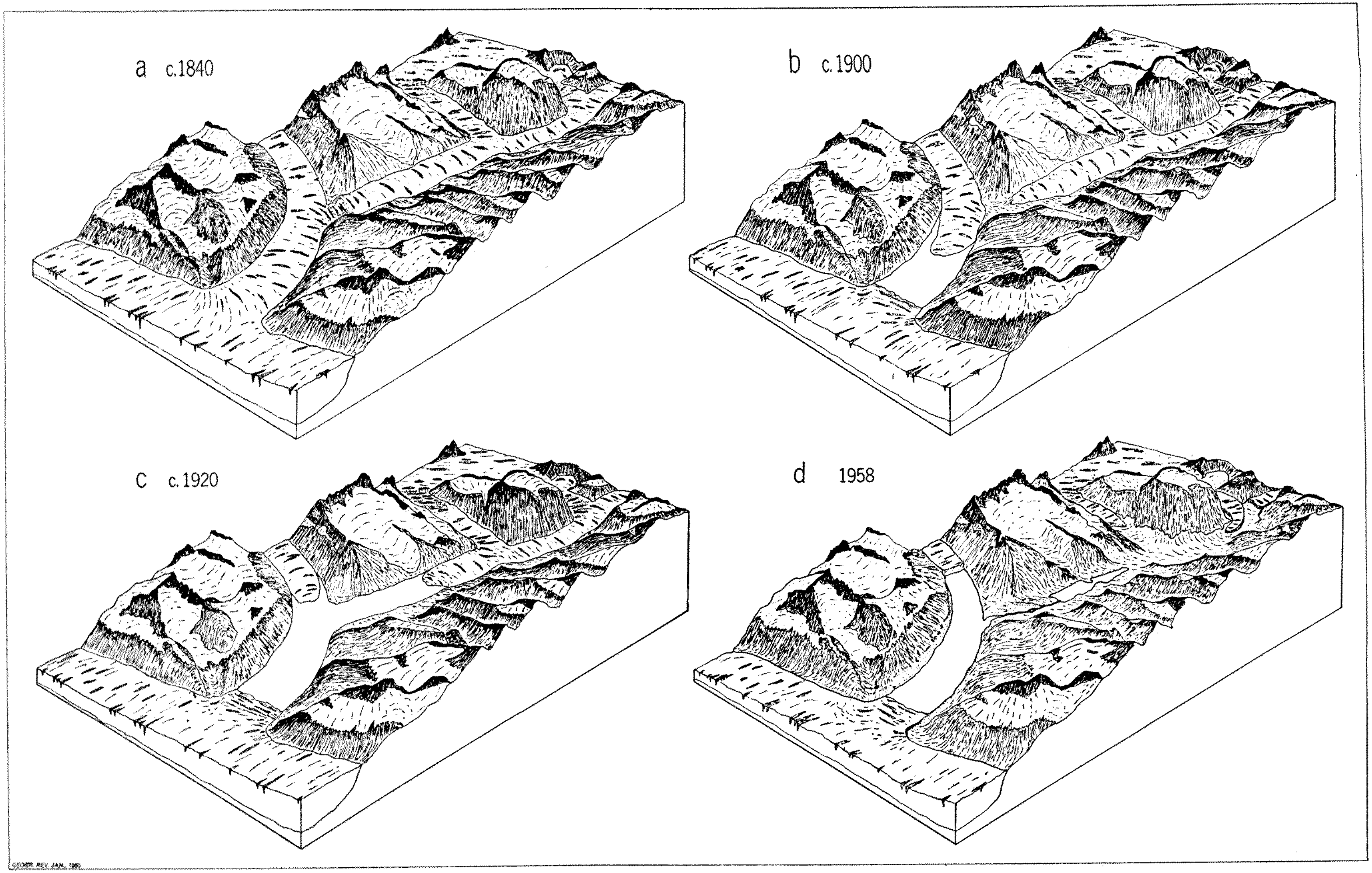


FIG. 2—Historical development of Tulsequah Lake.

is, in turn, magnified in the rapid contraction or expansion of glacier-dammed basins. Thorarinsson[9] has noted the relationship that exists in Iceland between glacier advance and the formation of ice-dammed lakes. Tulsequah-type lakes, on the other hand, are obviously associated with a general ice retreat. The reconstruction of Tulsequah Lake's historical development demonstrates this association.[10]

During the eighteenth and nineteenth centuries large volumes of ice spilled over the edge of the Juneau Ice Field into valleys tributary to Tulsequah Glacier (Fig. 2a). Heavier snow accumulation at lower elevations also increased glacier growth within the valleys. These feeder ice streams flowed steadily into the main Tulsequah trunk and attained a maximum height of 300 to 400 feet above the present valley floors.[11] About 1870, however, the glaciers began an accelerating retreat.[12] Lowering ice levels on the upper ice field reduced the overflow to small valley glaciers; in addition, less snow was accumulating in the warming, "rain shadow" tributary valleys. Tulsequah Glacier, with a larger and higher accumulation zone, receded more slowly. It thus formed an ice barrier across the valley recently vacated by its tributary (Fig. 2b). Surface runoff and glacial meltwater soon filled the gap between ice fronts, and calving stabilized distributary advance. The position of the ice dam has changed little since that time.

Sometime during this early phase of lake development, temporary equilibrium was achieved. A large cross-valley moraine, exposed only when the lake is drained (Fig. 9), indicates the terminal position of the tributary glacier at this time. For several years the lake filled only a 900- to 1200-foot gap between Tulsequah Glacier and the tributary. Subsequently the tributary glacier divided into separate tongues in the two upper valleys. The southwest tongue retreated more rapidly than the south tongue.

Tulsequah Lake reached its maximum depth of 640 feet by 1910. A photograph taken in that year (Fig. 3) shows the lake sometime after drainage. The high-water mark, visible along the valley walls, coincides with

9 Sigurdur Thorarinsson: [Vatnajökull: Scientific Results of the Swedish-Icelandic Investigations 1936-37-38] Chapter IX: The Ice Dammed Lakes of Iceland with Particular Reference to Their Values as Indicators of Glacier Oscillations, *Geografiska Annaler*, Vol. 21, 1939, pp. 216-242.

10 Although geological and botanical methods were the primary reconstruction tools, the observations of earlier investigators provided important verification of several points.

11 M. M. Miller: Preliminary Notes Concerning Certain Glacier Structures and Glacial Lakes on the Juneau Ice Field, *in* Scientific Observations of the Juneau Ice Field Research Project, Alaska, 1949 Field Season (edited by M. M. Miller; New York, 1952), *Amer. Geogr. Soc. Juneau Ice Field Research Project Rept. No. 6*, pp. 49-86; reference on p. 78.

12 D. B. Lawrence and J. A. Elson: Periodicity of Deglaciation in North America since the Late Wisconsin Maximum, *Geografiska Annaler*, Vol. 35, 1953, pp. 83-104; reference on p. 85.

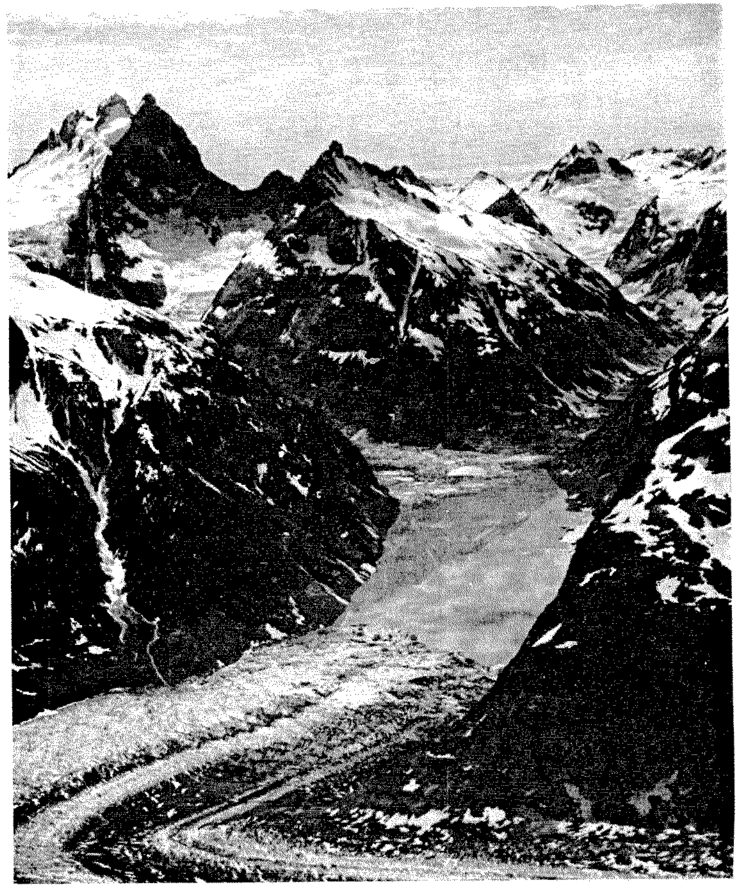


FIG. 3—Tulsequah Lake after drainage in 1910. The high-water line can be identified by the position of the stranded icebergs. Much of the ice in the upper valley is covered by moraine. (Photograph by International Boundary Commission.)

FIG. 4—Tulsequah Lake before drainage, July, 1955. The Juneau Ice Field plateau is directly behind the row of peaks on the horizon. The highest peak is the Devils Paw (8584 feet). (Photograph by Malcolm Greany.)

the highest strand remnants observed in 1958. Since Tulsequah Glacier maintained its vertical profile, high water remained constant at the maximum until about 1920. Volume increased, however, as the tributary glaciers retreated and enlarged the basin area. Maximum dimensions were probably reached between 1915 and 1920 when water filled two valleys to an estimated capacity of 239 billion gallons (Fig. 2c and Table I).

TABLE I—DIMENSIONS AND DRAINAGE, TULSEQUAH LAKE, BRITISH COLUMBIA

YEAR	MAXIMUM DEPTH		VOLUME (IN MILLIONS)			DATE OF DRAINAGE
	Feet	*Meters*	*Cubic feet*	*Cubic meters*	*U.S. gallons*	
1958	240	73	8,085	229	60,456	July 7–10
1957	—	—	—	—	—	Aug. 13–16
1956	256	78	8,821	250	66,000	Aug. 29–Sept. 1
1955	—	—	—	—	—	Sept. 4–7
1954	—	—	—	—	—	Sept. 11–14
1953	—	—	—	—	—	July 6–10
1952	—	—	—	—	—	Aug. 6–9
1951	—	—	—	—	—	July 26–29
1950	288	88	10,369	294	77,616	July 27–30
1949	—	—	—	—	—	Aug. 7–10
1948	—	—	—	—	—	July 23–27
1947	319	97	11,904	337	88,968	Aug. 5–9
1946	—	—	—	—	—	Aug. 4–8
1945	—	—	—	—	—	Aug. 8–11
1944	—	—	—	—	—	Aug. 15–19
1943	—	—	—	—	—	July
1942	349	106	13,438	380	100,320	July
1939	379	116	15,019	425	112,200	—
1932	—	—	—	—	—	Aug. 15–20
1930	475	145	20,432	578	152,592	—
1926	495	151	21,669	613	161,832	January
1910–1920	640	195	32,040	907	239,448 (maximum)	Summer (1910)

Sources of dates: 1932, Kerr, *op. cit.* [see text footnote 13 below]; 1942–1948, Stone, *op. cit.* [see text footnote 1 above]; 1949–1957, Consolidated Mining and Smelting Company of Canada Ltd.; 1958, field observation. Except for 1958, volumes must be considered estimates, since the precise positions of the tributary glaciers in a given year could not be determined.

Vertical ablation has gradually reduced the ice barrier since that time, and there has been an accordant annual drop in water level. By 1932 the lake level had lowered almost 200 feet. Forrest Kerr, a mining geologist, visited the site immediately after an outburst in that year. His description is vivid:[13]

Two days up the crevassed surface of the glacier brought us to the source of the flood—an awful place, an inferno of ice. On two sides of a great hole sheer granite walls rose to high, mist-wreathed peaks; on the third visible side was a section of the Talsekwe Glacier turned aside from the main valley. Its deeply crevassed mass merged with the

[13] F. A. Kerr: The Ice Dam and Floods of the Talsekwe, British Columbia, *Geogr. Rev.*, Vol. 24, 1934, pp. 643–645; reference on p. 645.

jumble of enormous ice cakes filling the hole—thousands of them, of all shapes and forms, creaking, cracking, and groaning as they settled on one another.

We could see where the water level had stood, about 900 feet above the outlet at the end of the glacier. The hole, formed by retreat of the glacier that once occupied this tributary valley and blocking of its mouth by the Talsekwe Glacier, was fully 3 miles long, 1 mile wide, and as much as, if not more than, 500 feet deep at the lower end. Into the rising lake that forms behind the dam the glacier discharges great icebergs.

Although the lake was frequently observed from passing aircraft, it was not revisited until 1949. By then it had achieved its present form (Fig. 2d). Subsequent reduction of the ice barrier has altered the dimensions of the lake (Table I), but not its essential configuration. The 1949 party, instead of coming up the glacier as Kerr had done, descended from the Juneau Ice Field. They remained in the vicinity of the lake for several hours but were unable to proceed farther than the southwest shore line. In his report Miller[14] commented:

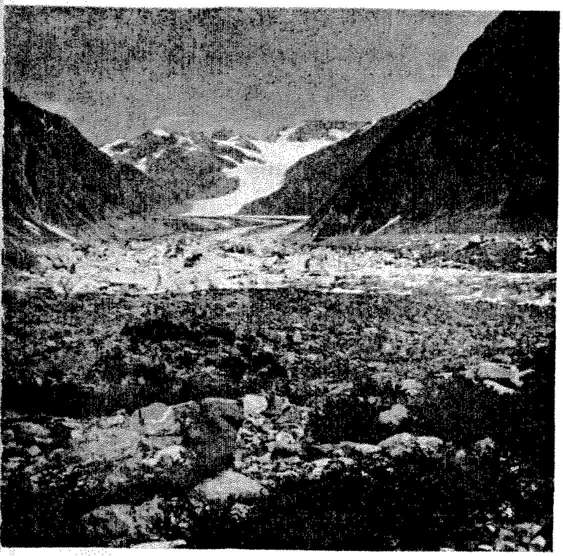
At the time of observation, the water level of this lake was seen to be at least 175 feet below a very prominent strand line upon (and below) which many stranded bergs could be seen. A countless number of bergs rested on the more gentle shore of the drained area to the west. These were scattered in profusion from the high water mark to the existing water's edge, and apparently had been left in these positions by the sudden release of water which had drained the lake exactly one month before.

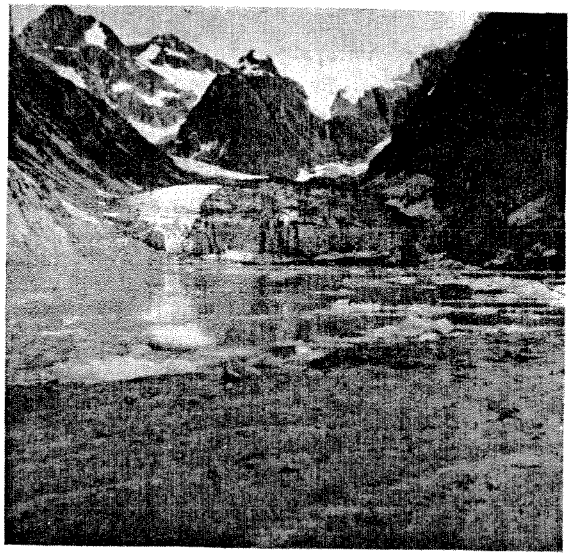
Tulsequah Lake continues to be a dynamic phenomenon, but its days as an ice-dammed lake must be numbered. If Tulsequah Glacier continues to recede, the impounded waters will eventually gain free egress to the lower valley. Only a remnant will remain—a shallow lake dammed by the earlier terminal moraine. Meanwhile, hydrologic and geomorphic processes will proceed at an accelerated rate. Outwash-imbedded bergs will leave kettle holes, unconsolidated sediments will shift and collapse, and the water will carry its perpetual load of ice and brown silt. A violent battle between constructive and destructive forces will continue until the ice barrier disappears and hydrologic forces return to relative stability.

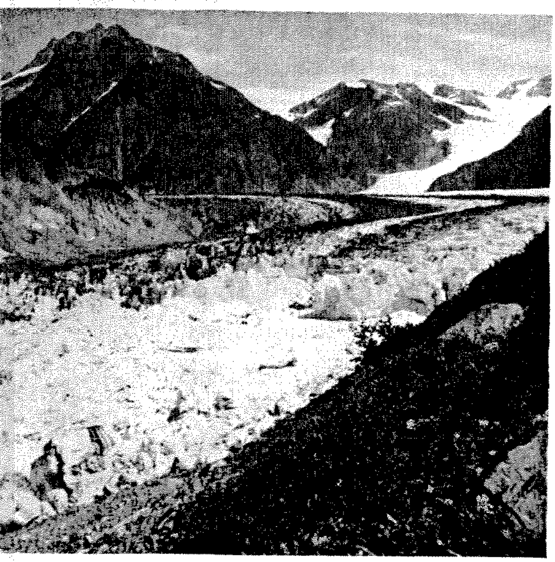
Drainage Frequency

Observers seem to agree that all Tulsequah-type lakes drain periodically, but except at populated sites the frequency and intensity of drainage remain conjectural. For reasons that will be explained later, it is believed that drainage frequency is determined by the rate at which the empty basin refills to

[14] *Op. cit.* [see footnote 11 above], pp. 77–78.







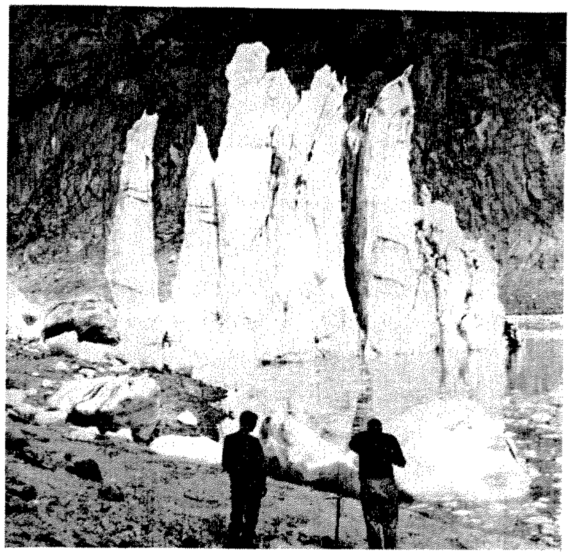


FIG. 5 (upper left)—Tulsequah Lake partly drained, July 9, 1958. The ice barrier is in the background. In the foreground is the oraine separating the upper and lower lakes.

FIG. 6 (upper right)—The southern end of Tulsequah Lake after drainage in 1958. Some water remains in the lake, dammed by moraine at the other end. The feeder glacier flows from the upper slopes of the Devils Paw complex. Its ice front, 225 feet high, has en sharply defined by calving during drainage. A small moraine shows frontal position before drainage began.

FIG. 7 (lower left)—Tulsequah Glacier ice barrier after drainage, 1958.

FIG. 8 (lower right)—Stranded iceberg after drainage, 1958. The berg is 125 feet high.

nine-tenths the height of its ice barrier. This rate is in turn controlled by climate, primarily by temperature and by the type and amount of precipitation. The annual march of temperature and precipitation indirectly regulates inflow through such factors as rate of glacier and snow-field melt, amount of snow storage, rate of direct surface runoff, and moisture availability. In 1958, for example, Tulsequah Lake emptied during the second week of July after an unusually warm winter and spring, whereas in 1955 heavy snow storage and late melting delayed drainage until the first week of September.[15] Similarly, a reported January outburst in 1926 can be attributed to an exceptionally warm winter preceded by heavy late-autumn rains.[16] There are, of course, many other meteorological combinations that also will unlock the floodgates.

Table I gives the recorded drainage dates for Tulsequah Lake. It is known that the lake has dumped annually since 1942. Lack of earlier recorded continuity prohibits precise comment, but it is suspected that annual refill must have been impossible during high-volume phases. On the basis of reservoir capacity and moisture availability, it is estimated that outbursts occurred every two years between 1900 and 1930. In the nineteenth century drainage was probably annual. There is no reason to believe that the lake has not drained at least periodically since youth.

Drainage Mechanics

The way in which water is released from Tulsequah-type lakes has been, and remains, hypothetical. There are two reasons for this. First, it is almost impossible to predict the exact day on which drainage will begin. Investigators have usually studied jökulhlaups as an interesting side line to the party's main problem. To make observations before, during, and after drainage requires either incredible luck or devotion of the entire field season to the lake site. Even in the latter case, there is no guarantee that the lake will drain. Past studies have therefore been based primarily on "before" and "after" conditions.

Second, even though the investigator is at the lake during drainage, he

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[15] Unpublished meteorological observations for Tulsequah Mine, British Columbia, furnished by the Consolidated Mining and Smelting Company of Canada Ltd., were used for most climatic comparisons. United States Weather Bureau observations at Annex Creek and Juneau in Alaska were also used.

[16] The 1926 outburst was reported to George Bacon of Tulsequah, British Columbia, by an early prospector. The prospector stated that floodwaters rose 12 feet and that huge ice blocks were carried many miles downstream. It is not known whether this was a true jökulhlaup, but climatic data seem to corroborate the statement. The normally small winter discharge and/or frozenness of the Taku River also lend credence to the story.

will still encounter difficulties. He can measure changes in water level and make other surface observations, but he cannot see the points of egress or trace subsurface escape routes. When the lake begins to drain, the ice barrier's floating tongue collapses and breaks into thousands of pieces. These range in size from minute particles to gigantic ice blocks measuring several hundred feet on a side. The resulting pile-up effectively screens the contact of water and ice (Fig. 7). Later, when the lake has drained, the area remains too unstable to permit safe investigation at close hand.

These difficulties were experienced in 1958. The field party did not arrive at the lake site until the fifty-sixth hour of the jökulhlaup. Changes in water level were measured for the remaining drainage period (Fig. 10). Fortunately, aerial photographs showed five water stages during the first two days. Stage, water temperature, and sedimentation records for Canyon Island (Fig. 1) provided excellent corollary information. Backwater measurements at the Tulsequah Gaging Station were also used.[17] Ground control was established after drainage, and a bathymetric map was plotted from aerial photographs (Fig. 9). Volumes and discharge were then computed. Measurements were not as precise as might have been desired, but it is believed that they provide a reasonably realistic picture of local bathymetry and hydrology.

Several investigators have attempted to explain Tulsequah-type outbursts. Kerr[18] believed that water escaped from Tulsequah Lake through a tunnel in the rock, which was later plugged by icebergs. The existence of such a tunnel seems unlikely in view of local rock types, and it is unreasonable to expect rock tunnels at every dumping lake. Miller[19] has suggested that Tulsequah water is released in a manner similar to the Lake George outbursts near Anchorage; that is, water builds up until its surface level reaches the level of the glacier, when it spills over and cuts a channel in the ice. Careful observation of the glacier surface and its lateral boundaries revealed absolutely no surface escape. It came as a surprise, in fact, that no upwellings or escape holes were evident anywhere along the 4½-mile route. Since this is a relatively shallow glacier, the subsurface pipes must be at or very near the glacier floor. The ice downstream from two dumping lakes impounded by Gilkey Glacier (Fig. 1) was observed later in the summer. No signs of surface discharge were seen, but the glacier surface was collapsed

[17] The Tulsequah Gaging Station is actually on the Taku River, about a mile upstream from its confluence with the Tulsequah River.

[18] *Loc. cit.* [see footnote 13 above].

[19] *Op. cit.* [see footnote 11 above], pp. 79–80.

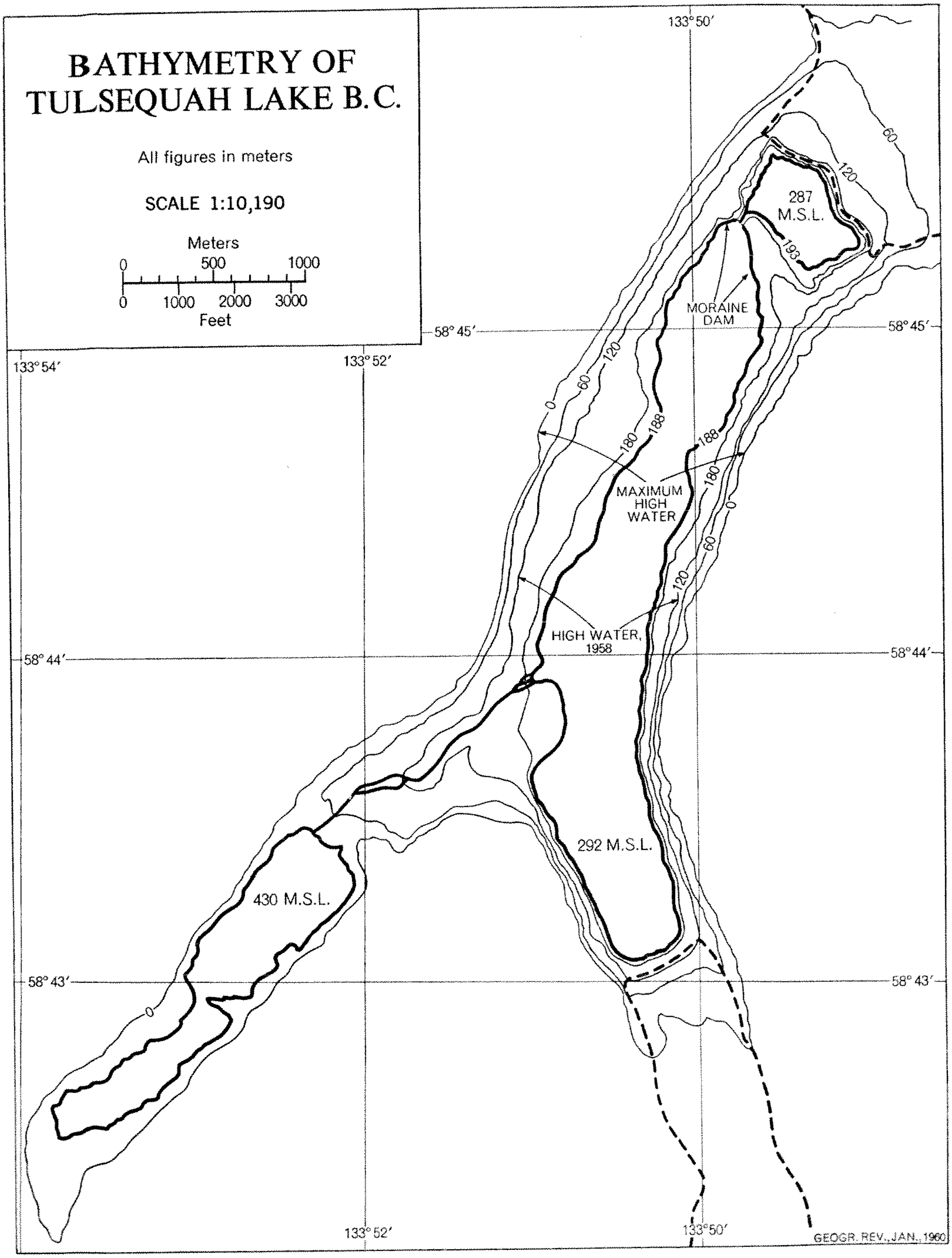

FIG. 9—Bathymetric map of Tulsequah Lake, redrawn from map surveyed and plotted by the author from aerial photographs taken by the Royal Canadian Air Force in 1958. The "0" level is 480 meters above mean sea level and represents the highest historical level of the lake; the 120-meter level represents the level of the lake before the 1958 outburst; the intermediate contours represent the various levels of the lake as the water drained out; and the 188-meter and 193-meter contours delineate the surface of the lake in front of and behind the moraine dam after the outburst. The dashed lines indicate the glacier boundaries. Specific elevations above mean sea level refer to the low-datum level and do not represent depths.

along its longitudinal axis, an indication, perhaps, of the existence of a similar subsurface escape route.

Thorarinsson[20] has proposed another theory, namely that water rises until it is nine-tenths the height of the ice barrier, after which it floats the barrier and is released. The usual criticism is that outflow would stop as

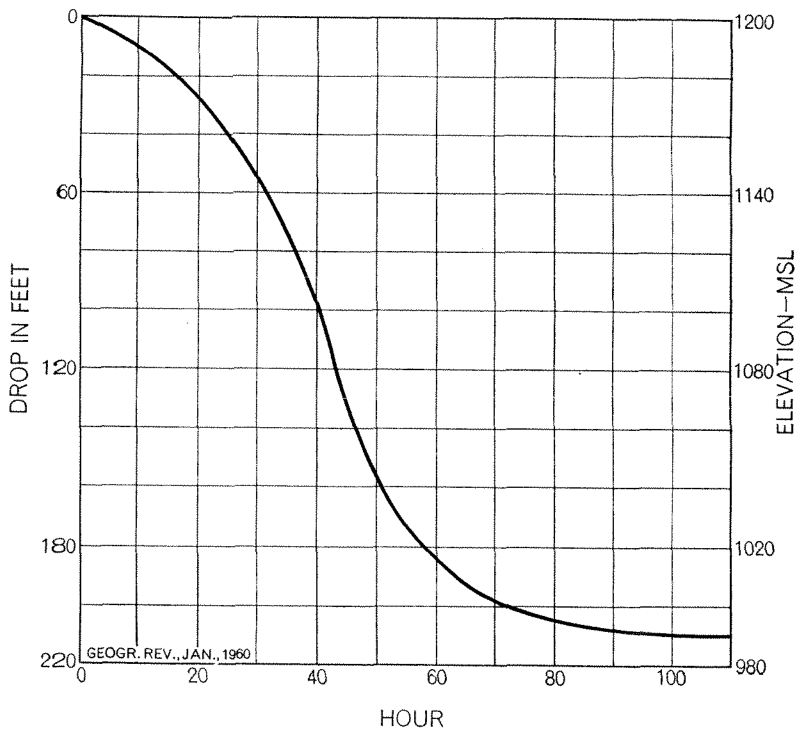

FIG. 10—Drop in surface level of Tulsequah Lake between 12 noon, July 6, and 2:00 p. m., July 11, 1958.

soon as the water level fell below nine-tenths of the barrier height.[21] The basin would then quickly refill to the critical level and trigger another release. Continuous minor oscillations of escape and closure would result. Moreover, it is unlikely that several miles of glacier ice could be floated at once. Although there is reason to discard this theory as an explanation for total catastrophic drainage, certain important relationships can be in-

[20] *Op. cit.* [see footnote 9 above], pp. 221–222.

[21] See, for example, J. W. Glen: The Stability of Ice-Dammed Lakes and Other Water-Filled Holes in Glaciers, *Journ. of Glaciology*, Vol. 2, No. 15, 1954, pp. 316–318, reference on p. 318; Olav Liestøl: Glacier Dammed Lakes in Norway, *Norsk Geogr. Tidsskrift*, Vol. 15, 1955–1956, pp. 122–149, reference on p. 123.

ferred from it. It is known that the advancing barrier of Tulsequah Glacier floats. From a study of aerial photographs of similar sites it can be seen that this is probably a common characteristic. At high-water stages the leading tongue is heavily crevassed, a phenomenon usually associated with extreme bed disturbance. Since the barrier ice flows near the horizontal or slightly uphill (a low-stress situation), the breakage must have some other cause; for example, frontal collapse when the lake empties (Fig. 11). Some ice is

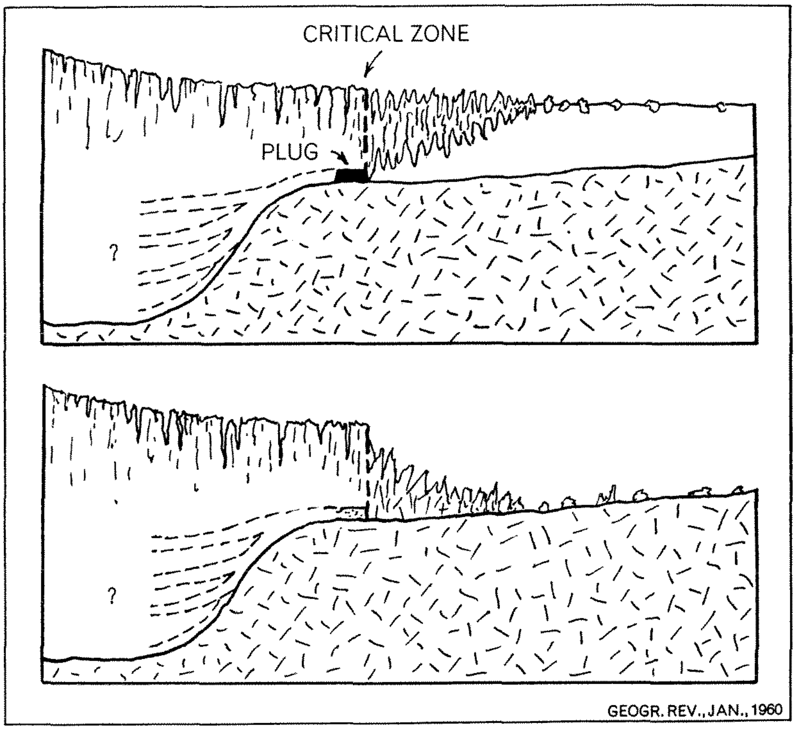

FIG. 11—Cross section of the ice barrier. In the upper view, the lake is filled with water, and heavily crevassed ice floats beyond the critical barrier. After drainage (lower view), the floating mass collapses. This accounts for extreme ice breakage in a zone of slight bed disturbance. Note the assumed position of the ice plug.

completely severed from the collapsed mass, but the remainder will refloat as the basin refills. At some point, however, there must be a critical zone where the ice is in contact with the rock floor and unable to collapse. This is easily identified by the sharp division between heavily and normally crevassed zones. When the water reaches nine-tenths the height of this critical zone, that ice also will be lifted, perhaps only momentarily and imperceptibly. This will give the water temporary access to a small area of the glacier floor and will change the water from a hydrostatic to a hydrodynamic force. If the water can open routes through the ice, glacier buoyancy will no longer be a requisite of escape. Instead, it will merely have triggered the outburst.

Glen[22] has suggested that a triggering mechanism is unnecessary; that water with a sufficient hydrostatic head can enlarge its own passageways. This, he says, should occur at about 200 meters' depth when water pressure is sufficiently greater than adjacent ice pressure to produce a shear force of one bar. The shear force should then open a tunnel in the ice barrier. This theory was developed empirically from ice-flow theory.[23] It does not seem to provide a satisfactory answer. In the first place, the hydrostatic head at Tulsequah Lake was only 73 meters in 1958. A head of 200 meters could not have developed even if an opening extended beneath the ice barrier, since only 210 meters separated the high-water level and the Tulsequah Glacier tongue. It remains problematical whether water pressure in deeper lakes can open and enlarge tunnels. Even with two or three bars of shear stress, the rate of enlargement would be slow. A 4½-mile tunnel could not be opened in one year, let alone in a few weeks or days. This is even more unlikely at the Gilkey Glacier lakes, which stand 10 miles above the glacier terminus. Furthermore, if these relationships between water and ice do exist, the tunnel should close up as soon as the hydrostatic head is lowered. As in the buoyancy theory, drainage oscillations would result. This is not the case. The Tulsequah tunnels remained open throughout the summer after the jökulhlaup. This was verified by the downstream escape of water when a 10-foot-high section of the moraine dam collapsed in August.

Liestøl[24] has suggested that, if water can in some way force a passage beneath the ice barrier, it will be able to extend and enlarge a tunnel by melting. This theory was applied to the Tulsequah problem and, with certain qualifications, seems to provide a reasonable explanation of drainage mechanics. First, it is assumed that water succeeds in forcing its way under the ice because of flotation of the critical barrier zone. Liestøl believes that passages are opened by the movement of ice along an uneven basement. Perhaps both factors exert an influence. Second, the subsurface outlets must be plugged in the critical zone by freezing. It is known that the tunnels remain open in the summer, but autumn freezing of the berg pile and the ice-clogged pipe openings seems likely. Third, subsurface tunnels must remain partly open throughout the year. If these assumptions are correct, and there

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[22] *Op. cit.* [see preceding footnote], p. 317.

[23] J. W. Glen: Experiments on the Deformation of Ice, *Journ. of Glaciology*, Vol. 2, No. 12, 1952, pp. 111–114; J. F. Nye: The Flow Law of Ice from Measurements in Glacier Tunnels, Laboratory Experiments and the Jungfraufirn Borehole Experiment, *Proc. Royal Soc. of London*, Ser. A, Vol. 219, 1953, pp. 477–489.

[24] *Op. cit.* [see footnote 21 above].

are indications that they are, melting could account for tunnel enlargement.

In 1958 maximum lake discharge was 1556 cubic meters per second (55,000 cubic feet per second) (Fig. 12). From this figure it was possible to compute the cross-sectional tunnel area necessary to accommodate peak flow at different velocities (Table II). Total tunnel volume was also computed in each instance. By using Liestøl's method, the amount of ice that could be melted at each velocity was determined by the formula $m_i = (PE-KE)/80\ k$, where m_i is the ice melted, PE the potential energy of the water, KE the kinetic energy, and k the conversion factor from calories to ergs. Figure 13 demonstrates the relationship between volume of

TABLE II—VELOCITY AND MELT RELATIONSHIPS, TULSEQUAH LAKE, BRITISH COLUMBIA

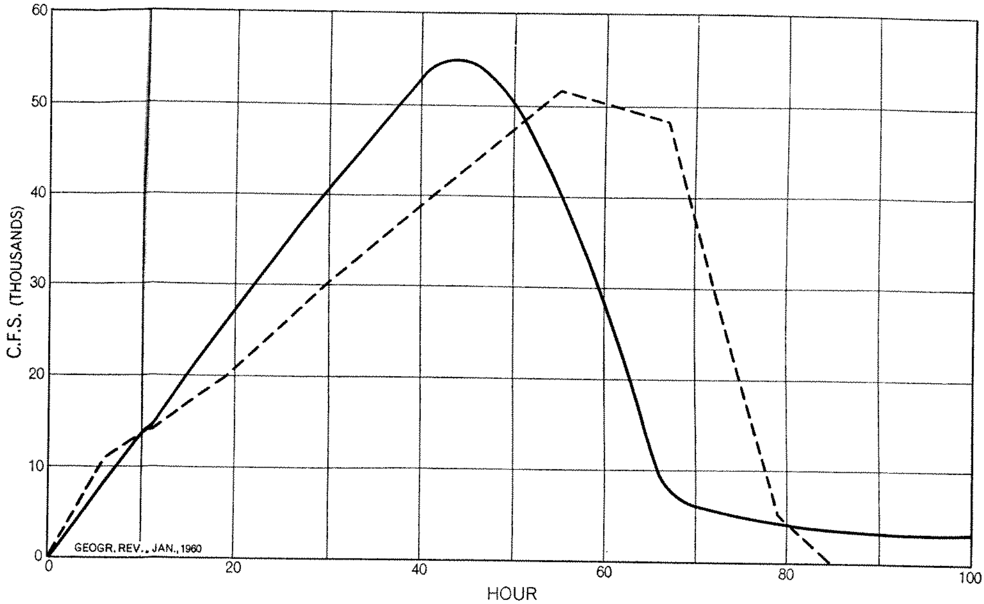
v		a_c	V	a'_c	V_m	
kph	m/sec	(square meters)	(millions of cubic meters)	(square meters)	(millions of cubic meters)	$\frac{V_m}{V} = \frac{a'_c}{a_c}$
5	1.4	1,112	8.062	123	0.886	11%
10	2.8	556	4.031	123	0.885	22
15	4.2	370	2.683	122	0.882	33
20	5.6	278	2.016	121	0.880	44
25	6.9	226	1.639	121	0.876	54
30	8.3	187	1.356	120	0.871	64
35	9.7	160	1.160	119	0.866	75

NOTE. v is velocity in kilometers per hour and meters per second; a_c is the tunnel cross section necessary to accommodate peak flow at a given velocity; V is the tunnel volume necessary to accommodate flow at a given velocity; a'_c is the tunnel cross-section area that the water is capable of melting at a given velocity; V_m is the volume of ice that would be melted at a given velocity; $V_m/V = a'_c/a_c$ is the percentage of necessary tunnel volume or cross-section area that would be melted at a given velocity.

ice melted and stream velocity within Tulsequah Glacier. It should be noted that there is little difference in the amount of ice melted at different velocities. Also, only 66 per cent of flow occurs before peak discharge (Fig. 12). This means that only 66 per cent of the energy is applied to tunnel enlargement before maximum tunnel needs are met.

Dividing ice-melt volume by total tunnel volume gives the percentage of space opened by melting. It will be seen from Table II that tunnel cross-section requirements decrease as velocity increases. Accordingly, melting accounts for a higher percentage of tunnel enlargement as velocity increases. Thus, at 5 kilometers per hour, only 11 per cent of a large-diameter tunnel would have been enlarged, whereas at 35 kilometers per hour 75 per cent of a small-diameter tunnel would have been enlarged. Although velocities of the subsurface streams are unknown, it is reasonable to assume that they flow between 20 and 35 kilometers per hour during the outburst. If so, the tunnels would be enlarged from two to four times their original size. Afterward, ice plasticity and collapse would partly reclose them.

The preceding computations have been based on flow through a single ideal tunnel by water at 0° centigrade. Higher water temperatures would



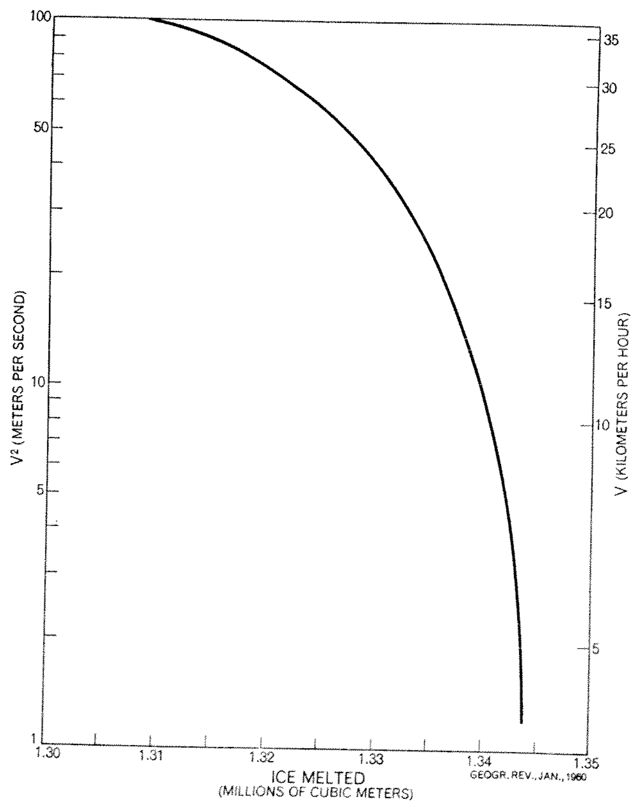


FIG. 12 (above)—Tulsequah Lake discharge in cubic feet per second from 12 noon, July 6, to 4:00 a. m., July 11, 1958. Discharge is shown by the solid line. The dashed line represents Canyon Island stage readings adjusted to this graph. Note the lag between lake drainage and the downstream flood wave.

FIG. 13 (right)—Ice-melting capabilities of the Tulsequah Lake discharge plotted against stream velocity. Melting ability approaches zero as the square of the velocity increases.

increase the quantity of ice melted. Also, it is known that subsurface drainage takes place through a complex of pipes. Five separate outlets disgorged water from the terminal tongue during the outburst. Two of them discharged most of the water, yet they were a kilometer apart. Maximum discharge shifted, in fact, from one pipe to the other on successive days. It can therefore be assumed that the glacier interior is honeycombed by pipes and channels of all sizes. This does not affect the computations, since the total units remain unchanged.

It is apparent that Tulsequah-type lakes do not drain according to a single, simple principle. Jökulhlaups are produced by a complex of interdependent forces, all acting in definite sequence. If one set of conditions is not met, the others will not follow. The first requisite is, of course, site. The lake basin can form only during a brief, transitory phase of glacial history. Even then, factors of topography, slope, elevation, and local climate exert control. A variation in any one of these factors may either increase lake dimensions or prevent lake formation entirely. Once established, the lake begins to record climate. The slightest changes in climate and glacial activity are immediately reflected in its fluctuating shore line. Short-term temperature and precipitation trends can be read in its drainage frequency. In short, accelerated geomorphic processes tell the dynamic story of landscape and climate.

At Tulsequah Lake a new chapter is added each year. During the spring and summer the lake fills with water until it is capable of floating its ice barrier. It is believed that, as the barrier lifts, water moves along the glacier floor to remnant subsurface pipes left partly open from the preceding year's outburst. Old channel plugs are either bypassed or reopened. The ice barrier resettles on its rock floor, but continuous flow has been established, and the escaping water will enlarge its tunnels by melting the walls. At the completion of drainage, the pipes gradually begin to close. The process is never completed, except that the barrier outlets do become totally plugged during the autumn freeze. When the lake refills, the process is repeated.

Admittedly, much of this is hypothetical. The subsurface hydrology of glaciers remains one of the great mysteries of glaciology, and our knowledge of it is confined to "educated guesswork." It is known that subsurface drainage is complicated, that water undoubtedly flows through a tortuous maze of channels, that slope and velocities vary, and that ice structure and bedrock configuration influence flow. No further categorical statements can be made. Surface observations do, however, provide valuable clues to subsurface behavior. It is believed that the 1958 data provided enough clues to corroborate the hypothesis.